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Smart Power Control in Supermarket Applications

- A Case Study

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Abstract

In this study, smart power control system strategies for Norwegian supermarket applications are investigated. The relevance of smart power control systems is supported by trends in the market and the political environment. Examples include political goals regarding increased penetration of renewable electricity in the grid, economic incentives found in electricity pricing schemes, an increased number of Norwegian prosumers, technical challenges opposed on utility companies and new available technologies.

The stated power control goals are to increase the degree of self-sufficiency by local PV generation and to decrease yearly electricity costs. The means of mitigating electricity costs are peak shaving and load shifting from high price to low price periods, principles which are graphically described in Figure 6. The supermarket KIWI Dalgård, which is under construction and located in Trondheim, is selected as the case study. It is used as a common thread for discussing alternative solutions and making design choices for the various subsystems and strategies which compose the suggested power control systems.

To make a basis for a realistic power control design, load data are gathered as historical data with hourly values for a full year. Applied electricity cost elements are real data from Nord Pool Spot and the local utility company Trønderenergi, for the investigated period May 2016 to May 2017. Insight into load data has been obtained by granted access to the energy monitoring database of KIWI, along with conversations with key KIWI personnel. To form a basis for power control design for a full year and to assess the internal flexibility of the loads, the load data has been studied with a daily, seasonal and yearly perspective as well as distributed on load types. A detailed model of the PV system planned at KIWI Dalgård has also been built in the simulation software PVsyst. Based on the load and generation curves of KIWI Dalgård, an evaluation of convenient storage technologies has been made, of which a thermal PCM storage solution was decided to be included in the case study simulations.

A study of global research publications has been used to identify suggested smart power control strategies which are to be evaluated in a case study context. To support understanding and relevance of the discussed systems, technical theory is generally supported with system examples and available solutions in the market when found. Included in the scope is the power control system context, which forms an important part of the decision basis. The basic architecture of a building automation system (BAS) is described as it forms the system to which the smart power control is to be adapted. Different stakeholders and their goals are discussed, as it forms a basis for how the system should be set up. A potential saving assessment for the case study is included as it gives guidelines of which equipment and complexity which can be justified when designing a power control system. After an overall assessment, a real time fuzzy logic control system and an optimized scheduling system have been chosen as alternatives to be further investigated for the case study. A full year of hourly simulations has been conducted, and results are compared for the suggested control schemes. Additionally, a sensitivity and scenario analysis is conducted to evaluate control system performance in different situations.

The proposed power control strategies of fuzzy logic real time control and optimized dispatch performed technically well according to the stated control objectives, however it proved difficult to generate economic revenue. The best performing control structure was the optimized scheduling system, which mitigated yearly electricity costs by 3.5 % and obtained a degree of self-consumption of 99.3 %. The largest savings were obtained by peak shaving. The main reason for the low savings obtained was the small potential for smart power control found in the case study, which was recognized by low consumption, flat load curves and 97 % direct self-consumption of PV electricity by the loads before smart power control was applied. For such a case, no control or a simple real time control structure requiring a minimum level of set-up time and installations seems to be most economically viable. Other constraints were market based, such as low energy grid tariffs and low variation in the hourly spot price. Still, the technical performance of smart power control systems was demonstrated, and the systems are believed to be attractive in more suitable applications. The relevance of smart power control increases with large grid tariffs, excess of distributed generation, sharp peak loads, large variation of electricity prices, and the number of synergies which can be integrated so that alternative cost components may be reduced.

Sammendrag

Oppgaven er en studie av smarte effektstyringssystemer for bruk i matbutikk. Politiske og markedsmessige trender er med på å gjøre smarte effektstyringssystemer stadig mer aktuelle. Blant dem er politiske mål for økt fornybarandel i energimiksen og tekniske utfordringer knyttet til dette, muligheten for senket strømregning, en økende andel plusskunder og nye tilgjengelige teknologier.

Det definerte målet for effektstyringssystemet er å øke selvforsyningsgraden av egenprodusert solstrøm, samt senke den årlige strømkostnaden gjennom kutting av effekttopper og å flytte laster basert på timesbaserte variasjoner i strømprisen. Oppgaven omkranser seg rundt en casestudie, som danner grunnlag for datainnhenting, dimensjonering og evaluering av mulige løsninger og alternativer. Norgesgruppen har tildelt KIWI Dalgård, lokalisert i Trondheim og under bygging, som casestudie. Gjennom fri tilgang på prosjektets planleggingsdokumenter og energimåledata fra KIWIs EOS-system, gir casestudien mulighet for et realistisk design av det foreslåtte energistyringssystemet.

Studien legger vekt på å innhente reelle data for å oppnå så realistiske resultater som mulig. Historiske og timesbaserte måledata for den undersøkte perioden mai 2016 til mai 2017 har blitt brukt som input til systemet. For å øke innsikt i måledataene, og for å kunne overføre data fra referansebyggene til casestudien på riktig måte, har samtaler med nøkkelpersonell i KIWI blitt aktivt benyttet. Den årlige, sesongbaserte og daglige variasjonen i strømforbruket har alle blitt studert for å fange opp relevant info for effektstyringssystemet. Ved modellering av forventet solstrømproduksjon har det blitt tatt utgangspunkt i avsatt areale for solcellemoduler i prosjektets planleggingsdokumenter. Detaljerte simuleringer av KIWI Dalgårds solcelleanlegg har blitt utført i simuleringsprogrammet PVsyst, der beregningen inkluderer en 3D skyggemodell. Basert på kurver for produksjon og forbruk, i tillegg til egenarten i byggets laster, har et lager blitt foreslått og dimensjonert. Det ble for KIWI Dalgård besluttet å gå for et termisk lager basert på et faseendringsmateriale. Timelige strømpriser og nettariffer er innhentet som reelle data for den undersøkte perioden, fra strømbørsen Nord Pool Spot og den lokale netteieren Trønderenergi.

En studie av det globale forskningsfeltet innen smarte effektstyringssystemer danner grunnlag for foreslåtte strategier til bruk i casestudien. Det er lagt vekt på å støtte opp presentert teori med eksempler og om mulig anvendelser i dagens marked. Det er også lagt vekt på effektsystemets kontekst, da den danner grunnlag for strategiske valg og forståelsen av effektsystemets rolle og grensesnitt. Beskrevet kontekst inkluderer prinsipp og oppbygning av et bygningsautomasjonsanlegg, samt hvordan prosjektets ambisjoner, kartlagte potensiale og stakeholderes interesser danner grunnlag for valg av strategi. Etter en totalvurdering har et system for realtidsstyring basert på fuzzy logic, samt et pre-optimert styringssystem basert på optimeringsalgoritmer blitt foreslått undersøkt i casestudien. Resultater fra den undersøkte perioden presenteres og sammenlignes for de to valgte systemene og et scenario uten styring for å undersøke systemenes merverdi. En sensitivitetsanalyse og en scenarioanalyse for forskjellige installerte solcelleanlegg og lagringsløsninger har også blitt tatt med, for å undersøke systemenes oppførsel under forskjellige rammebetingelser. Alt dette danner grunnlag for diskusjon og evaluering av de smarte effektstyringssystemenes egnethet.

De foreslåtte systemene presterte bra ut fra et teknisk perspektiv, men det ble funnet vanskelig å oppnå vesentlige økonomiske besparelser. Det beste resultatet ble oppnådd av det pre-optimerte styringssystemet, der 3.5 % reduksjon i årlige elektrisitetskostnader og 99.3 % egenkonsumeringsgrad ble oppnådd. De største besparelsene ble oppnådd ved kutting av effekttopper. Hovedgrunnen til de lave besparelsene var det begrensede potensialet som ble funnet i casestudien, som var kjennetegnet av lavt forbruk, flate lastkurver og en egenkonsumeringsgrad av solstrøm på 97 % før effektstyring ble tilført. For et slikt tilfelle er ingen effektstyringssystemer, eventuelt et basert på svært enkle strukturer og få og konvensjonelle komponenter, vurdert som det mest økonomisk hensiktsmessige. Andre begrensninger for besparelse ble funnet i markedet, da de timesbaserte spotprisene som oftest var flate og gav lite gevinstpotensiale for lastforflytning, samt at nettariffene basert på energi var lave. Alt i alt har likevel studien demonstrert muligheter og synergier som ligger i et smart effektstyringssystem. Det forventes å være attraktivt i et prosjekt der forholdene er mer tilrettelagt. Relevansen til et smart effektstyringssystem øker ved nivået på nettariffer og variasjoner i eletrisitetspriser, skarphet og høyde på effekttopper, mengden av uutnyttet solenergi og synergier vedrørende systemintegrasjon og annet som gjør at alternative kostnader kan reduseres.

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Abbreviations

BAPV	Building adapted PV
BIPV	Building integrated PV
DG	Distributed generation
DR	Demand response
DSM	Demand side management
DX	Direct expansion
EE	Energy efficiency
EMS	Energy monitoring system
BEMS	Building energy management system
MAPE	Mean average percentage error
MAS	Multi-agent system
MF	Membership function
MIP	Mixed integer linear programming
MPP	Maximum power point
MPPT	Maximum power point tracking
NREL	National Renewable Energy Laboratory
NVE	The Norwegian Water Resources and Energy Directorate
PCC	Point of common coupling
PCM	Phase changing material
PV	Photovoltaic
PWM	Pulse width modulation
STC	Standard test conditions
SOC	State of charge
SOH	State of health
TOU	Time of use

1 Introduction

1.1 Motivation and Background

In accordance with EU regulations, Norwegian policies are increasingly focusing on lowering CO_2 emissions [1]. Norway is committed to obtain 67.5 % renewable ratio in its total energy mix within 2020, which requires an increased renewable electricity generation [2].

Today's electricity pricing schemes provide economic incentives for power control for larger consumers through the peak power tariff. The Norwegian arrangement for prosumers provides an additional incentive for self-consumption of distributed generation due to the exemption of grid tariff, taxes and fees on distributed generation which is consumed at the generation point [3], [4]. Ongoing market changes regarding renewable energy generation and electricity pricing schemes create further business opportunities for smart power control. Traditionally, the time of use has not been regarded in Norwegian electricity pricing schemes. The advent of AMS meters, which according to regulations will be installed nationwide within 01.01.2019, allows for hourly monitoring of electricity consumption and generation. Hourly metering promotes hourly spot pricing, which creates a market for load shifting from high price periods to low price periods [5], [6].

In 2016, a 366 % increase in PV installations was experienced in Norway in reference to 2015 numbers [3]. Increased penetration of renewable energy energy in the grid leads to increased technical issues. Fluctuating electricity generation from renewable sources like solar generates challenges on the utility companies regarding energy balancing and quality of power supply, which constrains the allowable degree of solar penetration in the grid [7]. When applying peak shaving and increased self-consumption by power control on the generation site, these challenges can be mitigated. Stated in an other way, demand side flexibility supports an increased ratio of renewable electricity in the existing power grid. "As the grid becomes smarter, the model of self-consumption is expected to play a larger role while promoting energy security, efficiency and decarbonisation" [8], [9], [10].

The mentioned trends in the political sphere and the market facilitate new challenges and possibilities for power control systems. "Controlling peak demand can bring savings both from a customer and a grid owner perspective. For the grid, reducing peak demand reduces the need of new investments by releasing capacity in existing installations. From a commercial building owner point of view, lowering peak demand will lower peak electricity tariffs" [8]. With an increased number of service providers, business models, stakeholders and thereby complexity in the energy system, comes increased requirements to smart power control systems which can handle the various interests and constraints.

1.2 Research Objectives and Method

This study is a self-standing work based on a previous study by the same writer. The main goal was kept, which is "to design a model of a power control system for supermarket use, which is well suited for mitigating electricity costs and increasing the utilization of locally generated electricity" [8]. Generally, portions from the reference work have been recycled in this study when it covers the same theoretical background.

The goal was broken down into the following research objectives:

- Identify business cases for smart power control, today and with a future perspective.
- Assess alternatives for power control strategies and sources of flexibility from the global research field.
- Select a case study to test system performance. Select the most relevant strategy among studied alternatives and model the power control system for realistic operation.
- Obtain all necessary input data for a realistic operation scenario, including the modeling of the case study itself. The resolution of the data must be in accordance with what is needed to obtain control objectives.

The business model that was chosen required input data with hourly resolution. Input data to KIWI Dalgård, which was the chosen case study, was PV generation, load consumption, grid tariffs, electricity prices and weather data, which all needed to be modeled on an hourly basis. When case study simulations were conducted, comparisons were made for a real time fuzzy logic control system, an optimized dispatch system and a situation with no applied control. Simulations were conducted for a full year with hourly values, which required extensive data handling and modeling. Accordingly, software were used extensively at the various subtasks of this study, and only the result selection considered most relevant to the main goal has been presented. For each input and simulation category, the software, sources and databases which were considered most convenient were chosen. The list based on the case study simulation categories is as follows:

All cases:

- Load data from KIWI energy monitoring system
- Insight into KIWI Dalgård data by conversations with key personnel in KIWI
- PV generation data are modeled realistically in PVsyst
- Electricity spot prices from Nord Pool Spot
- Grid tariffs from the local utility Trønderenergi
- Data handling in Microsoft Excel
- Weather data from the Norwegian Meteorological Institute

Optimized Dispatch:

- Optimization model in FICO Xpress Optimization Suite
- Load predictions by XLSTAT

Real time control:

- Fuzzy logic control in MATLAB/Simulink

Smart power control has been a widely used term in this study, and requires a definition as the term "smart" is a floating term. The IEC definition of a smart grid is "electric power system which utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as:

- to integrate the behavior and actions of the network users and other stakeholders
- to efficiently deliver sustainable, economic and secure electricity supplies [11]"

In this study, smart power control has been understood as power control systems which are smart grid ready, i.e fits a smart grid context according to the IEC definition. Emphasis was put on control strategies utilizing artificial intelligence and/or computational power to handle various constraints and conflicting interests from the active players in the energy management system.

The contribution to the research field has mainly been to apply known smart control structures in a new setting, and comparing their performance for a detailed case study. Also, a methodology for the design process has been made, which is the basis for the structure of this thesis. There were no known research studies with yearly assessment of optimized scheduling systems or fuzzy logic in Norwegian supermarkets. In the global research field, multiple smart power control system have been suggested. Systems utilizing artificial intelligence and other control structures able to handle complex systems include multi-agent systems (MAS) [12], [13], [14], [15], fuzzy logic systems [16], [17] and optimized dispatch [18], [19], [20], [21], [22], [23], [24]. While fuzzy logic and optimized dispatch generates set points based on control algorithms, MAS is presented more like a building automation architecture, in which digital agents may interact to obtain goals. MAS has been suggested in combination with optimal dispatch systems [25], [26] and fuzzy logic [12]. A theoretical study has been made to provide an understanding of the mentioned control strategies, and consequently give a basis for understanding how they would function in Norwegian supermarket application. The suggested smart power control systems have been described along with some conventional solutions in todays market. The building blocks of the system and their interaction with the larger system have been explained. The technical installations, the grid and the user have all been taken into account when assessing control strategies. The suggested power control system have been tested in a case study by hourly simulations for a full year. Not all of the investigated technologies were included in the case study simulations, however a representative for smart power control were included in the simulations both for a real time system and the optimized dispatch system. For all conducted simulations, comparisons were made with a scenario with no control, to assess their added value.

1.3 Scope

This study includes a variety of control structures and their building blocks, as well as a detailed build up of a case study. Selection of the multiple components included in the case study and the investigated control structures has generally been made with basis in described alternatives. To keep the large focus area within an orderly and easy read format, clear limitations had to be made.

Generally, technical systems were described according to the following categories:

- When alternative system components were evaluated and compared to each other, only theory considered necessary to obtain a basic understanding of the technologies and make a decision towards the case study was presented.
- For technical system parts which were to be embedded in the case study simulations, information necessary to set up a realistic power flow by the control system was included.
- Selection of systems and system components was made on basis of a mixture of technical, environmental and economic considerations.

Regarding the economical aspects, it was decided only to include the yearly electricity costs in the calculations, to highlight the savings by smart power control of energy flows. Other costs, like installation costs, component costs, system assembly costs, planning costs, operation and maintenance costs etc. were generally not presented. The reader, by having a general understanding of market costs in the field, may balance the presented results with expected system costs, both now and in the future as installation costs are rapidly decreasing in the presented field. Even though system costs were not included explicitly, economic considerations were also included when choosing system parts for the case study and evaluating results.

Another limitation which has been made, is the time resolution used in the calculations. When conduction simulations on energy flows, only an hourly average of all energy flows was presented. By this choice, no calculations have been made on power quality and all the other technical issues and behavior in a 50 Hz electrical system. The chosen resolution is well in phase with the stated goal of designing a control system for increasing the degree of self-sufficiency and decrease electricity costs for the prosumer. In the Norwegian market situation which were studied, both of these are calculated based on hourly average values. Possible ancillary services to the grid were also discussed, although not quantified. They were included in the discussion as they are relevant to the goal of decreasing electricity costs and increasing the degree of self-sufficiency, by supporting future business models and increased renewable penetration in the grid.

The role of the suggested control system in a building automation system (BAS) is an important narrowing of scope as control occurs on many layers. The layers in the suggested control system are visualized by Figure 35 in Section 7.1. In the lowest layers, each of the load and generation components have their own control system, in this study called primary control. Example of this is a ventilation unit which controls air fan speed, a cooling case unit which keeps a reference temperature in order to conserve chilled foods and a battery control system which control internal power flows and constraints in the battery. Above this layer is often a building automation layer which handles interaction and communication among the various components based on some kind of logic, typically to obtain comfort/desired operation by using as little energy as possible. One example of deterministic logic might be "If no one is present, then turn off lights and the radiator in the break room". In this study, the smart power control schemes were to be added to a case study supermarket which has already been planned, and rules had already been established in the BAS for how the technical installations were to be operated how they should interact with each other. The task of the smart power control systems suggested in this study was consequently to add smart logic for how the PV system, the loads, and an added storage in the supermarket should be operated in order to reach the stated goals. The output of the power control systems is limited to provide hourly set point values or other commanding messages to the devices it manages. The receiving field device with their internal control, for instance a battery management system, will decide themselves how it is to solve the task it has been given without violating its own constraints. By this choice, no emphasis was made on control theory as it is the task of the primary control layer and outside the scope of this study.

1.4 Thesis Layout

The case study works as a common thread throughout this study, and the relevance of the discussed systems and components for the case study forms the basis for decision making. When subsystems like load profiles, the PV-system and the storage are discussed, design choices and calculations were generally made right afterwards as they were often needed as inputs to other subsystems. All the subsystem results were in the end modeled as input to the total power control system which were modeled in Section 8.

The thesis starts with a data acquisition process regarding the case study in Section 2 to 4. Firstly, KIWI Dalgård is presented as the case study, and an investigation of its loads is made to identify its daily, seasonal and yearly trend, as well as its internal flexibility potential and distribution of load types. Then, the build-up of the electricity bill and the Norwegian prosumer arrangement are described, and an electricity pricing scheme and its accompanying business cases for the operation of the power control system are decided. PV system theory is then presented for designing a realistic model of the PV system already planned for KIWI Dalgård by project planners. The model is built up in the time-series simulation software PVsyst, and includes detailed elements like a 3D shading model. The outputs of the collection of data process are the case study load and generation profiles, along with electricity pricing schemes and selected business cases, which form the basis for the design of the power control system.

Section 5 to 7 handle components and subsystems needed to build up a power control system. In Section 5, thermal and electric storages are discussed as principle alternatives for adding flexibility to KIWI Dalgård. In Section 6, different strategies and approaches when designing a power control system are discussed, along with describing typical building blocks. The understanding from Section 6 forms basis for understanding the example systems from the research field presented in Section 7, and for choosing which control system strategies should be applied for the case study.

After the decision of control strategy and modeling of all subsystems has been made, the design process of the total system and its performance on a yearly basis for the case study is treated In Section 8. The design process for the suggested systems includes a presentation of assumptions, mathematical models and graphical presentations of system topologies. Simulations are conducted with hourly values on a yearly basis, and results are presented.

Finally, results are discussed and evaluated in Section 9, and concluding remarks and suggested future research are presented in Section 10. The suggested smart power control systems perform well in controlling the power flows according to control objectives. However, it proved difficult to generate sufficient savings to justify the investment, mainly due to the low potential for power control found in the case study. Still, advantages by using smart power control systems have been demonstrated, and they may be attractive in more suitable applications.

2 Case Study Load Data

Generally, to determine a proper power control strategy for supermarkets, the energy usage patterns must be understood. For this reason, the data acquisition process starts with identifying the relevant load profiles for the case study. The load profiles will be used as reference when discussing all other elements of the power control system.

2.1 Case Study Presentation

KIWI Dalgård, a medium sized supermarket of 1200 m^2, is chosen as the case study. It is located in Trondheim, under construction, and will open for the public within the end of 2017. A view of its main facade is given in Figure 1. "Owned by Norgesgruppen, a large company in the grocery sector, it is subject to an ongoing ambition to provide climate neutral services. Their ambition includes being self-sufficient with renewable energy, eliminate greenhouse gas emissions and maximize recycling of waste (...) making them a potential applicant of smart power control (...). Norgesgruppen has shown interest for the project, and granted detailed information from the planning stage of KIWI Dalgård in order to facilitate a realistic power control system design" [8], [27].

Figure 1: Southwestern and northwestern facade of KIWI Dalgård

Limited work is done to map energy usage of Norwegian supermarkets. The few studies on the topic are based on a rather small selection on supermarkets, and show large individual variations [28]. For this study, the choice has been made to base discussions solely on measured data relevant to the case study. A challenge is that KIWI Dalgård was about to be put into operation at the time of writing. Consequently, energy monitoring data needed to be obtained from a reference building. To make the discussion as relevant to the case study as possible, energy monitoring data from KIWI Holter is used. KIWI Holter was put into operation April 2016, and according to KIWI it has a typical load profile of a modern KIWI store and is a natural reference installation for KIWI Dalgård. The store has hourly load data logged since May 2016, which forms a thorough and relevant source of data [29], [30]. In cases where the technical installations of KIWI Holter and KIWI Dalgård deviate, adjustments are made to comply with expected values for KIWI Dalgård. To provide insight into the relevant aspects of power control design, both daily variations, seasonal variations and distribution on load types are explicitly presented and discussed.

2.2 Supermarket Specifics

A supermarket is in this study defined as a large grocery store. Among the products offered are food and household products both in the frozen, chilled and room-tempered state. Typically, Norwegian supermarkets are sized in the range of $500-2000\,m^2$ [28]. "Supermarkets are chosen as the building type for this study because of their very interesting load profiles for matching PV generation. Whereas most building types in Norway are recognized by large peak winter loads, small summer loads and periods of down time throughout the year, supermarkets show a steady energy consumption at all seasons" [8]. Something else which is unique to supermarkets is the large ratio of thermal loads and thermal capacity, which in theory can be utilized for adding flexibility and decreasing costs in a power control system. This aspect will be further discussed in Section 2.3.

2.3 Assessment of Load Data

In order to estimate the load profiles for each of these categories for KIWI Dalgård, EMS data of KIWI Holter has been supported by insight into the project plan documents and dialogue with key personnel in KIWI [29], [31], [32]. Generally, these sources are used for presented load data for KIWI Dalgård when other sources are not stated. Support by key KIWI personnel also made it possible to detect and correct operation errors present in the monitored data.

2.3.1 Load Profiles

The energy monitoring system (EMS) of KIWI divides the load into three main categories, namely "Ventilation", "Cooling" and "Store". In order to get a more detailed understanding of the loads, they will for this study be separated into more and smaller categories. A 2014 report by The Norwegian Water Resources and Energy Directorate (NVE) divided energy consumption in supermarkets into the categories of space heating, hot water, ventilation, lighting, technical equipment and air conditioning [28]. These categories will be used as a basis for the load discussion.

To show yearly trends in supermarket consumption, the hourly total load of KIWI Holter from May 2016 to May 2017 was logged and displayed in Figure 2 [31]. The data shows how stable this supermarket load is, "always" exceeding 30 kWh/h. It is hard to see any distinct seasonal differences in the energy consumption. For the vast majority of the time, the load is between 30-60 kWh/h.

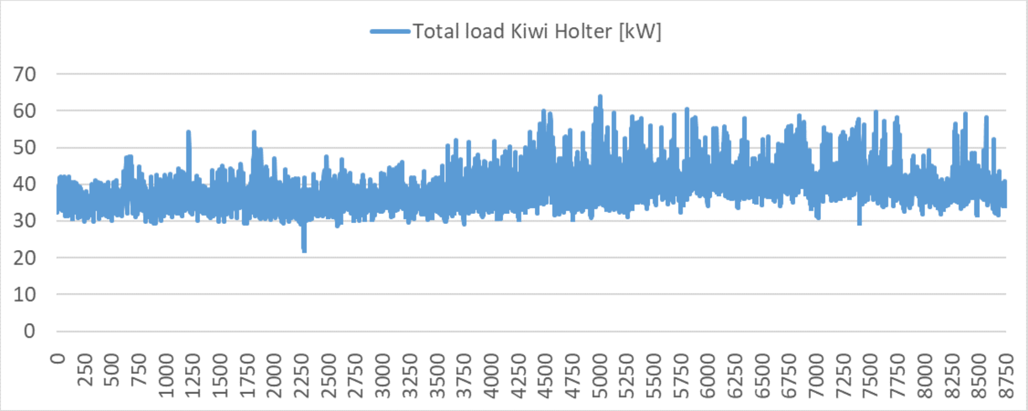


Figure 2: Measured hourly data showing yearly consumption trends of a typical KIWI store

To show the daily variation of the load, data from three example days of KIWI Holter, each representing different seasons, are displayed in Figure 3. By observation, the load curve is very flat on a daily basis for all the cases. No hourly period seems to be explicitly recognized by a lower or higher consumption for all the examples, except a small rise in consumption at the start of the working day. The result shows why supermarkets are a highly suitable building type for PV application, by being a stable consumer of locally generated electricity at all times.

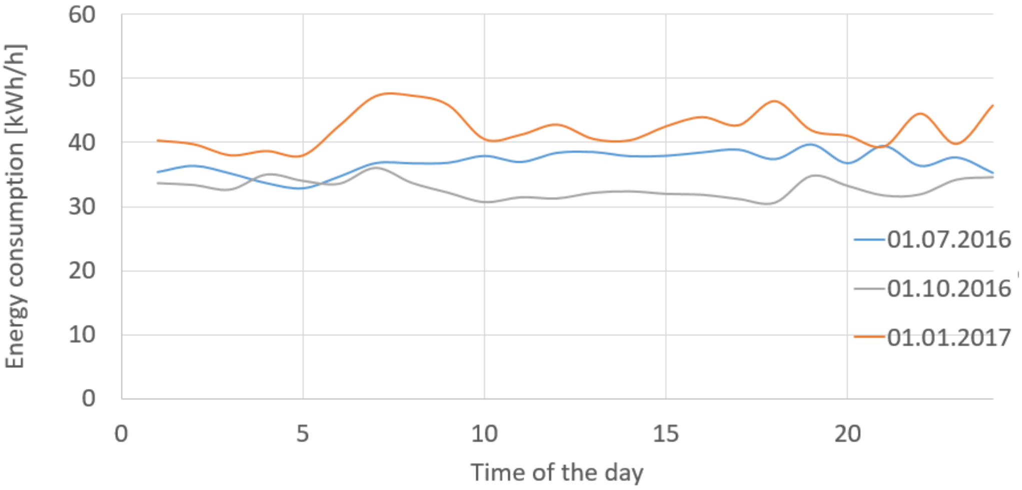


Figure 3: Daily consumption patterns for a typical KIWI store

There are some diffences between the technical installations of KIWI Holter, which is reference, and KIWI Dalgård, which need to be accounted for. The main differences are that KIWI Dalgård utilizes heat pump instead of direct el-based space and ventilation heating, local air conditioning of offices instead of centralized air conditioning, and plans to run ventilation at half capacity instead of full capacity during night. The electricity consumption by heat pumps and cooling machines is given by Equation (1),

$$Electricity\ consumption = \frac{Heating\,/\,cooling\ demand}{COP} \tag{1}$$

where the COP is the coefficient of performance. A COP of 3 is assumed for the heat pump, which is considered a conservative value for ground based heat pumps [33]. The operational hours of each load have been stated after conversations with key KIWI personnel [29]. By adjusting for the differences in technical installations between KIWI Holter and KIWI Dalgård, the predicted would-have-been load at the example day 24.05.2016 for KIWI Dalgård is viewed in Figure 4. For easier interpretation of the similar colored categories, the labels are organized top-down according to their value at the left starting point of the curve. The example day was chosen due to minimal temperature differences between day and night, which made it easier to recognize the contribution by each load category.

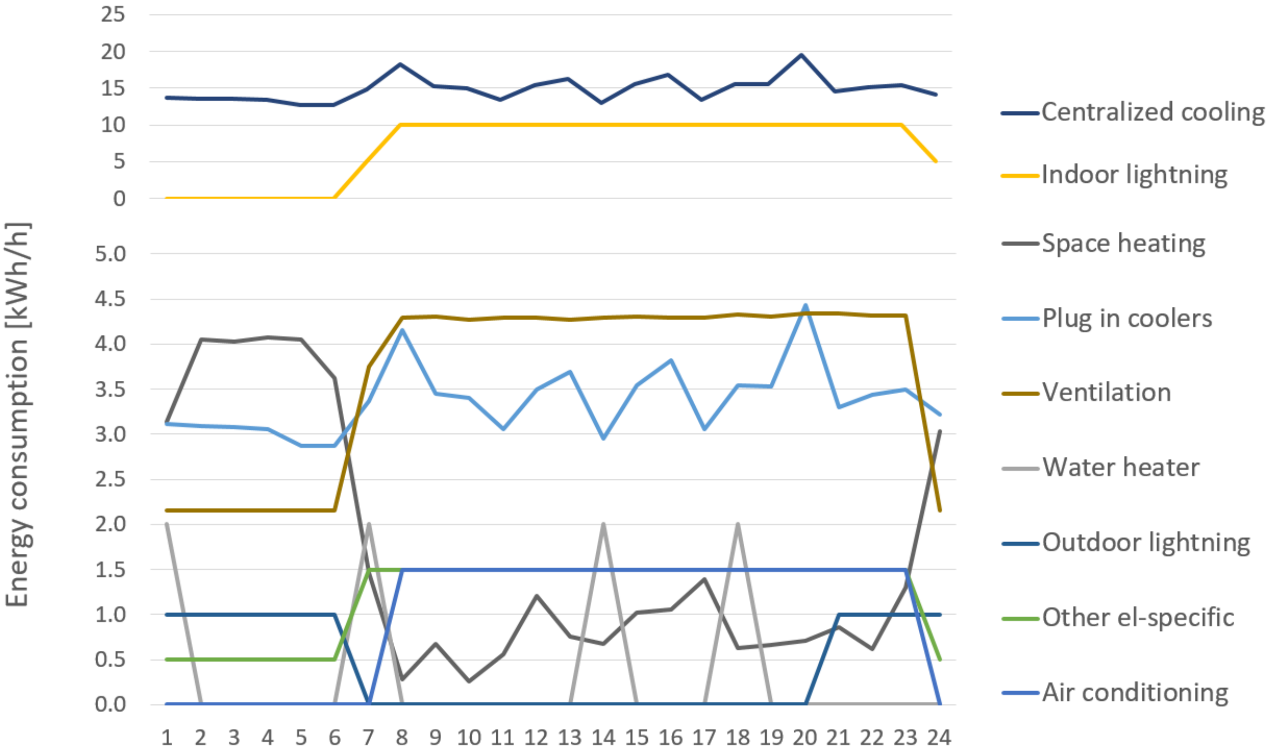


Figure 4: Expected daily load profile at KIWI Dalgård

In the same way as for the example date, KIWI Holter load data is converted into expected load data at KIWI Dalgård for the full year period May 2016 to May 2017. The hourly load data is used for designing the power control system for the case study. Further, explanations of load curve shapes and what is embedded in each load category are provided in Section 2.3.2.

2.3.2 Load Types

In this section, the load types are described using Figure 4 as basis, and the yearly load type distribution of KIWI Dalgård is presented. The single largest load in a supermarket is made up of the freezer and cooling units, statistically composing approximately 50 % of the total load [28]. Naturally, according to food storage requirements for chilled food, this load is never turned off and forms the main basis of energy consumption in the supermarket. For KIWI Dalgård, the system is built up as a centralized direct expansion (DX) system, of which a system scheme is viewed in Figure 47 in Appendix A. A centralized DX system topology is the most common for supermarket applications. DX means that the cooling circuit refrigerant is in direct heat exchange with the cooling cases, instead of using an intermediate ice water circuit, which would generate energy losses [34], [35]. Two different pressures are used for the low temperature DX cooling circuit, so that one single central topology can be used for both the cooler and freezer units. Figure 47 also shows how the waste heat in the refrigerant cycle is heat-exchanged and used for heating purposes. For KIWI Dalgård, the waste heat is heat-exchanged with the supply ventilation air. If residue heat remains after this stage, it is dumped into deep bore holes, which are used as a low temperature source for the heat pump responsible for space heating. In the planning documents of KIWI Dalgård, the supplier estimates a COP of 4.1 for the cooling machine in this planned operation scenario. In terms of flexibility, this interconnection between the cooling and heating system may have consequences for power control, as peak shaving of the cooling system may affect the heating system.

Some coolers are plug-ins, and consequently not included in the centralized systems. This is due to practical reasons; some coolers shift between being coolers and freezers due to seasonal sales campaigns, and some freezers are delivered by the food suppliers. It is assumed that the load curve of the plug-in coolers will have a similar shape as the explicitly monitored centralized cooling load. The demand of the plug-in coolers are inserted according to data from KIWI Fjeldset and KIWI Konowsgate, which are KIWI stores where these specific loads were monitored explicitly. For KIWI Dalgård, an extra DX cooler will be installed to cool office areas with respect to KIWI Holter, and this added load is put in the air conditioning category. The load is estimated according to the predicted heat load in offices by personnel and computers, and is assumed to run in the opening hours of the store.

Energy efficient LED lighting is used for this project, both for indoor and outdoor lighting. The indoor lighting of the store is on during the opening hours of the store, and the outdoor lighting is turned on at night. The sales areas are mainly heated by tempered ventilation air. The ventilation load includes both the electricity used for the fans and for additional heating of ventilation air, the latter for cases when waste heat from the cooling cycle is not sufficient. One of the fans is turned off at night, leaving 50 % consumption at this time. The additional heating for ventilation and the general space heating of the store are supplied by the heat pump. Radiators are installed for use in personnel rooms and offices, and aerotempers for entrance areas. Space heating is largest at night, which makes sense as there are no internal heat sources like lighting and people during the night, and heat needs to be supplied to keep indoor temperature at the desired level. A plug-in water heater is also installed, assumed to be activated during short time intervals in various times throughout the day. In the end, small and fixed electrical loads like pumps and general plug-ins are placed in a category named "other el-specific", with its maximum value during the opening hours of the store.

By applying the explained load distribution principles for the whole period May 2016-May 2017, the expected yearly load type distribution is displayed in Figure 5. An assumption which was made was that Sunday consumption is equal to night consumption. The figure shows a total consumption of less than 250 kWh/m^2yr, which is considered to be very low for supermarkets. For instance, it is less than half of the consumption which was measured in detail by the selection supermarkets used in the 2014 NVE report regarding supermarket consumption [28]. The result is well in accordance with experiences made by KIWI, who claims the energy consumption on a selection of their stores is less than halved in the latter years due to more emphasis on energy efficient technical installations.

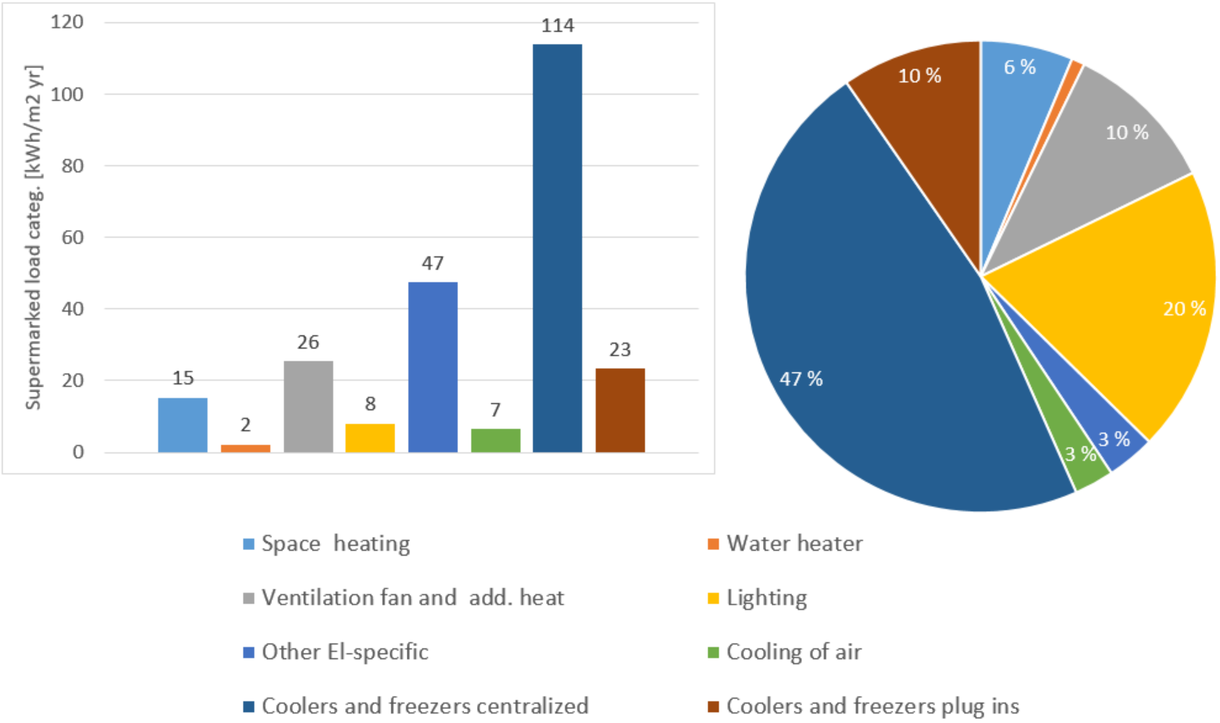


Figure 5: Average yearly load type distribution expected for KIWI Dalgård

2.3.3 Load Flexibility

In order to utilize the flexibility potential which lies in the loads themselves, this potential should also be assessed. For a load to be flexible and relevant to the power control system, it must be shiftable without compromising the quality of service, large enough for it to have an impact and available when needed. By utilizing flexibility, the resulting load curve might be modified into a more desired shape by peak shaving, load shifting and valley filling, principles depicted in Figure 6 [5]. Loads which are available for such applications, are considered flexible loads.

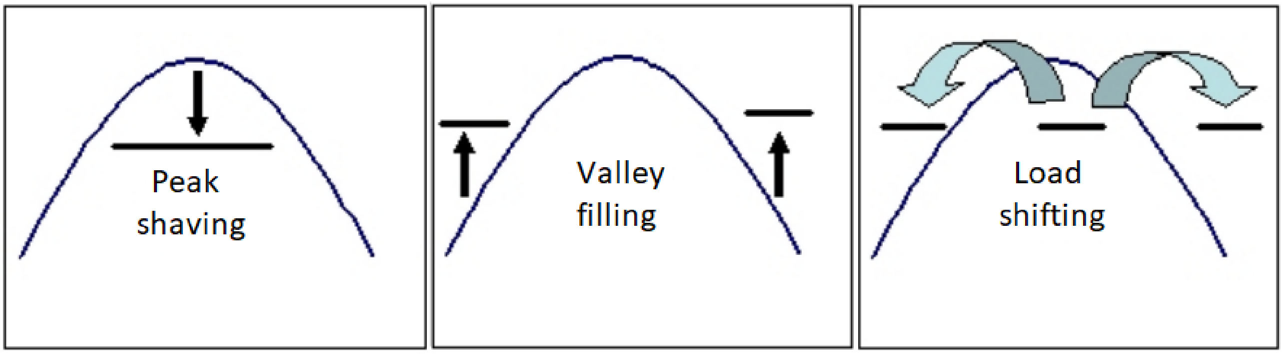


Figure 6: Peak shaving, valley filling and load shifting

Generally, thermal loads are flexible, as they are slow in nature and might be reduced for extended periods without affecting the system environment negatively. For example, the cooling of an insulated case containing mineral water, by having a large heat capacity, might be turned off off for hours without changing mineral water temperatures significantly. Loads which are fast and must be 100 % available in order to deliver the requested service, are not considered flexible. Table 1 evaluates load flexibility criteria for the load types found at KIWI Dalgård. When the mark is orange, the load is considered not flexible. An orange mark states that the flexibility is low.

	Space heating	Water heater	Vent.	Lighting	Other El-specific	Cooling of air	Central. cooling	Plug-in cooling
Shiftable load?	Yes	Yes	🟧 No	🟧 No	🟧 No	🟨 Low degree	🟨 Low degree	🟨 Low degree
Load size	Medium	🟧 Very small	Medium	Medium	🟨 Small	🟨 Small	Large	Medium
Shiftable when needed?	🟧 Seldom	🟨 Maybe	-	-	-	Probably	Yes	Yes

🟧 Not flexible

🟨 Low flexibility

Table 1: Flexibility assessment of internal loads at Kiwi Dalgård

The flexibility of each load type is considered to be specific for KIWI Dalgård, and is not automatically transferable to other stores, as the hourly load profile and the size of the various loads may vary from project to project. Among the loads, the freezing and cooling loads are considered the most flexible. They are also the largest loads, an consequently embed the largest potential. Being a thermal load with large heat capacity stored in the food products and well insulated cases, the load can theoretically be turned off for some time without bringing a large change of temperature. However, utilizing the food as thermal storage is problematic due to strict food storage requirements. "The Norwegian Food Safety Authority sets requirements regarding the storage temperatures of easily perishable food products. Chilled products should be kept below 4 ^{o}C if not otherwise stated by product packaging, and frozen products should generally be kept below $-18\,^{o}C$ [36]. For different product categories, different temperatures are ideal. Table 19 in Appendix A lists the typical storage temperature settings for different products at a KIWI supermarket [31]. The differentials state the temperature interval for each product category. Even though the interval settings can be narrowed down, thus creating a potential flexibility of shifting set point temperatures, some margins need to be left for defrosting purposes [37]. Among the chilled products at a KIWI store, only the beer and mineral water category can be subject to large temperature variations without affecting product perishability" [8]. The beer and mineral water cooling load accounts for about 1-3 kW consumption in the steady state. Thus, the cooling load in Table 1 is only considered shiftable to a low degree. The cooling of ventilation air is only done for demanding areas like computer offices. The load is at maximum on day time when peak shaving is needed, however the load is considered too small to be effectively used by a power control system.

The other loads are not considered flexible in terms of relevance for the power control system. The space heating load is a medium sized load in KIWI Dalgård terms, however it is generally largest at night when consumption is at a minimum. Consequently, it is not available when needed. For the winter season, space heating may also occur in the middle of the day. By inspection of the load curves of KIWI Dalgård, it was found that additional heating was needed about 33 % of the time for KIWI Holter during the winter season. However, considering that inland Holter is colder during winter time than coastal Trondheim, and that KIWI Dalgård plans to use a heat pump instead of direct electricity for space heating, the flexibility potential is very seldom believed to be larger than 2 kW [38], [39]. The resulting impression is that the combination of size and availability of this load is generally too low to be considered relevant as flexibility in the power control system. The ventilation and lighting loads are not considered flexible as they will affect the sale by directly affecting customer experience. El-specific loads are considered fixed. The hot water is a shiftable thermal load, however a very small load for KIWI Dalgård. It is also fluctuating, and may not always be available when needed by a power control system.

Summing up, there exists some flexibility potential in the KIWI Dalgård loads. At the same time, the flexible part of the loads is distributed on many small load types, and few of them have general availability. The communication, monitoring and control would have to be set up for every load which is to be subject to power control, which would make the cost larger than for setting up a single load with a larger flexibility potential. Cost structures treated in Section 3 show that only small cost reductions may be obtained by reducing peak consumption with a couple of kilowatts. For this study, it is decided not to utilize the integrated flexibility of the loads, as it is not believed to be cost effective. For the power control system, flexibility will primarily be added as an external storage, which is further discussed in Section 5.

3 Cost of Electricity

Most of the theory in this section originates from a previous study made by the same author [8]. One of the main goals of the control system is to mitigate electricity costs. To design the correct control objectives, the composition of the electricity bill must be understood. In this section, emphasis will be on price data which are relevant to the control system, and conclusions will be made on how the power control system can contribute to mitigation of electricity costs.

3.1 Choice of Electricity Pricing Scheme

Traditionally, retailers have worked as a mediate trader between end customers and Nord Pool Spot, offering various pricing schemes which do not take into account the time the electricity was used [5], [40]. With the advent of AMS-measurements, which measure electricity consumption on an hourly basis, and according to regulations which will be installed at all Norwegian customers within January 01, 2019, hourly spot price electricity schemes will become available to end consumers [6], [5]. Hourly spot pricing is the pricing scheme which makes most sense from a socioeconomic point of view, as the prices reflect the immediate marginal cost of production [40]. For this study, it will be used as the electricity price structure. It is reasoned both by the sosioeconomic argument, and by allowing for a potential business case for smart power control by load shifting from high price periods to low price periods. When conducting simulations for this study, electricity prices are obtained as historical data from the Nord Pool Spot web page [41]. Nord Pool Spot is the Nordic market operator, facilitating daily electricity exchanges in the Elspot market [41].

To give an impression of how the spot electricity price usually varies throughout the day, some examples are displayed in Figure 7. Although the price curves differ in shape, all curves in the example selection show an approximate 20 % deviation between the daily high and low electricity price. Also, the prices are generally lowest during night, when consumption is at the lowest.

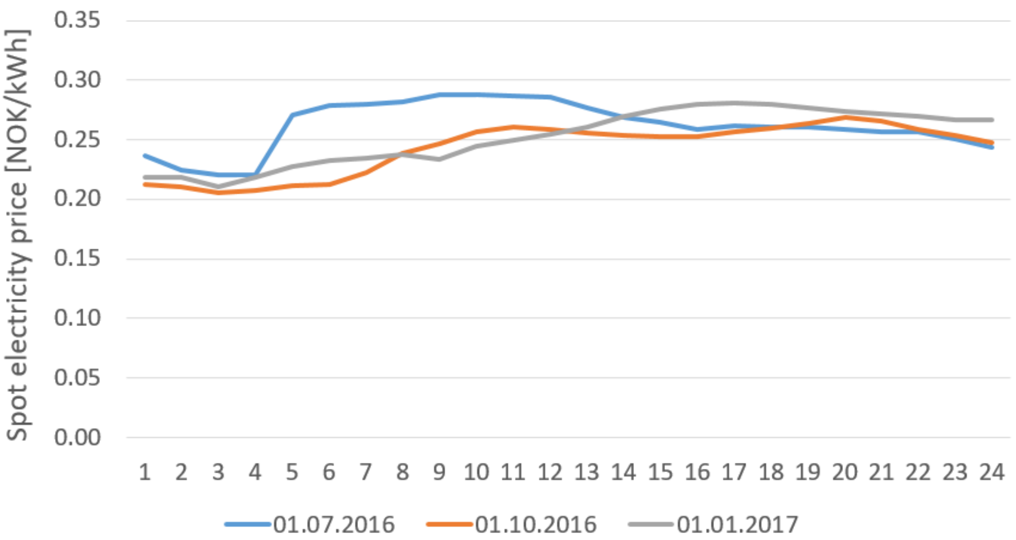


Figure 7: Examples of daily spot price curves

3.2 The Composition of the Electricity Bill

The electricity bill for Norwegian consumers is composed of cost of exchanged electricity, grid tariffs taxes and fees.

3.2.1 Electricity Price

Due to the chosen electricity pricing scheme, the cost of exchanged electricity is the spot price found at Nord Pool Spot at any given time, plus an additional fee set by the retailer to cover their cost. For this study, it is assumed that the customer is directly engaging in the Nord Pool Spot market to avoid the fee from the retailer.

The arrangement regarding tradable green certificates, which is described in Section 4.3.1, may represent both a support system and a fee for Kiwi Dalgård. The fee is generally paid for by Norwegian and Swedish consumers and is embedded as a small fee in the electricity price. KIWI Dalgård may also apply for support for their renewable energy installation. For this study, it is chosen to neglect both of these elements for simplicity reasons. The justification for this choice is that economic calculations are outside the main scope of this study, that the support level is not affected by power control but by generation, and that the fee is very small.

3.2.2 Grid Tariff Fees

The grid tariff fees are important for the business case of self-consumption of PV electricity. The case study is located in Trondheim, and tariffs provided by the local utility Trønderenergi will therefore be used as reference when discussing tariffs. The Norwegian distribution grid tariffs are composed of the elements shown in Figure 8, and decided by the local utility [40][42].

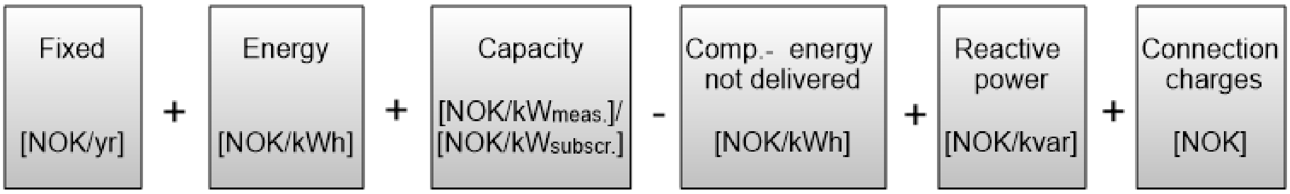


Figure 8: Norwegian electricity tariff elements

For both commercial and residential buildings, the tariffs normally depend on the main fuse size. The energy charge can be fixed or varied over time. The peak/capacity tariff is normally only used for main fuses larger than 125 A at 230 V or 80 A at 400 V [43], which is equivalent to a 55 kW demand. For the case of KIWI Dalgård, the grid tariffs claimed by the utility in Trondheim are the energy grid tariff of 0.213 NOK/kWh and the peak grid tariff of 500 NOK/kW, which are the tariffs used for the case study calculations [44]. For this study, the energy grid tariff is simply called the grid tariff, and it is explicitly stated when the peak tariff is discussed. Trønderenergi counts peak tariff according to the single largest hourly measurement within a 12 month period [44]. Reactive power charges are normally used only for customers with large reactive power consumption. Trønderenergi only charges reactive power when it exceeds 60 % of the active power withdrawal [44], which is not relevant to the case study.

Generally in Norway, taxes and fees related to electricity consumption are included in the grid tariff. In the end, VAT of 25 % is added to the overall cost, and collected by the utility [45]. For this study, the VAT is explicitly stated in formulas as it has relevance for some business cases.

3.3 Arrangements for Norwegian Prosumers

In order to facilitate distributed generation, Norwegian prosumers are granted an exception from the rules and regulations governing electricity production in Norway. The arrangement is called "Plusskundeordningen", covers end users that both produce and consume electricity behind the connection point, and is valid for grid injections up to 100 kW. The prosumer generally sells the injected power to the local utility at the area spot price, and pays for his imports in the same way as an ordinary consumer [4]. Since both grid tariff included taxes, the spot price and the VAT are paid when buying electricity from the grid, and only the spot price excluding VAT is gained by selling to the grid, the PV generated electricity should preferably be self-consumed [3].

3.4 Identified Business Opportunities by Smart Power Control

The goal of the designed power control system system is not to reduce overall energy consumption, but to use the electricity in a way that reduces cost. Three business cases have been identified for smart power control by an investigation of the electricity bill composition, namely peak shaving, self-consumption of PV electricity and load shifting. Peak shavings affect the peak capacity cost, self-consumption saves grid tariffs, taxes and fees, and load shifting utilizes hourly price variations. The potential savings are described by Equation (2) to Equation (4),

$$Savings\ by\ peak\ shaving = ((P^{peak\ default} - P^{peak\ shaved}) * c^{peak}) * (1 + VAT) \tag{2}$$

$$\begin{aligned} Savings\ by\ self-consumption = \sum_{t \in T} & ((P_t^{self-consumed} - P_t^{self-consumed\ by\ default}) \\ & * ((c^{import} + c^{grid\ tariff}) * VAT + c^{grid\ tariff}) \quad t \in T \end{aligned} \tag{3}$$

$$Savings\ by\ load\ shifting = \sum_{t \in T} (P_t^{charge} c_t^{import} - P_t^{discharge} c_t^{import}) * (1 + VAT) \quad t \in T \tag{4}$$

where P_t^{import}, P^{peak}, $P_t^{self-consumed}$, P_t^{charge}, $and P_t^{discharge}$, are energy flows of import, peak power, self-consumption, storage charging and storage discharging, respectively. c_t^{import}, c^{peak} $and\, c_t^{grid\ tariff}$ are the equivalent prices of energy imports (including grid tariff and electricity price), peak power and grid tariff stated explicitly. "Default", "no control" and "base case" will be used in this study to explain a state without implementation of smart power control. T is the hour number for the year ($t \in 1..8760$).

