Bjørnar Veie

Balancing Solar Energy and Load Consumption given Different Load Consumption Profiles

Master's thesis in Cybernetics and Robotics

Supervisor: Geir Mathisen

June 2020

Master's thesis

NTNU

Kunnskap for en bedre verden

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Department of Engineering Cybernetics

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MASTER THESIS DESCRIPTION

Candidate: **Bjørnar Veie**

Course: **TTK4900 Engineering Cybernetics**

Thesis title (Norwegian)   **Balansering av solenergi og forbruk gitt forskjellige forbruksprofiler**

Thesis title (English):   **Balancing Solar Energy and Load Consumption given Different Load Consumption Profiles**

Thesis Description: We want to study how well electric power from local solar power plants in Trondheim balance with the local demand for electric power. The study will be about load demand at three different sites belonging to respectively the industrial, the commercial and the residential sector.

An economic analysis of balancing the load data with the solar power in the three different sectors shall be performed. This analysis shall also treat the potential benefits of using electric batteries to compensate timely imbalance. In connection with this, a method for controlling the batteries should be proposed.

To better communicate the results, a visualization of the solar power and load demand for electric power, in the form of a graphical user interface, should be developed.

The tasks will be:
1. Perform a literature study of the possibility and used methods for load balancing with solar power.
2. Plan and implement the data acquisition concerning electric load demand and solar power production
3. Suggest a method for using electric batteries and a demand response method to support balancing of load demand and production from solar panels, based on the acquired data.
4. Implement the methods described in point 3. The implementation should include a visualization of the data and results.

Start date: 11. January, 2020
Due date: 25. June, 2020

Thesis performed at: Department of Engineering Cybernetics
Supervisor: Professor Geir Mathisen, Dept. of Eng. Cybernetics

Abstract

In the years to come there will be a growing strain on the power grid because of the massive focus on electrification in the society today. To be able to prevent the grid problems in a cost effective way both for the power grid companies and the end customers, new demand response and demand side management methods needs to be developed and used together with distributed power sources to lower the strain on the power grid. This thesis uses real load data from the industrial, commercial and residential sector and real solar power data from Trondheim to study if it is possible to reduce the strain on the grid in a cost effective manner in Trondheim, Norway. The thesis uses solar power plants and a load shifting strategy to lower the peak load and increase the potential economic savings. The thesis simulates many different solar power plant sizes to find a suitable size for the load data in each sector. The possibility of using batteries to boost the potential upsides of the PV power plant is also examined.

The key results show that there is potential to both reduce the peak load and to save money by doing so. The installation of a PV power plant is an expensive investment, but in the long term it will prove to be cost effective. The potential is largest in the commercial and industrial sector, while it is not as cost effective in the residential sector. The load shifting strategy also provided positive results, effectively helping to reduce the peak load and to increase the possible earnings. The drawback of the load shifting strategy is that some of the flexible load needs to be delayed for a period. The use of batteries did not prove to give any significant benefits in this thesis.

Sammendrag

I de kommende årene vil presset på kraftnettet øke på grunn av den storstilte elektrifiseringen som skjer i samfunnet i dag. For å forhindre de potensielle problemene dette medfører for kraftnettet på en kostnadseffektiv måte for både kraftselskapene og kraftkundene, må nye forbrukerfleksibilitetsmetoder og forbrukerstyringsmetoder bli utviklet og brukt sammen med distribuerte kraftkilder for å minske presset på kraftnettet. Denne avhandlingen bruker ekte lastdata fra den industrielle sektor, den kommersielle sektor og boligsektoren sammen med ekte kraftproduksjonsdata fra solcelleanlegg i Trondheim for å studere om det er mulig å redusere presset på kraftnettet på en kostnadseffektiv måte i Trondheim, Norge. Avhandlingen bruker solcelleanlegg og en lastforskyvningsmetode for å minske topplasten og for å øke potensielle økonomiske innsparinger. Avhandlingen simulerer flere forskjellige størrelser på solcelleanlegg for å finne en passende størrelse til de gitte lastdataene i de forskjellige sektorene. En undersøkelse om muligheten for å bruke batterier for å øke de potensielle oppsidene ved et solcelleanlegg er også gjennomført.

Hovedresultatene viser at det er mulig å minske topplasten og å spare penger. Installering av et solcelleanlegg er en veldig stor investering, men i det lange løp kan det vise seg at det er en kostnadseffektiv investering. Potensialet for topplastreduksjon og pengeinnsparing er størst i den kommersielle og den industrielle sektoren. Lastforskyvingsmetoden ga også gode resultater, ved å senke topplasten og øke den potensielle økonomiske gevinsten på en enkel, men effektiv måte. Ulempen ved å bruke lastforskyvingsmetoden er at noe av den fleksible lasten må bli forskjøvet og forsinket i en liten periode. Bruken av batterier viste seg å ikke gi noen signifikante fordeler i denne avhandlingen.

Preface

This thesis is submitted as the completion of my Master of Science degree at the Department of Engineering Cybernetics at the Norwegian University of Science and Technology. This thesis is loosely coupled with my work in the specialization project completed in TTK4550.

All the work done in this thesis is conducted by me between the start date and the due date of this thesis with two exceptions. Firstly, the use of the AMS Logger and code developed by Marius Lervik [Ler19]. His code is slightly altered by me to fit the work done in this thesis. Secondly, the use of code for downloading solar power data from one solar power plant in Trondheim, which was developed during my specialization project last semester. The use of additional Python libraries in the development of the software used in this thesis will be specified in the implementation chapter.

Acknowledgements

I want to thank Geir Mathisen, my supervisor during this thesis for giving me the opportunity to write this thesis. He provided me with the necessary equipment to be able to complete this thesis, and was also available to manage other practical details during the thesis work. I also want to thank Kjeldsberg Eiendom, and especially Sondre Leonhardsen for all the help during the thesis work. They provided me access to data from their PV power plants and gave me permission to measure load demands in some of their buildings both in the commercial sector and the industrial sector.

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Abbreviations

NTNU	=	Norges teknisk-naturvitenskapelige universitet
AMS	=	Advanced Metering System
HAN	=	Home Area Network
DSM	=	Demand-Side Management
DR	=	Demand Response
Li-Ion	=	Lithium-Ion
NaS	=	Sodium-Sulfur
PV	=	Photovoltaic
NYSERDA	=	New York State Energy Research & Development Authority
NYISO	=	New York Independent Service Operator
IEA	=	International Energy Agency
BESS	=	Battery Energy Storage Systems
MPC	=	Model Predictive Control
HVAC	=	Heating, Ventilation and Air Conditioning
S	=	South
SE	=	South-East
WE	=	West
GUI	=	Graphical User Interface
NaN	=	Not a Number
W	=	Watt
Wp	=	Watt-peak
Wi-Fi	=	Wireless Fidelity
Wh	=	Watt hours
k	=	kilo
SSR	=	Self Sufficiency Ratio

Chapter 1

Introduction

1.1 Background and Motivation

The current focus on electrification to reduce the impact fossil power have on the environment is going to cause problems for the power grid as we know it today. The power grid is not dimensioned to be able to meet the peak electric power demand in the future, and it is therefore necessary to examine methods to lower the pressure on the power grid. The methods used to lower the pressure on the grid also needs to provide economic incentives to the end customers so they are willing to use these methods. Therefore, studies on real load demand data are necessary to find simple methods to achieve these goals and lower the cost and ease the transition from today's power market to the power market of the future both for the end customers and the power companies managing the grid.

Usage of distributed power sources such as photovoltaic (PV) power can help reduce the impact of fossil power and the dependency of the grid. Such distributed power sources are very volatile, and with no way to prevent overproduction and underproduction, the presence of the power grid is still necessary. Installation of batteries can help reduce the volatility of the PV power plant, but not mitigate it completely.

This thesis will give an examination of the problem and a proposed solution for lowering the grid dependency. By developing an application with a graphical user interface (GUI) it will be possible to visualize the data and the results. To be able to perform an analysis, load data must be gathered, and a big part of the thesis work will be to make the data collection possible and efficient. At the end of the thesis, some insight should be provided in the economic viability of using PV power plants and batteries in Trondheim for lowering the dependency on the grid. The thesis will also bring some insight in demand response methods to lower the peak load from the grid.

1.2 Limitations and Focus

1.2.1 Lack of Data

The biggest limitation of this thesis is the lack of data. The thesis work started in January and lasted until June, so the amount of data possible to collect was limited. The load demand of the buildings used for data gathering in this study is expected to be different in different parts of the year, but it was not possible to gather data for a longer period due to the duration of the thesis work. In addition, a lot of factors, including the coronavirus, made the gathering of data delayed and more difficult. However, sufficient data is available for a preliminary analysis.

1.2.2 Data Quality

The data quality may also not be perfect because of the coronavirus. Some of the appliances that load data were gathered from for usage in this thesis did not have normal operation in the collection period. The reason for this is that some of the facilities were these appliances were situated were closed down because of the coronavirus. The ventilation in these facilities, which was the subject for data collection and monitoring was also switched off or not in normal operation for most of the data collection period.

1.2.3 Methods and Model Quality

The methods and models used in this thesis are not complete, and due to lack of time and relevancy in this thesis, some assumptions were needed to be made to simplify the models. This leads to some models being incomplete and not 100% realistic, but for the scope of this thesis they are sufficient. It should still be noted that there are shortcomings in some of these models and methods, which will be highlighted when the models and methods are presented and in the discussion chapter.

1.2.4 Focus

Since there is a lack of data from most of the year, and the data quality may be mixed, the thesis focus on the data which is considered reliable. Also, since no load data were collected prior to this thesis, the data collection was a big part of the thesis, so some focus during the thesis work was to develop an effective way to perform data collection. Another big part of the thesis work was to develop an application which was user friendly and easy to use, so it may be used by other students after this thesis is completed. The methods and models used for simulation in this thesis are by no means complete, so the analysis of the data will also not be complete, but an initial analysis of the data is performed in this thesis.

1.3 Contribution

This thesis contributes with an initial examination of the possible economical gains in Trondheim for using a PV power plant and a battery to reduce the need for power from

the grid. It is also developed a method for reducing the peak load demand from the grid. The usage of both real PV power data and real load demand data is a strong point for this thesis, since not all studies in this field are conducted with real data. The diversity of data is also a strong point, since it is collected load demand data from commercial, industrial and residential buildings. This diversity in data can help identify the sector where it is most beneficial to use PV power plants, batteries and load management methods to subsidize the grid power. The application developed during this thesis work can be used to visualize and simulate with your own data with some small adjustments. The application can help visualize the potential of a PV plant installation or a demand response method, to help the decision making and see potential benefits.

1.4 Disposition

The thesis starts with some basic theory and a literature review, where fundamental concepts needed to understand the contents of this thesis and similar studies and their results are presented. Afterwards, the method used to solve the tasks in this project is presented, together with the models used to make the solving of these tasks possible. Next, the implementation of the method is presented. Then, the key findings in the thesis are presented, before they are further discussed. At last, a conclusion and some suggestions for further work is given.

Chapter 2

Literature Review and Theory

This chapter lays the groundwork for understanding the field of study that this thesis is a part of. The chapter starts with an introduction to concepts that are necessary to define and describe before the reader engages in the rest of the thesis. After this first section, the rest of the chapter is a mix of a literature review, and some more theory concepts.

2.1 Basic Theory

2.1.1 Smart Grids

The smart grid uses two-way flows of electricity and information to create a distributed automated energy network. A smart grid can respond to events that occur on the grid, such as power generation, consumption, transmission and distribution, and adopt strategies corresponding to these events. Although a precise and comprehensive definition of smart grids has not been proposed yet, a specific explanation of the smart grid vision may be that a smart grid can be regarded as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to accomplish a system that is clean, secure, safe, reliable, and sustainable [FMXY12].

[FMXY12] further states that a smart grid may be divided into three major systems, smart infrastructure systems, smart management systems and smart protection systems. The smart infrastructure system is the underlying energy, information and communication infrastructure of the smart grid. It supports the aforementioned two-way flow of electricity and information, which is essential to the smart grid. This way, users can transfer electricity back to the grid if they generate an excess amount of solar energy from PV power plants. The backward flow is also important during power failures where smart grids may function at a reduced rate by using the energy produced by the user. The smart management system provides management and control services. By using the grids infrastructure it can keep on becoming smarter by developing new management applications and services. The smart protection system provides grid reliability analysis, failure protection,

and security and privacy protection services.

2.1.2   Demand Side Management

Demand side management (DSM) is an approach aimed at consumers, to make them energy efficient in the long term. According to [BC14], DSM frameworks are designed to manage the electric resources of users through a specific architecture, composed by the following components:

- Local generators: Energy plants such as PV power plants that can generate electric energy which in turn can be used locally or be sold back to the grid.

- Smart devices: Electric appliances that are able to monitor themselves, providing data such as energy consumption to a user.

- Sensors: Used to monitor data of interest such as temperature, air quality or light.

- Energy storage systems: A storage device that allow the DSM system to be flexible in its managing of electric resources.

- Energy management unit: This unit needs to define the schedule of appliances, the operation strategy of the energy storage system and the demand and supply profiles.

All of the components are connected trough a communication infrastructure.

Advantages of Demand Side Management

In [LCS17], the advantages of DSM in the electricity market are outlined. DSM can promote efficient operation of the market and restrain market power. DSM can realize instant information exchange about supply and demand, produce more reasonable and transparent transactions, speed up and improve the formation of an electricity price mechanism. DSM can also relieve demand congestion during peak hours and improve the reliability of the power system. It can ease investment pressure on power generation, transmission and distribution. Finally, DSM can greatly impact new prospects for the realization of energy conservation and reduction of emissions.

2.1.3   Demand Response

Demand response (DR) refers to actions taken by the consumer that use market price to influence the level and time of electricity demand. It is a change in normal consumption patterns in response to changes in the electricity price over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [LCS17].

Demand response can provide economic incentives to promote other projects as energy efficiency and energy storage in demand side management. Demand side management can boost and amplify the economic effectiveness of demand response [LCS17].

2.1.4   Categories of Demand Response Services

According to [LCS17], demand response can generally provide five services to an energy system. These five services are described in the following subsections.

Peak Clipping

Clipping the energy demand at a certain threshold. This threshold may be the threshold of the supply capacity or the threshold of the thermal requirements of the transmission system. This can be realized with direct load control, such as turning down the thermostat of a heater. There may also economic incentives for peak clipping, such as reduction of the peak load in energy systems where the energy price is proportional to the peak load.

Valley Filling

When the demand is low, which is not favorable for system stability, the load demand should be increased. This can be done by adding storage devices, such as thermal storage for heaters. This increases the total power consumption, but may not necessarily increase the bill.

Load Shifting

When the load is higher in a certain period, a portion of the load may be moved from that period to other periods. This relies on that you have appliances that may be postponed such as use of washing machines. Load shifting can both be done on a daily basis, where the load is shifted from peak time to off-peak time, or on a seasonal basis, between summer and winter. Load shifting does not reduce the total consumption, only time of use.

Strategic Conservation

This method may be used when the overall load exceeds the supply level. Customers are encouraged to reduce their consumption. This can be done on a small scale with replacement of traditional devices with devices which are more energy efficient, or on a larger scale. Providing consumption and cost details may also bring down the power consumption.

Strategic Load Growth

When the demand falls below the normal level of energy supply, the customers are encouraged to increase their consumption. Electrification technology, the term used for the new emerging electric technologies, has the potential to achieve this (e.g., the popularization of electrical vehicles). This may reduce the use of fossil fuel and give an overall lower resource usage.

2.1.5 Differences in Demand Response Customer Categories

There are several types of customers that may benefit from DR. Understanding these customers will give a better utilization of DR. In [LCS17], these customer sectors and their needs are outlined.

Residential Sector

In the residential sector, the number of customers are very high, and the types of appliances used are very diverse. The power consumption of appliances from different brands may be very different. Every customer has their own preference of usage, which means that each customer needs to be treated specifically.

Industrial Sector

This sector has a high electricity consumption at high voltage levels. The peak load is also significant. In order for DR to work in this sector, the usage pattern and the operation of appliances must be known. In some industries, this can reflect the manufacturing process to some extent and may be classified. Modification of the load may also be difficult since a lot of procedures are time sensitive and require precise order and duration, which means they may not be shifted. However, improvement of energy efficiency may still be possible.

Commercial Sector

The commercial sector usage pattern is quite typical. The main loads come from heating, ventilation, air conditioning and lighting systems. Modification of these systems are quite easy. They are easily controllable since they may be set to any value. In addition, the influence from external factors are fairly predictable. For example, lighting and heating will increase during winter. The commercial sector is together with the industrial sector the most suitable for DR programs.

2.1.6 Categories of Loads

In [LCS17], the different types of loads are presented. Loads can be classified by two standards; deferrable and nondefferable load, and adjustable (flexible) and nonadjustable loads.

Deferrable and Nondeferrable Loads

Deferrable loads may be stopped, restarted or shifted to other time slots. These loads may be scheduled by demand response programs to give a preferable load schedule. They may be shifted to off-peak hours to decrease peak load demand with an economical incentive. Modification of these loads must still be within the bounds of deadlines and operation times. Nondeferrable loads need to finish the schedule in a specified time and do not allow time shift and interruption.

Adjustable Loads and Nonadjustable Loads

Adjustable loads can be be adjusted to a lower level, such as heaters which may be set to a lower temperature at certain hours. Thermal loads are examples of adjustable loads. The total consumption may be reduced on the basis of the current electricity price. Reducing the consumption may affect the comfort of the customers. When a DR program is designed, the comfort of the customers must be taken into consideration. The nonadjustable loads are loads with a fixed consumption, such as computers and TVs.

2.2 Use of Renewables Today and Future Outlook

In their annual report for 2019 (with data from 2018), the International Energy Agency (IEA) reported on the status of renewables in the electricity market. Their findings are presented in [IEA19], and a summary of this report will be presented here. Use of renewables increased by 4% in 2018, and accounted for almost one-quarter of the global energy demand growth. Wind, solar PV and hydropower accounted for approximately a third of the growth each, while bioenergy accounted for most of the rest. In 2018, renewables covered approximately 45% of the world's electricity generation growth, which is now accounting for over 25% of the total global power output.

2.2.1 Trends by Technology and Sector

The power sector led the growth with electricity generation based on renewables increasing by 7%. The 7% is equivalent to around 450 TWh, which is the same as Brazil's entire electricity demand. This growth is slightly higher than the annual average growth of 6% since 2010.

China accounted for 40% of the growth in renewable-based electricity generation, followed by Europe, which accounted for around 25% of the total growth. The United States and India contributed a combined total of 13%.

Solar PV power had another year breaking records, growing 31%. Since 2015, the annual solar capacity additions have more than doubled in size. Electricity generations from wind grew by approximately 12%, which was similar to 2017. Hydropower output increased by 3%, which is more than in 2017 despite the declining global capacity additions since 2015. The result is explained by draught recovery and stable economic growth in Latin America, together with a strong capacity expansion and good water availability in China. Renewable electricity generated from other technologies than the three aforementioned grew by 7%, dominated by bioenergy.

2.2.2 Future Outlook

According to [IEA19], the use of renewables in all sectors needs to expand more quickly to be on track to meet climate goals, cleaner air objectives and provide access to modern energy sources. As it stands, the share of renewables in the power mix needs to rise from one-quarter as it is today, to two-thirds in 2040. Renewables need to rise from 10% to 25% in the provision of heat, and in the transport sector, renewables needs to rise from 3.5% to 19%.

2.3 Future Changes in the Norwegian Grid Tariff Structure

There has been proposed changes in how the grid tariff should be calculated for a residential customer in Norway. These changes are forward-looking in the sense that they propose a higher weight on how much power that is used at the same time. Since the Norwegian power grid must support the increasing power demand, and installing more capacity is very costly, this new proposal will encourage a more effective utilization of the power grid. The new price structure focuses less on how much energy you use, and more on how much power capacity you need [NVE20]. This new price structure will also facilitate electrification of the Norwegian society. There exist three different proposals, but all three encourage the customer to lower its peak demand.

2.4 Incentive-Based Demand Response

There are several motivation methods that encourage customers to participate in demand response programs. Incentive-based DR is suitable for industrial and commercial sectors. These methods offer incentives to customers depending on their behaviour in the DR programs. In some cases, the failure to meet requirements in the program will result in a penalty for customers. According to [LCS17], there are five types of incentive-based demand response.

2.4.1 Direct Load Control

The first type of incentive-based demand response is direct load control. This method is based on an agreement between customers and utilities, where the utilities can remotely control some of the customers' appliances such as air conditioners and water heaters. The customers get a notice of the direct control a short time ahead. Direct load control is primarily applied in the residential sector or small-scale commercial sector.

2.4.2 Interruptable/Curtailable Service

This method is normally applied to the industrial sector and large-scale commercial sector. When the system is congested (or there are problems with the grid system), customers are asked to reduce some loads to a certain level. If the customers apply these changes, they can receive a rate discount or bill discount. If they do not respond in the predefined time, they may receive a penalty.

2.4.3 Demand Bidding

In this method, customers may make decisions by themselves instead of being asked by the utilities to take part in DR programs. Taking into account the generation and demand situation, utilities announce the total amount of electricity that needs to be curtailed. Customers bid for the amount on the basis of their own situation and the wholesale market.

If their bid gets accepted, the customers must provide the specified curtailment, otherwise they will receive a penalty. This method is used by large-scale industrial customers.

2.4.4 Capacity Market Program

When the energy market is short of reserves, the customers are required to lower their consumption. The announcement is usually released one day ahead. By providing their ability of curtailment, customers may be rewarded a reservation payment: and if they provide the required reduction, they may receive an incentive. If they fail to provide the reduction, they may receive a penalty.

2.4.5 Ancillary Service Market

This method is similar to demand bidding, since customers also bid for electricity curtailments. The bids are offered to an independent system operator/regional transmission organization. The curtailments are used as operational reservation. Here, customers are paid according to the market price. Once the curtailments have been called, the customers are paid according to the spot price.

