Master's thesis

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

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Assessing local flexibility resources in a Zero Emission Neighbourhood with focus on space heat demand and battery storage

Master's thesis in Energy and Environmental Engineering
Supervisor: Karen Byskov Lindberg

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Abstract

Utilising energy flexibility in buildings can enable qualities such as reduced energy consumption, reduced peak loads, increased self-consumption, or provide flexibility services to the distribution grid. This thesis investigates the energy flexibility potential of a neighbourhood consisting of a school, a nursing home and a kindergarten. The neighbourhood, Oksenøya, is currently being built at Fornebu and is owned by the municipality of Bærum. Oksenøya is part of an energy system consisting of a district heating grid and an electricity grid. The aim is to obtain an operating strategy that reduces the energy costs for the neighbourhood by minimising the peak load on both energy grids. The thesis also studies how the neighbourhood can be utilised to provide flexibility services to the distribution grid.

Oksenøya is a ZEN pilot project. Therefore, it is studied both as three individual buildings and as a group of buildings to evaluate any advantages of operating with individual or common energy metering. The two energy systems have been investigated separately, enabling flexibility by using space heating flexibility for district heating and a stationary battery for electricity. The method used is "what-if" analyzes of a rule-based modeling approach. To establish the baseline, energy simulations are performed in the Building Performance Simulation (BPS) tool IDA ICE. The space heating flexibility schedules are then found by trial and error in IDA ICE, while the battery flexibility is modeled in Excel.

The study uses a conventional control strategy and manages to reduce energy costs by implementing energy flexibility measures. The recommended operational strategy from the results obtained is common energy metering, for both electricity and district heating, and control of flexible loads with the objective of reducing the total peak load. This results in a peak load reduction of 44.7% and 33.0% for district heating and electricity respectively, giving a total cost reduction of 16.1%. The study is limited to scenario modeling, which means that the real cost saving potential might be higher.

Furthermore, the study found that it is possible to shift a neighbourhoods peak load to the off-peak hours of the distribution grid. Oksenøya is a relatively small neighbourhood, and is therefore not sufficient to remove Fornebu's peak load. However, if flexibility measures are aggregated to a district level, it can have an actual impact on the distribution peak load. The results of this work have thus demonstrated that energy flexibility measures can be implemented with a rule-based control strategy that reduces energy costs and can help avoid grid expansion.

Sammendrag

Ved å utnytte energifleksibilitet i bygninger kan man realisere verdier som redusert energibruk, redusert topplast, økt selvforbruk, eller tilby fleksibilitetstjenester til distribusjonsnettet. Denne masteroppgaven undersøker energifleksibilitetspotensialet i et nabolag bestående av en skole, et sykehjem og en barnehage. Nabolaget Oksenøya bygges på Fornebu og eies av Bærum kommune. Oksenøyas energisystem består av et fjernvarmenett og et strømnett. Målet med oppgaven er å finne en driftsstrategi som reduserer energikostnadene for nabolaget ved å minimere topplasten på begge energinett. Oppgaven studerer også hvordan nabolaget kan brukes til å tilby flekibilitetstjenester til distribusjonsnettet.

Oksenøya er et ZEN-pilotprosjekt. Det blir derfor sett på som både tre individuelle bygninger og som en gruppe av bygninger, for å evaluere eventuelle fordeler ved å benytte individuell eller felles energimåling. De to energisystemene er undersøkt separat, så fleksibilitet muliggjøres ved romoppvarmingsfleksibilitet for fjernvarme og et stasjonært batteri for elektrisitet. Metoden som brukes er "hva-hvis" -analyser av en regelbasert modelleringsmetode. For å etablere et sammenligningsgrunnlag utføres energisimuleringer i bygningssimuleringsverktøyet IDA ICE. Forhåndsbestemte tidsplaner for romoppvarmingsfleksibilitet er deretter funnet ved prøving og feiling i IDA ICE, mens batterifleksibilitet er modellert i Excel.

Studien bruker en konvensjonell kontrollstrategi og klarer å redusere energikostnadene ved å implementere energifleksibilitet. Basert påresultatene er den anbefalte driftsstrategien felles energimåling for både strøm og fjernvarme, og kontroll av fleksible laster med sikte på å redusere den totale topplasten. Dette resulterer i en topplastreduksjon på henholdsvis 44.7% og 33.0% for fjernvarme og strøm, noe som gir en total kostnadsreduksjon på 16.1%. Studien er begrenset til scenariomodellering, noe som betyr at det virkelige potensialet for kostnadsbesparelse kan være høyere.

Studien fant også at det er mulig å flytte topplasten til et nabolag bort fra distribusjonsnettets topplasttimer. Oksenøya er et relativt lite nabolag, og er derfor ikke nok til å fjerne Fornebus topplast. Hvis man derimot øker fleksibilitetstiltakene til for eksempel distriktsnivå, kan det ha en faktisk innvirkning på distribusjonsnettets topplast. Resultatene av dette arbeidet har altså vist at energifleksibilitet kan implemeteres med en regelbasert kontrollstrategi som reduserer energikostnader og kan bidra til å unngå nettutvidelse.

Preface

This master thesis represents the final work of my Master of Science (MSc) degree in Energy and Environmental Engineering. It is written during the spring of 2021 at the Department of Electric Power Engineering in the Norwegian University of Science and Technology (NTNU).

The problem description is developed in collaboration with the municipality of Bærum. I want to express my appreciation to Camilla Bakken Torp and the rest of her team in Bærum municipality, for providing me with the information needed and for inviting me to their meetings so I could get a comprehension of what they wanted to attain from the thesis. I find the project incredibly interesting, and I am proud to be able to contribute.

I especially want to thank my supervisor Karen Byskov Lindberg for helpful guidance throughout the year, for always giving me support and motivation, and for sharing some of her enormous knowledge with me. Thank you for always making me trust my own decisions.

I would like to thank my family for their loving support in everything I do, and for always believing in me. I also have to thank my friends for always having my back and motivating me. Writing this thesis would not have been possible without all the incredible people in my life.

This thesis is written during the Covid-19 pandemic, which has been challenging at times. I am grateful that NTNU has been able to keep the campus open, as interaction with other students has been valuable in this special year.

My five years as a student at NTNU have been unforgettable and full of memories, so I want to thank all the people I have met along the way that have contributed to making the years in Trondheim some of the best yet.

Malin Valbø Kaaløy
Trondheim, June 2021

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1 Introduction

This chapter presents the motivation for the thesis. The main objective is introduced, as well as its limitations, and the structure of the thesis is displayed.

1.1 Motivation

This thesis is written in collaboration with the municipality of Bærum, which is one of the most populous municipalities in Norway[1]. Bærum municipality aim to be climate-smart and have therefore developed a strategic plan to reduce their carbon footprint, called Climate Strategy 2030 [2]. Their goal is to be an innovative municipality and promote role model projects. One of their most prominent areas for this is Fornebu. Fornebu is a peninsula in Bærum, located near the Norwegian capital, Oslo. Fornebu is an attractive business area that is also home to a few smaller residential areas. Due to the proximity to Oslo and appealing outdoor area, Fornebu qualifies as an even more attractive residential area. Today, it includes about 3 000 residential buildings that house 7 500 residents. In 2030, this number will increase to 11 000 residential buildings with 25 000 inhabitants. The 25 000 employees that are there today will increase to 30 000 [3]. The enhanced building stock implies an increase in energy use, and suggests that an expansion of the energy system is needed.

Fornebu is still under development, so it has the opportunity to test new, smart and sustainable energy solutions such as energy storage and distributed energy production. Fornebu will be a model area in terms of urban development, which means that research and industry are encouraged to use it for pilot projects to test new technologies and solutions in mobility, energy and buildings. Two of the key objectives of the Climate Strategy 2030 is for Fornebu to be a Zero Emission Neighbourhood (ZEN) within 2027 and for the whole municipality to be a low-carbon society by 2050 [2]. These goals will be achieved by involving various stakeholders in the establishment of the Zero Emission Neighbourhood at Fornebu to test new, innovative solutions that can subsequently be used in other areas of the municipality [4]. The energy system at Fornebu up to the year 2030 is studied as a preliminary project for this thesis [5], in order to assess the needs and challenges related to energy. The energy system consists of an electricity grid and a district heating grid, and subchapter 2.3 presents the most central results from this project.

Oksenøya is one of the innovation projects currently being built at Fornebu, and it is seen as a first step towards making Fornebu a ZEN. It will consist of a school for 1050 pupils, a nursing home with 150 residents, and a kindergarten for 300 children, meaning it will involve people of all ages [6]. The three buildings are intended to interact with each other, and will therefore be equipped with manageable loads. The school and nursing home will have photovoltaic

(PV) panels on the roof, and all three buildings will have access to a shared battery. In this way, the three commercial buildings at Oksenøya can provide flexibility in Fornebu's energy system. As the neighbourhood is currently under construction, the school and kindergarten are scheduled to open in August 2022, while the nursing home is scheduled to open in January 2023. Since the buildings do not yet exist, Building Performance Simulation (BPS) is used to simulate their behavior.

1.2 Scope

The scope of this thesis is to investigate the flexibility potential of a neighbourhood currently being built at Fornebu, called Oksenøya. The main objective of the flexibility measures is to reduce the energy costs by peak load shaving. In addition, an analysis has been conducted to review the use of energy flexibility in Zero Emission Neighbourhoods as a measure to prevent grid expansion. Since the energy system at Fornebu consists of both an electric grid and a district heating grid, these two systems have been investigated separately, aiming to reduce both the peak heating load and the peak electricity load.

The proposed method uses a rule-based modeling approach for a series of scenarios and conduct "what-if" analyzes to find a desirable operating strategy that reduces energy costs for the neighbourhood. The neighbourhood consists of a school, a nursing home and a kindergarten. It is studied both as three individual buildings and as a complex of buildings to investigate the advantages and disadvantages of operating with individual and common energy metering.

Flexibility is enabled utilising two assets: the thermal mass of the building and a stationary battery. To establish the baseline, simulations are performed in the Building Performance Simulation (BPS) tool IDA ICE where annual load profiles are obtained. For space heating flexibility, further simulations are performed in IDA ICE by changing the heating temperature set-point schedule and setting the objective in terms of the different scenarios. For the battery, the baseline load profile is derived in Excel, adding a model of a simple battery with the objective of reducing peak load and increasing PV self-consumption. Finally, six Key Performance Indicators (KPI) are created in terms of cost and consumption to evaluate the performance of the results.

1.3 Limitations

To make sure the scope is not too broad, district heating is limited to the flexibility of space heating and electricity is limited to the use of a stationary battery. The buildings have PV panels installed which contribute to energy flexibility as they charge the battery during times of surplus. However, it is the battery and not the PV panels that is categorized as a flexibility measure in this thesis. Space heating refers only to water-based radiators and not to the heating coil in the ventilation system nor domestic hot water use. Throughout this thesis, the term "heating flexibility" refers to the space heating flexibility provided by radiators.

The thesis uses a scenario modeling. This means that "what-if" analyses are performed to determine the best outcome from a set of predetermined scenarios. This suggests that the proposed operational strategy is not necessarily the optimal solution, but the most beneficial of the strategies tested.

The proposed BPS tool, IDA ICE, cannot model all three buildings at once. This is solved by modeling the buildings individually and then combining the different energy load profiles in an Excel spreadsheet to reflect a building assembly.

Due to complications in implementing obtained Building Information Models (BIM) in IDA ICE, simplified models are created that merge zones and windows, and that are approximate in terms of building shape. However, the simulations have shown that the energy consumption is reasonably accurate, so this is considered insignificant.

1.4 Structure of the thesis

The thesis is divided into the following parts:
Chapter 2, *Background*, provides a framework for Oksenøya and Zero Emission Neighbourhoods in general and presents background information for the aims of the thesis.
Chapter 3, *Theory*, introduces a theoretical background regarding energy use in buildings and use of energy flexibility in buildings. It provides a theoretical aspect of BPS tools and control strategies used in this thesis. A literature review of the use of BPS tools for energy flexibility has been conducted.
Chapter 4, *Method*, presents the data collected, how it is retrieved, and the method used to obtain the results. It presents the use of IDA ICE, the control strategies used and how costs are calculated.
Chapter 5, *Oksenøya: Case study*, provides all the input data used to perform the work in the thesis.
Chapter 6, *Scenarios*, provides detailed information on the various scenarios that are simulated.
Chapter 7, *Results*, presents the results and comments on the most important findings.
Chapter 8, *Discussion*, discusses the results and analyses any uncertainties. A suggestion for further work is given.
Chapter 9, *Conclusion*, concludes the thesis based on the results obtained and the discussion.

2 Background

This chapter presents background information regarding Oksenøya, ZEN and Fornebu´s energy system.

Remark: This chapter mainly build on work from the specialization project in TET4520, and thus results in extensive reproduction and usage of its content[5].

2.1 Oksenøya

Oksenøya is a pilot project in the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN), and a role model project in the FutureBuilt program. FutureBuilt´s vision is to show that it is possible to develop a city that is both climate neutral and attractive, by extending their projects well beyond the current building industry practice. Oksenøya should thus have even stricter environmental requirements than what the municipality normally aims for [7]. As a FutureBuilt project, one of the role model properties it should fulfill is "Innovative energy solutions". By this, FutureBuilt indicates local energy production, power management, energy storing and energy exchange between the buildings, transport and energy grid, to meet the need for energy and keep import and export to a minimum [8]. The buildings should also be BREEAM-NOR certified to the classification "Excellent", or preferably "Outstanding", which is a certification of the level of sustainability of a building, covering i.e. land use, contamination, material use, energy and transport [9]. Accordingly, Oksenøya is an impressive project that shall satisfy a series of ambitious requirements.

Veidekke is the contractor building Oksenøya. To reduce energy demand they use a three-step method. Figure 2.1 displays the concept of the three-step method. The main focus is on optimizing the building envelope to keep heat loss to a minimum. Second priority is to optimize the technical installations, by having controllable loads. Finally they will optimize the energy supply, which in this case is mainly based on district heating, electricity from the grid and electricity from the installed PV panels. Veidekke proposes to implement a variety of measures to reduce power peaks, such as presence sensors, efficient use of daylight by daylight control for lighting equipment, demand controlled ventilation, control system for charging of electric vehicles, and control system for all loads above 3kW [10].

Bærum municipality has decided to implement several innovative energy solutions in these buildings, such as manageable loads, PV panels and a battery. These are all relatively expensive technologies, with high investment costs. To compensate for the expenses related to investment, they want to reduce the operational costs, which are mainly related to energy. This thesis will investigate ways to reduce energy costs by utilizing the innovative technologies to reduce the peak energy load.