4 PV System Design

Most of the theory presented in this section is taken from a previous study by the same writer [8]. In this section, theory directly relevant to PV system design is treated. The emphasis is on choices which need to be made in the design process. In the end of the section, a realistic model of the PV installation planned at KIWI Dalgård is built using appropriate software, and simulation results are presented as hourly values for a full year. To build a grid connected PV system, the main units needed are shown in Figure 9, and depicted as follows [46]:

1. PV array
2. Inverter/Power conditioner unit
3. AC distribution centre and meters
4. Connection to AC loads
5. Connection to grid

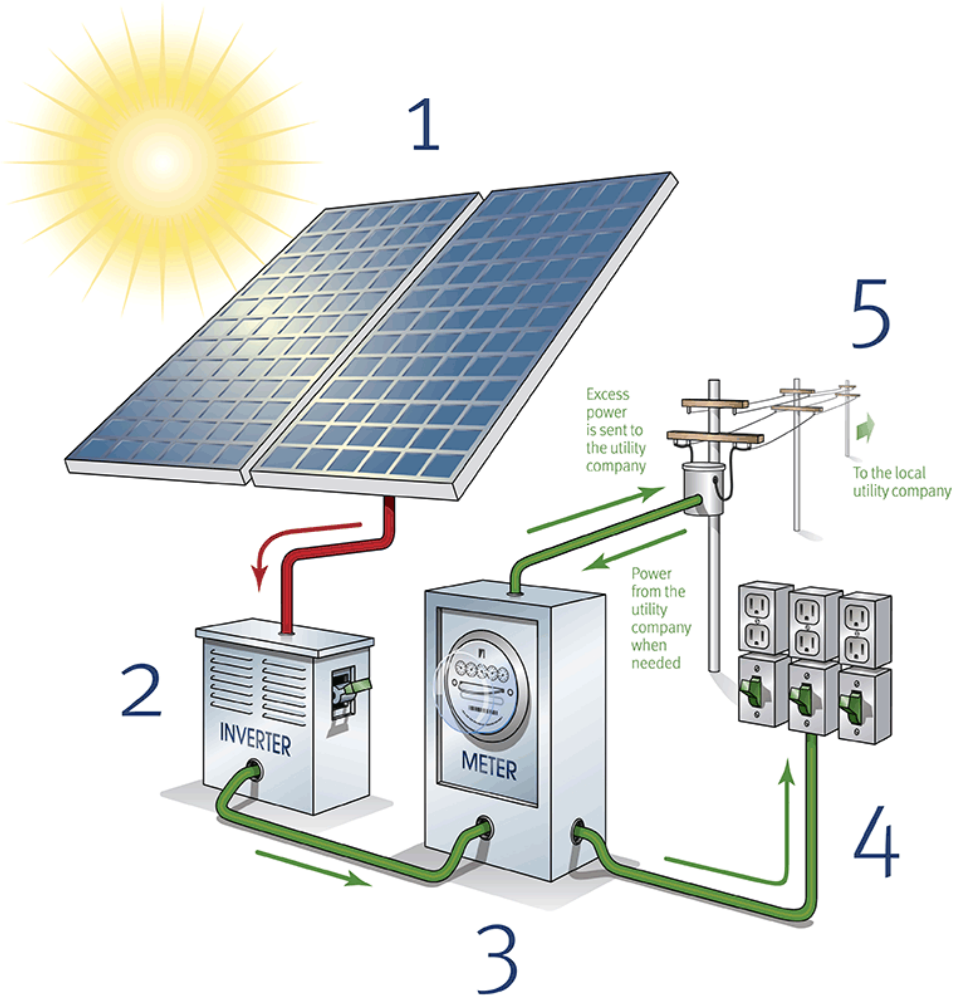


Figure 9: Basic grid connected PV system

PV generation capacity on commercial buildings in Norway is rapidly increasing, as viewed in Figure 10. In 2016, a 366 % increase in PV installation speed was observed compared to 2015 numbers, with commercial buildings accounting for the main growth [3].

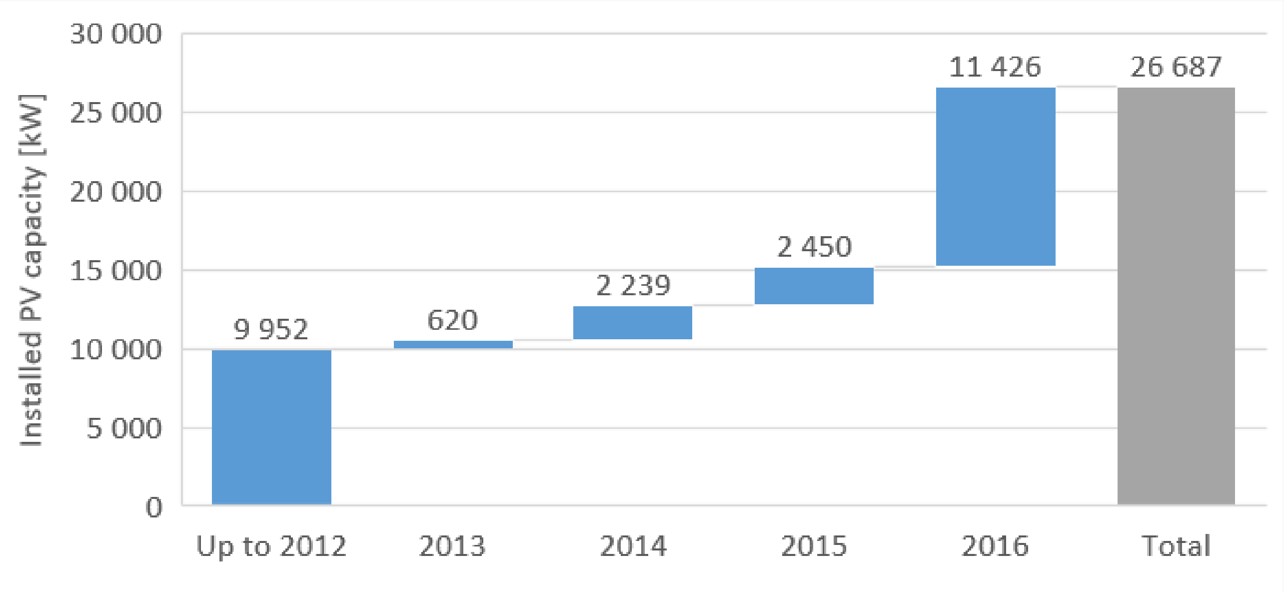


Figure 10: PV installations - Market development in Norway

4.1 PV System Components

4.1.1 The Solar Resource

The solar resource in Norway is, despite being located far north, fairly big. The solar map of Figure 11 shows that the Norwegian insolation is about 80 % of that in northern Germany, which is the leading European country when it comes to installed PV capacity [47]. Further, some brief theory regarding how the PV generation can be predicted, is presented.

4.1.2 Array Design and Performance

The basic building block of PV applications is the module, converting the solar energy into DC electricity. It consists of a number of pre-wired cells in series, which can be considered as diodes. A number of serial connected modules is called a string, and a number of parallel connected strings is called an array. How the modules and inverters are connected into arrays, impacts voltages, currents, reliability and efficiency of the system. PV modules are put in series to increase voltage and in parallel to increase current. As $P_{loss} = I^2 \cdot R$, voltages are preferably put as high as allowed by safety constraints in order to minimize power losses. The IV-curve of the array is displayed in Figure 63 in Appendix B, and is simply the sum of the IV-curves of the composing modules. For modules in parallel, the graphs are summarized along the I-axis, whereas modules in series are summated along the V-axis [48].

In order to maximize PV power production, it is desirable that all the modules work in their "maximum power point" area in the IV-diagram. This is defined as the point of the curve where $I \cdot V$ reaches its maximum, identified in Figure 62 in Appendix B, which shows the key expressions when dealing with PV performance [48]. V_{MPP} and I_{MPP} mean respectively voltage and current at the maximum power point, while V_{OC} and I_{SC} are valid for open circuit conditions [48].

Rated values are provided by manufacturers at Standard Test Conditions (STC) as Maximum Power Point (MPP) values. STC corresponds to 1 kW/m^2 insolation and 25 °C cell temperature, and is enabling a fair

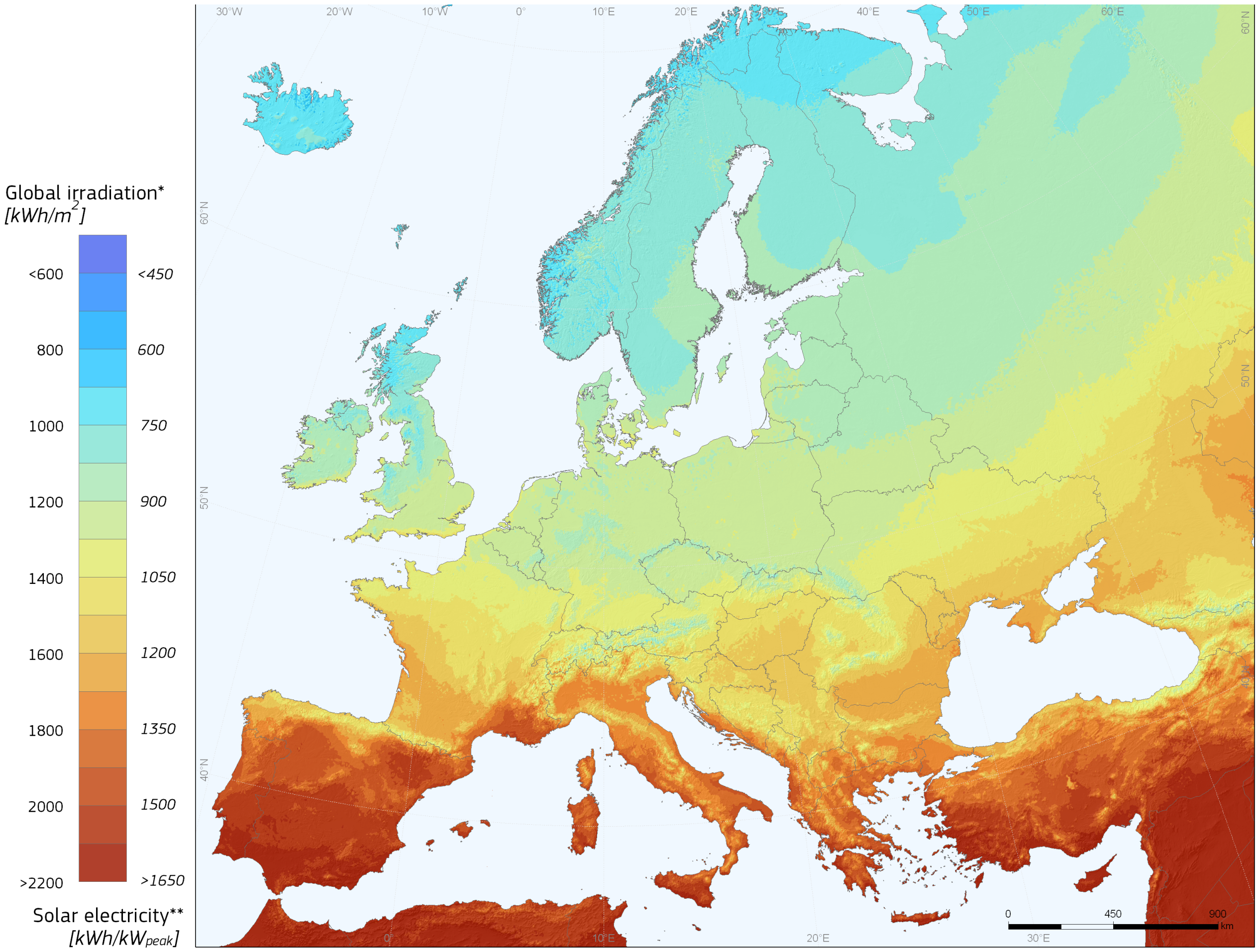
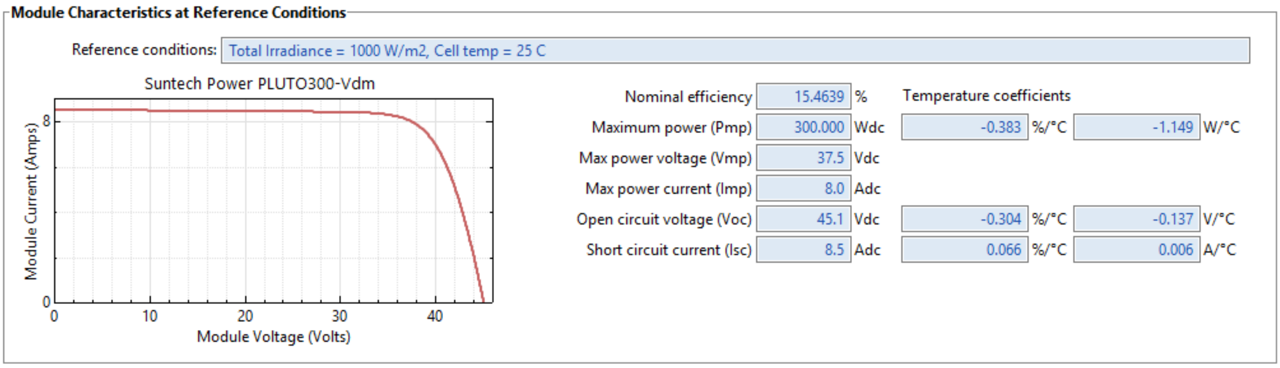


Figure 11: The solar resource in Europe

comparison of commercial PV modules. Technical performance of a PV module also varies with temperature, included in technical data sheets as temperature coefficients. Typical efficiencies of commercial PV modules are 6-20 %, depending on technology, with a typical temperature coefficient of P_{max} ranging from approximately $-0,2-0,6\%/K$. An example of a module data sheet is depicted in Figure 12 [49]:



Module Characteristics at Reference Conditions

Reference conditions: Total Irradiance = 1000 W/m2, Cell temp = 25 C

			Temperature coefficients			
Nominal efficiency	15.4639	%				
Maximum power (Pmp)	300.000	Wdc	-0.383	%/°C	-1.149	W/°C
Max power voltage (Vmp)	37.5	Vdc				
Max power current (Imp)	8.0	Adc				
Open circuit voltage (Voc)	45.1	Vdc	-0.304	%/°C	-0.137	V/°C
Short circuit current (Isc)	8.5	Adc	0.066	%/°C	0.006	A/°C

Figure 12: Example of performance data for a PV module

4.1.3 Inverter Function and Topology

The inverter is the heart of the PV system, connecting the AC and DC side [50]. It provides many functions and services, the most usual being [48], [50], [51]:

- DC to AC Power Conversion
- Optimization of power through MPPT control
- System monitoring and detection of errors
- Circuit protection*

**This includes ground fault protection and circuitry to disconnect the PV system from the grid if utility power is lost*

As an inverter has limitations regarding power, voltages and currents, the designer needs to make sure that these dimension criteria are not exceeded during operation. The most central constraints are listed below:

- Maximum power
- MPP tracking voltage range
- Range of input operating voltage
- PV start voltage
- Maximum DC input current
- Maximum input short circuit current

Usually when designing PV-strings, the MPPT tracking voltage range conforms the binding constraint. As module voltages in a string are series connected, the min and max numbers of modules per string are found by these simple equations:

$$Modules_{min} = \frac{Inverter\ MPP\ tracking\ voltage_{min}}{Module\ V_{MPP,\ min}} \tag{5}$$

$$Modules_{max} = \frac{Inverter\ MPP\ tracking\ voltage_{max}}{Module\ V_{MPP,\ max}} \tag{6}$$

$V_{MPP,min}$ and $V_{MPP,max}$ are found when adjusting for the expected max and min temperatures during day time operation, by using temperature coefficients from technical data sheets.

To ensure that the inverter can handle "worst case scenario voltages", i.e open circuit voltage across the string, it is also ensured that $V_{OC}\ String \leq Inverter\ operating\ voltage_{max}$. After designing the string with respect to voltage ranges, it is checked whether the string short circuit current will keep within the maximum DC input current limit of the inverter. If not, the maximum DC input current will be a binding constraint of the inverter. When more than one string are connected to one inverter, the design constraint is that the inverter must be able handle the sum of the string currents.

Multiple inverter configurations are possible, the most common showed in Figure 13 [52]. The centralized configuration is mainly used in PV plants larger than 10 kW_p. For this solution, multiple parallel connected strings are connected to the same inverter, each having a blocking diode to prevent reverse currents during unbalanced operation [53]. The main advantage of this solution is the simple design and the low component cost of the installation. This solution is however especially sensitive to shading/varying conditions in different parts of the array, creating module mismatches and consequently power losses. Another disadvantage is reliability, as an error or maintenance operation in the central inverter will bring down the entire array [48].

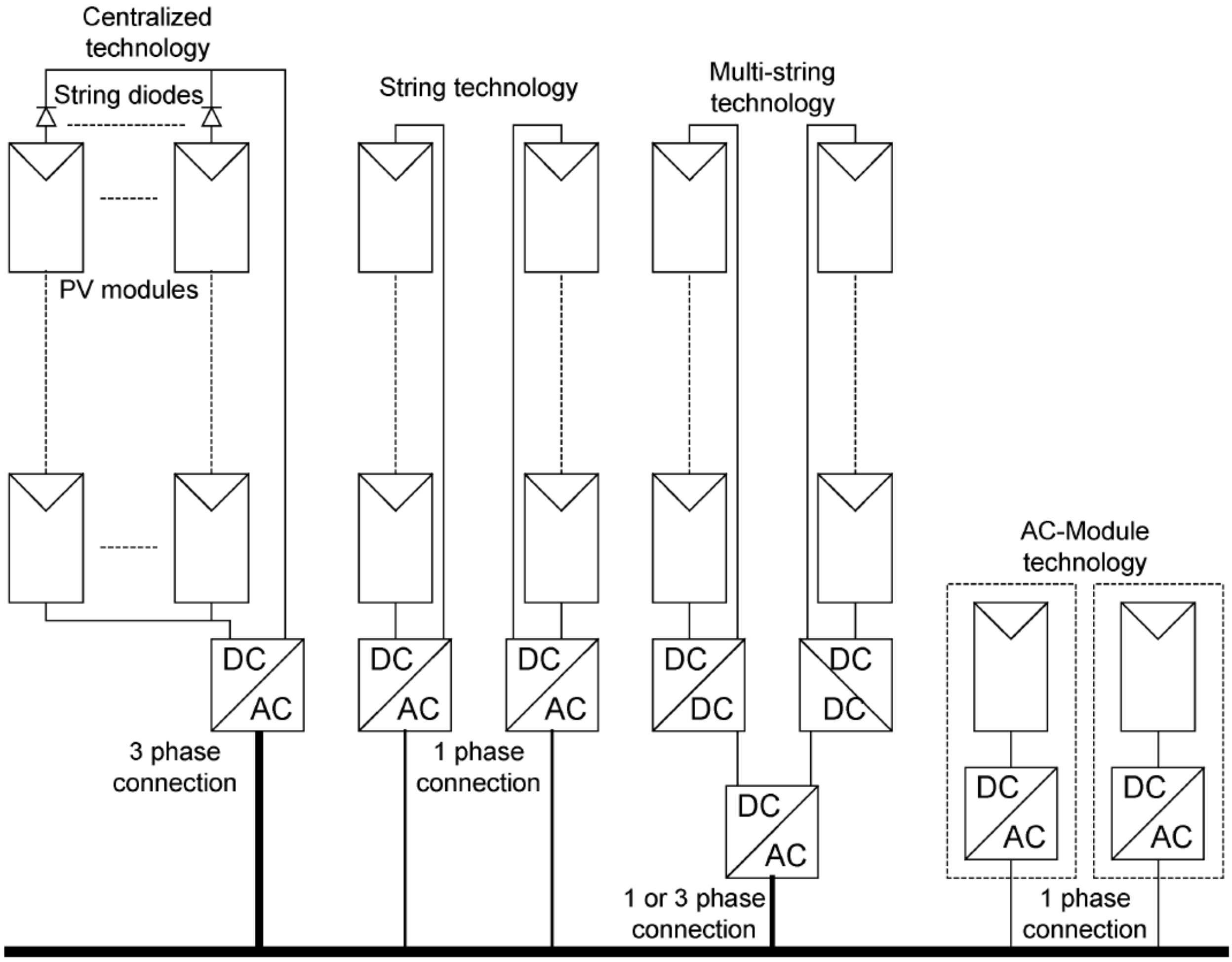


Figure 13: Inverter topologies

The string configuration uses one inverter per string, giving the advantage that each string can be power optimized. Each string is run independently of each other, both in terms of a flexibility and a reliability point of view. As more inverters are needed than for the centralized configuration, component cost is increased [53].

The multi-string technology combines some of the advantages with both the centralized and string configurations. It can be considered as a central inverter with optimizers. The DC/AC inverter uses a common voltage on the DC side, however each string may experience different MPPT voltages because of shading and other local differences. The optimizers are DC/DC converters which keep both string and inverter voltage at their optimal values. Consequently, this configuration provides string optimization while only needing one central inverter. [53]

The AC-module technology forms the contrary of the centralized configuration. For this solution, each module has its own inverter, naturally maximizing power output as each module will be run in its MPPT point. This is also the most flexible solution, as the system can be easily extended as project economy improves, and space geometry is less constraining as the modules do not need to be connected in equally lengthened strings. From a reliability point of view this is also a beneficial solution. If one module is brought down, the rest of the system will work as usual. Module and inverter might be fabricated in corresponding pairs as a plug and play system, which lowers competence requirements of the installer, saves installation time and thereby costs. Cabling cost might be decreased as there is no need for expensive DC cabling. All these advantages needs to be balanced with the main drawbacks of this solution: The multiple inverters needed increase both component cost and maintenance needed, and availability might be an issue [48].

When deciding PV system configurations, project constraints give weighting to the pros and cons of the different configurations. This might lead to different optimal solutions for different cases. A comparison of the discussed inverter topologies is depicted in Table 2, and a choice will be made based on the case study data in Section 4.5.

	Centralized configuration	String configuration	Multistring configuration	AC module configuration
Number of phases	3-phase	1-phase	1 or 3-phase	1-phase
Optimizing	Per array	Per string	Per string	Per module
MPPT Efficiency		+	+	++
Performance during shading		+	+	++
Maintenance cost	++	+	+	
Reliability		+		++
Inverter cost	++	+	+	
Cabling cost				+

Table 2: Comparison of inverter configurations

4.1.4 Other Components

A brief description of the remaining elements of a PV system is given. The AC distribution system connects the local electricity production, the grid and the loads. It can be considered the heart of the electrical system in the commercial building.

The meter measures the electricity flow, and is configured according to the billing arrangement used. For a spot price arrangement where electricity is only sold in a net export situation, one meter is sufficient for the whole system, and is placed on the grid side.

Other components being part of the PV system are components used for connection and protection, like cabling, grounding, fuses and switches. A simple overview of the PV system protection is displayed in Figure 14 [54].

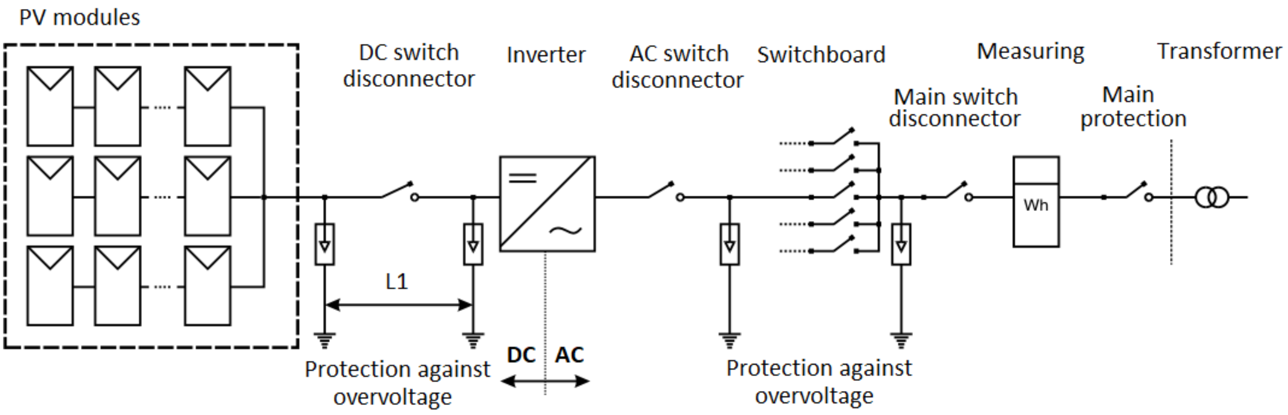
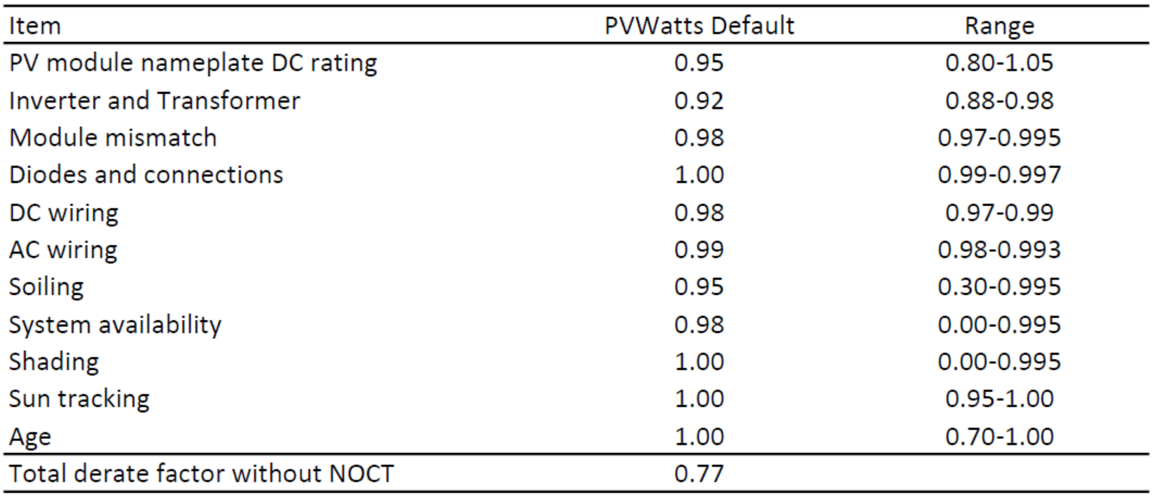


Figure 14: Overview of PV system protection

4.1.5 Derate Factors

In PV system operation, there are numerous factors affecting PV production output. The yield may differ significantly from the technical data, which are given at STC conditions. The U.S. National Renewable Energy Laboratory (NREL) has made an online PV prediction calculator, called PVWatts, which provides an overview of typical derate factors, depicted in Table 3 [48], [55]. Every derate factor is accompanied by its range, showing how the different topologies and technologies used may have a large influence on the system yield. Excluded from the derate factor list is the nominal operating cell temperature (NOCT), which is used to calculate how cell temperature during operation affects module efficiency [48].



Item	PVWatts Default	Range
PV module nameplate DC rating	0.95	0.80-1.05
Inverter and Transformer	0.92	0.88-0.98
Module mismatch	0.98	0.97-0.995
Diodes and connections	1.00	0.99-0.997
DC wiring	0.98	0.97-0.99
AC wiring	0.99	0.98-0.993
Soiling	0.95	0.30-0.995
System availability	0.98	0.00-0.995
Shading	1.00	0.00-0.995
Sun tracking	1.00	0.95-1.00
Age	1.00	0.70-1.00
Total derate factor without NOCT	0.77	

Table 3: PVWatts derate factors

PV systems are especially sensitive to shading. If no measures are taken, the shading of a single cell can dramatically reduce the output of the module. As each cell can be considered a diode, shading makes it reversed biased, resulting in a voltage drop across the cell due to its internal resistance, and consequently a large loss in production output. To reduce the problem regarding cell shading, bypass diodes are used, bypassing the cells affected by shading to avoid the voltage drop. The usual approach for the manufacturer is to provide just a few diodes, where each one covers a certain number of cells within the module. Dirt can be considered as a type of shading, decreasing system efficiency. For uniformly distributed dirt, the percent of sun blockage by dirt lowers the output by a similar fraction [48].

The derate factors are dependent on the general design of the PV system, and choices are made in Section 4.5.

4.2 Grid Connected PV - Challenges, Services and Requirements

Distributed generation (DG) from fluctuating renewable energy sources like wind and solar can be challenging for the grid, but the DG systems may also offer ancillary services enhancing grid performance [7]. In this section, some of the most important challenges, utility requirements and ancillary services regarding DG are discussed.

The primary reason for using PV inverters was to convert the produced electricity according to grid standards [7]. According to the IEEE Standard 1547, all PV inverters are continuously monitoring the voltage and frequency at their connection point [56]. The fact that an inverter is also practically able of converting any input voltage to any output voltage, gives it a large possibility of providing ancillary services to the local electrical installation [7].

For every grid in Norway, the Norwegian PQ code represents the power quality requirements on the delivery side. It is more rigid than the European Norm EN 50160 [57]. There are not yet made uniform national technical requirements to prosumers in Norway, and different utilities may operate with different regulations. The Norwegian company REN is working on developing standards regarding grid connected DG on behalf of Norwegian utilities. The aim is an approach to the EN 50438 that is adapted to Norwegian conditions. EN 50438 is the European norm for technical requirements to micro-generation plants connected to the low voltage grid [58], [59]. Their publications are therefore used as source when discussing utility requirements in this section [60]. Further, some power quality challenges related to PV injections into the grid are described, along with the corresponding utility requirements made by REN and the offered solutions by the inverter.

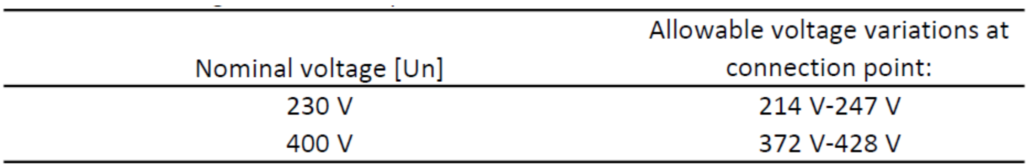
4.2.1 Voltage Control

Challenges

Many regions in the Norwegian LV distribution systems are rather weak, making voltage quality a key challenge when injecting large PV currents into the grid. The two critical conditions are summer peak generation, when grid voltage is large, and winter peak load, when grid voltage is at a minimum [61]. Voltage regulation in traditional (radial) power systems assumes power flow from the substations to the loads. When applying DG, the current direction is reversed, which may interfere with the voltage control of the traditional distribution feeder and lead to inconvenient control behaviors. As an example, PV generation close to a transformer with automated voltage control might tell the control system that demand on the feeder is reduced. The regulator may response by lowering the voltage on the feeder and consequently bring the end-of-feeder customers below the voltage requirements, as viewed in Figure 64 in Section B [62]. On the other hand, DG increases voltage at the generation spot, which may bring the surrounding customers above the accepted range of the Norwegian PQ code, if they are close to the local transformers and thereby close to the upper limits.

Utility requirements

Requirements are that the DG should not bring the one minute average voltage level at the connection point outside the ranges viewed in Table 4, to avoid unacceptable voltage levels at other consumer points.



Nominal voltage [Un]	Allowable voltage variations at connection point:
230 V	214 V-247 V
400 V	372 V-428 V

Table 4: Technical requirements regarding voltage variation

Other requirements are that the PV unit should not cause the total asymmetry of the line voltages to exceed 2 % of the nominal voltage of the grid. DC currents should not be injected into the grid.

Inverter functionalities

Even though DG might interfere with voltage control of the distribution feeder, it may also provide voltage support. Among ancillary services which are technically available for inverters are active and reactive power control, which can be used to regulate the voltage level at the connection point. Active power control includes limiting active power by changing MPPT control settings, and using an electrical storage to control active power injections into the grid. For reactive power control, reactive power might both be consumed and injected both day and night, as there is no need for active power input from the PV plant in order for it to work [63] [64]. Using a 3-phase inverter or communicative coupling of single phase inverters, unbalanced generation from the PV system can be held below the threshold value determined by the utility [65]. Figure 65 in Appendix B shows a control scheme for a inverter regarding reactive power, asymmetry and harmonics. When the inverter is connected to the PCC, services regarding voltage control, asymmetry control, and harmonic mitigation may be provided for all electricity drawn from the PCC. This will in turn enhance local grid power quality [7].

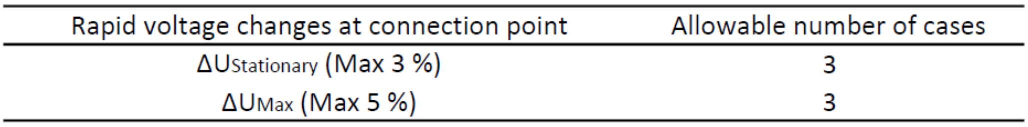
4.2.2 Voltage Flicker

Challenges

Fluctuating output from a PV system might lead to rapid voltage changes in the electrical system. If these voltage changes occur at an inconvenient magnitude and frequency, flicker might occur, which is blinking and color changing lighting sensible to the human eye. Fortunately, the voltage changes associated with PV generation tend to be smoother than the ones creating most annoyance for humans. However, the voltage changes might interact with the rest of the electrical systems, creating annoying voltage flicker which might be complex to understand and solve [62].

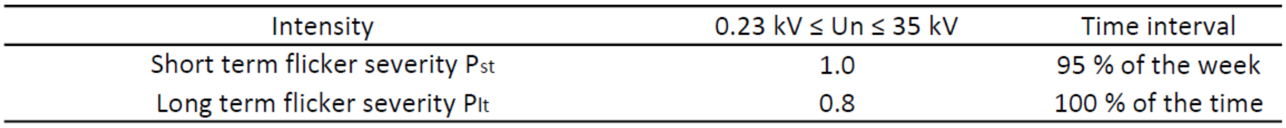
Utility requirements

The DG should not cause more voltage changes above the threshold requirements shown in Table 5. Table 6 sets requirements for short and long term severity flicker. A P_{st} value of 1 indicates the level where a majority of the population find the flicker irritating [66].



Rapid voltage changes at connection point	Allowable number of cases
$\Delta U_{Stationary}$ (Max 3 %)	3
ΔU_{Max} (Max 5 %)	3

Table 5: Technical requirements regarding maximum allowable rapid voltage changes per day



Intensity	0.23 kV ≤ Un ≤ 35 kV	Time interval
Short term flicker severity P_{st}	1.0	95 % of the week
Long term flicker severity P_{lt}	0.8	100 % of the time

Table 6: Technical requirements regarding flicker

Inverter functionalities

The fast dynamic response of reactive power offered by a pulse width modulation (PWM) inverter may be used to mitigate voltage flicker [64]. In order to verify that the PV inverter can fulfill the technical requirements, unit certificates and a declaration of conformity of the inverter manufacturer might be used [65].

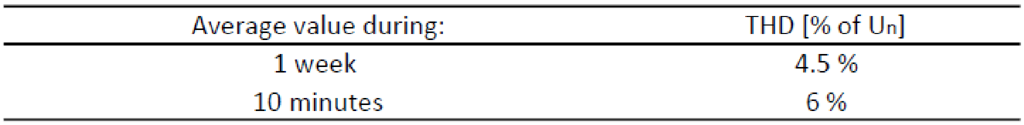
4.2.3 Harmonics

Challenges

The power electronics of a PV generation spot may produce harmonics.

Utility requirements

The total harmonic distortion (THD), which is the percentage of the voltage which is distorted from the nominal shape, should not exceed the requirements in Table 7.



Average value during:	THD [% of U_n]
1 week	4.5 %
10 minutes	6 %

Table 7: Technical requirements regarding harmonics

Inverter functionalities

New inverters based on PWM are able to generate a sine wave with a small extent of harmonic currents, and should normally satisfy the national requirements [62]. Filters might be added to the inverter when needed in order to keep the harmonics of the PV plant at an acceptable level [64].

4.2.4 Power System Protection and Reliability

Challenges

Other issues which need to be discussed when applying DG to the grid is its impact on grounding, islanding, reliability and short circuit levels. The discussion based on these challenges is based on the work of Barker and Mello [62].

As for all electrical installations, proper grounding is needed to ensure that over-voltages do not occur during fault either on the utility side or the consumer side. It should be made compatible to the grounding configuration of the local grid.

Islanding might be part of the design ensuring larger reliability of the system, as the DG is able to take over during a fault in the external grid. In order for this to work properly, the DG units need to be reliable and well coordinated with the protection equipment and sectionalizing of the utility grid. When the system is not designed to operate in islanded mode, islanding is an important security issue requiring special attention. High risk could occur if a service worker works on a section of the grid which is disconnected by the utility, but connected to a local DG spot. Also, when a switch reconnects the DG with an energized grid, mismatched voltages might create overvoltage harming local equipment. Harming of equipment will also occur if the DG is not designed to keep voltages and frequencies in the required range during islanding. In order to avoid unwanted islanding, active protection equipment needs to be applied to the inverter so that it disconnects the local PV generation as soon as there is a fault in the utility grid. Another issue by connecting DG to the grid is that the short circuit levels will be modified, which can affect the local power system protection. For the case shown in Figure 15, the coordination between the fuse and breaker is compromised because of the local DG spots, which might lead to unnecessary fuse trips and reducing reliability of the system [62].

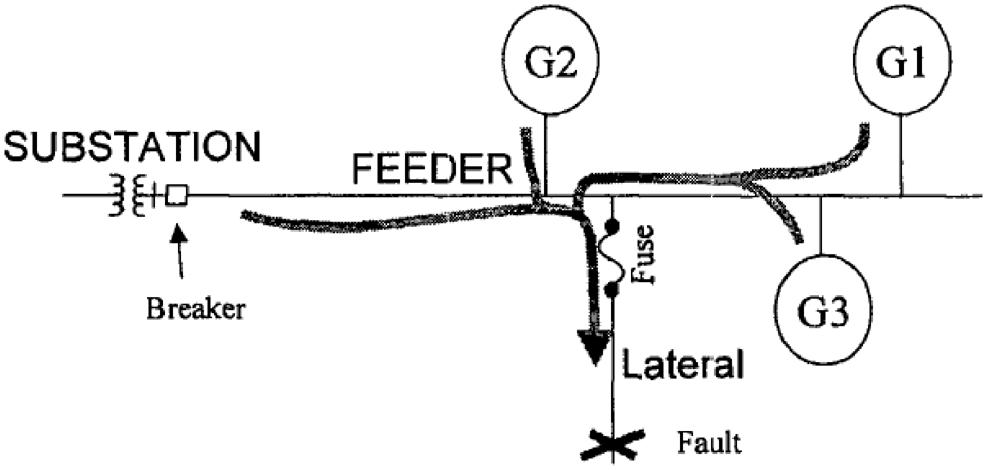


Figure 15: Fuse and breaker mismatch due to DG

Utility requirements

Grounding for a PV system should be made according to general practice for electrical installations. Table 8 shows maximum disconnection time as response to over/under-voltages. For the case of extreme frequencies, requirements are that the DG should disconnect within 0,5 seconds, as viewed in Table 9.

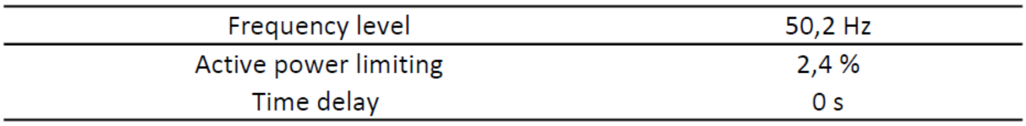
Voltage in % of nominal voltage U_n	Max. disconnection time [s]
U >> 115	0.2
U > 110	3
U < 90	3
U << 85	0.2

Table 8: Technical requirements regarding response to over/undervoltages

Frequeny [Hz]	Max. disconnection time
f > 52	0.5
f < 47.5	0.5

Table 9: Technical requirements regarding response to extreme frequencies

When system frequency exceeds 50.2 Hz, active power limitation should be made according to Table 10.



Frequency level	50,2 Hz
Active power limiting	2,4 %
Time delay	0 s

Table 10: Technical requirements regarding active power limiting

There are also specific inverter requirements. An inverter without galvanic isolation should have measuring and disconnection functions for ground fault currents, and insulation levels from 1 $k\Omega/V$. Also, a re-connection strategy after disconnection with low mismatch regarding frequencies and voltage angles is required so that large currents and voltages do not occur as result of re-connection to an energized grid.

Inverter functionalities
As previously mentioned, inverters are continously modelling frequency and voltage at the point of connection. They can be configured so as to disconnect/limit their output according to the requirements [65].

4.2.5 Power Losses

DG might lead to reduction of losses in the grid as there is less need for distributing electric power over large distances, if it is strategically placed [62]. On the other hand, DG placed on feeders with extra low thermal capacity might lead to increased power losses. As DG often is customer owned, utilities have limited possibilities of deciding the location of DG power plants [62].

4.2.6 Future Ancillary Services to the Grid

The advent of advanced inverters makes a large penetration of renewables into the grid technically possible, however no mature market schemes for grid ancillary services have been developed yet in Norway. By adding some inverter functionalities and enable remote control by the utility, DG inverters might join the FACTS devices used by the utility to enhance AC system controllability and stability and to increase power transfer capability [67], [56]. Through fast dynamic control of reactive power, the inverter might take a similar role as the STATCOM; a so-called PV-STATCOM, regulating the voltage, increasing the stability during faults and power transmission capacity on the lines. In such a scope, utilities might save money by a reduced need of installing such devices themselves, and PV plant owners might increase their business platform [63].

By applying batteries in the systems, further ancillary services may be provided. "In the future, customer-level BES systems have the potential to be aggregated and provide active grid support. This potential will be facilitated by the implementation of International or European connection and communication standards. It will also require further IT improvement, with pooled virtual storage having the potential to be influenced or directed by the real time situation of the grid" [68].

Issues which need to be addressed include compensation to DG owners for ancillary services provided, availability requirements, standards regarding disconnection and operation, and ownership structures [56]. According to the local utility Trønderenergi, there is no juridical barriers to providing ancillary services to the grid in Norway, and the utility companies decide themselves whether they want to participate in such arrangements [69]. In Trondheim, a bilateral arrangement had already been made regarding peak shaving with a large customer, however no mature structures had been established for such arrangements. Being monopolists, the utilities can not own power sources themselves, and need to buy ancillary services involving power injections from an external partner, which may in principle be a prosumer. As in any market, the involved parties need to agree on a service and a price which are mutually beneficial. Also, the utility companies need to make sure they keep control of grid operation.

4.3 PV Subsidies in Norway

In this section, PV subsidies relevant to the commercial building sector are discussed. The Norwegian government does not provide any direct subsidies of rooftop PV in commercial buildings [70]. Some relevant supporting schemes are still described.

4.3.1 Tradable Green Certificates

Tradable Green Certificate (TGC) is a market based subsidy designed to make renewable energy competitive in a free market structure. Such a scheme has been implemented as a common arrangement in Norway and Sweden, motivated by a goal to increase renewable generation by 28,4 TWh within 2020. The subsidy is technology neutral in order to facilitate generation from the most cost competitive energy sources [71].

In practical terms, the renewable energy producer approved for TGC receives one for every MWh produced. The TGCs are financial assets to be sold. The government creates demand by requiring electricity providers to have a certain amount of their sold electricity covered by the certificate [71], [72]. In this way, the government can control the amount of renewable electricity produced. As the goal is to meet EU directives within 2020, a generation plant needs to be put into operation within the end of 2021 in order to apply. The arrangement might be extended, as it is currently considered to use it for facilitating additional 18 TWh within 2030 [71].

The main barrier in order to be approved for TGC is the application process, which requires documentation and an application fee. The application fee is supposed to reflect the government's cost of processing applications. The fee is 15 000 NOK for installations up to 100 kW, and 30 000 NOK for installations up to 5 MW [73]. In practice, this makes only the larger PV installation relevant to this subsidy.

4.3.2 Enova

Enova does not support PV rooftop systems on commercial buildings directly. However, they provide support schemes which may be indirectly relevant to PV and smart power control systems. One support program is called "Buildings with high energy performance", and supports buildings with energy performance which exceeds technical norms [70]. Another relevant support scheme is called "Innovative technologies for buildings of the future", which supports buildings with innovative energy solutions, based on a set of criteria [74].

4.4 PV System Software

Simulation software are important tools for predicting the yield and cost competitiveness of PV systems. They are of high importance as they are often used in the initial phase when it is decided whether the system is economically attractive or not. There are various simulation tools available on the market, offering a wide range of services [75]. An overview of commercial software is presented, then one software will be chosen for the case study. In order to obtain a realistic production yield and decision support through simulations, the following tools are useful [48], [75], [65]:

- Product database
- Local weather database
- Possibilities of a wide range of different system configurations
- Modelling locational factors as shading, tilt angle, orientation and spacing of modules
- Including derate factors
- Checking whether equipment operates within its permissible range

- Pricing and economical calculations
- Result export in suitable units and formats

Some simulation tools offer all the services mentioned above, while others only offer some. The German Solar Energy Society (DGS) has offered a 2013 overview of the PV software market, based on the calculation method of the software [65]. The different calculation methods will be explained based on this source. The overview is depicted in Figure 16.

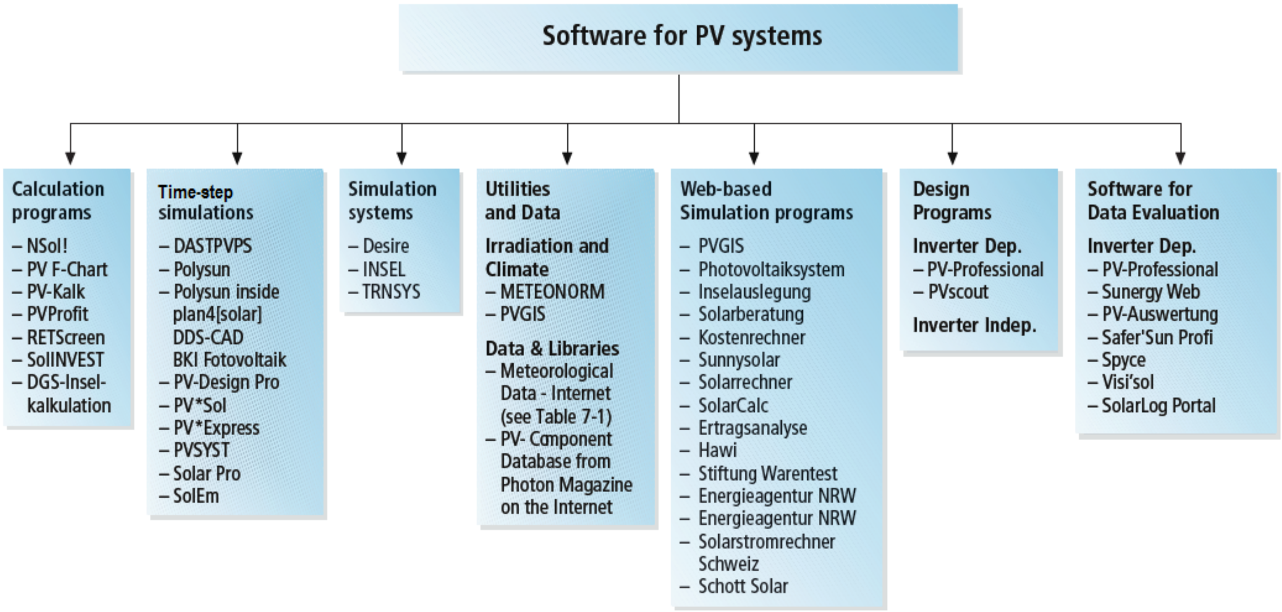


Figure 16: PV simulation software

The "calculation program"-category provides simple calculations, based on mainly statistical methods. They yield mostly monthly values, and are often inexpensive and fast to use. Normally, this group has a low degree of flexibility, and can mostly be used on standard systems.

The time-step simulations offer a large range of applications, and are intended to model the real system as realistically as possible. In order to do this, products, weather, locational factors etc. are modeled as close as possible to reality. These programs often have a user friendly and pedagogical interface. When local weather data are not included in the simulation tool database, some tools facilitate importing of external weather data from irradiation and climate databases. Output data may be presented in hour by hour values or sometimes even shorter time intervals. Among time-step simulation software which are not included in the DGS list, but are compatible with Meteonorm output, are PVS and SAM [76].

The meaning of the category "simulation systems" in this context is systems which are used when the time-step simulation does not offer sufficient functions. It might be that a completely new system should be designed, some extra functions need to be added, or that the system should be modeled together with some external installations. INSEL and TRNSYS are known simulation packages, but other tools used in mathematical and electrical engineering, such as PSpice and MATLAB/Simulink, may also be used. These simulation systems have a large degree of flexibility and complexity and may demand a long learning time to master. They are therefore mostly used for research and development purposes.

The "utilities and data"-category includes resource databases for weather and products, which may be loaded into the compatible simulation tools. Web-based simulation programs are similar to an online version of the calculation programs category, and are mostly used by private investors or in early project phases. Design programs are supporting tools for the design process. Typically, they model single components and system parts in order to get to know the components better than what can be stated in a manual. The data evaluation software is used for monitoring, and is often connectable to web portals and smart phones.

When modeling the PV system in this study, PVsyst will be used as it is a time-step simulation software well suited for designing a realistic PV system on an hourly basis, and is frequently used among Norwegian consultants [77].

4.5 Case Study Modeling and Simulations in PVsyst

In this section, the case study PV system is modeled. To make a realistic model of the PV system planned at KIWI Dalgård, architect drawings from the project planning documents have been used as source, as well as conversations with the project leader at KIWI [78]. KIWI Dalgård is at the time of writing under construction, however the area to be covered by PV modules has been decided by the project, of which an overview is given in Figure 48 to 52 in Appendix B. The planned area has been respected, and the PV system has been modeled according to the presented PV theory in this study. In the end, simulations are conducted and presented for a full year.

4.5.1 Location and Choice of PV modules

The approximate PV covered area which was measured on the recieved architect drawings, was 620 m^2 on rooftop, 145 m^2 on the southwestern facade, 30 m^2 on the northwestern facade and 20 m^2 on the southeastern facade. The southwestern facade has an azimuth angle $\varphi \sim 60^o$ with respect to south, which forms the basis for calculating the the azimuth angles of the other facades. The PV modules on the facade are planned as building integrated PV (BIPV), of which the PV modules replace other facade materials. Generally on facades, PV modules may obtain a large coverage area as it is desired to place every PV module adjacent to the next. On the rooftop, the system is planned as a building adapted PV (BAPV) system, of which the modules are mounted on a construction on top of the roof. A normal topology to increase PV coverage ratio of such systems is an east-west orientation, of which twin strings are placed back to back on a common mounting construction with opposite tilts with respect to the horizontal [77]. Considerations need to be made regarding access, removing of snow, drainage etc. Consequently, the PV modules may not cover the full area. When building up the PV system in the simulation software PVsyst, it was desired to build the model with equally lengthened strings for all the PV covered areas to maximize voltage of PV generation and consequently decrease losses, and some simplifications were made regarding geometry. For this reason, strings with a 20 module length were generally chosen, which fit well with the width of the supermarket. 15 strings were placed on the rooftop with a southwest/northeast twin orientation and with a 10^o degree tilt, 4 strings were located on the southwestern facade, and one string each on the northeastern facade and the northwestern facade. The equivalent PV module area by this choice was 490 m^2 on the rooftop, 130 m^2 on the southwestern facade and 33 m^2 each on the northwestern and northeastern facades. The applied area is considered a quite realistic cover of the available areas, bearing in mind that some rooftop areas need to be set aside for access, removing of snow, drainage etc. A generic 250 W_p and 1.63 m^2 module was chosen in PVsyst in order to make manufacture-independent simulations. It has a 15 % efficiency, which can be considered average for PV modules [48]. KIWI Dalgård plans to use both thin film and crystalline PV modules, which makes an average module efficiency seem like a reasonable assumption [78].

Main shading elements were included in the model by 3D shading models provided in the simulation software. Figure 17 shows the four floor tall building block on the south west side of KIWI Dalgård which was included in the shading model. Figure 18 shows the shading model in action at a winter day. A horizon was also modeled for KIWI Dalgård to reflect the hill on the northwestern side of KIWI Dalgård, viewed in Figure 53. The resulting sun path charts for the various PV covered surfaces of KIWI Dalgård are depicted in Figure 54 to Figure 58 in Appendix B. It is seen that shading is a significant mitigator of PV generation throughout the year, especially on the facades.

Figure 17: Surrounding areas of KIWI Dalgård

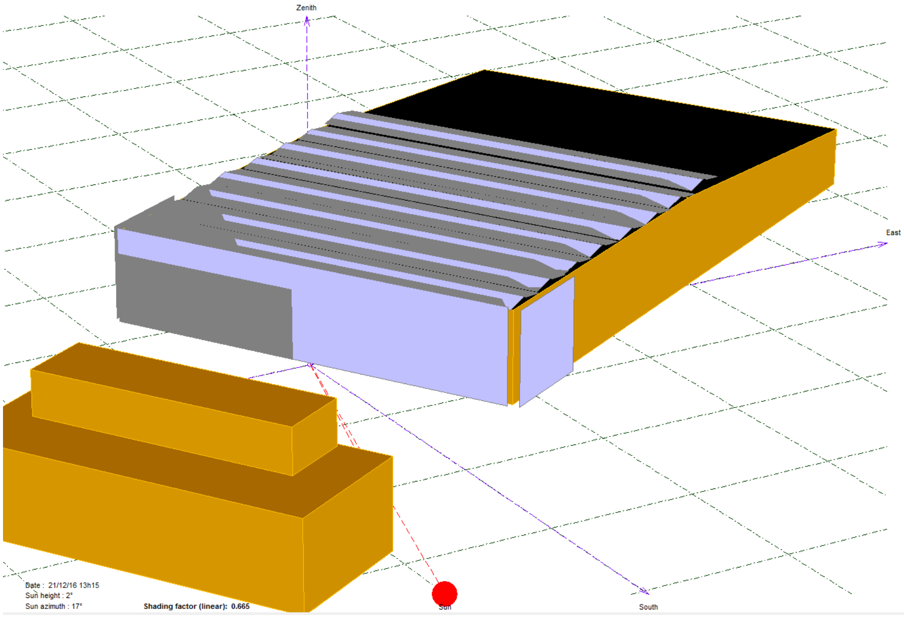


Figure 18: 3D shading model of KIWI Dalgård, showing grey shaded area on December 21th at 1 pm

4.5.2 Inverter Configuration

For the case study, many PV modules are mounted on a vertical facade close to ground, which naturally will be subject to frequent shading and possible varying solar conditions among the strings. As the PV panels are integrated in the facade, there will be low accessibility regarding maintenance of the modules. The horizontal insolation in Trondheim is not more than approximately 890 kWh/yr [79], making large system efficiency particularly relevant. Taking these considerations into account, the following inverter properties are considered to be of especially large importance for the case study:

1. Performance during shading
2. Accessability
3. Inverter cost
4. MPPT performance

According to Figure 2 and the discussion of Section 4.1.3, the multistring configuration is considered a good alternative, showing good performance on the highlighted criteria. The AC module configuration performs well on most criteria, but seems inconvenient in this case due to the low accessibility from its natural location on the backside of the modules. Also, it seems reasonable to reduce the number of inverters for a 100+ module installation. The multistring configuration requires less inverters than the string configuration without compromising efficiency, which makes it a preferable choice for the case study.