2.5 Time-Based Demand Response

The other motivation method for customers to participate in demand response programs is time-based DR. This method utilizes fluctuation in electricity prices according to the cost of generation and the demand for the electricity. These methods are suitable for the residential sector. In [LCS17], four types of pricing schemes are outlined.

2.5.1 Flat Pricing

This is the most used pricing scheme. The electricity price is constant, so the only way to reduce the electricity bill is to reduce the total consumption. The price may be altered seasonally.

2.5.2 Time of Use Pricing

Here, the prices are different in different time slots. Within a slot, the price is flat. Usually, the price is predefined for one day. When using this scheme, it is beneficial to shift the load to lower price slots.

2.5.3 Critical Peak Pricing

This scheme is derived from the Time of Use pricing scheme. In this scheme, the peak demand period is picked out and the price is significantly higher in this period. This scheme is used to bring down the peak demand. The price can be set on the basis of the demand level or the time of day. Three different types of pricing have been considered. The three types are fixed-period critical peak pricing, variable-period critical peak pricing, and

variable critical peak pricing. In the fixed-period critical peak pricing scheme, a specified period during a day is selected and a fixed high price is applied. In the variable-period critical pricing scheme, the period is not fixed. The utilities are free to choose when to trigger the critical peak pricing on the basis of some predefined criteria. In the variable critical peak pricing scheme, the period is fixed but the price may vary on the basis of the current demand situation.

2.5.4 Real-Time Pricing

In this scheme, the price fluctuates frequently, normally by hours. The change of price may reflect the demand and supply in the market. This scheme requires that two-way communication between utilities and customers is available. The customers are notified of the changes in a day-ahead manner, hour-ahead manner or 15-min-ahead manner. Based on the price and their situation, customers may decide their own consumption pattern. The utilities may change the price according to the current generation, current demand and the customers' reaction to the former price. This scheme is more applicable to the industrial and the commercial sector. There are two main drawbacks of this scheme. It relies on continuous real-time data exchange, which is not favorable for the customers, and this data exchange requires a large-scale data processing unit which increases the complexity of the whole system. Some examples from Canada and the United States shows that this scheme generally reduce peak demand and provide a flat consumption pattern.

2.6 Energy Management in the Residential Sector

[SSM16] studies a nonlinear predictive energy management strategy for a residential building with a rooftop photovoltaic system and a lithium-ion battery. The focus in this paper is to close the gap between building energy management formulations, advanced load forecasting techniques, and nonlinear PV/battery models. The energy management problem is formulated as a Model Predictive Controller. The load data is gathered from a single family home in Los Angeles. The maximum power for the PV system is 250 kW, while the size of the battery pack is 1.3 kWh. The results show that a cost reduction of 35% is possible for a home with a PV and battery system.

[KVC14] evaluates a two-stage optimization framework for energy management of residential PV/battery systems to identify the benefits of a longer prediction horizon, together with the general benefits of residential PV/battery systems coupled with a energy management system. A multi-stage stochastic optimization framework is proposed to solve the problem at hand. The multi-stage approach uses a stochastic mixed-integer linear programming for longer horizon predictions, and a more detailed shorter horizon solver using dynamic programming. The results show that a PV/battery system results in lower financial costs since it is more beneficial economically to store the excess PV energy than to sell it back to the grid and because the control algorithm makes sure that the maximum state of charge of the battery is available during peak periods. The results also show that a longer prediction horizon results in better results, since the battery state of charge can be controlled better. An example of this is that the battery state of charge can be lower at the

end of a day with high load demand and low PV production if the algorithm predicts that the next day there will be higher PV production and a lower load demand.

In [TSRG12] a smart building is assumed to be supplied by different power sources such as PV, battery, the grid and combined heat and power powered by gas fuel. The microgrid the smart home is a part of can both buy from and sell electricity to the grid. The electricity price is determined in a day-ahead manner. The paper tries to optimize the solution of the problem of scheduling the energy sources of the building. In addition, the paper investigates the effect of the battery on operation costs. The loads considered in this paper are heating, ventilation, air conditioning and lighting, and the problem is solved as a mixed integer programming problem. The results show that significant costs savings are achieved if the solar energy is fully utilized and the operation of the electrical storage is optimized. The inclusion of a battery reduces the energy costs by 6.5%, however, the cost of the battery is not considered and the battery capacity used was 50 kWh which is fairly high.

2.7 Energy Management in the Commercial Sector

[JWM$^+$17] proposes a two-stage hierarchical energy management method for office buildings, which covers uncertainties in solar power generation, load demand and outdoor temperature. Stage 1 is used to minimize the operating cost of the microgrid through a day-ahead optimal economic dispatch method, while stage 2 is an intra-hour adjustment strategy to smooth out the power exchanges. The method uses batteries from electric vehicles as flexible resources. The day-ahead dispatch schedule proved to reduce the daily operating costs of the microgrid with 14.2% from $197.2 to $169.2.

[WZLB17] presents two control algorithms, for two-stage energy management, including load forecasting. The two algorithms are called SPLET and sample-average approximation based SPLET (SAA_SPLET). The two stages are day-ahead scheduling and real-time operation. First, the algorithm tries to find the amount of power to buy from the day-ahead market while leveraging the flexibility of the load. Then, in the second stage, the real-time demand is satisfied. The case study performed in this paper showed promising results with a 7.2% and 6.9% cost reduction for SPLET and SAA_SPLET respectively. The paper also mentions that either vehicle to building battery systems, which is using the batteries of electric vehicles as flexible energy sources, and stand alone battery systems may act as countermeasures for the mismatch between the day-ahead scheduling and the real-time demand to further reduce the operation cost.

Merei, Sauer, Moshövel and Magnor presents a techno-economic analysis of PV-Battery systems for commercial buildings in [MMMS16]. The building in question is a German supermarket. The paper presents results for optimization of self-consumption and degree of self-sufficiency. The load data and solar power data are real measurement data. The results show that systems with PV peak power up to twice the peak load are the most economical of the considered scenarios. The electricity costs may be reduced by 10-15% by using PV systems. The results also show that including a battery storage system may increase the self-consumption and degree of self-sufficiency slightly, but it is not economically viable for their applications, since the electricity costs does not significantly decrease.

[MAED$^+$17] presents an integrated optimisation of PV and battery systems for commercial buildings in the United Kingdom. The purpose of their model is to optimize the selection, operation and capacity of PV and battery systems, to be able to serve as an assisting framework for assesing technology investments in this sector. A mixed-integer linear programming approch is used to formulate the optimisation problem. The data sets used in this paper are half hour electricity demands and prices, irradiation levels from weather stations, and technology databases. The results show that almost 30% of the total energy for their case study may be generated by a PV system, but that the optimal PV and battery solution has a 8-year payback time, which is quite a long time.

2.8   Economic Gains Utilizing Load Optimization

In [ZLY$^+$17], models of time-shiftable (deferrable) and adjustable (flexible) loads were used to optimize the load in order to make full use of local renewable energy and decrease energy costs. They used a Quantum Particle Swarm Optimization algorithm to solve the day-ahead optimal economic dispatch problem. Their results show that the optimization of time-shiftable and adjustable loads in a day-ahead optimal economic dispatch problem of the micro-grid can indeed give improvements in terms of peak-shaving and valley filling for the electric load. This result lead to a decrease in operation and maintenance costs of 33.33%. In addition, environmental costs were also reduced since the method tried to make use of local renewable energy.

In [LSR16], a study from 2015 conducted by representatives from the Solar Energy Research Institute of Singapore, it was shown that a promising decrease in energy cost savings were possible in a dynamic market pricing environment. In this study, modified versions of Earliest Deadline First and Least Laxity First scheduling algorithms were used to solve the problem of scheduling deferrable loads with real-time electricity market pricing and renewable generation forecast. Their results showed a promising decrease of costs as the renewable penetration level and deferrable load percentage increased. The problems introduced by infrequent solar energy generation and variable demand forecasts were also studied. Their results showed that the resulting scheduled load profile fits the solar energy generation profile in shape if the variability of generation is considered.

In [Sia14], several cases of DR/DSM applications in the industry were presented. Alcoa, the major consumer and supplier of electricity in the United States, provides regulation as an additional service. In order to be able to give this additional services through control of smelter loads, Alcoa installed an energy management system, smelter potline load control system, and metering and monitoring systems. Loads were monitored and stored every 2 seconds. Cycling the aluminium smelting potline and controlling the voltage of the potlines were the DR strategies that were mostly used. The revenues from the DR participation allowed to pay back the cost of the system (of around $700,000) in only 4 months.

Several load reduction and DR programs are promoted in New York State [Sia14]. Lafarge Building Materials, a cement processing plant, can shed 22 MW of optional load by shutting down their rock crushing equipment, while the rest of the plant can continue its production thanks to the the storage capacity of the facility. The load curtailment payment is made in agreement with NYSERDA's Peak Load Reduction Program. The plant is also

a participant in NYISO Day Ahead DR Program, which means that it can sell the unused energy into the market. Even if the implementation costs were quite high for the project, it generated around $2 million of revenues.

In [ZOK11], an investigation of the impact of demand side management on residential customers was performed. The paper investigated the impact of a DSM scheme which shifted high power loads to reduce the overall peak of households which were connected to the same low voltage feeder. They used historical load data with a high resolution for the households. The control strategy they used was a simple direct load control strategy. If the total load was bigger than a predefined value, the residents were not able to start a high power appliance at that instance (currently running high power appliances were not affected). The results were very promising. The peak load got reduced by 13%-21%, depending on the simulation parameters. In addition, the disturbance for the residents were minimal. The number of waiting occasions were 1.66 times per year on average, and the average waiting time for each occasion was 1.7 minutes. That is equivalent to waiting to start your washing machine for 2 minutes, 1 to 2 times a year. That is a negligible inconvenience.

A study conducted in 2018 on maximizing utility for an autonomous microgrid using demand side management was presented on the 2018 IEEE Electrical Power and Energy Conference and can be found in [PIH$^+$18]. The study presented a real-time algorithm for cost optimization in a renewable energy source microgrid environment. The algorithm has two goals; utility maximisation and cost reduction. The algorithm creates an optimal power scheduling of variable loads. Moreover, the study presents utility maximisation solutions on the combined energy profile of the microgrid, where the aim is to minimize the aggregate energy cost and maximise both the provider's and user's satisfaction. The minimization of the aggregated energy cost aims to reduce the peak to average ratio of the aggregated energy profile. Their results show that the algorithm was effective and the total cost was reduced by approximately 3%. The algorithm did also lead to lower peaks and a more smooth power demand profile.

In [YLF$^+$19] a multi-objective strategy was formulated including an optimal load scheduling which aimed to minimize both the cost of power and the emission in a grid-connected microgrid with additional energy resources. The additional energy resources consisted of a PV system, a wind turbine, a diesel engine and batteries. The different energy sources had different cost of energy and emission costs. The load was generated using a simulation tool. The result showed that the cost of power and emissions were lower early in the morning, when the power came from mainly from renewables. The cost was higher in the evening, but the overall cost was reduced using their optimization algorithm.

2.9 Batteries

2.9.1 Use of Battery Systems Today

In a survey by SINTEF in [SIN19], the use of batteries connected to the grid was presented. SINTEF show that the total installed capacity of batteries have risen a lot in recent years. From 2013 to 2017 the total installed capacity have gone from being under 0.5 GWp in 2013 to 2.58 GWp in 2017. The rise of installed capacity is primarily because of projects

in USA, South-Korea and Japan. In Europe there are around 200 installed batteries. The main use of these batteries in Europe is to help integrate production of renewable energy, and the batteries are most often connected to PV systems or wind turbines.

SINTEF also did a survey on the amount of batteries in Norway with a capacity of over 15 kWh. They found that there were 17 battery projects in Norway with a capacity of 15 kWh or more. All the batteries, except one, were connected to the grid. A lot of the batteries are connected to PV systems, but very few of them have the optimal size considering the size of the PV system and the load demand. This means that the batteries have limited benefits. The control method of these batteries are diverse. Some have a real-time control method, some are controlled by an algorithm which choose the best strategy after looking at the sun forecast, while some use a control scheme which is determined by the load demand which was measured the previous year [SIN19]. The use of batteries is projected to increase in the next years together with the decrease in price.

2.9.2 Review of Energy Storage Systems for Microgrid Applications

In [FHK$^+$18], several energy storage systems for micro-grid applications are comprehensively reviewed. In this thesis, only battery storage systems are considered. The main battery storage systems will be described in this section.

Lead-Acid Storage Systems

According to [FHK$^+$18], lead-acid batteries are the most widely used rechargeable storage with its various sizes and designs. The lead-acid battery has a high efficiency (70% - 80%), and a high cell voltage. They are less expensive than other battery technologies and are highly suitable for micro grid applications. Other advantages of the lead-acid battery include an excellent charge retention and energy density with a fast response and a long life cycle (5-15 years). Traditional lead-acid batteries had a shorter life cycle and other limitations, but newer, more advanced lead-acid batteries have overcome these limitations. The development of lead-acid batteries has focused on materials for performance improvements and implementation of these batteries for applications in the integrated wind, photovoltaic power and automobile sectors. The main disadvantage of lead-acid batteries is their size, they are quite heavy.

Lithium-Ion (Li-Ion) Storage Systems

In [FHK$^+$18], lithium-ion batteries are described as the fastest growing technology in recent years. A Li-ion battery is capable of storing energy at the megawatt scale. The popularity of this battery technology is due to its size, its efficiency of over 90%, its high energy density, its rapid response time and attractive self-discharge rate. The self-discharge rate is a measure for the rate at which the battery loses capacity. The experimental results presented in [FHK$^+$18] show that Li-ion batteries exhibits an acceptable performance under typical micro-grid scenarios. To prolong the Li-ion battery life the current level must maintain the range of maximum dynamic charge and discharge current. The battery voltage should also be maintained in the range of maximum charge and discharge voltage. The main disadvantages of the Li-ion batteries are its cycle depth of discharge and high cost.

The cost of Li-ion cells is expected to decrease with large-scale production. In conclusion, Li-ion batteries may be the best-suited storage technology for islanded micro-grids because of its size, light weight, long life time, efficiency and potential.

Sodium-Sulfur (NaS) Storage Systems

The Sodium-Sulfur technology is widely applicable for load leveling, voltage sag minimization, and stabilizing renewable energy power generation. A big drawback for this technology is that it needs to operate at a high temperature since the chemical reaction needs both sodium and sulfur to be in a liquid state. This leads to a increased cost to its implementation. However, recent advances in this field have given the batteries a higher energy density and a lower cost. As a potential storage system in micro-grids, it shows high efficiency, a long life cycle and a fast response during full charging and discharging operation. In light of this information, countries such as Japan and China are investing in large-scale applications of this battery technology.

2.9.3 Studies of Energy Storage Systems

Standalone Hybrid Solar-Wind-Battery System for a Remote Island

In [MYL14], a detailed feasibility study and techno-economic evaluation of a standalone hybrid solar-wind-battery system for a remote island was presented. Solar radiation and wind data from a previous year was used. The load profile used was estimated. A battery with a nominal capacity of 3000 Ah, efficiency of 86 % and maximum depth of discharge of 70% was used in the simulations. Simulations were performed to find the best parameters for optimizing net present cost and cost of energy. The effects of the PV panel sizing, wind turbine sizing and battery bank capacity on the system's reliability and economic performance were examined. The island used in the study was a small island outside Hong Kong.

The results showed that such a system was able to bear the load of the island, and that a lot of energy was lost when the battery was full. The wind and solar power complemented each other very good. An extremely small unmet load was experienced throughout the year, amounting to approximately 66.6 kWh, which is approximately 0.07% of the total load. The results also showed that an increase in the PV capacity lead to a decrease in the battery bank size, so it is very much of interest to optimize the net present cost. A solar-wind system produced less waste electricity and had a lower cost of energy. The economic benefits of the solar-wind-battery system grew together with the size of the consumption load. The study concluded that it was possible to replace a diesel generator with a 100% renewable energy power generation system.

Power Systems' Optimal Peak-Shaving Applying Secondary Storage

The results of a study conducted in 2012 are presented in [LS12]. This study derive an analytic design method for attaining optimal peak shaving. The analysis performed in the study gives the lowest possible peak, given only the demand profile of the load and the capacity of the energy storage system. In the case of periodic loads with a 800 MWh

energy storage capacity (11.2% of the total daily energy consumption), this method was able to shave off about 170 MW of the daily peak power. The main problem with this study is that the optimal peak shaving method only holds for lossless storage devices, which is not realistic.

Battery Storage Systems for Peak Shaving Applications in Germany

In [PSHE+19] the potential of Battery Energy Storage Systems (BESS) together with PV systems for peak shaving application in the non-residential sector in Germany is studied. The study considers four types of non-residential buildings: office, fire station, hotel and sports centre. Their results provide an overview of profitable BESS sizes depending on installation costs and grid demand limit. The results also indicate supporting factors. Firstly, PV systems could help to reduce the necessary storage capacity for maintaining the maximum demand while staying within the desired grid demand limit. Secondly, peak shaving with BESS may also enhance the grid support characteristics of the buildings, but this option is not economically feasible under current pricing conditions, since the size of the BESS will get to large.

More specifically, the used load profiles are not measured for three of the buildings, but generated using a simulation environment. The electricity consumption of the sports centre is measured over a 12 month period. The time series data on PV generation used in the paper was obtained by a simulation. The simulation was performed for each building individually. The results regarding peak shaving using only BESS shows a peak reduction between 45% and 80%. A PV system enhances this capability by a few percent. Their sensitivity analysis of BESS installation costs shows that demand peak shaving with a BESS becomes economically feasible when capacity installation cost crops below 850 €/kWh.

Peak Shaving with Photovoltaic-Battery Systems

The Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany, investigated to what extent a PV-battery system could compensate the capping of the feed-in power by buffering the peak energy and presented the findings in [BHE+15]. They developed a novel forecast based control scheme for PV-battery systems. The method forecast the excess PV energy and derives a charging schedule for the battery to store the energy from the excess PV production. This charging strategy makes sure not to fully charge the battery to early, so the feed in power to the grid from the PV system does not get too large. This is good since it maximizes self-consumption. Their results indicate that their method is able to save around 100 000 €, compared to the standard operation method used today.

Adaptive Scheduling of Batteries for Peak Shaving using Model Predictive Control

In [VHSB18], a load forecasting technique and demand management algorithm using model predictive control was developed. The method was deployed and used together with a 165 kWh battery system. The goal of the demand side algorithm is to determine the optimal schedule for the battery for minimizing electricity cost while satisfying the customers' load and obeying the operational constraints of the battery. The obtained results

showed that the MPC algorithm was able to reduce the electricity bills by 13.5% per year.

Combined HVAC and Battery Scheduling for Demand Response in a Building

[VHS19] discusses and simulates a demand management algorithm on a building with a battery energy storage system and Heater, Ventilation, Air-Condition system (HVAC) scheduling using MPC. The energy storage system is used for modification of the load shape and minimizing the demand charge of the building. Initially, the paper focused on optimizing BESS using MPC, but later on, HVAC is modeled and used in the optimization. The final part of the article co-optimizes battery and HVAC schedules to minimize the annual electricity bill without causing discomfort for the residents of the building. Their simulations show that 22% annual savings in the electricity bill is possible using the combined optimization of HVAC set-points and BESS. The co-optimization decreases the peak demand bill by increasing the off-peak energy consumption. Side effects of using MPC included a longer battery life.

Chapter 3

Method

3.1 Application Specification

The main application is an application which the user can use to navigate and set the wanted parameters. Therefore a graphical interface for the user is developed. The main graphical application also needs some utility functions to get the data for the application and perform a simulation. The behaviour of the application may be described by the following list.

Solar Power Data

1. The application must be able to automatically download and store solar power production data from both PV power plants on a CSV format once a day.

2. The application must be able to read in and transform the data to a useful format.

3. The application must be able to do some preprocessing and filtering on the data.

Load data

4. The application must be able to read in and transform the data to a suitable format.

5. The application must be able to do some simple preprocessing on the data.

Graphical User Interface

6. The GUI must be able to display the solar power data and load data for a given day.

7. The GUI must have a button for changing the date to display the data for.

8. The GUI must be able to take input from the user on which simulation parameters that are to be used.

Simulation

9. The application must be able to perform a simulation given simulation parameters.

10. The application must be able to display the results of the simulation through the GUI.

3.2 Microgrid Model

The microgrid model in this thesis is made up of 6 different components. The grid, which represents the main power grid connected to the microgrid. Electricity meters which monitors the electricity flow in the system. A PV power plant which is the local power source in the microgrid. Inverters which transforms the electricity from DC to AC or from AC to DC. A battery which can store electricity. The AC bus which is where the electricity goes through towards the load. Lastly, the load which is many different power appliances. The load data and the data from the PV plant are real data collected from locations in Trondheim and are presented in section 3.5. The electricity coming from the grid is calculated using the load data, the PV power plant data and the battery. The battery data is not collected from a real battery, but a simple battery model is used in the software, presented in section 3.4. It should be noted that the system is not actually coupled like this in real life. The PV power plant is situated at a different location than the load, but the PV power plant is modeled such that it should supplement the grid to serve the load. This microgrid model can also be seen as a demand-side management system as described in section 2.1.2, where the PV power plant is the local generator and the battery is the energy storage system. The electricity meters act as a fusion between sensors and smart devices, monitoring the energy consumption data. The energy management unit is not specified in the model, but the control strategies described in 3.7 may be used by such an unit.
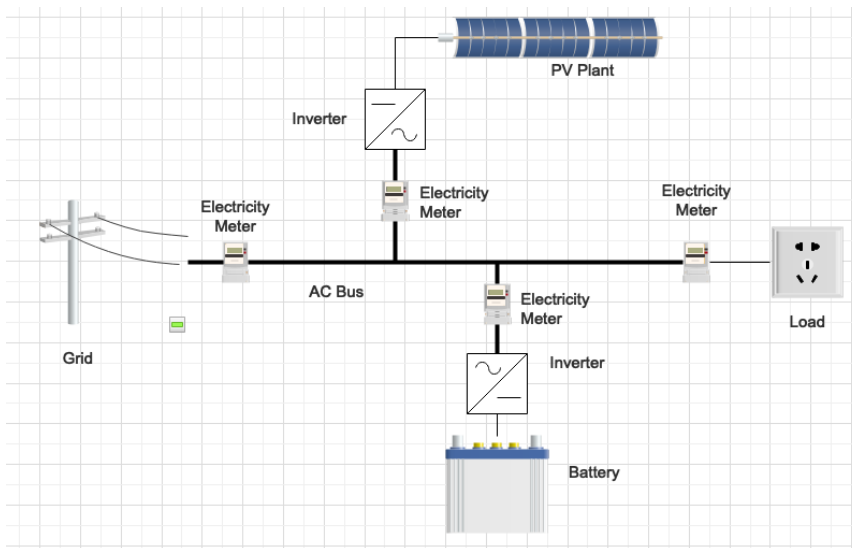
Figure 3.1: An illustration showing the microgrid model used in this thesis

3.2.1 Assumptions

- All inverters are assumed to be perfect, that is, there is recorded no loss in the inverters.