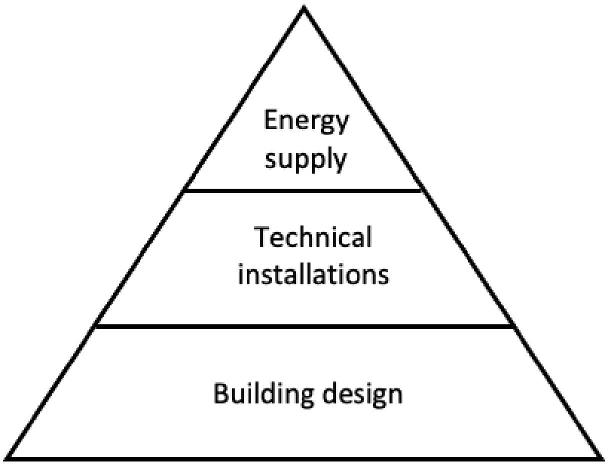

Figure 2.1: Concept of three-step method by Veidekke

2.2 ZEN

Oksenøya will be built as a Zero Emission Neighbourhood (ZEN), and is a pilot project in the Research Centre on Zero Emission Neighbourhoods (FME ZEN). A ZEN is a further development of the concept of Zero Emission Buildings (ZEB), and it can in one way be seen as a clustering of several ZEBs. However, ZEN do have slightly different Key Performance Indicators (KPI) than ZEB, and especially the potential of peak energy reduction plays a greater role for ZEN as they have the possibility of building interaction.

ZEN creates new opportunities such as integrated systems that reduces costs and avoids sub-optimality, along with a bigger capacity to balance supply and demand through energy flexibility. It also arises some challenges as many stakeholders are involved that needs to cooperate for innovation [11]. ZEN can mean both Zero Energy Neighbourhoods or Zero Emission Neighbourhoods. Since Norway has a high share of electrification, and an energy mix that mostly consists of hydro power, the main focus is on reducing emissions. In most European countries, however, the focus is more on energy, as reduction in energy use is important for decarbonization considering the energy mix has a high share of non-renewables [11].

The Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) is a collaboration between researchers, municipalities, governmental organizations and the industry. They seek to develop solutions for neighbourhoods with zero greenhouse gas emissions, and are currently working on nine ZEN pilot projects in Norway, of which one of them is at Fornebu; Flytårnet and Oksenøya. Their definition of a Zero Emission Neighbourhood is still an ongoing process as their pilot projects are currently being tested, but for their first guideline report, the definition is the following [12]:

“...a neighbourhood is defined as a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A zero emission neighbourhood aims to reduce its direct and indirect greenhouse gas (GHG) emissions towards zero over the analysis period, in line with a chosen ambition level with respect to which life cycle modules, buildings, and infrastructure elements to include.”

To document how much a ZEN pilot area has managed to reduce GHG emissions, a reference project is designed. The reference project is the ZEN but fit to today´s standards, such as the current building code TEK17, and typically no ZEN criteria are implemented. This way it can be investigated how much energy the neighbourhood would use if not designed as a ZEN. Oksenøya is first modelled according to TEK17 and this thesis investigates the economic savings of operating it as a ZEN.

2.3 Fornebu´s energy system

As a preliminary project for this thesis, an analysis of the energy system at Fornebu in 2030 has been conducted to evaluate when peak loads in the distribution grid are expected to occur, and the magnitude of the peak loads. The energy system at Fornebu consists of an electric grid and a district heating grid, which both will have to be expanded in the near future due to the building development going on at Fornebu. The electricity system today consists of a 78 MW transformer station at the entrance of the peninsula of Fornebu. It is planned for a new transformer station at Koksa, further down at the peninsula to provide for the increase in energy consumption due to new buildings. All buildings built after year 2000 are obligated to connect to the district heating grid, so they only consume electricity for technical appliances. The district heating system today consists of seawater-based heat pumps, whom are connected to other transformerstations than the one at Fornebu. The system has a heating capacity of 88.4 MW including heat pumps and boilers, and only supplies buildings built after 2000.

2.3.1 Today

Today the peak in the electricity grid occur in the morning, on a weekday, during the winter. Measured values from the transformer station at Fornebu reveals that the peak reaches 56.7 MW in 2018. It has to be kept in mind that this was a relatively warm year so for security in not overloading the grid, it needs even more capacity. The peak in the district heating grid also occur in the morning, on a weekday, during winter. There are no measured values for the district heating, but according to the simulation carried out, the peak reaches 23.7 MW at its highest.

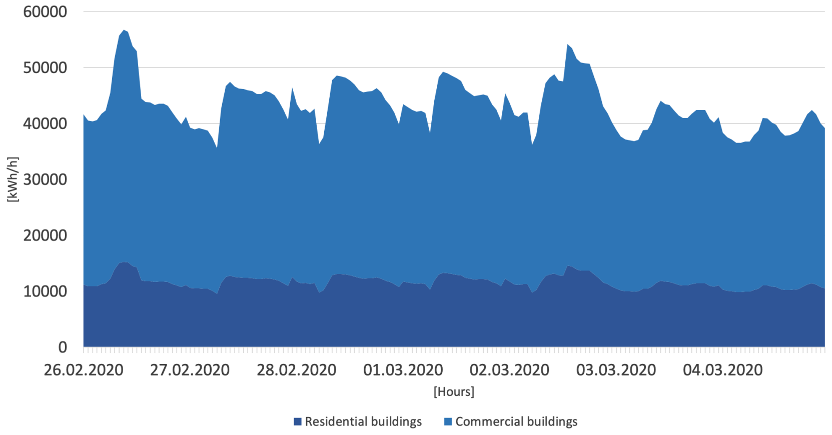

Figure 2.2: Weekly electricity load profile during winter, 2020 [5]

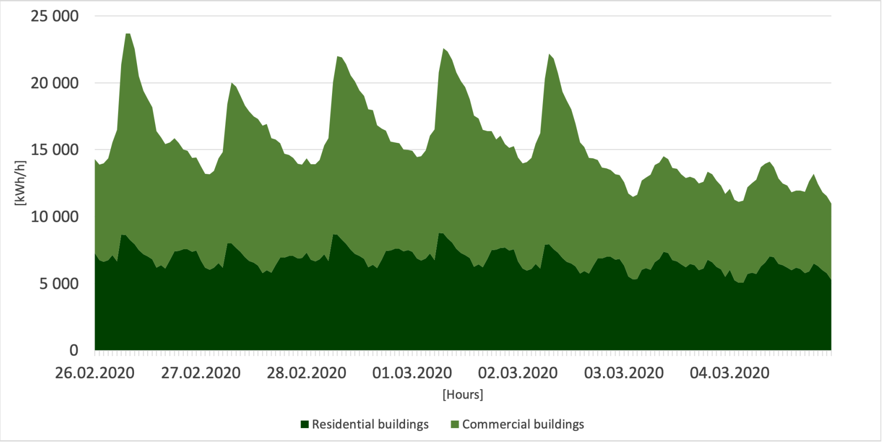

Figure 2.3: Weekly district heating load profile during winter, 2020 [5]

2.3.2 Future

By 2030, a huge electrification of the transport sector is expected, including an extensive increase in district heating demand. Regarding electricity, a load profile for charging of electric vehicles (EV) has been received from a co-student. It is based on a "dumb" charging pattern, which means that people are not aware of their consumption, and thus charges their EV when it is most convenient. This often applies to the hours in the afternoon when people come home from work. Consequently, the shape of the daily load profile changes, making the peak occur in the afternoon instead of in the morning. Including the charging of EVs, simulations found that the peak load in 2030 will reach 73 MW. Through an analysis, results found that there is a possible 4 MW difference between actual and simulated values, and there is a metro under construction that will draw 10 MW. Taking into account these aspects, the peak can be expected to reach 87 MW. For the district heating, the shape of the daily load profile remains the same, only with a higher magnitude. The peak in 2030 is expected to reach 57 MW, which is more than twice as high as the current peak. Because of the huge increase in heating demand, the district heating system will have to be expanded. It can thus be seen as likely that any new heat pump will be connected to a transformer at Fornebu, meaning the electricity demand can increase even more. Table 2.1 presents an overview of the peak loads at Fornebu found in the specialization project.

Table 2.1: Results from specialization project [5]

	Electricity peak load [MW]	**District heating peak load [MW]**
2020	56.7	23.7
2030	87	57

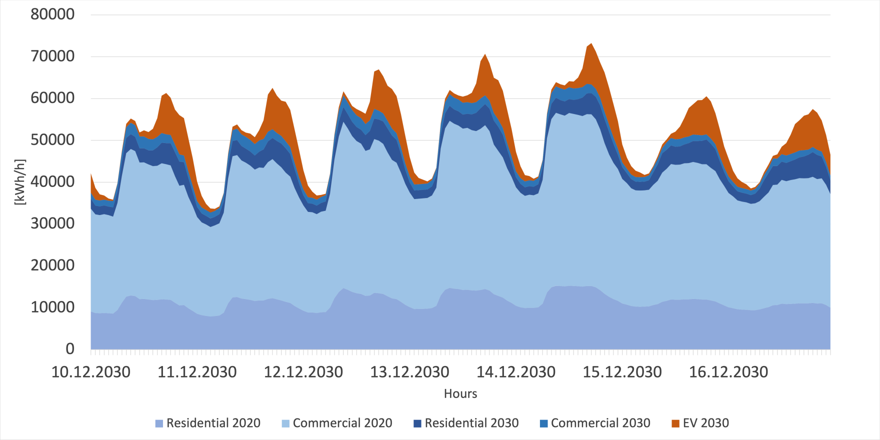

Figure 2.4: Weekly electricity load profile during winter, 2030 [5]

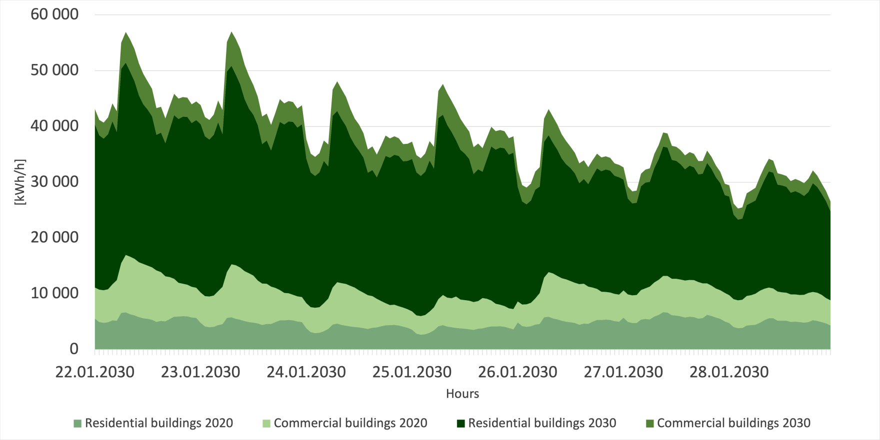

Figure 2.5: Weekly district heating load profile during winter, 2030 [5]

3 Theory

This chapter provides a theoretical aspect of energy use in buildings and building energy flexibility, as well as energy prices, BPS tools and control strategies. A literature review on use of BPS tools for building flexibility is conducted.

3.1 Energy use in buildings

In Norway, buildings consume 40% of the total final energy use [13], meaning that the energy use in buildings is of considerable importance in the energy system. The Norwegian standard for energy performance of buildings[14] divides energy use in buildings into space heating and cooling, domestic hot water, lighting, ventilation and technical equipment. In residential buildings, thermal energy demand, such as space heating and domestic hot water is dominant [15], while in commercial buildings, the electricity demand, so equipment and ventilation is more dominant [16].

For buildings in Europe there are certain standards, regulations and building codes to follow when building, or retrofitting a building. To make sure all buildings are as energy efficient as possible, these standards are guidelines to help calculating the building energy performance[17]. From the European Energy Performance of Buildings (EPB) standards, each country can further develop their own guidelines and regulations, so for Norway, the two most important documents to follow are NS3031:*Energy performance of buildings: Calculation of energy needs an energy supply*[14], and TEK17: *Regulations on technical requirements for construction works*[18]. NS3031 defines typical control schedules and yearly energy use for internal loads such as light, technical equipment, occupancy and domestic hot water (DHW). TEK17 provides technical requirements for buildings in Norway. It contains i.e. minimum U-values, minimum ventilation airflow and minimum specific energy demand for particular building categories. Another standard one can choose to follow is the passive house standard, NS3700 for residential buildings and NS3701 for commercial buildings. The buildings at Oksenøya are said to satisfy the demands from the passive house standard, hence will they follow NS3701.

Since an eminent part of energy in Norwegian buildings is heating, a relevant aspect is thermal comfort. Heating is applied so that the occupants in a building are not cold, so when reducing heating it is important to keep in mind that thermal comfort shall still be maintained. The European standard EN ISO 7730, defines thermal comfort as specified:

“Condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction can be caused by warm or cool discomfort of the body as a whole, or by an unwanted cooling (or heating) of one particular part of the body.”

Since "Condition of mind.." implies a subjective state, thermal comfort can depend on both individual conditions and environmental parameters such as air temperature, humidity, air velocity, and solar radiation. Individual conditions may include age, gender, health status, clothing, or activity level. Therefore, it is important to remember that it is the body's response that determines the experience of comfort, and not necessarily the environmental parameters[19]. It is hence a widely held view that thermal comfort is complex. To quantify the thermal condition of the body, there has been established a set of parameters, Predicted Mean Vote (PMV), and derived from this, Percentage of People Dissatisfied (PPD)[19]. PMV uses a scale of a persons thermal situation, ranging from Hot to Cold, with Neutral in between. By neutral it is meant that a person does not want their ambience to be neither warmer nor cooler. PPD provides an estimated percentage of people in a group that will be dissatisfied with their surroundings, either too warm or too cold. To rely on these indicators it requires that activity level (MET) and clothing level (CLO) is set correctly. In the respective buildings at Oksenøya, both MET and CLO can vary in time and type of occupant. Considering this, it has been decided to base the evaluation of thermal comfort solely on air temperatures.

Air temperature is simple to measure, and is the most common parameter to describe thermal conditions[19]. If there are radiating sources in a room, operative temperature is more practical to apply than dry-bulb temperature, as it includes both ambient air temperature and mean radiant temperature. Analyzing the operating temperature in a building can give a good indication of the thermal comfort. According to TEK17 §13-4, recommended values for operative temperature with light work is 19-26 °C. It also states that daily temperature variations should not exceed 4°C. According to [20] the neutral temperature for residents in nursing homes in areas that needs heating during winter is 21,6°C, so for the nursing home this is taken as a premise when analyzing the thermal comfort. For the other buildings, the TEK17 recommendation is used. It is assumed that as long as the TEK17 requirement is met, thermal comfort is acceptable.

3.2 Energy flexibility

This subchapter provides an overview of what energy flexibility in buildings is, and why it is necessary. It further investigates energy storage and space heating flexibility, as they are the flexibility measures used in this thesis.