When selecting inverters, an inverter with large operating voltage and multi-MPPT features is desired. Large operating voltages increase system efficiency, and multi-MPPT means that the inverter comes with a multistring configuration. Among the PVsyst alternatives, Sungrow SG8KTL-EC was used in the simulations, as it performed well on the desired functions. For this topology, each inverter is connectable to two optimized strings. An example of the selected system array and inverter configurations in PVsyst is depicted in Figure 59 in Appendix B.

4.5.3 Derate Factors

All derate factors were chosen according to the PWWATTS default values previously viewed in Figure 3, except derate factors regarding inverter and transformer, shading and sun tracking, which were calculated by the simulation software. The other derate factors were chosen as default values, because it does not seem clear why this PV installation should perform otherwise. The derate factors calculated by the PVsyst simulations are displayed in Figure 60 and 61 in Appendix B. The discussed graphs and tables regarding derate factors show a slight inconsistency between the PVsyst loss categories and those used by PVWATTS. One reason for this is that the PVsyst derate factors are not stated independently for each element, each loss is defined as percentage of the previous energy quantity [79].

Based on the modeled horizon, shading and location of the modules, PVsyst calculated 36 % losses by shading, sun tracking, and horizon for the facades altogether. The total facade system losses, disregarding PV module efficiency, were calculated to be about 50 % on a yearly basis. For the rooftop PV, losses by shading, sun tracking, and horizon were calculated to be about 9%. The total system losses were found to be about 27 %. As previously mentioned, shading losses are modeled according to 3D simulation models regarding shadings and horizons. The sun tracking derate factors are dynamically calculated by PVsyst and show the share of horizontal insolation incident on the collection plane, decided by the tilt and azimuth angle of the module. The yield by an average facade PV module is according to the loss diagrams about 30 % lower than for the average rooftop module, which is a quite significant difference.

4.5.4 Results

Simulation has been conducted for a full year for the modeled PV system of KIWI Dalgård. The result will be used in the design of the power control system. Due to the vast amount of generated data, only portions of the results are displayed. An example weekly generation profile with good solar conditions is viewed in Figure 19, which compares generation to load consumption. It is seen that the PV system is well designed with regards to direct self-consumption by the loads.

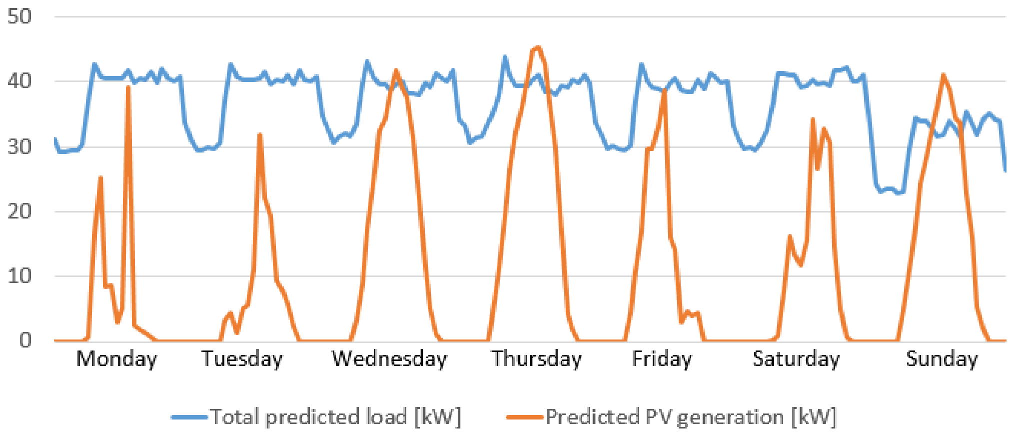


Figure 19: Load and PV generation profile at KIWI Dalgård of an example week

To increase understanding on how the system would perform the rest of the year, Figure 20 shows the total generated and lost electricity distributed on a monthly basis. The installation generates a total of 62 500 kWh/yr, mostly concentrated in the period March to September. The graph shows how the derate factors kick in at different times of the year. Especially noticeable are the losses from November to January, which are especially large due to the horizon blocking most of the low hanging winter sun. The unavailability of the inverters is modeled as a down time period in March, explaining the large system loss in this month.

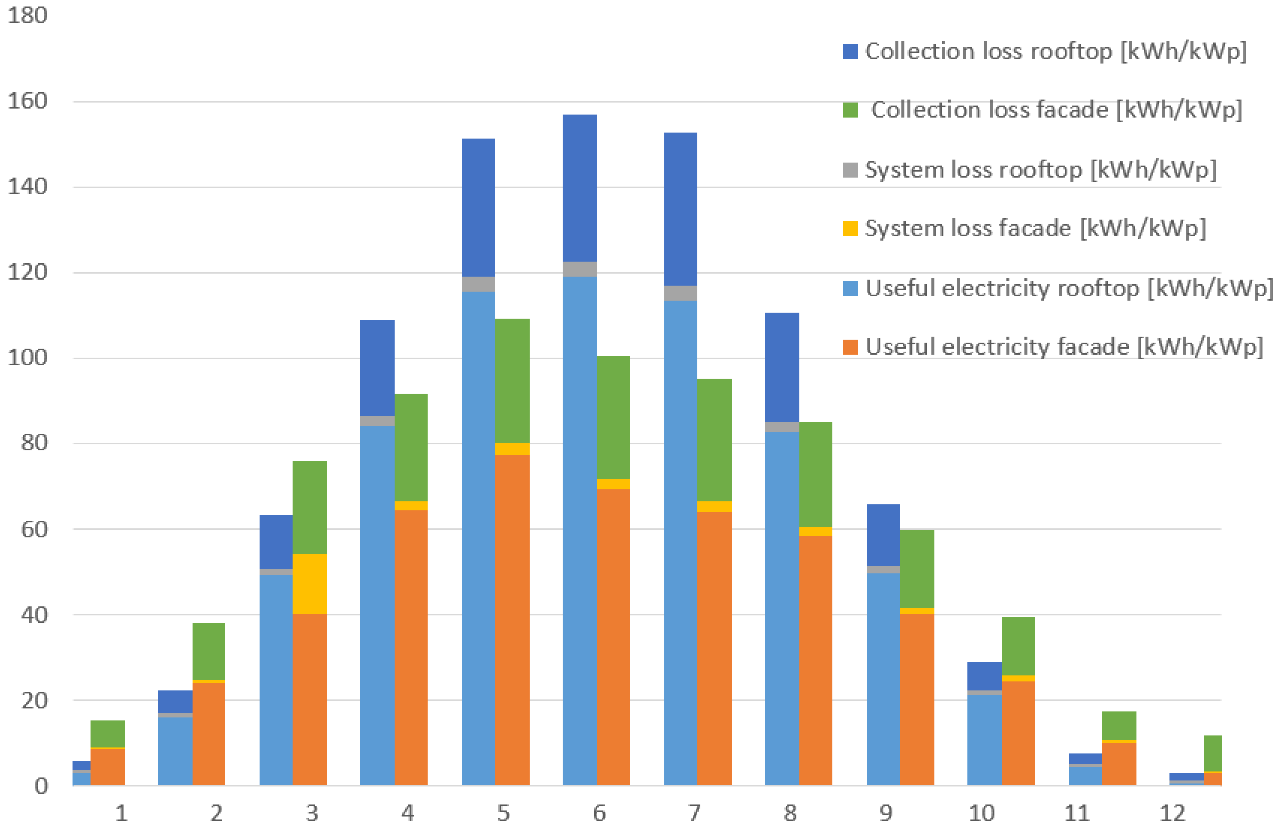


Figure 20: Generated and lost PV electricity on a monthly basis

With emphasis on PV generated electricity as input to a power control system, an overview of the net hourly and daily export is needed. This information will be provided in Section 5.3 as an input for deciding needed energy and power capacity of the storage.

5 Storage

To accomplish load shifting by peak shaving and valley filling, a storage solution is needed. Storages for load shifting are generally divided into electrical and thermal storage categories. In this section, both electrical and thermal storage systems with their components and control are treated, to form a basis for deciding storage for the case study. The technological theory is supported by relevant example applications to enhance understanding of a real system and its topology. In the end, a storage solution is chosen for use in the case study system simulations, based on the generated PV and load predictions and practical project constraints. If one or more of the following conditions are valid, applying storage might be relevant [80]:

- time-varying electricity pricing schemes
- peak power load significantly exceeds base power load
- large grid power tariffs or scarcity of supply
- backup capacity is needed
- load curves dynamics cause trouble for direct supply

The economy of storage systems might be decided by [80]:

- shape of load profile
- control strategy
- operation strategy
- size of storage
- savings by reduction of direct supply capacity by applying storage

All of the variables mentioned above make it hard to present research results which are directly comparable and/or have direct relevance for the case study. If one or more of the elements listed above deviate between two projects, results may not be transferable. Other variables like storage technology use, local differences in price levels and ambient conditions will also affect results obtained. Keeping this in mind, theory in this section is presented with the aim of providing insight and decision support when designing storage systems.

5.1 Electrical Storages

Electrical storage technologies for high power applications include batteries, pumped hydro storages, supercapacitors, compressed air energy storages and flywheel storages. Electrical storages are used for different applications like peak shaving and load shifting, supporting grid transmission and distribution and frequency regulation. A comparison of the power ratings of the mentioned electrical storage technologies is given in Figure 66 in Appendix C. [81]. The different technologies have different core areas of feasability, as different applications and sizes put different requirements regarding energy capacity, power density, space required, speed of charge/discharge, environmental issues, leak currents, safety during operation etc. [82]. Key requirements when load shifting in supermarket applications in Norway are believed to be space constraints, energy efficiency, cycles per lifetime, installation cost and environmental friendliness. The total load consumption of KIWI Dalgård was in Section 2 found to be approximately 50 kW or below, and the time frame relevant to load shifting is hourly. In accordance with these assumptions and the power ratings viewed in Figure 66, the battery technology will be chosen as the electrical storage most relevant to the case study. Batteries are compact, static electrical storage devices which are considered sufficiently fast for the application of this study.

Battery technology	Power range (MW)	Discharge time (ms–h)	Overall efficiency	Power density (W/kg)	Energy density (Wh/kg)	Storage durability	Self-discharge (per day)	Lifetime (yr)	Life cycles (cycles)
Lead–acid	Up to 20	s–h	0.70–0.90	75–300	30–50	min–days	0.1–0.3 %	5–15	2000–4500
NaS	0.05–8	s–h	0.75–0.90	150–230	150–250	s–h	20 %	10–15	2500–4500
NaNiCl2	50	2–5 h	0.86–0.88	150–200	100–140	s–h	15 %	15	2500–3000
Ni–Cd	Up to 40	s–h	0.60–0.73	50–1000	15–300	min–days	0.2–0.6 %	10–20	2000–2500
Li-ion	Up to 0.01	m–h	0.85–0.95	50–2000	150–350	min–days	0.1–0.3 %	5–15	1500–4500
VRFB	0.03–3	s–10 h	0.65–0.85	166	10–35	h–months	Small	5–10	10,000–13,000
Zn–Br	0.05–2	s–10 h	0.60–0.70	45	30–85	h–months	Small	5–10	5000–10,000

Battery technology	Total capital cost €/kW			Total capital cost €/kWh		
	Min	Average	Max	Min	Average	Max
Lead–acid	1388	2140	3254	346	437	721
NaS	1863	2254	2361	328	343	398
NaNiCl2	874	1160	1786	973	1095	1211
Ni–Cd	2279	3376	4182	596	699	808
Li-ion	2109	2512	2746	459	546	560
VRFB	1277	1360	1649	257	307	433
Zn–Br	1099	1132	1358	170	220	281

Table 11: Comparison of different battery technologies, economically and technically

There are multiple battery technologies available on the marked for high power applications, and many research articles have been assessing technical and economical performances. A 2014 Finnish study presents a collection of studies between 2010-2013 investigating life cycle costs and technical performance for comparison purposes. The variations in research results are accounted for by being presented as ranges. The total capital costs presented here are for grid-scale battery systems, and include the cost of purchase, installation and delivery of the batteries, battery control system, engineering and protection costs etc. Key results for some of the most common battery types are displayed in Table 11 [82], with emphasis on criterias relevant to system design.

The results from Table 11 show a large internal variation in the cost for each technology. A 2013 Swiss study comparing life cycle costs of battery technologies, although based on a smaller selection of research articles, points to the fact that the insecurity in the input data is often larger than the differences in cost between the technologies. Thus, it is hard to point at a single leading battery technology [83]. Prices are also rapidly changing for some battery technologies, and data which are more than 3 years old might show a quite different picture today. Li-ion batteries are considered the most relevant battery technology for this study because of its high power and energy density, and having the largest energy efficiency among the alternatives. It is according to the 2010-2013 results in Figure 11 among the more expensive alternatives, however costs of Li-ion batteries have since then been and are still decreasing with its increased use in electric vehicles and stationary applications. An example of small scale storages for self-consumption of electricity, is the 14 kWh and 5 kW Tesla Powerwall 2, which is being advertised at an average total cost of 1 500 Euro/kW or 550 Euro/kWh including VAT and installation costs [84]. Also, significant progresses have been made regarding cycle life. As an example, Mercedez Benz introduced its new generation of home storage systems in 2017, advertising an expected system lifespan of 8 000 cycles [85].

5.1.1 Battery Management System

The battery management system (BMS) protects and controls the battery. Services include [86]:

- Measure voltages, currents and temperatures of the battery
- Management of battery pack voltages, currents and temperatures to keep them within their constraints at all times, and balance the packs so as to maximize battery capacity
- Evaluation based on measurements, so that factors like battery SOC, resistance, capacity and state of health may be calculated and displayed
- External communications
- Logging

The interface between the BMS system and external power control systems for battery scheduling is thought as follows: The BMS system receives hourly set points for amounts of charging/discharging by the pre optimized and real time control system. The BMS system decides itself how it wants to distribute the speed of charging/discharging within the hour, so as to fulfill the kWh/h requirements. The BMS system may also control voltage at the DC bus, and the primary control of the BMS will if necessary overrule the required set points to keep the rate of charge/discharge currents and the battery SOC within battery limits.

5.1.2 Aging of Batteries

Aging of batteries is an important consideration when designing battery systems. Relevant terms when discussing aging of batteries are degradation of the state-of-health (SOH), SOC_{avg} and SOC_{swing}, terms which are defined by Equation (7), (8) and (9) [22].

$$D_{SOH} = \frac{C_{full}^{nom} - C_{full}}{C_{full}^{nom}} \tag{7}$$

$$SOC_{avg} = \frac{SOC_{low} + SOC_{high}}{2} \tag{8}$$

$$SOC_{swing} = SOC_{high} - SOC_{low} \tag{9}$$

Figure 21 shows the degradation of Li-ion batteries as function of SOC_{avg} and SOC_{swing}, based on a suggested model [22]. The resulting graphs give important insight for operation planning and dimensioning of batteries in a life cycle perspective. The battery lifetime seems to be strongly affected by the average SOC level which the battery is kept on, and how deeply it is charged/discharged for each cycle.

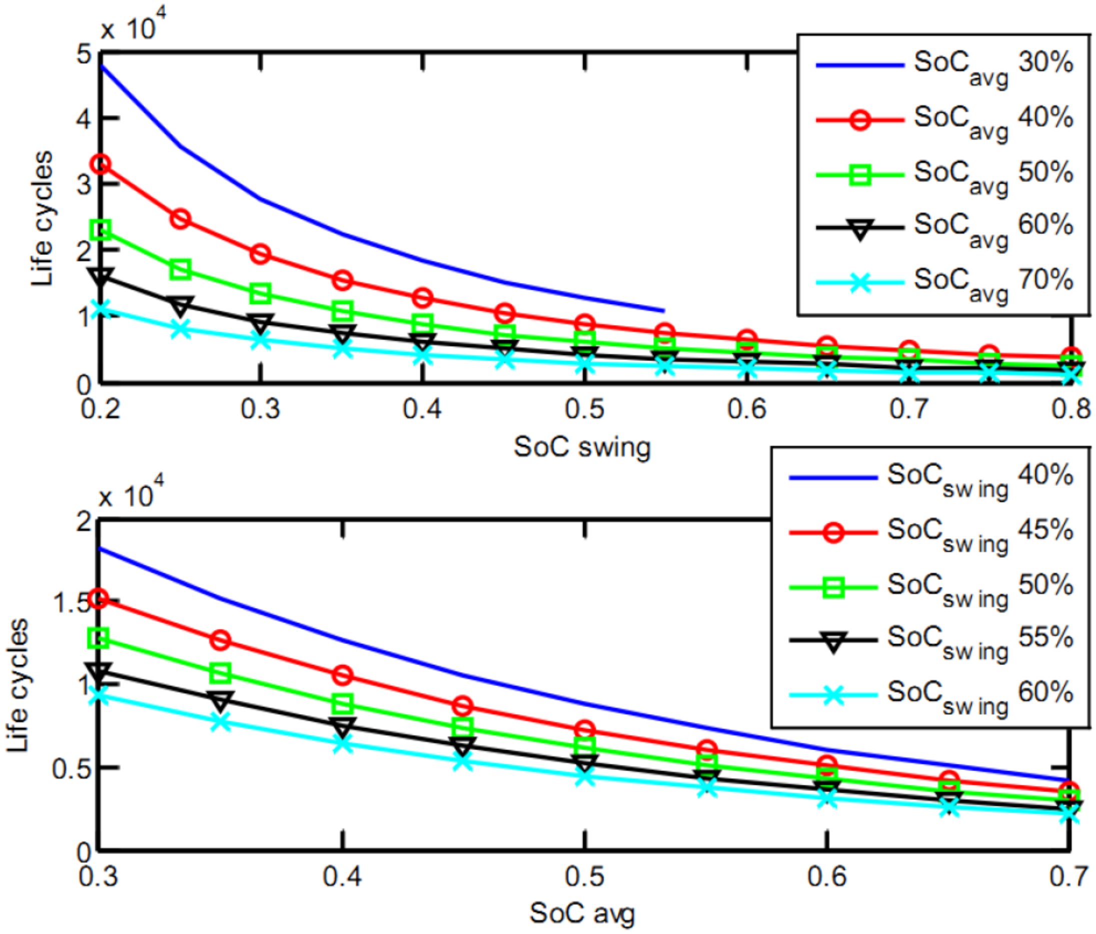


Figure 21: Degradation of SOH of a Li-ion battery as function of SOC_{avg} and SOC_{swing}

5.1.3 Security Issues

Batteries are very energy dense containers representing potential safety hazards. Precautions need to be made both regarding handling, transportation and storage. Potential hazards include electrical shock, environmental hazards by acids and heavy metals, and potential of explosions or fire. The largely power dense Li-ion battery is especially challenging as it produces its own oxygen during operation, consequently reducing the ways a fire might be put down. When putting down a Li-ion fire, using water is strongly discouraged, among better options are to use inert gases [87]. To decrease fire and explosion risks by storage of large batteries, one might want to store them apart from the building envelope in their own container, which increases the installation costs.

5.1.4 Applications

Batteries store electricity, which is the highest form of energy in terms of exergy. When discharged, it can therefore be used for all types of loads. Typical applications in a microgrid are to balance PV generation or peak shaving and load shifting of building loads. It can also be used to provide ancillary services to the grid in terms of frequency and voltage support. By utilizing optimized energy scheduling, the battery can be automated to charge and discharge at an optimal timing [88]. Some examples of relevant market applications for batteries are further explained.

Fronius Energy Package
One example of an energy management system for PV self-consumption and with smart grid capabilities is the Fronius Energy Package. Its configuration diagram is depicted in Figure 67 in Appendix C. For this topology, the inverter itself is equipped with integrated data communication, WLAN and Ethernet. It is able to receive and send information on the Modbus channel, thus integratable with conventional protocols. It is integratable with both Fronius Li-ion solution and the Tesla Powerwall battery. For now, the system only supports residential sizes from 3-5 kW. However, the system is developing and improvements are expected in near future, along with zero export capabilities through connections to the smart meter [89], [90].

Eltek
The Norwegian company Eltek offers storage systems for small scale microgrids. Their systems are configured by combining different prefabricated modules, for scalability and flexibility for different applications. Their products include the Rectiverter, which is a combined rectifier and inverter capable of handling AC and DC loads and generation simultaneously. They also offer PV rectifiers like the HE Solar rectifier, batteries and monitor and control systems which are compatible with each other. Their control system is available for external communications and overruling through Ethernet connection. An example configuration is viewed in Figure 68 in Appendix C [91], [92], [93].

5.2 Thermal Storages

Thermal storages are substances with a large heat capacity which store energy by maintaining a ΔT with respect to the space it is supplying. Included in the term are building thermal mass (BTM), thermal energy storage (TES) systems and phase changing materials (PCM), all of them applicable for peak shaving, load shifting and valley filling of thermal loads as showed in Figure 22 [94]. In both the BTM and TES strategies, the temperature of the thermal storage medium will change during operation, while a PCM storage utilizes the phase change of a medium, allowing it to store large amounts of thermal energy without changing storage temperature. A PCM storage provides a 5-14 times higher thermal storage density than sensible thermal storages, which is a large advantage in space constrained areas [95]. Previously discussed in Section 2.3, rigid food storage temperature requirements make it highly important to keep stable supplying temperature from the cooling medium. For the supermarket application, PCM storage is therefore considered to be the most relevant thermal storage strategy.

5.2.1 PCM Thermal Storages

The most important requirements of a PCM are large latent heat and high thermal conductivity. Other desired features are that the medium used is chemically stable, low in cost, non-toxic, non-corrosive and with melting point at the desired operation point. Different classes of materials offer different latent heat and melting temperature ranges. Cooling applications at or below freezing points are in the melting point range of water or aqueous salt solutions [96].

PCM materials can be incorporated in many creative ways. The two main applications in buildings are either to integrate PCM in building structures or in HVAC systems. Among the main methods of integrating PCM in building structures are immersion, encapsulation and direct corporation. An examples of an immersion process is simply to impregnate a building material in a feasible PCM so as to fill the pores of the building material. Encapsulating is a second option, classified in micro- and macro-encapsulation. For

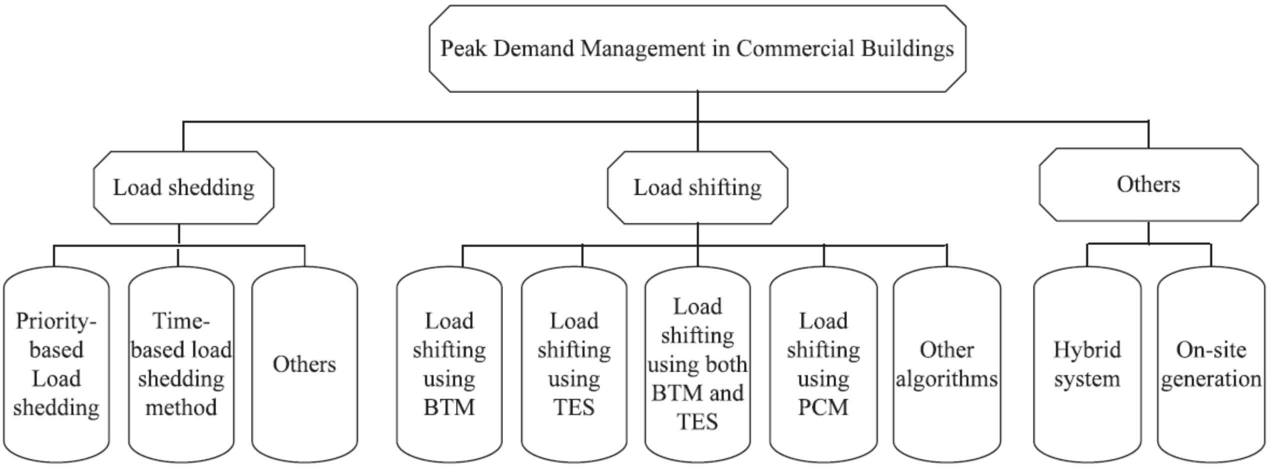


Figure 22: Thermal storage solution strategies used for peak demand management

micro-encapsulation, the PCM is encapsulated in many small packages which can take various forms. An example of micro-encapsulation would be to create a matrix wall by distributing micro-encapsulated PCM into the concrete mixture. In such an example, the micro-encapsulation prevents corrosion and other undesired interaction between the PCM material and the concrete. For macro-encapsulation, large packs are used instead of many small ones. Direct corporation is when the PCM is added to the structure without any capsulation. In cases where this solution works well, it is by principle a more economic solution with a better heat transfer. When integrating PCM in HVAC systems, the PCM is often stored in a tank, which is charged/discharged by heat exchanging it with energy carrying HVAC circuits [94].

5.2.2 Passive and Active Control of PCM Thermal Storages

Thermal storages can both be used for applications with and without active control. Thermal storages without control are typically passive storages which smoothe the temperature of their surroundings. An example of such storage is a concrete wall in a classroom, which will slowly absorb energy during high temperature hours and release energy during low temperature hours, thus mitigating temperature variations in the room. For such systems, numerical simulations show that a 10-20 % decrease of peak load can be obtained both for air conditioned areas and refrigeration containers by only incorporating PCM in the structural walls [94], [97].

Active control of a thermal storage implies controlling the timing and rate of charge/discharge. Examples of simple and deterministic control strategies are predefined hours for charging/discharging or room temperature-based control where the temperature set point is predefined for each hour. In such simple systems, charging can be predefined to happen at night when electricity is cheap or when possibilities exist for heat exchanging with cold ambient conditions. There is a need for developing optimal control strategies to improve the economics and operation of thermal storages [94].

5.2.3 Examples of PCM Applications in Refrigeration Systems

Example of large industrial cooling application
Previously discussed in Section 2.3, relevant temperatures for supermarket applications are $0-4^oC$ for cooling and $-18-22^oC$ for freezing application. A Swedish 2008 Ph.D study investigated industrial cooling applications utilizing PCM materials in the cooling temperature range. An example is a dairy factory in Ludbreg, Croatia, where an ice bank system delivered by the company Frigoterm was used for peak power mitigation of the refrigeration unit and built according to the principle of Figure 69 in Appendix C [80]. By economic analysis, the system was found to be most economic liable when applying a load leveling strategy, with a

claimed payback time of less than 0,5 years. For a load leveling control strategy, the partial storage is applied so that the refrigerant machine always runs at 100 % capacity. In that operating scenario, the ice bank is discharged when demand exceeds refrigerator capacity, and charged when demand is below refrigerator capacity, thus limiting necessary size of the cooling machine.

Example of supermarket cooling applications
A 2017 NTNU study investigates the possibility of PCM storages for cooling cases in supermarket applications [98]. The aim of the study is to design a simple, low cost PCM storage for easy integration with conventional cooling cases and CO_2 cooling machines. The system is set up as a DX system like that of KIWI Dalgård, meaning that the refrigerant is in direct contact with each of the cooling cases. By adding some extra pipes and valves within each cooling case, the refrigerant circuit can be modified also to include the PCM storage and enable "offline" operation of the cooling cases. For the cooling cases, low cost PCM mediums as pure water or water brine are proposed. Figure 23 shows the system behavior during four operation modes. Seen from the DX cooling machine, the PCM storage behaves as a normal cooling load. In Figure 23a, the PCM storage is charged during normal operating mode. Valves 4,6,7 and 8 are open in this mode, allowing the CO_2 refrigerant to flow through both the evaporator and heat exchange with the PCM storage. Valve 5 is the expansion device which is always open when the evaporator is fed, i.e when cooling is offered to the cooling case. Figure 23b shows a normal operating mode with the PCM storage being inactive, and the cooling case only interacts with the centralized DX cooling machine. To obtain this operation mode, valve 7 and 8 are closed. Figure 23c shows an operation mode where the PCM storage is charged and no cooling is offered to the cooling case, for example during defrosting of the cooling case. Finally, Figure 23d shows offline operation of the cooling case. For this mode, valve 4,6 and 7 are closed, so that the centralized cooler is disconnected and the PCM storage gets the full cooling responsibility. Table 12 gives an overview of necessary mass and volume storages to supply a 2 kW thermal cooling load for a selected duration, based on simulations [98].

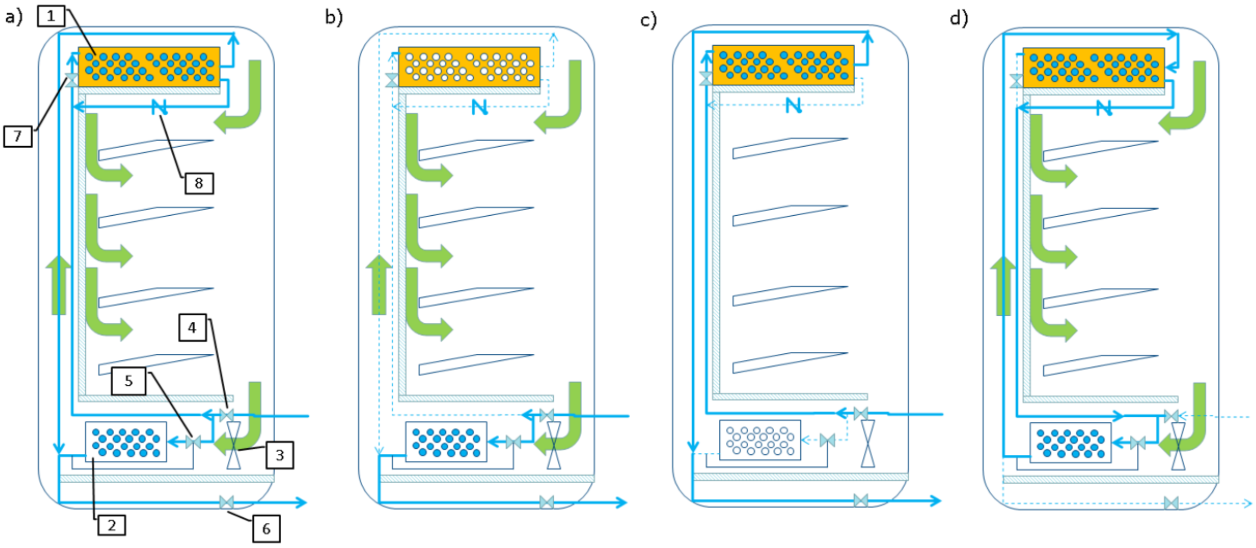


Figure 23: Cooling cases utilizing PCM in four operation modes

	Pure Water		Brine (8%)		Brine (14%)	
Melting Temperature	0°C		-5°C		-10°C	
Duration [h]	Mass [kg]	Volume [liter]	Mass [kg]	Volume [liter]	Mass [kg]	Volume [liter]
1	21	22	22	21	23	20
2	43	43	44	42	45	41
3	64	65	66	63	68	61
4	86	86	88	84	90	82
5	108	108	112	105	113	102

Table 12: PCM integrated cooling case - duration vs mass and volume of the PCM storage

5.2.4 Considerations regarding Economics, Aging and Security of PCM Thermal Storages

When discussing economics of PCM thermal storages for supermarket applications, emphasis is put on potential and not on current market price. The reason for this is that PCM thermal storages for such applications are an immature market, especially in Norway. Another reason is that the price is naturally very much dependent on system topology, temperature levels, requirements and materials being used. Among the discussed systems and applications, the NTNU research project for a Norwegian supermarket seems most relevant and applicable for KIWI Dalgård. Considerations regarding aging, security and economics are therefore made for this specific system, using conversations with the responsible professor, Armin Hafner, as source [37]. The cooling application in the NTNU research project and for KIWI Dalgård, are almost identical, and water/ice may be used as a free storage medium in the cooling cases. The few conventional parts needed are According to Figure 23 a few meter steel pipes, some valves and a simple tube heat exchanger. Producing a low cost storage is a main focus of the research project, as the long term ambition of the project is integrated cooling storage cases which are suitable for the market in developing countries. The resulting impression is that this technology has the potential of being cheap if sales barriers like marketing and mass production may be overcome. Regarding cycle life, there is no aging involved regarding chemistry of ice/water, and the cycle life is in principle infinite. Security is not an issue either when using ice/water as storage medium.

5.3 Choice of Case Study Storage

When choosing storage for KIWI Dalgård, project details are used as the decision base. The task of the storage is twofold:

1. Enable increased self-consumption of solar electricity
2. Reduce electricity costs by enabling peak shaving, load shifting and valley filling

5.3.1 Assessment of Needed Capacity and Economic Saving Potential

Storage size should be decided based on which of the two criteria it is which results in the largest storage requirements. In Section 2, it was explained how hourly load profiles for the period May 2016 to May 2017 were obtained for use in the case study. In Section 4, a PV system according to project case study data was modeled, and simulations for a full example year were conducted. Storage dimensions will be decided based on the overlap by these two curves. To support the decision on which storage might be appropriate for the case study, and avoid overflow of information, some key insights were extracted by using the Microsoft Excel COUNT, SUM, COUNTIFS and SUMIFS functions.

Firstly, storage dimensioning with emphasis on avoiding PV exports was investigated. For this case, Table 13 and Table 14 display how the export situations are distributed on hourly injection sizes and accumulated energy within a day. When assessing economical sizing of the battery, it is important to identify the loss/gain by a step increase/decrease in battery size. According to Table 13, there are never larger exports than 23 kW for this example year. Table 13 shows that for a 10 kW (40 %) capacity on the battery, 94 % of the counted export hours may be fully stored, along with 89 % of the total exported electricity. Stated in a different way, the numbers tell us that if a 23 kW storage was to be dimensioned to capture all solar energy, the top 13 kW would only be usable for storing 11 % of the energy, given that energy capacity is not a constraint. It is also noted that exported energy without utilizing storage is only about 2 000 kWh. The saving potential by avoiding exports is as previously mentioned in Section 3.4 the grid tariffs, taxes and fees. To give an estimate on yearly saving potential by self-consumption, the grid tariff of Trondheim, which according to Section 3 is 0.23 NOK/kWh, and the average spot electricity price level from May 2016 to May 2017 of 0,29 NOK/kWh are assumed. This gives, according to Equation (3) in Section 3.4, a yearly saving potential of only $2\,000 kWh * (0.21\, NOK/kWh + VAT * (0.21\, NOK/kWh + 0.29\, NOK/kWh)) = 670\, NOK$. The result tells that storage must be very cheap for it to have relevance for the case study. According to Section 4.5, the total yearly PV generation for the example year is 62 500 kWh for KIWI Dalgård. The fact that $(62\,500 - 2000)\,/\,62\,500 = 97\,\%$ of the solar generation is self-consumed without applying storage tells that the solar installation is based on traditional economical sizing. The total yearly load consumption for KIWI Dalgård according to the load data is 306 000 kWh, giving a degree of self-sufficiency of about $62\,500\,/\,306\,000 = 20\,\%$. By applying smart power control and storage, the degree of self-sufficiency may be increased by allowing a larger PV installation without causing large export losses. When assessing case study system simulations in Section 8, scenario analysis will be applied for different PV system and storage sizes to reveal potentials.

Hourly exports *	Counted hours	% of export hours	kWh export	% of kWh	Part of kWh below 10 kW	% of kWh below 10 kW
0-5 kW	183	51 %	411	20 %	411	100 %
5-10 kW	117	33 %	842	41 %	842	100 %
10-15 kW	35	10 %	416	20 %	350	84 %
15-20 kW	16	4 %	268	13 %	160	60 %
20 + kW	5	1 %	112	5 %	50	45 %
Total	356	100 %	2048	100 %	1813	89 %

*Max. hourly export: 23 kW

Table 13: Hourly case study export situations

Even though the planned PV installation for KIWI Dalgård only seem to contain low economic relevance for storage, it is interesting to take a look at the energy storage requirements as they form basis for later sensitivity analysis and discussions. Table 14 shows accumulated daily exports for different energy ranges. For the example year, export is present in 89 days. For almost all of them, accumulated export is below 50 kWh. However, 45 % of the energy is found in days with more than 50 kWh exported electricity. The 6th column in the table shows the average energy capacities needed in the storage to capture all energy in each of the daily ranges. The 7th column tells how much energy may be captured for each of the ranges by a storage with 10 kW power capacity. A 93 kWh battery is needed to store all export up to 10 kW for all days in the year. For this case, 20 / 23 = 89 % of the yearly export energy is stored, which is in accordance with the key numbers in Table 13.

Daily exports*	Counted days	% of days	kWh export	% of kWh	Avg. storage a day [kWh]	Avg. stored by 10 kW [kWh]
0-50 kWh	79	89 %	1126	55 %	14	16
50-100 kWh	5	6 %	333	16 %	67	57
100-150 kWh	4	4 %	424	21 %	106	80
150+ kWh	1	1 %	165	8 %	165	93
Total	89	100 %	2048	100 %	23	22

*Max. daily export: 165 kWh

Table 14: Daily case study export situations

Secondly, the necessary potential for peak shaving is assessed. In Table 14, key numbers for peak power and load shifting potential for KIWI Dalgård are viewed. Due to an average load consumption of 35 kW, all consumption exceeding 35 kW may in theory be subject to load shifting, peak shaving and valley filling. It is also shown that the yearly peak import from the grid is 53 kW. Regarding power capacity, peak shaving to 35 kW is straight forward by adding an 18 kW storage capacity. However, with an ambitious peak shaving target comes large requirements regarding energy storage capacity and cycle life, since the storage will have to be active very often. Table 15 shows that the storage will be active 4 %, 27 % and 57 % of the time if the peak capacity target is put to 45 kW, 40 kW or 35 kW, respectively. Previously mentioned in Section 3, the peak demand tariff relevant to the case study is 500 NOK/kW. To avoid load shifting of large energy quantums, which probably would require very large energy storages, peak shaving to a 45 kW limit is used as a basis when conducting simulations. The yearly saving potential for this strategy is (53-45)kW*500 NOK/kW = 4 000 NOK, which will require at least 8 kW storage capacity.

Another saving potential is to charge the storage during periods with low electricity prices, and to discharge it during high electricity price periods. The random selection of price curves previously shown in Figure 7 in Section 3.1, showed an approximate 20 % deviation between daily low and high, with prices being lowest at night. To make load shifting based on spot pricing economically viable, costs related to efficiency and cycles should be lower than the potential savings. When spot price curves show a relatively flat shape like those viewed in Figure 7, a very cheap and energy efficient storage with low cycle cost is needed for load shifting to be a viable business case.

Total load*	Counted hours	% of export hours	kWh load	% of kWh	Part of kWh within range	% of kWh within range
0-35 kW	3781	43 %	106232	35 %	294167	96 %
35-40 kW	2625	30 %	99559	33 %	7684	3 %
40-45 kW	1992	23 %	83506	27 %	3826	1 %
45-50 kW	344	4 %	16032	5 %	552	0 %
50+ kW	18	0 %	922	0 %	22	0 %
Total	8760	100 %	306252	100 %	306252	100 %

*Max. load: 53 kW; Avg. load: 35 kW

Table 15: Hourly peak loads and load shifting potential of case study

5.3.2 Choice of Storage Type

The choice of storage solution will be decided almost solely by economic considerations, due to the small margins found by power control of the case study. A cheap, efficient storage with low cycle cost seem to be deciding, and storage will by this reason be chosen as the system which to the largest degree fulfills these requirements for the case study. Among the studied concepts, the PCM storage showed in Figure 23 is considered to have largest relevance. It is integrated in the cooling case, which minimizes losses as any leakages of cooling energy will contribute to the cooling of the cases. It is probably a cheap solution, as no changes need to be done regarding piping etc. outside the case, and simple and conventional parts like pure water, metal pipes, valves and a tube heat exchanger are used. Low cost was an important feature of the design of the product, as one motivation was to design a storage cheap enough for wide application in development countries [37]. An advantage with ice storage banks is its endless cycle life, enabling it to participate in load shifting based on spot prices without added costs. This potential of added savings might be crucial in a project with low economic margins. A drawback with utilizing a thermal storage system is its lacking ability for a two way power flow towards the grid, which in time may would open new business opportunities as discussed in Section 6.1. On the other hand, the thermal storage is usable for all the criteria stated in this section: Absorbing excess PV electricity, peak shaving and load shifting due to its contact with the largest and steadiest load in the supermarket, namely the cooling load.

5.3.3 Choice of Storage Dimensions

To decide cooling storage dimensions, the practical constraints are evaluated. Table 16 contains data from the planning documents regarding supermarket cooling cases for KIWI Dalgård, which make up about 60 % of the total cooling load according to Column 7 [32]. The remaining cooling part of the load is in the dairy room and storage rooms for fruit and waste. These rooms are not compatible with the integrated cooling case storage design and would require a different storage solution. It is seen that the heat load for most cooling cases exceeds the 2 kW heat load which was the design base for the PCM integrated cooling case explained in Section 5.2.3. However, due to the PCM integrated cooling case still being in the research phase, it is assumed that larger capacities will be available when the product enters the market. The NTNU professor responsible for the project confirmed that the example system reviewed in the research article only showed on example of many possibilities worth investigating in [37]. For the case study, PCM storage cases with 3 kW_{th} capacity each will be assumed, which is sufficient to supply the average cooling case load with a 20 % safety factor to account for insecurities. A storage large enough for 5 hours offline operation is desired to add flexibility to the system and increase load shifting potential. For simplicity, the same PCM storage size is assumed for all the cooling cases. According to extrapolation of Table 12, a 150 l PCM storage would be required. It is assumed that the 150 l storage may be made with a 3 kW_{th} power capacity. As described in Section 2.3.2, the cooling supplier estimated a COP of 4.1 for the operation of the cooling machine. Using Equation (1) from the same section, the stored electrical energy is $(3 kW_{th} * 5h * 14 cases)/(4.1 kWh_{th}/kWh_{el}) = 52 kWh_{el}$ electrical energy. For load shifting, storage capacity will for this study always be stated in electrical energy terms, as it is the term relevant for the business cases. Regarding power capacity, its accumulated value is $(3 kW_{th}/case * 14 cases)/(4.1 kWh_{th}/kWh_{el}) = 10 kW_{el}$ for the cooling cases altogether. A 10 kW and 52 kWh storage is according to the previous discussion believed to be sufficient for PV storage, peak shaving and the majority of load shifting for this project, and will be the base storage used for the case study system simulations.

Coolig case types	Length of case [mm]	Number of cases	Heat load per case [kW]	El. load per case [kW]	Total el. load [kW]	% of total cooling load
Mineral water	2500	2	2.33	0.55	1.11	8 %
Beer	2500	2	2.33	0.55	1.11	8 %
Fruit	3750	2	3.50	0.83	1.66	12 %
Smoothies	3750	1	3.50	0.83	0.83	6 %
Other	3750	4	2.13	0.51	2.02	15 %
Other	3750	2	2.97	0.71	1.41	10 %
Other	2500	1	1.43	0.34	0.34	2 %
Total*		14	2.60	0.62	8.48	62 %

*Total avg. cooling load = 13.6 kW

Table 16: Electrical consumption and heat load of case study cooling cases

For the simulations, sensitivity analysis will be applied, and scenarios where electrical storages might be relevant to the case study will be discussed. When discussing building automation system design today and in the future, both electrical and thermal storages will therefore be included.

6 Strategies Influencing Power Control System Design

Depending on the interest of the various stakeholders, different power control strategies might be suitable. Also, the nature and requirements of the technical installations might affect which strategies are appropriate. In this section, some principles and strategies which form the basis for power control system design will be presented and discussed, both for understanding the system solutions presented in Section 7, and for choosing an appropriate strategy for use in the case study.

6.1 Energy Management Policy and Markets

When optimizing energy control or scheduling, principle choices need to be made regarding goals and markets. Different stakeholders might have different interests. Some examples include [99]:

- The building operator and the consumers act as a single entity with a common interest.
- The building operator and the consumers act as separate entities with separate interests.
- The main interest is to provide ancillary services to the grid, and to participate in other external markets like the spot pricing market.
- The main interest is to optimize the operation in the local "market", such as the interaction between the distributed generation, storage and flexible loads in the local microgrid.
- The main interest is to optimize indoor comfort.

Traditionally, building automation systems (BASs) have been focusing on monitoring and control of installations inside the building envelope. There are also numerous ways of utilizing customer side flexibility for ancillary services to the grid. NERC an NAESB have outlined an overview of different options regarding demand response programs, viewed in Figure 24 [10]. Ottesen and Tomasgard argue that for the smart grid potential of retail side participation to be substantially utilized, the flexibility should participate in the wholesale side of the market [24].

In theory, saving potential occurs both when utilizing flexibility to provide ancillary services to the smart grid, and when utilizing the flexibility potential to reduce the electricity bill and increase self-consumption of DG. Depending on the chosen policy and target for energy management, different system setups, topologies and technologies with different risks and investment costs might be wanted. Some devices might be used in different markets, like an electric battery, which in theory both can be used to offer ancillary services to the grid, and to balance the local microgrid. The potential savings and thereby the attractiveness of each market might depend on future and uncertain factors, such as future incentives, rules and regulations, variations in electricity prices, peak power tariffs and how the smart grid will look like in the future. Also, the stakeholders, and/or their energy management policies might change within the system lifetime. In order to design a flexible system with respect to these markets and policies, it might be preferable to design a system adaptable to future changes without extensive reprogramming and investments. When extending the system barrier of the control systems, the system gets more complicated. This leads to larger requirements on the communication and cooperation side, which increase the relevance of more intelligent systems.

6.2 Tools for Demand Response

Buildings consume 40 % of worldwide energy demand. When the grid aims to get smarter and more flexible, integration of buildings in the control strategy is crucial because of its large potential. Buildings may affect the grid in a number of ways, both as producers and consumers. Terms used for explaining this process are flexible load management, demand response (DR) and demand side management (DSM) [100].

Previously explained in Section 3, the peak capacity tariff is one of the elements composing the electricity bill, providing an incentive for the customer for mitigating peak capacity. From the utility perspective, peak

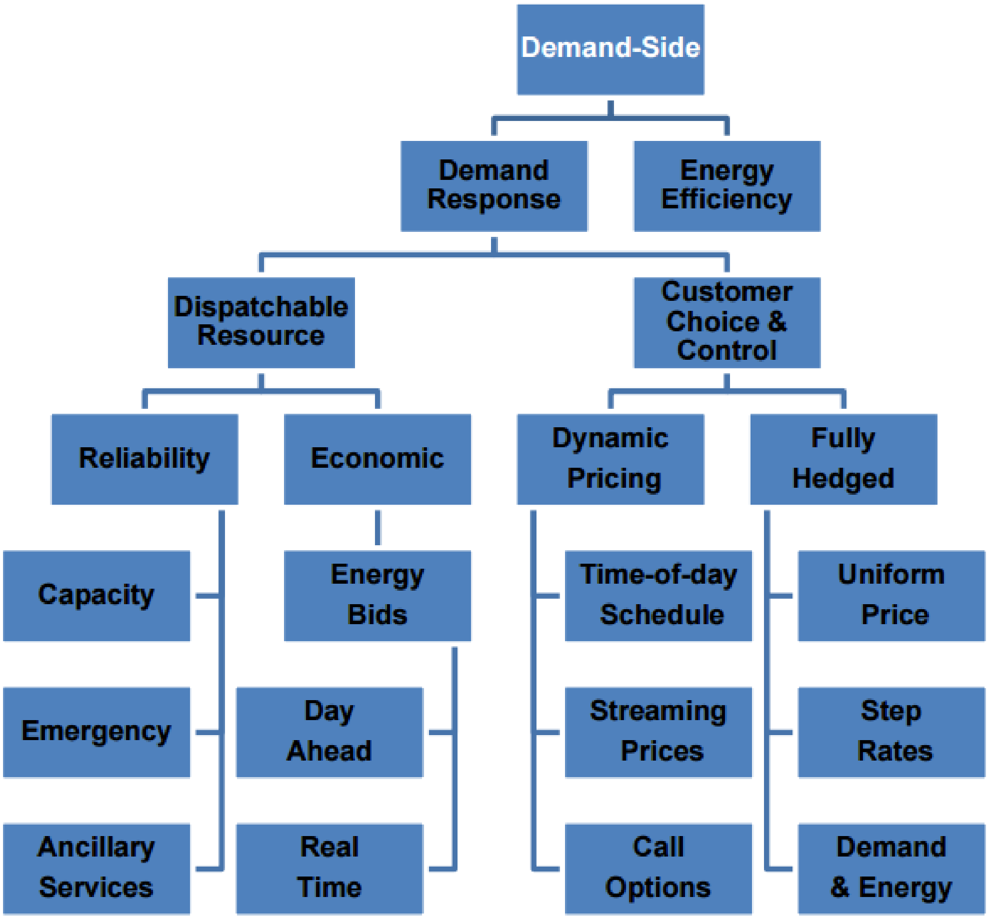


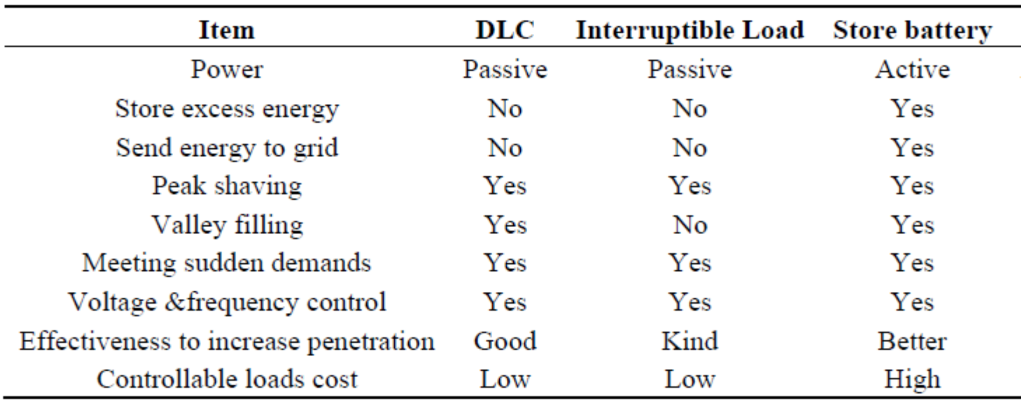
Figure 24: Demand response program options according to NERC and NAESB

power mitigation enables increased utilization of existing infrastructure and reduced need for further investments. This is particularly important with the increased use of troubling residential loads like instant water heaters, induction cookers and electric vehicles [5]. Also, with increased penetration of DG in the grid, releasing transmission capacity is expected to be increasingly important. In the future, it is believed that the capacity and quality of the power will be more important, and the kWh of energy less important than it is in today's power tariff structures [101]. In this section, some tools and terms regarding building blocks of smart power control systems which utilize DR are described.

6.2.1 Demand Side Management

A lot of terms are used for describing various responses to grid demand on the consumption side. Demand side management (DSM) is a wide term covering general energy improvements on the consumption side. Usually, it is used from the grid perspective. It might be divided into the four main categories of energy efficiency, time of use (TOU), demand response (DR) and spinning reserve (SR), which say something about the time frame and the nature of the DSM type, as viewed in Figure 70 in Appendix D. In this context, energy efficiency is understood as one-time installations to make a general reduction of energy usage, exemplified by the insulation of the building envelope. TOU in this context means control of consumption according to a fixed and pre-determined time scheme. DR control is based on real demand, according to dynamic input signals. The DR is considered market based when it responds to price signals, and physically based when it responds to physical needs in the grid. Spinning reserve relates to the active reserve of the system ready to be implemented instantly if necessary [102]. From a prosumer perspective, DR can also be used for dynamic consumption of DG or to provide other ancillary services. In this study, DR will be limited to market based DR for the grid interface (load shifting by price signals), and energy based DR within the prosumer site (PV self-consumption and peak shaving). Focus is on the energy flows, not on the various physical needs of the system.

An overview of controllable loads and their potential for providing ancillary services to the grid is displayed in Figure 17 [103]. Also, other load contributions like connection of electrical vehicles were suggested by the study, but are left out of the displayed figure because they were out of the scope of this study. Direct load control (DLC) is a control scheme by which the loads are under direct control by the DSO. It is based on agreements between the customer and the DSO, of which limits in time and load types are among contractual elements. Interruptible load demand (ILD) means that the customer agrees to reduce demand when the grid requests it, as a balancing service. If it fails to deliver on the contractual agreement, a penalty fee will occur [104], [105].



Item	DLC	Interruptible Load	Store battery
Power	Passive	Passive	Active
Store excess energy	No	No	Yes
Send energy to grid	No	No	Yes
Peak shaving	Yes	Yes	Yes
Valley filling	Yes	No	Yes
Meeting sudden demands	Yes	Yes	Yes
Voltage &frequency control	Yes	Yes	Yes
Effectiveness to increase penetration	Good	Kind	Better
Controllable loads cost	Low	Low	High

Table 17: Controllable loads and their potential for grid ancillary services

6.2.2 Forecasting

Forecasting enables optimal power scheduling systems based on a time horizon, like the optimized scheduling system described in Section 6.3.3. The quality of the forecasted values regarding all inputs is a guideline for the potential value of an optimization model. For an optimized scheduling system, all input values to the optimization problem which are required and uncertain need to be forecasted. In the case of a supermarket with PV generation, the load, electricity costs and the PV generation need to be forecasted. Some of these elements may depend on uncertain input variables which also need to be forecasted as part of the process. For instance, the PV generation depends on the insolation, temperature and wind speed in the area. The cooling load might depend on outdoor temperature and the number of people present in the supermarket. The degree of detail required in the input data depends on how much uncertainty which is accepted. A pragmatic approach is to only include the input data which largely affect the main forecast categories. In this section, forecasting methods are discussed and choices are made regarding the case study.

Weather Forecast
There are numerous weather forecast services on the market, offering global weather information via the web. Requirements are that the weather service for each project provides sufficient and local weather data and is compatible with the power control system. Typically, weather service providers provide two main alternatives: A paid and thoroughly forecasted service, or a free service which is less detailed [106]. Suppliers on the Norwegian market include MxVision WeatherSentry, Yr and StormGeo among others [107], [108] [109].

Load and Generation Forecast
Forecasting of loads in both short, medium and long term is a vast research field with many conventional solutions. Among available methods are multivariate regression, time series, exponential smoothing, decomposition, and more advanced and improved methods like artificial neural networks, expert system, genetic algorithm, wavelet decomposition and evolutionary programming. There are also various indices for evaluating forecasting accuracy, one of them being Mean Absolute Percentage Error (MAPE) [110].