- All excess electricity from the PV plant that is not going to the load or battery is curtailed.

- The voltage stability is assumed to be maintained.

3.3 Economic Model

The economic model is developed to be able to concisely express the total savings of energy costs, also including the price of installation for batteries and PV modules. It must be noted that the prices of the PV modules and batteries are approximate, and that these prices change rapidly. This model may therefore not be applicable some years in the future.

The capital investment prices found for PV modules [PV 19], inverters [MAED$^+$17] and batteries [Blo19] are listed in table 3.1.

	Price
PV	3.9 NOK/Wp
Inverter	0.95 NOK/Wp
Battery	1545 NOK/kWh

Table 3.1: Investment cost for PV modules, inverters and batteries

The calculation of price of electricity is different for each sector in Norway. The residential sector pays a grid tariff, which consists of a fixed tariff, an energy tariff, and a consumption tax. The commercial/industrial sector pays the same tariffs, but this sector usually needs to pay a power tariff as well. The costs of energy shown in table 3.2 and the power tariff structure shown in table 3.3 are taken from [Ten20], which is the electricity company that provides energy to all the buildings this paper takes load data from. [Ten20] claims that the power tariff is calculated from the highest hourly average power from the measured facility in a given month. Summer prices are applied from March to October, while the winter prices are applied in November, December, January and February.

	Residential	Commercial/Industry
Fixed price	2437.5 NOK/year	8800 NOK/year
Energy price	0.24375 NOK/kWh	0.0625 NOK/kWh
Consumption Tax	0.201625 NOK/kWh	0.201625 NOK/kWh
Power tariff	No	Yes

Table 3.2: Costs of energy for the different customer sectors

In addition to these tariffs, everyone needs to pay for the electricity they consume. There were no historical data on the electricity price from Tensio, the electricity company which provides the electricity to these sites. Therefore, the hourly electricity spot price was

	Summer	Winter
0-200 kW (P_1)	45 NOK/kW/month	60 NOK/kW/month
201-500 kW (P_2)	40 NOK/kW/month	53 NOK/kW/month
501-800 kW (P_3)	35 NOK/kW/month	47 NOK/kW/month
>800 kW (P_4)	30 NOK/kW/month	40 NOK/kW/month

Table 3.3: The power tariff price structure

gathered from Nord Pool [Nor20], which is the leading power market in Europe, in which the Norwegian power companies buy their electricity from. The electricity companies usually add a fixed price of approximately 0.1-0.2 NOK/KWh in addition to the spot price, and this will also be done in this paper.

3.3.1 Calculation of the Economic Results

The equations in this section lay out the foundation for how the economic results are found. The costs are split into investment costs and energy costs. The investment costs are the costs of buying a PV plant, inverters and a battery. These costs are one time payments. The energy costs are the costs of energy usage, described in table 3.2-3.3. The operational and maintenance costs are not covered in this thesis.

The investment costs are described by the following equation

$$C_I = 3.9 * P_{\text{PV}} + 0.95 * P_{\text{Batt}} + 1545 * K_{\text{Batt}} \tag{3.1}$$

where C_I is the investment costs, P_{PV} and P_{Batt} are the peak power out of the PV plant and in and out of the battery in Wp, respectively. It is assumed that these $P_{\text{PV}} = P_{\text{Batt}}$. K_{Batt} is the size of the battery in kWh.

The energy costs are different for the different customer sectors. The following equations describe the energy costs in the different sectors:

$$C_{Res} = 2437.5 + (0.24375 + 0.201625 + E_d) * U \tag{3.2}$$

$$C_{Ind} = 2437.5 + (0.0625 + 0.201625 + E_d) * U + C_P \tag{3.3}$$

$$C_{Com} = C_{Ind} \tag{3.4}$$

where C_{Res}, C_{Com} and C_{Ind} denote the energy costs for a residential building, a commercial building and a industry building, respectively, E_d is the daily electricity price (spot price and fixed addition) in NOK/kWh, and U denote the energy usage in the building in kWh. C_{Com} is set as the same as C_{Ind} in this section, since the load measurements are not extraordinary far off in magnitude, and it is unclear which payment schedule the commercial building use, and for the sake of this thesis it is more interesting to look at possible savings in the power tariff for several load profiles. C_P denote the costs from the power tariff and is given by the following equation

$$C_P = 45 * P_1 + 40 * P_2 + 35 * P_3 + 30 * P_4 \tag{3.5}$$

if it is summer, and by this equation

$$C_P = 60 * P_1 + 53 * P_2 + 47 * P_3 + 40 * P_4 \tag{3.6}$$

if it is winter. P_1, P_2, P_3 and P_4 are the number of kilo watts in the ranges displayed in table 3.3.

3.4 Battery Model

The battery model used in this paper is very simplistic. The aim of the paper is not to have the most realistic battery performance, since the battery is only a small part of the focus area. The model used here is built on some assumptions, presented in section 3.4.1. The battery control strategy used in this paper is described in section 3.7.1.

3.4.1 Assumptions

The assumptions stated in this section are basic assumptions. That means that there may be several assumptions not noted here, because of the authors lack of knowledge on the subject and the lack of relevancy for this thesis. The assumptions are summarized in the list below.

- The battery depth of discharge is assumed to be 100 %. This assumption is valid since no thorough economical analysis on the battery costs is presented. So it is possible to just upscale the battery to counteract a depth of discharge of less than 100 %.

- It is assumed that there is no self discharge of the battery.

- It is assumed that the charge and discharge characteristics are equal. In particular this means that it the maximal charge/discharge power is equal.

- The temperature does not affect the behaviour of the battery.

- The battery efficiency is assumed to be 100 %. This means that no power is wasted by the battery. This assumptions is not valid and realistic in real life since there is some loss in the electro-chemical conversion in the battery cells.

3.4.2 Parameters

The battery model parameters are the parameters which the user need to set in order to configure the battery model correctly. The only parameter that needs to be set by the user is the battery capacity. The battery capacity is given in kWh. The rest of the elements in the simulation is using W, not KWh. Therefore, a conversion is necessary. The rest of the behaviour of the battery is handled by the control strategy of the battery.

3.5   Data Bank

The data bank used in this thesis is gathered from several sites. The solar data is gathered from two different PV power plants situated in Trondheim, while all load data from the industrial sector is gathered from EC Dahls in Trondheim. The load data from the commercial is collected from an office building at Sluppen, Trondheim, while the load data from the residential sector is gathered from a household at Moholt, Trondheim. In this section, the data bank and the method used to gather the data are presented.

3.5.1   Solar Data

The two PV power plants are situated roughly in the same area on the rooftop of Lysgården and on the rooftop of Kjeldsberg Eiendom, both situated at Sluppen in Trondheim, with longitude and latitude as shown in table 3.4. However, the solar panels have a different tilt angle and direction. The solar panels on the rooftop of Kjeldsberg Eiendom have the characteristics shown in table 3.5. The Kjeldsberg Eiendom plant is very small with a nominal power of 1.085 kWp, but the data may be upscaled. The PV power plant at Lysgården is much bigger, with a nominal power of 120 kWp, the data may be upscaled or downscaled. 234 solar panels at Lysgården are facing west, while 234 different solar panels are facing east. All panels have a tilt angle of $10°$.

Latitude	Longitude
63.4	10.4

Table 3.4: The latitude and longitude of the two PV plants

	Panel 1	Panel 2	Panel 3	Panel 5	Panel 8	Panel 9	Panel 10
Direction	SE	SE	S	S	S	WE	WE
Tilt angle	$70°$	$34°$	$70°$	$22°$	$34°$	$70°$	$34°$

Table 3.5: The solar panels with their respective tilt angles and the direction they are facing on the rooftop of Kjeldsberg Eiendom

3.5.2   Load Data

The industrial load data is gathered from two industrial buildings owned by Kjeldsberg Eiendom. The main part of the load data is taken from a building operated by the EC Dahls Brewery. Some load measurements are also gathered from a nearby climbing centre. The load data is gathered two ways; the overall load for a big part of the EC Dahls building is gathered using three AMS loggers, described later in 3.5.2, while more specific load data is gathered using DENT ELITEpro meters, described later in 3.5.2. The loads measured by the DENT ELITEpros are flexible loads, while the loads measured using the AMS loggers are not considered flexible. The characteristics of the loads measured by the DENT ELITEpros are presented in table 3.6.

	Current	Voltage
Electric Heater	224 A	400 V
Ventilation Concert Hall 1	80 A	400 V
Ventilation Concert Hall 2	80 A	400 V
Ventilation Climbing Centre 1	125 A	230 V
Ventilation Climbing Centre 2	120 A	230 V

Table 3.6: The characteristics of the loads measured by DENT ELITEpro meters

The residential load data is collected using an AMS logger. The data coming from the household is normal households appliances and an electric car charger. This load data is not considered flexible since the AMS logger measures all loads in the residential unit. The load data coming from commercial buildings is also measured using AMS loggers. Here, data from one of the loggers is not considered flexible, since it measures all non-flexible load from an office building, while the other logger is considered flexible, since a ventilation system and heaters are covering most of the measured load.

DENT ELITEpro XC

DENT ELITEpro XC is a tool for pinpointing electric usage and quantifying the load of a power cable. It can measure and store consumption data. The ELITEpro XC is line-powered from the service being measured, which eliminates the need for external power. Accompanying software provides necessary means to set up the meter and retrieve data from it [DEN11].

AMS Logger

The AMS logger is an embedded system designed and developed by a former Master student at NTNU. The logger is connected to smart electricity meters (AMS) through the HAN gate of the AMS meter with an Ethernet cable. The data is then sent through the Ethernet cable to the AMS logger. The AMS logger receives the data and makes the data available at its UART pins. An USB to UART converter chip converts the serialized data, and through an USB gate on a computer the data is received. A program to save the data coming from the AMS meter to the computer is used. This program is also developed by the former Master student.

3.6 Physical Setup on Location

The physical setup on location is quite simple both for the DENT ELITEpro and the AMS logger. The necessary equipment to make a physical setup is listed in 3.7.

The AMS logger takes its power from the computer trough the micro-USB cable. The USB to UART cable is also connected to the computer and the UART channels on the AMS logger. The Ethernet cable is establishing a connection between the AMS Smart Meter and the AMS logger. A 4G router is set up at one location to be able to gather data remotely. The rest of the data needs to be gathered on location. A batch script is made

AMS Logger	DENT ELITEpro XC
A computer	One current clamp per measured phase
A Micro-USB cable	Voltage leads
USB to UART cable	-
Ethernet cable	-
Optional: A 4G Router	-

Table 3.7: The necessary equipment for a physical setup of the AMS logger and the DENT ELITEpro XC

ensuring that the logging program is starting again on the computer in case of a power loss to minimize data loss.

The voltage leads connected to the DENT ELITEpro serves both to measure the voltage and to power the DENT ELITEpro. The current clamps are connected to a phase each to measure the current flowing through that phase. The DENT ELITEpro meters does not need external power and can be situated on location for a long time without the memory getting full.

Pictures of a physical setup for both the AMS logger and DENT ELITEpros are shown in figure 3.5.2 and figure 3.3.
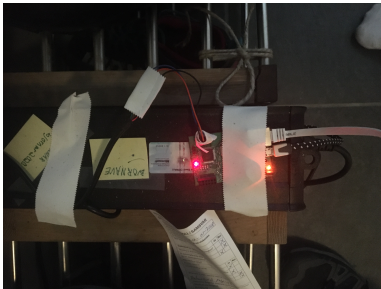
(a) The AMS logger and the computer on location
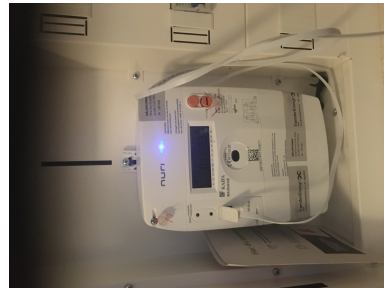
(b) An AMS smart meter with an Ethernet cable connected to the HAN gate

Figure 3.2: A typical physical setup of the AMS logger and an AMS Smart Meter at location

3.7 Control Strategies

3.7.1 Maximise Self Consumption

This battery control strategy aims to maximize the self consumption in the system. That means that no battery power leaves the battery, unless it is being used directly to fulfill the load demand. The strategy also makes sure that excess PV power is stored in the battery if there is storage left. A flowchart showing the strategy is presented in figure 3.4.
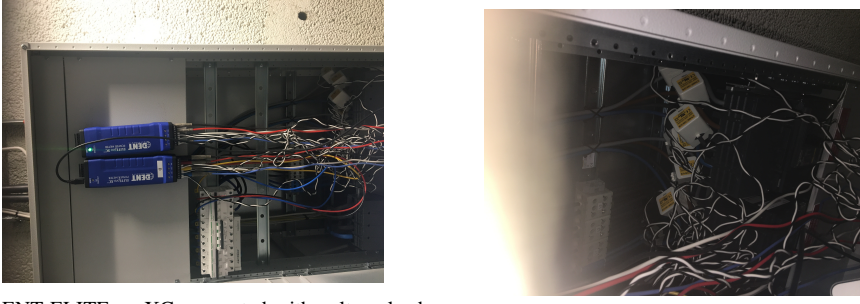
(a) DENT ELITEpro XC connected with voltage leads and current clamps

(b) White urrent clamps connected to different phases

Figure 3.3: A typical physical setup of a DENT ELITEpro XC with current clamps at location

3.7.2 Load Shifting Control Strategy

The load shifting strategy used in this thesis is adopted from the strategy used in [ZOK11]. It is a load shifting method using direct load control. It is also partly a load clipping method, since it is clipping the load at a certain threshold. The method is built upon a simultaneity factor. The simultaneity factor describes the relationship between the load at a given time and the theoretical maximum load, if all peak loads of all measured appliances happen at the same time. The simultaneity factor is described mathematically by the following equation:

$$\eta = \frac{\max\limits_{t \in [1,T]} \left[\sum\limits_{i=0}^{N} L_{it} \right]}{\sum\limits_{i=0}^{N} \max\limits_{t \in [1,T]} (L_{it})} \tag{3.7}$$

Here, L_{it} is the measured load of appliance i at time t. The theoretical maximum value of the simultaneity factor is 1, which happens if the peak load of the non-flexible and flexible data happen at the same time. Since the goal is to minimize the peak load on an hourly basis, the method gets altered a bit. A moving average of the last 60 minutes is calculated as the measured load, while the maximum possible load is the maximum average load recorded in a clock hour. This is given by the following equation

$$\eta_H = \frac{\max\limits_{t_A \in [1,T]} \left[\sum\limits_{i=0}^{N} L_{it_A} \right]}{\sum\limits_{i=0}^{N} \max\limits_{t \in [1,T]} (L_{it_H})} \tag{3.8}$$

where L_{it_A} is the moving average of the last sixty minutes, while L_{it_H} is the highest recorded average clock hour load.

This measure can be used as a threshold to make sure that the load does not go over this load or this load multiplied with a scalar between 0 and 1.
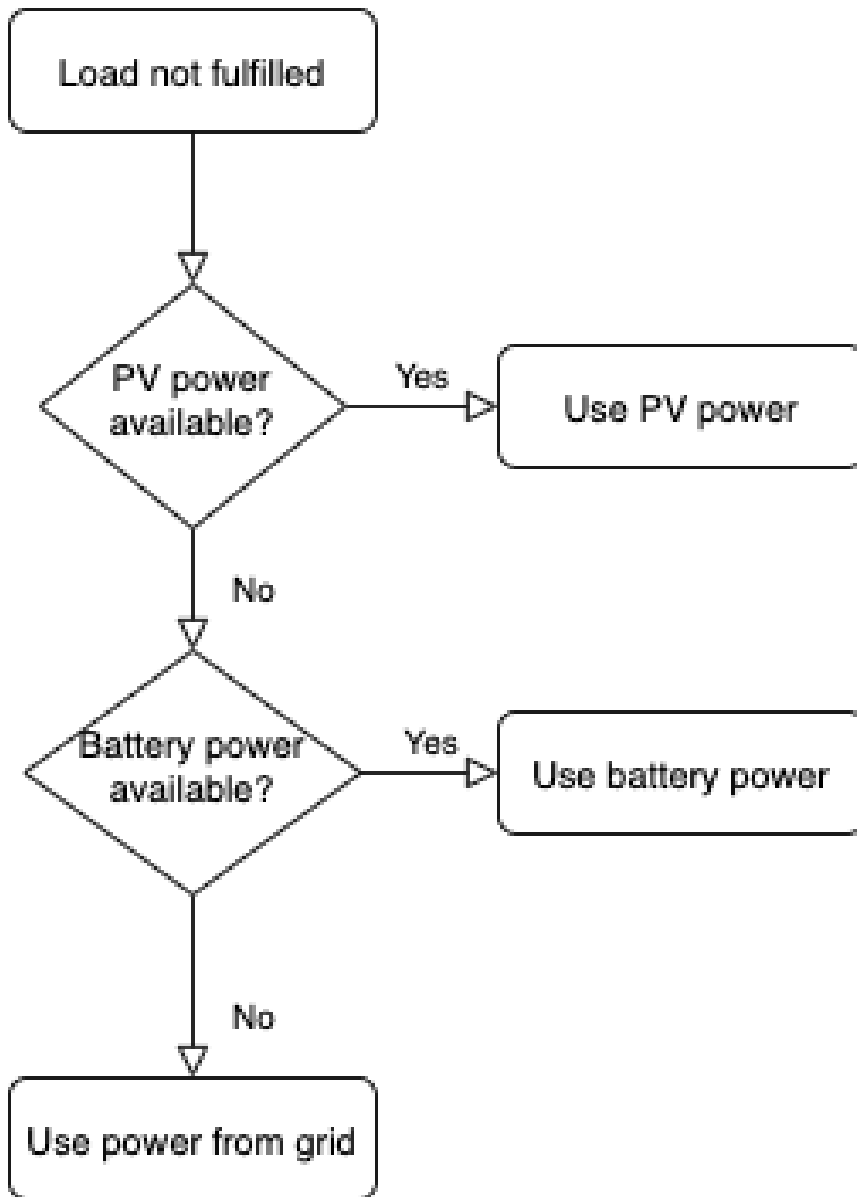
Figure 3.4: The strategy used to maximize self consumption

This is ensured through a control scheme which calculates the simultaneity factor and the moving average at each timestep and prohibits flexible appliances to use more power if the threshold is reached. If the load from non-flexible appliances keeps increasing when the maximum is reached, the flexible loads may need to reduce their power usage. The reduced power usage of the flexible appliances will be shifted to a later time.

In this control strategy, there will be a hierarchy of actions. The most important thing is to uphold the restriction of the threshold, by using battery power and reducing and shifting the flexible loads. If it is not possible to uphold the restriction, the rest of the power needs to be supplied by the grid. This is illustrated in figure 3.5. If the restriction is upheld the next goal is to maximize self consumption, by using PV and battery power to satisfy the as much as possible of the remaining load. It is also important at this stage to fulfill the load demand of the flexible loads which may have been shifted from an earlier time. At last, there is time to manage the battery. If there is still PV power left, the battery will be charged, if not, the battery will be discharged to meet the remaining loads if possible. The load not fulfilled by the battery or the PV plant will be fulfilled by the grid.

3.8 Test Cases

In order to test the effectiveness of the control strategies in terms of economic savings in different scenarios, different test parameters needs to be used. These parameters may be different PV power plant sizes and different battery sizes. This is done to find the correct size of the PV power plant and battery versus the magnitude of the load data to get the best economic results. This will also ensure that the load shifting strategy gets tested in different cases, to see if the strategy works better with certain loads, PV and battery characteristics.

First, base case tests will be performed, to be able to identify the correct PV power plant size for the given load data and to be able to see if the methods function correctly. After that, more specific tests for each sector and load data will be done. To be able to test effectively, the test case will only involve subsets of the PV data. Running the simulation several times for each day of the year would be too time consuming. A subset of PV data is therefore chosen from each season, to get representative data from each season. Every simulation will simulate on a 24 hour basis, more specifically, each simulation will consist of many instances of simulations with load data and PV power data from 24 hours.