As stated, buildings in Norway account for about 40% of the total final energy consumed [13]. If the energy that buildings consume can be used in a smarter way, total energy use, and in particular peak loads may be significantly reduced. Since Norway is a cold country, the heating demand for buildings in general is considerable. Through communication technology, building heat loads has a great potential as flexibility sources [21]. Since all buildings have some degree of thermal inertia, heat loads have the ability to be disconnected for shorter time periods without compromising the indoor thermal comfort. With smart metering, residential customers have an easier way of using their electricity in a better way by the ability to observe their consumption and adjust to i.e. the electricity prices. That makes it cheaper for the customer, and at the same time reliefs more capacity in the grid and for generation. Loads like space heating can quickly be curtailed for short time periods while still maintaining indoor comfort. The same applies for charging of electric vehicles which can easily be moved to times with low electricity prices without affecting their availability. Commercial buildings use much ventilation and cooling, which are also loads that can be reduced in times where the energy price is low without disturbing comfort and air quality. In the Nordic countries, more than 1/4 of the power consumption is in the industry[22], where activities are in process all the time, even with high power prices. Since it is a sector that uses a lot of power, managing to reduce it will have a great impact on total energy use. However, it is a sector where disconnection in certain times can be challenging, i.e. in the aluminium industry. This shows the importance of using the energy smarter where it is achievable.

The Norwegian power system operator, Statnett´s report about flexibility in the Nordic power market [22] illustrates how different household appliances can provide flexibility. Thermal loads such as water heaters, electric radiators and heat pumps can be both moved and substituted. It is estimated that heat pumps in Norway can move up to 3 GW during peak hours. Cooling is mostly used in refrigerators and freezers in Nordic households, making it a smaller contributor to the energy demand than heating, however, it can still assist by quick responses, such as for frequency control. The report also studies ventilation, which does not require constant actuation as long as the air quality is satisfying. Ventilation draws little power in households, but more in larger commercial buildings such as schools, offices or hospitals. Temporarily reduced ventilation will also reduce heat loss due to ventilation, hence also the total heating demand of the building.

More consumer flexibility is likely to be expected in the near years, either in new ways of consumption, or smarter use of existing consumption. A combination of installing smart meters, growth of electric vehicles and increase in residential buildings with smart house technologies suggests good possibilities for consumer flexibility. Since it can be challenging for the regular consumer to adjust to the price variations manually, automatic control is a convenient tool. There already exists i.e. apps like Tibber [23], that can help the customer control their consumption in a smarter way.

In the recent years there has been an increase in number of buildings with installed onsite PV panels. As the PV panels are becoming cheaper, the profitability of self-produced power is increasing. With later regulations it is possible to sell PV power back to the grid when the production exceeds the demand of the building. This can be a flexibility measure as it gives more power to the grid at times when the customer can sell the surplus power, and when the customer is using their own produced power it relieves capacity in the grid [24].

In the Annex 67: Energy Flexible Buildings [25], a preliminary current state assessment regarding energy flexibility has been carried out, where a number of various European countries have rated their own "Current readiness level" within the following categories:

1. Application of energy flexibility in buildings.
2. Solutions to manage energy flexibility in buildings.
3. Users acceptance of activated flexibility in buildings.

In this evaluation, Norway have given themselves the highest score on category 1 and 3, while they for category 2 have rated themselves with the lowest score. This signifies that the appliances to implement flexibility exist, and it is accepted among users. However, the issue is how to manage it. Managing energy flexibility should therefore be a main focus point within studies of energy flexibility in the years to follow.

3.2.1 Energy storage

Use of energy storage is a major area of interest in the field of energy grids. It is a tool that can provide stabilization and flexibility in a grid with more intermittent renewable energy sources. There exists several types of energy storage. Electric storage can be such as batteries or hydrogen storage, and thermal storage can be water accumulation tanks or integrated thermal mass. Technologies such as batteries and hydrogen storage are relatively expensive, but as an emerging technology the price is decreasing [26].

NVE expects a 50% reduction in cost for batteries in the grid towards 2030 [27]. Due to the cost reduction, Bloomberg New Energy Finance claims in a report from 2019 that installed capacity of stationary batteries worldwide will be 150 times larger in 2040 than in 2018. Batteries can be used in both small and big scale, with various objectives. Big scaled batteries in the grid can be used for voltage support, or it can be profitable for the grid owner if it is cheaper than grid expansion. Small scaled, distributed batteries can be profitable for the owner due to reduction in the energy bill, either by reduction in peak load, reduction in energy use during peak hours or increased self-consumption. Since Norway does not have feed-in-tariffs, maximizing self-consumption is naturally incentivized since the price paid for sold electricity to the grid is lower than the price for buying electricity from the grid, due to grid tariffs[28]. A battery can also have a direct income, for example by using it for arbitration. This means that power is bought from the grid, and charged into the battery when prices are low, and then the battery is discharged and the power sold to the grid with earn when prices are high. Also, the battery owner can be paid for offering services such as frequency support for balancing [27]. Small scaled batteries are already becoming a legitimate part of the energy system, as the amount of electric vehicles are growing. Since the transport sector is continuing to electrify, its potential of acting as a flexibility contributor increases as well.

NVE estimates that by 2030 the transport sector in Norway will make up a battery capacity of 100 GWh [21]. On average, vehicles are parked for about 22 h daily, making it possible to shift the charging as long as the customers have the vehicle fully charged when needed [29]. For instance, instead of charging the car when it is plugged in at 17.00 when the energy demand is often high, it can be charged at night when energy demand is lower. This may also be cheaper for the customer as the power price usually decreases in low-demand hours. With the situation today, batteries in the electricity grid are gradually becoming competitive, while batteries for smaller consumers are expected competitive in a few more years. However, it can be seen as likely that if several services such as congestion management or frequency containment reserve are combined, it can actually become profitable [30].

3.2.2 Flexibility using space heating

Since Norway is a cold country, buildings require a reasonable amount of space heating, and hence does HVAC systems contribute with a lot of a building´s energy. Due to a buildings thermal inertia and internal mass from its furniture, HVAC systems can both unload and preload while still maintaining thermal comfort. To investigate HVAC flexibility, a baseline profile is first needed to determine the original load profile. From this load profile, new temperature set-points can be determined and change the load profile as wanted. Two common strategies for heating and cooling systems are temperature reset and pre-heating/cooling. With temperature reset, loads are reduced in peak hours regardless of what the current temperature is. This is a simple way to relieve the grid. However, the thermal comfort should not be sacrificed, and temperature reset does not give any guarantee that thermal comfort will be remained. Pre-heating, or pre-cooling is increase of loads in the hours before the start of a peak. Utilizing the thermal inertia of a building can be cost-effective without compromising thermal comfort. Peak load reduction is hence dependent on and varies with different thermal mass. Using HVAC systems for flexibility does not require extensive changes and new investments, so it is a cost-efficient way to improve a building´s energy flexibility. If an HVAC system is to be combined with any kind of thermal storage, it may as well be able to provide long term flexibility services [31].

The advantage of utilizing the thermal mass of buildings as heat storage is that it is already available in the building, and only requires an extra investment in controllers for the heating system. In most commercial buildings and in newer residential buildings this is not even needed as the heating system is often connected to a controller system already. Commercial buildings usually represent a larger share of energy consumption than residential buildings, and their heating system is usually quite significant. This creates an even greater potential for load shifting through the use of space heating and thermal mass in commercial buildings [32].

3.3 Energy prices

3.3.1 Electricity

The electricity market works the same way any other market do, ruled by supply and demand. When the demand is high, the use of resources is high, so the price will be high as a signal to decrease consumption, and vice versa. Besides, commercial buildings are charged for the highest power output each month, which is an incentive to decrease the coinciding energy use, to make sure that it does not exceed neither the installed capacity nor the grid transmission capacity. Adding a peak load tariff for residential customers is a suggestion that has been up for hearing[33], but have for now been discarded, as it is supposedly too complex for the normal end-user to understand. Yet, to have an incentive for peak load reduction, it can be expected to apply for residential customers in a few years anyway. The daily electricity market, also called the spot market, that Norway participates in is run by NordPool, and mainly consists of the Nordic and Baltic countries.

The electricity price consists of three parts; grid tariffs, electricity procurement and taxes, whereas each of the parts make up about one third of the total price. Electricity procurement is the price from the spot market, and grid tariffs are set by the distribution grid company. The grid company is responsible for operation, maintenance and development of the grid. The grid rates during winter are usually higher than during summer. This is to indicate that to cover the highest peak loads during winter time, the grid needs to be expanded, which is expensive, and mostly needed for these specific peaks. The purpose is to make the customers distribute their energy use on these types of days, to avoid high power peaks.

3.3.2 District heating

To incentivize district heating, the district heating price is set to never exceed the price for electric heating, according to the Energy law §5-5 [34]. District heating is not yet liberalized in Norway, meaning that there is no market for selling and buying district heating, like the spot market for electricity. Therefore, the price is set by the distinct district heating company themselves, and can vary between months during a year, while maintaining the Energy law.

3.3.3 Future energy prices

The Norwegian Water Resources and Energy Directorate, NVE, have performed an analysis of how the Nordic and European electricity market will evolve until 2040 [35]. The report concludes that the average price of electricity will rise towards 2040 and be more stable over the years, but that there will be more short-term fluctuations due to power plants that cannot be regulated. Electricity consumption in buildings is decreasing because of energy efficiency measures, but due to an increase in electrification, the total electricity consumption is expected to stay approximately the same. Power exchange with the rest of Europe will be of importance to the development of the electricity price considering connections to i.e. Germany and Great Britain, which increases the trading capacity by about 40%. Since the rest of Europe is also installing more wind and solar power as a result of the EU´s renewable energy directive [36], the daily fluctuations in prices will increase, which will affect hourly power prices in Norway. Because of the fluctuations in power accessibility, a flexible energy use and more storage options will be even more favourable in the future and can help stabilize the electricity prices. District heating prices are not assumed to have a free market in the near future, so it is expected that they will continue to follow the electricity prices.

3.4 Building Performance Simulation

Building Performance Simulation (BPS) is defined in [37] as

"Computational building performance modeling and simulation ... is multidisciplinary, problem-oriented and wide in scope. It assumes dynamic (and continuous in time) boundary conditions, and is normally based on numerical methods that aim to provide an approximate solution of a realistic model of complexity in the real world".

Using BPS is desirable as it creates Building Energy Models (BEM) that gives the opportunity to make good design decisions for buildings and their technical systems. Building Information Models (BIM) is a commonly used tool in the industry of architecture, engineering and construction [38]. BIM is a digital representation of a building, that contains accurate information and allows for interoperability with other software tools, such as BPS tools. Various BPS tools takes BIM files as input to create the BEM, as it already contains numerous information about the building [39].

3.4.1 IDA ICE

IDA Indoor Climate and Energy (IDA ICE) is a BPS software developed by the Swedish company EQUA Simulation for studying thermal indoor climate of zones in a building, as well as energy consumption of entire buildings [40]. It has a simple user interface, but can also perform more advanced analyzes. It can be used to simulate a single- or multi-zone building, with an energy plant, and one or more air handling systems. It takes in weather files, and takes into consideration humidity and carbon dioxide within the building, as well as wind and temperature driven airflow. Simulations performed can be related to particular aspects like heating, cooling or energy, and gives detailed results as both numerical values and graphs with hourly intervals. Results can be such as temperatures, air flows, energy demand and heating, and based on these results one can modify the inputs to further improve the model. How advanced the model is depends on the user, as it is designed for simple user interface, but also has possibilities to add more advanced inputs. Because of its adaptability in user inputs needed, it can perform simulations on both simple buildings, but also on more complex buildings. Elements that can be defined are i.e. HVAC systems and other energy systems, building construction materials, climate zones, controllers, internal heat gains and schedules for internal loads [41].

3.5 Use of BPS tools for energy flexibility in literature

Use of BPS tools is important in building operation to anticipate the buildings energy potential. A literature review has been conducted to see how BPS tools have been used in prior studies, and what the possibilities are.

[42] uses IDA ICE to investigate the flexibility potential in low-energy residential buildings by using space heating. The buildings studied are a single-family house and an apartment block, both built according to the Danish Building Regulation 2015. Space-heating flexibility is performed by activation of inherent thermal mass. The goal of using the flexibility is to increase the use of renewable energy by increasing energy use when there is abundance in production, and use less when production is limited. The thermal mass is being charged by increasing the air temperature set-point, and discharged by decreasing it. A reference study is conducted at first, using thermostatic control with constant air temperature set-point of 22°C. From this, two ways of modulating set-point temperature is considered. The first scenario increases the set-point temperature to 24°C for a period of time, to counteract for abundance of renewable energy in the energy system. This way, heating is stored in the thermal mass. The other scenario decreases the set-point temperature to 20°C for a time period to counteract for little or no renewable energy available in the energy system. In this scenario heating is curtailed so that heat is released from the thermal mass. To not compromise thermal comfort for the occupants, the limit for comfortable conditions is set to 22°C ± 2°C. This complies with the thermal comfort Category 2, "Normal level of expectations for new buildings" according to the standard EN-15251.

The study found that with flexibility events under moderate weather conditions during the Danish heating season, that started at 06:00 and lasted 8 hours, heating energy added is larger than energy curtailed for both the single-family house and the apartment block. There are clear asymmetries between added and curtailed energy in all cases. The study concludes that the amount of energy to be curtailed in single-family houses is limited, but that if aggregated to a neighbourhood or district level it can have a more significant impact. However, for abundant production of renewable energy the buildings are able to act as storage media, which shows that low-energy buildings are highly robust for such implementations.

[43] compares different rule-based control strategies such as price based, CO_2 based and schedule based control, performed in IDA ICE. It found that when a residential building with direct electric heating uses a schedule-based control, it is extremely effective in reducing energy use during peak hours. However, this control strategy may generate new peaks during pre-peak periods, in addition to have a higher energy use during pre-peak hours compared to the other control strategies. The study found that the use of price-based control to reduce energy costs in Norway is not really profitable, as spot prices in Norway do not fluctuate much during a day due to the high share of storable hydro power. A price-based control strategy is therefore probably more favourable in other countries with a higher share of intermittent renewable energy sources that cannot be stored. A price-based control strategy has been tested in Denmark, and found to increase electricity use, but still reduce costs. The schedule based control proved better for the case of direct electric heating than with a heat pump, but still it states that since in Norway, the most important objective is to reduce energy use during peak-hours, a schedule based control is considered the best solution.

[44] uses the BPS tool TRNSYS to perform rule-based control on four energy flexibility sources, and demonstrates the risk of implementing a poor rule-based control. The study shows that with the flexibility actions, they have the possibility to decrease annual energy costs of up to 4%, but if implemented improperly they risk increasing the costs by 9%. It also states that when using RBC, one can obtain "a bound universe of possible results", so i.e. Model Predictive Control or direct control might give better, or somewhat different results.