Multiple linear regression, a simple and intuitive method of load forecasting, is used for this study. It is applied in many studies for the same purposes, like the studies of Bao and Ottesen and Tomasgard [23], [24]. In multiple linear regression, the forecasted load is a linear sum of the variables affecting the load as viewed in Equation (10), "where y_i is the value observed for the dependent variable for observation i, x_{ki} is the value taken by variable k for observation i, and e_i is the error of the model" [111]. Both of the studies are pointing out that the accuracy on the multivariate regression increases when intraday data are used for continually updating the analysis, as opposed to running it once a day [23], [24].

$$y_t = a_1 x_{1t} + a_2 x_{2t} + (...) + a_n x_{nt} + e_t \tag{10}$$

When building up the regression formula, the selection of exogenous explanatory variables which are to be included needs to be decided. Ottesen and Tomasgard suggests using "the hour of the day, whether the hour belongs to a working day or not, the outdoor temperature and finally which month the hour belongs to" as exogenous explanatory variables in the formula. Also, a moving average component was added for workdays, referring to the gap between forecasted and real time value 24 hours back. Consequently, the multiple regression formula was presented according to Equation (11).

$$\begin{aligned} L_t = \mu &+ \sum_{h=1}^{24} D_{t,h}^{hour} D_t^{workday} \alpha_h^{workday} + \sum_{h=1}^{24} D_{t,h}^{hour} D_t^{workday} \beta_h^{workday} \tau_t \\ &+ \sum_{h=1}^{24} D_{t,h}^{hour} D_t^{nonworkday} \alpha_h^{nonworkday} + \sum_{h=1}^{24} D_{t,h}^{hour} D_t^{nonworkday} \alpha_h^{nonworkday} \tau_t \\ &+ \sum_{m=1}^{12} D_{t,m}^{month} \gamma_m + \sum_{h=1}^{24} D_{t,h}^{hour} D_t^{MA(24)} \theta_h \varepsilon_{t-24} + \varepsilon_t \; t \in T \end{aligned} \tag{11}$$

In the formula, dummy binary variables are used to denote the hour, month, whether it is a workday or non-workday, and whether a moving average component should be included for the load forecast of each hour. "T is the hour number for the year ($t \in 1...8760$) and h is the hour number of the day ($h \in 1...24$). (...) μ is a constant, τ_t is the outdoor temperature and ε_t is the residual" [24]. After the model was calibrated using historical data from a Norwegian University building, the model was claimed to be tested real-time in January 2013 with a MAPE value of 10.7 %.

The available software for conducting multivariate regression includes the freely available student software of MATLAB and XlSTAT, the latter being a Microsoft Excel Add-on [111], [112]. For this study, XLSTAT will be applied when conducting multiple variate regression.

In the same way as load forecasting, generation forecast can be conducted by multivariate regression based on historical data and explanatory variables affecting generation. For PV generation, short term correlation at an adequate level may be obtained by using temperature and insolation as independent explanatory variables [113].

Electricity Price Forecast
Real time electricity prices are published day ahead by Nord Pool Spot on a daily basis [41]. For this reason, no forecasting is principally needed when assessing day ahead optimization.

6.2.3 Big Data and Machine Learning

The basis for learning is information, and learning potential increases with the number of relevant data available. In order to make optimal scheduling decisions in a complex energy system, information is needed regarding the past and present operation and the predicted future. Like explained in the forecasting section, quality of prediction enhances the value of an optimized scheduling system. To make a perfect prediction, all affecting explanatory variables in theory needs to be logged and understood. Patterns need to be recognized in order to understand how the various inputs both individually and by interaction affect what is to be predicted. It is evident that large amount of data, so called big data, need to be obtained to generate understanding and predictions of high quality once the systems get complex. It is also evident that powerful tools are needed to process the data. By machine learning, which is basically an advanced form of statistical methods utilizing computational intelligence, large data may be collected and handled and deep level patterns may be recognized at a level which far exceeds human capacity. The output of a well conducted machine learning process are precise predictions of future behavior of all inputs, and may be used to design high quality optimization models [114]. Also, insight obtained by machine learning may be monitored to provide valuable information to operation managers.

An increasing number of companies utilize the combination of machine learning and optimization techniques in their energy management systems for optimized scheduling, monitoring and other appliances. An example is the Ennext system by SMA, which was presented at the end of May 2016 at the Intersolar conference in Munich [115]. The system was presented as an energy management system for commercial buildings, of which machine learning was used to gradually learn energy consumption and generation at the site. Possible applications included optimized scheduling of a battery with regards to a decided goal, for instance minimized costs or maximized self-consumption. The system was also claimed to support ancillary services to the grid. Another application was an embedded digital energy adviser. By notifications, it provides recommendations to the user, for instance regarding which and how large PV system and storage should be installed, based on its learning and a product database. Another example of companies offering power control systems utilizing machine learning and optimization models is the Norwegian company eSmart Systems. They provide services regarding energy monitoring and control for various applications in the energy sector, like cities, utilities and single prosumers [116].

6.3 Control Strategies

Portions of this subsection are taken from an earlier work by the author of this study [8]. The chosen control strategy sets guidelines for which possibilities may be embedded in the system. Depending on the goal and requirements of the control, different strategies may be suitable. There are many power control strategies for microgrid applications suggested by researchers. Among them are deterministic rule, fuzzy logic, optimized scheduling and multi-agent systems (MAS) [117], [18]. In this section, these suggested control structures are described.

6.3.1 Deterministic Rule

The deterministic rule strategy is an example of a "top-down" control strategy based on a central controller using a written program with pre-defined rules. The strategy is recognized by prescribed if-then rules with distinct boundaries for all operating modes [118]. Examples of functions are "if then"-functions like: if the electricity exceeds a certain value, then reduce consumption" [14]. For this structure the system has no ability to resonate, but is subject to pre-defined rules written for every case by the designer. An example algorithm topology is depicted in Figure 25 [117]. The distinct boundaries between the different scenarios are clearly observed in the Figure.

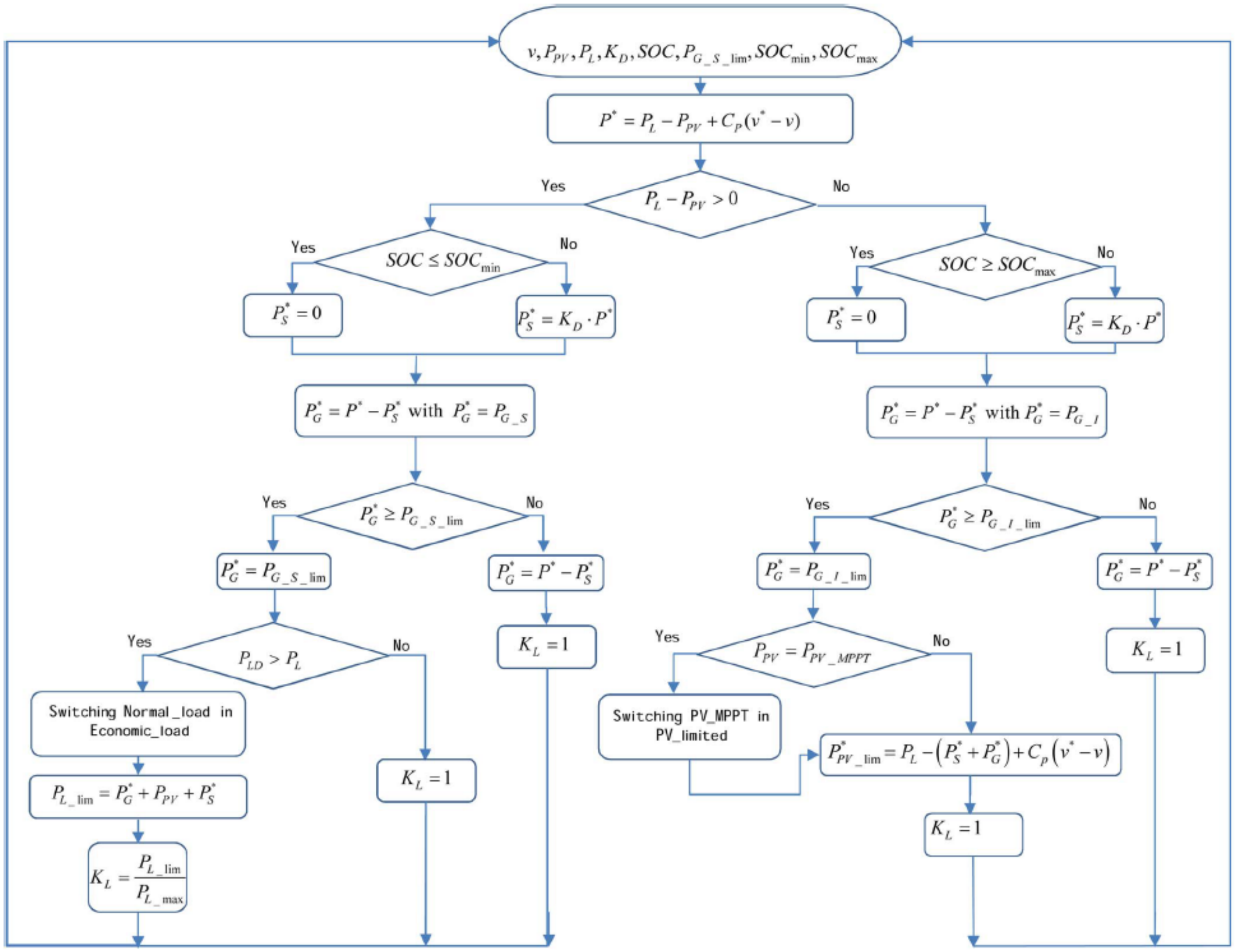


Figure 25: Example of flowchart for a deterministic rule control structure

The following traditional arguments have been used for applying deterministic rule based systems [119]:

- Human knowledge is translated into conditional if-then rules
- It is a system adaptive for improvements. As skills and experiences increase, rules can be better stated.
- The possibility of controlling a wide range of complex systems
- The system is intuitive and uses natural human language

Critics of this control strategy points to the following cons [14]:

- The control strategy requires an extensive rule base. If a specific event is not covered, the system will be unable to respond adequately
- A low degree of flexibility. With a changed system configuration, the rules may need to be completely restated.

6.3.2 Fuzzy Logic

Fuzzy logic separates from binary logic by not understanding truth as being 1 or 0, meaning all true or not true at all, but that it can be something in between, called fuzzy. Fuzzy logic permits degrees of truth [120]. As an example, a battery SOC might be considered 100 % small when $SOC = 0\,\%$, 50 % small when $SOC = 25\,\%$ and 0 % small when $SOC = 50\,\%$. For a control system, fuzzy control finds compromises between various conflicting objectives for each operation scenario [16]. Fuzzy logic is a rule based system, however it separates from the deterministic rule system by the different rules gliding into each other and being active simultaneously [118], [121]. There are different types of fuzzy inference processes, having in common that they use a set of fuzzy if-then rules to map an input space to an output space [122]. For this study, the Mamdani-Type is explained.

Mamdani-Type Fuzzy Inference Process explained by an example

Fuzzy control has three stages: Fuzzification, inference and defuzzification [16]. The stages are easiest explained by providing an example with few variables. The chosen example is provided by Mathworks, and is the known tipping problem occuring at a restaurant [120]. Tipping is in this example a function of food taste and the quality of service. Food and service are each evaluated on a scale from 0 to 10, where 0 is miserable and 10 is perfect.

The aim of the fuzzification stage is to connect each variable to a proper category related to certain actions, in other words degrees of membership to different action sets [121]. For the restaurant example, the input variables are food and service quality, each given fuzzy subsets and member functions (MFs) as shown in Figure 26 and 27. Firstly, the input values are defined into categories called fuzzy subsets. The service is divided into the fuzzy subsets "poor", "good" and "excellent". Food are divided into the categories "rancid" and "delicious". Each subset is associated with an MF ranging from 0 to 1, i.e. 0 to 100 % . The MF assigns both an interval to the subset, and a degree of membership within that interval [120]. In the example, the service has a 100 % membership with the "poor" subset when service is 0. According to Figure 26, a service of 2 has about 40 % membership with the "poor" subset, and about 20 % membership with the "good" subset. Stated in other words: The service is considered 40 % poor an 20 % good when being 2 on a scale from 1 to 10. An input value can either be given as an absolute value, or as a relative value to its reference value. The output variable is also assigned to subsets and membership functions. Tipping subsets are "cheap", "average" and "generous", as depicted in Figure 28. In the example, the variables have been given 2 to 3 subsets. However, multiple variations of fuzzy subsets might me chosen [16]

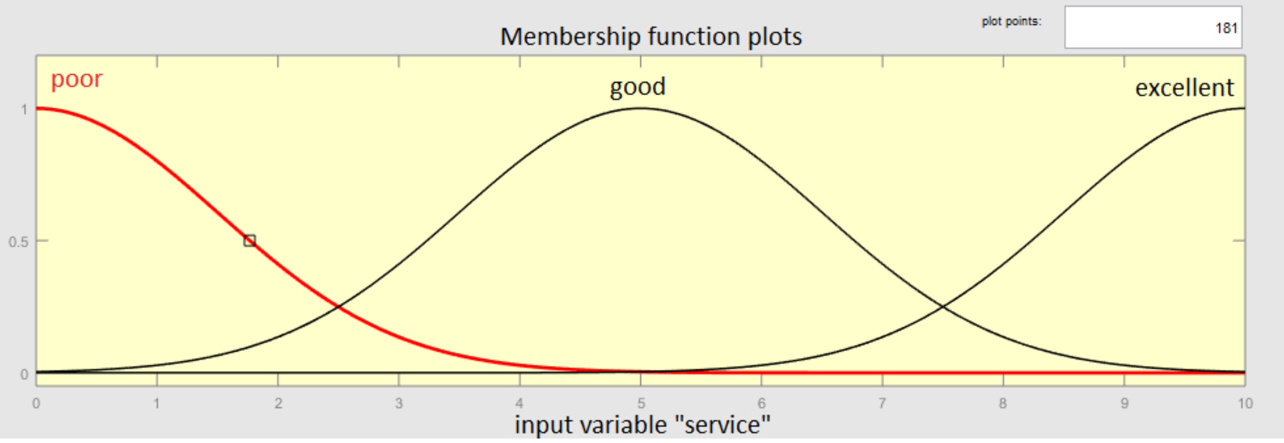


Figure 26: Example problem fuzzy logic - fuzzification stage of the service input variables

In the inference stage, the rule base for the system is obtained according to the objectives, constraints and means of action defined initially. The rules are given as "If-then"-rules. In the given example, the following rules may be reasonable:

1. IF service is poor OR food is rancid, THEN tip is cheap
2. IF service is good, THEN tip is average
3. IF service is excellent OR food is delicious, THEN tip is generous

When different subsets are fulfilled to a different degree, their membership value and how the rule is stated determines which subset is deciding. When the "OR" dependency is used, the subset with the largest membership is deciding. It is also possible to decide an "AND"-dependency, in which case the subset with the least membership value is deciding. When more than one rule is active at a time, all rules will contribute

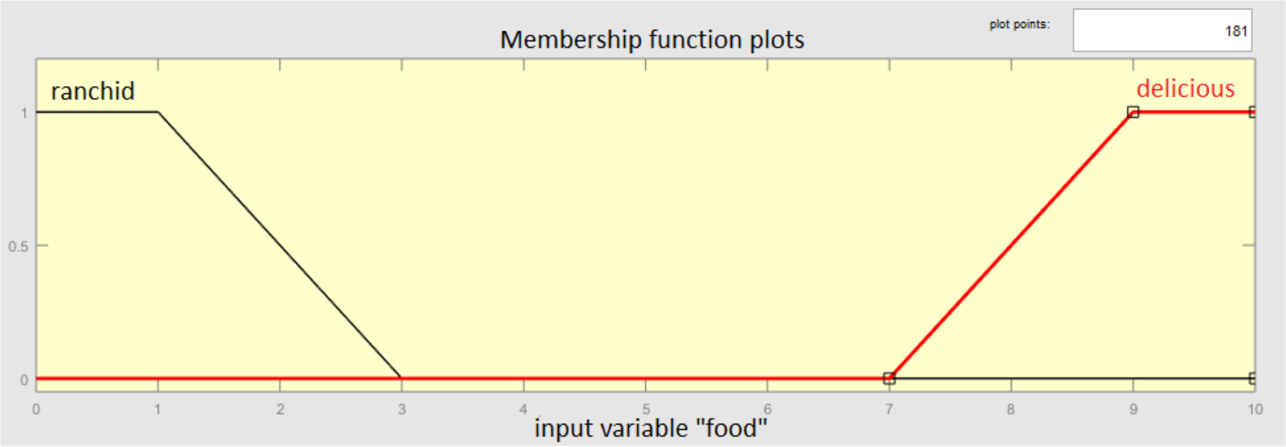


Figure 27: Example problem fuzzy logic - fuzzification stage of the food input variables

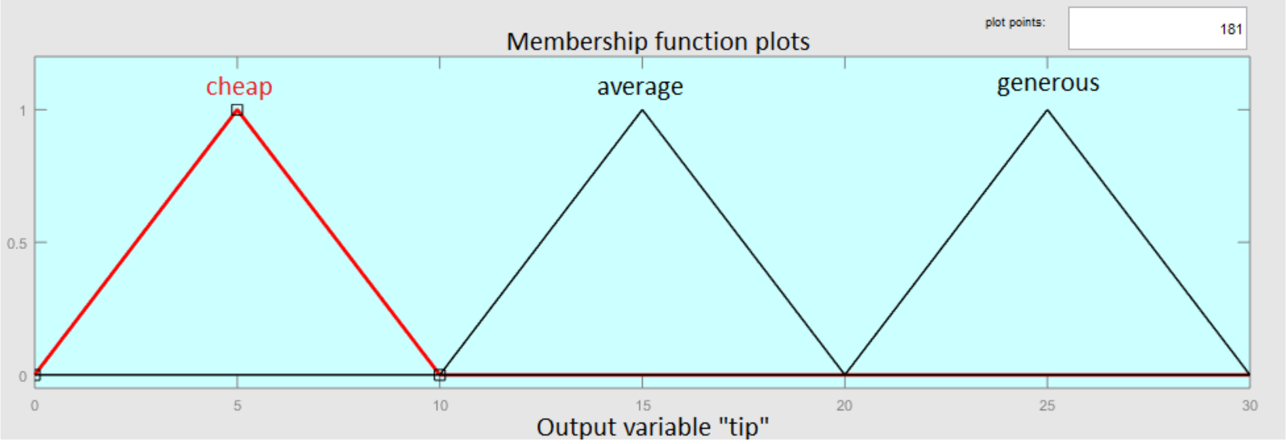


Figure 28: Example problem fuzzy logic - defuzzification stage of the output variable

to the output action of the controller [120]. The concept of compromise between rules are viewed in Figure 29. For the case of $Service = 5$ and $Food = 8$, Rule 2 has a 100 % membership, Rule 3 has a 50 % membership, and the output value is chosen as a compromise by being the gravity point of the resulting output area graph.

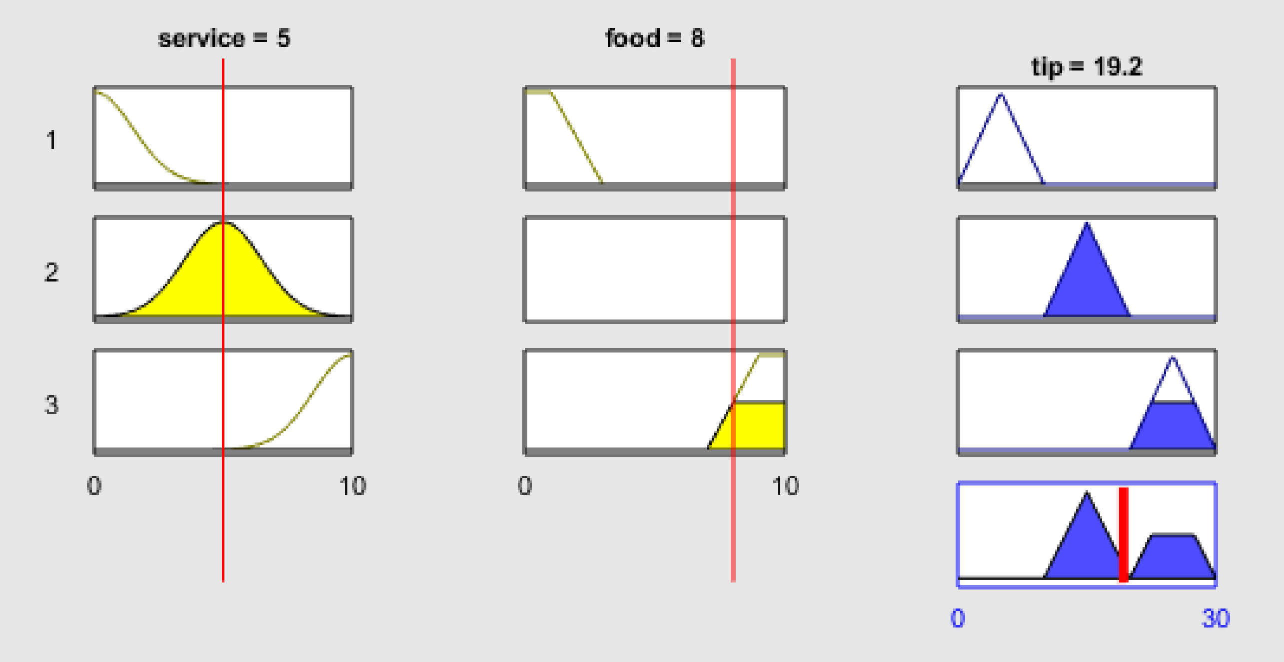


Figure 29: Example problem fuzzy logic - rule viewer

The defuzzification step includes connecting the nonlinear relationship between input and output variables. In this step, an output value is assigned by the controller. When the MFs and rules have been stated, all inputs to the systems are related to a certain output value by the explained fuzzification, inference and defuzzification processes, and the result by two input variables is presented as a 3D curve. The solution domain for the tipping problem is depicted in Figure 30, showing how fuzzy logic carries out solutions with unsharp boundaries according to changes in the input variables of the system.

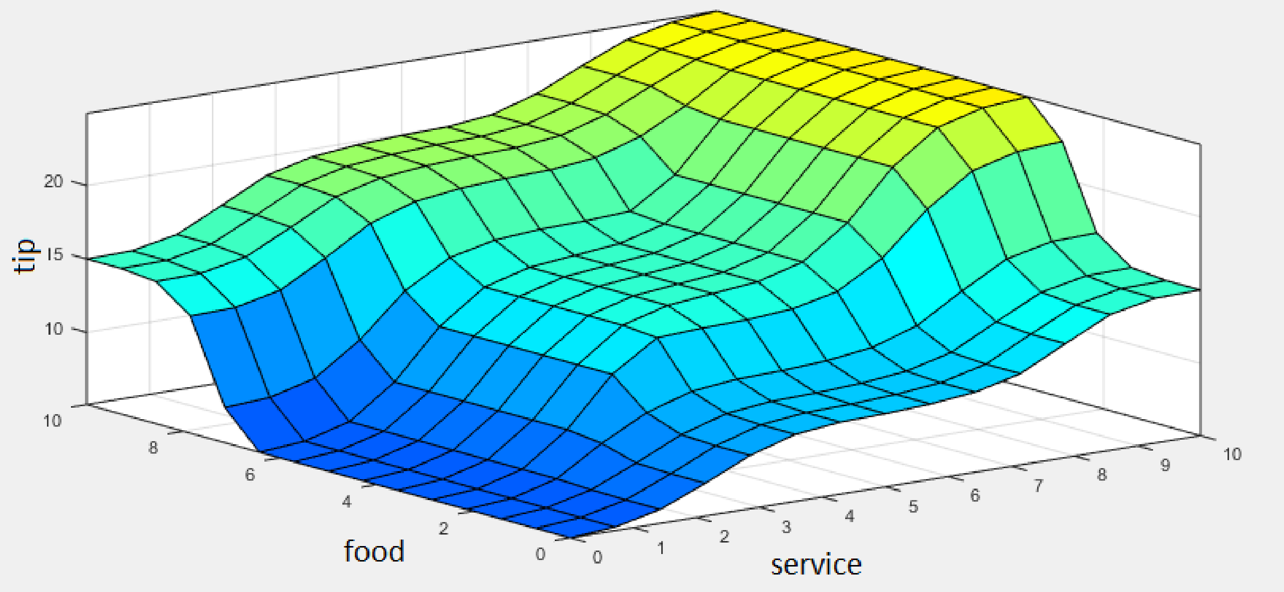


Figure 30: Example problem fuzzy logic - solution domain

Claimed advantages by using fuzzy logic are as follows [120], [121]:

- Suitability for control systems working under multiple and shifting operation conditions
- Flexibility
- Toleration of imprecise data

- Intuitiveness, by building on natural language and communication forms
- Well designed for incorporation expert experience
- Able of modeling nonlinear functions, regardless of complexity
- Can be integrated with conventional control systems
- Instead of devices running in on/off mode, they can be run in part load, which is beneficial for some devices and opens up a variety of new possibilities.

Disadvantages with this control structure are claimed to be [123]:

- Manual tuning and time consuming re-tuning when the system is modified
- Intuitive design may not clearly outperform well tuned systems of other control structures
- Dimensionality. It is hard to use more than three input variables without distorting interpretability for the end user.
- Availability. For a centralized controller topology, the system will stop working for a fault in the controller.

6.3.3 Optimized Scheduling

In order to do power control in an optimal way, optimization techniques may be applied [23]. Peak shaving and load shifting will follow the same principle for thermal and electrical storage systems, although they are designed for different application areas. Bao et al. suggests load shifting by control based on real time load forecast and dynamic programming for load shifting with batteries [23]. Chunchun and Wei suggest a similar approach for load shifting a cooling aplication by a PCM thermal storage [21]. Based on these sources, the principle algorithm for a day ahead optimization model with real time correction includes the following:

1. Collection of input variables relevant to forecasting. Examples include historical load and local generation data and variables which are expected to affect them, like temperature, season, hour of the day, etc. The performance on the load shifting will depend on realistic input data for such an optimization model.
2. Load and generation curve forecasting.
3. Day ahead optimization based on day ahead forecasted data
4. Real time monitoring of data for real time correction of the optimization models. Real time correction is argued to be a flexible solution as the optimization model is able to take in any deviation from forecasted values and automatically update the control strategy according to the goal and constraints in the optimization model.

The performance on the load shifting will depend on realistic input data, as previously discussed in Section 6.2.2 and 6.2.3. An example scheme of an optimized control system strategy is viewed in Figure 31 [23]. The battery can in this context be understood as either electrical or thermal storage.

Generally, scheduling is optimized for an expected operation scenario, which is built on predictions and forecasts which will sometimes deviate from real life behavior. Especially, deviations from forecasts should be expected from hard-to-predict-sources like solar and load variations which depend on human behavior. A key question when performing such optimization techniques is how to handle the uncertainty. The accepted uncertainty will also form guidelines for the chosen time frame. Ottesen and Tomasgard suggest three alternatives to deal with the forecasting problem. One alternative is a deterministic planning, where daily forecasts are applied. In this scenario, forecast values are chosen every 24 hours. Real time electricity prices are published by Nord Pool Spot on a daily basis, and are certain one day ahead [41]. However, weather forecasts which will influence renewable DG, like insolation and wind speed, and load forecasting

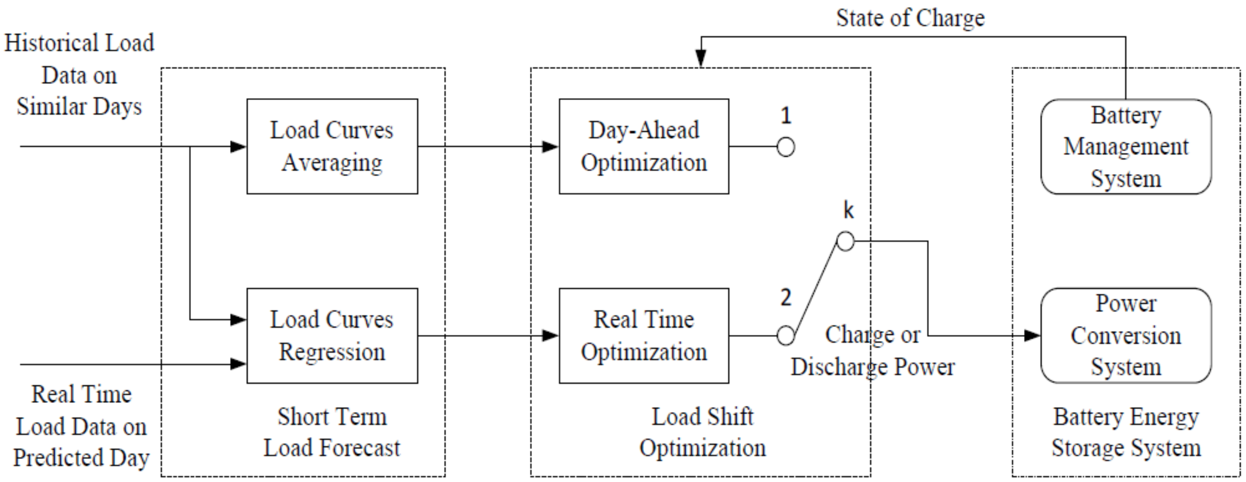


Figure 31: Example of load shifting control strategy

with a 24 hour time frame also embed uncertainty. To further reduce the gap between forecasted and real time values, deterministic planning with a rolling horizon can be used. For this structure, the optimization model is updated more frequently, for instance every time a new forecasting report is received. A third alternative is rolling horizon stochastic planning, where different scenarios and their probabilities are included in the model, as opposed to the deterministic planning where only one scenario is determined. This gives a larger flexibility in adapting to real time changes, and may give added value depending on the real time behavior. For optimized control of slow systems like the schedueling of an ice bank storage, Chunchun claims that hourly updates of the optimization model is sufficiently fast to accomplish real time control [21]. In a microgrid case where fast speed control of frequency and voltage is applied, and the optimized scheduling deviates from real time values, Hong et al. suggests that real time automated control should overrule the set points provided by the optimization model [99].

6.3.4 Multi-Agent Systems

"Multi-agent systems (MAS) consist of multiple intelligent agents which interact to solve problems which may be beyond the capabilities of a single agent or system" [15]. Agents are a well known term in software engineering, and represent distributed artificial intelligence in the system [13]. MAS follows a "bottom up"-strategy, as opposed to the traditional "top-down" strategy by a central deterministic design [14].

Multi-Agent systems have already been implemented on the grid side in a centralized grid topology for modeling electricity markets, grid protection, fault restoration and grid control. With increased use of smart grid topologies, including microgrids, DG and a two way flow of information and energy flows, larger requirements on operation and control are included in the consumers and distribution system. Because of its ability to handle large and complex systems, MAS has in recent years been suggested for operation and control of microgrid applications [15]. "Throughout the literature, one of the most popular ways to enable decentralized control systems is by MAS. Its capacity to tackle complex problems, based on cooperation, coordination and negotiation of individual units, called agents, has been highlighted in different research works" [12].

MAS concepts and architecture
In its simplest form and at the lowest hierarchical level, an agent behaves like an ordinary sensor in a control system. It contains a sensor which monitors an environment, and reacts to changes in environment by generating an action output according to pre-programmed goals, as shown in Figure 32. Properties embedded in an agent is [15], [12]:

- Autonomous: Agents are programmed to have ownership over their tasks, and seek to influence so as to reach goals without the interaction of humans or external devices
- Social: Agents are able to communicate, interact and negotiate with other agents.
- Reactive: Agents have the ability to react and respond to sensed changes in their environment.
- Proactive: Agents take initiatives according to a programmed set of tendencies, so as to actively reach their goals.

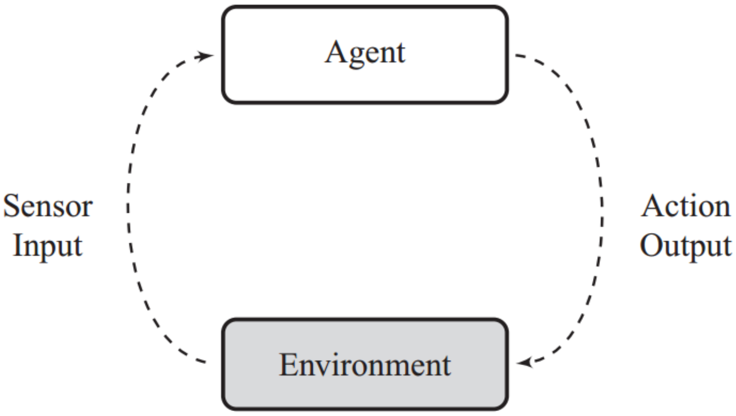


Figure 32: Simple agent acting in an environment

By its nature, MAS is a way of decomposing the larger and complex problems and systems into series of subproblems and subsystems which are able to intellectually interact as to pursue the global goal. When organizing agents in systems, each of the agents have assigned goals, responsibilities, available actions and a given range of knowledge to be equipped for their tasks. Each agent tries to maximize its assigned goal, and at the same time work together in order to reach a global goal without opposing the constraints imposed on each agent.

There are many suggested topologies for agent systems. Agent roles in each of the mainly used topologies are [15], [12]:

- Centralized: Agents are controlled by a central agent by master/slave relationships with one way communication and influence.
- Distributed: In a distributed (flat) structure, each agent has only partly control and knowledge of the total system. They share and solve global tasks together by sharing information and negotiating, through a request and response system.
- Hierarchical: In a hierarchical system, some agents have authority over others. Typically, these agents handle larger amounts of data and have knowledge about a larger part of the system than the agents in the lower layer. The higher the agent is in the hierarchy, the more critical their tasks are. They can accept or deny requests and impose forced actions on the lower agents, in order to reach global goals.

A simple example of how a desentralized system can be set up is viewed in Figure 33 [14]. In the example, a PV module, a battery, a super capacitor and the grid are connected to a DC bus which is to be kept voltage stable. In this distributed (flat) structure, each agent controls one element. The responsibility for keeping the voltage stable on the DC bus, is owned by the agent which at any time holds a virtual, tradable token. They can also shift between current and voltage control, if it benefits the system at the given time. One operation scenario may be that the the super capacitor holds the token, and consequently controls the bus voltage. When its SOC declines to a given level, it may request that the battery takes over voltage control. If the battery agent has sufficient SOC, it will accept the request. Reliability increases in such a scheme, as it is sufficient when one element in the total system is able to keep the voltage stable at the bus at any given time. Components can be removed/added from the system without the need of reprogramming the rest of the components, which is beneficial for scalability and flexibility.

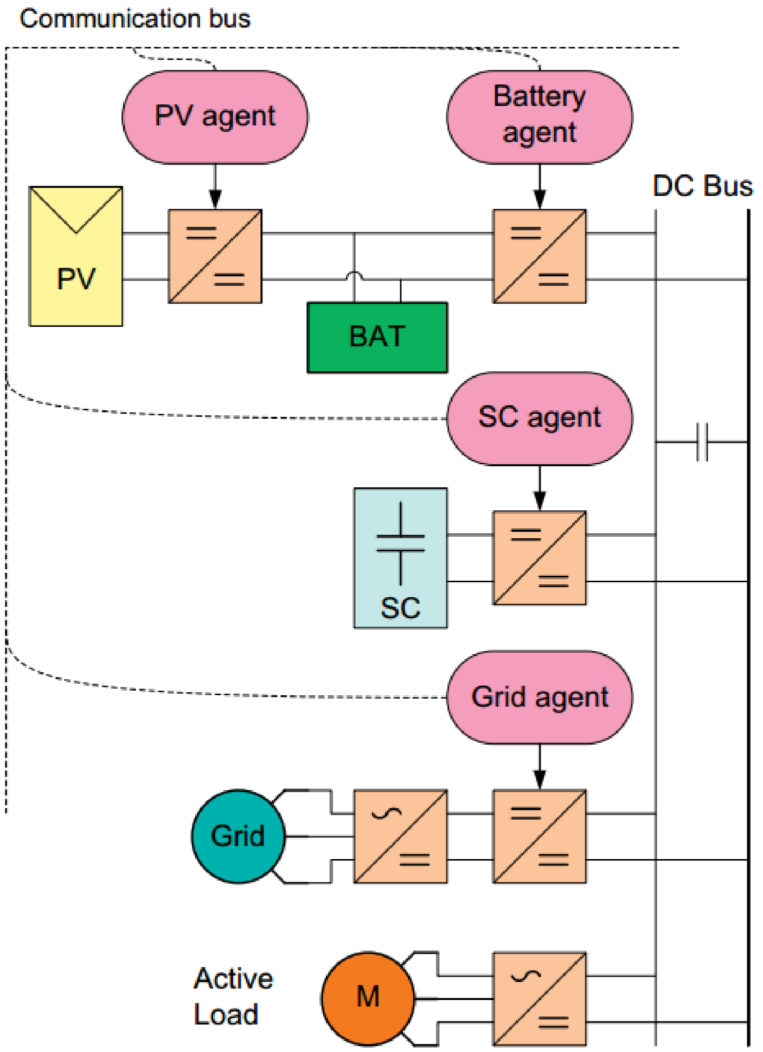


Figure 33: DC microgrid system applying multi-agent control structure

Software Platforms Generally, the design of MAS systems in software platforms consists of four main stages [15]:

1. "Analysis: Modeling agent roles and behaviors. Identifying the application domain and problem.
2. Design: Defining solution architectures for problems identified in the analysis step
3. Development: Programming agent goals, ontology and functionality
4. Deployment: Launching generated MAS, run-time agent management, message passing and data processing".

Existing software platforms for designing MAS systems include JADE, ZEUS and VOLTTRON, which are designed for different core applications. VOLTTRON is presented further, due to its ideal application being in the field of BEMS/BAS [15]. VOLTTRON is the result of a desire to combine BAS and smart grid control. It is developed at the Pacific Northwest National Laboratory, as a part of the Future Power Grid Initiative as an open source software platform, which is freely available on the web. It supports programming of many functions desired for grid ancillary services and load control, including applications viewed in Figure 34 [99], [124]. The VOLTTRON software contains drivers for communication with most Modbus and BACnet systems, which are examples of common communication protocols [125], [15]. VOLTTRON is built up as a three layer hierarchical system, each layer containing specific agent classes [15]:

- "Cloud agent: Publishing data to and from a remote platform.
- Control agent: Interact with devices.
- Passive agent: Interact with sensors and record data".

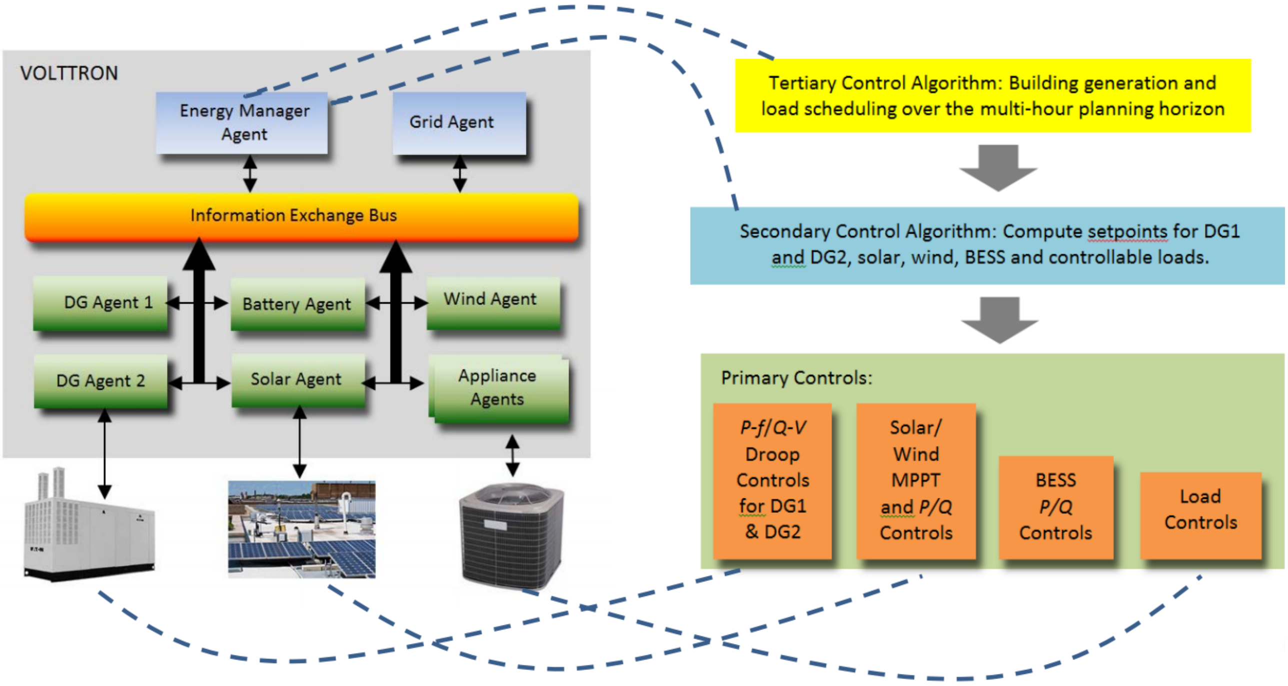


Figure 34: Example of VOLTTRON EMS system topology

Pros and Cons

A MAS is claimed to have the following advantages [126], [14], [15]:

- When programming a MAS, each component can be controlled independently. This allows the designer to focus on management on only one element at the time and focus on the problems and limitations of each individual component, instead of having to deal with the whole system simultaneously. Thus, this structure offers a simpler design process with a high degree of flexibility and reliability. The overall system will still work because of the dialogue and cooperation between the agents. Also, the system can be extended with extra components without needing the reprogramming of the whole system.
- Because of the opportunity to shift responsibilities and control modes, there will be a fault tolerance for the components. This will give higher reliability, compared to everything depending on the functionality of a central controller.
- MAS is in its nature built up as a distributed architecture with local information and decision making, which is a good match with microgrids and distributed generation control.

There are also some challenges related to the MAS approach. A 2005 study points at challenges regarding the coordination between the agents, some of them being [126], [15]:

- Delay in communication between the tokens
- The possibility of disturbed communication links between the agents
- Relative information uncertainty. The different agents may have access to different data, which may create an unbalanced ability to resonate well among the agents. Applying weighting is a way to deal with this issue.

- The study on agent behavior during emergent behavior can not always be predetermined, which might lead to unpredictable outcomes
- Most current MAS control implementations are software based. To implement them with hardware system has not yet been subject to widely testing.
- The increase in computational power allows researchers to model larger systems than before. The agent behavior when the systems include many layers and agent types is still a field of research and is not yet well understood.
- When implementing smart grid technology which is autonomous, new challenges arise regarding cyber security

6.4 BAS Communication

Control devices of the various technical installations in a commercial building may come from different manufacturers with different communication setups. To avoid that each technical installation works independently of each other, with their own cabling, monitoring etc, all technical equipment can be integrated to a common communication channel in a BAS system. "The fundamental idea is to manufacture control devices which talk in an identical and universal language regardless of the brand and model of each device" [121]. This is made possible through the use of standardized protocols, which can be understood as communication languages.

There are various communication protocols available for use in Building Automation Systems (BAS). Statsbygg, who is one of the leading players in determining standards in Norwegian commercial buildings, prefers BACnet, KNX, M-BUS, ModBus RTU, LON over TCP/IP, which are considered recognized and open protocols [127]. In addition to the internal BAS communication over the system protocol, a web communication layer, sometimes called IP/Management layer, may be added to allow communication with the outside world over the web. Through wifi connections, the web layer may also facilitate monitoring and control for laptops and smart phones by system managers and other users [106].

Typically in Norway for BAS systems in larger buildings, bus-technology is used as a common control and communication network [127]. The bus is a communication channel, which can be either wired or wireless, and the communication network can, depending on the manufacturer, be build on various topologies. The communication messages between the devices are preferably sent according to a common system protocol. Different protocols can be used in a common BAS, by utilizing gateways for translation purposes [106].

7 Power Control Systems

In this section, examples of power control systems building on the power control structures and tools discussed in Section 6 are presented. At first, a general BAS architecture and how it is set up for KIWI Dalgård, is presented. When describing the systems, emphasis is not put on total system descriptions, but on their principle differences, as they provide alternatives for the case study. In the end, a suggested control strategy for the case study is selected.

When discussing power control systems, it is important to be clear about the time horizon which is to be used. In this study, a division is made between real time systems and optimized scheduling systems. A real time system only reacts to real time inputs, and contains no time horizon structure. An optimized scheduling system bases its scheduling on forecasts with a certain time horizon. It is evident that an optimized scheduling system will perform better that a real time control system due to its future insight and its mathematical setup based on optimizing algorithms, however a real time system is less complex, requires much less input and is much cheaper to install [128]. The cost by upgrading to an optimized scheduling system needs to be justified by the added value, and consequently a market will probably be present for both control structures. The selection of power control systems in this section aims to cover both of these basic structures to provide alternatives for use in the case study. The discussed control strategies in Section 6 were deterministic rule, fuzzy logic, optimized scheduling and MAS. By their setup, deterministic rule and fuzzy logic were described as real time control systems, while MAS were described more like a BAS architecture suitable for both real time and optimized scheduling applications. MASs are consequently described for both of the mentioned applications. The deterministic control schemes are mainly included because they represent a very simple and conventional control structure which makes up a comparison basis for the smart power control systems in focus.

7.1 BAS - the Base Architecture

The suggested control systems in this section are not meant to replace the energy management network and the already embedded logic offered by a conventional BAS, when not stating otherwise. On the contrary, they are thought to integrate into it by adding some extra functionalities and utilize the existing communication network. When discussing the alternative control strategies, weight is put on how they can adapt to the existing BAS framework. Firstly, a general BAS framework is described, before the existing setup at KIWI Dalgård and how it may interact with external power control systems is described.

The base architecture for automated power control in buildings, which the suggested power control systems will be adapted to, is the building automation system (BAS). A short and general introduction to BAS will therefore be offered. BASs may be considered the heart of an intelligent building. Generally, it integrates the control systems of the HVAC, lighting, elevator, fire and security into a common automation and communication platform [121]. A principle view of a BAS architecture for the load and generation elements suggested for the case study is depicted in Figure 35. The architecture is layer based. As explained in Section 6.4, the controllers, sensors and meters are all assumed to communicate through an open information network (bus-system), which might be wired or wireless, and in a common language (protocol). The components in the system which are subject to measurements or control are placed in the component layer. The controllers and devices which are monitoring and/or controlling the components, are located in the control layer. Examples of this are the PV inverter which maximizes PV generation by MPPT tracking, the cooling case valves which keep the cooling cases at the set point temperature, and the ventilation units which control air supply rate and temperature. Such internal control of each subsystem will in this study be called primary control. The web based communication occurs on the open IP layer. Through wifi connections, the system may also be monitored, controlled and designed on laptops and smart phones by system managers through this information layer. The building automation layer may contain a centralized control logic platform with embedded logic, which states how the various devices connected to the common network are supposed to interact to obtain a goal. A typical goal of building automation systems is to obtain comfort/desired operation by using as little energy as possible [106]. The logic may be deterministic, of which

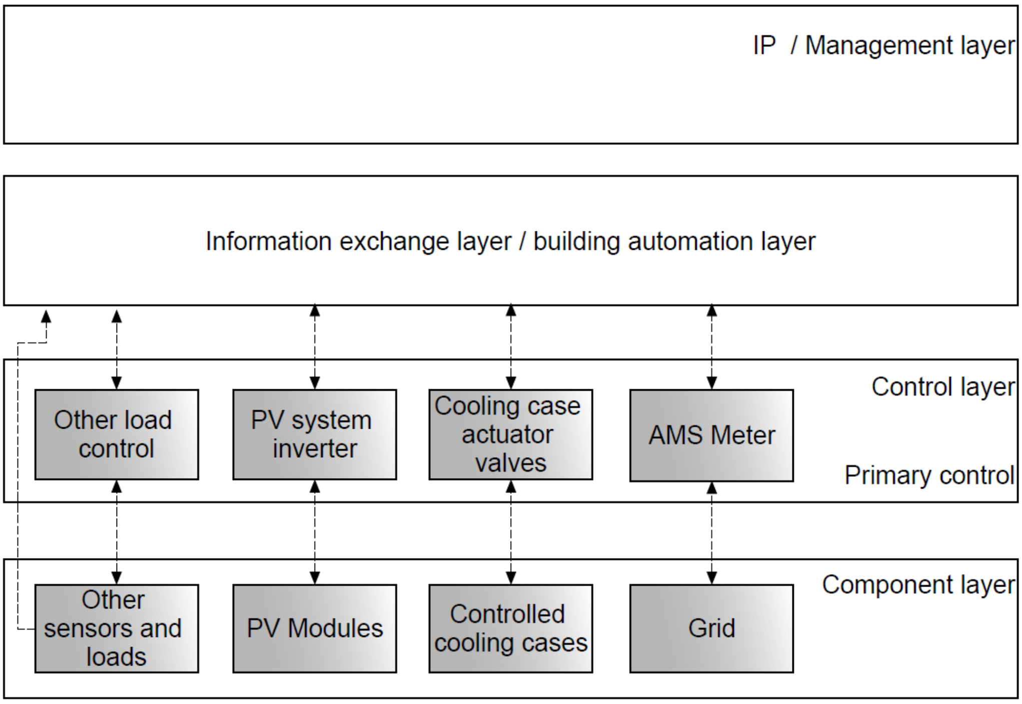


Figure 35: BAS Basic architecture

an example might be "If no one is present, then turn off lights and the radiator in the break room". The generated output from the logic rules generally needs to be communicated to the various devices over the system protocol. The logic type and platform used may also be different, of which examples are described among the intelligent system examples of this section.

Information regarding how the BAS is set up at KIWI Dalgård and how smart power control may be integrated, is made using conversations with key KIWI personnel as source [29]. The communication network of the existing BAS at KIWI Dalgård is set up similarly to what is viewed in Figure 35. A wide range of inputs from sensors and energy measurement devices are communicated via the commmuncation network to the management layer, where it is monitored by a software called IWMAC. IWMAC acts as a central unit for monitoring, communication and control in the system. The applied protocol for field communication is Modbus, and external communication is web based. The communication network connects all of the load, generation and sensor elements, and allows for multi-directional communication. Regarding control, KIWI Dalgård shows a deviation from how Figure 35 was described. Control algorithms are not set up in the centralized building automation layer for various interaction among load and generation components. The selected components that are subject to interactive control are the cooling machine, the heating system and the ventilation system. The simple, deterministic logic used for interactive control among these components are programmed directly into their regulators, thus a decentralized control scheme is used. However, the chosen regulators allow being subject to external control by received set points. Consequently, in the existing BAS frame, external control of these systems by adjusting their set points in the management software IWMAC is possible.

The existing BAS setup described for KIWI Dalgård may be utilized when adding a smart power control system. By connecting to the communication network, all monitored data that is required from within the building may be read from a single point. Also, the needed web-based input regarding forecasts may be set up by adding them to the existing IP layer communication framework. The output of the suggested smart power control system are set points. In the same way as the regulators may receive external set points form IWMAC, it may receive external inputs from the suggested power control systems. The communication between a smart power control system and the building installations should be distributed via the centralized communication network provided by IWMAC, due to its already embedded communication on the correct protocols with each device.

7.2 Deterministic Control Schemes

To make relevant examples of conventional deterministic control schemes for peak shaving, load shifting and PV self-consumption in the Norwegian market today, conversations with Norwegian building automation advisors and entrepreneurs have been used as source [129], [106].

Among relevant conventional techniques for control based on deterministic rules are:

- Mode control. If consumption exceeds a prescribed limit, a battery discharge mode is activated to shave peak. The discharge might be to a certain SOC level, and prescribed algorithms may tell when and at what speed the battery should recharge. Likewise, battery charge mode may be activated when P_{export} exceeds zero due to PV generation, until the battery is fully charged.
- Set point control. By set point control, the flexibility of a thermal system or a thermal storage is utilized. For example, load consumption may be increased by lowering the set point temperature of a cooling circuit by a couple of degrees if P_{export} exceeds zero.
- Time based control. Control based on predetermined time sets. For instance, a water heater may be heated at night to avoid the morning peak.
- Forecast based control. Forecast control may be made in combination with time based control. For instance, if a sunny day is forecasted, and it is summer time, the battery is discharged a day ahead. Forecasting values may be utilized in conventional real time systems by being fed in the same way as an ordinary real time sensor value.
- On/off control. An example is load shedding of slow thermal loads or dispensable loads by turning off a load switch if consumption exceeds a prescribed limit.
- Control by graphical relationships. For example, a heating system might be fed with settings as a function of outdoor temperature, by a $P_{heat} = f(Temperature)$ relationship. An output value might also be set up to be dependent on linear relationships with a multiple of input factors.

7.3 Fuzzy Logic Based Systems

A relevant fuzzy logic control application in supermarkets is proposed by Zhang et al. [16]. The goal of the system was to reduce the peak imports from the grid and to increase the utilization of local PV generation. Ancillary services to the grid were not a motive, focus was on utilizing local renewable generation, reducing electricity cost and avoiding interrupting of services. A battery was used for peak shaving and valley filling so that loads were unaffected. A simplified system topology is viewed in Figure 71 in Appendix E. To ensure battery availability throughout the day, different fuzzy rule bases were applied in different periods. The different modes were as follows:

1. Peak power period mode: For this mode, the fuzzy rule base objectives were limiting peak power consumption. The mode was recognized by the active discharge of the battery when approaching limits. The peak power period mode covered in the middle of the day, when PV generation was also on top. Fuzzy rules were added for active self-consumption of PV excess energy.
2. Shoulder period mode: Two shoulder periods were used, one before the peak period and one after. In the shoulder period before the peak power period, energy availability was weighted highly in the fuzzy rule base. In the shoulder period after the peak power period, the battery continued to maintain its control of peak power consumption and PV self-consumption, although small requirements were expected.
3. Off peak period mode. In the off peak period, the battery was actively charged for being ready for the next day. When large PV generation was expected by forecasting, charging was put on hold.

A result of system performance is viewed in Figure 72 in Appendix E. For the studied case, the control system was able to shave peak power consumption by 30 %, both in a one week, one month and one year basis [16].