3.8.1 Residential Sector Data

Here, only the control strategy to maximize self consumption will be used, since no flexible loads are measured separately. Even though there are no flexible loads present, it does not mean that there is no potential for economical savings. The residential data will be tested for different sizes of PV plants and batteries to see if it is possible to save money for a residential house using solar power in Trondheim.
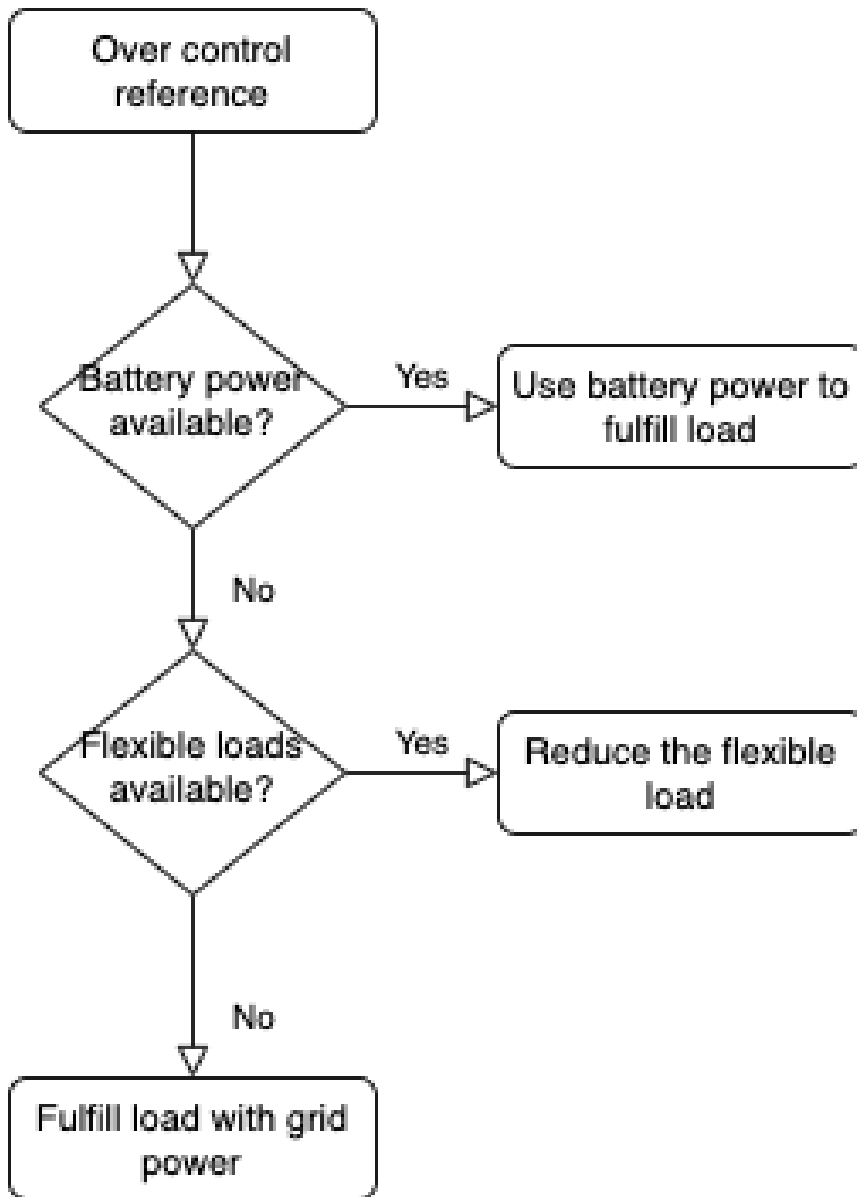
Figure 3.5: The strategy used to lower the load demand to fulfill the control reference restrictions

	Strategy	PV Size (kWp)	Battery Capacity (kWh)	Season	η_H
Base Case 1	Maximize Self Consumption	1, 5, 10	0	Spring, Summer, Autumn, Winter	-

Table 3.8: The base case for testing in the residential sector

	Strategy	PV Size (kWp)	Battery Capacity (kWh)	Season	η_H
Case 1	Load Shifting	1	1, 5	Spring, Summer, Autumn, Winter	-

Table 3.9: The cases which will be simulated for the data from LoggerRes

3.8.2 Commercial Sector Data

The data from the commercial building comes from both fixed and flexible loads, hence it is natural to use the load shifting control strategy. To test the effectiveness of the load shifting strategy, it will be tested against the strategy to maximise self consumption with similar parameters. Several PV plant sizes and battery sizes will be tried also here, to attempt to maximize the economic earnings. The load shifting strategy without the help of a PV power plant and a battery will also be tested. This is done to be able to identify how effective the method is without the help of a PV power plant.

	Strategy	PV Size (kWp)	Battery Capacity (kWh)	Season	η_H
Base Case 1	Maximize Self Consumption	50, 100, 250	0	Spring, Summer, Autumn, Winter	-
Base Case 2	Load Shifting	50, 100, 250	0	Spring, Summer, Autumn, Winter	1

Table 3.10: The base cases for testing in the commercial sector.

	Strategy	PV Size (kWp)	Battery Capacity (kWh)	Season	η_H or η_H reduction
Case 1	Load Shifting	100	0	Spring, Summer, Autumn, Winter	0.04, 0.1, 0.12
Case 2	Load Shifting	100	1, 5, 10	Spring, Summer, Autumn, Winter	1
Case 3	Load Shifting	0	0	Spring, Summer, Autumn, Winter	0.96, 0.9, 0.88

Table 3.11: The cases which will be simulated for the data from LoggerOffice

3.8.3 Industrial Sector Data

As for the industrial data, a similar study to the one in the commercial sector will be applied. But since the load demands are bigger in the industrial sector, the PV power plants may need to be scaled bigger in this sector. Similarly to the commercial sector case, the load shifting strategy will be tested without the support of a PV power plant and a battery.

	Strategy	PV Size (kWp)	Battery Capacity (kWh)	Season	η_H
Base Case 1	Maximize Self Consumption	100, 250, 500	0	Spring, Summer, Autumn, Winter	-
Base Case 2	Load Shifting	100, 250, 500	0	Spring, Summer, Autumn, Winter	1

Table 3.12: The base cases for testing in the industrial sector. These cases will be simulated for the combined load data of the three AMS loggers placed in the industrial sector

	Strategy	PV Size (kWp)	Battery Capacity (kWh)	Season	η_H or η_H reduction
Case 1	Load Shifting	500	0	Spring, Summer, Autumn, Winter	0.02, 0.04, 0.08
Case 2	Load Shifting	500	1, 5, 10	Spring, Summer, Autumn, Winter	1
Case 3	Load Shifting	0	0	Spring, Summer, Autumn, Winter	0.98, 0.96, 0.92

Table 3.13: The cases which will be simulated for the data from LoggerInd

3.9 Performance Parameters

In this section, the different performance parameters will be presented. The performance parameters are the parameters which will measure the success of the implementation or how the method performed.

3.9.1 Economic Performance Parameters

The economic performance parameters are very important. These parameters will lay out the economic implications of using both PV power and battery, and implementing a strategy to reduce the peak load. The parameters are listed here:

- Investment costs, as described in equation 3.1

- Monthly energy cost savings using PV power and using batteries with the energy costs as described by equation 3.2-3.3.

- Monthly power tariff savings using PV power and using batteries with the power tariff as described by equation 3.5-3.6.

- Annual savings in energy costs and power tariff costs using PV power and using batteries.

- Monthly energy cost savings using the load shifting method, with the energy costs described by equation 3.2-3.3.

- Monthly power tariff savings using the load shifting method with the power tariff as described by equation 3.5-3.6.

- Annual savings in energy costs and power tariff costs using the load shifting method.

- Break even point, by looking at the annual and monthly savings and the investment costs. How long it will take until the investment cost is earned back by the savings.

- The potential earnings after 18 years (normal life time expectancy for solar power plants are 18-20 years) after subtracting the investment costs.

- Economic difference using the load shifting method versus the method only maximizing self consumption.

3.9.2 Other Performance Parameters

These parameters are used to supplement the economic performance parameters. They can help describe the economic results, but also point out weaknesses or strong sides of the control strategies used in this thesis. These parameters are listed below:

- Average delay of the flexible load. How long is power from flexible loads delayed before they are fulfilled. It must be noted that this delay is not the average delay for all flexible load, it is only the average delay of the flexible load that got delayed.

- Peak reduction in percent and in watts using the load shifting method and the maximize self consumption method.

Chapter 4

Implementation

The code is mostly written in Python using a Python IDE called Pycharm. The reason Python was chosen was due to its ease of use and compatibility with pandas and other useful packages. All packages (libraries) are installed through Pycharm's package installer called "pip". Pip is the standard installer for Python packages, which means that you can assume that all required packages can be downloaded and installed through pip. The AMS logger code is written in C. Most of this code is not written by the author of this thesis, but another Master student. Information about the AMS logger implementation can be found in [Ler19]. This thesis will only cover the brief changes in the code. The rest of the implementation will be described in a top-to-bottom manner, which will give an orderly and thorough explanation of the subject matter. Each major component will be described thoroughly in this chapter. At the end, a small note on the changes in implementation for the AMS logger will be presented.

4.1 Retrieving Solar Panel Data

The data from solar panels are gathered from two different PV plants, one on the roof of Lysgården, one on the roof of Kjeldsberg Eiendom. The two plants uses two different APIs, but the retrieval is similar so the data retrieval will be described only once.

4.1.1 Packages

A complete list of packages used for data retrieval is listed here.

- requests: A library for making HTTP requests in Python.

- os: This library is used to access the file system on the computer. It makes directories and file paths for files which contains the data from the solar panels.

- datetime: The datetime library is used to get the current date for naming and for retrieving the correct data from the server.

- json: Used for handling data on the JSON format.

4.1.2   Implementation of the Solar Data Retrieval

The solar panels on the roof of Kjeldsberg Eiendom uses an API called Tigo REST API V3, while the API for the solar panels on the roof of Lysgården is provided by Solarlog. The Tigo REST API V3 is listed in appendix A, while a document like this does not exist for the Solarlog API. These two APIs are very similar, so the data retrieval can be described generally. The general idea of the data retrieval is shown in figure 4.1. These actions are performed in standalone scripts, which means that they do not depend on other programs to run. Batch scripts are written, instructed to run the data retrieval program. They are scheduled to run daily by the Windows Task Scheduler.

   The data retrieval program can be summarized by the following points, and supported by figure 4.1.

1. The authentication credentials are read in from a separate file and saved in the program. The authentication credentials are needed to access the data from the solar panels through the API. They are therefore needed in every HTTP GET request.

2. The credentials are placed in the path together with the date to get data from and other needed information that the HTTP GET request needs.

3. The path is used in the HTTP GET request to the server containing the solar panel data through the API.

4. After the data is retrieved, the useful data is unpacked from the server response.

5. At last, the data is saved on a CSV format, with a filename which makes it easy to identify which date the data is from.

The diagram in 4.1 illustrates step 3-5, which is the retrieval part of the program. The different outcomes of the actions are also shown. If something fails, the program stops, if not it follows the description above. The written code only takes care of the client side, the server side is taken care of by either TIGO or Solarlog, the providers of the API and the services for logging the data from the different PV power plants.

4.2   Data Handler

The data handler takes care of reading in the data files, preprocessing and filtering and presenting the data in a suitable format for the simulation and GUI. This applies to both the load data and the solar data. The data is stored in files in many different formats, so the data handler must handle different data with different approaches.

4.2.1   Packages

The packages used in the data handler is listed in the following list.

- os: Used to access files and directories.
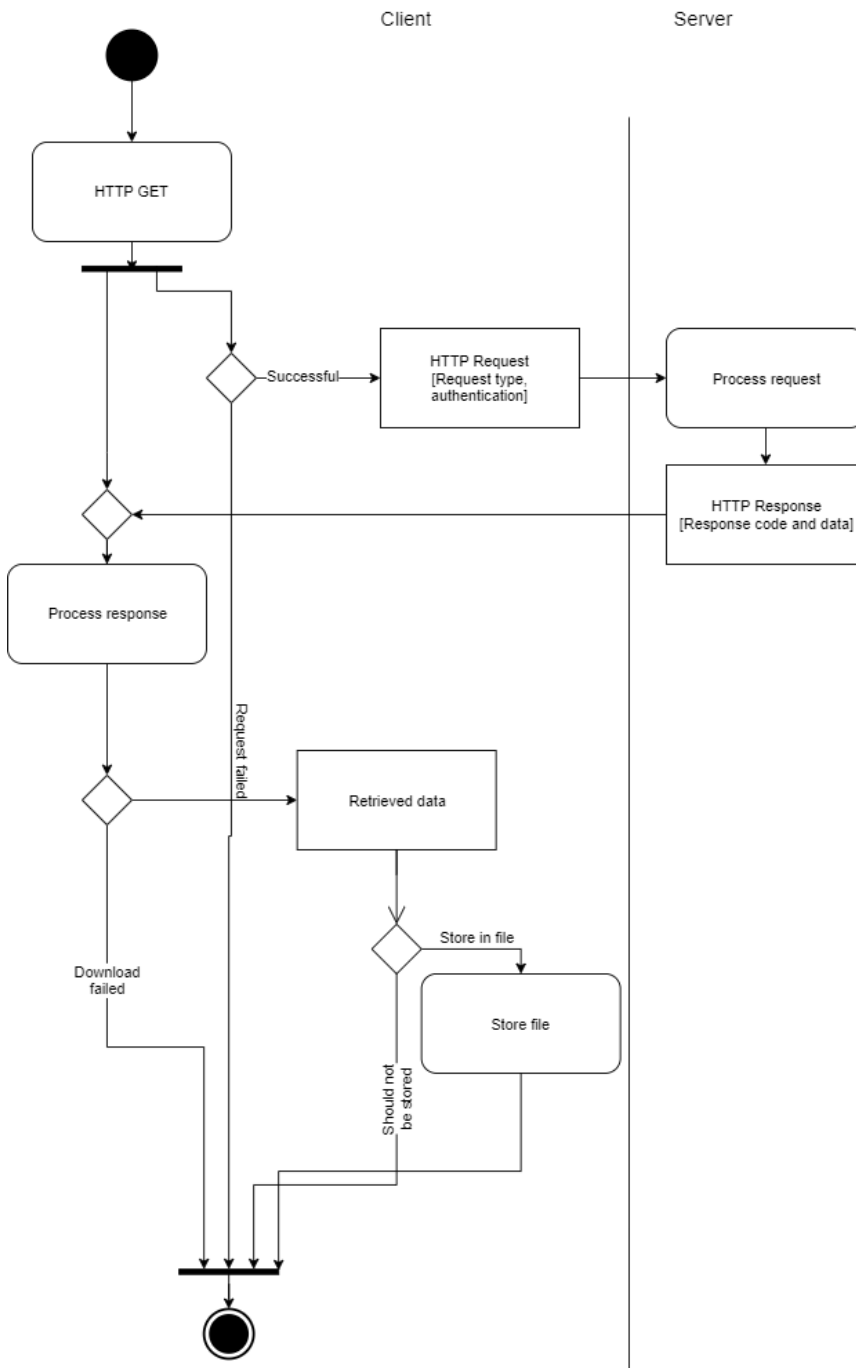
Figure 4.1: An activity diagram showing the actions performed in a HTTP GET request and the following steps, handling the data

- pandas: A Python data analysis library. Used to be able store the data in data frames. These data frames ease the data management. This package also gives access to utility functions for these data frames.

- numpy: Package for scientific computing in Python. Here, it is enabling some filtering.

- csv: For handling csv files more effectively.

4.2.2   Implementation of Data Handler

The different data gets handled in a unique way, but each piece of data will go through a similar process. This means that each file will go trough the same steps, but the details in each step are not alike. The main process will be described first, before the details for each piece of data will be described.

A high-level view of the implementation for each piece of data is described in the following list:

1. The program tries to read in a file and save it in a data frame.

2. Preprocessing and filtering is done if necessary.

3. The program makes sure there are entries for every minute of a day.

4. If all the previous steps are successful, the data frame is saved to the data set.

A more detailed description of the implementation for each piece of data will follow in the following sections.

Implementation for the Solar Data From Kjeldsberg Roof

The details for this piece of data are shown in an activity diagram in figure 4.2. Since the data from the Kjeldsberg roof is handled for each solar panel individually, it needs to be merged into one data frame in the end, to get the data from the whole plant. The preprocessing and filtering include checking if a file is empty, replace the NaN entries in the data frame with 0, checking if the file includes sufficient data for a day and checking if there are data from all 7 data frames for a given day. The data is only collected by the API from sunrise to sunset, so the data frame needs to be expanded to contain data for every minute of the day. It is assumed that the value is 0 for every data entry before sunrise and after sunset.

Implementation for the Solar Data From Lysgården

The implementation details for the data from Lysgården is presented in figure 4.3. The data from Lysgården is more consistent, so less preprocessing is needed. The data frame needs to be reversed and expanded so the data frame contains values for each minute of the day. The data from Lysgården is unfortunately only sampled with a 5 minute interval. To be able to get data from every minute, interpolation between two neighbouring data points is performed.
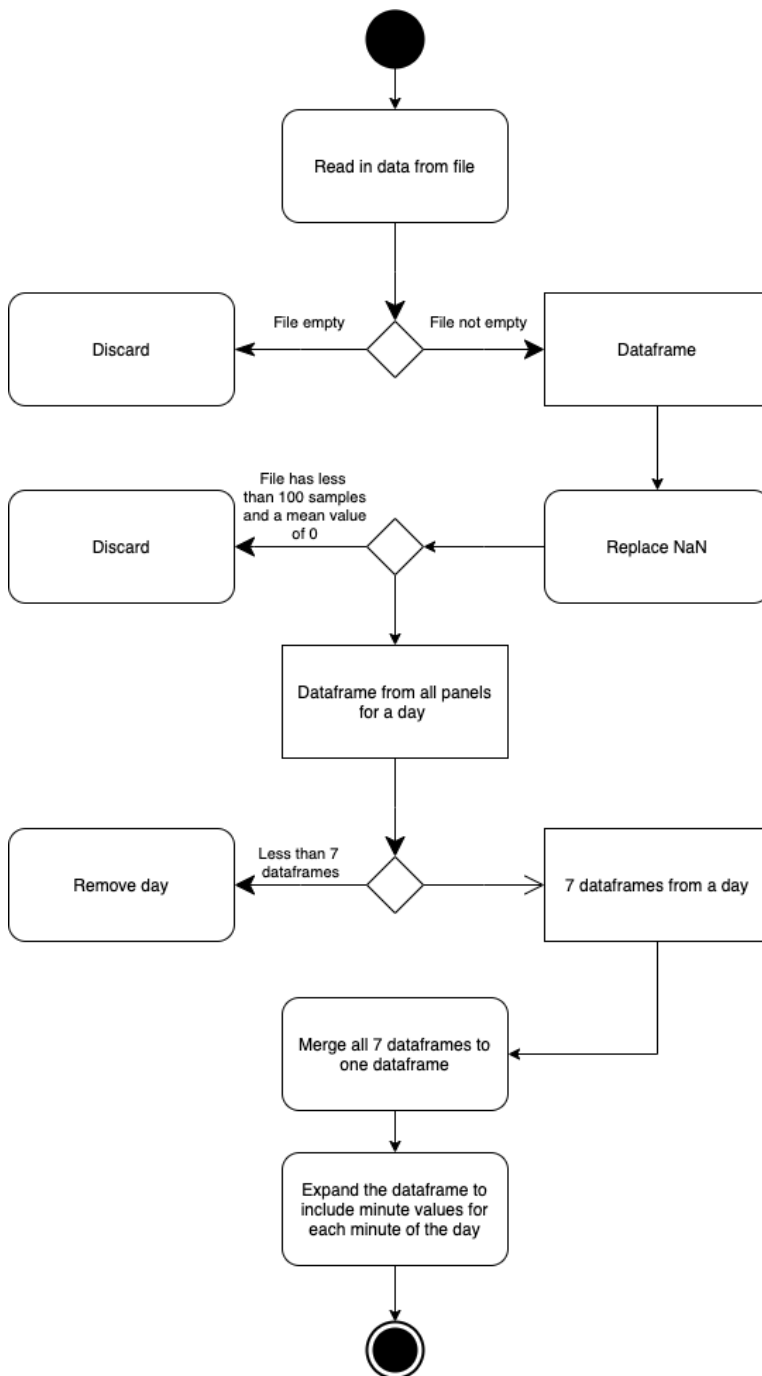
Figure 4.2: An activity diagram showing the details in the implementation for the solar data from the Kjeldsberg roof.
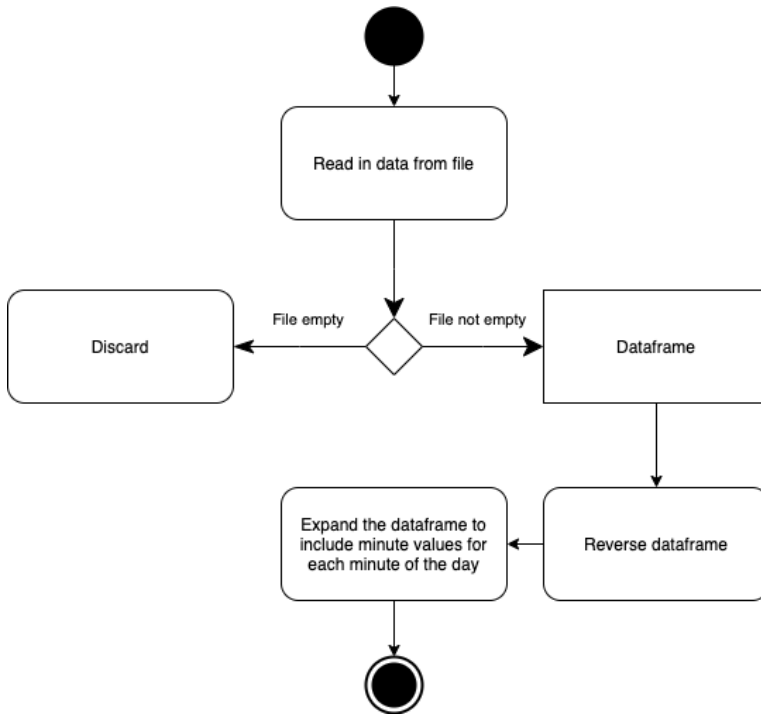
Figure 4.3: An activity diagram showing the details in the implementation for the solar data from Lysgården

4.2.3 Implementation for the AMS Logger

The data from the AMS logger needs more processing when read in. Some of the data gets discarded, since it is not necessary in this thesis. Only the time of measurement and the measurement value is kept. Then, the times of measurement and the measurement values gets placed in a data frame. The data frame also gets resampled to minute values, since the measurements occur more often than once a minute. This step is necessary to have measurements occur on the same frequency as the rest of the data. The data is also converted from kilo watts to watts and multiplied with a factor, which is individual for each AMS meter. A graphical illustration of the actions described in this section is shown in figure 4.4. Note that the data from the three different AMS loggers in the industrial sector gets merged into one entry, called "LoggerInd".
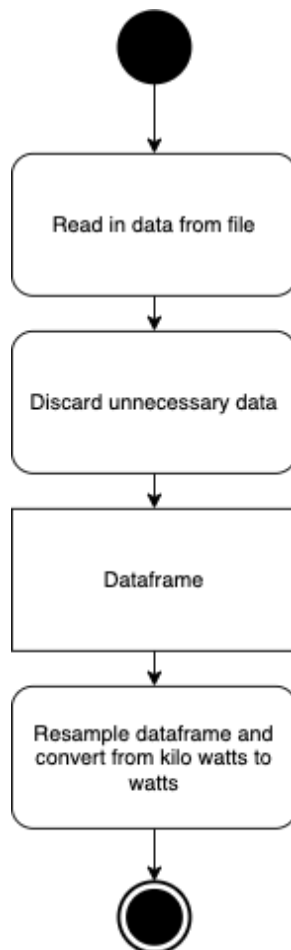
Figure 4.4: An activity diagram showing the details in the implementation of the data handler for the data coming from the AMS logger

4.2.4 Implementation for the DENT ELITEpro XC

The DENT ELITEpro data has a lot of redundant information, since the ELITEpro measures and logs the voltage, ampere and kilo watts for each phase, together with the time of measurement. In this thesis, only the time of measurements and the power usage at each measurement step are of interest. The first peace of action that is done with the data after it is read in as a dataframe is to gather the dataframe columns of interest. The date of measurement and the time of measurement needs to be concatenated, since they are read as two different dataframe columns by the application. The power measures from the different phases also needs to be added together to get the total load demand at the time of measurement. The power also gets converted from kilo watts to watts. All the data from one DENT ELITEpro comes in one file. If it is to function with the rest of the data, it needs to be split into separate days. After that is ensured, all that is left is to check if the dataframe contains data from the whole day. If it has data from the whole day, it is added to the final data set. An illustration of this procedure is shown in figure 4.5. Note that this procedure is run once for every file.