3.6 Control strategies

To utilize energy flexibility, different control strategies can be applied and the most common ones are presented in this subchapter.

3.6.1 Rule-Based Control

Rule-based control (RBC) is based on a set of pre-defined rules to control a system. It does not require a mathematical model, so it is relatively simple to implement. Due to its simplicity it is the current most common control practice. This control strategy does however, require well defined control rules to be an effective control strategy. RBC can have several control algorithms, such as i.e. momentary or predictive. A momentary algorithm evaluates whether to increase or decrease the set-point temperature based on inputs from the current situation, such as minimum indoor temperature, maximum temperature of DHW, and current hourly electricity price. A predictive algorithm evaluates whether to increase or decrease the set-point temperature based on a forecast of the situation, such as the trend of future electricity prices [45]. RBC decides the control inputs based on a set of "if, then" rules, whereas the conditions and actions are often associated with parameters that needs to be chosen. The strategy is highly dependent on the user, because choice of rules and associated parameters will determine whether the performance of the control is good or not[46]. RBC for a building with PV and battery can be that the building will always use produced PV when possible, and store any surplus in the battery. When there is no, or too little PV generation available, the building will discharge available energy from the battery [47].

A huge advantage of RBC is that it does not require an exact mathematical model of the system, and it is possible to create a model based on only a small amount of experimental data. A set of rules can be decided without knowing the underlying dynamics, so the operator can produce a control strategy learned by experience. The disadvantage of RBC however, is that achieving the optimal solution can be difficult, even with the required expertise[48]. RBC is a conventional control strategy, that is the control method used today. It does lead to a reduction in energy consumption and peak energy, but as it is not an optimized control strategy, and the performance of the control is highly dependent on the chosen rules, it does not necessarily exploit the full potential of a building [49].

3.6.2 Model Predictive Control

Model predictive control (MPC) is more complex, and require more implementation than other non-optimal control strategies such as RBC. It aims to control the system while satisfying a set of constraints. It takes forecasting into account, while optimizing the current stage. It minimizes an object function, i.e. cost, to calculate the optimal control inputs over a finite prediction horizon. Current state measurements and weather forecasts, as well as a mathematical model of a building predicts the future behaviour of a building [50]. From simulations, upgrading and optimizing a buildings control system has even proved to be cost-effective compared to refurbishment of buildings. MPC has proven to significantly reduce energy consumption of a building in simulations, but is still lacking proper implementation into real, in-use buildings. The reason why MPC has a way to go regarding implementation in practice is because all buildings are unique regarding building envelope, subsystems, hardware and software solutions etc, so it requires tailored design of the control strategy [49].

4 Method

The data collected for this thesis and a description of how it is obtained, as well as use of the BPS tool and the methodological approach are presented in this chapter.

4.1 Data

The data regarding the building shape and envelope is extracted from Building Information Model (BIM) files received from the municipality of Bærum. The BIM files are opened in Solibri where information about building shape, dimensions and materials is displayed. All the required information regarding the physical properties of the buildings is thus extracted from Solibri.

Erichsen & Horgen is the consulting engineer for the project's HVAC systems, and have therefore created SIMIEN files for the three buildings to calculate annual energy use. These files were received for the specialization project in October 2020. From the files, more detailed information is obtained on the buildings' energy systems, such as heating and ventilation. In addition, the SIMIEN files provides U-values for walls, roof, floor and windows. The results from the SIMIEN energy simulations are used as a comparison for the IDA ICE models created to ensure that the determined energy consumption is reasonably accurate. IDA ICE can better account for the heat stored in the thermal mass of the building compared to SIMIEN. Therefore, a lower total energy consumption in IDA ICE is accepted when comparing the energy consumption.

In order to calculate energy cost, it is necessary to identify the prices for the two energy systems. For electricity, spot prices are average hourly prices from 2013-2020 obtained from NordPool Historical Market Data [51]. Grid tariffs are obtained from the grid owner Elvia [52]. For district heating, all prices are paid to the system owner, therefore prices are sourced from Oslofjord Varme [53] as of 1st of February 2021.

4.2 IDA ICE

IDA ICE is used to simulate energy consumption. In Norway, SIMIEN is the leading energy calculation tool [54], and would have been practical to use since files of the buildings already exist. However, SIMIEN does not have the possibility to perform simulations with a fluctuating heating set-point schedule, and therefore IDA ICE is chosen. IDA ICE is a viable tool for investigating energy flexibility since it is possible to decide which parameters should be considered and which should not. The first step in IDA ICE is to implement models of the buildings. This is done using the previously obtained information, as explained in subchapter 4.1. In order to verify that the implemented models in IDA ICE are somewhat correct, an energy simulation is performed and compared with the results of the energy simulation in SIMIEN. The result from this simulation forms the baseline for comparison and further development.

As mentioned in subchapter 3.4, IDA ICE needs a BIM to be able to create a BEM. IDA ICE has the ability to create the BIM within the program itself, or one can import it in an IFC format [55]. Essentially it is preferable to implement IFC files, as architects have made accurate and detailed models of the buildings at Oksenøya. It should be possible to prepare any IFC for IDA ICE by using Simplebim according to the software developer EQUA[56]. After much trying of implementing the received IFC files it proved not to be feasible. The recommendation was therefore to create the BIM from scratch within IDA ICE. Much time was already lost so the building envelope had to be greatly simplified. The total area and volume should be approximately the same, but to reduce computation time, zones and windows are merged. Computation time is reduced since IDA ICE makes mathematical models for all elements of the building. These simplifications have been studied in the literature [57, 58] and have been proved not to noticeably affect the total energy use. When zones are merged, internal mass used for heat storage is lost, but this is compensated for by adding artificial internal mass as input.

In IDA ICE version 4.8 PV panel modeling is included, however is it a very simple model that only takes into account area, tilt angle and orientation, and efficiency. For this reason, the PV production results are only estimates based on these inputs. Version 4.8 does not have the ability to implement a battery. This issue is solved by creating a simplified, non-optimized model of a battery in Excel.

4.3 Work process

The first step in the work process is to implement the buildings in IDA ICE, as described in subchapter 4.2. Heating flexibility is simulated by specifying a predefined schedule for the heating set-point temperature. The schedules are determined using trial and error in IDA ICE to achieve the main objective for a set of scenarios. The schedules are found with the objective of reducing peak load as much as possible, without compromising thermal comfort according to subchapter 3.1. Battery flexibility is simulated by deriving the baseline load profiles from IDA ICE to Excel. In Excel, the battery is modeled using a simple rule-based approach.

In order to find a desirable operating strategy, a number of realistic scenarios are established. Essentially, Oksenøya will be equipped with individual energy metering for each building, for electricity and district heating. However, since Bærum municipality owns all the buildings,

they will pay all the energy bills. A suggestion from them is therefore to look at common metering as a measure to reduce energy costs, to see if it is worthwhile to consider common energy metering instead of individual metering. The aim of the flexibility measures will vary depending on the metering point chosen, as flexibility will then be used differently. On this basis, it is decided to investigate individual and common energy metering, and to study both, with and without flexibility measures. As flexibility can be seen as a means to limit expensive grid expansions, it is interesting to investigate the potential of controlling Oksenøya to avoid Fornebu's peak grid hours. As an additional scenario, Oksenøya is treated as a ZEN with common metering, which is then controlled to avoid peak hours at Fornebu.
To be able to evaluate the accomplishment of the scenarios a set of KPIs is established. The KPIs adopted are the following:

- **Energy cost** [kNOK/year]: The total annual cost for the energy consumption, for district heating and electricity.
- **Peak load cost** [kNOK/year]: The annual cost for peak load tariff, for district heating and electricity.
- **Total cost** [kNOK/year]: The sum of energy cost and peak load cost, for district heating, electricity, and both.
- **Yearly energy use** [MWh/year]: Total MWh consumed annually.
- **Yearly maximum peak load** [kW]: The maximum peak load for Oksenøya measured by the energy meters for district heating and electricity.
- **PV self consumption** [MWh/year]: The amount of PV generated that is self-consumed.

4.4 Investigating energy flexibility

4.4.1 District heating: Space-heating flexibility

Peak load reduction within the district heating system is accomplished by utilising space heating flexibility. This is done through a rule-based control strategy that aims to reduce the peak heating load by increasing the heating set-point previous to the original peak and then decrease it. In performing such a strategy, it is assumed that a baseline simulation has been completed so that the peak hours are known in advance.

4.4.2 Electricity: Battery

Investigating the electricity flexibility is done by utilising the stationary battery. The battery has a capacity of 700kW, and the charging and discharging efficiency is assumed to be 95%. The battery can be used for two purposes, increasing PV self consumption, and reducing peak loads. To increase PV self consumption, surplus PV is stored in the battery, and only sold to the grid if the battery is fully charged. Since it is usually not profitable to keep the battery charged for a long period of time, it will discharge in the evening if the battery State of Charge (SOC) is above an upper limit. For peak load reduction, the battery is modeled to discharge when the import demand reaches a predefined maximum value.Even though a maximum demand value is set, the demand exceeds this value at times, in particular if PV generation is low and demand is high. To cope with any peaks that occur before PV production starts, the battery will charge during the night if the SOC is below a set limit.

4.5 Cost calculations

The costs for energy are calculated using Excel, and district heating cost and electricity cost are calculated separately. Costs for both energy and peak load are calculated for all scenarios over the period of one year. VAT is not included in the cost calculations. If VAT is considered, all numbers will increase by 25%.

The electricity cost includes the spot price, the grid tariffs and the electricity fee. Energy market costs correspond to electricity bought from the market at spot price, minus the PV production sold to the market for spot price. Equation 1 shows how the total electricity price is calculated. p_{spot} refers to the spot price, in [NOK/kWh], E_{import} and E_{export} refers to the electricity imported and PV production sold to the grid in [kWh]. $p_{energy,el}$ includes energy grid tariffs and electricity fee, both in [NOK/kWh]. $p_{peak,el}$ is the peak load grid tariff in [NOK/kW], and $P_{max,month}$ is the highest power output each month in [kW]. $C_{fixed,el}$ is the fixed price paid at each metering point every year, in [NOK/year].

$$C_{tot,el} = (p_{spot} \times (E_{import} - E_{export})) + (p_{energy,el} \times E_{import}) + (p_{peak,el} \times P_{max,month}) + C_{fixed,el} \tag{1}$$

District heating costs only includes costs to the grid operation company, Oslofjord Varme[53], as prices include energy price, grid tariffs and additional fees. Equation 2 shows how the total district heating cost is calculated. $p_{energy,dh}$ refers to the price paid for energy in [NOK/kWh], while $Q_{demand,dh}$ is the heating energy used in [kWh]. $p_{peak,dh}$ is the district heating peak load tariff in [NOK/kW], and $P_{max,dh}$ is the maximum annual subscribed power, in [kW]. $C_{fixed,dh}$ is the fixed price paid at each metering point every month.

$$C_{tot,dh} = (p_{energy,dh} \times Q_{demand,dh}) + (p_{peak,dh} \times P_{max,dh}) + C_{fixed,dh} \tag{2}$$

5 Oksenøya: Case study

This chapter gives an overview of the input values that apply to Oksenøya, and that have been used in this thesis.

5.1 IDA ICE simulation

All input values have been carefully selected to ensure that the results are as accurate as possible. Most of the inputs for the IDA ICE simulation are values obtained from the SIMIEN models.

The ventilation system in all buildings has a Variable Air Volume (VAV). SIMIEN offers the possibility to choose a maximum and a minimum airflow for this. IDA ICE only gives the possibility to choose one value, so the resulting value from the SIMIEN simulations is chosen.

As mentioned earlier, the building sketches are simplified and only consist of the building envelope and floor dividers. To compensate for the loss of internal walls and furniture for thermal inertia, IDA ICE has a feature that takes as inputs the square meters of internal walls and furniture in each zone. The area of internal walls is obtained from SIMIEN, while the surface area of furniture is assumed to be ± 50%.

The ZEN is installed with PV panels. Much information is needed to model PV production. The total area of installed PV panels on Oksenøya is 2600 m^2, on the roof of the school and nursing home. However, Bærum municipality could not provide any information on what amount is installed on which building. Since the nursing home has a higher energy consumption and peak load than the school, 1600 m^2 is assumed for the nursing home and the remaining 1000 m^2 for the school. The tilt angle is 10 °, and the orientation is either towards south, or half towards east and half towards west. For simplicity, the south orientation is chosen, and the efficiency is assumed to be 18% based on typical values[59]. The PV panel inputs results in an annual PV production of 150 MWh on the school and 240 MWh on the nursing home.

The time of use for the ventilation system is 10 hours, from 07.00-17.00, in accordance with NS3031[14]. Since the focus of the thesis is on space heating, only the water-borne radiator system is controlled and not the heating coil in the ventilation system. This means that the ventilation system also provides heat via the heating coil from 07.00-17.00 every day. Table 5.1 shows the U-values for the buildings, 5.2 shows the input values for the ventilation system and 5.3 shows the inputs for the heating system.

Table 5.1: U-values

Building	**Element**	**Value**	**Unit**
School	Walls	0.1891	W/(m^2K)
	Roof	0.1007	
	Floor	0.1351	
	Windows	0.74	
Nursing home	Walls	0.1701	W/(m^2K)
	Roof	0.09834	
	Floor	0.1098	
	Windows	0.74	
Kindergarten	Walls	0.1186	W/(m^2K)
	Roof	0.1044	
	Floor	0.1098	
	Windows	0.74	

Table 5.2: Set-points of the ventilation system

Building	**Feature**	**Value**	**Unit**
School	Air exchange rate	2.2	L/(m^2s)
	Heat exchange efficiency	83	%
	Supply temperature	19	°C
	SFP	1.2	kW/(m$^3/s$)
Nursing home	Air exchange rate	2.2	L/(m^2s)
	Heat exchange efficiency	82	%
	Supply temperature	19	°C
	SFP	1.2	kW/(m$^3/s$)
Kindergarten	Air exchange rate	1.7	L/(m^2s)
	Heat exchange efficiency	82	%
	Supply temperature	20	°C
	SFP	1.2	kW/(m$^3/s$)

Table 5.3: Inputs heating system

Feature	**Value**	**Unit**
Rated power	50	W/m^2
Supply temperature	55	°C
Return temperature	45	°C

Standard schedules for automatic regulation of internal loads are obtained from NS3031. Heat gain from the internal loads is assumed 100% for commercial buildings. Figure 5.1, 5.2 and 5.3 shows the NS3031 schedules for the buildings at Oksenøya[14].