7.4 Centralized Optimized Scheduling Systems

Ottesen and Tomasgard suggest a method for scheduling energy flexibility in buildings, based on a real time electricity pricing scheme and peak power tariffs [24]. The optimization technique used was mixed integer linear programming, which facilitated the use of linear constraints and binary variables. The model was also taking into account the possible interaction between electrical and thermal systems. The optimizing model was made to minimize costs and constraints imposed by each participating component and the physical laws of the system, so that an optimum may be found without violating any constraints. The model is flexible so as to include various sources of DG, import, storage units and DSM strategies. The objective function which was to be minimized, when excluding the stochastic variables, is given by Equation (12).

$$\begin{aligned} min \sum_{a\in A}\sum_{t\in T} P_{a,t}^{import}\chi_{a,t}^{import} + \sum_{a\in A} P_a^{peak}\chi_{a,t}^{peak} + \sum_{o\in O}\sum_{y\in Y}\sum_{t\in T} G_{o,y}^{startup}\alpha_{a,t}^{start} + \sum_{d\in D^c}\sum_{y\in Y}\sum_{t\in T} X_{d,y}\varphi_{d,y,t} \\ - \sum_{a\in A}\sum_{t\in T} P_{a,t}^{sales}\chi_{a,t}^{export} \end{aligned} \tag{12}$$

Where

- $P_{a,t,s}^{energy}, P^{peak}$ and $P_{a,t}^{sales}$ are the prices of energy import, peak power and energy sales respectively, for energy carrier a and period t.
- $\chi_{a,t}^{import}, \chi_a^{peak}$ and $\chi_{a,t}^{export}$ are energy flows of import, peak power and export, respectively
- $G^{startup}$ is the startup cost of generation
- $\alpha_{a,t}^{start}$ is a dummy binary variable for turning on/off generation of energy carrier at time t
- X and φ are related to the cost and amount of load curtailing

A case study was conducted for a Norwegian university college building for the month of January 2013. The model was run as a deterministic model with daily forecasts, and the strategy was claimed to reduce the monthly cost by 12 % compared to a case where no flexibility was used. Most of the savings were due to peak power mitigation [24].

7.5 Multi-Agent Based Systems

7.5.1 Real Time Control Systems

MAS platform for general building automation control

Hurtado et al. [12] proposes to use a MAS platform for general load control in commercial buildings, as a replacement for other types of logic in the automation layer. The goal of the proposed system was to maximize experienced indoor comfort by controlling the HVAC systems. A three-layer hierarchical strategy was chosen for indoor quality control of respectively the total building, building zones and building rooms, as viewed in Figure 36. The agents make decisions based on a fuzzy rule base, telling how the volumetric flows of air should be regulated to enhance comfort. The fuzzy rule based controllers were designed with two inputs, which were the error and change in error between an input signal and a reference value. In this case, the error was the deviation between the input value and the set point for optimal comfort experience according to comfort science. The fuzzy logic controller was set up according to the following rules [12]:

1. IF the error is negative (comfort output above the set points), AND the change of error is negative (in the previous step the controller was driving the system output upwards), THEN the controller should turn its output downwards, i.e. reduce volumetric flows. Considering a negative feedback, this means a positive control action.
2. IF the error is positive (comfort output below the set points), AND the change of error is positive (in the previous step the controller was driving the system output downwards), THEN the controller

should turn its output upwards, i.e. increase volumetric flows. Considering a negative feedback, this means a negative control action.

3. IF the error is positive, AND the change of error is negative, THEN the controller does not need to take any further action.
4. IF the error is negative, AND the change of error is positive, THEN the controller does not need to take any further action.

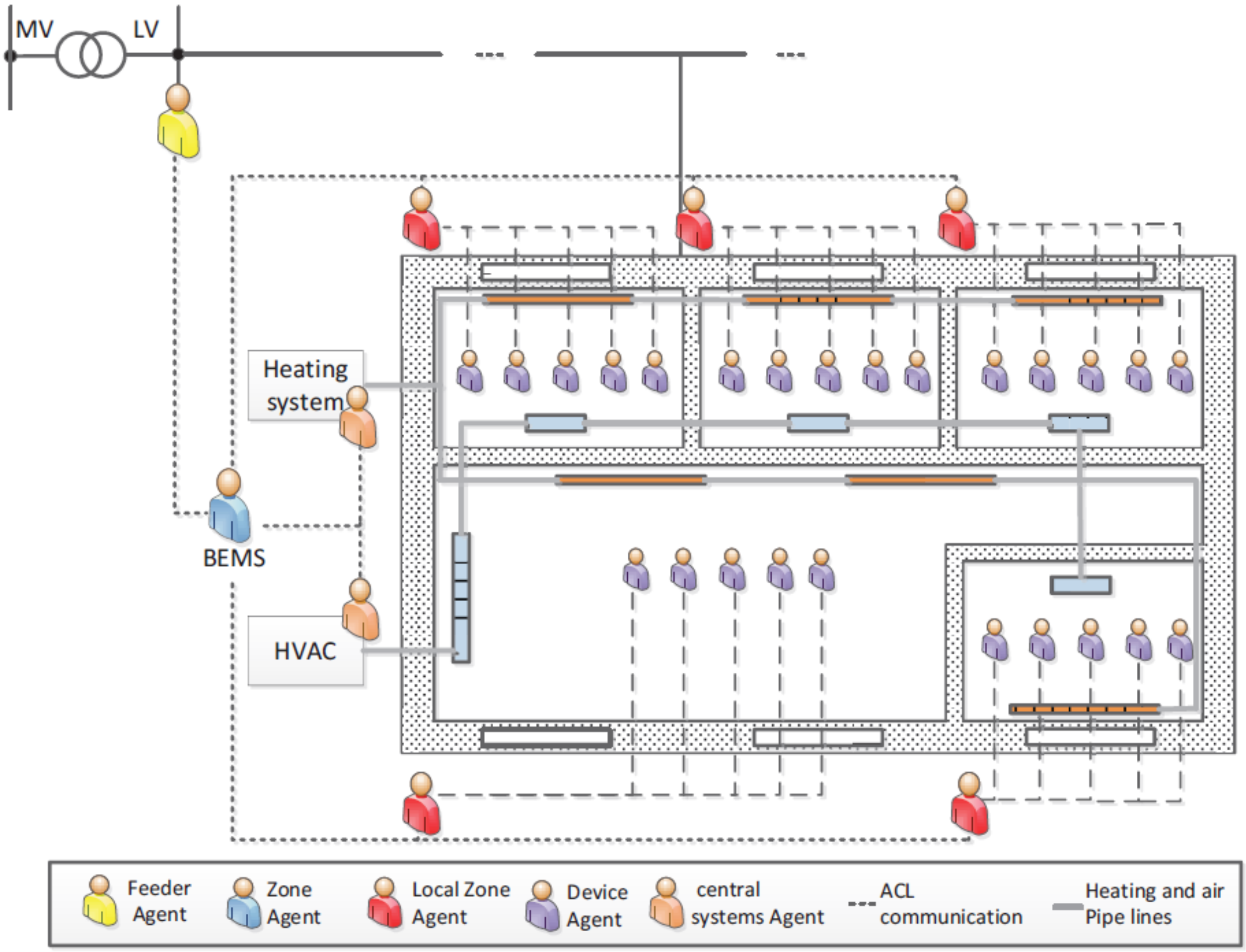


Figure 36: Overview, three-layer hierarchical multi-agent structure

The comfort level obtained compared to a no-control scheme are depicted in Figure 73 in Appendix E. Comfort was the goal, and the simulation only detected people between 8 am and 5 pm. When people were not present, the control was consequently down to a minimum to save energy costs.

7.5.2 Optimized Scheduling Systems

Total microgrid control with optimized scheduling in a MAS framework

Hong et al. [99] proposes an energy scheduling algorithm based on a the MAS based platform VOLTRRON, which is tailored for small- to medium size commercial building microgrids. The idea was to integrate the operation of traditional BAS control, DG control and microgrid physical constraints into one common power control system.

A hierarchical three-layer control strategy was suggested, based on the time perspective of the control, of which an overview is given in Figure 34. Primary control is local control of the generation, load and storage sources. The local controllers, such as a battery control system, have the ability to receive and respond to updated set point values by external sources. Secondary control are the computed set points based on the optimization model used by the tertiary control. The tertiary control algorithm is based on optimized energy scheduling with a longer time horizon based on mixed-integer programming (MIP). The suggested objective function was to maximize total welfare or to minimize cost, taking the various constraints of the system into account. The control system suggested by Hong et al. is highly advanced. The tertiary control constraints have taken into account the energy flow and the voltage and frequency quality requirements both in an economic mode and in an islanded/emergency mode. It is also able to handle various DG units of different types [99]. It is however also possible to simplify the constraints when there are less requirements and complexity embedded in the system.

The system was built up as a multi-agent system built on the open software VOLTTRON platform, which is further explained in Section 6.3.4. The primary controllers are represented with agents, which are the communication link between the primary controllers and the other layers. Both the secondary and tertiary control layer are implemented in agents, which are providing bi-directional communication with the other agents in the system and making decisions regarding energy management. "During the energy planning of the tertiary control, the device agents submit electronic bids which represent both the prices and capacities for which they are willing to produce or consume energy. The energy manager agent then clears the bids through executing a central energy scheduling algorithm and informs the device agents on the resultant energy schedules" [99].

BEMOSS - A MAS framework tailored for building automation control

VOLTTRON is an open source software platform, on which specific applications and setups can be built according to system specific interests. An example of a system which is built on the VOLTTRON platform is the Building Energy Management Open Source Software (BEMOSS) platform. Its software architecture is viewed in Figure 37 and shows intuitively how the applications are built on the VOLTTRON open software, and how it communicates both with local technical equipment and external communication and monitoring with the smart grid and other sources [130].

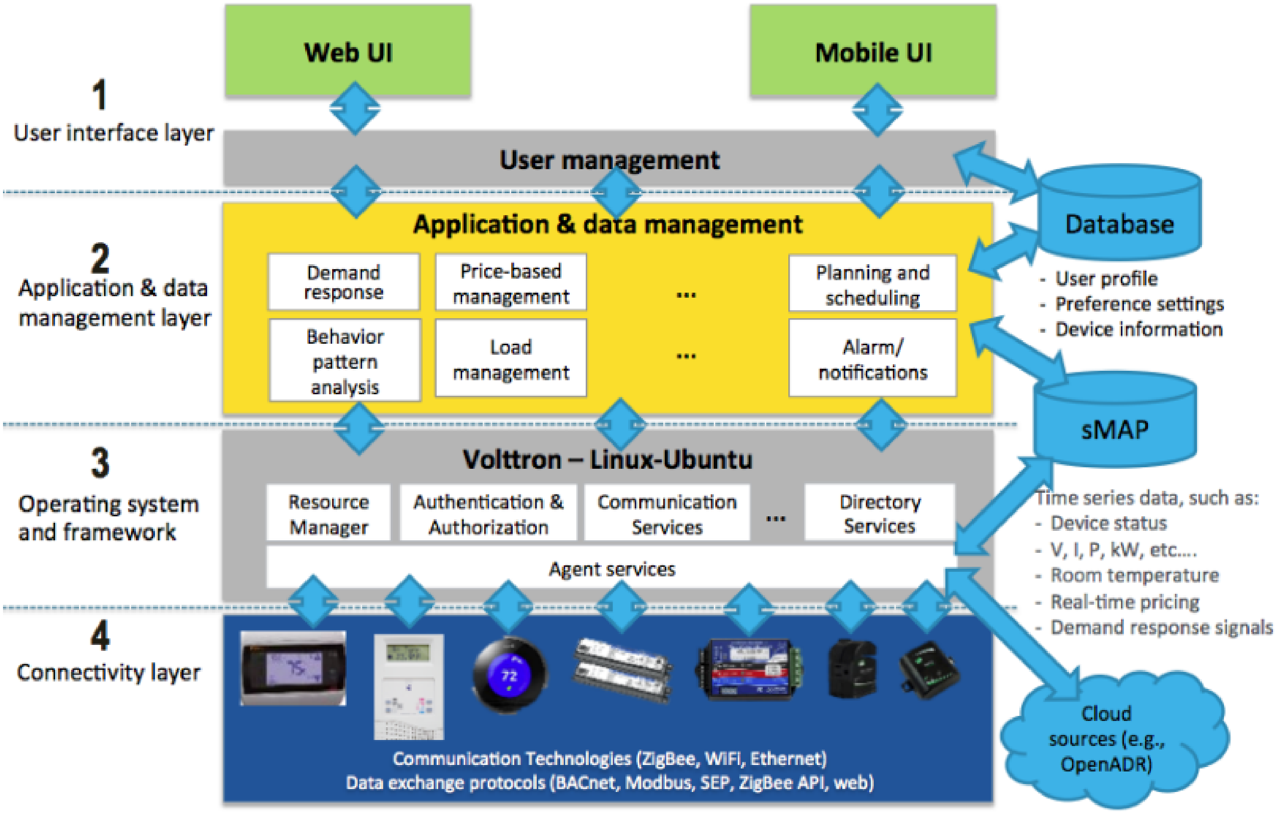


Figure 37: BEMOSS architecture

The BEMOSS system is aimed for usage in commercial buildings in small- and medium sized commercial buildings up to 5 000 m^2, to make automated systems more attractive and affordable in a segment where traditional BAS buildups often have been considered to costly and thus been neglected by building owners. To facilitate intelligent control, its data acquisition is based on a time-series model, where inputs are continuously collected with time. Therefore, it has to be equipped with a powerful time-series database able to handle big data. It is designed for controlling HVAC, lighting and plug in loads, and supports the protocols viewed in Figure 74 in Appendix E. The development is on an early stage. Further system development plans include offering "scalability, robustness, plug and play, open protocol, interoperability, cost-effectiveness as well as local and remote monitoring" [130]. Some of the most important agent types utilized in the BEMOSS system are [130]:

- "Discovery agent: This agent searches for a new device which can be detected by BEMOSS, identifies device model, classifies device type, and specifies appropriate API class for a device. Discovery agent also instantiates a suitable control agent for each device.
- Control agents: Control agents include thermostat agents, lighting load agents and plug load agents. These agents are generated automatically to monitor, communicate and control hardware devices after they were discovered by the Discovery agent.
- Database agent: This agent communicates and interfaces with the database to store time-series data and with the relational database to store metadata.
- OpenADR agent: This agent receives demand response request from a utility or an aggregator through a web service in the cloud. It then notifies selected agents of a DR event.
- Demand response agent: This agent communicates and coordinates with control agents. This is to reduce peak demand consumption during a certain period, according to the price signal or the demand reduction signal received from the OpenADR agent".

7.6 Choice of System for Case Study Simulations

The choice of smart power control strategy to be used in the case study should be based on the net added value which will be added to the system. The cost of implementing and operating a power control system needs to be balanced with the obtained savings. To justify the use of larger and more complex systems, the added value should be significant. To form a decision basis, the choice has been made to do case study simulations for more than one of the suggested power control schemes. To cover the main categories of smart power control systems suggested in this study, two main strategies are chosen to be compared for the case study:

1. A real time control system based on fuzzy logic
2. An optimized scheduling system which is real time updated

The two principle strategies are expected to be quite representative for most of the systems which are discussed in this study. A deterministic rule based system is, when thoroughly made, believed to approach the fuzzy logic real time control. According to Section 7.2, there are conventional control systems based on deterministic rule which utilize 2D-function relationships between input and output exogenous variables. In sum, well tuning of various 2D-relationships is believed to approach the 3D-relationships designed in a Mamdani based fuzzy logic controller. Also, an optimized scheduling system can be accomplished by different control strategies and prediction methods, like multivariate regression or machine learning. The MAS which was found in the research literature assumes that all the interactive control among the devices is built as a MAS framework, which would conflict with the assumed existing installation at KIWI Dalgård. Previously mentioned, the only installations participating in interactive control are the cooling system, the heating system and the ventilation system, and their internal control logic are already embedded in their regulators. Hence, the choice has been made not to do case study simulations for the MAS framework. However, the MAS framework allows for control based on fuzzy rules and optimized dispatch, and the conducted simulations are therefore believed to form a discussion basis for how a MAS would perform for KIWI Dalgård. The discussion section also opens up for evaluating the suitability of other described power control strategies.

8 Case Study Total System Simulations

The goal stated in Section 1.2, was "to design a model of a supermarket power control system well suited for mitigating electricity costs and increasing the utilization of locally generated PV electricity". In this section, the various choices and results obtained by studying the power control subsystems are assembled into the smart power control systems which are to be studied. The section also describes the modeling of the fuzzy logic control system and the optimized scheduling system which were chosen for case study simulations.

The control objectives and components participating in the selected power control systems have already been decided. In Section 2, case study load data was obtained from reference installations and converted to expected values for KIWI Dalgård for the period May 2016 to May 2017. Section 3 described the setup of the electricity bill, that an hourly spot electricing scheme was chosen for the case study simulations, and that the business cases of peak shaving, load shifting based on hourly prices and PV self-consumption were chosen. A full year of hourly PV generation values was obtained in Section 4, based on a designed PV system sized to cover the area set aside in the project planning documents of KIWI Dalgård. In Section 5.3, a 10 kW and 52 kWh thermal PCM storage, distributed on 14 PCM integrated cooling cases, was chosen as the most relevant storage solution for KIWI Dalgård. It was believed to fulfill the requirements of low installation cost, large efficiency and low cycle cost to the largest the degree, which was particularly important due to the low potential savings by smart power control which were identified for KIWI Dalgård.

For each selected system, simulations are conducted for a full year of expected operation at KIWI Dalgård, and results are presented with hourly resolutions. In the end, sensitivity and scenario analysis will be added to the results, to indicate the change of performance when some key inputs are modified, and form a basis for further discussion. For all conducted simulations, results will be compared with the base case to highlight their added value. The base case is defined as operating KIWI Dalgård without applying storage and smart power control.

8.1 Design of Optimized Scheduling System

In this section, a system design is proposed and simulations are conducted for an optimized scheduling power control system for KIWI Dalgård. The following control objectives are selected:

- Peak shaving
- PV self-consumption
- Load shifting from high price periods to low price periods

8.1.1 Suggested System Topology

The suggested system topology is viewed in Figure 38. For the sake of transparency and understanding, the components active in the smart power control system are explicitly displayed, and the interface with the rest of the BAS framework is included in the model. A lot of inputs are needed in the optimization algorithms. Information internally available in the BAS framework, like load consumption PV generation and SOC of storage, are set up as input to the system. It was described in Section 7.1 how the BAS framework of KIWI Dalgård was built up, and how the suggested smart power control structures may integrate in the framework to access information and send control signals to field devices. Information needed from the web, like forecasting services, are collected in the IP layer by agreements made with information suppliers. It is not assumed that the existing BAS framework includes optimized scheduling software. Consequently, the optimization model is assumed to be made in an independent, appropriate software, and placed in the IP layer. Due to the optimized scheduling system adding logic to the BAS, it was chosen to call this layer for the IP/Logic/Management layer. The power control system exercises both tertiary and secondary control. The tertiary and secondary control terms are the same as for the VOLTTRON system depicted in Figure 34: Tertiary control is the scheduling process, and the secondary control computes set points based on the optimized scheduling, which is sent to the cooling case actuator valves in the control layer. The set points are sent via the communication hub IWMAC, which just repeats/translates the signal so that it is understood by the valves controlling the storage cases.

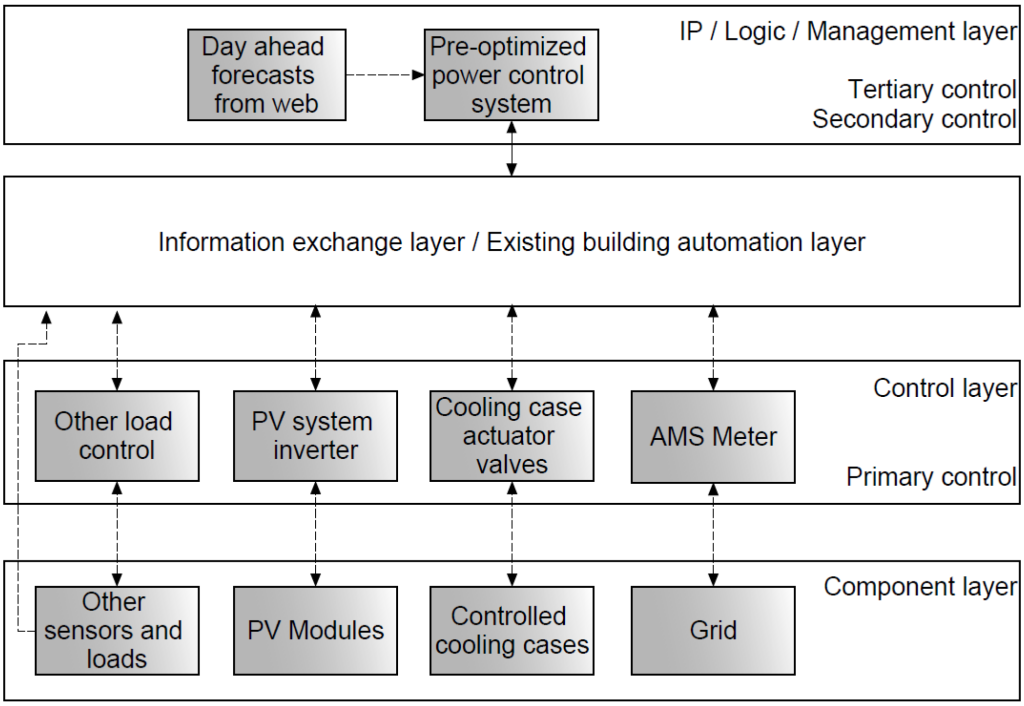


Figure 38: Suggested architecture - case study optimized scheduling system

The suggested topology of the optimization model itself is viewed in Figure 39, which is a slight modification of the control scheme previously viewed in Figure 31 in Section 6.3.3. The modeling process of the internal blocks is explained in the rest of this section. Most choices and reasoning regarding methods and data to be utilized in the different blocks have already been made in the end of the relevant theory sections. In these cases, a short summary and referrals are given.

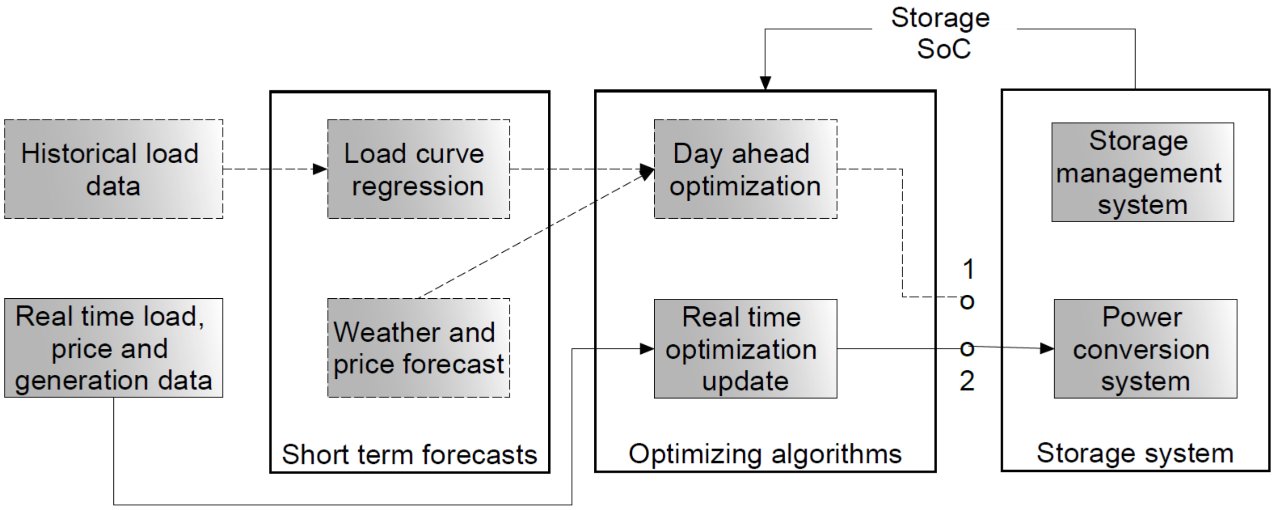


Figure 39: Case study - optimized scheduling control scheme

8.1.2 Assumptions and Choices Made in the Modeling Process

Firstly, some basic assumptions and strategies need to be made in order to build up the optimization algorithms in this project. It is desired to run simulations for a full year in the case study to assess model behavior at all seasons, however practical constraints require some pragmatic choices in order to conduct such simulations. Firstly, the energy monitoring data for KIWI Holter which were used for predicting KIWI Dalgård behavior in Section 2 had its origin in May 2016, which makes earlier load data unavailable. Due to the time frame of this study, it is not possible to use a full year of historical data to predict behavior, and then run the model a year against fresh data. Secondly, the weather and price forecasts used in this model are not available for a full year. Due to these constraints, it is decided to run a full year simulation based on historical data. It was chosen to run the optimization model as a deterministic model with a 24 hour horizon, which was also made by Ottesen and Tomasgard [24]. To reflect the fact that the model in real operation only has a 24 hour horizon when using historical data, a constraint was added which requires the optimized storage scheduling to occur at 24 hour intervals throughout the year.

Figure 38 visualizes two complementing pathways to be used in a robust optimization scheme: Day ahead optimization and real time updating by the model. According to the theory presented in Section 6.3.3, the optimization model can capture and include real time deviation on predicted behavior by updating the model often. Still, a realistic prediction is needed as a basis for planning future scheduling. The more realistic the prediction, the less value is lost by course changes in the schedule due to updated information. Again, some assumptions need to cover the gap between day ahead and real time optimization when conducting a full year of simulations. For this study, the interface is solved by assuming a close to perfect prediction of future consumption and generation. Even though this is a strict requirement to put on the system, it may be defended due to the fact that emerging machine learning techniques in combination with big data are expected to predict future operation far better than what is possible by traditional and simpler techniques. In a future operation scenario, assuming a close to perfect prediction is consequently considered to be an acceptable assumption for this study. On this basis, the optimization will be made on basis of the monitored load data from May 2016- May 2017. It is previously explained in Section 2 how historical load profiles from May 2016 to May 2017 were obtained and modified so as to predict equivalent load data for KIWI Dalgård. By assuming a correct prediction, storage SOC only needs to be defined at the starting point. Its dynamic development throughout the year will then be handled by the optimization model. In the same way, price data from Nord Pool Spot from May 2016 to May 2017 will be used in the model. It was explained in Section 4.5 how PV generation data for a full and random year was obtained by PVsyst simulations. This data will be used as PV generation data in the model.

8.1.3 Load Curve Regression

Even though a prediction of future loads by regression methods is not used as input in the optimization model in this study, a load regression model for KIWI Dalgård is included in the case study as it gives insight into elements affecting consumption and forms basis for future discussions. Emphasis is accordingly put on simplicity and intuitiveness in the process for an easier interpretation of the model and results. Historical load data is used for predicting future load consumption based on explanatory variables. According to the considerations made in Section 6.2.2, the multivariate regression method and the software XLSTAT was decided to be used for predicting loads in the case study. The explanatory variables are chosen according to the considerations made by Ottesen and Tomasgard [24], and consist of the hour of the day, the month of the year, whether it is a working day or not and temperature. In addition, a moving average component is added which refers to the residue between predicted and measured load 24 hours back. Ottesen and Tomasgard suggested Equation (11), which is previously stated in Section 6.2.2, to be used as the regression formula. For the case study, some simplifications have been made on this formula. Instead of setting up the explanatory variables as a function of each hour, each explanatory variable is set up with an independent linear contribution which is constant for all hours. This decision will somehow decrease the accuracy of the regression, however gains are made in a simpler and more intuitive interpretation of the results. By this modification, Equation (13) describes the load prediction for KIWI Dalgård used in the case study. The denotion "D" indicates a dummy binary variable, which has the value 1 when the variable is active, and 0 when inactive. By example, $D_t^{h=1} = 1$ only between 0 am and 1 am, and "$D_t^{workday} = 1$ only from Monday to Saturday when the store is open. Other variables are active at all times, like temperature τ. The MA(24) variable refers to the residue 24 hours back and is naturally only activated from Tuesday to Saturday to utilize the reference data from a similar day.

$$
\begin{aligned}
L_t = \mu + D_t^{workday}\alpha^{workday} + D_t^{nonworkday}\alpha^{nonworkday} + \sum_{h=1}^{24} D_{t,h}^{hour}\alpha_h^{hour} \\
+ \sum_{m=1}^{12} D_{t,m}^{month}\alpha_m^{month} + \tau_t\alpha^{\tau} + D_t^{MA(24)}\varepsilon_{t-24}\alpha^{\varepsilon_{t-24}} + \varepsilon_t \quad t \in T
\end{aligned}
\tag{13}
$$

The obtained explanatory variables and coefficients which are used for load predictions in the optimization model are depicted in Table 18. By reading the table, an impression of the elements affecting the load profiles for a full year is made. According to the table, consumption is generally 7 kW larger on a workday than on a non-workday. Consumption is lowest at night, has a general peak between 7 and 8 am, and is fairly flat the rest of the working day. By looking at the outdoor temperature coefficient, the minus sign suggests that the general consumption decreases slightly with increasing temperatures, which may be considered strange when the cooling load is the largest single load in the store. However, it may reflect the fact that the building envelope and cooling cases are well insulated, so that outdoor temperature only to a small extent impacts the cooling load. According to the monthly coefficients, consumption is generally lower in summer than in winter, and consumption peaks occur in March. If the data are used to identify sources to the viewed trends, an even deeper understanding and enhanced control of the consumption in the store may be obtained. This can for instance be facilitated by a machine learning model.

Furthermore, some key numbers indicating the accuracy of the regression are presented. The r^2 value obtained is 0.76, indicating that 76 % of the load profile behavior can be explained by the included explanotary variables [111]. A MAPE (Mean Average Percentage Error) value of 7.9 % was obtained during the simulations. The predicted values by regression as function of the monitored values are depicted in Figure 82 in Appendix G. The grey lines mark the barriers inside of which, 95 % of the values are found.

To get a deeper understanding of which of the main load categories which were most precisely predicted by the chosen explanatory variables, the load profile was split between the centralized cooling part of the load and the other loads. For the centralized cooling load, a r^2 value of 0.32 and a MAPE value of 10.8 % were obtained. For the other loads, a r^2 value of 0.86 and a MAPE value of 8.7 % were found. According to these data, the cooling load has the loosest connection to the chosen explanatory variables, and the majority of the factors (68 %) influencing the cooling load are not included in the model. To predict the load better, more complex regression methods and more relevant explanatory variables should be added for this load. The predicted values by regression as function of the monitored values for the split loads are depicted in Figure 83 and 84 in Appendix G.

Explanatory variable	Interpretation	Coefficient	Value, coeff.
µ	intercept		25.242
$Dt^{workday}$	workday	$\alpha^{workday}$	7.125
$Dt^{nonworkday}$	nonworkday	$\alpha^{nonworkday}$	0.000
$Dt^{h=1}$	h=1	$\alpha^{h=1}$	-2.438
$Dt^{h=2}$	h=2	$\alpha^{h=2}$	-4.278
$Dt^{h=3}$	h=3	$\alpha^{h=3}$	-4.281
$Dt^{h=4}$	h=4	$\alpha^{h=4}$	-4.063
$Dt^{h=5}$	h=5	$\alpha^{h=5}$	-4.143
$Dt^{h=6}$	h=6	$\alpha^{h=6}$	-3.167
$Dt^{h=7}$	h=7	$\alpha^{h=7}$	3.441
$Dt^{h=8}$	h=8	$\alpha^{h=8}$	9.289
$Dt^{h=9}$	h=9	$\alpha^{h=9}$	7.413
$Dt^{h=10}$	h=10	$\alpha^{h=10}$	7.232
$Dt^{h=11}$	h=11	$\alpha^{h=11}$	7.344
$Dt^{h=12}$	h=12	$\alpha^{h=12}$	7.280
$Dt^{h=13}$	h=13	$\alpha^{h=13}$	7.456
$Dt^{h=14}$	h=14	$\alpha^{h=14}$	8.599
$Dt^{h=15}$	h=15	$\alpha^{h=15}$	6.823
$Dt^{h=16}$	h=16	$\alpha^{h=16}$	7.345
$Dt^{h=17}$	h=17	$\alpha^{h=17}$	7.099
$Dt^{h=18}$	h=18	$\alpha^{h=18}$	8.233
$Dt^{h=19}$	h=19	$\alpha^{h=19}$	6.689
$Dt^{h=20}$	h=20	$\alpha^{h=20}$	8.490
$Dt^{h=21}$	h=21	$\alpha^{h=21}$	7.127
$Dt^{h=22}$	h=22	$\alpha^{h=22}$	6.576
$Dt^{h=23}$	h=23	$\alpha^{h=23}$	7.248
$Dt^{h=24}$	h=24	$\alpha^{h=24}$	0.000
$Dt^{m=1}$	m=1	$\alpha^{m=1}$	-0.438
$Dt^{m=2}$	m=2	$\alpha^{m=2}$	0.482
$Dt^{m=3}$	m=3	$\alpha^{m=3}$	2.259
$Dt^{m=4}$	m=4	$\alpha^{m=4}$	1.051
$Dt^{m=5}$	m=5	$\alpha^{m=5}$	-0.896
$Dt^{m=6}$	m=6	$\alpha^{m=6}$	0.253
$Dt^{m=7}$	m=7	$\alpha^{m=7}$	0.363
$Dt^{m=8}$	m=8	$\alpha^{m=8}$	-1.000
$Dt^{m=9}$	m=9	$\alpha^{m=9}$	-0.482
$Dt^{m=10}$	m=10	$\alpha^{m=10}$	-1.329
$Dt^{m=11}$	m=11	$\alpha^{m=11}$	-0.291
$Dt^{m=12}$	m=12	$\alpha^{m=12}$	0.000
τt	Temperature	α^{τ}	-0.093
$Dt^{MA(24)}{*\varepsilon\_\{t-24\}t}$	Residual ε_{t-24}	$\alpha^{\varepsilon\_\{t-24\}}$	0.417

Table 18: Load regression KIWI Dalgård - obtained explanatory variables

8.1.4 Mathematical Formulation of the Scheduling Problem

In accordance with theory presented in Section 6.3.3, an objective function and a set of constraints are used to calculate the optimized scheduling. The model should include all relevant costs and constraints in order to find the best solution. The mathematical formulation of the scheduling problem is inspired by the work of Ottesen and Tomasgard [24], however modified so as to better fit the case study context. In the case study, only one storage, one local generation source and one import source are used, as opposed to the model of Ottesen and Tomasgard, covering various sources of DG, import and storage units. Start-up costs for storage and generation are considered to be zero in the suggested system. No curtailment of load is suggested, and is consequently not included in the model. Also, as explained in the assumptions made for this section, a constraint is added to ensure that optimization occurs in 24 hour intervals, even though a full year of historical data is used by the model. The loads added to the model are considered non-flexible, and the added storage is the only flexible source added to the model. On this basis, the mathematical constraints are further explained. Variables are explained as they are introduced, if they are not self-explanatory.

Objective function
The objective function which is to be minimized is given by Equation (14).

$$min \sum_{t \in T} (P_t^{import} c_t^{import} + P^{peak} c^{peak} + C^{fixed}) * (1 + VAT) - \sum_{t \in T} P_t^{export} c_t^{export} \quad t \in T \tag{14}$$

where P_t^{import}, P^{peak} *and* P_t^{export} are energy flows of import, peak power and export, respectively, and c_t^{import}, c^{peak}, c_t^{export} and C^{fixed} are the equivalent prices of energy import, peak power, energy sales and the fixed yearly cost. T is the hour number for the year ($t \in 1..8760$). The VAT is explicitly stated to visualize how it is embedded in the import cost, but not included in the income by sales, as explained in Section 3.4.

Energy balance constraints
The energy balance constraint is given by Equation (15).

$$P_t^{import} + PV_t^{forecast} + P_t^{discharge} = P_t^{export} + P_t^{load} + P_t^{charge} \quad t \in T \tag{15}$$

meaning that the energy flow added to the system by grid import, PV generation or by storage discharge at all times is equal to energy exported or consumed by the system, like grid exports, loads and charging of the storage.

Import constraint
The import constraint forms the set point for peak shaving, and is set by a balanced view on risk and the desire to maximize the usage of the battery. It was decided in Section 5.3 to peak shave to 45 kW. The import constraint is consequently set according to Equation (16).

$$P_t^{import} = 45\,kW \quad t \in T \tag{16}$$

Storage constraints
Storage constraints are given by the equation set (17) to (21). They are defining constraints on, respectively, storage energy balance, charging speed, discharge speed, SOC max and SOC min. As the base case, it was decided in Section 5.3 to install a thermal storage with a capacity equivalent to 10 kW and 52 kWh electrical storage. The charging capacity was set differently from the discharge capacity for practical reasons: The power capacity was in 5.3 chosen to be 10 kW, however the supermarket cooling cases it is supplying may only consume 8 kW, thus forming an extra constraint on the discharge capacity. Also, the choice of the SOC minimum value requires an explanation. Normally for batteries, SOC min is put above 0, typically at 10 %. However, as this is a thermal battery utilizing the phase change of ice/water, no technical constraints are seen which would require the SOC min to be set above 0.

$$SOC_t = SOC_{t-1} + P_t^{charge}\eta^{charge} - \frac{P_t^{discharge}}{\eta^{discharge}} \ \ t \in T \tag{17}$$

$$SOC_t - SOC_{t-1} <= 10kW \ \ t \in T \tag{18}$$

$$SOC_t - SOC_{t-1} >= -8kW \ \ t \in T \tag{19}$$

$$SOC_t <= 52\, kWh \ \ t \in T \tag{20}$$

$$SOC_t >= 0\, kWh \ \ t \in T \tag{21}$$

Time frame constraint
As stated in the assumptions, a constraint is added to reflect the fact that the model in real operation would only have a 24 hour horizon, even though in this case a full year of data are known at the simulation start. It was chosen to form the constraint as a storage constraint, requiring the total charge and discharge of the battery to be equal within a 24 hour time frame. This is equivalent to require the storage to be at a specific level at the end of the day, to ensure storage availability for the next day. The constraint is mathematically given as Equation (22).

$$\sum_{1+24(d-1)}^{24+24(d-1)} P_t^{charge}\eta^{charge} = \sum_{1+24(d-1)}^{24+24(d-1)} \frac{P_t^{discharge}}{\eta^{discharge}} \ \ d \in Days, \tag{22}$$

where $Days \in 1..365$ is the number of days within a year. The simulations were modeled using the FICO Xpress Optimization Suite [131], and results are presented in Section 8.3. The script used for the optimization model is displayed in Appendix H.

8.2 Design of Real Time Fuzzy Logic Control System

In this section, the modeling process of the fuzzy logic real time control system for case study simulations is described. Portions of the text structure and descriptions are taken from a previous study by the same author [8].

8.2.1 Suggested System Topology, Objectives and Strategic Choices

The fuzzy logic real time control system is set up with the following control objectives:

- Peak shaving
- PV self-consumption

Due to the real time control scheme, load shifting based on electricity spot prices is not assessed as it would require a scheduling based on a time horizon. Load shedding is not assessed as it would conflict with assumed customer requirements. Accordingly, necessary inputs for real time control according to the objectives and goals are chosen as follows:

1. The net import is needed as input to know power flow levels, and may at any given time be read from the meter. Defining the net import as $P_{load} - P_{PV}$, the variable may also cover export situations.
2. The storage SOC at any given time is also chosen as input as it forms basis for charging and discharging decisions to ensure storage availability at any given time for the desired applications.

3. A PV forecast input is needed to equip the controller for handling both import and export situations.

The main challenge for the control system is to utilize the small sized storage for two conflicting applications: For peak shaving availability, storage should be fully charged, while for PV self-consumption availability, storage should be fully discharged. By nature, export and peak imports do not occur simultaneously, which makes it possible to prepare the system for both situations by utilizing simple prediction methods available on the market for real time control schemes. This is done by utilizing an insolation forecast as input, added to the system so that it is understood by the system as a real time sensor. The forecast is used to calculate predicted export situations 6 hours ahead, and this forms the third input in the fuzzy logic controller. This method is used by conventional control systems in Norway today, as described in Section 7.2. The weather forecast is at any time given as 6 hours ahead values. By this time frame, the 52 kWh and 10 kW storage chosen in Section 5.3 may have time to fully discharge based on predicted export situations before capacity is needed. An assumption is made regarding forecasting quality for simplicity reasons. The fuzzy logic control system is a real time system, and monitored data are used directly for the simulation period May 2016-May 2017. It is assumed that the 6 hour ahead export forecast is correctly predicted so that historical data may be used in simulations.

Generally, the control system is designed so as to be available for peak shaving, as larger cost penalties occur for missing peak shaving than for missing some hours of self-consumption. The idea is that storage is only prepared for PV self-consumption when the scenario is expected. The output of the controller is a signal to the control valves, which states whether and by which degree the storage should be in the state of discharge, charge or standby.

An overview of the suggested control scheme is displayed in Figure 40. In the same way as described for the optimized scheduling system, the fuzzy logic control system may integrate in the existing BAS framework at KIWI Dalgård to access information and send control signals to field devices. Its adaptation to the BAS architecture of KIWI Dalgård, which was described in Section 7.1, is thought as follows: The short term weather forecast is provided by a web based weather forecast service and imported to the IP layer. Meter and SOC data are collected from the information hub IWMAC. The fuzzy logic control system is designed in a convenient computer software and connected to the BAS in the IP layer. The set points are sent via the communication hub IWMAC, which just repeats/translates the signal so that it is understood by the valves controlling the storage cases.

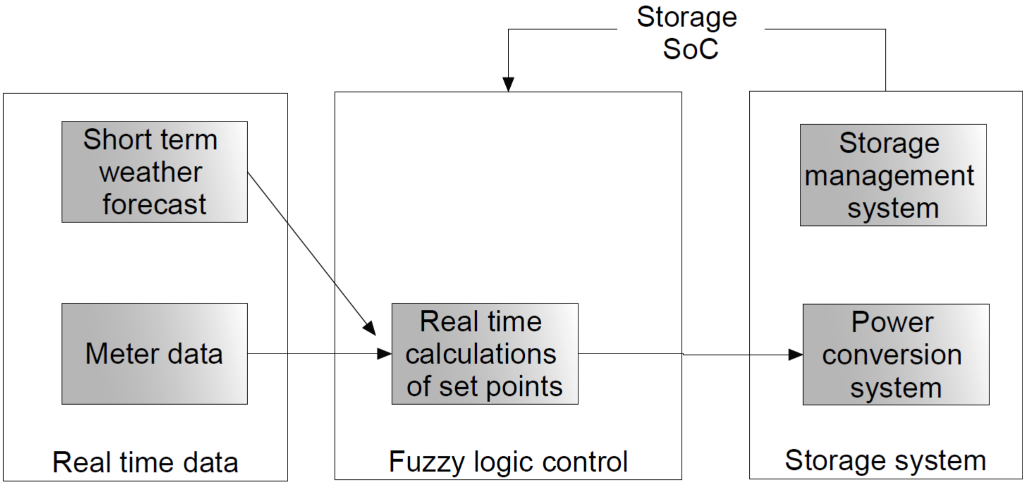


Figure 40: Case study - fuzzy logic control scheme

Constraints regarding imports and exports and control aims were treated in Section 5.3. The following constraints are relevant to the input variables:

- P_{import}: Based on load and generation data, $-23\,kW < P_{import} < 53\,kW$. The controller aims to keep P_{import} within the following limits: $0\,kW < P_{import} < 45\,kW$.
- SOC: The SOC level ranges from 0 kWh (0 %) to 52 kWh (100 %)
- $P_{export forecast}$: At any given time equal to $P^{PV}_{t+6} - P^{load}_{t}$, when the expression yields a positive value. Otherwise, the input value is set to 0, as not to affect the control. No load forecasting has been suggested for use in this real time control system, which is reflected in the formula used for export forecasts. The export forecast was added because it was needed, and because it can be adapted to conventional real time control structures.

Zhang et al. suggested that the fuzzy logic control system should be divided into operating modes to ensure storage availability at all times [16]. For this study, it has been decided to divide into two modes: A day-time mode, when focus is on dispatching the storage so as to obtain control objectives, and a night-time mode, when focus is on charging the storage for next day availability. This day-and-night division of modes is considered natural for this project, as both peak demand and export are expected to occur at day-time, and demand and electricity prices are generally lower at the night, which is suitable when charging the storage. For each of the modes, the fuzzy logic control needs to be configured individually.

8.2.2 Day-time Mode - Membership Functions, Rules and Solution Domain

In this section, the design of the day-time control mode is treated. The store opens at 6:30 am and closes at 11:30 pm, and day-time is consequently defined to be from 6 am to midnight. The day-time mode is the main mode of the system, and yields the largest complexity. The main tasks of the day time mode are stated as follows, in the following order of priority:

1. Peak shave down to the chosen 45 kW import limit
2. Store all excess PV electricity
3. Ensure storage availability
4. Only use the storage when it has an impact

In accordance with the theory presented in Section 6.3.2, each of the input and output variables is connected to a MF, which connects the input variable to states. The MFs and their shape form the basis for the controller output. As an example, the build up of the MFs for the P_{import}-input is used to include the desired constraints of this input variable. The careful choice of MFs is of high importance for a fuzzy logic controller, and here the control system can be tuned. Each input variable is assigned to the number of MFs needed in order to obtain appropriate rules. The input and output to the fuzzy logic control system are viewed in Figure 75. The MFs used for the case study and their domain are depicted in Figure 76 to 79 in Appendix F. Four categories are used for the P_{import}-category: "negative", "default", "large" and "discharging may occur". The latter is used to avoid export due to discharging of the storage when import is already close to zero. The SOC input embeds three categories: "low", "medium" and "large", while the input $P_{export forecast}$ contains only one category: "present". The output, named "storage mode", embeds the three categories of "discharge", "standby" and "charge".

In order to obtain a simple and intuitive design, as few rules as possible should be stated in order to reach the objectives. The rules are given as "if-then"-rules, and are the laws of the control system. The different input variables may be combined using $and/or - relations$. When the "and"-relation is used, the input variable which obtains the criterion the least is deciding, while the opposite is valid for the "or"-relation. Each input variable can either be assigned as itself, or by its opposite by using the "not"-relation.

The rules chosen for the case study have basis in the membership function terms, and are as follows:

1. If P_{import} is *large* THEN Storage mode is *discharge*
2. If P_{import} is *negative* THEN Storage mode is *charge*
3. If P_{import} is *positive+* AND $P_{export forecast}$ is *present* THEN Storage mode is *discharge*
4. If P_{import} is *positive+* AND SOC is *low* THEN Storage mode is *charge*
5. If P_{import} is *default* AND SOC is *not low* AND $P_{export forecast}$ is *not present* THEN Storage mode is *standby*

The rules are highly intuitive, which is a large advantage of the fuzzy logic control system. The interaction of the different rules however raises the complexity. The goal of Rule 1 is peak shaving: The storage is discharged when demand is large.

The goal of Rule 2 and 3 is self-consumption of PV generation. Rule 2 is similar to Rule 1 only for the opposite case: The storage is charged during excess PV generation. Rule 3 facilitates self-consumption by discharging the storage when excess PV generation is forecasted, to ensure storage availability in a few hours.

Rule 4 is solely about availability, however it has a lower priority than peak shaving and self-consumption, and is designed so that it may not conflict with the prior. The "and"-relation is used to ensure that the storage is only charged when the import is positive + (above 0 with a margin of at least 10 kW). The reason for this is that a less than 10 kW import indicates that an export situation is emerging. To charge the storage during this condition would be to sabotage self-consumption goals. In the same way, the "and"-relation is used so that the storage, when low in SOC, is only charged to a middle level SOC in day-time, to be ready for both self-consumption and peak shaving. If the storage SOC is at a low level, it is typically after a peak shaving period or before an export situation, and it is improbable that a new large peak demand will occur soon. Thus, a middle level SOC is considered to be sufficient availability for the prioritized peak shaving control objective for this instance.

Rule 5 is a balancing rule, telling that if nothing special is going on, the storage should be at standby. This is done by multiple "and"-relations for all default inputs.

All the rules are simultaneously active, and may interact with one another during operation. The balanced interconnection between the rules may result in the need of re-tuning the whole rule base if modifications are necessary.

8.2.3 Night-time Mode - Membership Functions, Rules and Solution Domain

The night time mode is valid from midnight to 6 am. The only differences from the day-time mode are the objectives and the rule base, which will be presented in this section. The night-time is recognized by a low demand and low electricity prices. It is a simpler control mode as neither peak shaving or self-consumption is expected to be needed. The night-time objectives are further presented, in the following order of priority:

1. Ensure storage availability when day-time starts
2. Only using the storage when it has an impact

Generally, the storage should be fully charged when day-time starts to be prepared for the prioritized objective of peak shaving. The rules chosen for the case study have basis in the membership function terms, and are as follows:

1. If P_{import} is *positive +* AND $P_{export forecast}$ is *present* THEN Storage mode is *discharge*
2. If SOC is *not large* AND $P_{export forecast}$ is *not present* THEN Storage mode is *charge*
3. If P_{import} is *large* THEN Storage mode is *standby*

Rule 1 is the same as Rule 3 for day-time mode: It facilitates self-consumption by discharging the storage when excess PV generation is forecasted, to ensure storage availability for a few hours.

Rule 2 tells that the storage should be fully charged if an export situation is not expected.

Rule 3 is a balancing rule, telling that the charging can stop when the storage is fully loaded.

8.2.4 Solution Domains

In this section, examples of solution domains are presented for both modes. For a fuzzy logic controller, every operation point will be associated with its related output as long as the operation point is within the defined range. The resulting output product of all operation points combined is the solution domain, which is a 3D surface. The surface is a function of two input variables and a third fixed variable. Due to each mode containing three inputs, there is an infinite number of solution domains in the model. By generating these surfaces, the controller can itself reason the appropriate output for any given operation point, which is a reason why fuzzy logic controlling is expressed as an artificial intelligence system. Two examples of solution domains are presented for each mode, and the surfaces which are considered most informing are selected. The day-time solution domains are presented in Figure 41 and in Figure 80 in Appendix F, showing output as function of P_{import} in combination with SOC and $P_{export forecast}$, respectively. The night-time solution domains are presented in Figure 42 and in Figure 81 in Appendix F, showing output as function of P_{import} in combination with SOC and $P_{export forecast}$, respectively. For all combinations, the output is in the range of [-0.67,0.67], which is equivalent to [-8 kW (discharge),10 kW (charge)] due to the set up of the real time model.

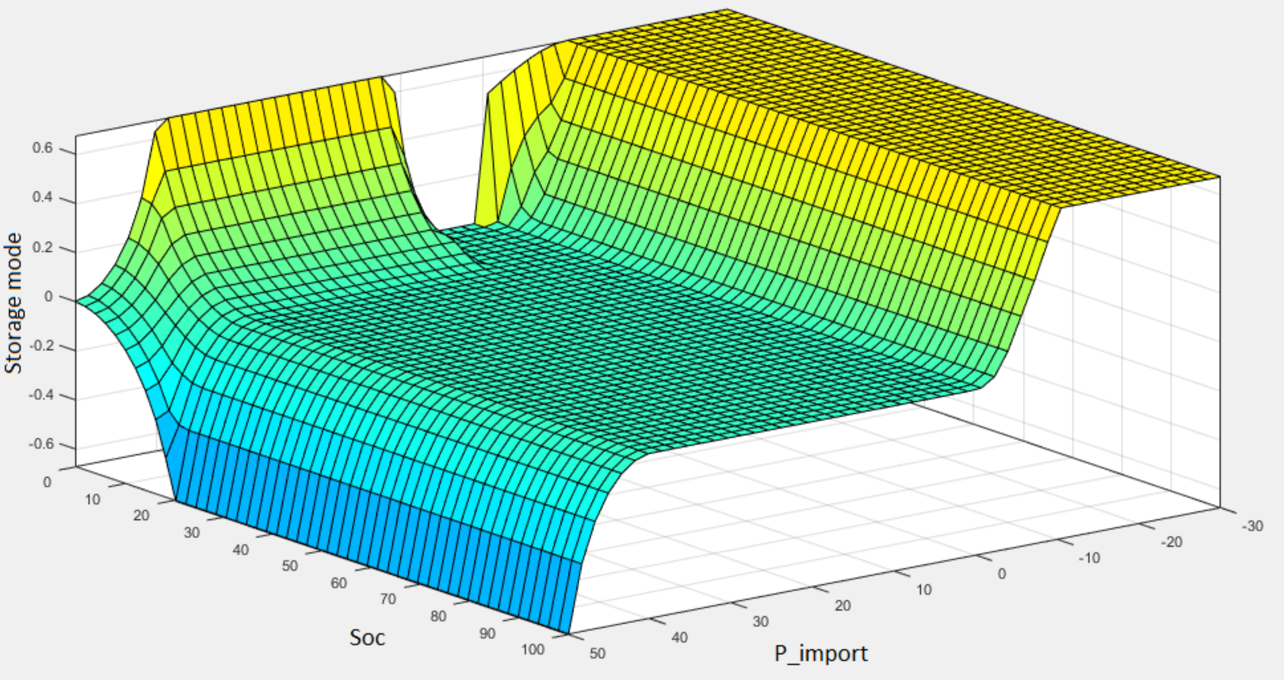


Figure 41: Solution domain of fuzzy logic day-time mode - P_{import} vs SOC, given no predicted export

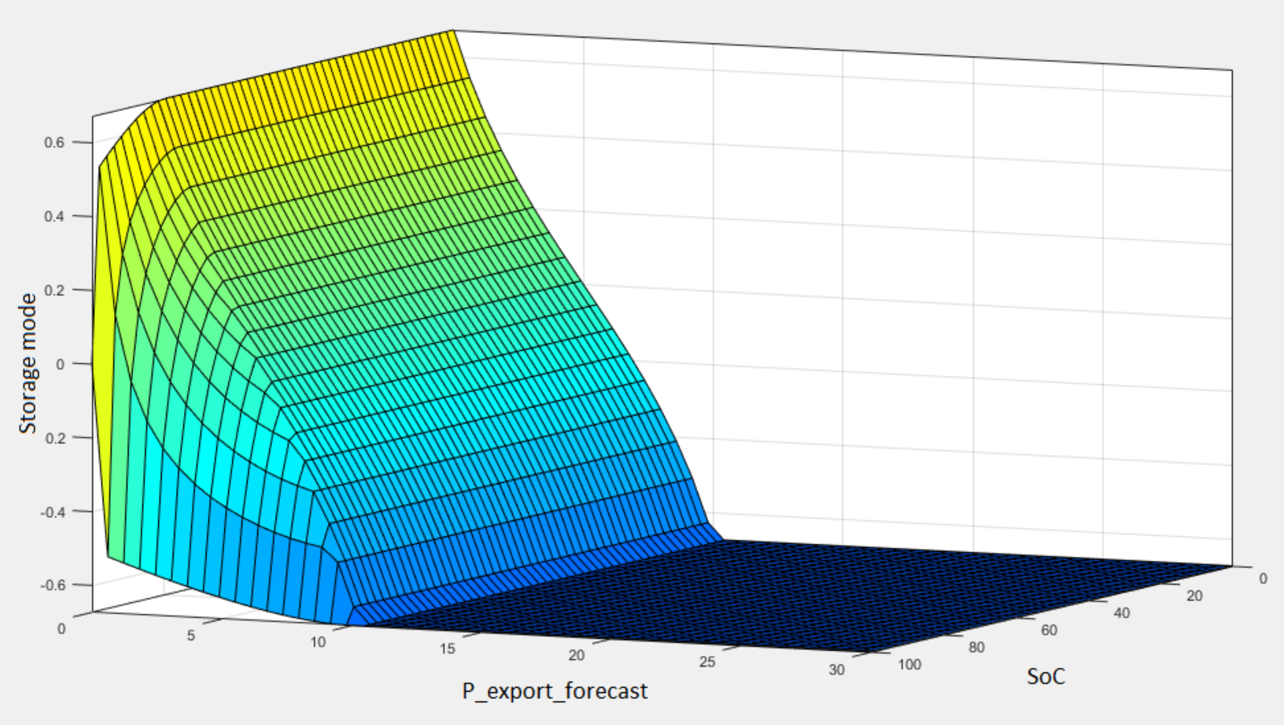


Figure 42: Solution domain of fuzzy logic night-time mode - SOC vs $P_{exportforecast}$, given a medium charged storage

8.2.5 Setting up the Real Time Control Model in MATLAB/Simulink

To conduct operation phase simulations of the power control system, a model of the storage controlled by the fuzzy logic control system was modeled in the simulation software MATLAB/Simulink. The input and output of the fuzzy logic controller are depicted in Figure 43. Some practical blocks were added to the signal flow to handle different operation modes. Pulse generators and switches were used to turn the day- and night-time mode on/off. Gains were used to reflect the fact that the charging and discharging capacity of the storage were slightly different due to the approximately 20 % over-sizing of the storage with regards the demand of the selected cooling cases. The fuzzy logic output determines how the storage is to charge/discharge at any given time. The day-time and night-time modes are never active simultaneously, and the output signal is accordingly made as a single output signal adding the signal from the day-time and night-time mode. The model has been used for hourly simulations for a full year, of which results are presented in Section 8.3.