4.3 Graphical User Interface

The main application is equipped with a graphical user interface to make the setting of the simulation parameters as easy as possible. This way the user gets presented with the different parameters of the simulation and gets to choose the preferred simulation. The GUI also gives a good visualization of the data and the results.

4.3.1 Packages

- tkinter: The main package used in this part of the application. It is the de-facto standard GUI package in Python and part of the Python standard library.

- matplotlib: Used to visualize the data and results. Also imports some tkinter widgets needed to implement a matplotlib plot in a tkinter widget.

- collections: Part of the Python standard library. Used here to be able to use a ordered dictionary.

- pandas: Used here for creating data frames and concatenating several data frames

- copy: Used for taking a deep copy of a class variable

- os: Used for accessing the file system on the computer

- json: Used for serializing and deserializing data to and from the json format

4.3.2 Implementation of the Graphical User Interface

The GUI consists of three main windows; the parameter settings window, the results window and the data window. The data window and the parameter settings window are available from the start of the application, while the results window pops up after a simulation is run.
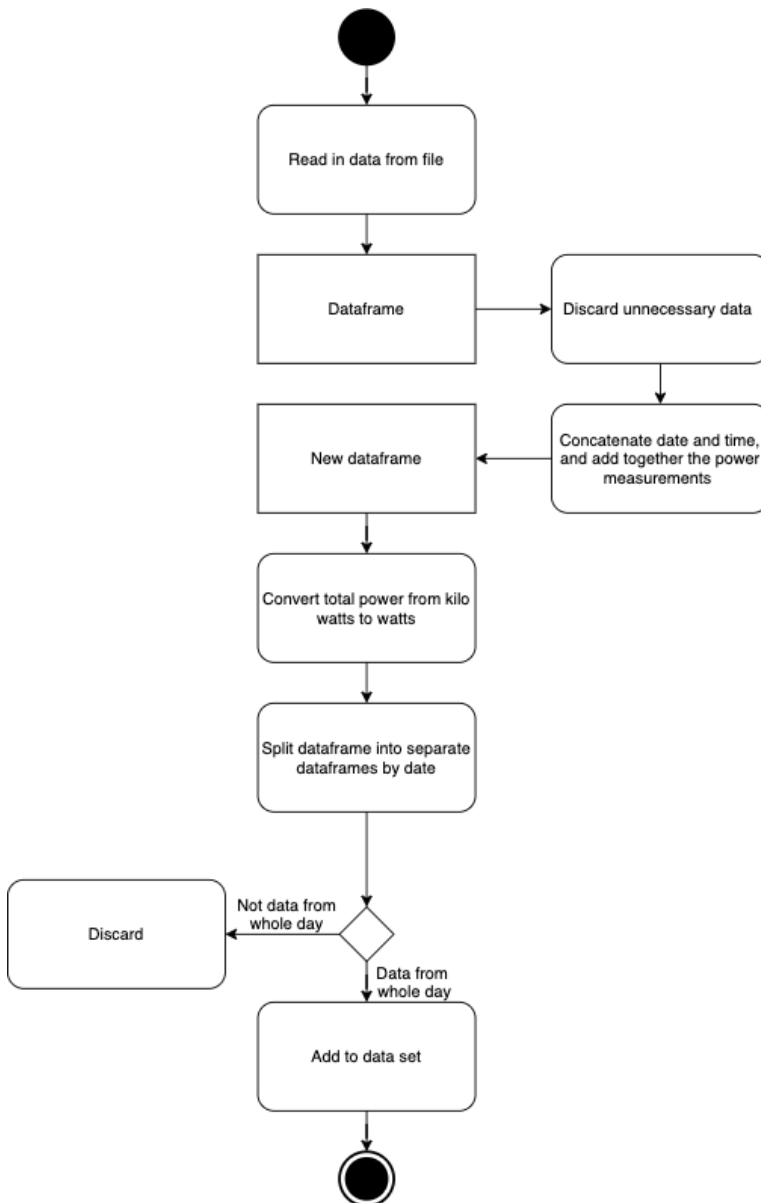
Figure 4.5: An activity diagram showing the details in the implementation of the data handler for the data coming from the DENT ELITEpro XC

Every graphical element in this part of the application is implemented using tkinter widgets. These widgets needs to be initialized and configured, before being placed in a tkinter frame. Each window gets instantiated as an instance of a class. The class structure is made up of a parent class called "Window", with three child classes called "Matplotlib-Window", "ParameterSettingsWindow" and "PlotResultsWindow", which inherits from the "Window" class.

The data window consists of two main elements; a plot and buttons. The plot displays the data for a given day and a given data set. The buttons have a variety of functions. There are buttons for switching to the previous and next day to display and a button for quitting the application. There is a drop down menu for choosing data set for both the PV data set and the load data set, and a drop down menu for the date for which the data should be shown for the PV data, the load data and the flexible load data. The flexible loads to display are chosen through checkboxes. In addition to this, the standard matplotlib toolbar is added at the bottom. An image showing the simulator data window is presented in figure 4.6. Here, the data displayed is the PV data from the 30th of April 2020 together with the load data from the office AMS logger and the flexible load data from the same office building on the same date.

The parameter settings window consists of drop down menus, checkboxes, and entry fields to set the parameters wanted in the simulation and a button for starting the simulation. It is possible to make a custom simulation from this window or to choose a test case which is defined in another Python file. If you decide to make a custom simulation, the results will be shown in a results window, with plots of the wanted results. If you decide to use a test case, the results will be saved to a file. Figure 4.7 shows the parameter settings window.

The results window show various plots of the simulation results. These plots are decided prior to running the application, so the user will not be able to decide which plots to show. This window also have a button for closing the window and the standard matplotlib toolbar with various options to zoom in on the plots, save the plots and highlight some parts of the plots. Figure 4.8 shows the results window for a "Maximize Self Consumption" simulation.

4.4 Control Strategies

The control strategy module contains all functions necessary to perform a simulation. The functions is fed with data to use in the simulation and simulation parameters, and returns the result of the simulation. The two control strategies described in section 3.7 contain similar implementation details, but the load shifting strategy is more involved and intricate. The implementation of both strategies will be presented here.

4.4.1 Packages

- numpy: Package for scientific computing in Python. In this module it is used to create numpy arrays and do some operations on these arrays.
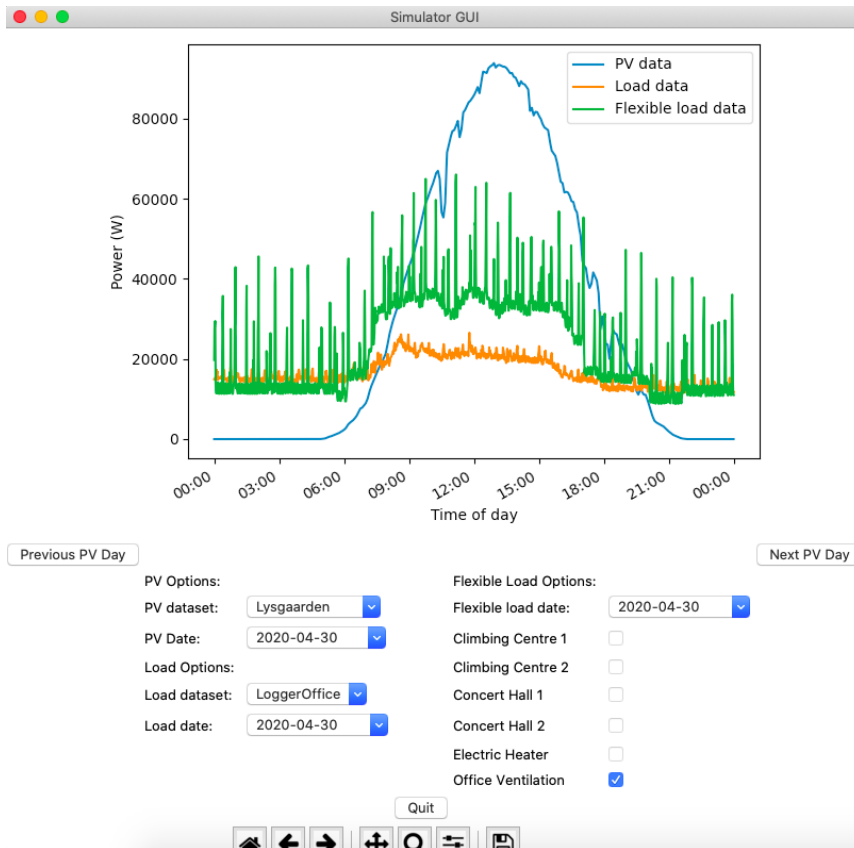
Figure 4.6: The simulator data window
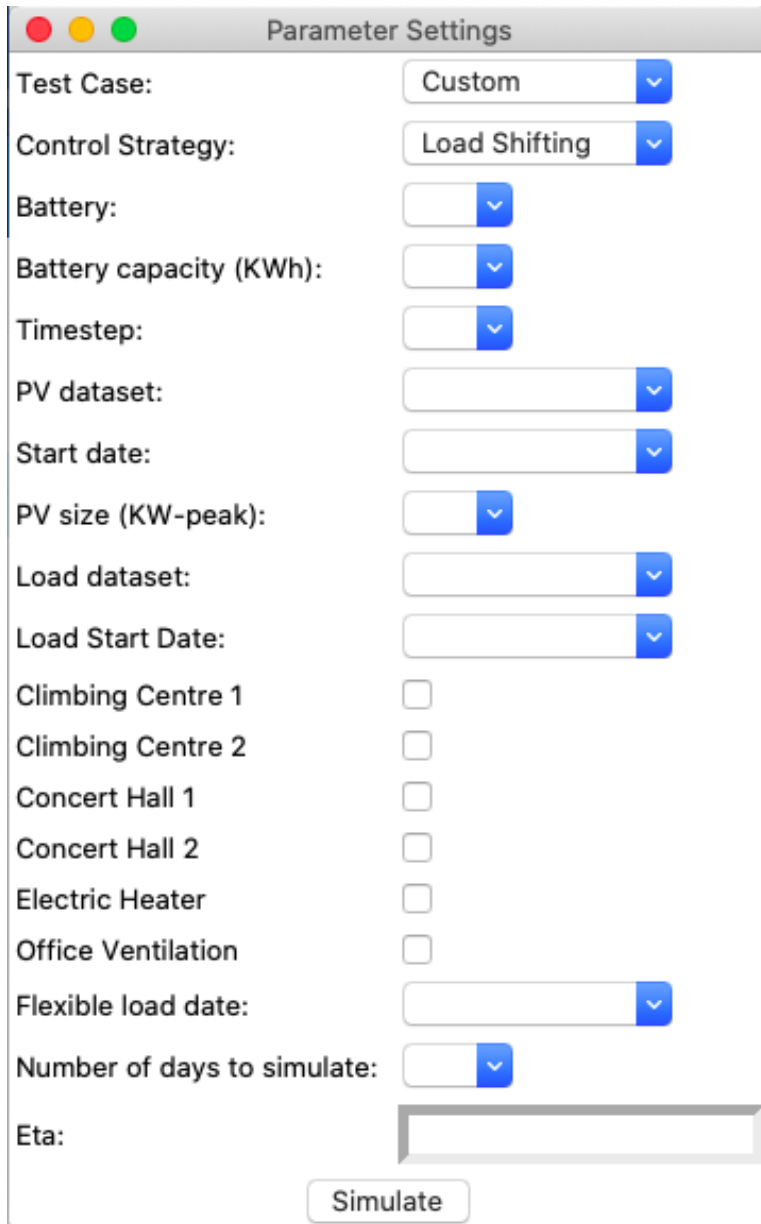
Figure 4.7: The parameter settings window
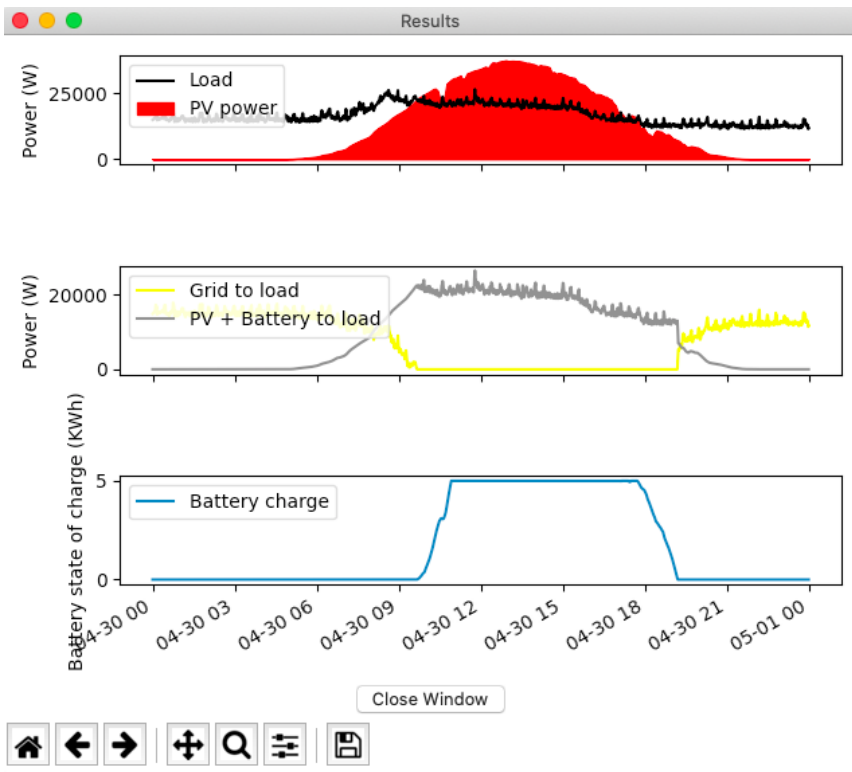
Figure 4.8: The results window

4.4.2 Implementation of the Control Strategies

This section will contain details which is valid for both control strategies, before splitting up in two, where each control strategy will be described in detail.

Both control functions perform a input data validity check, where the number of data points is checked both for the data coming from the PV plant and the load data. This is done to ensure that there are no data points missing from one of the data sets. From there, all the simulation variables are initialized. The data frames containing the simulation data are also transformed to numpy arrays for performance reasons and also for ease of use in the simulation. After the simulation the results are put in a dictionary and returned. The simulation is different for the two control strategies, so it will be described more in detail in the following sections. An activity diagram showing the outline of the implementation of the control strategies is shown in figure 4.9. The "Simulate" box in this figure is going to be described thoroughly in the following sections.

Implementation of the Strategy to Maximize Self Consumption

This strategy is only controlling how much energy is going to the battery. So for each step in the simulation the residual PV power, if any, gets placed in the battery if it is not full, and the battery is used to fulfill the load if there is still load to fulfill and there is power in the battery. If no residual PV power or battery power is available, the residual load is fulfilled by the grid. The battery charge level is updated after each step of the simulation. The implementation is illustrated using an activity diagram in figure 4.10. Note that this figure represents one step in the simulation. These actions are performed in a loop until the simulation is finished. This figure represents the "Simulate" action in figure 4.9 if the maximise self consumption control method is chosen for the simulation.

Implementation of the Load Shifting Strategy

The load shifting strategy is a bit more involved. The most important thing in the simulation is to not exceed the preset threshold if possible. This is done by controlling both the flexible load and the battery. The goal is to maintain normal operation as long as the threshold is not exceeded. Therefore, the implementation is made in such a way that battery power is used to fulfill the flexible load if the threshold is being exceeded. If no battery power is available, the flexible load gets postponed to a time where the total load is so low that some extra flexible load does not make the system exceed the threshold. An additional threshold is added to the flexible load. The flexible load and shifted flexible load that gets fulfilled should not be exceeded. If there is no flexible load available to postpone and no battery power available, while the system is about to exceed the threshold, the system still needs to fulfill the load, knowing that it will exceed the threshold. This is due to the fact that not all the load is possible to postpone and must be fulfilled.

When all the flexible load for all previous timesteps are fulfilled, the algorithm works similarly to the maximize self consumption strategy with battery charging if residual PV power is still available and discharging if there is still load to fulfill. A detailed activity diagram for this strategy is shown in figure 4.11. This figure is only showing one step of the simulation. These steps will continue until the simulation is finished. It represents
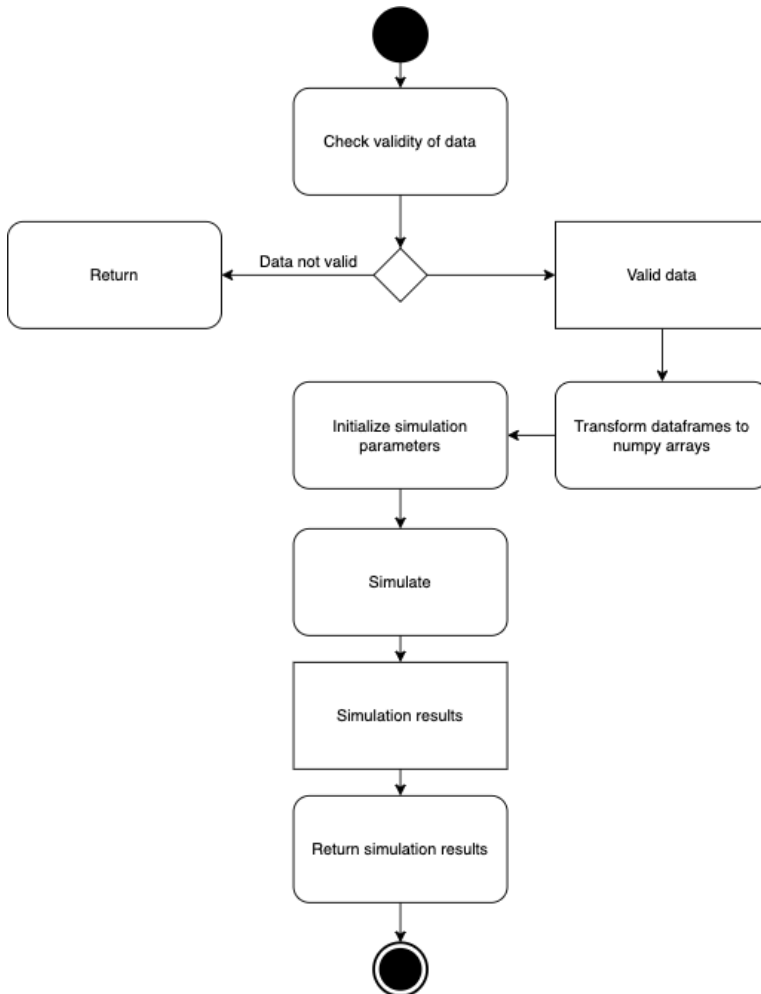
Figure 4.9: The general outline of the control strategy implementation
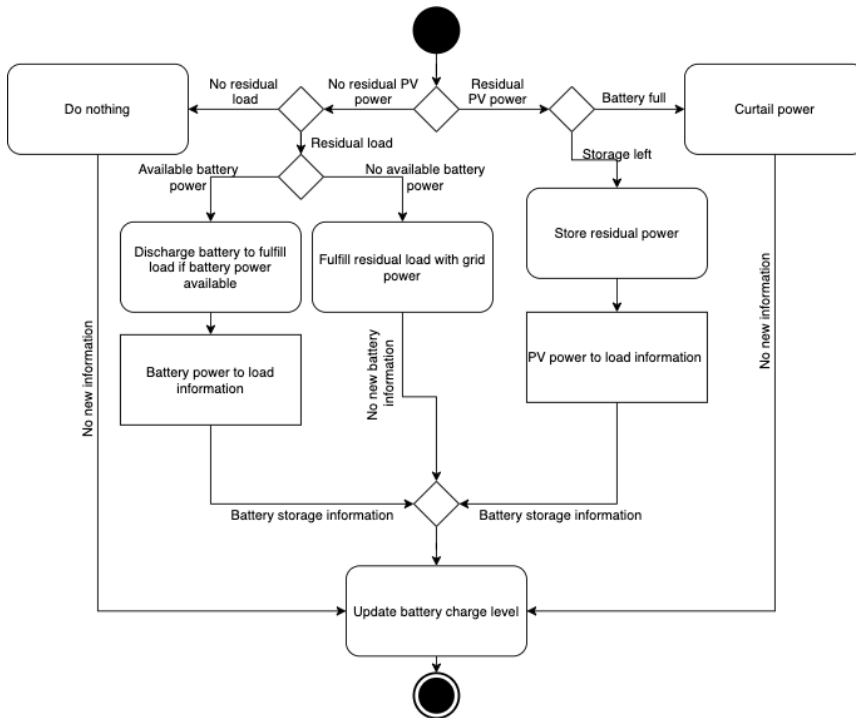
Figure 4.10: The implementation of one step in the simulation performed using the maximize self consumption strategy

the "Simulate" action in figure 4.9 if the load shifting method is used. The dotted lines in figure 4.11 are used to try and group together actions that are linked in some way. The dotted "Maximize self consumption battery control" action box represents the battery control strategy shown in figure 4.10.