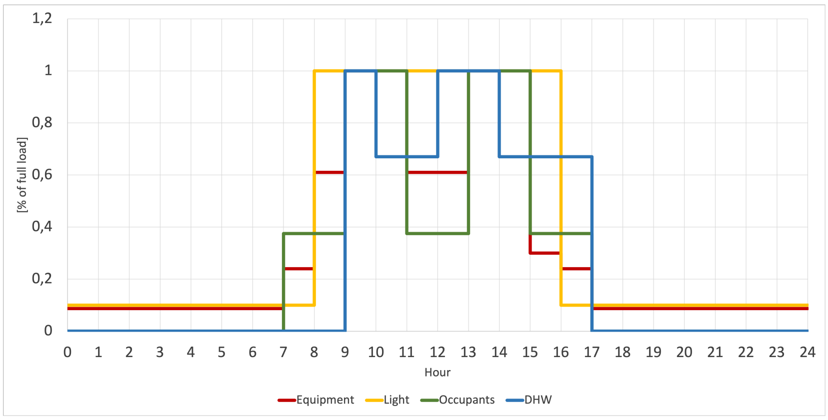

Figure 5.1: NS3031 - Schedule for school

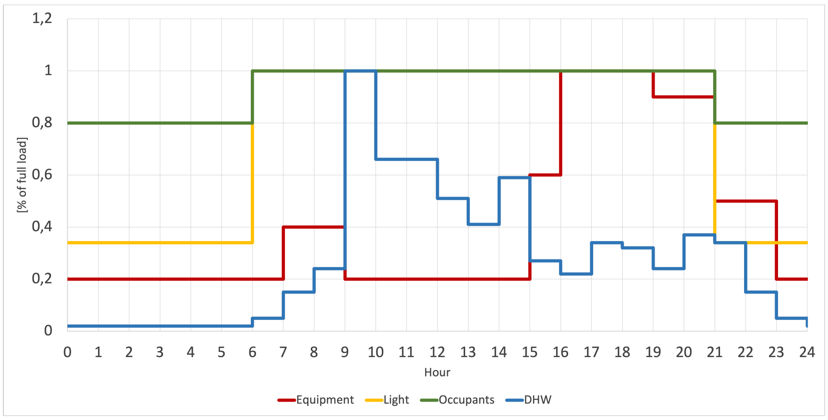

Figure 5.2: NS3031 - Schedule for nursing home

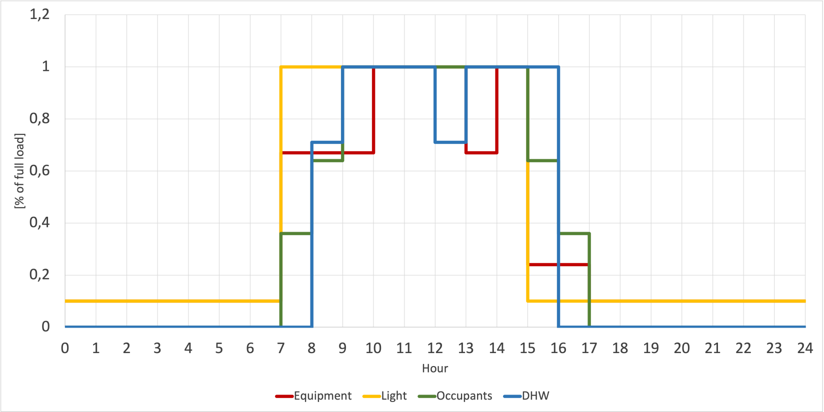

Figure 5.3: NS3031 - Schedule for kindergarten

5.2 Energy cost

The electricity costs include spot price, grid tariff and electricity fee. The spot price is an averaged value for every hour of the year from 2013-2020, taken from NordPool's Historical Market Data[51]. The grid tariffs are taken from Elvia's grid tariffs for commercial customers[52], and vary with the seasons. Grid tariffs for Elvia´s commercial customers consist of a fixed annual part, a variable energy part that charges the kWh used, a variable peak load part, that charges the highest power output each calendar month, in addition to taxes. Taxes included in the grid tariffs are payments to the energy fund Enova. In addition, an electricity fee is imposed by the government, and is set to 16.69 øre/kWh for 2021. Table 5.4 presents the grid tariffs from Elvia[52] that relate to Oksenøya.

Oslofjord Varme is the district heating company that has concession for Fornebu and have set the price for district heating at Oksenøya. The price for district heating consists of an energy part and a peak load part, in addition to a yearly fixed price for each metering point. The energy cost is calculated for each kWh measured at the metering point, and should account for the actual energy use. The peak load cost is calculated according to a yearly subscribed amount of kW, corresponding to the maximum amount of district heating one can withdraw from the heating central at once. Figure 5.4 exhibits the prices for district heating from Oslofjord Varme[53]. The prices are set from 1st of February 2021, and are the prices used to calculate the energy costs in this thesis.

Table 5.4: Electricity grid tariffs and district heating prices

Grid	**Component**	**Season**	**Price**	**Unit**
Electricity	Fixed annual		340	NOK/year
	Energy tariff	Summer	3.9	øre/kWh
		Winter	7	
	Peak load tariff	Summer	22	NOK/kWh/h
		Winter 1	120	
		Winter 2	67	
District heating	Fixed		325	NOK/month
	Energy tariff		80	øre/kWh
	Peak load tariff		550	NOK/kWh/h

6 Scenarios

This chapter describes all the scenarios carried out in this thesis. The main objective of each scenario is described, as well as the difference in input parameters. Five scenarios are carried out, with different goals regarding energy use. For all scenarios, two things are considered: the use of space heating for flexibility and the use of the battery for flexibility. Table 6.1 gives an overview of what is included in each scenario.

Table 6.1: Overview of scenarios

	Individual metering without flexibility	**Common metering without flexibility**	**Individual metering with flexibility**	**Common metering with flexibility**	**Common metering with Fornebu flexibility**
Energy metering	Individual	Common	Individual	Common	Common
Heating flexibility	No	No	Reducing individual peak load	Reducing total peak load	Avoiding Fornebu´s peak hours
Battery	No	No	Nursing home	Shared	Shared/ Fornebu

6.1 Baseline: Individual metering without flexibility (BASE)

The baseline is the original situation, where the buildings have individual energy metering, and no flexibility measures are applied. However, generated PV is used, since PV panels are installed, and without a battery they are not considered a means of flexibility in this thesis. Since the energy metering is individual, it is assumed that the PV panels on the school and the nursing home belongs to them respectively. The kindergarten does not have installed PV panels and will therefore not have any reduction in its demand. The surplus PV is sold to the electricity grid.

The SIMIEN files show that the space heating system has a night temperature setback, and Figure 6.1 shows the set-point temperature schedule for the three respective buildings. Due to the night temperature setback in heating set-point, all the buildings have a peak heating load in the morning when space heating and ventilation systems are activated. The buildings have a high thermal inertia, so since they cool down during the night, they require a lot of energy to quickly reheat the building, so the peak heating load always occurs in the morning, during the first hours of operation. This is seen in the results.

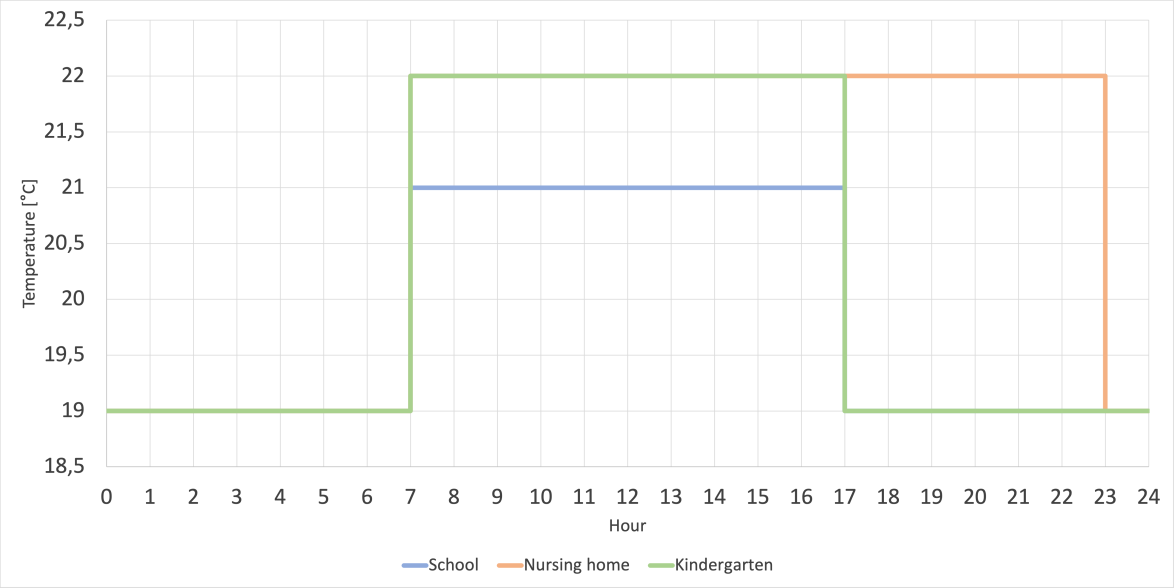

Figure 6.1: Set-point temperature schedule, BASE

6.2 Common metering without flexibility (COM)

This scenario investigates how the energy costs will change if Oksenøya is allowed to be billed as one common entity. No flexibility measures are applied here either, but the energy metering ischanged fromindividual to common. Oksenøya is being built as a pilot project in FME ZEN, which means its goal is to become a ZEN. One of the advantages with a ZEN is the interoperability, which is only an economic advantage if there is a common energy meter. For heating, the total energy consumption will be exactly the same, but since the heating peak loads for the three buildings do not necessarily occur in the same hour, the total peak heating load is expected to be reduced. For electricity, the PV generated is now available to all three buildings, so more of the PV can be consumed, which means that both the energy imported and the peak electricity load are expected to decrease.

6.3 Individual metering with flexibility (IND-flx)

In this scenario the buildings have individual energy meters, but flexibility measures are applied. The buildings are operated independently. For heating flexibility, new heating set-point schedules are applied, with a focus on reducing the individual peak load of each building compared to the baseline. To compensate for the peak heating load that normally occurs in the morning, the heating set-point is increased earlier in the night, to heat the building before the start of the operating hours. Figure 6.2 shows the set-point temperature schedules found through trial and error, that results in the best peak load reduction. Due to thermal inertia, it is chosen to increase and decrease the temperature set-points gradually rather than instantly, as instantaneous changes result in larger fluctuations in the daily load profiles.

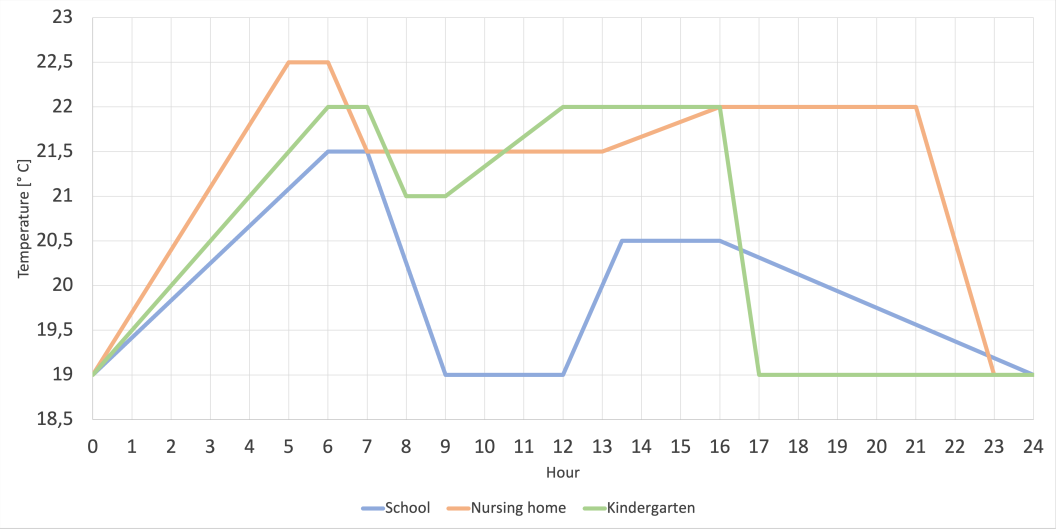

Figure 6.2: Set-point temperature schedule, IND-flx

For battery flexibility, the battery is placed at one building as the regulatory framework does not allow sharing the utilisation of a stationary battery between buildings with separate metering. The battery is tested at each of the buildings and found to be most economical when placed at the nursing home. The maximum demand limit for the individual battery is set at 200 kW as this gave the best results in reducing peak load.

6.4 Common metering with flexibility (COM-flx)

This scenario investigates the buildings with common energy metering and flexibility enabled. This means that all the PV production and battery capacity can be used by whoever needs it, and the goal of heating flexibility is to reduce the aggregated peak load. All buildings are modeled to reduce energy consumption during the peak hours of Oksenøya.

For heating flexibility, the main focus is on reducing the peak load for the total heating demand. The peak heating load for the collective demand also occurs in the morning, so the strategy of increasing the heating set-point at night and decreasing it in the first hours of operation is proceeded. Figure 6.3 shows the schedules for heating flexibility with emphasis on reducing the collective peak heating load. For battery flexibility, the focus is also on reducing the peak load for the collective electricity demand. The same approach is used as for IND-flx, but at a larger scale as the total demand is higher. The maximum demand limit for the shared battery gives the best results when set at 300 kW.