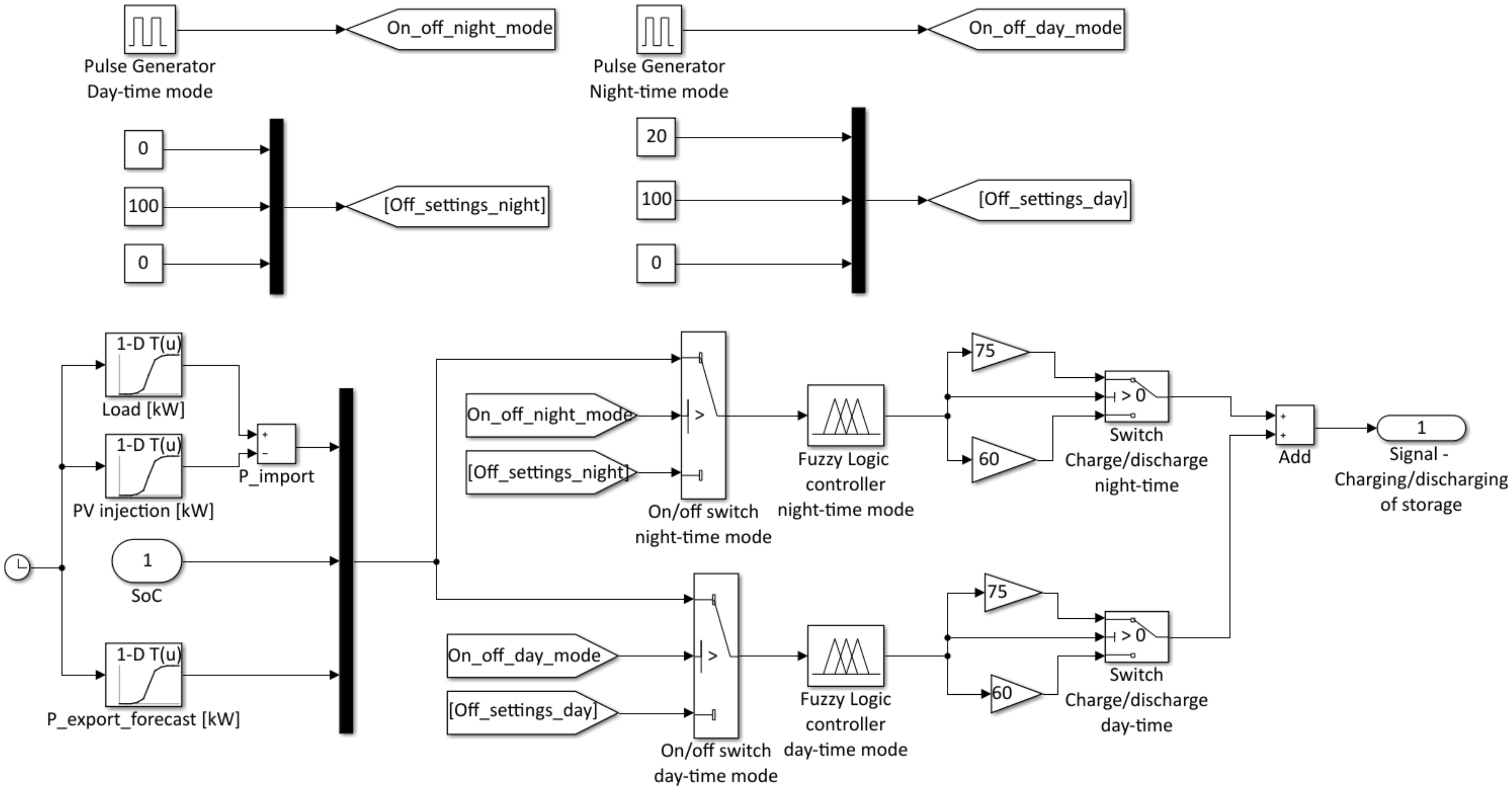


Figure 43: Case study input and output data for the fuzzy logic control system

8.3 Results

Results obtained by case study simulations for both the real time fuzzy logic control system an the optimized scheduling system are presented in this section. For the sake of comparison, results are presented together, and compared to a base case with no storage or additional control.

The results obtained are multiple arrays of 8760 values, reflecting the hourly operation of a full year. For the sake of readability, only results directly connected to the end goal are presented, i.e decreased yearly electricity costs and increased self-consumption of PV electricity. It is important to note that only the yearly cost of buying/selling electricity is included in the results. Other costs, like installation costs, operation and maintenance costs, planning costs etc. are not included in the presented results as those have been considered to be outside the scope. The reader needs to balance the presented savings with costs related to the set up and operation of the power control systems and their added components. Comments and discussions will be made which also includes the cost aspect, however numbers are generally not given.

8.3.1 Terms and Formulas Used

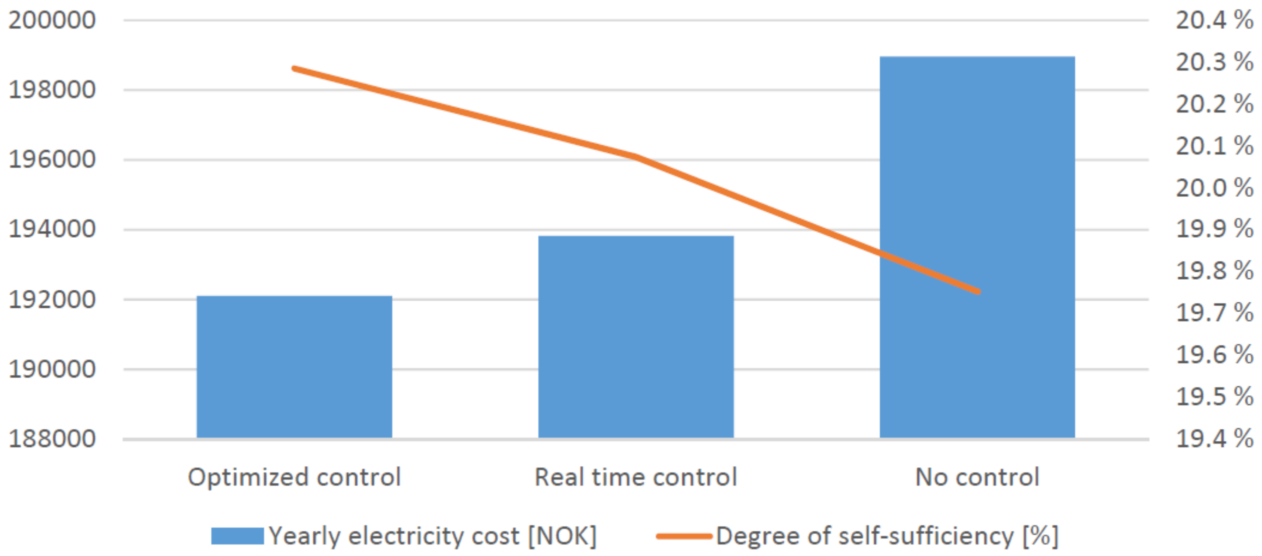
For easier interpretation of presented results, terms and formulas used are described. Some equations have previously been presented, and references are provided. The savings obtained by peak shaving, self-consumption and load shifting were stated by Equation (2) to (4) in Section 3.4. The yearly electricity cost was given by Equation (14) in Section 8.1.4. Equation (23) and (24) show how the self-consumption of solar and the degree of self-sufficiency are calculated.

$$Self\,consumption\,of\,solar = \sum_{t\in T} \frac{PV_t^{forecast} - P_t^{export}}{PV_t^{forecast}} \quad t \in T \tag{23}$$

$$Degree\,of\,self-sufficiency = \sum_{t\in T} \frac{PV_t^{forecast} - P_t^{export}}{P_t^{load}} \quad t \in T \tag{24}$$

8.3.2 Main Result

The main result obtained is depicted in Figure 44. All presented data are yearly. It is seen that among the suggested control structures, the yearly savings are largest for the optimized scheduling case. The savings are however limited, showing only about 7 000 NOK or 3.5 % yearly cost reduction compared to the base case. The performance of the real time control scheme is as expected in between the optimized and base case, however closer to the optimized case. Self-consumption of electricity shows the same trend as the yearly cost: slightly better for the optimized scheduling system, the real time control being in between the optimized system and the base case. The tabulated part of the figure states that 97 % of the PV electricity was already consumed in the base case, leaving only a small potential for the smart power control and explaining the low increase in self-consumption. Both the optimized and real time control obtained peak shaving down to 45 kW, which yields the vast majority of the savings. The tabulated part shows that the difference in performance between the optimized and real time control system consists of an increased self-consumption of electricity, and savings obtained by load shifting. The latter was as previously described only included in the optimized controller due to its embedded time horizon. It should be noted that the "saved on load shifting"-calculations are, according to the formula, influenced both by load shifting with regards to price variations, and the load shifting that occurs during charging/discharging of PV electricity. This latter effect explains why the load shifting is less than zero for the real time fuzzy logic scheme. The peak export incident is identical for the real time and no control scheme, however largest for the optimized control scheme. This unexpected effect was deliberately made by the optimized controller, which found that load shifting this way based on electricity prices gave reduced costs due to large daily price variations for this incident.



Tabulated main results		Optimized control	Real time control	No control
Yearly electricity cost	[NOK]	192101	193815	198955
Saved on avoiding export	[NOK]	548	331	
Saved on peak shaving	[NOK]	4832	4832	
Saved on load shifting	[NOK]	1474	-24	
Self consumption of solar		99.3 %	98.3 %	96.7 %
Degree of self sufficiency		20.3 %	20.1 %	19.8 %
Max export	[kW]	29.6	24.5	24.5
Total exported	[kWh]	437.0	1065.4	2048.0
Total generated	[kWh]	62547	62547	62547
Potential, degree of self sufficiency		20.4 %	20.4 %	20.4 %

Figure 44: Case study main result of yearly simulation

8.3.3 Sensitivity Analysis

A sensitivity analysis has been conducted to visualize the result dependency of varying input factors. To visualize added value by smart power control, results for the optimized and base case are viewed together for all investigated incidents. It was decided to use the optimized control and not the fuzzy logic control as representative for smart power control, since it proved to be much more flexible. The optimized system based on mathematical constraints could effectively handle modified inputs and yield optimized results without modifying the model itself. The fuzzy logic controller which was used in this study needed time consuming retuning when inputs values were modified. In accordance with the displayed main results, it is believed that the results obtained by the fuzzy logic controller would be in between the optimized control and the no control line, closest to the optimized situation. The sensitivity analysis is depicted in Figure 45. For easier interpretation of the multi-colored curves, the coupled labels are organized top-down according to their value at the left starting point of the curve. The accurate numbers which are graphically displayed in the Figure are found in Table 20 in Appendix I.

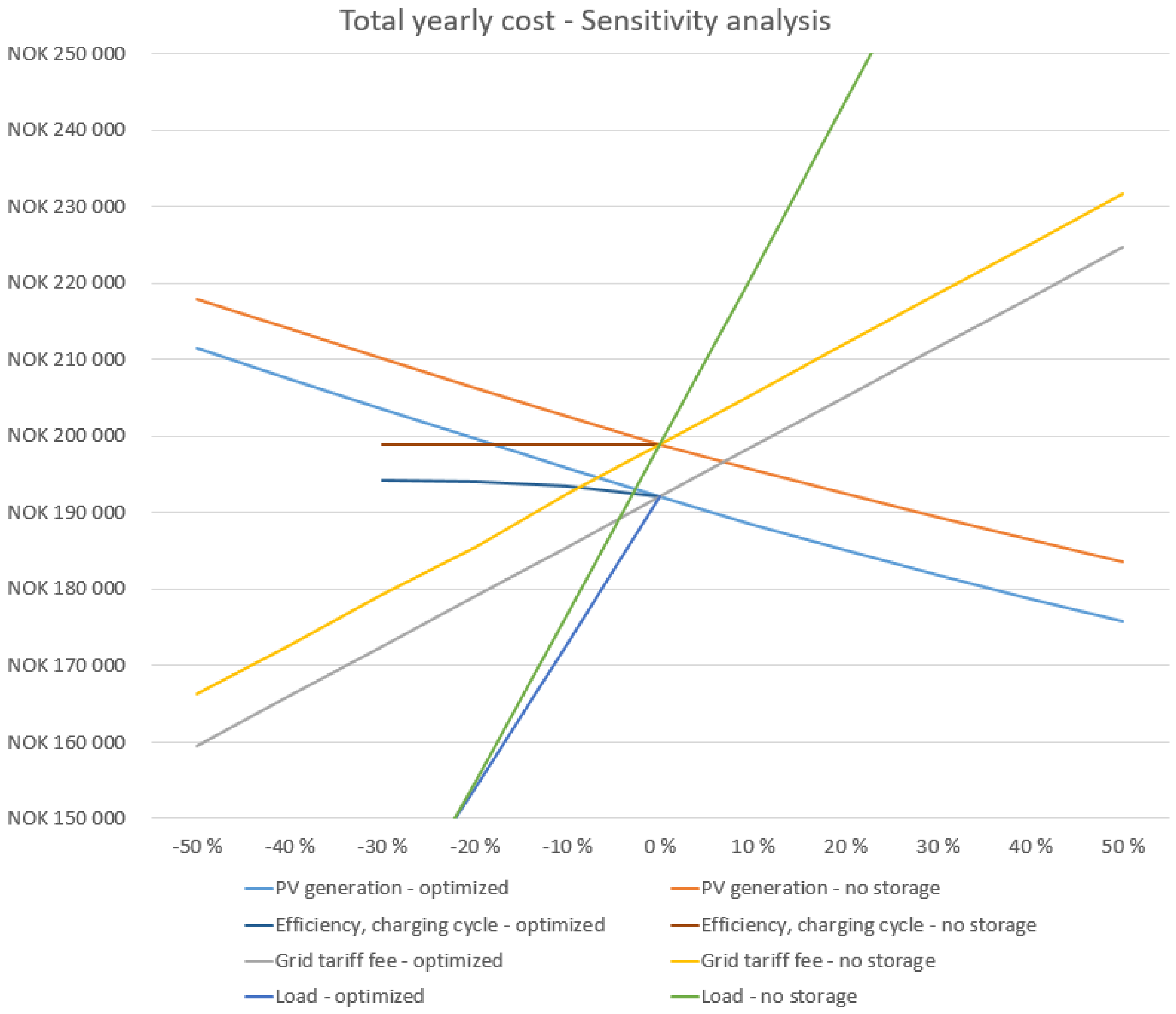


Figure 45: Case study sensitivity analysis

Figure 45 shows that the saved yearly costs by the optimized system, with reference to the base case, are very stable both for varying PV generation and grid tariff fees. When storage efficiency is decreased, load shifting is profitable in a less number of cases, and the storage lowers its activity. The sensitivity analysis for the load size category shows odd behavior, however it is deliberately made so in order to reveal an interesting point: It was decided to peak shave down to 45 kW in the planning process. In theory, if some years show large changes in load consumption, peak shaving will be true to its set point even when it conflicts the goal of lower electricity costs. When demand is increased, the storage was no longer able to peak shave down to 45 kW and constraints was consequently violated in the optimization model, yielding no results. When demand is considerably decreased, all savings by peak shaving are lost, displayed by the intersection of the curves. The result shows the importance of flexible system setups which are able to update their set points with trend changes in load consumption, and to calibrate the system in response to updated forecasted or anticipated values.

8.3.4 Scenario Analysis - For Alternative PV and Storage Installations

A study on how the system would perform during different PV system and storage sizes has also been assessed. The chosen thermal storage solution in the case study was added for all available cooling cases in the supermarket, which left no room for increasing storage size without changing technology. When a scenario analysis is performed assuming larger storage sizes, an electric battery will be assumed as storage.

The storage is modeled slightly differently when an electric storage is assumed. The case integrated thermal storage was modeled with $\eta = 100\,\%$, as dissipated cooling energy was usable for the cooling cases. For the electric storage, a total cycle efficiency of 90 % is applied according to Li-ion data previously viewed in Table 11. To limit battery aging, an issue described in Section 5.1.2, it has been decided to keep the battery within an SOC range of $10\% < SOC < 90\%$. The battery is sized according to desired power capacity, which is decided to be 70 % of the peak export power throughout the year for the different PV system sizes. The relation between power and energy capacity is decided to be equal as for an example storage found in the market [84].

Results of the scenario analysis is viewed in Figure 46, which show the total yearly electricity costs and the degree of self-sufficiency for the optimized scheduling system and the equivalent base case. A more extensive and detailed view of the results is located in Table 21 in Appendix I. It is observed that the added value of the smart power control system increases with PV system size and storage size. However, the increase in savings is not very significant. Results show that the smart power control is more effective at increasing the degree of self-sufficiency than it is to reduce electricity costs, when the system is designed for significant overflow generation with respect to the load. A degree of self-sufficiency of 46 % was obtained for a three times larger PV installation than the initial design and a large storage. It should also be mentioned that an export constraint needs to be added to the model when the PV system and storage power capacity get large, not to violate the constraints of the prosumer scheme "plusskundeordningen" described in Section 3.3.

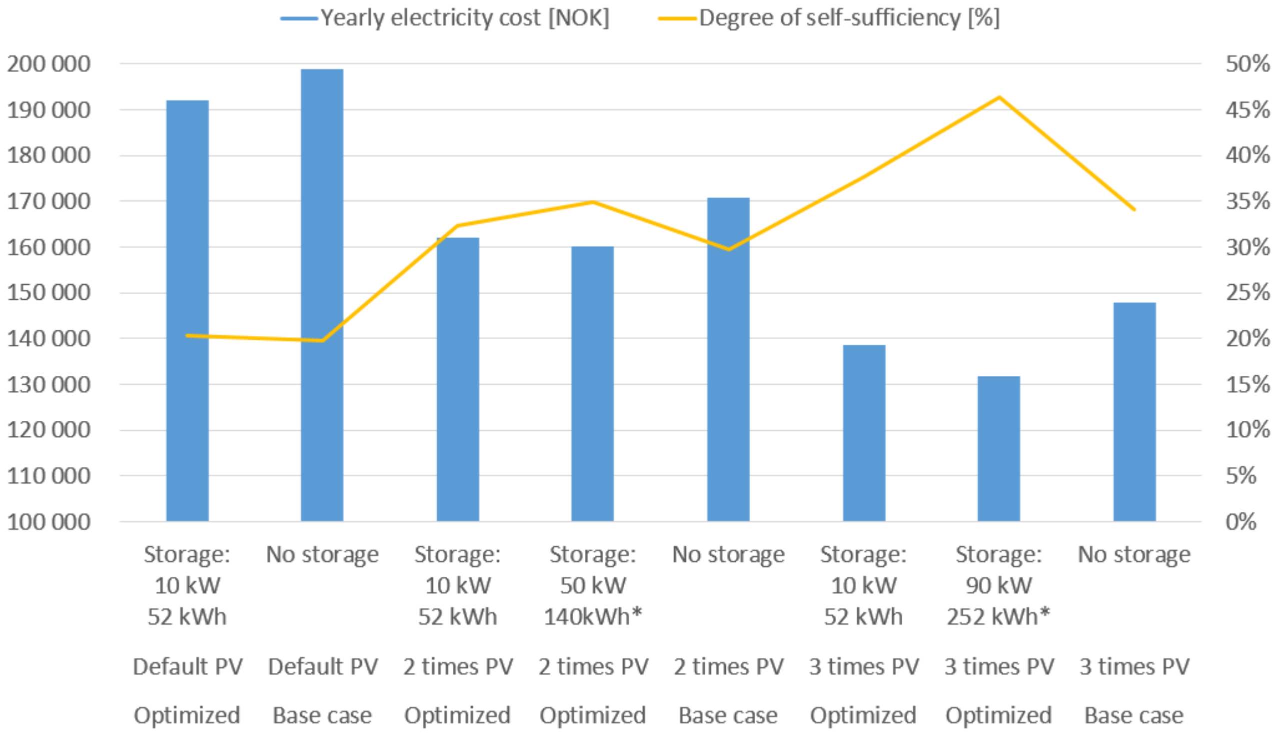


Figure 46: Case study scenario analysis

9 Discussion

Given the obtained results, the greatest challenge for smart power control in supermarkets seems to be economic performance. Even though multiple economic synergies were suggested to be included in the design, by peak shaving, load shifting and self-consumption, only small savings were obtained. The optimized case showed a 3.5 % decrease in yearly electricity costs compared to the base case. In the more detailed reference study by Ottesen et. al, 12 % savings were obtained [24]. A main difference between the studies is that the reference study was for a large Norwegian University building with a 3 MW peak load and a much steeper load curve, involved multiple energy carriers, studied a month with high electricity prices and included demand side management of loads. All of these factors influence results, and highlight the need of utilizing power control schemes suitable for the individual installation. Generally, factors which increase probability of an economic viable power control design are large peaks, a fluctuating load curve, high degree of flexible loads and other integrated storage elements, large hourly price variations of energy carriers and presence of DG based on renewable energy. Also, the larger the installation which is to be controlled, the larger net savings are made by a percentage reductions of costs. The mentioned factors were only to a small degree present in the case study. It was stated in Section 2.2 that supermarkets already had beneficial load curve, which made them very suitable for PV applications. The initial load curve was so smooth that it almost looked like the output of a power control system, leaving small potential for improvements. The potential of the suggested power control systems, which worked properly regarding load shifting, peak shaving and self-consumption, should not be judged by its economic performance in this study, and its potential impact would be better visualized in a more suitable application.

The designed power control systems worked well according to the stated objectives of peak shaving, self-consumption of PV electricity and load shifting, given system constraints. The main saving made by the system was regarding peak shaving. Both the optimized system and the real time control system successfully obtained the peak shaving goal. Regarding increased self-consumption of PV generation, the optimized scheduling performed very well in utilizing the storage. Self-consumption of PV electricity was raised from 96.7 to 99.3 %, which is a 78 % realization of the excess PV generation, approaching the theoretical 89 % limit found in Figure 13 in Section 5.3 for a 10 kW storage without energy storage constraints. For the optimized dispatch system, it is believed that the whole theoretical potential of 89 % was not obtained due to the limit in energy capacity of 52 kWh, and due to the few cases when load shifting was prioritized due to large daily price variations. The real time control system did not perform as well as the optimized dispatch system with regards to PV self-consumption, and captured 48 % of the excess PV generation. Losses with regards to the optimized dispatch system is understood as losses related to the system being a real time system without a time horizon, and by unoptimal tuning. The result is considered acceptable, since peak shaving was chosen as the main priority when designing the controller. The only system utilizing load shifting as part of its control scheme was the optimal dispatch system due to its time horizon allowing forecasts of load, generation and prices. The limited gain by load shifting which was obtainted, about 1500 NOK/yr, is mainly explained by flat spot price curves. By visual inspection of the example electricity spot price curves previously viewed in 7 in Section 3.2, it was found that difference between daily high and daily low price level was about 0.06 NOK/kWh. Assuming an average price difference of 0.03 NOK/kWh, the chosen energy storage of 52 kWh, and assuming only one full charging cycle per day due to the shape of the price curves, the theoretical yearly load shifting savings are $(0.03\, NOK/kWh * 52\, kWh/day * 365\, days/year) * (1 + VAT) = 712\, NOK/year$. It is evident that the average daily load shifting gain must have been larger than 0.03 NOK/kWh, due to the fact that 1500 NOK/yr was obtained by optimized dispatch. Intuitively, it may be estimated to be closer to 0.06 NOK/kWh, which is well in phase with the yearly standard deviation of the spot price curve in the investigated period. Still, the impression stands that the optimized model performed very well regarding load shifting, subject to its constraints.

An interesting discussion is the degree of complexity which can be justified for the power control system in such an application, as the complexity is the main cost driver of the control system along with the storage. Peak shaving control is based on a very simple rule, and only need one single input from the meter measuring consumption at any given time. A simple deterministic control by sending an on/off signal to a load switch connected to the centralized cooling machine, based on meter readings, would in theory be usable for peak shaving. Regarding PV self-consumption, the storage could in the same way be connected to a deterministic mode control, entering storage mode as soon as the meter senses an export situation. A challenge of such a system would be storage availability, however a solution controlled by simple time-settings might be a tempting method to solve the issue, due to the strong time-dependency of the load. The load curve regression result viewed in Table 18 shows that time-determined inputs as time of day, month of year and whether there is a working day or not, to a significant extent can be used for predicting load values. By studying the hourly import curves, it is found that excess generation of PV electricity only was found in the period March to September. The two days with the largest peak imports were at events like the day before Christmas eve and Christmas eve, respectively. The finding that a lot of system behavior is time dependent, makes sense as supermarket daily life consists of customers with general time-based shopping habits, goods which are delivered at specific times during the week, pre-determined work shifts and opening hours along with time-control of some technical installations like indoor and outdoor lighting, to mention some. On the other hand, it might be hard to include both peak shaving and self-consumption as control objectives in a time-controlled availability scheme. The load curve regression shows that the hour of the day which is most strongly related to large consumption, is at 8 am in the morning, just before the sun gets visible over the neighboring rooftops. Studies of the load curve show that large morning demands might also occur in the solar season. In such a scenario, a choice must be made to prioritize either peak shaving or increased self-consumption in all cases where a large morning demand can be expected. Alternatively, two storages might be installed, one part being responsible for peak shaving and another part for self-consumption of PV. This alternative will of course increase installation costs. It might also help to combine time-based control with forecasting, a structure previously described in Section 7.2. Generally, it can be stated that simple control schemes only require simple control structures. When an increased number of control objectives are required, the control may need to be more complex to handle it. Each added control objective should be justified to be worth the extra leap in control investments. The justification should be in accordance with a goal, which could be either based on profit requirements or other interests. For the case of KIWI Dalgård, peak shaving based on a simple load switch seems to be the only control scheme making economical sense as a very cheap control scheme needs to be implemented when margins are very tight. For power control to be justified economically, the storage solution also needs to be very cheap, so that the total cost combined with storage and additional power control plus required margins do not exceed the peak power shaving savings obtained within the expected system lifetime.

One of the main control objectives was to increase the degree of self-sufficiency, however the planned installations left almost no potential for smart power control, by 97 % of PV electricity already being directly consumed by the loads. A scenario analysis with more ambitious PV installations was conducted to evaluate system performance under such circumstances. According to the result obtained in Figure 46, the degree of self sufficiency is increased by 10 % when the PV system size was doubled and no power control was assumed. In other words, half of the extra generated PV electricity will be consumed by the load itself when a two times larger PV system size is installed. By utilizing smart power control in this scenario, the degree of self-sufficiency can be increased to 32 or 35 %, respectively. An even larger degree of self-sufficiency might also be obtained by installing three times as much PV as originally planned. For this scenario, the optimized scheduling with a large storage raises the degree of self-sufficiency significantly compared to the alternatives, up to 46 %. Also for this case, savings by the power control system were for the first time rapidly increasing with regards to the case with no storage. The reason for this is that the supermarket load only to a small extent is able to directly consume the added PV generation from the case with 2 times PV to the case of 3 times PV. A drawback of the 46 % self-sufficiency scenario is the large storage capacity needed. An interesting and more economic scenario for obtaining a large degree of self-sufficiency is if KIWI Dalgård starts offering charging of electric vehicles to its customers. In such a scenario, electric cars would compose a free storage for a large installed PV system, and charging speed allowed by the charging controller could be dependent on PV generation. Also, the optimized scheduling system would increase attractiveness in such a scenario.

The sensitivity analysis shows that the gain obtained by smart power control is quite stable, even with changes in inputs regarding PV generation and grid tariffs. Even with a 50 % increased PV generation, the difference in performance between the optimized dispatch and the no storage system is similar with the default PV generation scenario. The tabulated version of the sensitivity analysis in Figure 20 in Appendix I shows increased savings of only 1100 NOK for the mentioned case. The answer is mainly found in the supermarket load curves causing most of the increased PV generation to be directly consumed by the load, and low grid tariffs and electricity prices. Another reason is that the storage capacity is too small to capture all excess PV generation. In the sensitivity analysis, it was observed that an increased grid tariff fee only to a small extent increases the savings made by smart power control. The reason for this is that the business case depending on grid tariff fees is PV self-consumption, and the PV self-consumption potential was very low as 97 % of PV electricity was directly consumed by the loads in the originally planned installation. Both the grid tariff, which is mainly decided politically, and the portions of excess PV electricity should preferably be larger to make an attractive business case of increased self-consumption for KIWI Dalgård.

Storage efficiency is especially important in power control systems with small economical margins. As previously discussed, the spot price curves were fairly flat on a daily basis, and an estimated average load shifting of 0.06 NOK/kWh was assumed. The average retail price in the period May 2016 to May 2017 was 0.287 NOK/kWh, giving an average load shifting value of about 20 %. A storage with a full cycle efficiency of 80 % would by nature carry a 20 % loss, and leave almost no saving potential by load shifting. When the installation cost, which should be distributed on every charging cycle, is included, this impression is further strengthened. From an environmental point of view, 20 % dissipated energy in a load shifting scheme can hardly be defended when other benefits are small. In short, a very high efficiency combined with a very low installation cost and a less flat spot electricity price curve is needed for load shifting to be a viable business case, also from an environmental point of view. For KIWI Dalgård, the load shifting control objective can be justified by assuming a water/ice PCM storage integrated in the cooling cases, probably minimizing costs, environmental impacts and maximizing usable efficiency for the storage. Still, load shifting was not a viable business case in itself, yielding only about 1500 NOK/yr in saved costs. If it should be included, it should be included for KIWI Dalgård as an added control objective based on an already installed storage unit.

Precise load prediction and a flexible control structure are key components of the system, as peak shaving composes the larges saving potential. In the sensitivity analysis, the point was made that the peak shaving set point needs to be put correctly, otherwise the savings by peak shaving may be decreased or even lost. For the conducted simulations in the optimized scheduling system, the problem could easily have been solved by defining the peak capacity cost as a P_{max} value and not as a fixed chosen value. By this step, the optimization model would have found the optimum itself based on any given load curve, and the system would be highly flexible. Still, for a real control system the yearly load curve must be based on predictions for the full year or by each month, depending on the peak tariff fee structure by the utilities. For a small sized commercial building like KIWI Dalgård, with an energy efficient building envelope and where loads are quite stable and predictable, one might want to take a risk and assume the same load level every year. However, there are multiple scenarios which might lead to change in peak consumption, like replaced equipment, newly installed equipment by new services provided, errors in technical installations etc. For larger buildings with a less detailed understanding of energy consumption, solid prediction measures get increasingly important. For such scenarios, more advanced and precise prediction measurements as big data sampling combined with machine learning might be needed to obtain the peak shaving potential. By proper monitoring and display, such systems also may be used for providing general understanding to operation personnel and detect error on equipment, which might be added value needed to justify the system for stakeholders.

The fuzzy logic control system performed quite well according to objectives when well tuned, however showed low flexibility and required time extensive modeling to balance the rule sets. As mentioned in the result section, sensitivity and scenario analysis was not conducted for the fuzzy logic control system as it often required time consuming re-tuning when changes were made on the system input. Also, when 3 inputs were used in the system, it got hard to get an intuitive overview on how the system would perform during all scenarios, as the solution surface plots by natural 3D constraints only were visible for two variables and one fixed variable at a time. This lack of overview left a larger uncertainty for the designer than it did for the optimal scheduling system, and required more time spent on evaluating the output. To ensure availability, an extra mode needed to be added at night with emphasis on storage charging. In the main reference study by Zhang et al, 6 modes were applied for good performance. On the other hand, any real time control system is believed to require some kind of mode control for availability reasons. When no time horizon is applied, the system can not know whether storage dispatch should occur now or if a better opportunity comes later, given a constrained storage resource. By applying modes based on insight by experience or predictions, chances are greater that the control system will behave beneficially. Still, the complexity of the fuzzy load controller seemed to come with larger cost than benefits for the case of KIWI Dalgård. Included in the consideration is an expectation that the controller will have to be updated based on changes of supermarket operation within the lifetime of the installation, which might be a time-extensive process. Simpler and more distributed real time control schemes, each having responsibility for one task and based on conventional cheap components, might seem more promising when the potential for savings is as low as for KIWI Dalgård.

The optimized scheduling system is a powerful tool equipped for handling large and complex systems. Its implementation is easier justified the more synergies which are added. In the study by Ottesen and Tomasgard, which was used as source when building up the constraints of the optimized scheduling model, multiple storages, energy carriers, start up costs, load control structures and even scenarios were part of the model design. It can be easily imagined how such a system might also include many buildings in its design, and due to its web based interface, it may be located anywhere. One imagined scenario is that such a system may be built for controlling all of the hundreds of KIWI Store located in Norway, requiring only minor adjustments for each individual store due to the similarity between the supermarkets. Another possibility is to reverse the sequence of operation and use the insight obtained by big data and machine learning as some kind of digital energy adviser. As described in Section 6.2.3, SMA provides systems both for the residential and commercial sector with an energy management system and a digital energy adviser integrated in the same system. They advice that the energy management system is first put into operation, and by machine learning and connection to product databases and other databases, it might suggest if and to which extent storages, PV systems, etc. should be installed to save costs or obtain other goals [115]. Maybe it would suggest adding electrical charging at a certain price to KIWIs customers, as earlier mentioned in the discussion section? It is easy to imagine that such a digital energy adviser has larger potential than a human being giving advice based on a much smaller memory and scope of data. If KIWI Dalgård was connected as part of a larger power control system, the optimized scheduling system probably would come with a lower cost per supermarket and yield increased attractiveness for stakeholders.

MAS was covered in the theory section as a promising control strategy for commercial buildings with PV, however it was not included in case study simulations as it would be in conflict with the logic framework which was already established in the BAS of the case study. An interesting question is how the system would perform if all the load, generation and storage devices were controlled by agents. To make evaluations, an hierarchical agent topology is assumed as described in Section 6.3.4. Firstly, a MAS with a real time control system is assumed, with one agent responsible for peak shaving, one for load shifting, one for PV self-consumption and one for availability. Each hour, they may send set point suggestions to the chief agent, based on their communication with the field agents controlling the devices. The suggestions may be organized as offers including cost and savings by the suggested actions, and a chief agent may tell which offers which are accepted for the next hour. The responsibility for operation according to control decisions made by the chief agent, could be shared among the field agents controlling the storage and other flexible loads by distributing a "token", depending on their simultaneous capability and cost for doing so. When allowing the agents to interact, multiple flexibility sources may be working together without needing to make complex control algorithms. If some components were to be replaced or added, only the agent controlling the modified device would need to be reconfigured, and no change would be needed in the optimization algorithms. More reliability would also be added by a decentralized structure. The value of the MAS would increase with larger component groups theoretically equipped for doing the same task, for example increase demand. If an optimized dispatch model was to be assumed, the optimization algorithms may need to be stated otherwise than for the case study. As long as the optimization model includes all individual components and their state at any given time, and the output is who should do what at any given time, no flexibility is set off for agent interaction. The strength of the MAS structure may be viewed more easily when running many scenarios over the system lifetime, where agent interactions provide added value to the systems. Also, savings by replacing deterministic logic frames may be included, if a new installation is about to be constructed.

The large degree of stable thermal loads in supermarkets makes thermal storages relevant, by enabling them to offer all year charge and discharge opportunities to a power control system. Cons when choosing a thermal storage are their potential for low cost, high efficiency, no security issues and up to infinite cycle life. PCM was found to be the most relevant thermal storage technology for supermarkets, due to their compactness and availability for offering cooling at a fixed temperature, which is particularly important due to strict food storage requirements. The suggested storage solution for KIWI Dalgård is still in the research phase, and make a future alternative for supermarkets. If smart power control was to be installed today, an electrical battery is a good alternative which does not require existing installations to be reconfigured. However, using a different storage might change which of the control objectives that should be implemented, and it might especially affect control objectives only motivated by economic savings, assuming that the thermal storage would be cheaper. Due to the limited cycle life of batteries, costs by running a cycle should also be reflected in the control algorithms. In economic terms, an electrical storage should only be activated when its cycle cost is lower than the savings made by running the cycle, and it is not believed that load shifting will be economically viable today for electric batteries, due to the flat spot pricing curves. The peak grid tariff in Trondheim is 500 NOK/kW, and if the battery lifetime is 10 years and focus is on peak shaving only, the battery should have a less than 5000 NOK/kW installation if the payback method is used. Assumption in this calculation is that no synergies are assumed and that energy capacity is not a constraint. Another disadvantage is that if a Li-ion battery was chosen, it probably would have to be located in an outside container due to safety issues, which would further increase costs. Self-consumption of PV electricity is not necessarily only motivated by economic savings, and the owner needs to determine which economic requirements should be imposed on the system. According to Figure 21 in Section 5.1.2, SOC_{avg} and SOC_{swing} should be considered included in the optimization algorithms for economic operation of the storage, due to their impact on battery lifetime. Some advantages are also present when choosing an electrical storage. An electrical storage has more flexibility and potential synergies than a thermal storage in present and future operation, for instance it may be used to provide ancillary services to the grid. Its availability is also probably more secure than for the PCM cooling cases, as the latter depend on the cooling load level in the cases, which probably varies with refilling of products, defrost operations and opening and closing of doors. A centralized thermal PCM storage could also be considered as an alternative for KIWI Dalgård. One drawback of this solution is that the centralized cooling circuit would need to be modified to include the storage, which would lead to increased costs and might affect cooling system warranties.

The uncertainty embedded in the results are mainly included in the validity of the assumptions being made for the different elements composing the control system. Uncertainty accumulates in the modeling chain by subsystems and inputs being dependent on each other. To conduct simulations for a full year only based on historical data, multiple assumptions needed to be made. Cooling load data were based on estimations made by the supplier of the cooling cases. The total load data were obtained by adapting monitored data from reference installations, based on conversations with key KIWI personnel. The PV generation was based on PVsyst simulations for a random year, and not on measured data. The storage was dimensioned with basis in the assumed load and PV generation data, and a storage technology from a university research project was chosen. For each subsystem like storage, PV system etc, assessment could also have been made regarding uncertainty for each modeled component in the system. In the case study, theoretical simulations were conducted, not taking practical constraints deviating from ideal behavior into account. Some input factors were made with higher quality than what would have been available for a real time system. One example is assumptions made during forecasting. Both for the optimized scheduling system and real time control system, a perfect prediction was assumed to allow historical data to be directly injected into the model and allowing for a full year simulation. This allowed the controller to avoid losses due to prediction errors. Another source of insecurity is the discharge availability of the PCM storage integrated in the cooling cases, which in reality depends on the cooling case load at any given time. Among other simplifications is that practical communication challenges regarding speed and protocols were not addressed in the simulations, as theoretical simulations with perfect communication capabilities were conducted. Generally, the energy business is not an exact science, and is influenced by many uncontrollable factors like human behavior and weather. By all the assumptions made in the various building blocks and dependent elements of the system, there is no guarantee that the system in real operation would give results according to the ones obtained in this study. The tendency of idealized assumptions in many cases makes it more probable that the obtained results show the potential of the controllers given a defined set of constraints. Although the accumulated uncertainty is large, this is not necessarily a problem. On the contrary, such modeling might be wanted by involved stakeholders. The ever ongoing dilemma by modelers is that better models can be made, but at a certain point no one would be willing to pay for it. Time consumption has value, and balanced decisions need to be made continually in the planning process. By transparency of risk related areas, decision makers may have an adequate platform despite the many simplifications made when modeling a complex system like a power control system.

Potential assessment is an important part of early phase power control design. By data handling in Microsoft Excel, an early assessment of potential savings by smart power control was it made, which formed a basis for the selection of a low tech thermal storage. The estimations showed compliance with results which were later obtained by case study simulations. Transparent and available load, generation and price data from the case study, along with fairly simple business cases, made it quite easy to predict savings with a reasonable accuracy. By experience and knowledge of the market, along with the good data which was available, a choice of a suitable power control system could have been made by an early economic potential assessment, and some alternatives could have been put on hold at an early stage. By doing this, a lot of resources may have been saved in the planning phase. For this study, it was decided to continue with case study simulations of two selected systems because from an academic viewpoint, the relative performance of the controllers made highly interesting inputs to the scenario analysis, sensitivity analysis and the discussion. In Section 7, it was claimed that "the cost by stepping up to an optimized scheduling system needs to be justified by the added value, and consequently a market will probably be present for both control structures". It may be concluded that a medium sized supermarket with an average consumption of 35 kW may be too small for justifying complex control structures with forecasting and multiple inputs. However, potentials and benefits of a complex and powerful control systems were identified also for a relatively small case study, and once larger saving potentials are identified in an early project assessment it may be a relevant alternative. It is believed that revenue can be made within today's market framework, when the case study installations and services are properly designed for it, seen from a building operator perspective. Other stakeholders that may have interest in smart power control, are utilities, politicians and the society as whole, as large grid investments may be avoided and a larger penetration of renewable DG can be penetrated into the grid. Political incentive structures should be made so that building operators get their share of their added benefits and cost savings to the society. To maximize social welfare, incentives may be targeted to regions where smart power control is needed to avoid alternative investments, solve problems or facilitate other political goals.

10 Conclusion and Future Research

This chapter contains the concluding remarks from the work, and suggests further research objectives.

10.1 Concluding Remarks

Changes in both the political environment and the market create an increased demand and business opportunities regarding smart power control. Conventional control methods may struggle to facilitate a flexible and robust design when many control objectives are desired simultaneously. Many smart control strategies are suggested in the global research field, among them being MAS, fuzzy logic and optimized dispatch. Smart power control strategies offer large technological opportunities. They may be adapted to conventional BAS frameworks or constitute a framework of its own for general building automation. By utilizing computational intelligence and big data handling, large and complex systems may be broken down to interactive subsystems and mathematical formulations which may handle a large variety of interests and constraints, and promote reliability and flexibility. Realistic electricity pricing schemes now and in the near future provide cost saving opportunities by peak shaving, increased self-consumption and load shifting by electricity price variations.

For the case study, the proposed power control strategies of fuzzy logic real time control and optimized dispatch performed technically well according to stated control objectives, however it proved difficult to generate economic revenue. The best performing control structure, the optimized scheduling system, mitigated yearly electricity costs by 3.5 %, of which the largest savings were obtained by peak shaving. The potential savings of control objectives regarding self-consumption and load shifting are strongly related to the level of grid tariff fees and electricity price level variations, which are very low in Norway. Other constraints on the yearly savings were case study defined. The initial PV system design of KIWI Dalgård already had a high degree of self-consumption of PV electricity, and left only small potential for improvements. Before smart power control was added, 97 % of the PV electricity was already directly self-consumed by the load. Also, the energy efficient and well operated supermarket which was investigated offered a very flat load curve with small potential for peak shaving and load shifting. For such a case, no control or a simple real time control structure requiring a minimum level of set-up time and installations seems to be the most economically viable. More complex control structures based on forecasting, like the optimized scheduling system, are easier justified when used in a more suitable application.

The relevance of smart power control increases with large grid tariffs, excess of distributed generation, sharp peak loads, large variation of electricity prices, and the number of synergies which can be integrated so that alternative cost components can be reduced.

10.2 Future Research

Suggested areas for further research in this topic include:

- An assessment of which type and size of buildings which are most promising regarding the utilization of smart power control systems.
- Conducting simulations for a full new year where the load and generation data are not known ahead, to see how the system performs.
- Including the component cost, start up costs and systems cost in the models and make a total evaluation of economic performance. This should be done for a case where economic sustainability is more realistic. Also, evaluate future expected costs for the various elements of the system and assume its future attractiveness.
- For a building type and size which yield large potential for large power control: Identify potential synergies and storages which can be integrated in the initial design of the building process without

raising costs significantly. What additional services can be added to maximize the degree of self-sufficiency and minimize electricity costs?

- Developing realistic business cases for providing ancillary services to the grid. Identify possibilities and challenges for various stakeholders. Evaluate system requirements to make the business case attractive for the utility, the building owner and from a socioeconomic point of view.
- Designing a suitable case study candidate in a MAS framework which integrates traditional BAS control with DG and ancillary services to the grid, based on optimization algorithms. The VOLTTRON system or other free and open systems for university students might be suitable. When assessing economic potential, include realistic scenarios like changed and broken equipment over the system lifetime, and the value of added reliability for the user.