Threshold not exceeded and flexible load available — Battery power available — Fulfill flexible load with battery

No flexible load or threshold reached

New battery information

PV power available — Fullfill flexible load with PV power

Flexible load available — Fullfill flexible load until threshold is reached

PV information

No flexible load

Flexible load

Postpone flexible load

Postponed flexible load and control reference not exceeded?

No postponed flexible load

Postponed flexible load available

No PV or battery power available

PV or battery power available

Control reference exceeded

Residual PV power available?

Maximize self consumption battery control

Fulfill all residual non-postponeable load still in system

Fulfill postponed flexible load with grid power

PV power available — Fulfill postponed flexible load with PV power

Battery power available — Fulfill postponed flexible load with battery power

Postponed flexible load updates

Figure 4.11: The implementation of one step in the simulation performed using the load shifting strategy

4.5 Result Extraction

The result extraction module contains the functions necessary to extract the results from the result files, and show them to the user in a easy way. This module also reads in the

daily electric prices and uses them in the result calculations.

4.5.1 Packages

- pandas: Used for managing data frames

- os: Used for accessing the file system

- json: Used to read and write json files

- datetime: Used to transform date strings to datetime objects

- numpy: Package for scientific computing in Python. Used for summation, mean and max operations here.

- matplotlib: Used for plotting results

4.5.2 Implementation of the Result Extraction

After the simulations are done, the files containing the results needs to be read and the results needs to be extracted. This is a simple implementation, which reads in the results, sorts them by control method, does some simple calculations then displays the wanted results by printing them out or plotting them. The calculations depends on which results that are to be displayed. The different calculations corresponds to the performance parameters listed in section 3.9. An activity diagram showing the overall structure of the result extraction implementation is shown in figure 4.12.

4.6 Changes in the Implementation of the AMS Logger

This section will only present a brief list of the changes made in the implementation of the AMS logger. The list will be brief and not go into detail on how the entire AMS logger functions. If this is of interest, it is available in [Ler19]. The main change in functionality is that the AMS logger is now working offline and is transmitting data through an USB to UART cable, rather than uploading it to a cloud service. This is ensured by the following steps:

- Remove the initialization of the Wi-Fi microchip to prevent the program from stopping when it detects that no microchip is available.

- Remove any code trying to reconnect to the chip, to prevent the code entering a reconnect loop.

- Make sure that the chip only sends messages with power usage, as no other message is needed in this thesis.

- Make sure that the correct data is put on the UART channel of the chip instead of being sent to the Wi-Fi microchip.
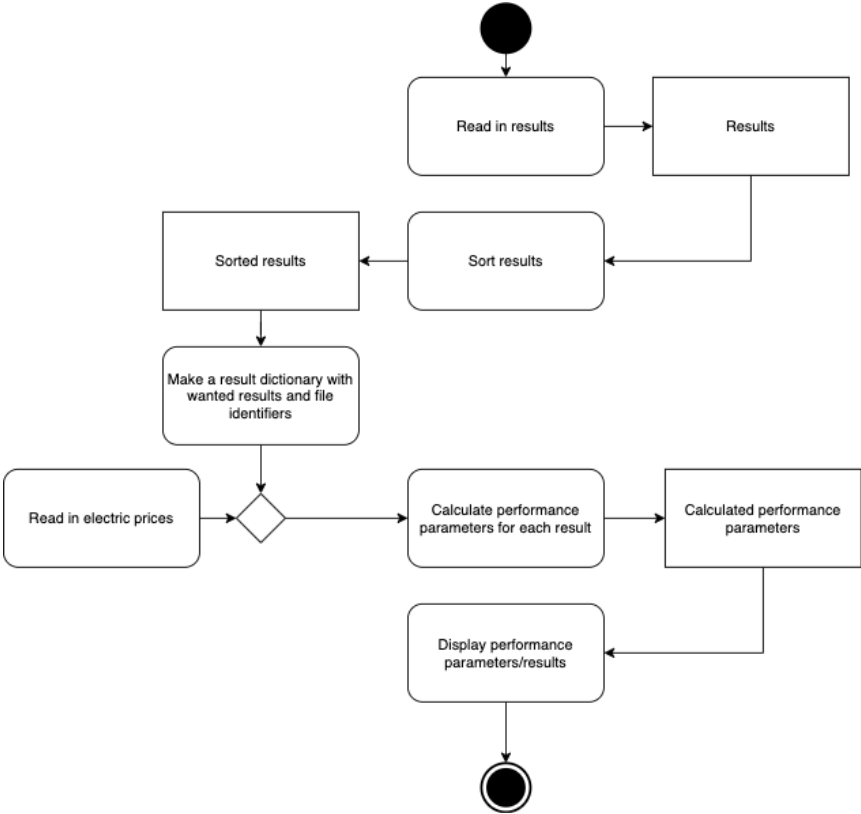
Figure 4.12: The implementation of the result extraction

This is the only changes made in the C code. An additional change is made in the code on the receiving end of the USB to UART cable. This is only a Python file written by the same author of the C code. This Python code is only logging and saving files with the data coming from the AMS logger. The only change made to this code is to add a timestamp from the clock of the computer to the logged data. If interested in the implementation of the Python logger code, it can be read about in [Ler19].

Chapter 5

Results

The results chapter will present and describe the results provided by running simulations in the implemented application. The chapter will not discuss the implications of the results, this will be done in chapter 6. The results presented in this chapter are presented using the performance parameters described in section 3.9. Other results which are not directly connected to these performance parameters will also be presented here.

It should be noted that the peak reduction in the tables in this chapter is the average maximum hourly peak reduction for all days simulated in the given season.

5.1 Load Data Scaling

Due to the lack of load data for most of the year, the same load data needs to be used for all seasons. There is no way to gain access to accurate load data from a whole year at these sites at the time of this thesis work, but it is possible to scale the load after historical load data at the sites from the commercial and industrial sector. There are records of high level load data measurement from these sites, and this data will be used to get an accurate scaling of the load data for the correct season. There are unfortunately no such records for the residential sector data, so the residential data will have the same scale for all seasons. The data used to find the scale are daily load data from the dates used in the simulation in the different seasons.

Table 5.1 present these scale factors. The basis scale is 1, and since the load data are collected in the spring, the spring scale factor remains 1. In the industrial sector, the summer load is a bit smaller than the spring load, while the autumn and winter load is bigger. In the commercial sector, the load from all other seasons are higher, and they get a scale factor above 1.

	Spring (Basis)	Summer	Autumn	Winter
Residential Scale Factor	1	1	1	1
Commercial Scale Factor	1	1.09	1.60	1.65
Industrial Scale Factor	1	0.72	1.13	1.41

Table 5.1: The scaling factor in the different sectors in different seasons

5.2 Base Case Results

5.2.1 Residential Sector

The base case results for the residential sector are presented here. Three different PV power plant sizes were used, as presented in table 3.8. The PV plant sizes were adjusted and scaled in the software to match the parameters. The peak reduction and monthly savings in energy costs are presented in table 5.2, while the remaining economic results are presented in table 5.3. These results describe the economic possibilities for investing in PV power plants of different sizes given the load data from the residential sector, both in the short term and the long term.

From table 5.2 it is clear to see that there is almost no peak reduction and monthly savings in the winter, for all three PV plant sizes. The biggest peak reduction and savings are in the summer. It is generally higher savings in the autumn than in the spring, but the peak reduction is higher in the spring. Understandably there are higher savings in energy costs per month for higher PV plant sizes. Generally it is a very low peak reduction, with the highest average peak reduction occurring in the summer with a PV plant size of 10 kWp with a magnitude of under 0.5 kW.

Season/ PV Size	Peak Reduction (W, %)	Monthly Savings Energy Costs (NOK)
Spring/1	50, 1.2	29
Summer/1	102, 2.5	74
Autumn/1	31, 0.8	37
Winter/1	∼0, ∼0	1
Spring/5	210, 5.2	81
Summer/5	342, 8.5	195
Autumn/5	67, 1.7	109
Winter/5	∼0, ∼0	6
Spring/10	267, 6.6	108
Summer/10	464, 11.5	248
Autumn/10	93, 2.3	143
Winter/10	∼0, ∼0	13

Table 5.2: The results for the residential sector base case with the maximize self consumption strategy strategy

In table 5.3 it is shown that the annual savings are quite low in the residential sector, so it is not cost effective to invest in PV power plants with a capacity of 10 kWp. The investment costs of this PV power plant are to big to be able to break even in the lifespan of the PV power plant. The most cost effective option is the PV power plant with a size of 1 kWp, which has a break even point of 9.2 years. However, the potential life time earnings are very limited.

Strategy/ PV Size	Investment Costs (NOK)	Annual Savings (NOK)	Break Even Point (Years)	Potential Earnings After 18 years (NOK)
Maximize Self Consumption/1	3902	423	9.2	3712
Maximize Self Consumption/5	19510	1173	16.6	1604
Maximize Self Consumption/10	39019	1536	25.4	0

Table 5.3: The economic results for the base case in the residential sector for the maximize self consumption strategy

5.2.2 Commercial Sector

The base case results for the commercial sector are presented in table 5.4, 5.5 and 5.6. These results describes the similarities and differences between the maximize self consumption and load shifting method for the base case in the commercial sector, together with the economic possibilities in the commercial sector. The test cases used in this simulation is presented in table 3.10.

Table 5.4 and 5.5 show mostly the same information, which is to be expected since there are almost no restrictions used in the simulation using the load shifting strategy. The results show that the savings are at their peak in the summer, while there are almost no savings in the winter compared to the other seasons. The summer has a much higher peak reduction than the other seasons. With PV power plant sizes of 50 kWp and 100 kWp there are bigger peak reductions in the autumn than in the spring, but as the PV plant size grows to 250 kWp the peak reduction in the spring surpasses the peak reduction in autumn. However, the monthly savings in energy costs is always higher in the autumn than in the spring. It should also be noted that the monthly savings in the power tariff costs are much less than the monthly savings in energy costs. The average delay of the flexible load using the load shifting strategy is low for all seasons, which is to be expected with an almost non-existent restriction on the peak load. The reason why there is a small average delay is that the moving average peak load can be higher than the highest average clock hour load.

In table 5.6 the economic results of the base cases with the two different control strategies and different PV plant sizes are presented. The annual savings are almost identical for the maximize self consumption strategy and the load shifting strategy. The annual savings go up significantly for each expansion of the PV power plant capacity, but so does the investment cost. This means that the break even point is earlier for the smaller PV power plants with 10.8, 11.6 and 14.8 years to break even for the 50 kWp, 100 kWp and 250 kWp PV power plants respectively. Although the annual savings are considerably higher for the 250 kWp PV power plant it is not as cost effective as the 100 kWp PV power plant

Season/ PV Size	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/50	2365, 4.3	116	937
Summer/50	5370, 9.0	277	2692
Autumn/50	3227, 3.7	268	1674
Winter/50	187, 0.2	9	34
Spring/100	3781, 6.9	138	1805
Summer/100	8838, 14.9	395	5094
Autumn/100	4122, 4.7	319	3347
Winter/100	333, 0.4	18	67
Spring/250	7230, 13.3	202	3200
Summer/250	15931, 26.8	747	9250
Autumn/250	6202, 7.1	445	7868
Winter/250	651, 0.7	44	169

Table 5.4: The results for the commercial sector base case with the maximize self consumption strategy

Season/ PV Size	Avg Delay (Minutes)	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/50	4.6	2376, 4.4	116	937
Summer/50	0	5370, 9.0	277	2692
Autumn/50	0.6	3227, 3.7	268	1674
Winter/50	15.1	289, 0.3	9	34
Spring/100	4.6	3784, 6.9	137	1805
Summer/100	0	8838, 14.9	395	5094
Autumn/100	0.4	4122, 4.7	319	3347
Winter/100	15.2	434, 0.5	18	67
Spring/250	4.5	7230, 13.3	202	3200
Summer/250	0	15931, 26.8	747	9250
Autumn/250	0.4	6202, 7.1	445	7868
Winter/250	15.1	752, 0.8	44	169

Table 5.5: The results for the commercial sector base case with the load shifting strategy

at the current investment price. The most cost effective solution for the life time of the
PV power plant is the 100 kWp PV power plant with the potential for earnings of 213692
NOK over an 18 year period.

Strategy/PV Size	Investment Costs (NOK)	Annual Savings (NOK)	Break Even Point (Years)	Potential Earnings After 18 years (NOK)
Maximize Self Consumption/50	195095	18021	10.8	129283
Maximize Self Consumption/100	390190	33549	11.6	213692
Maximize Self Consumption/250	975475	65775	14.8	208475
Load Shifting/50	195095	18021	10.8	129283
Load Shifting/100	390190	33546	11.6	213638
Load Shifting/250	975475	65775	24.8	208475

Table 5.6: The economic results for the base case in the commercial sector for both the maximize
self consumption strategy and the load shifting strategy

5.2.3 Industrial Sector

In this section the results of the base cases presented in table 3.12 are presented. These
results show the base case results for the industrial sector with different PV power plant
sizes. Table 5.7 and 5.8 show the respective results for the maximize self consumption
strategy and the load shifting strategy, including short term economic implications, while
table 5.9 shows the economic implications over a longer period.

The results are very similar for both control strategies using the industrial sector data.
The peak reduction and monthly savings in energy costs are slightly higher for the load
shifting method, but the difference is very small. The trend here is similar to the other
sectors with the summer as the season with most savings and the highest peak reduction,
while the winter is the season with small economic savings and a small peak reduction.
The spring has a significantly higher peak reduction and higher monthly savings for both
the power tariff and the energy costs than the autumn in the industrial sector, except for
the PV power plant with a size of 500 kWp, where there are bigger power tariff savings in
the autumn. There is a small average delay of the flexible load in the spring, summer and
autumn, while it is much bigger in the winter.

The economical results in table 5.9 show that there are possibilities for earnings in
the industrial sector. The results are almost identical for the maximize self consumption
strategy and the load shifting strategy. The break even point is the lowest for the PV plant
size of 100 kWp, but the low annual savings compared to the two other plant sizes make
it the least profitable. The largest PV power plant size of 500 kWp has the highest break
even point of 10.1 years, but because of the high annual savings it has the largest potential
earnings after 18 years with the potential of earning 1521250 NOK.

Season/ PV Size	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/100	9248, 3.3	1408	3385
Summer/100	11960, 5.9	1062	7916
Autumn/100	5940, 1.9	881	2116
Winter/100	653, 0.2	6	163
Spring/250	13277, 4.7	1656	8433
Summer/250	16040, 7.9	1674	19600
Autumn/250	10577, 3.4	1572	5291
Winter/250	1582, 0.4	16	408
Spring/500	16604, 6.0	1788	15085
Summer/500	20935, 10.4	2562	31502
Autumn/500	14414, 4.6	1934	10582
Winter/500	2880, 0.7	31	816

Table 5.7: The results for the industrial sector base case with the maximize self consumption strategy strategy

Season/ PV Size	Avg Delay (Minutes)	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/100	3.0	9364, 3.4	1408	3385
Summer/100	2.3	11980, 6.0	1062	7916
Autumn/100	9.9	6014, 1.9	881	2117
Winter/100	23.9	882, 0.2	24	164
Spring/250	3.1	13380, 4.8	1656	8434
Summer/250	2.0	16060, 8.0	1673	19601
Autumn/250	8.4	10652, 3.4	1572	5292
Winter/250	28.3	1799, 0.5	25	408
Spring/500	3.1	16707, 6.0	1788	15085
Summer/500	2.0	20955, 10.4	2562	31502
Autumn/500	8.2	14487, 4.6	1934	10583
Winter/500	23.7	3099, 0.8	31	816

Table 5.8: The results for the industrial sector base case with the load shifting strategy

Strategy/PV Size	Investment Costs (NOK)	Annual Savings (NOK)	Break Even Point (Years)	Potential Earnings After 18 years (NOK)
Maximize Self Consumption/100	390190	50811	7.7	524408
Maximize Self Consumption/250	975475	115950	8.4	1111625
Maximize Self Consumption/500	1950950	192900	10.1	1521250
Load Shifting/100	390190	50871	7.7	525488
Load Shifting/250	975475	115983	8.4	1112219
Load Shifting/500	1950950	192903	10.1	1521304

Table 5.9: The economic results for the base case in the industrial sector for both the maximize self consumption strategy and the load shifting strategy

5.3 Test Cases

The test cases in this section uses the PV power plant size which corresponded to the highest earnings after 18 years in each sector. More specifically, test case 1 in the residential sector, test case 1 and 2 in the commercial sector and test case 1 and 2 in the industrial sector uses this PV power plant size. It should also be noted that the η_H used for reference for the η_H reductions in test case 1 in the commercial and industrial sector are the η_H that came out as a result of the base case simulation using the load shifting strategy with the same PV power plant size as the size which will be used in test case 1 in the commercial and industrial sector.

5.3.1 Residential Sector

There is only one additional test case to the base case in the residential sector. This test case shows the influence of batteries of different sizes on the monthly savings in energy costs. The results for test case 1 in the residential sector are presented in table 5.10. The parameters used in this simulation are found in table 3.9. The results show that it is during the spring that the battery is most in use in the residential sector. The battery is also on average never fuller than 50% of the smallest battery size. There is also a small use of the battery during the summer and the autumn. The monthly savings are still very small in the residential sector and is not significantly increased by the introduction of batteries.

5.3.2 Commercial Sector

In the commercial sector, there are three test cases in addition to the base cases which where discussed in section 5.2. The results of test case 1 in the commercial sector are shown in table 5.11. The parameters used in this simulation are found in table 3.11. The results in 5.11 show that the peak reduction is significantly higher with a bigger η_H reduction. This also translates to the monthly power tariff savings. These savings go significantly up for all seasons. There are also some small changes in the monthly energy cost savings from the η_H reduction of 0.04 to the other two η_H reductions. The monthly energy cost savings go up slightly both for the winter season and the autumn season. The

Season/ Battery Size	Avg Maximum Battery Charge (kWh)	Monthly Savings Energy Costs (NOK)
Spring/1	0.5	31
Summer/1	0.4	80
Autumn/1	0.05	37
Winter/1	0	1
Spring/5	0.5	31
Summer/5	0.4	80
Autumn/5	0.05	37
Winter/5	0	1

Table 5.10: The results for the residential sector, test case 1 with the maximize self consumption strategy, with different battery sizes

reason for this will be discussed in chapter 6. The average delay of the flexible load also go up significantly with the reduction of η_H. The average delay grew from a small delay of under 10 minutes with a η_H reduction of 0.04 to a bigger delay ranging from 17.2 minutes to 53.2 minutes with a η_H reduction of 0.12.

Season/ η_H Reduction	Avg Delay (Minutes)	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/0.04	9.6	4697, 8.6	152	1805
Summer/0.04	9.7	10011, 16.9	485	5048
Autumn/0.04	6.0	6209, 7.1	449	3347
Winter/0.04	7.5	1965, 2.2	214	67
Spring/0.1	17.6	6851, 12.6	358	1805
Summer/0.1	16.5	12352, 20.8	618	5048
Autumn/0.1	15.2	10594, 12.2	741	3347
Winter/0.1	41.7	6716, 7.5	577	130
Spring/0.12	23.4	7721, 14.2	393	1805
Summer/0.12	22.2	12898, 21.7	662	5048
Autumn/0.12	17.2	11996, 13.8	791	3349
Winter/0.12	53.2	8138, 9.1	769	184

Table 5.11: The results for the commercial sector test case 1 with the load shifting strategy and η_H reductions

The long term economic results for test case 1 in the commercial sector are shown in table 5.12. With more power tariff savings the annual savings go up significantly and the break even point goes down, which further strengthens the potential for earnings throughout the life time of the PV power plant. The potential earnings increases from 234428 NOK with an η_H reduction of 0.04 to 291506 NOK and 311864 NOK for an η_H reduction of 0.1 and 0.12 respectively.

Strategy/ η_H Reduction	Investment Costs (NOK)	Annual Savings (NOK)	Break Even Point (Years)	Potential Earnings After 18 years (NOK)
Load Shifting/0.04	390190	34701	11.2	234428
Load Shifting/0.1	390190	37872	10.3	291506
Load Shifting/0.12	390190	39003	10.0	311864

Table 5.12: The economic results for test case 1 in the commercial sector for the load shifting strategy with η_H reductions

The results from test case 2 in the commercial sector are found in table 5.13. The parameters used in this simulation are found in table 3.11. These results show how the battery was utilized in different seasons with different battery sizes. Table 5.13 shows that the battery was fully charged at some point every day in the summer and spring for all battery sizes, but in the other seasons, the battery was not utilized at all. The battery improved the monthly savings in energy costs during the summer, and slightly during the spring for bigger battery capacities, but in the other seasons the monthly savings remained at the same level for all battery sizes. There were no additional savings in the monthly power tariff.