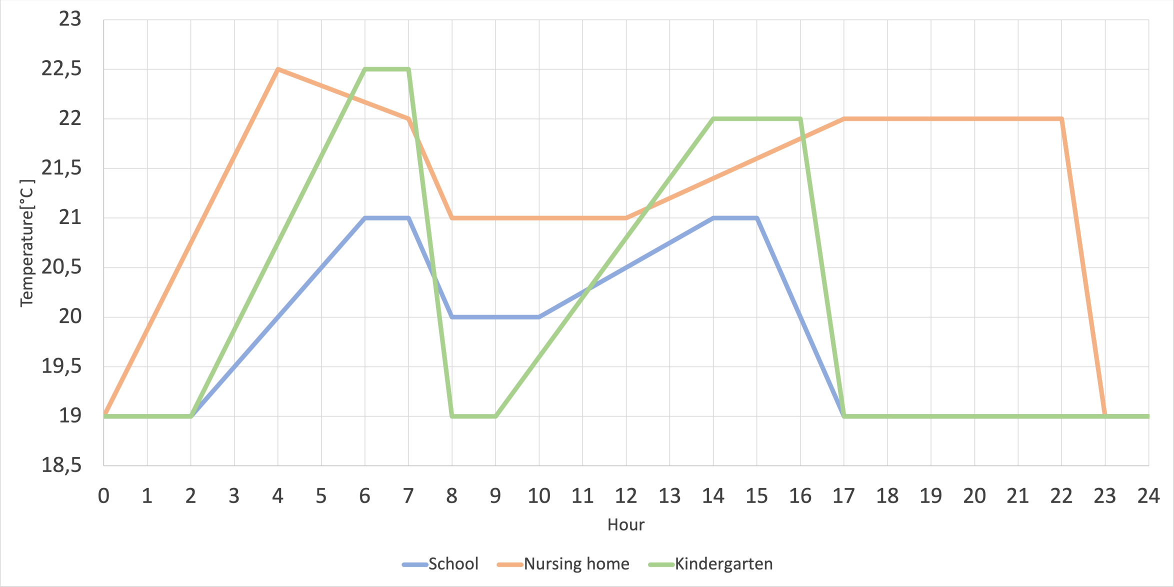

Figure 6.3: Set-point temperature schedule, COM-flx

6.5 Common metering with Fornebu flexibility (COM-FRNB-flx)

The final scenario is somewhat different from the others, as its main goal is to reduce energy use on Oksenøya during Fornebu's peak hours. It turns out that the peak hours of Oksenøya coincide with the peak hours of Fornebu, so the strategy from the previous scenarios is maintained, but with slight changes. Fornebu's peak hours for both heating and electricity are determined in the specialization project [5], and can be found in subchapter 2.3. The peak heating load occurs between 06.00 and 09.00, so the aim is to increase energy use from 00.00-05.00 to avoid heating from 06.00-09.00. Space heating is completely removed, but the district heating still delivers heat to the ventilation heating coil and domestic hot water. Figure 6.4 shows the heating set-point schedule for this scenario.

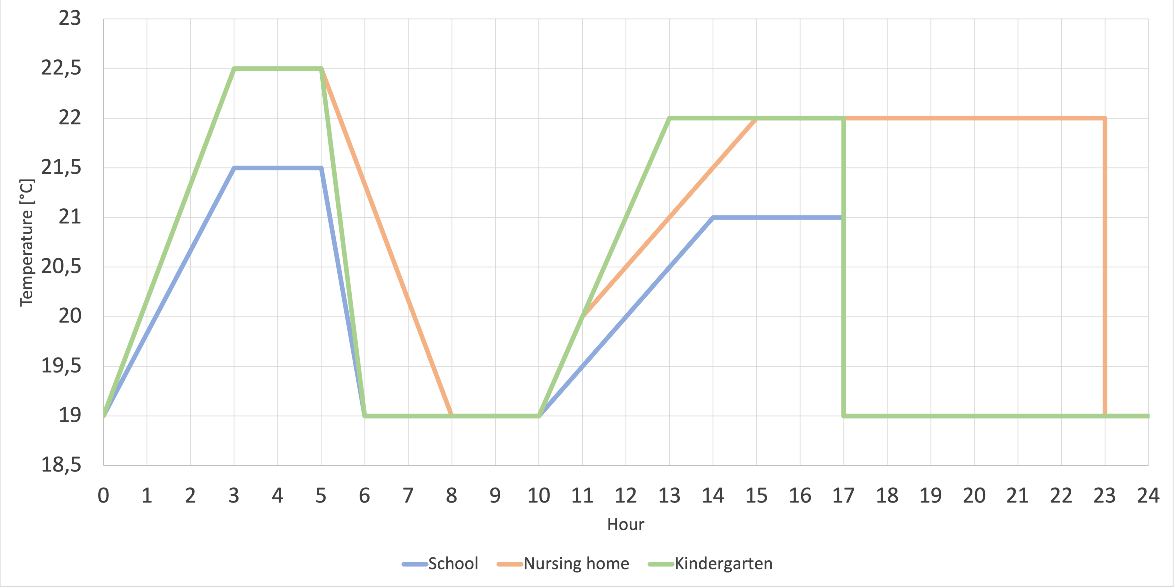

Figure 6.4: Set-point temperature schedule, COM-FRNB-flx

The electricity peak load occurs in the afternoon, which is due to the charging pattern of electric vehicles. Therefore, the electricity consumption of the buildings should be reduced from 17.00 to 21.00. Oksenøya´s demand is considered after the consumption of their own PV production and the sale of the PV surplus to the grid. The battery is charged when the demand at Fornebu is low and discharged when the demand is high. Since the goal of this scenario not is to reduce the peak load on Oksenøya, but to shift it to Fornebu´s off-peak hours, the only import limit on the battery is its maximum capacity. The battery is set to discharge between 12.00-22.00 as the peak usually occur in those hours, or when Fornebu´s demand exceeds 50 MW.

7 Results

This chapter first presents and compares the results from the simulated scenarios, and further provides an overview of the KPI results. The electricity costs contain many elements, so a detailed overview of what the cost components consist of can be found in the Appendix.

7.1 Individual metering without flexibility

BASE is simulated with an assumption of no flexibility measures and individual metering.

7.1.1 District heating

District heating costs are calculated according to Equation (2) in subchapter 4.5. Table 7.1 displays the district heating costs for the baseline. The energy cost and peak load cost are relatively similar in magnitude, but the energy cost is slightly higher.

Table 7.1: District heating costs, BASE

Component	**Cost [NOK]**
Fixed annual	11 700
Energy tariff	664 626
Peak load tariff	525 344
Total	1 201 669

7.1.2 Electricity

Table 7.2 displays the electricity costs for the baseline, calculated according to Equation (1) from subchapter 4.5. Energy market costs reflects the purchase of electricity in the spot market. Energy grid costs includes the energy dependent part of the grid tariff and the electricity tax, whereas grid peak costs reflects the peak load tariff.

Table 7.2: Electricity costs, BASE

Component		**Cost [NOK]**
Fixed annual		12 240
Energy	Market	359 934
	Grid	295 472
Grid peak		284 797
Total		952 443

7.2 Common metering without flexibility

To evaluate the benefit of a common energy meter instead of individual metering, the same condition as for the baseline is modeled, but with only one common energy meter.

7.2.1 District heating

For heating with common metering, the total heating consumption is the same as for individual metering, but the maximum peak load measured by the energy meter is reduced. The peak heating load occurs at approximately the same time during the day, but the maximum peak load for all three buildings does not necessarily occur on the same day. Figure 7.1 shows the aggregate of each building on their respective day with the highest peak load, compared to the day with the highest total peak load. No flexibility measures are implemented in this scenario, but it demonstrates the economic impact on the peak load tariff of having common metering instead of individual metering. The highest total peak load with individual metering reaches 955 kW, while the peak load with common metering reaches 919 kW. Table 7.3 gives an overview of the district heating costs. The energy costs are not decreased, but the peak load costs are slightly reduced. The annual fixed cost is reduced as it relates to each metering point.

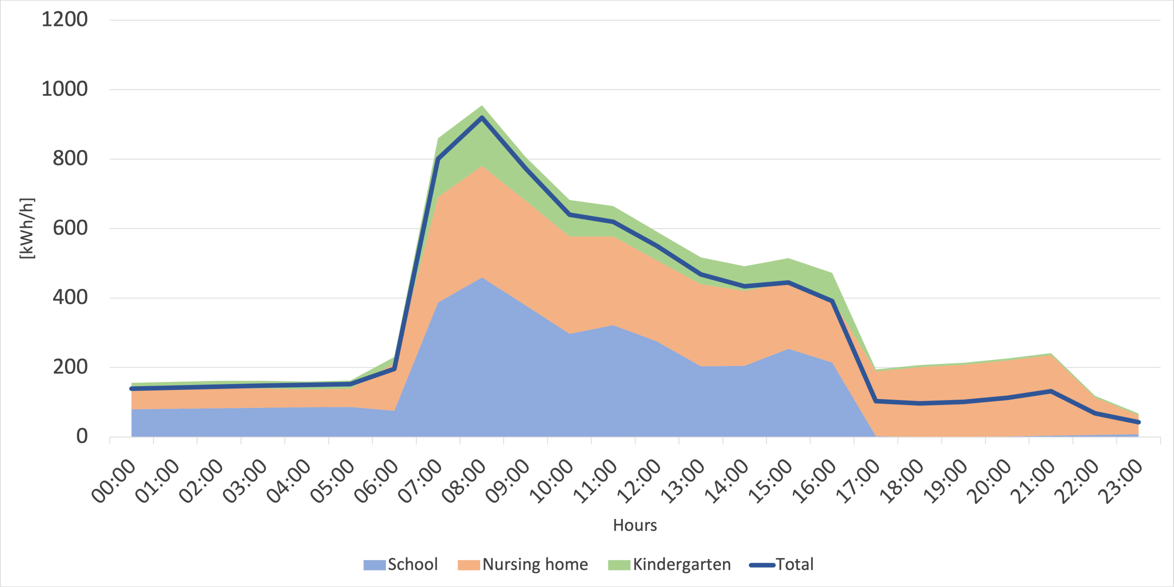

Figure 7.1: District heating load profile, BASE compared to COM

Table 7.3: District heating costs, COM

Component	**Cost [NOK]**
Fixed annual	3 900
Energy	664 625
Peak load	505 644
Total	1 174 169

7.2.2 Electricity

One of the advantages of common metering is that all buildings can use the generated PV, so the self-consumption increases and therefore the grid import decreases. This affects energy import more than necessarily the peak load. Since the neighbourhood consists of three different buildings that have different usage and occupancy, they reach their peak at different times during the day, which the peak load tariff does not take into account. Figure 7.2 shows the three individual buildings on their respective day with the highest peak load, compared to the total load on the day with the highest peak load. With individual metering, the buildings must pay for a maximum of 452 kW, while they with common metering only pays for a maximum of 361 kW. Table 7.4 shows the electricity costs for this scenario, and it is the grid energy costs and the grid peak costs that are reduced the most, while the energy market costs remain practically the same.

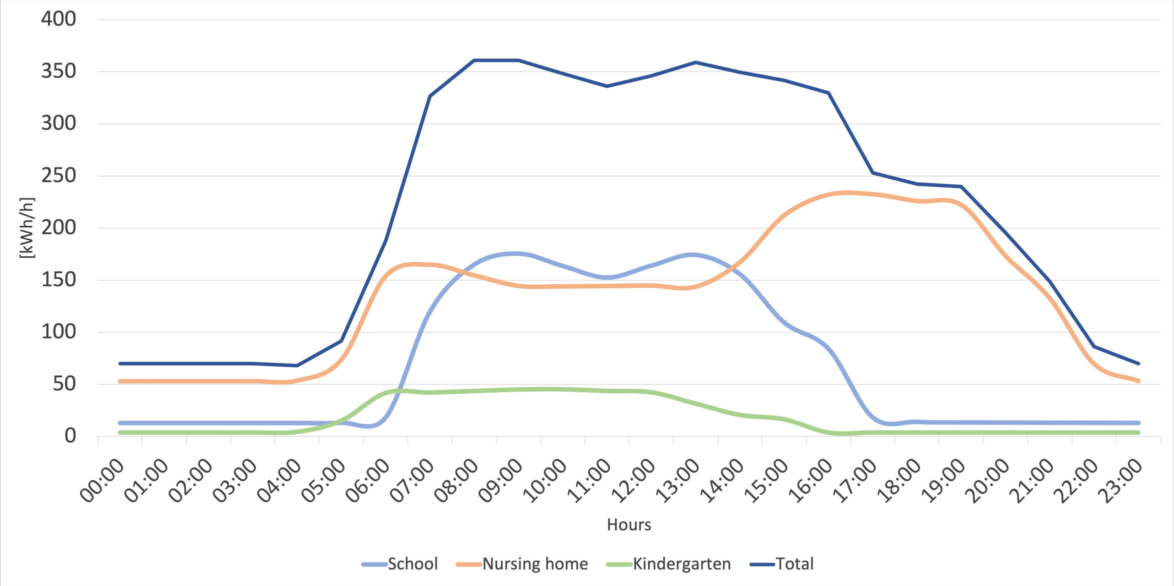

Figure 7.2: Electricity load profile, BASE compared to COM

Table 7.4: Electricity costs, COM

Component		**Cost [NOK]**
Fixed annual		4 080
Energy	Market	359 935
	Grid	285 220
Grid peak		225 387
Total		874 622

7.3 Individual metering with flexibility

7.3.1 District heating

Figure 7.3, 7.4 and 7.5 presents the daily load profiles for the school, nursing home and kindergarten, respectively. The day with the highest peak load for BASE is compared to the daily load profile for the day with the highest peak load after implementing individual heating flexibility. The "worst days" are compared, so the load profiles are not necessarily from the same day, but from the respective days with the highest peak load. For the school, the maximum peak load drops from 459 kW at 08.00 to 301 kW at 06.00. For the nursing home, the maximum peak load drops from 321 kW at 08.00 to 249 kW at 04.00. For the kindergarten, the maximum peak load drops from 174 kW at 08.00 to 100 kW at 05.00. Table 7.5 shows an overview of the district heating costs for this scenario. The energy cost increase a little, but as the peak load cost is reduced even more, the total cost is reduced.