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Appendices

A Case Study - Load Data

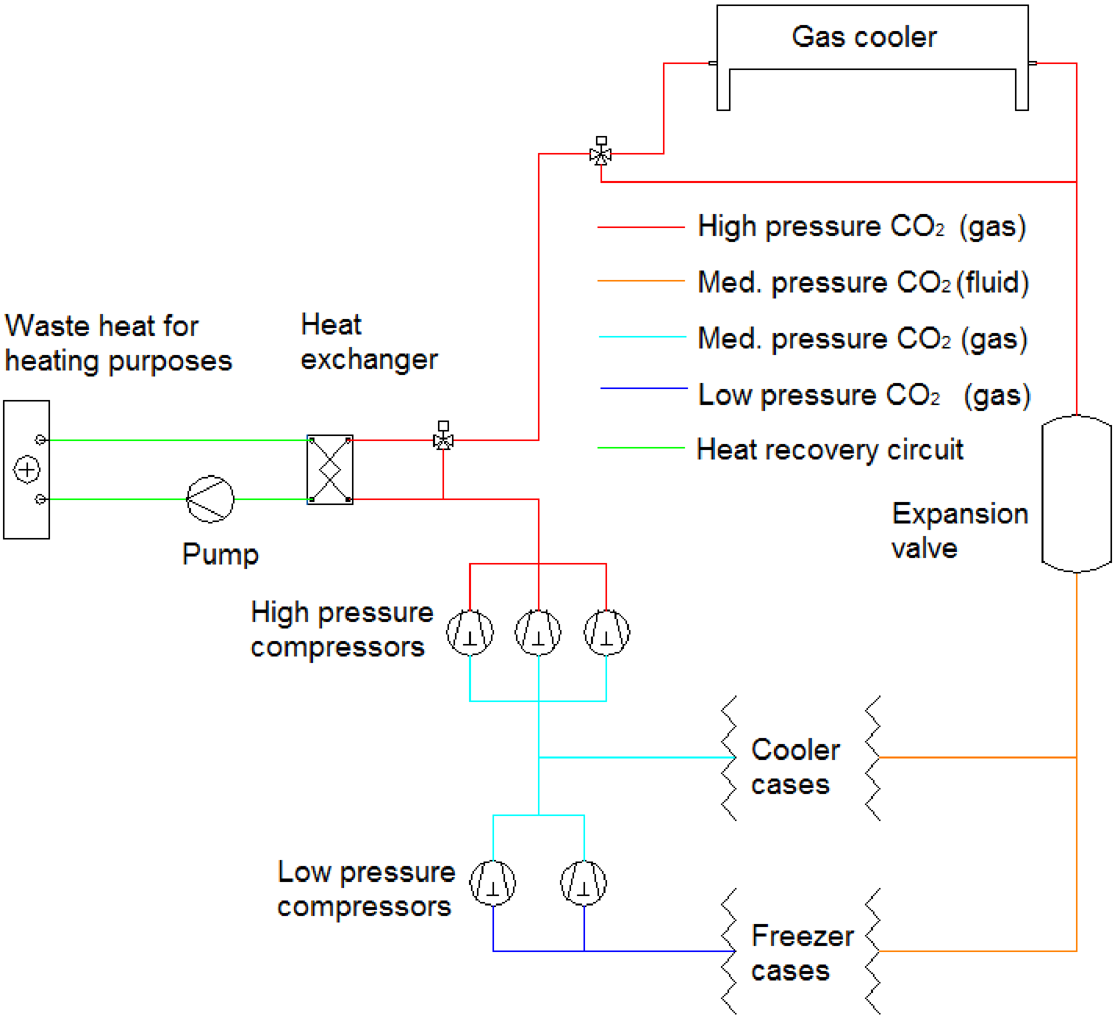


Figure 47: Centralized cooling configuration of KIWI Dalgård

Category	Set point temperature [°C]	Differential [°C]
Freezer cases	-20	4
Fruit	6	4
Beer and mineral water	6	4
Diary products	2	2
Other	3	4

Table 19: Storage temperatures of chilled products in a typical KIWI supermarket

B Case Study - PV System Design

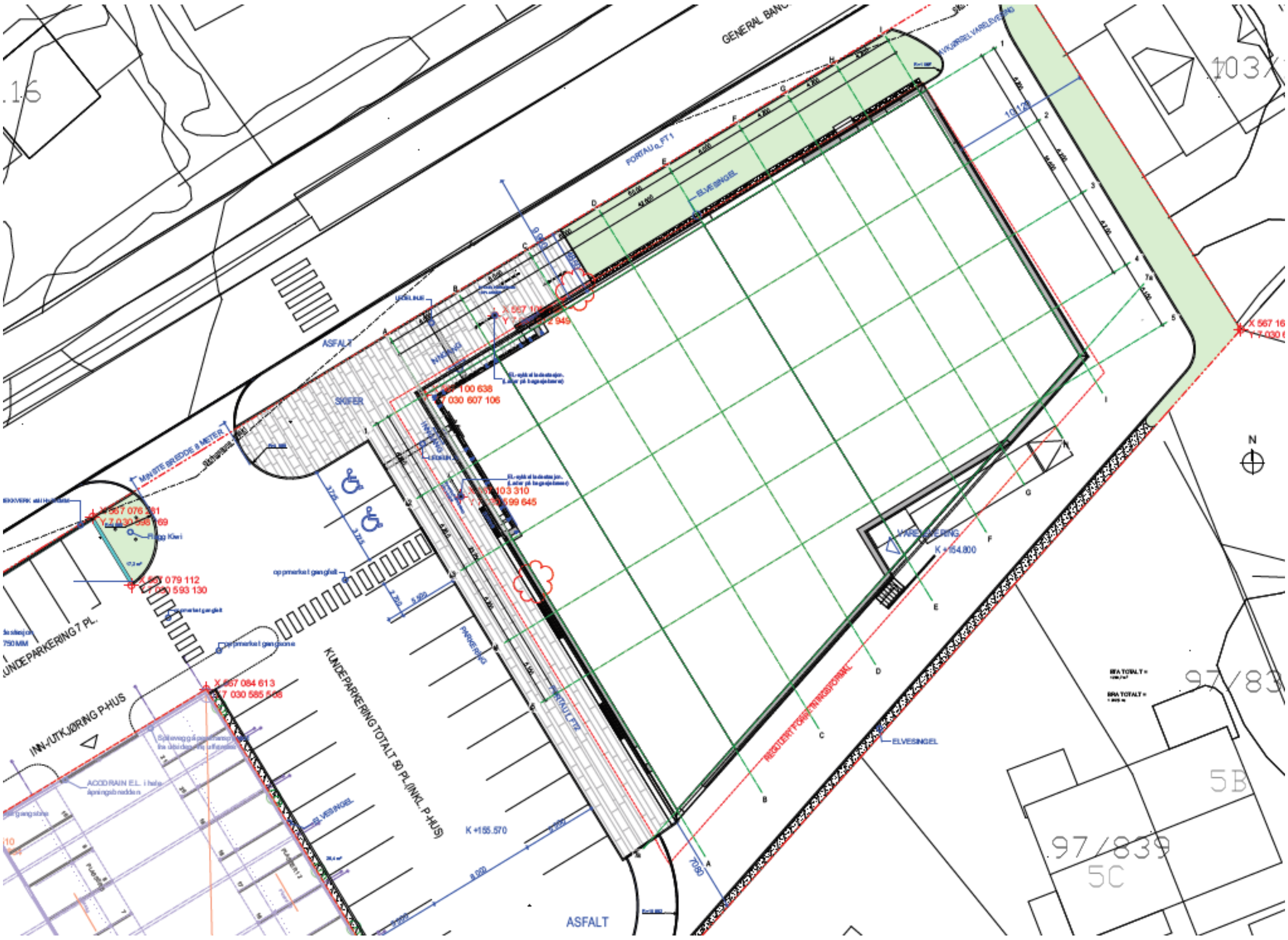


Figure 48: Orientation of KIWI Dalgård

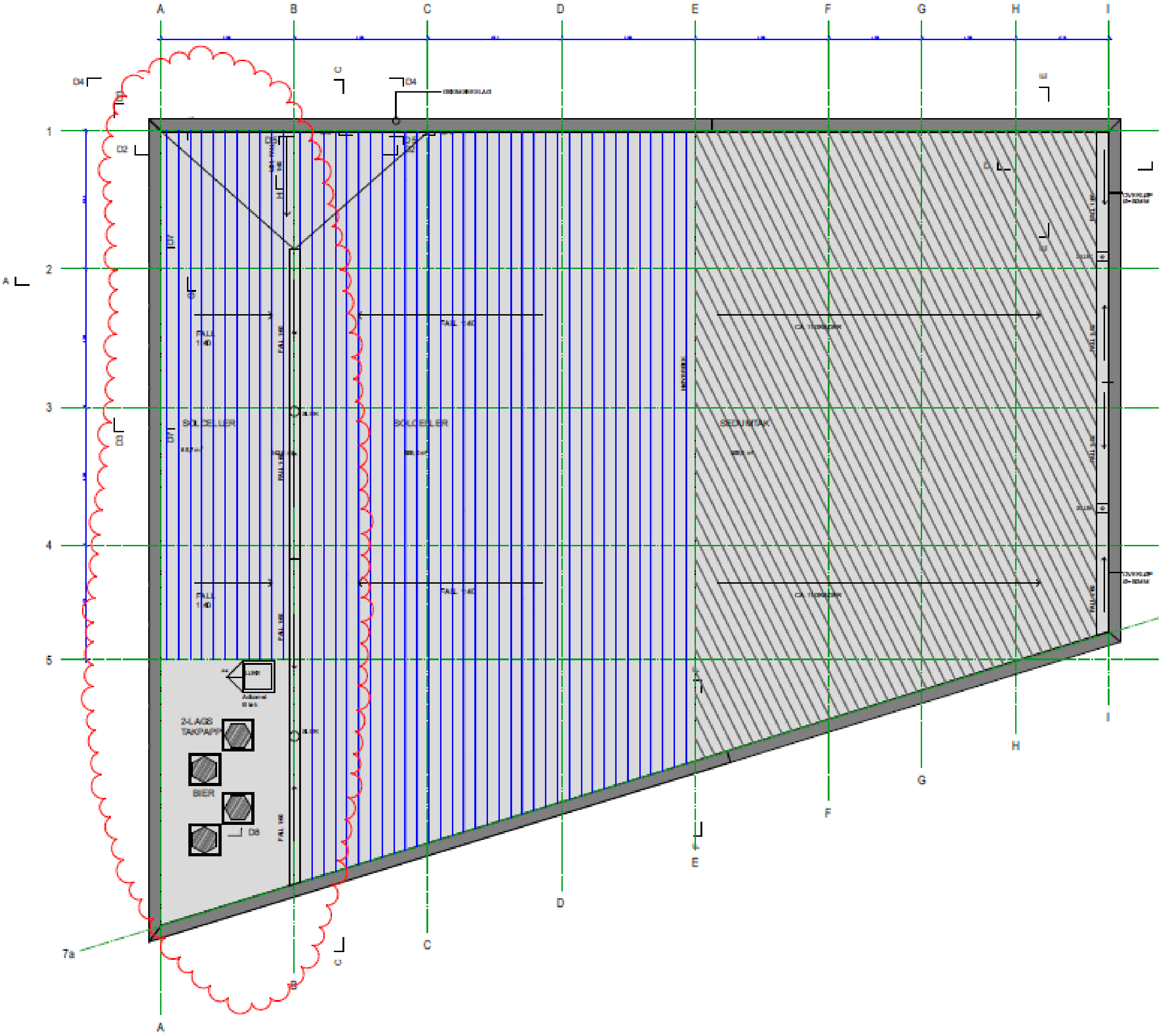


Figure 49: KIWI Dalgård - Planned PV area on rooftop, marked in blue

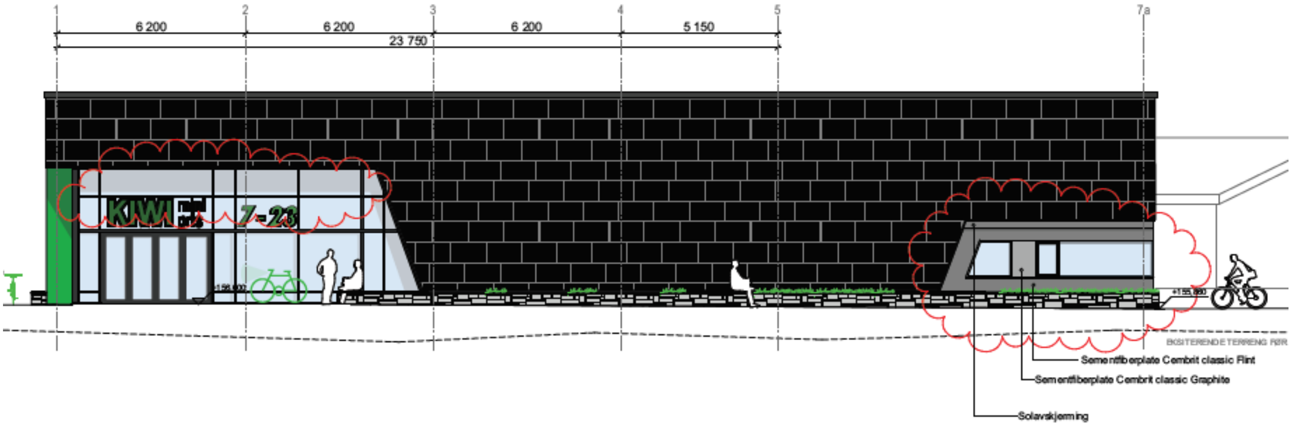


Figure 50: KIWI Dalgård - Planned PV area on the southwestern facade, marked by black facade panels

Figure 51: KIWI Dalgård - Planned PV area on the northwestern facade, marked by black facade panels

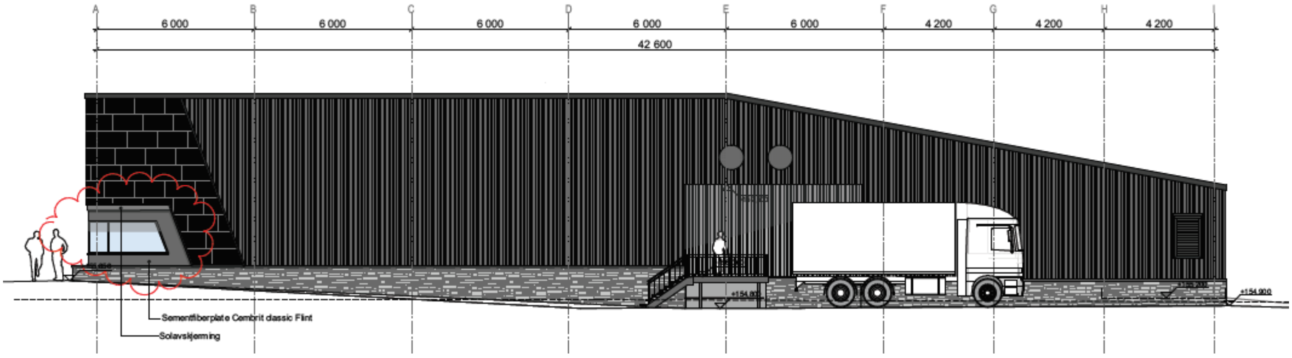


Figure 52: KIWI Dalgård - Planned PV area on the northeastern facade, marked by black facade panels

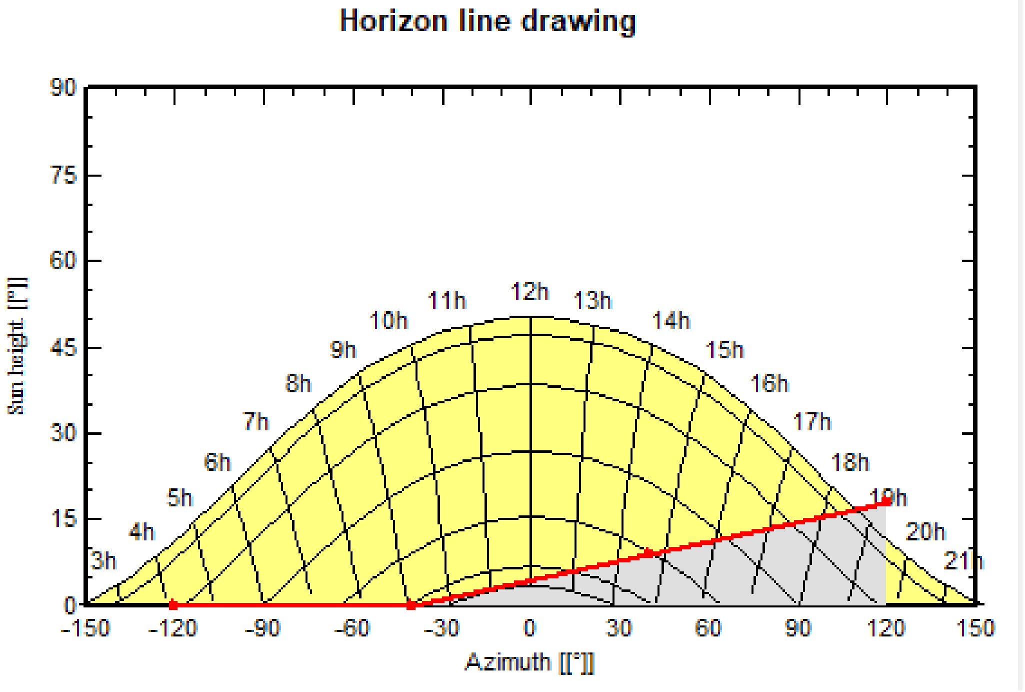


Figure 53: Modelled horizon for KIWI Dalgård

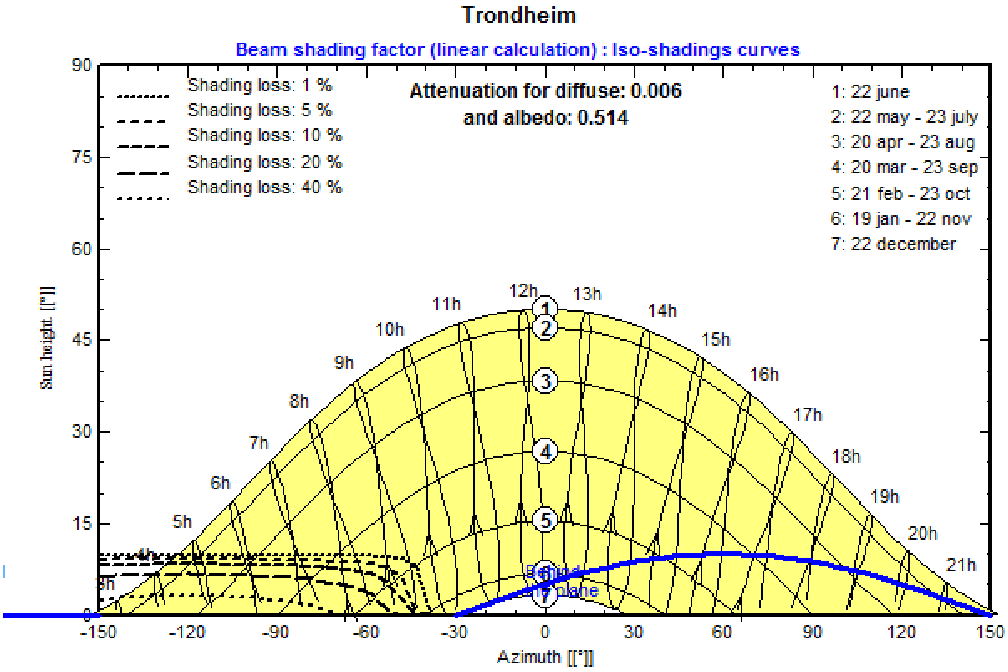


Figure 54: Sun path diagram for northeastern tilted rooftop PV

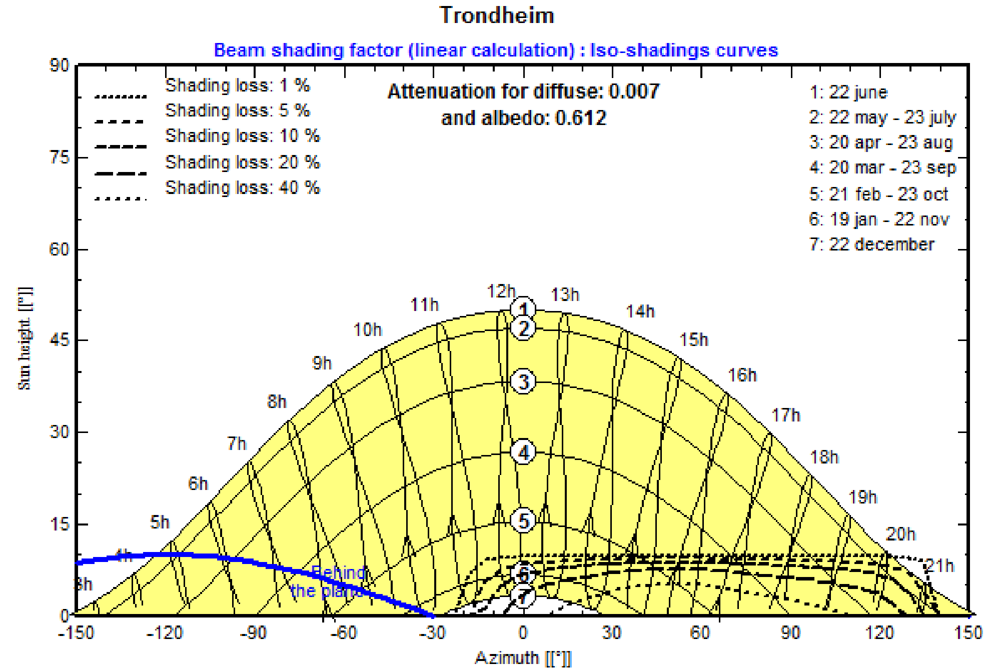


Figure 55: Sun path diagram for southwestern tilted rooftop PV

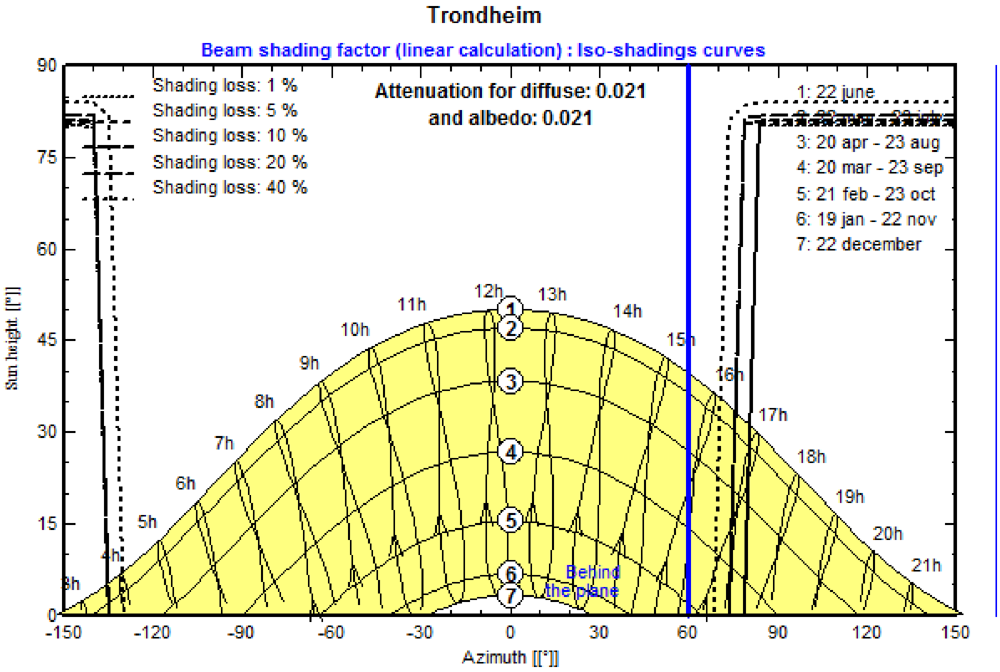


Figure 56: Sun path diagram for northwestern facade

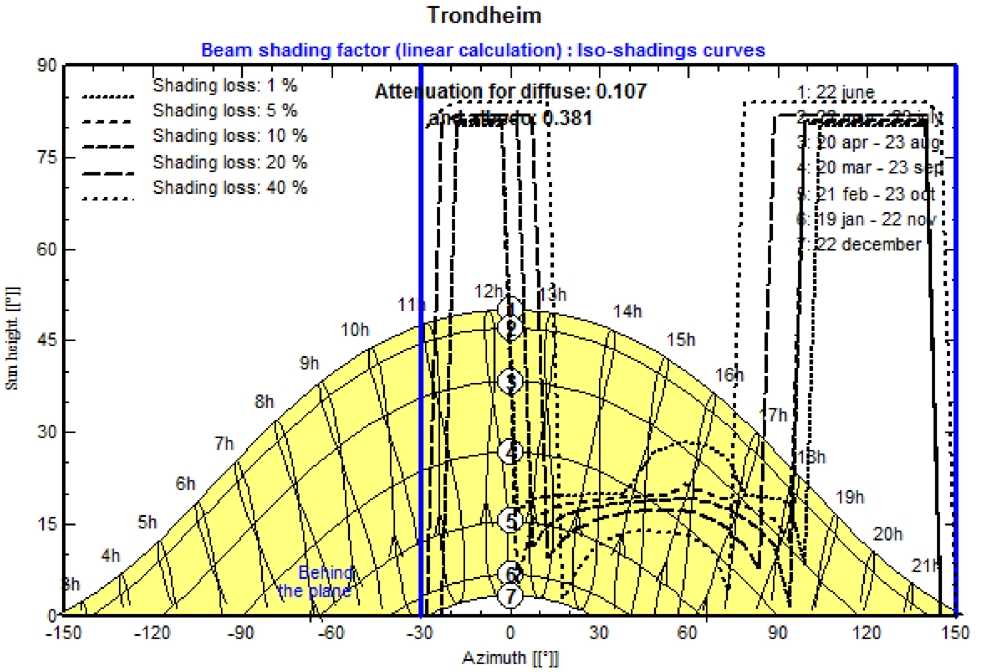


Figure 57: Sun path diagram for southwestern facade

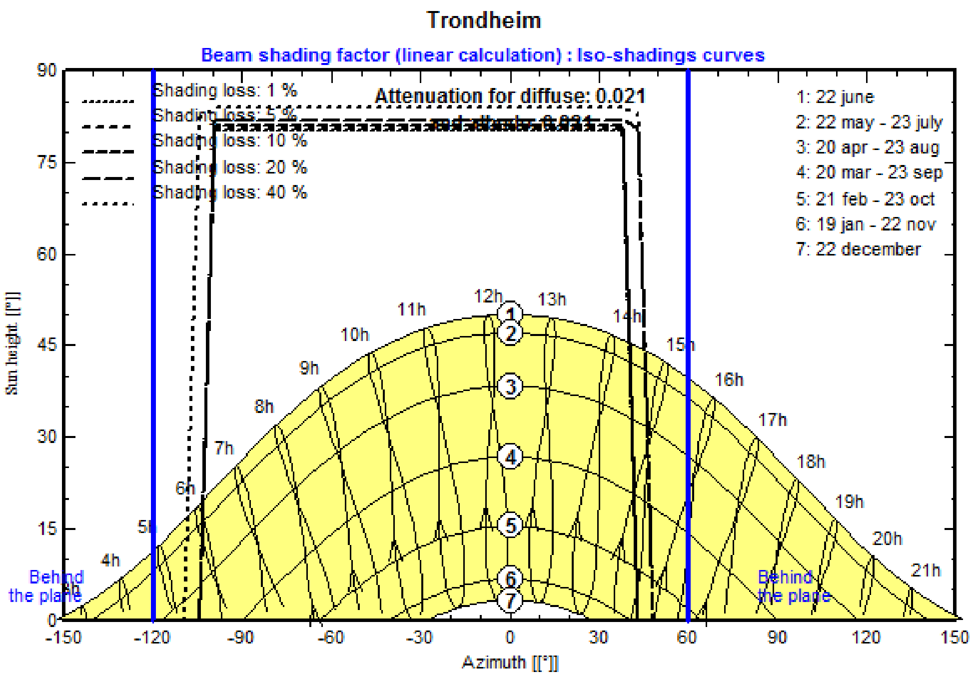
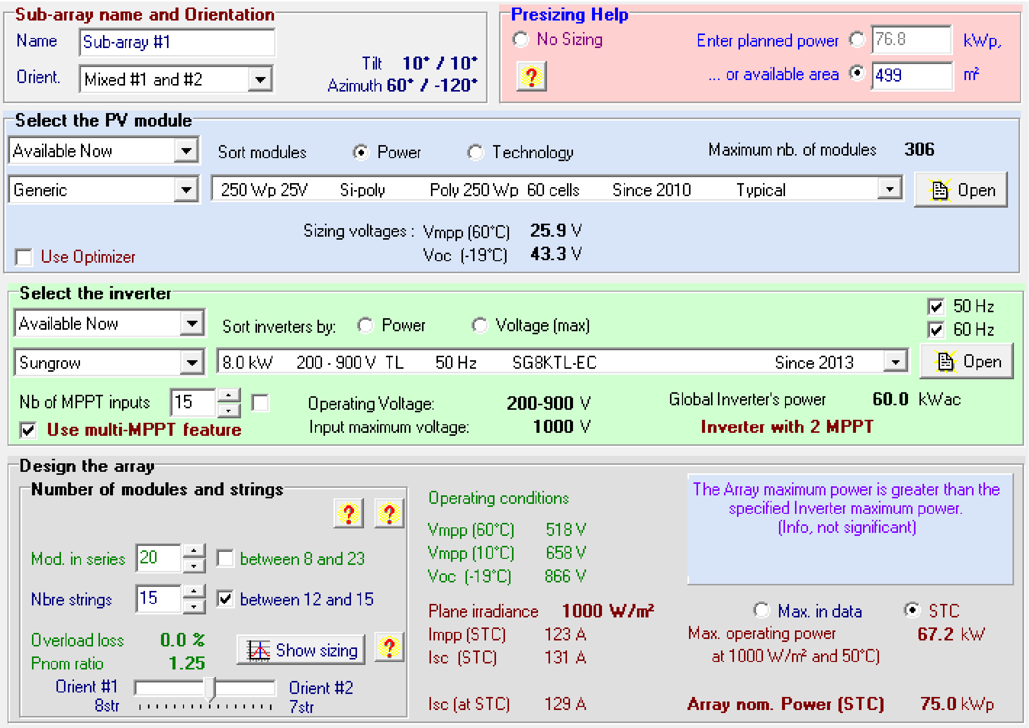


Figure 58: Sun path diagram for southeastern facade



Sub-array name and Orientation

Name: Sub-array #1

Orient.: Mixed #1 and #2

Tilt 10° / 10°

Azimuth 60° / -120°

Presizing Help

○ No Sizing

Enter planned power ○ 76.8 kWp,

... or available area ● 499 m²

Select the PV module

Available Now

Sort modules ● Power ○ Technology

Maximum nb. of modules 306

Generic

250 Wp 25V Si-poly Poly 250 Wp 60 cells Since 2010 Typical

Sizing voltages : Vmpp (60°C) 25.9 V

Voc (-19°C) 43.3 V

☐ Use Optimizer

Select the inverter

Available Now

Sort inverters by: ○ Power ○ Voltage (max)

☑ 50 Hz

☑ 60 Hz

Sungrow

8.0 kW 200 - 900 V TL 50 Hz SG8KTL-EC Since 2013

Nb of MPPT inputs 15 ☐

Operating Voltage: 200-900 V

Input maximum voltage: 1000 V

Global Inverter's power 60.0 kWac

Inverter with 2 MPPT

☑ Use multi-MPPT feature

Design the array

Number of modules and strings

Mod. in series 20 ☐ between 8 and 23

Nbre strings 15 ☑ between 12 and 15

Overload loss 0.0 %

Pnom ratio 1.25

Orient #1 8str

Orient #2 7str

Operating conditions

Vmpp (60°C) 518 V

Vmpp (10°C) 658 V

Voc (-19°C) 866 V

Plane irradiance 1000 W/m²

Impp (STC) 123 A

Isc (STC) 131 A

Isc (at STC) 129 A

The Array maximum power is greater than the specified Inverter maximum power. (Info, not significant)

○ Max. in data ● STC

Max. operating power at 1000 W/m² and 50°C) 67.2 kW

Array nom. Power (STC) 75.0 kWp

Figure 59: Rooftop system selection in PVsyst

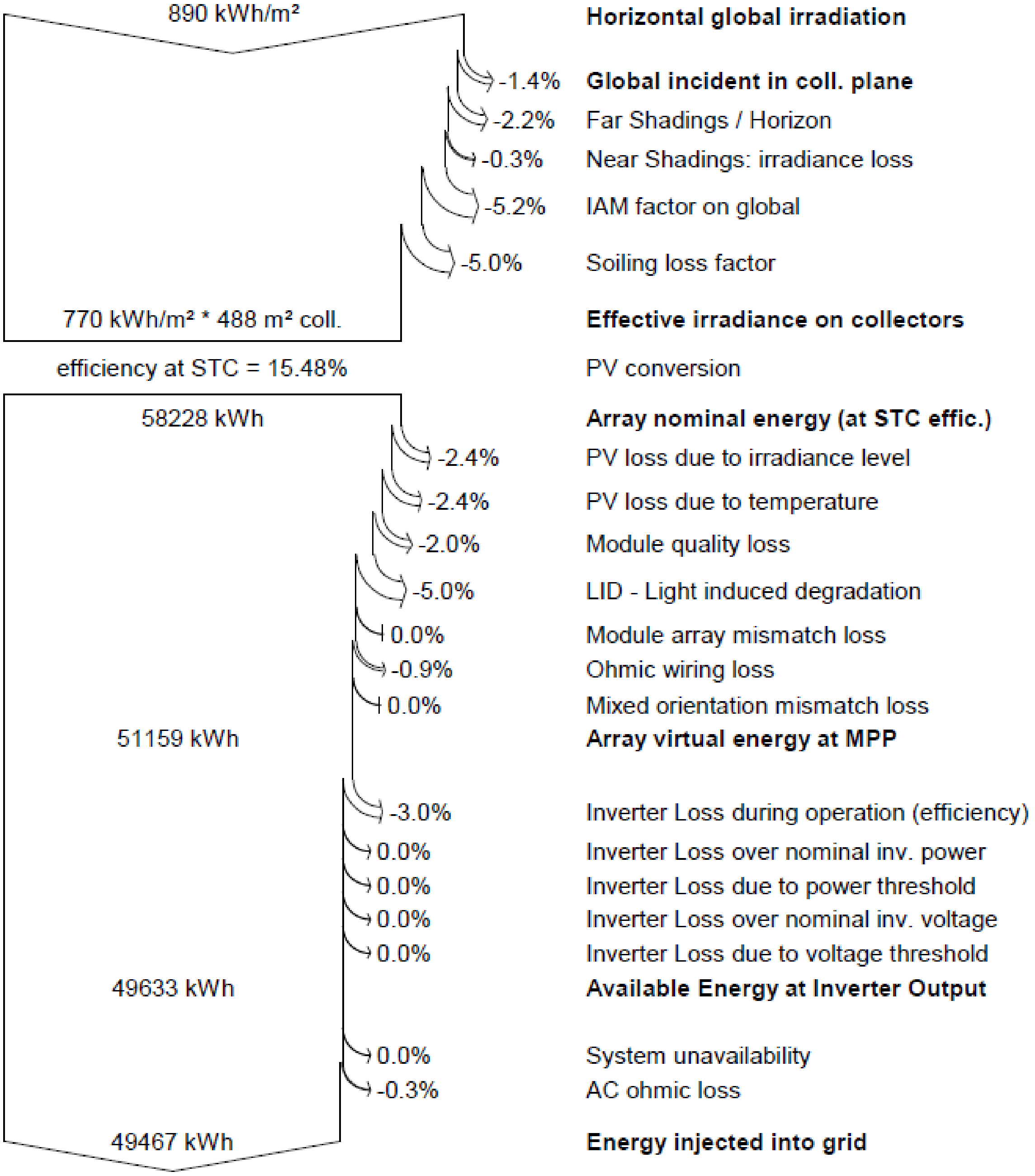


Figure 60: Rooftop system losses according to PVSyst

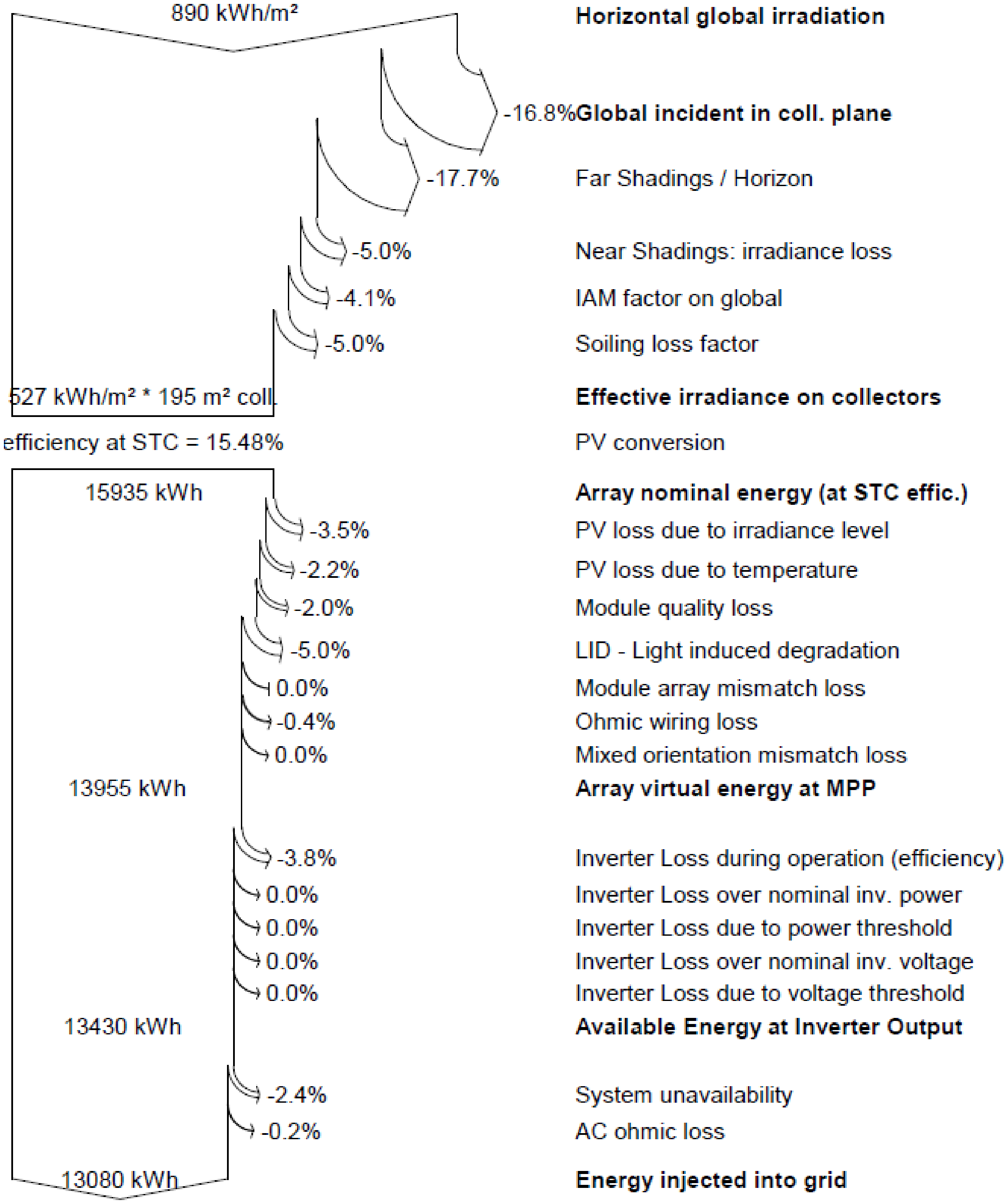


Figure 61: Facade system losses according to PVSyst

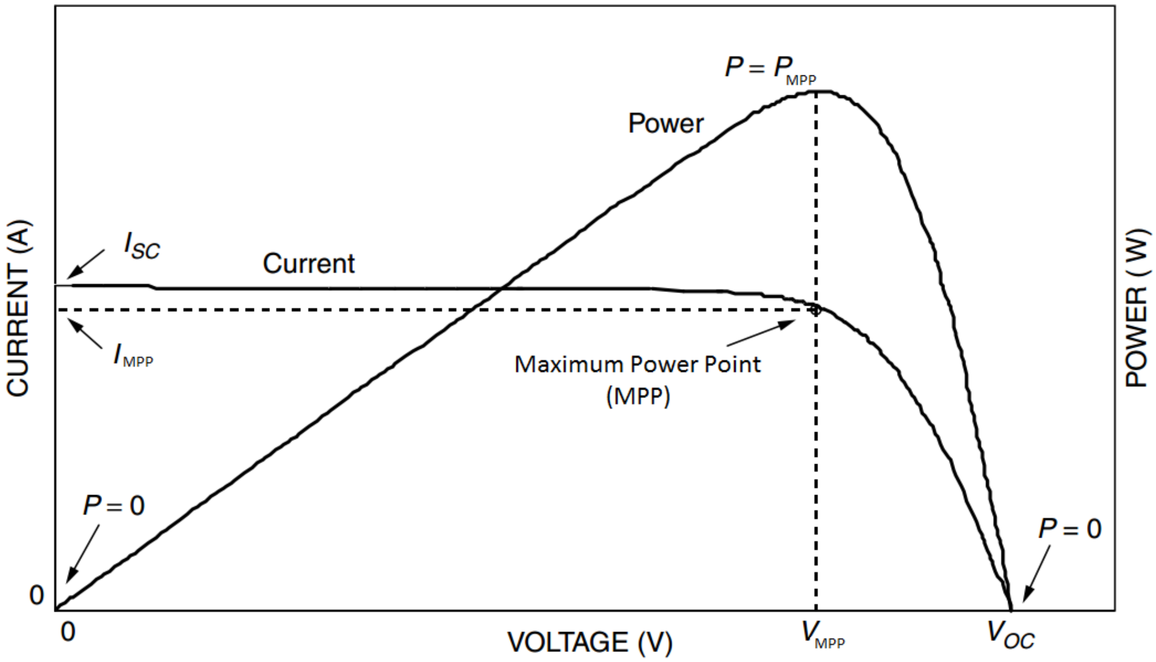


Figure 62: The IV-curve and power output of a PV module

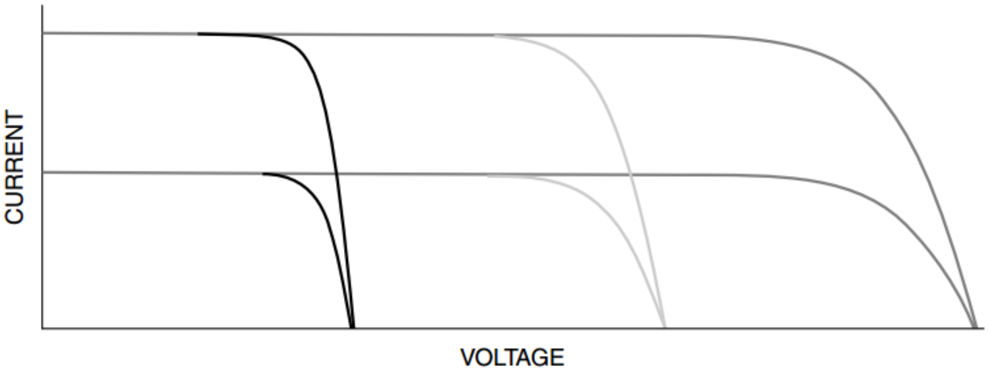


Figure 63: IV-curve of an array consisting of two strings of three modules each

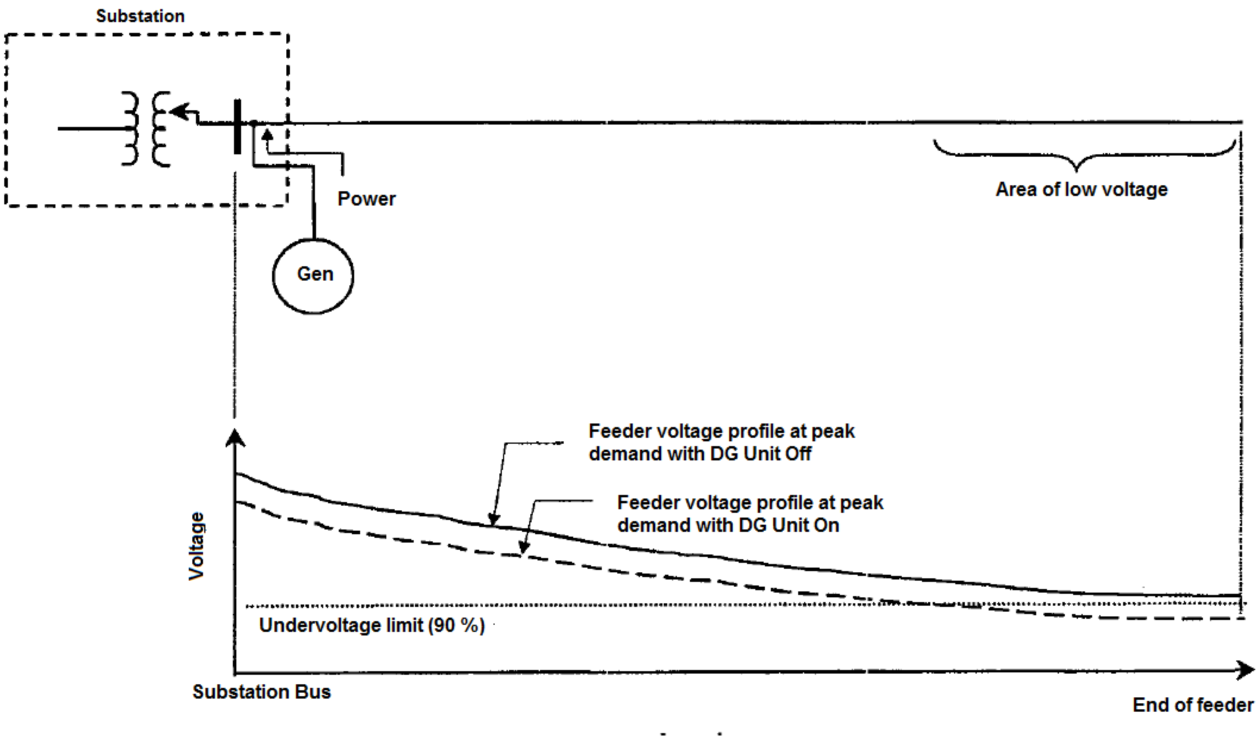


Figure 64: Example of PV interfering with local voltage control

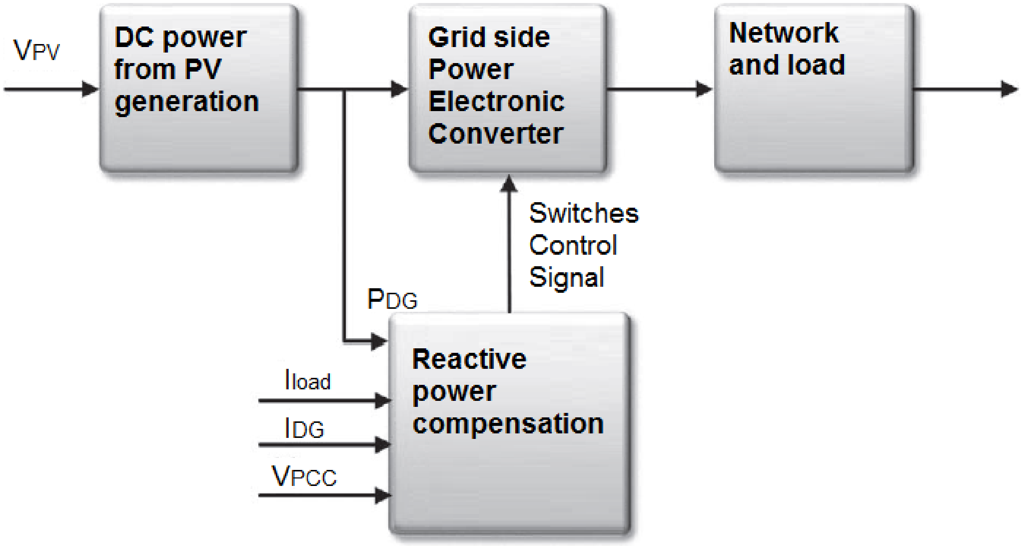


Figure 65: Inverter control of reactive power, assymetry and mitigation of harmonics

C Storage Theory

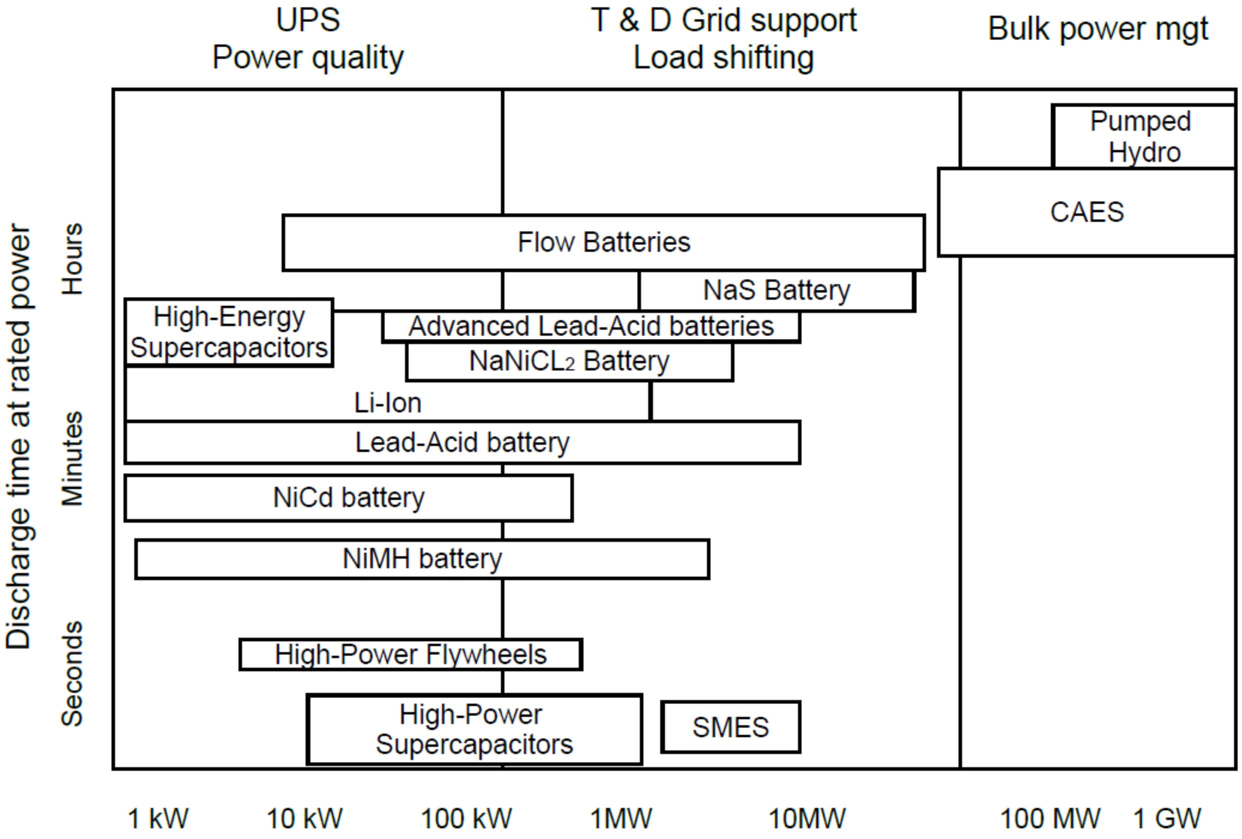


Figure 66: Comparison of electrical storage power ratings

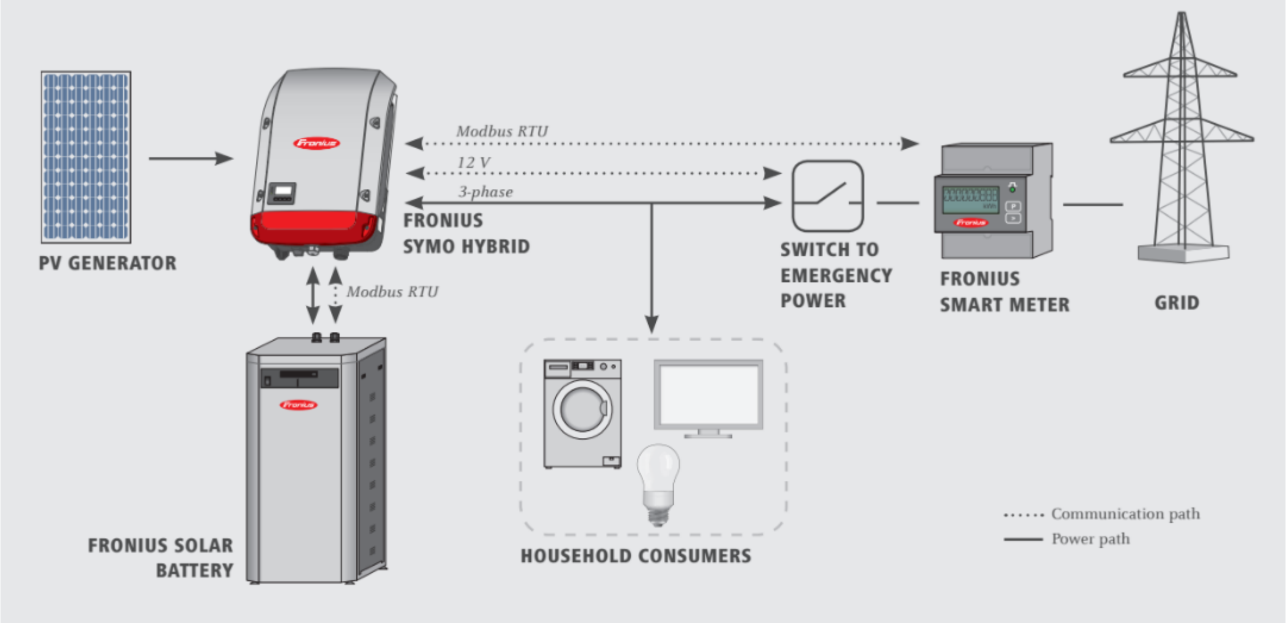


Figure 67: Fronius Energy Package - configuration diagram DC system

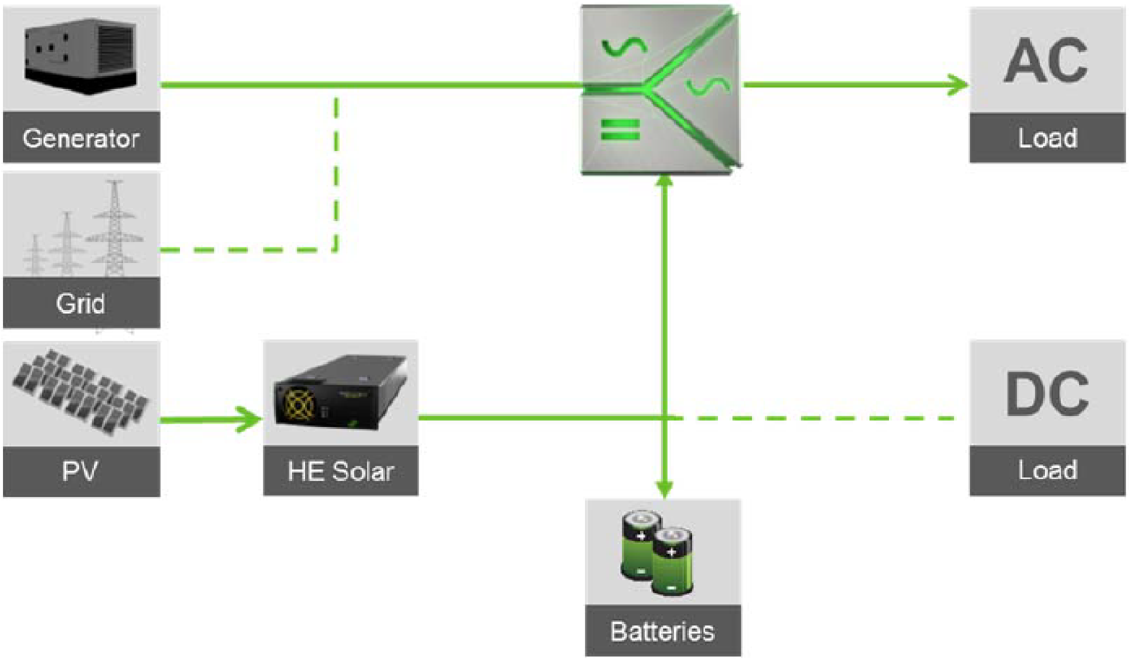


Figure 68: Eltek microgrid system - example configuration

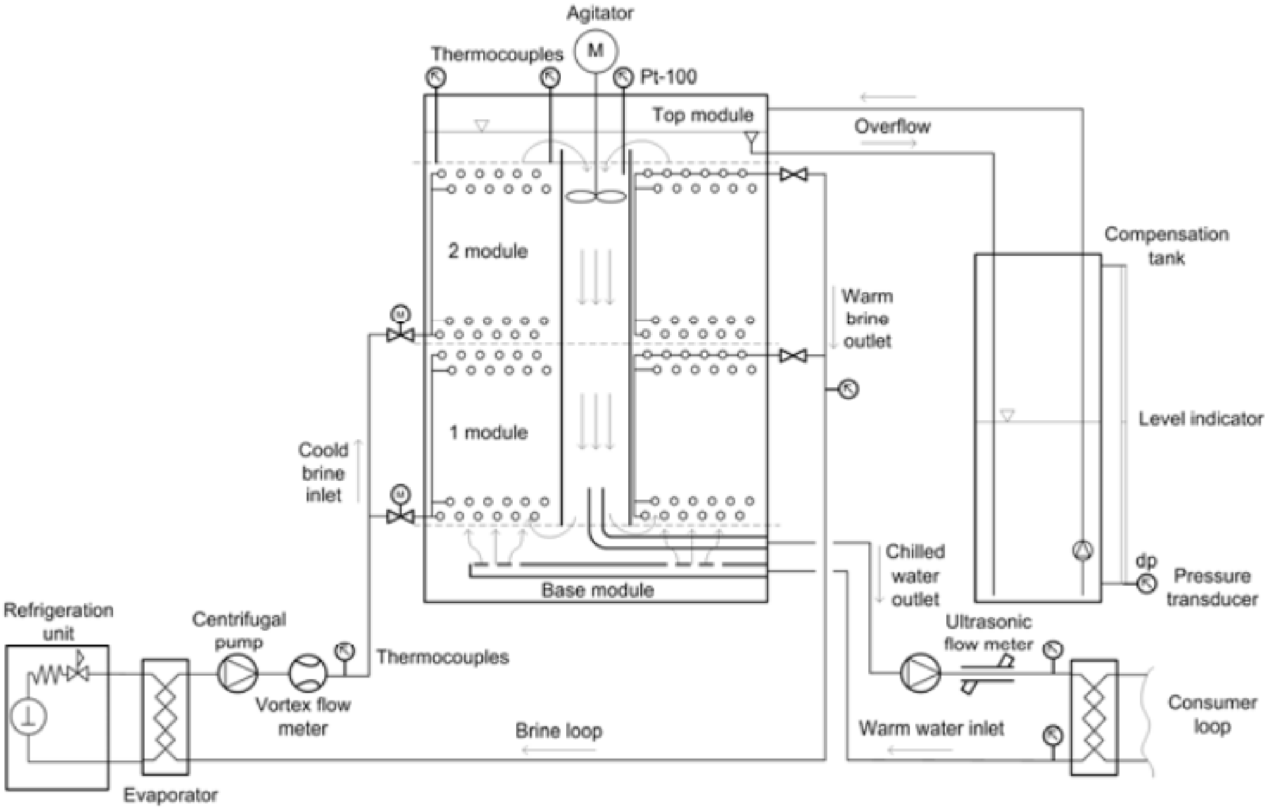


Figure 69: Ice bank cooling system used for diary application

D BAS Strategy Theory

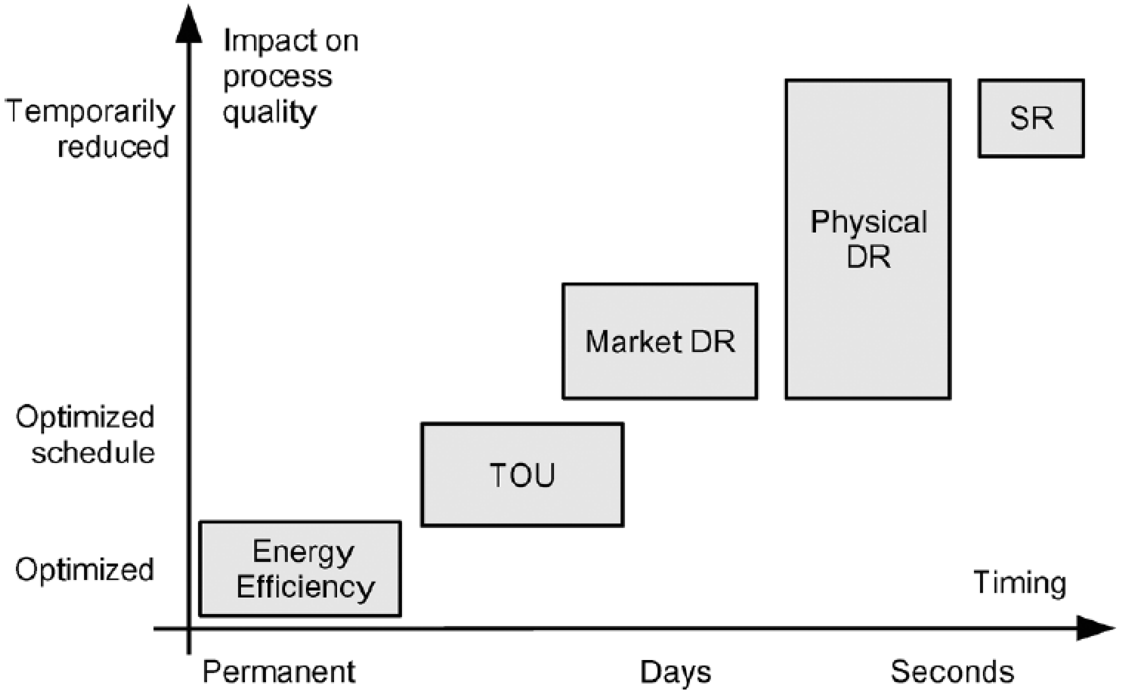


Figure 70: Categories of DSM

E BAS Design Examples

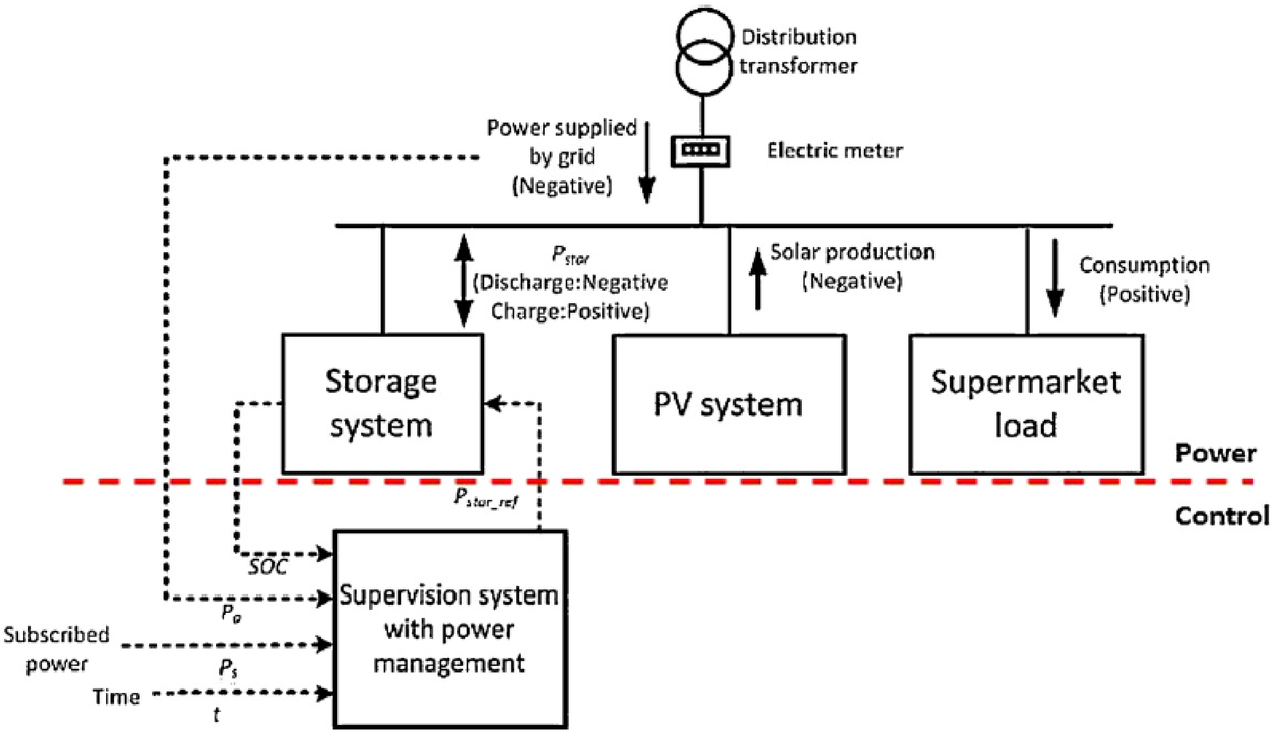


Figure 71: Suggested fuzzy logic control scheme by Zhang et al.