Season/ Battery Size	Avg Maximum Battery Charge (kWh)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/1	1.0	138	1818
Summer/1	1.0	395	5124
Autumn/1	0	319	3347
Winter/1	0	18	67
Spring/5	5.0	138	1821
Summer/5	5.0	395	5145
Autumn/5	0	319	3347
Winter/5	0	18	67
Spring/10	10.0	138	1821
Summer/10	10.0	395	5155
Autumn/10	0	319	3347
Winter/10	0	18	67

Table 5.13: The results for the commercial sector, test case 2 with the load shifting strategy and different battery sizes

In table 5.14 the results for test case 3 in the commercial sector are presented. The parameters used in the simulation to provide these results are found in table 3.11. The results show how well the load shifting strategy work for lowering the highest recorded average hourly load in a month, without the help of a PV power plant. The results show that it is possible to lower the average hourly peak load by a substantial amount. With the lowest η_H reduction of 0.04, from 1 to 0.96, the average peak reduction ranges from 511

W to 1237 W, but by lowering the η_H to 0.9 and 0.88, the average peak reduction ranges from 2749 W to 6188 W and from 3765 W to 7814 W, respectively. This results in annual savings of 1770, 4209 and 5406 NOK and potential earnings of 31860, 75762 and 97308 NOK over a 18 year period. The average flexible load delay is however also increasing with a bigger η_H reduction. This means that the average delay grows from under 8 minutes for all seasons with a small η_H reduction, to up to 42.3 and 56.2 minutes with a η_H of 0.9 and 0.88, respectively. It should also be noted that the monthly savings in the power tariff are bigger during the winter than in the rest of the seasons.

Season/ η_H	Avg Delay (Minutes)	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Annual Savings (NOK)	Potential Earnings After 18 years (NOK)
Spring/0.96	5.2	511, 0.9	88		
Summer/0.96	5.5	530, 0.9	104	1770	31860
Autumn/0.96	5.8	1237, 1.4	185		
Winter/0.96	7.3	1153, 1.3	213		
Spring/0.9	25.9	2749, 5.0	190		
Summer/0.9	28.9	3013, 5.1	260	4209	75762
Autumn/0.9	35.9	5771, 6.6	384		
Winter/0.9	42.3	6188, 6.9	569		
Spring/0.88	39.6	3765, 6.9	244		
Summer/0.88	50.1	4365, 7.3	291	5406	97308
Autumn/0.88	56.2	7612, 8.7	494		
Winter/0.88	51.3	7814, 8.7	773		

Table 5.14: The results for the commercial sector, test case 3 with the load shifting strategy, no PV plant and battery, with different η_H

5.3.3 Industrial Sector

The industrial sector has three test cases in addition to the base cases discussed in section 5.2. The results for test case 1 are found in table 5.15, while the parameters used in the simulation are found in table 3.13. These results show how the 500 kWp PV power plant contributed to peak reduction together with a η_H reduction from the benchmark η_H found in the base case tests. Table 5.15 shows that the η_H reduction contributes to a higher peak reduction, and higher monthly savings in power tariff. The average delay also has a steady increase together with the increase in η_H reduction, where the average delay of the flexible load is increased 6-7 times from the lowest η_H to the highest η_H reduction, depending on the season.

The economic results from test case 1 are found in table 5.16. The economic prospects look promising in this test case. The annual savings go up over 10 000 NOK from the η_H reduction of 0.02 to the η_H reduction of 0.08, and the break even point is moved from 10.0 years to 9.5 years. The potential earnings over an 18 year period are also very high for all three η_H reductions, but they are increasing with the increasing η_H reductions.

Table 5.17 is showing how the addition of a battery is influencing the monthly savings

Season/ η_H Reduction	Avg Delay (Minutes)	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/0.02	11.7	19287, 6.9	1998	15100
Summer/0.02	13.4	22871, 11.3	2633	31523
Autumn/0.02	16.2	17741, 5.6	2188	10609
Winter/0.02	15.5	7180, 1.8	444	832
Spring/0.04	27.3	23163, 8.3	2036	15156
Summer/0.04	26.1	25455, 12.7	2737	31585
Autumn/0.04	25.7	21737, 6.9	2294	10703
Winter/0.04	33.1	12945, 3.3	1052	895
Spring/0.08	74.5	30483, 10.9	2154	15384
Summer/0.08	62.7	30899, 15.4	2938	31781
Autumn/0.08	69.1	29161, 9.2	2414	11266
Winter/0.08	103.8	22300, 5.8	1534	1335

Table 5.15: The results for the industrial sector case 1 with the load shifting strategy and η_H reductions

Strategy/ η_H Reduction	Investment Costs (NOK)	Annual Savings (NOK)	Break Even Point (Years)	Potential Earnings After 18 years (NOK)
Load Shifting/0.02	1950950	195981	10.0	1576708
Load Shifting/0.04	1950950	199374	9.8	1637782
Load Shifting/0.08	1950950	206418	9.5	1764574

Table 5.16: The economic results for test case 1 in the industrial sector for the load shifting strategy with η_H reductions

in both power tariff costs and energy costs. The parameters used in this simulation are provided in table 3.13. Similarly to test case 2 in the commercial sector (5.13) and test case 1 in the residential sector (5.10), table 5.17 shows that the battery is most utilized throughout the spring and summer, and less utilized in the other seasons. The monthly savings are however not influenced by the use of batteries.

Season/ Battery Size	Avg Maximum Battery Charge (kWh)	Monthly Savings Power Tariff (NOK)	Monthly Savings Energy Costs (NOK)
Spring/1	1.0	1788	15902
Summer/1	1.0	2562	31515
Autumn/1	0	1934	10583
Winter/1	0	31	816
Spring/5	5.0	1788	15902
Summer/5	5.0	2562	31515
Autumn/5	0	1934	10583
Winter/5	0	31	816
Spring/10	10.0	1788	15092
Summer/10	10.0	2562	31515
Autumn/10	0	1934	10583
Winter/10	0	31	816

Table 5.17: The results for the industrial sector, test case 2 with the load shifting strategy and different battery sizes

In table 5.18 the results for test case 3 in the industrial sector are presented. They are the result of a simulation with the parameters presented in table 3.13. In this test case, there is no battery or PV power plant to influence the average peak reduction, only the load shifting strategy. The table shows that there are possibilities for earnings by only using the load shifting strategy. The annual savings reach 12258 NOK with a η_H of 0.92. This results in potential earnings of 220644 NOK over an 18 year period. The annual savings and potential earnings over an 18 years period with an η_H of 0.98 and 0.96 are 3024 NOK and 7248 NOK, 54432 NOK and 130464 NOK, respectively. The average delays of the flexible loads range from 11.9 minutes to 15.9 minutes with an η_H of 0.98, from 27.1 minutes to 34.2 minutes with an η_H of 0.96, and from 82.8 minutes to 99.6 minutes with an η_H of 0.92.

5.4 Load Data Characteristics

The results in this chapter shed light on how the load data used in this thesis is built up, how big it is, the shape and how big part of it is flexible. These results may help explain the economic results covered earlier in this chapter.

Season/ η_H	Avg Delay (Minutes)	Peak Reduction (W, %)	Monthly Savings Power Tariff (NOK)	Annual Savings (NOK)	Potential Earnings After 18 years (NOK)
Spring/0.98	11.9	2521, 0.9	267		
Summer/0.98	14.4	1592, 0.8	131	3024	54432
Autumn/0.98	15.1	3028, 1.0	185		
Winter/0.98	15.9	4143, 1.1	425		
Spring/0.96	30.4	6384, 2.3	574		
Summer/0.96	27.1	4173, 2.1	343	7248	130464
Autumn/0.96	32.4	7345, 2.3	585		
Winter/0.96	34.8	9948, 2.5	914		
Spring/0.92	90.2	13828, 5.0	907		
Summer/0.92	82.8	9551, 4.7	653	12258	220644
Autumn/0.92	93.6	15728, 5.0	1024		
Winter/0.92	99.6	20238, 5.1	1502		

Table 5.18: The results for the industrial sector, test case 3 with the load shifting strategy, no PV plant and battery, with different η_H

5.4.1 Share of Flexible Load

In table 5.19 the share of flexible load in the load data is presented. In the residential sector, no flexible load is measured separately, so there is no flexible load in the mix. In the commercial sector, the share of flexible load is very high, with a share of over 50 %, while the share is lower in the industrial sector with a share of 8.8 %.

	Spring	Summer	Autumn	Winter
Residential	0 %	0 %	0 %	0 %
Commercial	57.9 %	57.9 %	57.9 %	57.9 %
Industrial	8.8 %	8.8 %	8.8 %	8.8 %

Table 5.19: The share of the load that is flexible

5.4.2 Average Hourly Load and PV Power in Different Sectors

In figure 5.1, 5.2 and 5.3 the average load and PV power distribution over the hours of the day is presented. The PV power plant sizes are 1, 100, and 500 kWp in the residential, commercial and the industrial sector respectively. The general load profile is gathered from the summer, with scaling applied, as described in section 5.1. The residual load profiles are gathered from each season, with scaling applied. The residual load is the load left after the produced PV power is used.

The load is on average higher than the PV power in all seasons. In the residential sector the load is at its peak late in the evening, while at its lowest early in the morning and during the day. In the commercial sector, the load is quite stable and high between 8 in the morning and 16 in the afternoon. At other hours it is much lower. In the industrial

sector the load is at its peak in the middle of the day, but the load is very high throughout the whole day.

In the residential sector the generated PV power is generally low. The amount of PV power produced during the summer is the highest in the residential sector. The amount produced during autumn and spring seams to be very similar, but in the autumn, most of the PV power is produced before midday, while in the spring the most of the data is produced after midday. The amount of PV power produced in the winter is very low. There is generally a mismatch in shape between the load profile and the PV power profile. The residual load follows the general load strictly, with a slightly smaller magnitude where there is PV power to use.
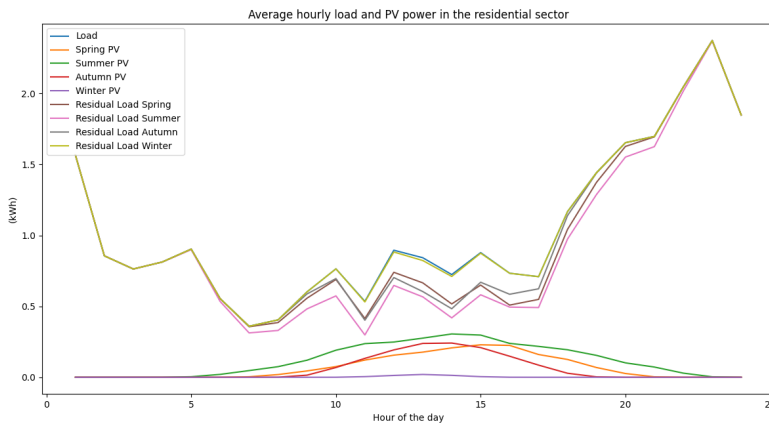
Figure 5.1: The average hourly load and PV power in the residential sector

In the commercial sector, the load profile and the PV power profiles have a similar shape. It is on average produced the most PV power in the summer and in the autumn. During the spring, the peak power produced occurs later in the afternoon than in the other seasons. During winter, not a lot of PV power is produced. It seams like the peak in residual load appears quite early in the day, when the load is high, but before the PV power production reaches its full potential. When there is a lot of PV power available, the residual load decreases before it reaches a new local maximum in the afternoon when the load is still high and the PV power production is lower.

In the industrial sector, the load profile is much flatter than the PV power profiles, but the average daily peak of the PV power corresponds quite well with the average daily peak of the load demand. It is on average produced the most PV power during the summer, but there is not a lot less PV power produced during the spring. The winter produces the least PV power also in the industrial sector. In the industrial sector, the residual load creates an U-shape in the spring, summer and autumn. This means that the peak load during the day gets counteracted by the PV power production for three out of four seasons. During winter the PV power production is too low to make an U-shape.
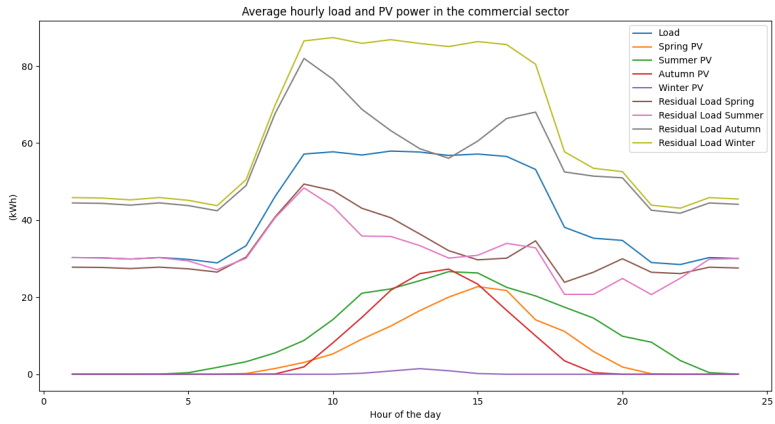
Figure 5.2: The average hourly load and PV power in the commercial sector
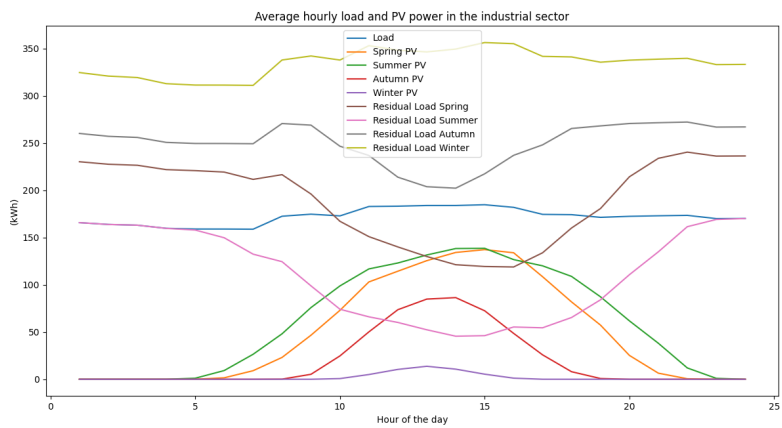
Figure 5.3: The average hourly load and PV power in the industrial sector

Chapter 6

Discussion

6.1 Load Characteristics Influence on Savings

6.1.1 Residential Sector

In the residential sector, there was not a lot of savings. The reason for this is mainly the small PV power plant, which results in a small potential gain from distributed energy production, but the load power profile would create problems if the PV power plant was bigger. The biggest load demand is during the evening, probably because of the electric car charger. At this time, the PV power production is very low, which means that the load profile would not be utilized with a bigger PV power plant, and the PV power plant would be oversized for the load demand at peak PV production times. This factor makes it difficult to save a lot of money using a PV power plant in the residential sector with this load profile.

6.1.2 Commercial Sector

In the commercial sector the load profile is quite different. The load is big during peak PV production, which means that the load profile can be utilized. During seasons with a substantial amount of PV power, a lot of money were saved both in energy costs and power tariff costs, as seen in table 5.4, 5.5 and 5.6. This did make investments in PV power for this particular load profile economically viable.

This sector has a high share of flexible load, which means that the non-flexible base load is quite low. This makes the potential for lowering the peak load quite high, which reflects the results in test case 1 (table 5.11-5.12) in this sector. The power tariff savings went up quite significantly, without increasing the average flexible load delay much, compared to the industrial sector. This can be explained by the residual load profile in figure 5.2. The residual load profile has its peak around 11 in the morning in the spring, summer and autumn. On average, the highest recorded load hour will be recorded at that time in these seasons. This peak is quite sharp and is significantly higher than other peaks during

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the day, which means that the hourly moving average value of η_H at other times of the day will usually be lower, and no flexible load will be postponed for a long time. Since the peak is quite sharp, it will not be many minutes with a critically high η_H, which means that the average delay will be short. The only season that did not have this sharp peak was the winter season. The average delay was also usually higher during the winter season.

6.1.3   Industrial Sector

In the industrial sector, the load profile is quite flat, with a high base load throughout the day. The PV power in this sector is also quite high during spring, summer and autumn, which gave the residual load profile an U-shape. Since the PV power is high, there were a lot of savings in energy costs and in power tariff costs. This made the annual savings high, as shown in table 5.9. The most expensive alternative, a PV power plant with a size of 500 kWp, was the most cost effective because of the high base load, which made it possible to use a big PV power plant size. Despite the fact that the share of flexible load is quite low, there were possibilities to increase the monthly power tariff savings by a lot, especially during the winter, were the monthly power tariff is more expensive

The high base load did however make the average delays using the load shifting strategy large. Since it for the most part is no sharp peak where the recorded hourly load is much higher than the rest of the load, the load shape will be very flat in the peak load hours, and the flexible load data is more exposed to longer postponement. The peak load hours will also get flattened even more when load shifting occurs, since some of the load from the peak will get moved slightly to a time when η_H is not over the threshold. The shape of the residual load also shows that the flat base load outside of the PV production hours will on average be the peak both in spring and summer, which further drives home the point that the load profile in the peak load hours is flat. The same can be said about the load profile in the peak load hours during the winter. The residual load profile is not U-shaped, but the profile during peak load hours is still quite flat.

6.2   Load Shifting Strategy vs. Maximize Self Consumption Strategy

The load shifting method and the maximize self consumption method both utilizes the PV power similarly. The base cases in the commercial and the industrial sector were designed to prove that the methods both behaved similarly and to get similar results.

The two methods differ when comparing the maximize self consumption results in table 5.4 and 5.7 with the load shifting results in table 5.11 and 5.15. Here, the load shifting method is able to achieve additional savings in power tariff costs by reducing η_H and in essence, reduce the threshold. This leads to additional savings, especially during the winter months, which has a high potential for power tariff savings given the increased power tariff prices during the winter months. The maximize self consumption strategy did not give any substantial power tariff savings during the winter. There were also improvements in other seasons, but the biggest difference was in the winter season. The biggest savings are still in energy costs thanks to the PV power plant, but some extra savings are possible using

the load shifting method.

The drawback of the load shifting method is that it creates some delays in the flexible load. The reason why only flexible loads are deferred is that the flexible appliances have some slack, so they are able to deffer some load and still maintain normal operation. How long that these appliances can deffer some of its load depends very much on the situation and the appliance, and is not something that will be discussed in this thesis.

6.3 Influence of Batteries in the System

The inclusion of batteries was not a huge success. The investment costs went up, and no significant boost in earnings were noticed. The reason for this may be that the batteries were not big enough to make a big difference in the months where residual PV power were available. The load demand and PV power was so big compared to the size of the battery so the small contribution from the battery went unnoticed. It also did not help that the battery was not utilized during the autumn and the winter. In these seasons it only functioned as an expense.

The shape of the load profile in the commercial and industrial sector did also not help. The load demand was the largest during the hours when the produced PV power was the largest, so there were not too much residual PV to store in these periods.

6.4 Influence of Flexible Load Delay

The flexible load delay influences the energy costs savings in a non-wanted way. Since all simulations are using data from 24 hours, there is a chance that some flexible load does not get fulfilled if the load is delayed just before the simulation ends. This "power leakage" can lead to false additional savings in energy costs, since the simulation does not pick up this leakage. This is especially apparent in table 5.11 and table 5.15. In these tables, the energy cost savings increase quite a lot when the threshold is lowered and the average delay increase, when there is no reason for why they should increase. In practice this load will roll over to the next day and will be fulfilled there.

In this thesis, this problem could be mitigated by simulating for several days, but a decision was made to only have 24 hour simulations for the ease of extracting results and to limit the run time of the simulation.

6.5 Model Shortcomings

The models used in this thesis are limited, and more accurate results could be achieved using more accurate models. But in this thesis work, which is a preliminary study on this type of data with a limited data foundation the models will suffice. However, some of the limitations will be discussed here.

6.5.1 Economic Model

The economic model used for calculating the economic viability of investments in PV power plants, inverters and batteries are somewhat limited. The only cost that is accounted for is the investment cost. Additional costs such as operation and maintenance cost of the investment are not accounted for in this thesis. The same can be said for installation costs, which is a one time cost when investing in PV power plants or batteries. The investment cost calculation used in this thesis is also linear, which is not necessary the case in real life. Accurate investment cost models are beyond the scope of this thesis, and were never considered to be included in the thesis work. The price of PV power plants and batteries are also constantly changing, but the price used in this thesis is, by the best knowledge of the author, in the right price area.

Net Present Value calculations for the investment were at one point considered to be included. These calculations are way more accurate than the simple economic calculations made in this thesis for measuring the economic viability of an investment. However, since these calculations only apply to specific cases where it must be known how much of the investment will be covered by a loan and how much will be covered by equity, and the respective interest rates on debt and equity must be known, it would not be very informing to perform such calculations. These calculations are also not in the scope of this thesis.

6.5.2 PV Power Plant, Inverters and Battery Models

There are some assumptions made for the PV power plant which does not necessarily hold up in reality. It is assumed when finding the potential earnings after 18 years and the break even point that the solar panels will maintain their efficiency throughout their lifetimes. This is not true, and is something that may be considered in other studies.

Another assumption that is not valid is the fact that all inverters in this thesis is assumed to have no loss. This is not true in reality, and should be taken into account if someone is considering an investment in a PV power plant or a battery.

The battery model used in this thesis is very simple. The battery assumptions are listed in section 3.4.1. A more accurate battery model should be considered if the behaviour of the battery is of great importance, but in this thesis this was not the case.

6.6 Data Validity

The load data gathered in this thesis is load data from a limited time period during spring 2020, which means that the load data used for simulation in the other seasons are not necessarily correct. The magnitude of the data is somewhat accounted for by scaling with the scale factors presented in table 5.1. The shape of the load is however not accounted for, and accurate 1-minute interval data from every day of a year is not possible to obtain at this time. The load data used in this thesis will not paint a correct picture of the load data from other seasons, but as a preliminary study in this field the data foundation will need to suffice.

6.7 Potential Improvements

The biggest limitation in this thesis is the lack of data. If load data from a whole year was available for use at the start of the thesis, and no effort in collecting the data was necessary, more effort could have been laid in developing better models and more effective load balancing methods.