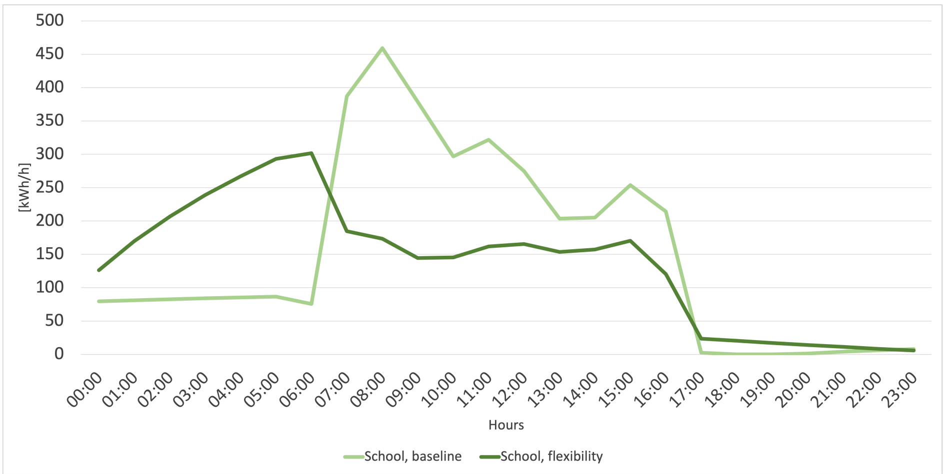

Figure 7.3: Individual heating flexibility at the school

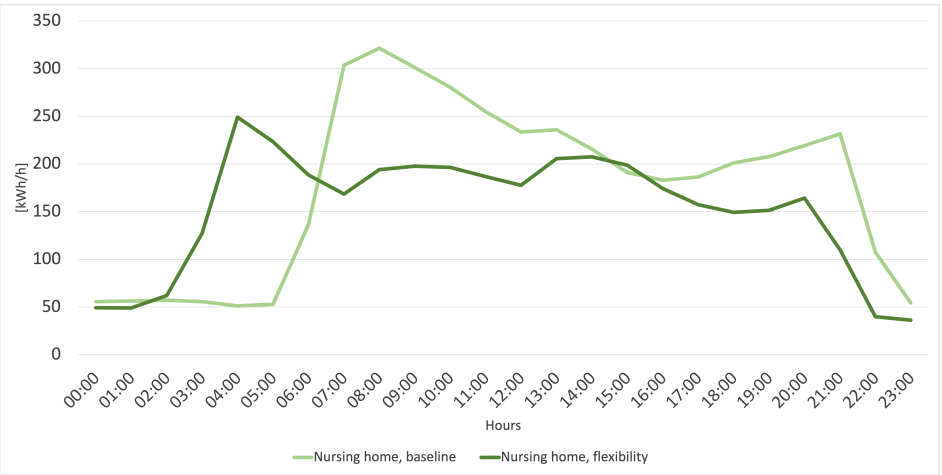

Figure 7.4: Individual heating flexibility at the nursing home

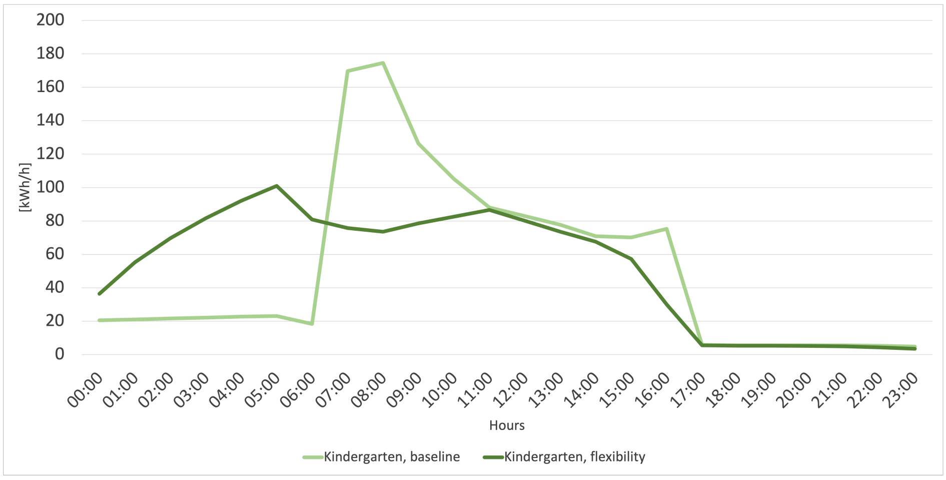

Figure 7.5: Individual heating flexibility at the kindergarten

Table 7.5: District heating costs, IND-flx

Component	**Cost [NOK]**
Fixed annuall	11 700
Energy tariff	679 977
Peak load tariff	358 497
Total	1 050 174

7.3.2 Electricity

For individual metering, the battery is placed at the nursing home. Figure 7.6 shows the day with the highest peak load for the nursing home without PV, with PV, and with PV and battery. On this particular day, the peak load is kept below 200 kW, which corresponds to the maximum demand limit set. Without the use of the battery, the peak load reaches 232 kW. The battery is charged during the night, and since there is no PV surplus to charge the battery on this day, the charge from the night is used to limit the peak load. Table 7.6 shows an overview of the electricity costs for this scenario. The grid peak cost is reduced most, while the grid energy cost is reduced slightly and the grid market cost is hardly reduced.

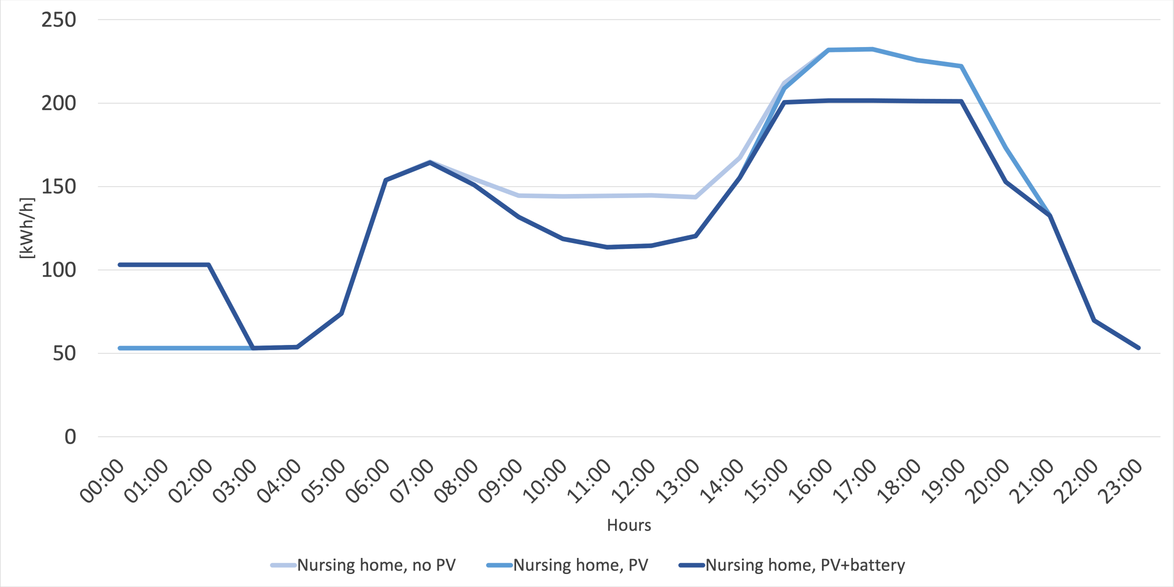

Figure 7.6: Individual battery at the nursing home

Table 7.6: Electricity costs, IND-flx

Component		**Cost [NOK]**
Fixed annual		12 240
Energy	Market	359 811
	Grid	293 473
Grid peak		267 243
Total		932 767

7.4 Common metering with flexibility

7.4.1 District heating

Figure 7.7 compares the accumulated daily load profile from BASE with the total daily load profile after implementing flexibility measures and introducing common energy metering. The peak load in the baseline reaches 955 kW, while it is reduced to 528 kW by implementing heating flexibility and common energy metering. The peak load is shifted so that it now occurs from 04.00-06.00 instead of 08.00. The total energy consumption is nearly the same, but the shape of the load profile is changed. Table 7.7 displays an overview of the district heating costs from this scenario. The energy cost is increased slightly, while the peak load cost is almost halved.

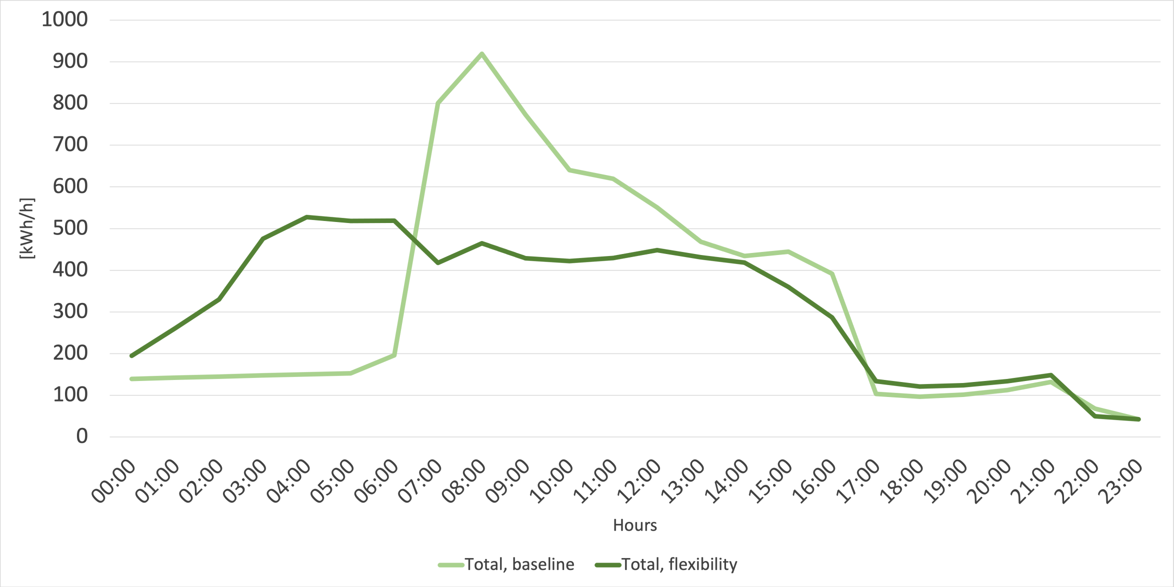

Figure 7.7: Heating flexibility with common energy metering

Table 7.7: District heating costs, COM-flx

Component	**Cost [NOK]**
Fixed annual	3 900
Energy tariff	672 961
Peak load tariff	290 153
Total	967 014

7.4.2 Electricity

For electricity, common metering allow for the battery to connect to all three buildings. Figure 7.8 compares the total daily load profile without PV, with PV, and with battery and PV.

The load profile is from a winter day, so PV production is low. In this case, it is beneficial that the battery is charged at night, as it then has enough capacity to keep the demand below 300 kW. By using the battery, the peak load is reduced from 361 kW to 300 kW. Table 7.8 presents the electricity costs. The peak grid cost is greatly reduced, as is the grid energy cost. The grid market cost is barely reduced, but a bit more than in the previous scenarios.

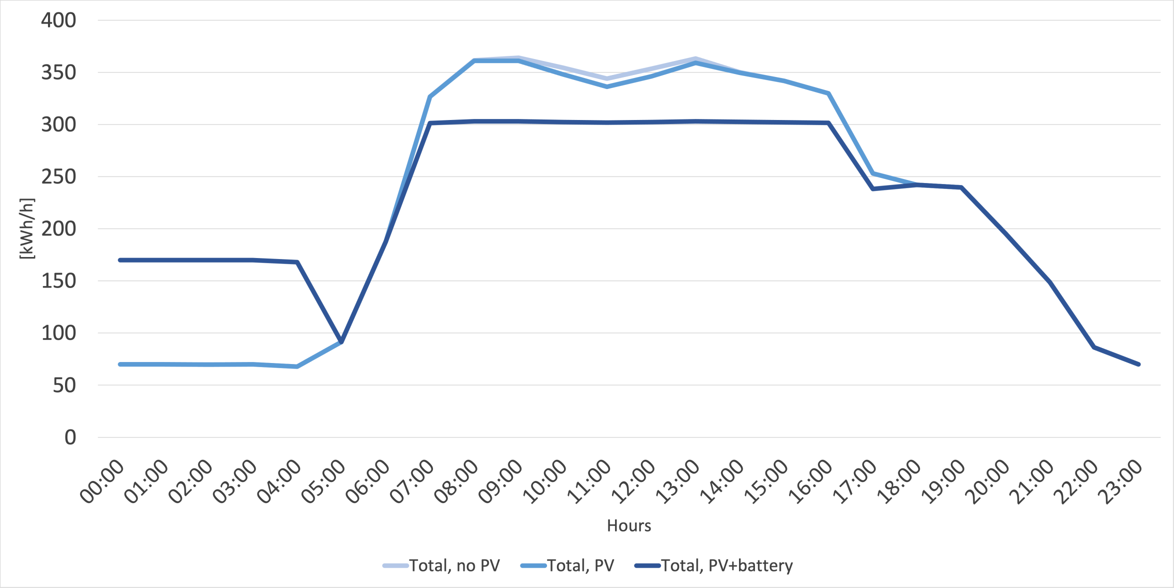

Figure 7.8: Shared battery

Table 7.8: Electricity costs, COM-flx

Component		**Cost [NOK]**
Fixed annual		4 080
Energy	Market	358 709
	Grid	283 546
Grid peak		194 263
Total		840 598

7.5 Common metering with Fornebu flexibility

7.5.1 District heating

Figure 7.9 shows the impact of Oksenøya on the district heating load of Fornebu in 2030 if no flexibility measures are implemented. Figure 7.10 shows how Oksenøya contributes to the district heating grid at Oksenøya by shifting its heating load from the peak hours of Fornebu to the off-peak hours. The dark blue area on top is Oksenøya, aggregated with the rest of Fornebu, while the light blue line gives a better illustration of the load profile, shown on the right axis. The peak load for Oksenøya shifts from 08.00, when Fornebu is also quite high, to 03.00, when Fornebu is at its lowest. Since only space heating is controlled, it is not possible to completely remove the energy use for heating during Fornebu's peak hours, as the ventilation system starts automatically when occupancy begins, as mentioned in subchapter 5.1. This scenario does not have cost reduction as a main objective, but it still reduces the total cost compared to BASE. Table 7.9 shows the district heating costs for this scenario. The energy cost is slightly increased while the peak load cost is reduced.