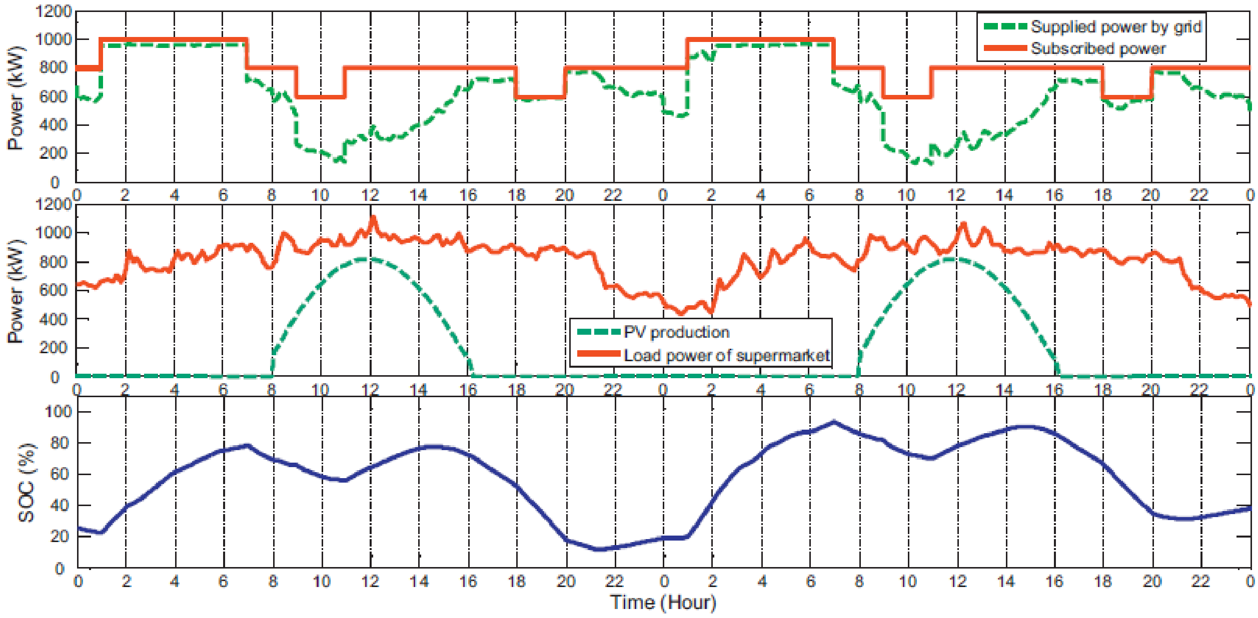


Figure 72: Result - Two day simulation of fuzzy rule base control system by Zhang

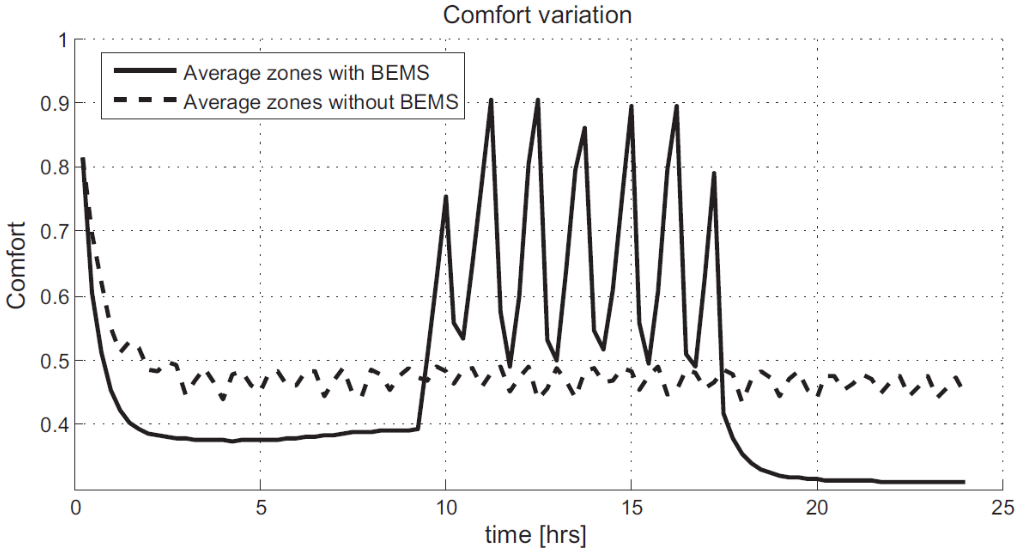
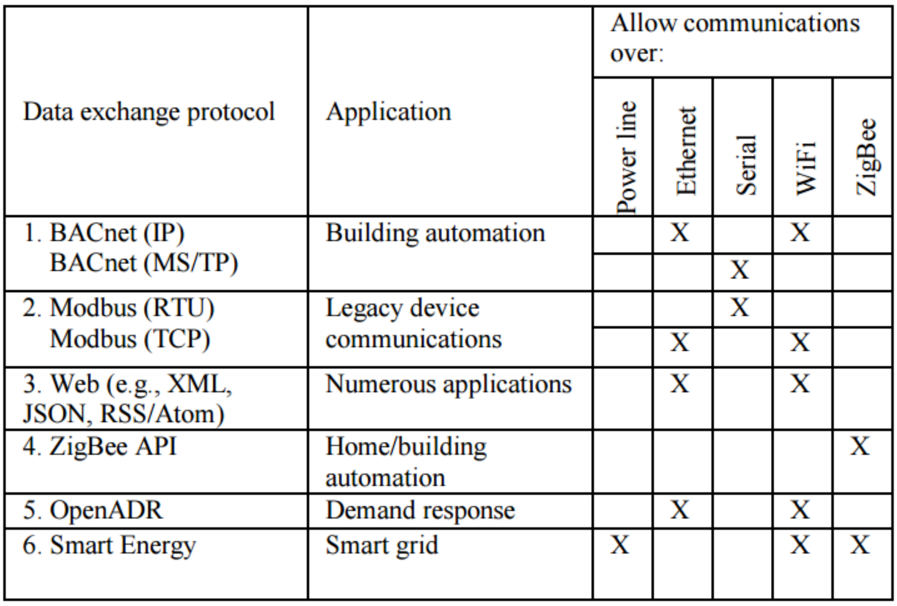


Figure 73: Comfort level results, real time control by MAS with fuzzy logic reasoning



Data exchange protocol	Application	Allow communications over:				
		Power line	Ethernet	Serial	WiFi	ZigBee
1. BACnet (IP)	Building automation		X		X	
BACnet (MS/TP)				X		
2. Modbus (RTU)	Legacy device communications			X		
Modbus (TCP)			X		X	
3. Web (e.g., XML, JSON, RSS/Atom)	Numerous applications		X		X	
4. ZigBee API	Home/building automation					X
5. OpenADR	Demand response		X		X	
6. Smart Energy	Smart grid	X			X	X

Figure 74: Supported BEMOSS communication protocols as of 2014

F Case Study - Fuzzy Logic Control Design

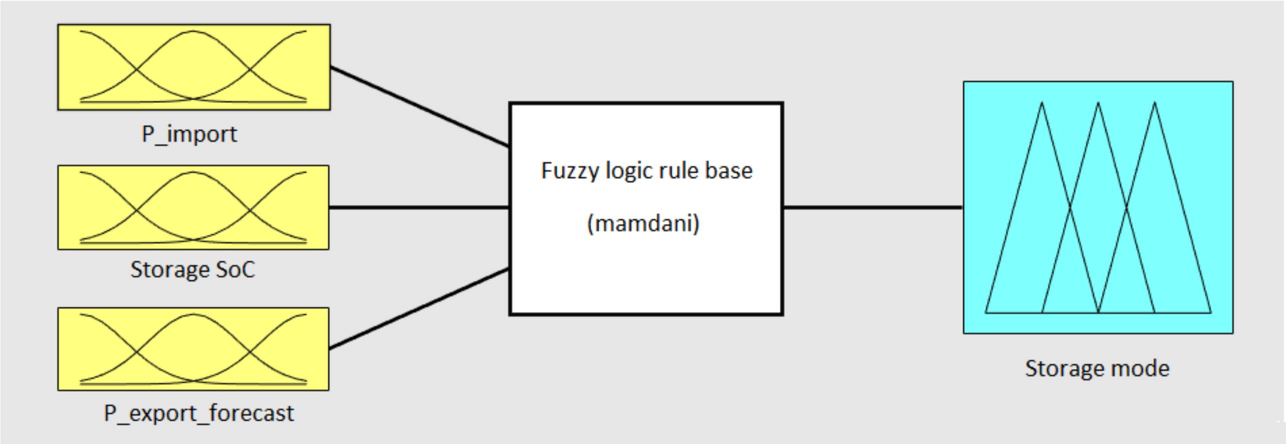


Figure 75: Case study - Fuzzy logic control topology

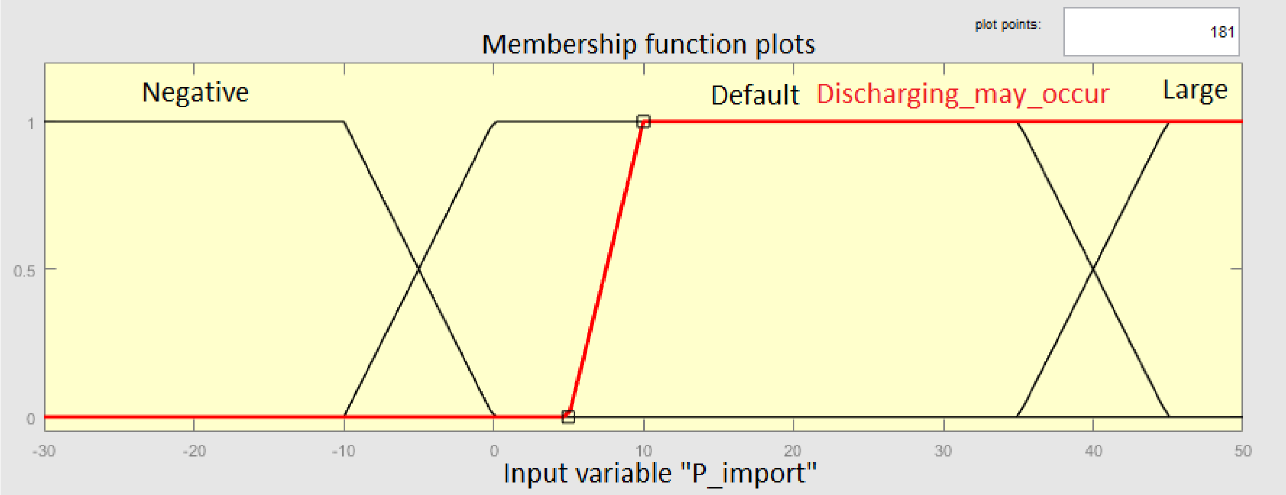


Figure 76: Fuzzification stage - Input variable "P_{import}"

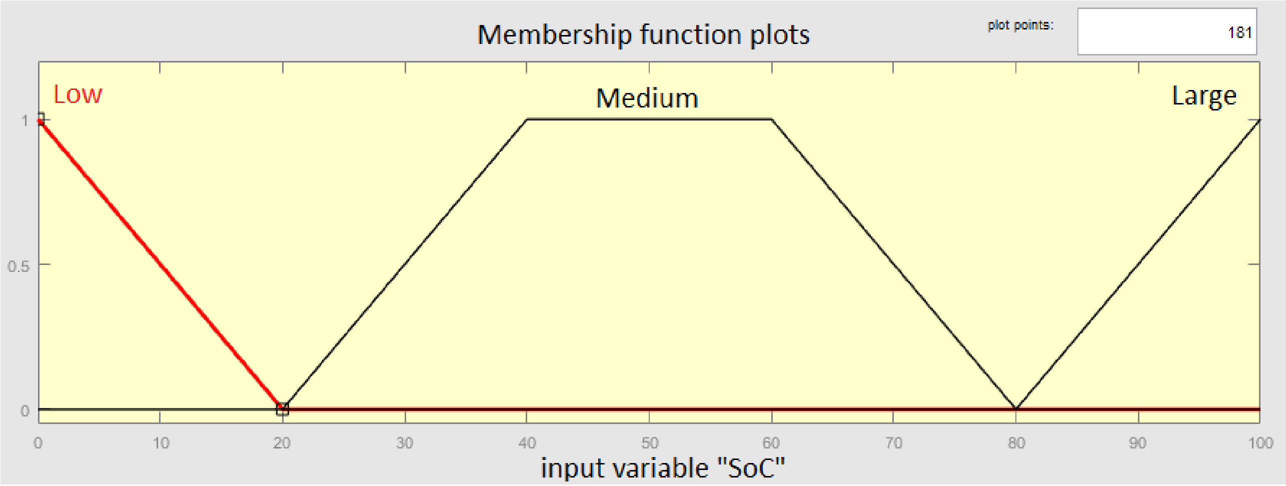


Figure 77: Fuzzification stage - Input variable "SOC"

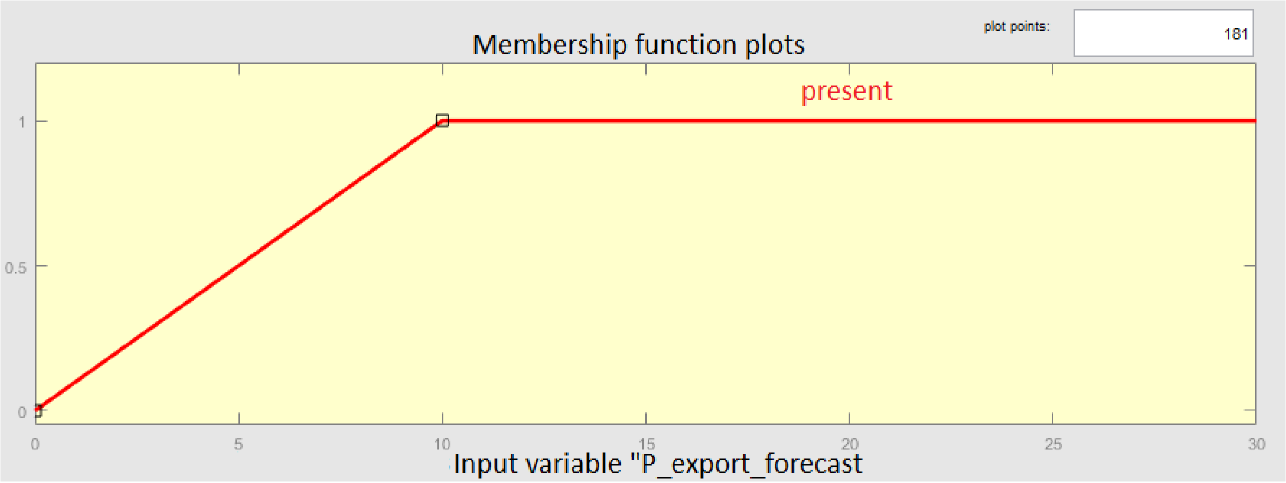


Figure 78: Fuzzification stage - Input variable "$P_{exportforecast}$"

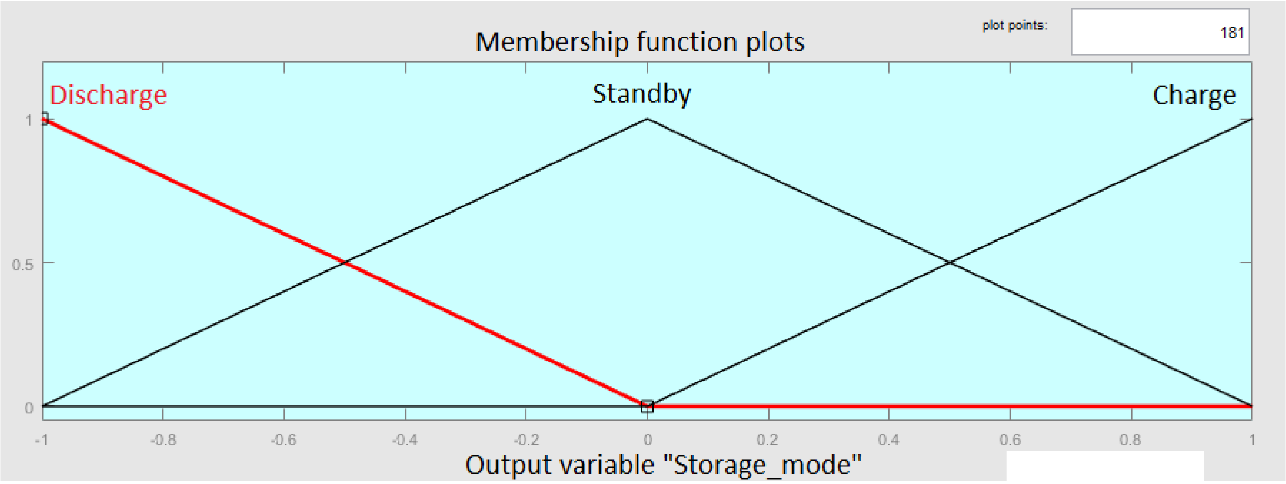


Figure 79: Fuzzification stage - Output variable "Storage dispatch"

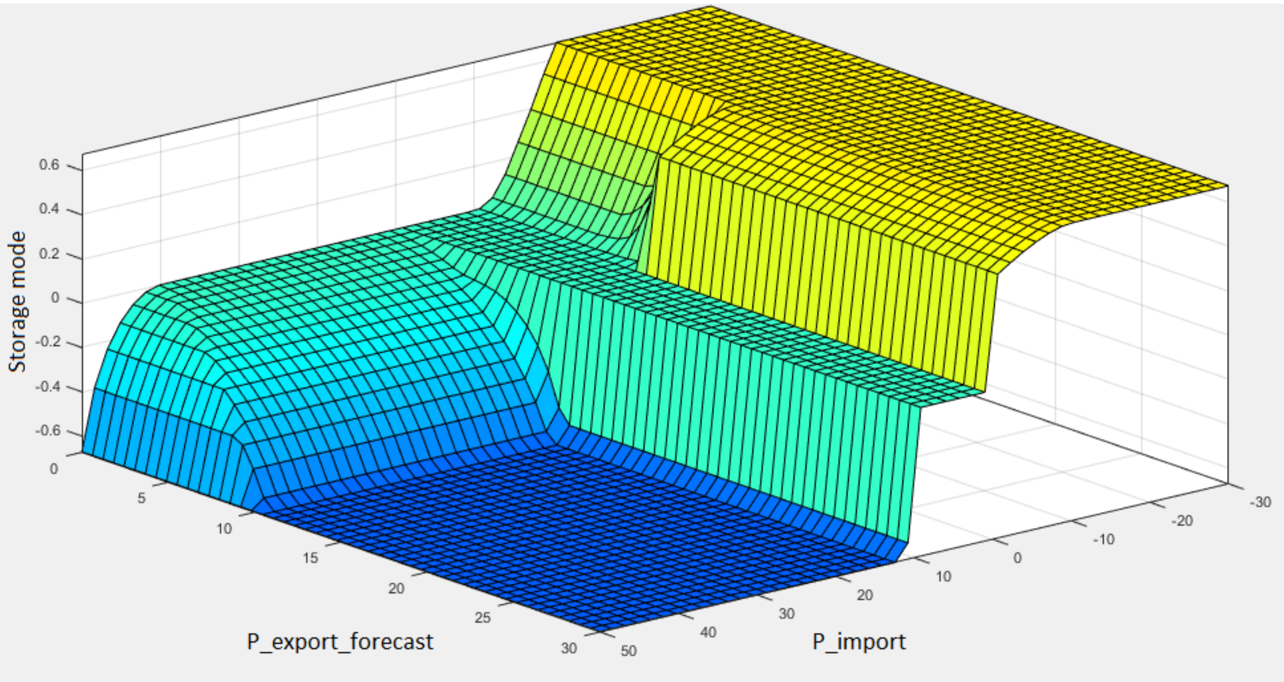


Figure 80: Solution domain of fuzzy logic day-time mode - P_{import} vs $P_{export forecast}$, given a medium charged storage

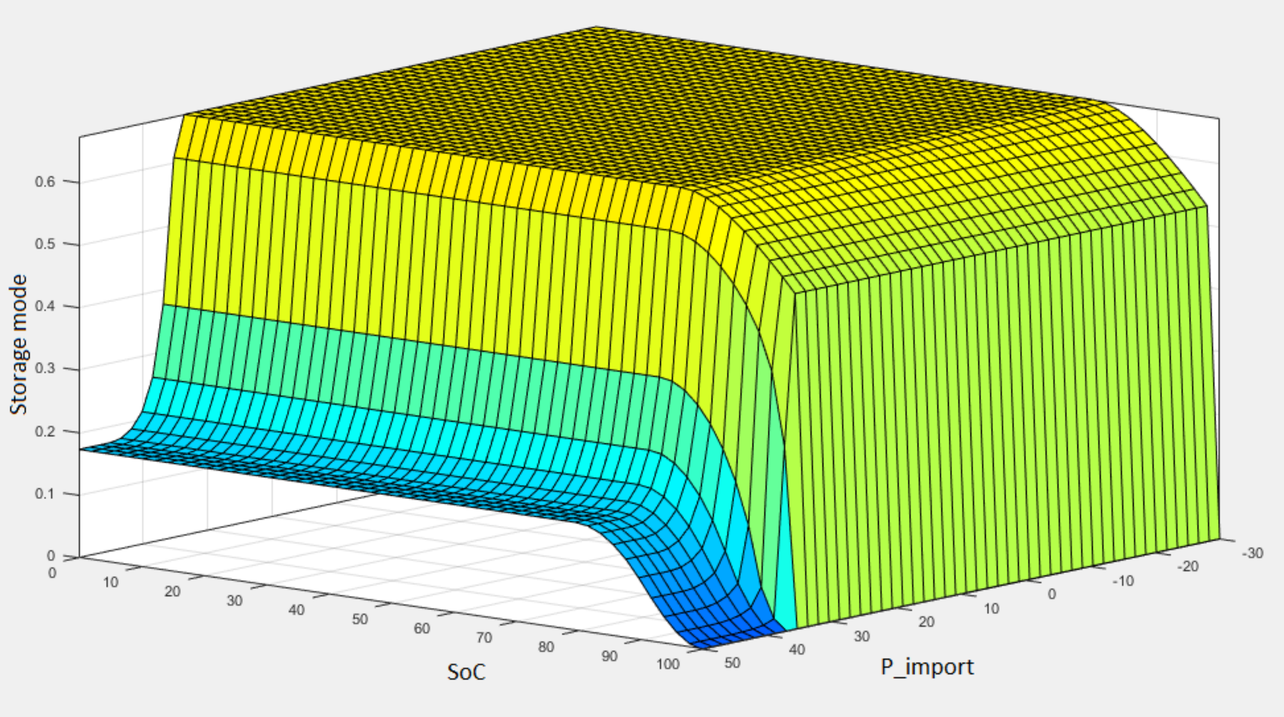


Figure 81: Solution domain of fuzzy logic night-time mode - SOC vs P_{import}, given no predicted export

G Case Study - Regression Analysis

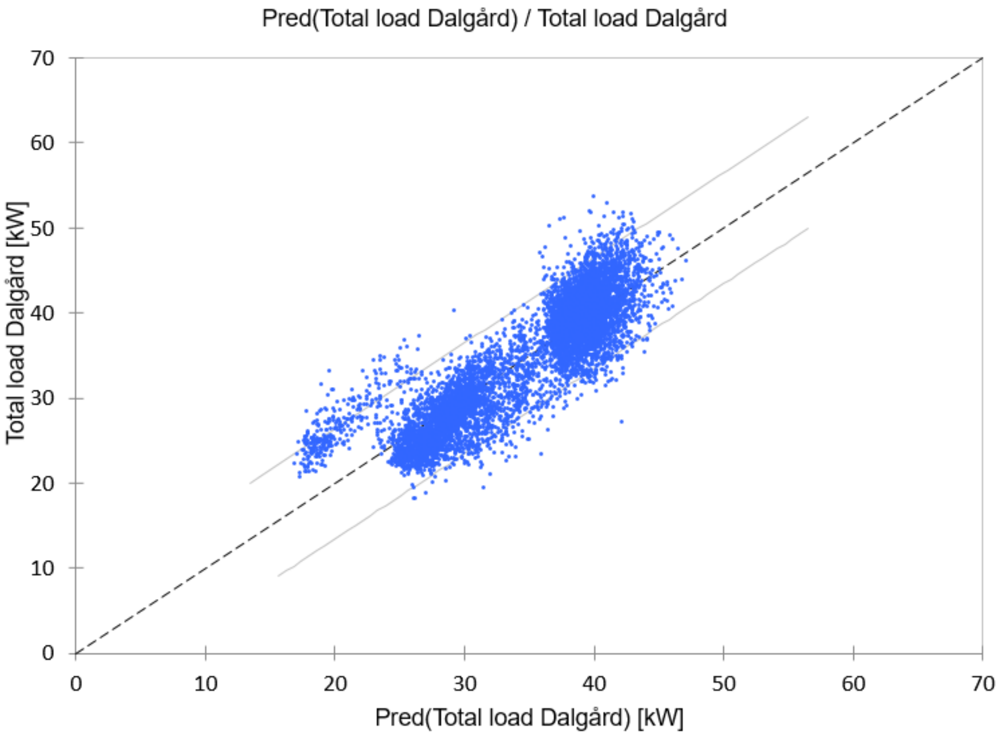


Figure 82: Monitored data versus regressed data for case study total load profile

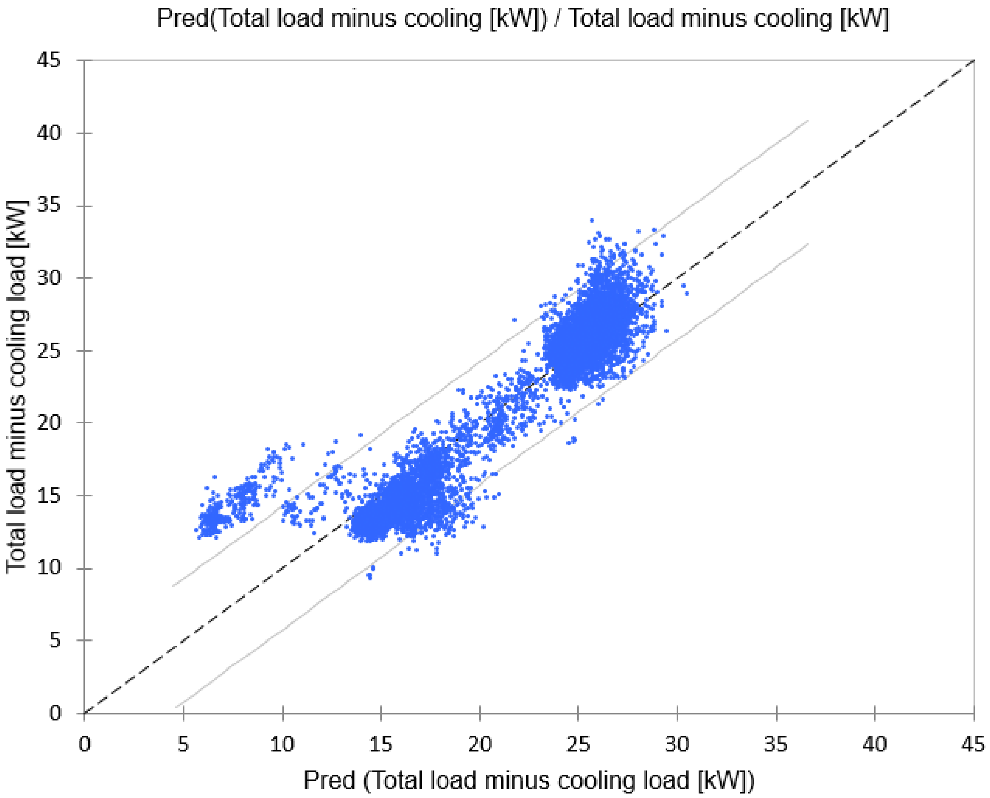


Figure 83: Monitored data versus regressed data for case study total load minus cooling profile

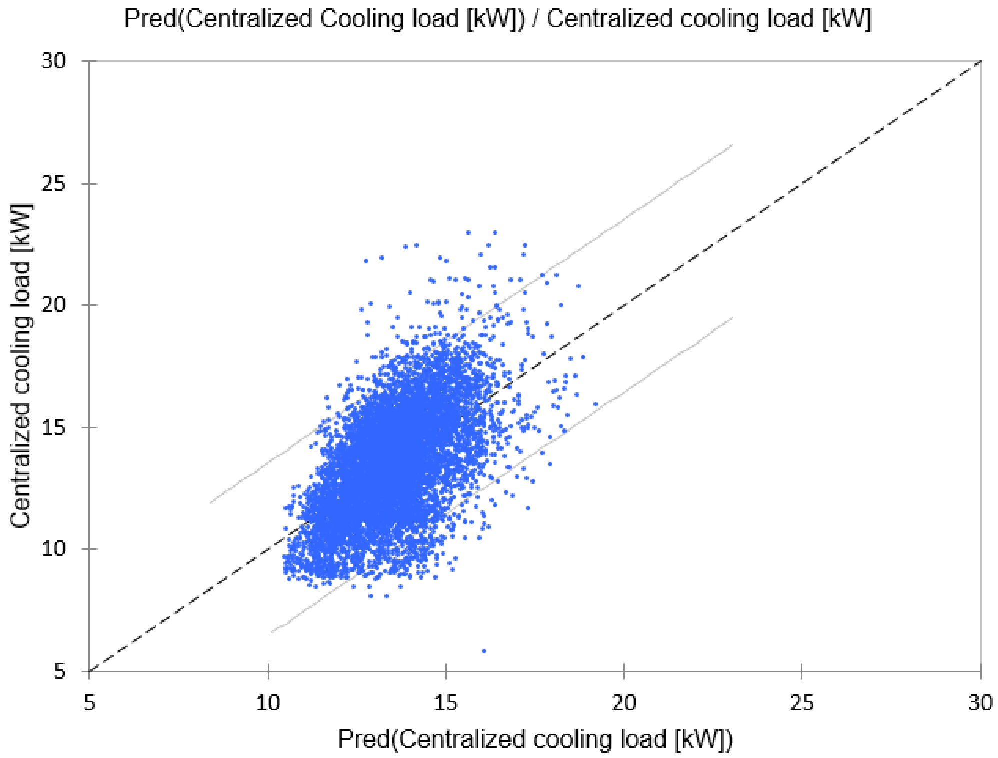
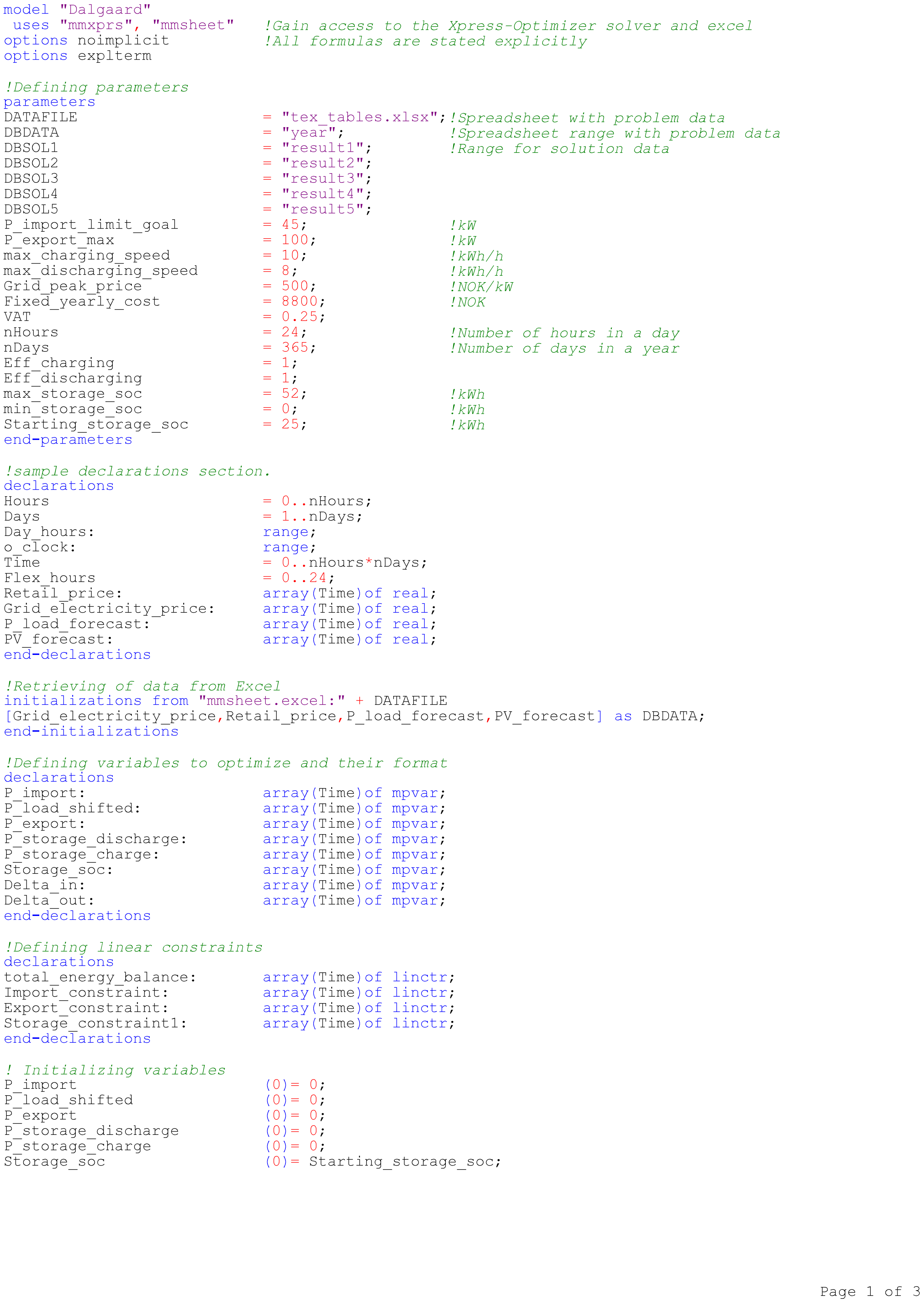


Figure 84: Monitored data versus regressed data for case study centralized cooling load

H Case Study - Optimization Model Script



```
model "Dalgaard"
 uses "mmxprs", "mmsheet"   !Gain access to the Xpress-Optimizer solver and excel
options noimplicit          !All formulas are stated explicitly
options explterm

!Defining parameters
parameters
DATAFILE                    = "tex_tables.xlsx";!Spreadsheet with problem data
DBDATA                      = "year";           !Spreadsheet range with problem data
DBSOL1                      = "result1";        !Range for solution data
DBSOL2                      = "result2";
DBSOL3                      = "result3";
DBSOL4                      = "result4";
DBSOL5                      = "result5";
P_import_limit_goal         = 45;               !kW
P_export_max                = 100;              !kW
max_charging_speed          = 10;               !kWh/h
max_discharging_speed       = 8;                !kWh/h
Grid_peak_price             = 500;              !NOK/kW
Fixed_yearly_cost           = 8800;             !NOK
VAT                         = 0.25;
nHours                      = 24;               !Number of hours in a day
nDays                       = 365;              !Number of days in a year
Eff_charging                = 1;
Eff_discharging             = 1;
max_storage_soc             = 52;               !kWh
min_storage_soc             = 0;                !kWh
Starting_storage_soc        = 25;               !kWh
end-parameters

!sample declarations section.
declarations
Hours                       = 0..nHours;
Days                        = 1..nDays;
Day_hours:                  range;
o_clock:                    range;
Time                        = 0..nHours*nDays;
Flex_hours                  = 0..24;
Retail_price:               array(Time)of real;
Grid_electricity_price:     array(Time)of real;
P_load_forecast:            array(Time)of real;
PV_forecast:                array(Time)of real;
end-declarations

!Retrieving of data from Excel
initializations from "mmsheet.excel:" + DATAFILE
[Grid_electricity_price,Retail_price,P_load_forecast,PV_forecast] as DBDATA;
end-initializations

!Defining variables to optimize and their format
declarations
P_import:                   array(Time)of mpvar;
P_load_shifted:             array(Time)of mpvar;
P_export:                   array(Time)of mpvar;
P_storage_discharge:        array(Time)of mpvar;
P_storage_charge:           array(Time)of mpvar;
Storage_soc:                array(Time)of mpvar;
Delta_in:                   array(Time)of mpvar;
Delta_out:                  array(Time)of mpvar;
end-declarations

!Defining linear constraints
declarations
total_energy_balance:       array(Time)of linctr;
Import_constraint:          array(Time)of linctr;
Export_constraint:          array(Time)of linctr;
Storage_constraint1:        array(Time)of linctr;
end-declarations

! Initializing variables
P_import                    (0)= 0;
P_load_shifted              (0)= 0;
P_export                    (0)= 0;
P_storage_discharge         (0)= 0;
P_storage_charge            (0)= 0;
Storage_soc                 (0)= Starting_storage_soc;
```

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Figure 85: Fico Xpress Script - Part 1 of 3

```
! Declarations objective function
declarations
total_cost:                 linctr;
P_grid_electricity_cost:    linctr;
P_grid_peak_cost:           linctr;
P_retail_cost:              linctr;
P_sales_revenue:            linctr;
Fixed_cost:                 linctr;
end-declarations

!###################################################################################
! Calculations of revenue and costs
!###################################################################################

P_grid_electricity_cost:=   sum(tt in Time|tt>0)(Grid_electricity_price(tt)*P_import(tt));
P_grid_peak_cost:=          P_import_limit_goal*Grid_peak_price;
P_retail_cost:=             sum(tt in Time|tt>0)(Retail_price(tt)*P_import(tt));
P_sales_revenue:=           sum(tt in Time|tt>0)(Retail_price(tt)*P_export(tt));
Fixed_cost:=                Fixed_yearly_cost;

!###################################################################################
!Objective function
!###################################################################################

total_cost:=                (1+VAT)*(Fixed_cost+P_grid_electricity_cost+P_retail_cost+P_grid_peak_c

!###################################################################################
!Constraints
!###################################################################################

! Energy balance
forall (tt in Time) do
total_energy_balance(tt):=
    PV_forecast(tt)+P_import(tt)+P_storage_discharge(tt)
    =P_export(tt)+P_storage_charge(tt)+P_load_forecast(tt);
end-do

!Import constraint
forall(tt in Time) do
Import_constraint(tt):=
    P_import(tt)<=P_import_limit_goal;
end-do

forall(tt in Time) do
Export_constraint(tt):=
    P_export(tt)<=P_export_max;
end-do

! Storage constraints
forall (tt in Time) do
    Delta_in(tt)+ Delta_out(tt)<=1;
    Delta_in(tt) is_binary;
    Delta_out(tt) is_binary;
end-do

forall (tt in Time) do
    Storage_soc(tt) <= max_storage_soc;
    Storage_soc(tt) >= min_storage_soc;
end-do

forall (tt in Time|tt>0) do
    Storage_soc(tt)
    = Storage_soc(tt-1)+P_storage_charge(tt)*Eff_charging-P_storage_discharge(tt)/Eff_discharging;
end-do

forall (tt in Time) do
    P_storage_charge(tt) <= Delta_in(tt)*max_charging_speed;
end-do

forall (tt in Time) do
    P_storage_discharge(tt) <= Delta_out(tt)*max_discharging_speed;
end-do

! Time frame constraint
forall (dd in Days) do
o_clock:= (1+24*(dd-1)..24+24*(dd-1));
Storage_constraint1(dd):=
    sum(oo in o_clock)(P_storage_charge(oo)*Eff_charging)
    =sum(oo in o_clock)(P_storage_discharge(oo)/Eff_discharging);
end-do

! Solve the problem
minimize(total_cost);
```

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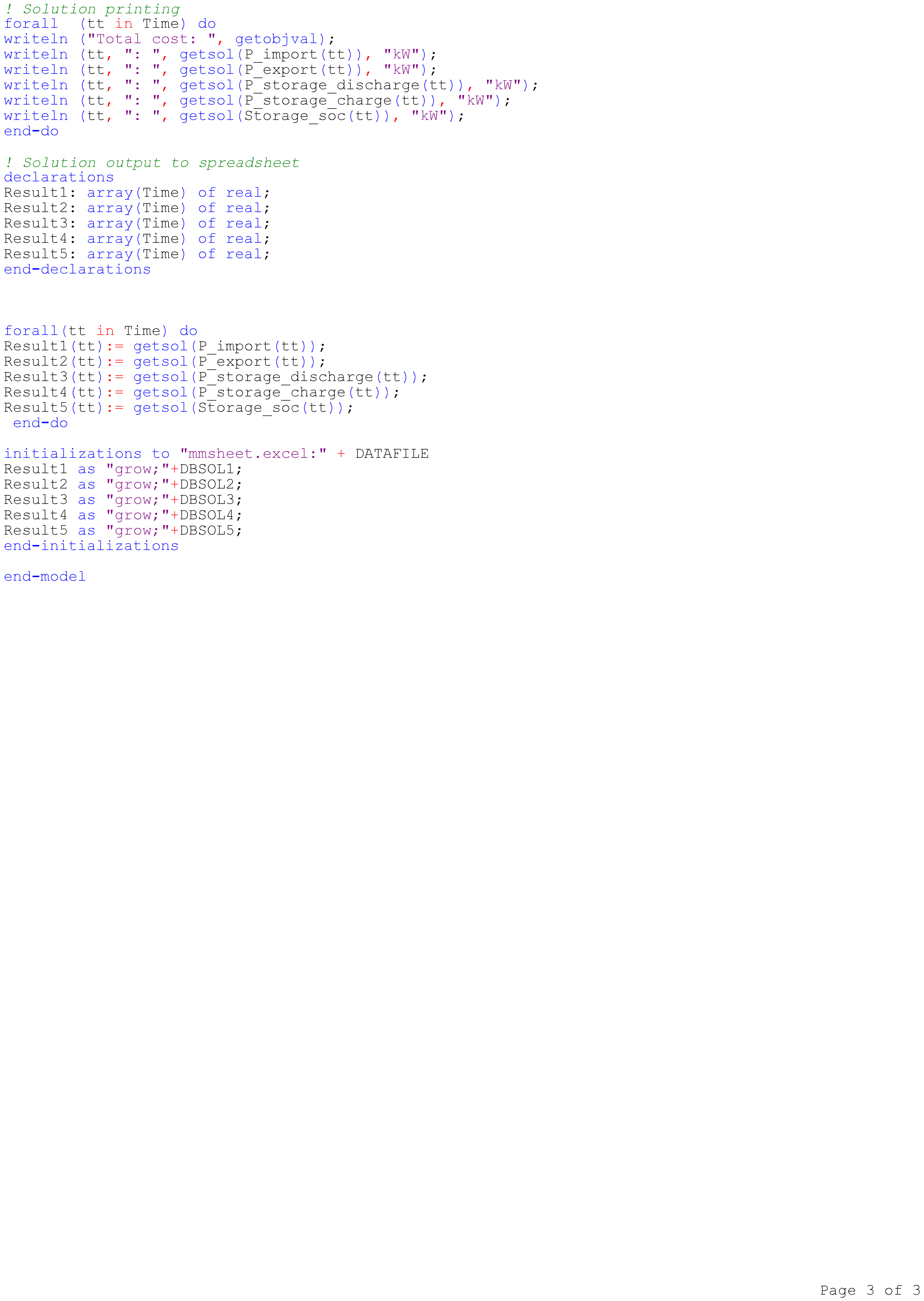
Figure 86: Fico Xpress Script - Part 2 of 3



```
! Solution printing
forall  (tt in Time) do
writeln ("Total cost: ", getobjval);
writeln (tt, ": ", getsol(P_import(tt)), "kW");
writeln (tt, ": ", getsol(P_export(tt)), "kW");
writeln (tt, ": ", getsol(P_storage_discharge(tt)), "kW");
writeln (tt, ": ", getsol(P_storage_charge(tt)), "kW");
writeln (tt, ": ", getsol(Storage_soc(tt)), "kW");
end-do

! Solution output to spreadsheet
declarations
Result1: array(Time) of real;
Result2: array(Time) of real;
Result3: array(Time) of real;
Result4: array(Time) of real;
Result5: array(Time) of real;
end-declarations



forall(tt in Time) do
Result1(tt):= getsol(P_import(tt));
Result2(tt):= getsol(P_export(tt));
Result3(tt):= getsol(P_storage_discharge(tt));
Result4(tt):= getsol(P_storage_charge(tt));
Result5(tt):= getsol(Storage_soc(tt));
 end-do

initializations to "mmsheet.excel:" + DATAFILE
Result1 as "grow;"+DBSOL1;
Result2 as "grow;"+DBSOL2;
Result3 as "grow;"+DBSOL3;
Result4 as "grow;"+DBSOL4;
Result5 as "grow;"+DBSOL5;
end-initializations

end-model
```

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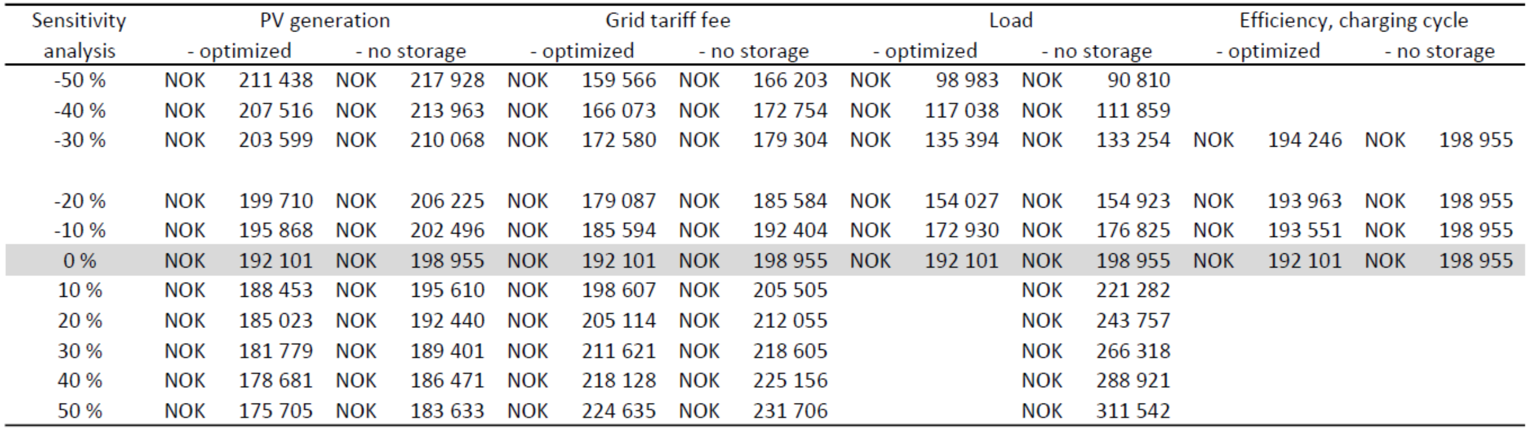
Figure 87: Fico Xpress Script - Part 3 of 3

I Case Study - Results



Sensitivity analysis	PV generation - optimized	PV generation - no storage	Grid tariff fee - optimized	Grid tariff fee - no storage	Load - optimized	Load - no storage	Efficiency, charging cycle - optimized	Efficiency, charging cycle - no storage
-50 %	NOK 211 438	NOK 217 928	NOK 159 566	NOK 166 203	NOK 98 983	NOK 90 810		
-40 %	NOK 207 516	NOK 213 963	NOK 166 073	NOK 172 754	NOK 117 038	NOK 111 859		
-30 %	NOK 203 599	NOK 210 068	NOK 172 580	NOK 179 304	NOK 135 394	NOK 133 254	NOK 194 246	NOK 198 955
-20 %	NOK 199 710	NOK 206 225	NOK 179 087	NOK 185 584	NOK 154 027	NOK 154 923	NOK 193 963	NOK 198 955
-10 %	NOK 195 868	NOK 202 496	NOK 185 594	NOK 192 404	NOK 172 930	NOK 176 825	NOK 193 551	NOK 198 955
0 %	NOK 192 101	NOK 198 955	NOK 192 101	NOK 198 955	NOK 192 101	NOK 198 955	NOK 192 101	NOK 198 955
10 %	NOK 188 453	NOK 195 610	NOK 198 607	NOK 205 505		NOK 221 282		
20 %	NOK 185 023	NOK 192 440	NOK 205 114	NOK 212 055		NOK 243 757		
30 %	NOK 181 779	NOK 189 401	NOK 211 621	NOK 218 605		NOK 266 318		
40 %	NOK 178 681	NOK 186 471	NOK 218 128	NOK 225 156		NOK 288 921		
50 %	NOK 175 705	NOK 183 633	NOK 224 635	NOK 231 706		NOK 311 542		

Table 20: Case study sensitivity analysis results tabulated

System combinations		Optimized Default PV Storage: 10 kW 52 kWh	Base case Default PV No storage	Optimized 2 times PV Storage: 10 kW 52 kWh	Optimized 2 times PV Storage: 50 kW 140kWh*	Base case 2 times PV No storage	Optimized 3 times PV Storage: 10 kW 52 kWh**	Optimized 3 times PV Storage: 90 kW 252 kWh*	Base case 3 times PV No storage
Yearly electricity cost	[NOK]	192 101	198955	162 061	160140	170 620	138 589	131 651	147 962
Saved on avoiding export	[NOK]	548		2699	5416		3668	12555	
Saved on peak shaving	[NOK]	4832		4832	4832		4832	4832	
Saved on load shifting	[NOK]	1474		1028	232		872	-1077	
Self consumption of solar		99.3 %	96.7 %	79.0 %	85.6 %	72.6 %	61.5 %	75.7 %	55.6 %
Degree of self sufficiency		20.3 %	19.8 %	32.3 %	34.9 %	29.7 %	37.7 %	46.4 %	34.1 %
Max export	[kW]	29.6	24.5	79.3	92.8	73.3	132.3	100.0	125.5
Total exported	[kWh]	437.0	2048.0	26219.4	18087.2	34276.2	72285.4	45673.8	83257.4
Total generated	[kWh]	62547	62547	125094	125094	125094	187641	187641	187641
Potential, degree of self sufficiency		20.4 %	20.4 %	40.8 %	40.8 %	40.8 %	61.3 %	61.3 %	61.3 %

Table 21: Case study results for different PV system and storage dimensions

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