The models used in this thesis can be improved a lot, as discussed earlier in section 6.5. More accurate models give more accurate economic predictions which will give better answers to if load balancing methods are economically efficient.

There are potential improvements to the load shifting strategy as well. With small improvements, this strategy could become something that can be used in real time. If sophisticated prediction methods are used for predicting both the available PV power in the near future and the load demand, this method can be used in real time with the threshold dynamically changing, to reach the desired trade off between load shifting and delay of flexible loads.

Chapter 7

Conclusion

In this thesis, an investigation of the potential of PV power plants to relieve the stress on the power grid in three different sectors and to gain potential economic benefits of this is conducted. The PV power plants had different sizes to be able to fit the load data in the most cost effective way. In addition, a method for balancing the load demand to lower the peak load is proposed and tested. The effect of batteries for reducing the volatility of the PV power and for potential economic upsides are also investigated.

The literature review gave insights in the current focus of research in this field of study, potential economic benefits, demand response and demand side management methods and motivation for conducting a study in this field. The theory gave a brief introduction to terms and themes used in this thesis, together with a survey of the current state of the technologies used in this thesis.

The results differ in the three different sectors. There are much bigger potential up-sides in the commercial sector and the industrial sector compared to the residential sector, both in terms of reducing the peak load and in potential economic savings. This is partly because of the load shape, partly because of the size of the PV power plant, and partly because of the opportunity to lower the peak load using the load shifting strategy. The results revealed that the commercial sector is less prone to long delays of the flexible load than the industrial sector. The results did not show a lot of potential benefits of using a battery to decrease the volatility of the PV power plants, since the potential economic savings were very limited or non-existing. This result was somewhat surprising. However, since the data foundation used in this thesis is very limited, the results can by no means be seen as complete or 100% accurate, but it will suffice as a preliminary study and analysis.

Chapter 8

Further Work

In this chapter, a short list of some possible further work is provided. Most of the suggestions here are based on the discussion in section 6.7.

- A study with more data available. This would provide more reliable results and give a better picture on the economic viability of investing in PV power plants, batteries and using demand response strategies.

- Develop the load shifting method from a method using historical data, to a method that can work in real time.

- Improving the models used in this thesis so the results are more accurate.

- Develop new load balancing methods, using other demand response and demand side management methods.

- A study using optimization methodology to minimize the peak load given delay constraints and other constraints.

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Appendix A

Tigo REST API V3

Tigo REST API V3

Introduction

This api is used to work with the Tigo Energy platform to automate the retrieval and creation of elements. It will attempt to adhere to standard REST calls found in most REST implementations.

Parties

Server - The Tigo platform and urls associated with the api
Client - Third party user with api access to the Tigo platform and/or Tigo api.

Data Transfer

All input and responses will be in JSON format. Additional values may be added at any time but will not affect previous functionality unless stated otherwise.

Base URL

https://api2.tigoenergy.com/api/v3/

Protocols

GET - Will be used when you want to retrieve information from the server.

Authorization

The v3 api implements an auth token system. This allows you to use a token to authenticate endpoints on the Tigo platform.
The preferred method of authentication is using a header with a header Authorization tag.

Example:

Authorization: Bearer ABCDE

Curl Example:

curl -H "Authorization: Bearer ABCDE" "https://api2.tigoenergy.com/api/v3/<endpoint>"

OAuth Apps Authorization (Coming Soon)

OAuth Apps will allow you to use a secret key to gain authorization or access to data. The advantage with apps will allow you to develop on the Tigo platform as a service that does not require a username and password to gain access. It will also allow individual users to approve or deny access to there system with a ui interface. This method will take advantage of the Bearer token therefore it is advantageous to implement the Bearer token.

HTTP Error Codes

Code	Description
2xx	Success
3xx	Connection changes or issues
4xx	Client issue
5xx	Server issue

Error Response

A json error response may be accompanied with HTTP codes

```
{
    "name": "Unauthorized",
    "message": "You are requesting with an invalid credential.",
    "code": 0,
    "status": 401
}
```

Return Header & Rate Limiting

It is good practice to pay attention to headers since they may return additional information about your request. Some examples include rate limiting of api calls or additional information about the intended API endpoint.

X-Rate-Limit-Limit	Max limit in number of requests
X-Rate-Limit-Remaining	Remaining number of requests
X-Rate-Limit-Reset	Number of seconds till limit reset
X-System-Config-Update	Timestamp of last config update, when system id is specified

Note about document

Copy and pasting from this document may place the improper quotes "" when running commands. If something is not working please check the quotes first.

Users

GET Login

Login and get an authorization token and user_id. This uses basic auth to send the username and password.

Example Call

GET https://api2.tigoenergy.com/api/v3/users/login

CURL Example

curl -v -u "{username}:{password}" "https://api2.tigoenergy.com/api/v3/users/login"

Output Parameters

Name	Description	Comments
user_id	User id	
auth	Auth string for Oauth authentication	
expires	Time auth expires ISO 8601	
user_type	String for type of user	"Basic", "Installer", "Partner"

Example Response

200 OK
```
{
    "user": {
        "user_id": 1,
        "auth": "ABCDE",
        "expires": "2016-09-01T00:00:00-08:00"
        "user_type": "Basic",
    }
}
```

GET Logout

Logout the current user auth token

Example Calls

GET https://api2.tigoenergy.com/api/v3/users/logout

CURL Example

curl -v -H "Authorization: Bearer ABCDE" "https://api2.tigoenergy.com/api/v3/users/logout"

Example Response

```
200 OK
{
    "name": "OK",
    "message": "Logged out user",
    "code": 0,
    "status": 200
}
```

GET users

List the current user. Will only be able to query currently logged in user.

Example Calls

GET https://api2.tigoenergy.com/api/v3/users/1

CURL Example

curl -v -H "Authorization: Bearer ABCDE" "https://api2.tigoenergy.com/api/v3/users/1"

GET Parameters

Name	Description	Comments
*id	User id to get info	Must have access to this user

* Required fields

Output Parameters

Name	Description	Comments
user_id	Id of the user	
login	Login for the user	
first_name	First name of the user	
last_name	Last name of the user	
email	Email of the user	
company	Company the users is associated with	
street	Street location of user	
city	City location of user	
state	State location of user	
zip	Zip location of user	
country	Country location of user	
mobile	Mobile number of user	
user_type	Type of users currently	"Basic", "Installer", "Partner"

Example Response

200 OK

```json
{
    "user": {
        "user_id": 1,
        "login": "1",
        "first_name": "John",
        "last_name": "Smith",
        "email": "123@123.123",
        "company": "Tigo",
        "street": "123 Fake St.",
        "city": "Faker town",
        "state": "CA",
        "zip": "123456",
        "country": "United States",
        "mobile": "1231231234",
        "user_type": "Basic"
    }
}
```

Systems

GET systems

List the current set of systems you have access to.

Example Calls

GET https://api2.tigoenergy.com/api/v3/systems
GET https://api2.tigoenergy.com/api/v3/systems?limit=50

CURL Example

curl "https://api2.tigoenergy.com/api/v3/systems" -v -H "Authorization: Bearer ABCDE"

GET Parameters

Name	Description	Comments
page	Page to display of systems	
limit	Number of systems to limit	Default 10 (MAX 500)
sort	Field to sort on	Default system_id

* All parameters are optional

Output Parameters

Name	Description	Comments
system_id	Id of the system	
external_id	External id of the system	
status	Status pending or active	"Pending", "Commissioning", "Ready", "Active"
name	Name of the system	
street	Street location of system	
city	City location of system	
state	State location of system	
zip	Zip location of system	
country	Country location of system	
latitude	Latitude coordinate of system	
longitude	Longitude coordinate of system	

timezone	Timezone of system	
company	Company who installed system	
contact_name	Contact of installer for the system	
contact_email	Email of installer	
power_rating	System power rating	Watts
created	Date the system was created	ISO 8601
commissioned	Date the system was commissioned	ISO 8601
decommissioned	Date the system was decommissioned	ISO 8601

Example Response

200 OK

```json
{
  "systems":[{
    "created": "2014-05-16T20:50:45+00:00",
    "city": "PO 123",
    "company": "One Cool Dude",
    "contact_name": "John Smith",
    "country": "United States",
    "external_id": "test",
    "system_id": 1,
    "latitude": 12.3456789,
    "longitude": 12.3456789,
    "name": "Test System",
    "power_rating": 12000,
    "state": "Faker City",
    "street": "123 Fake Street",
    "zip": "12345"
  },
  {
    "created": "2014-05-16T20:50:45+00:00",
    "city": "PO 123",
    "company": "One Cool Dude",
    "contact_name": "John Smith",
    "country": "United States",
    "external_id": "test2",
    "system_id": 2,
    "latitude": 12.3456789,
    "longitude": 12.3456789,
    "name": "Test System",
    "power_rating": 12000,
    "state": "Faker City",
    "street": "123 Fake Street",
    "zip": "12345"
  }]
}
```

GET systems

Get a single system you have access to.

Example Calls

GET https://api2.tigoenergy.com/api/v3/systems/1

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/systems/1" -H "Authorization: Bearer ABCDE"

GET Parameters

Name	Description	Comments
*id	Tigo id of the system	

* Required fields

Example Response

200 OK
```
{
  "system":{
    "created": "2014-05-16T20:50:45+00:00",
    "city": "PO 123",
    "company": "One Cool Dude",
    "contact_name": "John Smith",
    "country": "United States",
    "external_id": "test",
    "system_id": 1,
    "latitude": 12.3456789,
    "longitude": 12.3456789,
    "name": "Test System",
    "power_rating": 12000,
    "state": "Faker City",
    "street": "123 Fake Street",
    "zip": "12345"
  }
}
```

GET systems/layout

Returns the electrical configuration of the system. That contain multiple components that make up the system.

Example Calls

GET https://api2.tigoenergy.com/api/v3/systems/layout?id=1

GET Parameters

Name	Description	Comments
*id	Tigo id of the system	

* Required fields

Curl Example

curl -v "https://api2.tigoenergy.com/api/v3/systems/layout?id=1" -H "Authorization: Bearer ABCDE"

Example Response

```
{
  "system": {
    "system_id": 1,
    "inverters":[
      {
        "inverter_id": 1,
        "inverter_type_id": 1,
        "label": "Inverter 1",
        "object_id": 1,
        "inverter_serial": "ABC",
        "mppts": [
         {
           "mppt_id": 1,
           "label": "MPPT 1",
           "strings":[
            {
               "string_id": 1,
               "label": "String A",
               "short_label": "A",
               "object_id": 2,
               "panels": [
                {
                   "panel_id": 1,
                   "label": "A1",
                   "short_label": 1,
                   "serial": "O4C05B8001234",
                   "type": "TS4-S",
                   "source_id": 1,
```

```
                        "object_id": 3,
                        "panel_type_id": 1,
                    }
                ]
            }
        ]
        }
    ]
    }
  ]
  }
}
```

Objects

GET objects/system

List the objects on display for data query. This may be different from system/layout.

Example Calls

GET https://api2.tigoenergy.com/api/v3/objects/system?system_id=1

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/objects/system?system_id=1" -H "Authorization: Bearer ABCDE"

GET Parameters

Name	Description	Comments
*system_id	Tigo id of the system	

* Required fields

Output Parameters

Name	Description	Comments
id	Id of the object	
label	Name of the object	
object_type_id	Type of the object	
parent_id	Id of the parent object	-1 is root node
datasource	Key of the datasource	Null for no direct source
children	Array of object_ids of children objects	
ui	Attributes that define display	X: x position Y: y position MP: Max Power Rating Label: Additional label X1,Y1,X2,Y2: Coordinates for a line DR: Minutes to data repeat Z: Zoom level or scale

Example Response

200 OK

```json
{
 "objects":[
  {
   "id": 1,
   "label": "System",
   "object_type_id": 1,
   "parent_id": -1,
   "datasource": null,
   "children": [2,5]
   "ui": {
     "X": 100,
     "Y": 100,
     "MP": 5000
    }
  },
  {
   "id": 2,
   "label": "String A",
   "object_type_id": 3,
   "parent_id": 1,
   "datasource": null,
   "children": [3]
  },
  {
   "id": 3,
   "label": "A1",
   "object_type_id": 2,
   "parent_id": 2,
   "datasource": "04C05B800ACE.panels.A1",
   "children": [3],
   "ui": {
     "X": 150,
     "Y": 150
    }
  }
 ]
}
```

GET objects/types

List the available object types

Example Calls

GET https://api2.tigoenergy.com/api/v3/objects/types

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/objects/types" -H "Authorization: Bearer ABCDE"

Output Parameters

Name	Description	Comments
object_type_id	Id of the object type	
label	Description of the object type	

Example Response

200 OK
```
{
 "object_types":[
  {
   "object_type_id": 1,
   "label": "System"
  },
  {
   "object_type_id": 2,
   "label": "Panel"
  },
  {
   "object_type_id": 3,
   "label": "String",
  }
 ]
}
```

Sources

GET sources/system

List the available sources and datasets for a system.

Example Calls

GET https://api2.tigoenergy.com/api/v3/sources/system?system_id=1

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/sources/system?system_id=1" -H "Authorization: Bearer ABCDE"

GET Parameters

Name	Description	Comments
*system_id	Tigo id of the system	

* Required fields

Output Parameters

Name	Description	Comments
+sources	Array of available sources	
- serial	Reference serial	This could change if replaced
- last_checkin	Timestamp of last checkin ISO 8601	Based on server timezone America/Los_Angeles
- timezone	Unix based timezone	This does not correlate with last_checkin
- control_state	Enumerated string	"on", "wait_on", "wait_off", "off" wait indicates command is pending or waiting for response from source
+sets	Array of available sets	
- set_name	Name of available dataset	Part of sets array
- last_min	Time of last update by min ISO 8601	Part of sets array, last local time minute
- last_day	Time of last update by day ISO 8601	Part of sets array, last local time day

* Please note there could be multiple sources and multiple sets for each

Example Response

200 OK

```json
{
  "sources":[
    {
      "serial": "04C05B80092B",
      "last_checkin": "2016-08-23T13:30:00-08:00",
      "control_state": "on",
      "sets": [
        {
          "set_name": "panels",
          "last_min": "2016-08-23T13:15:00-08:00",
          "last_day": "2016-08-22T00:00:00-08:00"
        },
        {
          "set_name": "Wattnode",
          "last_min": "2016-08-23T13:10:00-08:00",
          "last_day": "2016-08-22T00:00:00-08:00"
        }
      ]
    }
  ]
}
```

Data

GET data/aggregate

Get aggregated data from the server

Example Calls

GET https://api2.tigoenergy.com/api/v3/data/aggregate

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/data/aggregate?system_id=1&start=2014-09-23T00:00:00&end=2014-09-23T23:59:59&level=min&param=Vin" -H "Authorization: Bearer ABCDE"

GET Parameters

Name	Description	Comments
*system_id	Id of the system	Tigo id of the system
*start	Start time of data	Local time 2014-09-23T00:00:00
*end	End time of data	Local time 2014-09-23T23:59:59
level	Type of aggregation	"min", "day" Default: min
sensors	Whether to include sensor data true or false	"true", "false" Default: true
param	Type of data to return	*"Pin", "Vin", "RSSI" Default: Pin
object_ids	Csv of object ids	1,2 Default: all
header	Output of header type	"id", "key" Default: "id"

* Required Fields

Notes

- P = power, V = voltage; in as Pin mean power from the panel.
- Minute level data will be shown as Watts for Pin
- Day level data will be shown as Energy for Pin
- Note header can change in this format unless object_ids specified

Example Response

200 OK

Datetime,1,2,3
2014/09/23 00:06:23,23,23,23
2014/09/23 00:06:24,23,23,23
2014/09/23 00:06:25,23,23,23
2014/09/23 00:06:26,23,23,23
2014/09/23 00:06:27,23,23,23
2014/09/23 00:06:28,23,23,23
Datetime,1,2
2014/09/23 00:06:28,23,23

Example with header key

200 OK
Datetime,04C05B800ACE.panels.A1_Vin,04C05B800ACE.panels.A2_Vin,04C05B800ACE.panels.A3_Vin,
2014/09/23 00:06:23,23,23,23
2014/09/23 00:06:24,23,23,23
2014/09/23 00:06:25,23,23,23
2014/09/23 00:06:26,23,23,23
2014/09/23 00:06:27,23,23,23
2014/09/23 00:06:28,23,23,23
Datetime,04C05B800ACE.panels.A1_Vin,04C05B800ACE.panels.A2_Vin
2014/09/23 00:06:28,23,23

GET data/combined

We typically have data coming in as panel level data. We then combine the data to present at different levels of the system. An example would be the entire system or a particular string. This endpoint will automatically combine the data into a single number for each object id.

Example Call

GET https://api2.tigoenergy.com/api/v3/data/combined?system_id=1&agg=hour&start=2016-09-07&end=2017-09-07

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/data/combined?system_id=1&agg=hour&start=2016-08-16T08:00:00&end=2017-08-16T08:03:00&objects_ids=1,2" -H "Authorization: Bearer ABCDE"

GET Parameter

Name	Description	Comments
system_id	Id of the system	ID of the system.
level	Enumerated string of levels	Long name: minute, hour, day, month, year Short name: mi, h, d, m, y
start	Start timestamp	Local time 2014-09-23T00:00:00
end	End timestamp	Local time 2014-09-23T23:59:59
object_ids	CSV of object ids	Each id will be the combined data of the parent items. Default is system level combination.

* Required Fields

Notes

- Minute level data will be shown as Watts
- Greater than minute level data will be shown as Watt Hours
- Aggregation above hour will set time for start 00:00:00 and end 23:59:59
- Soft limits on data ranges are enforced, an error will return if it is too large of a range.

Example Response

200 OK
DATETIME,1,2
2016/08/16 08:00:00.000,1170,35
2016/08/16 08:01:00.000,1175,36
2016/08/16 08:02:00.000,1195,38
2016/08/16 08:03:00.000,1216,50

GET data/summary

Get some basic information from a system.

Example Call

GET https://api2.tigoenergy.com/api/v3/data/summary?system_id=1

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/data/summary?system_id=1" -H "Authorization: Bearer ABCDE"

GET Parameter

Name	Description
*system_id	ID of the system.

* Required field

Response Fields

lifetime_energy_dc	Integer|Lifetime energy
daily_energy_dc	Integer|Daily energy
updated_on	Timestamp|ISO|Last updated
last_power_dc	String|Numbers of days of data for year

Example Response

```
200 OK
{
    "summary": {
        "lifetime_energy_dc": "18607879.27",
        "daily_energy_dc": 0,
        "updated_on": "2014-11-18T00:00:00-08:00",
        "last_power_dc": 0
    }
}
```

Alerts

GET alerts/system

Get all the events that the user is subscribed to

Example Call

GET https://api2.tigoenergy.com/api/v3/alerts/system?system_id=1

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/alerts/system?system_id=1" -H "Authorization: Bearer ABCDE"

GET Parameter

Name	Description	Comments
*system_id	Id of the system	ID of the system.
language	String for language	Default: EN DE, EL, EN, ES, FR, IT, JP, KO
start_added	Start time of alert added	Local time 2014-09-23T00:00:00
end_added	End time of alert added	Local time 2014-09-23T23:59:59
page	Integer of page	Default: 0 Results are paginate adjust page with this param
limit	Integer of page size	Default: 50 Number of alerts to show

* Required Fields

Output Parameters

Name	Description	Comments
+alerts	Alerts envelop contains array	
- alert_id	ID of the alert	
- added	ISO 8601 when alert added	
- generated	ISO 8601 when the alert was generated	
- title	Name of the alert	
- message	Details on the alert	Contains the details in HTML
- description	Information about the alert	Contains information and resolution
- system_id	System id of the alert generated	
- unique_id	Unique id of the type of alert	

| - last_day | Time of last update by day ISO 8601 | Part of sets array, last local time day |

Example Response

200 OK

```
{
    "alerts": [
        {
            "added": "2016-07-09T07:08:10-07:00",
            "alert_id": 1,
            "description": "<p>Your Tigo system has detected low
energy production on your PV system.</p><p><b>Troubleshooting
Steps:</b></p>",
            "generated": "2016-07-09T06:54:34-07:00",
            "message": "",
            "system_id": 1,
            "title": "Tigo Alert: Low Power Production on PV System",
            "unique_id": 200
        },
        {

            "added": "2016-05-13T16:28:22-07:00",
            "alert_id": 37337296,
            "description": "<p>Your Tigo system has detected a string
of PV modules that has shutdown.</p><p><b>Troubleshooting
Steps:</b></p>",
            "generated": "2016-05-13T16:24:16-07:00",
            "message": "String ID: \n- String A (2016-05-13 12:17)",
            "system_id": 1,
            "title": "Tigo Alert: String Shutdown",
            "unique_id": 106
        }
    ]
}
```

GET alerts/types

Get all the different alert types

Example Call

GET https://api2.tigoenergy.com/api/v3/alerts/types

CURL Example

curl -v "https://api2.tigoenergy.com/api/v3/alerts/types" -H "Authorization: Bearer ABCDE"

GET Parameter

Name	Description	Comments
language	String for language	Default: EN DE, EL, EN, ES, FR, IT, JP, KO

* Required Fields

Output Parameters

Name	Description	Comments
+alert_types	Alert Types array envelope	
- alert_type_id	ID of the alert type	
- title	Short description of alert	
- description	Information and resolution	
- unique_id	Unique id of the type of alert	

Example Response

200 OK
```
{
    "alert_types": [
        {
            "alert_type_id": 24,
            "description": "<p>Your Tigo system has detected a PV
module with low energy production.</p><p><b>Troubleshooting
Steps:</b></p>",
            "title": "Tigo Alert: Low Power Production on PV Module",
            "unique_id": 300
        },
        {
            "alert_type_id": 25,
            "description": "<p>Your Tigo system has detected a string
of PV modules with low energy production.</p><p><b>Troubleshooting
Steps:</b></p>",
            "title": "Tigo Alert: Low Power Production on PV String",
            "unique_id": 301
```

```
        }
    ]
}
```

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