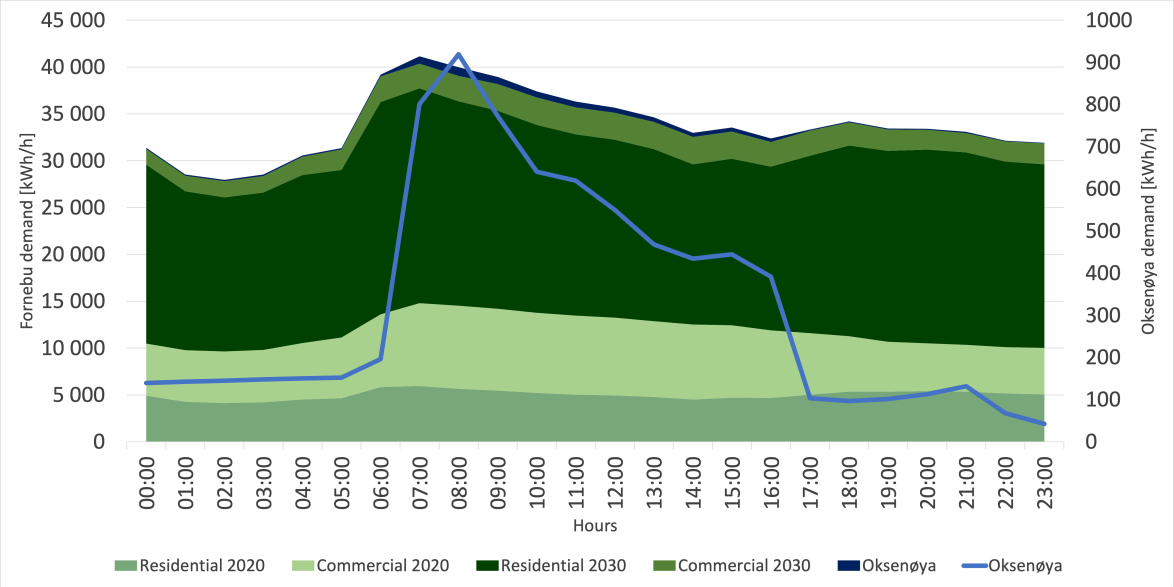

Figure 7.9: District heating load profile for Fornebu without heating flexibility from Oksenøya

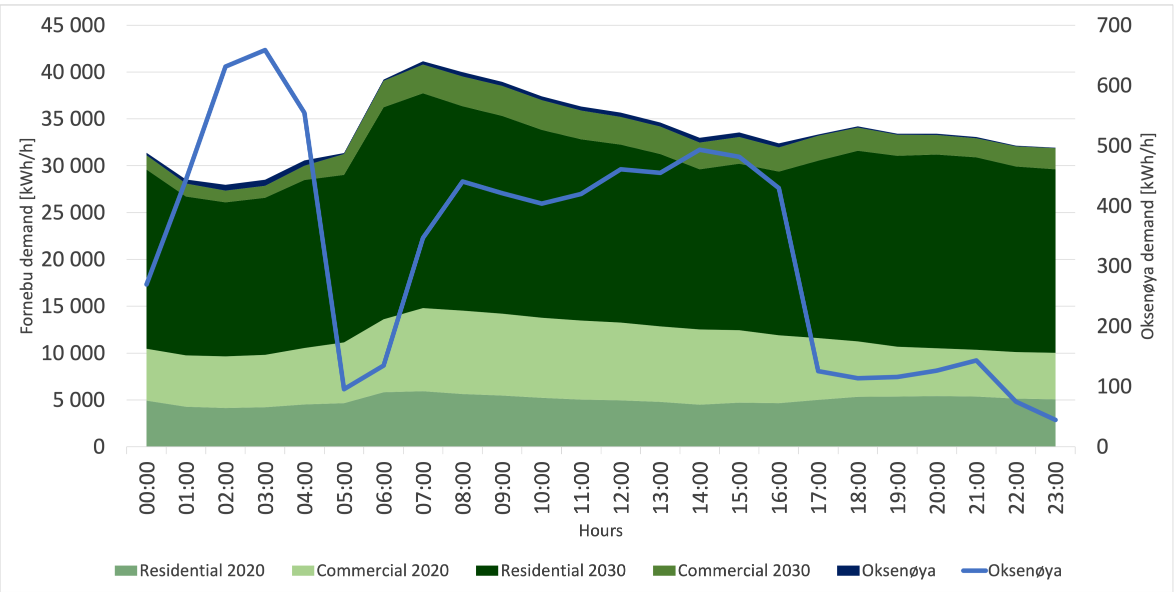

Figure 7.10: District heating load profile for Fornebu with heating flexibility from Oksenøya

Table 7.9: District heating costs, COM-FRNB-flx

Component	**Cost [NOK]**
Fixed annual	3 900
Energy tariff	692 138
Peak load tariff	364 914
Total	1 060 952

7.5.2 Electricity

Figure 7.11 shows the electricity load profile of Fornebu in 2030, based on [5], without flexibility measures from Oksenøya. Figure 7.12 shows how Oksenøya contributes to Fornebu's energy system with its production of PV and battery. Since the battery is intended for a ZEN consisting of three commercial buildings, it is relatively small compared to the grid at Fornebu. The electricity consumption at Oksenøya increases at 19.00, which is because all the battery capacity has been used this day. Table 7.10 shows the electricity costs for this scenario.

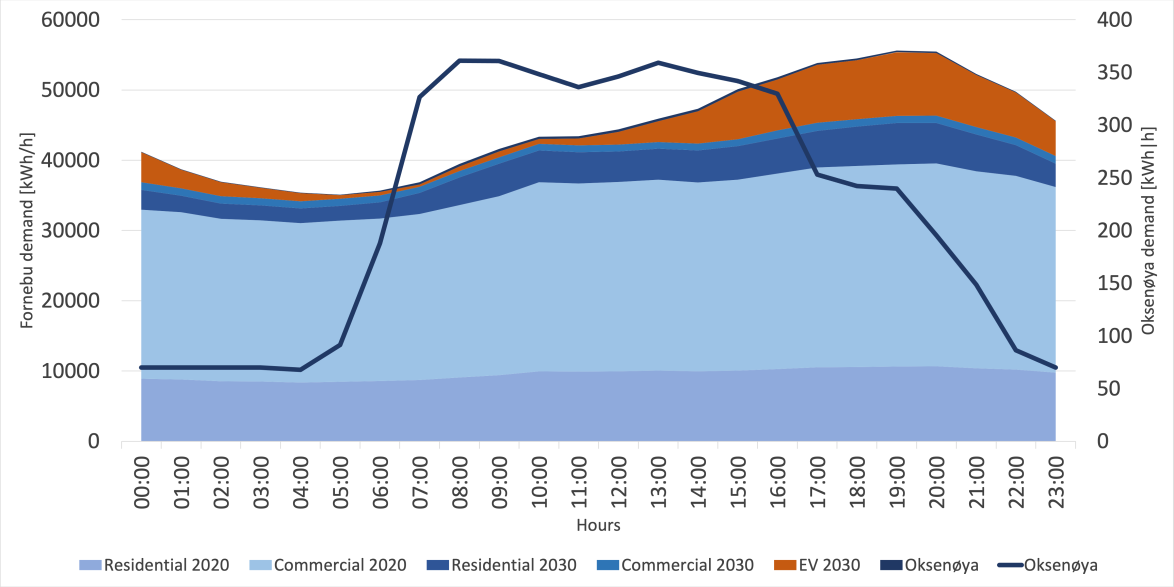

Figure 7.11: Electric load profile for Fornebu without battery and PV from Oksenøya

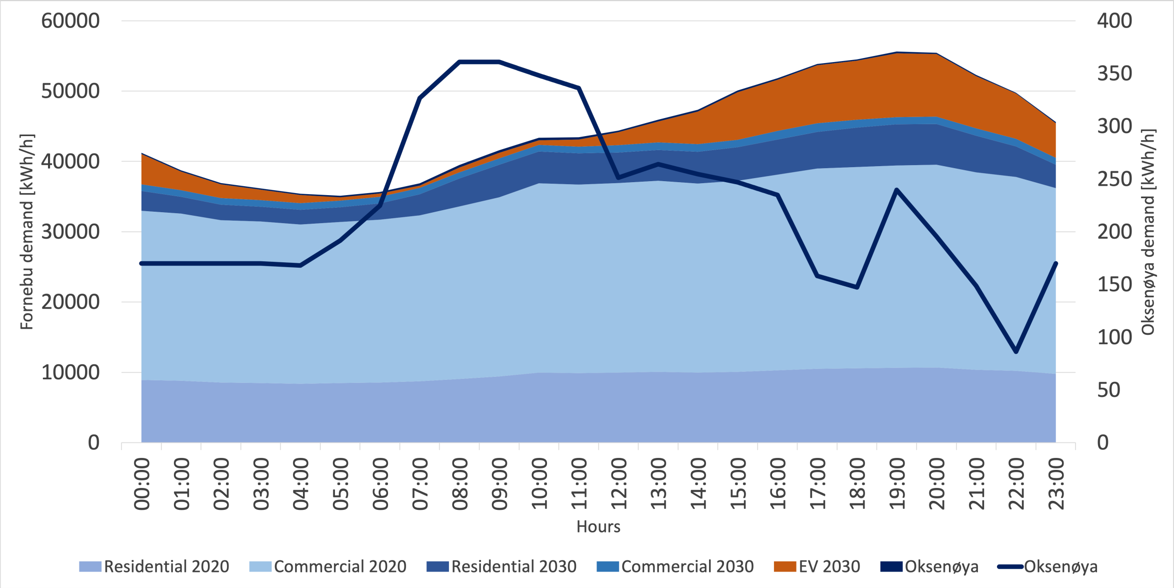

Figure 7.12: Electric load profile for Fornebu with battery and PV from Oksenøya

Table 7.10: Electricity costs, COM-FRNB-flx

Component		**Cost [NOK]**
Fixed annual		4 080
Energy	Market	365 248
	Grid	293 326
Grid peak		269 978
Total		932 632

7.6 Comparison of results

This subchapter gives an overview of all the results constituted in this thesis. Table 7.11 presents the KPIs for all scenarios. The first two parts of the table, Cost and Consumption, shows the accurate values for each scenario. Energy and peak load costs are in [NOK], while total cost is in [kNOK]. Energy consumption and PV self consumption are in [MWh], while peak load consumption is in [kW]. The other two parts of the table shows the percentage difference for the cost and consumption compared to the baseline. Figure 7.13 compares the total district heating load profile for all scenarios. Figure 7.14 compares the total electricity load profile for all scenarios. Figure 7.15 shows a graph of all costs, for both heating and electricity, energy and peak load, as well as total costs, for all scenarios. Due to the proportional difference, the costs for heating and electricity are shown on the left axis, while the total costs are on the right axis.

Table 7.11: KPIs

		BASE	**COM**	**IND-flx**	**COM-flx**	**COM-FRNB-flx**
Cost						
Energy [NOK]	Heat	664 625	664 625	679 976	672 961	692 138
	El. grid	295 472	285 220	293 473	283 546	293 326
	El. market	359 934	359 935	359 811	358 709	365 248
Peak load [NOK]	Heat	525 344	505 644	358 497	290 153	364 914
	El	284 797	225 387	267 243	194 263	269 978
Total [kNOK]		2 154	2 049	1 983	1 808	1 994
Consumption						
Energy [MWh]	Heat	831	831	850	841	865
	El	1 376	1 327	1 366	1 318	1 365
Max. peak load [kW]	Heat	955	919	652	528	663
	El	452	361	422	303	459
PV self consumption [MWh]		307	356	323	381	368
Cost [% of BASE]						
Energy	Heat	664 625	0	+2.3	+1.3	+4.1
	El. grid	295 472	-3.5	-0.7	-4.0	-0.7
	El. market	359 934	0	-0.03	-0.3	+1.5
Peak load	Heat	525 344	-3.7	-31.8	-44.8	-30.5
	El	284 797	-20.9	-6.2	-31.8	-5.2
Total		2 154	-4.9	-7.9	-16.1	-7.4
Consumption [% of BASE]						
Energy	Heat	831	0	+2.3	+1.2	+4.1
	El	1 376	-3.6	-0.7	-4.2	-0.8
Max. peak load	Heat	955	-3.8	-31.7	-44.7	-30.6
	El	452	-20.1	-6.6	-33.0	+1.5
PV self consumption		307	+16.0	+5.2	+24.1	+19.9

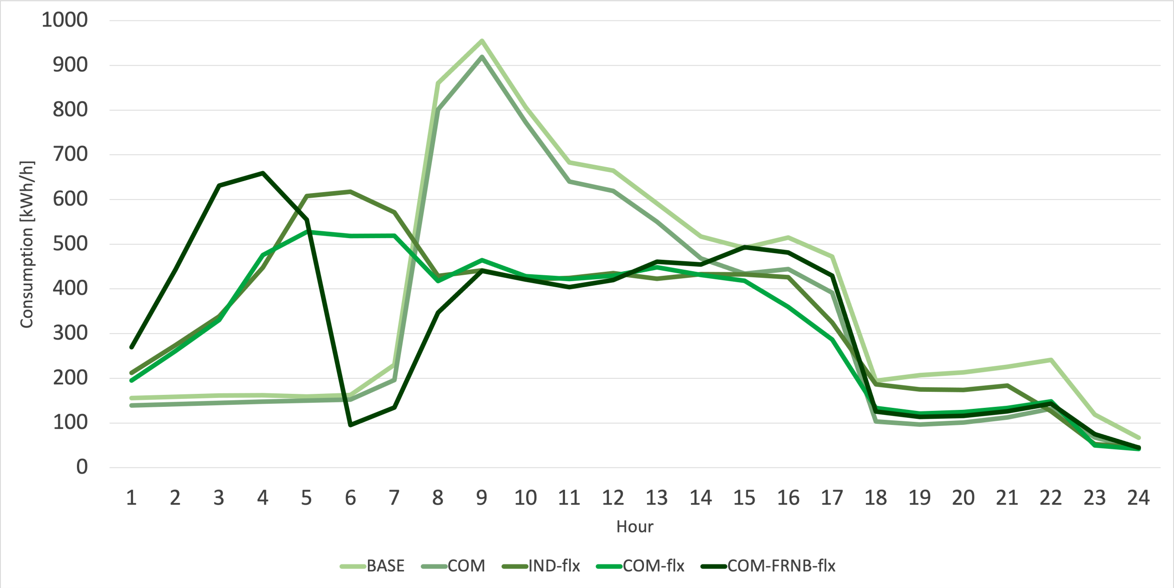

Figure 7.13: Total heating load profile for each scenario

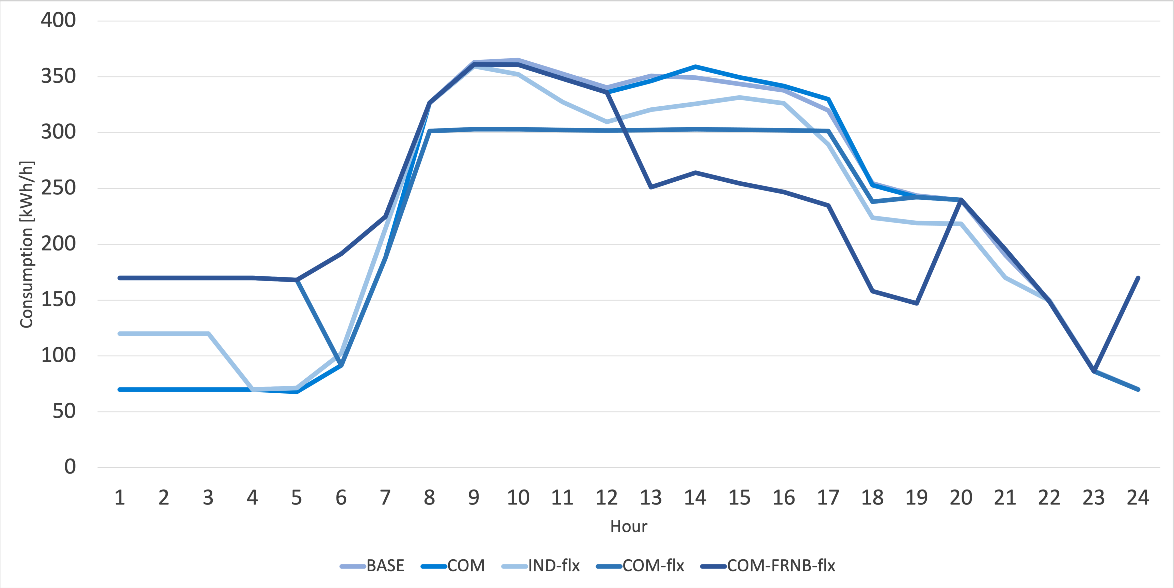

Figure 7.14: Total electricity load profile for each scenario

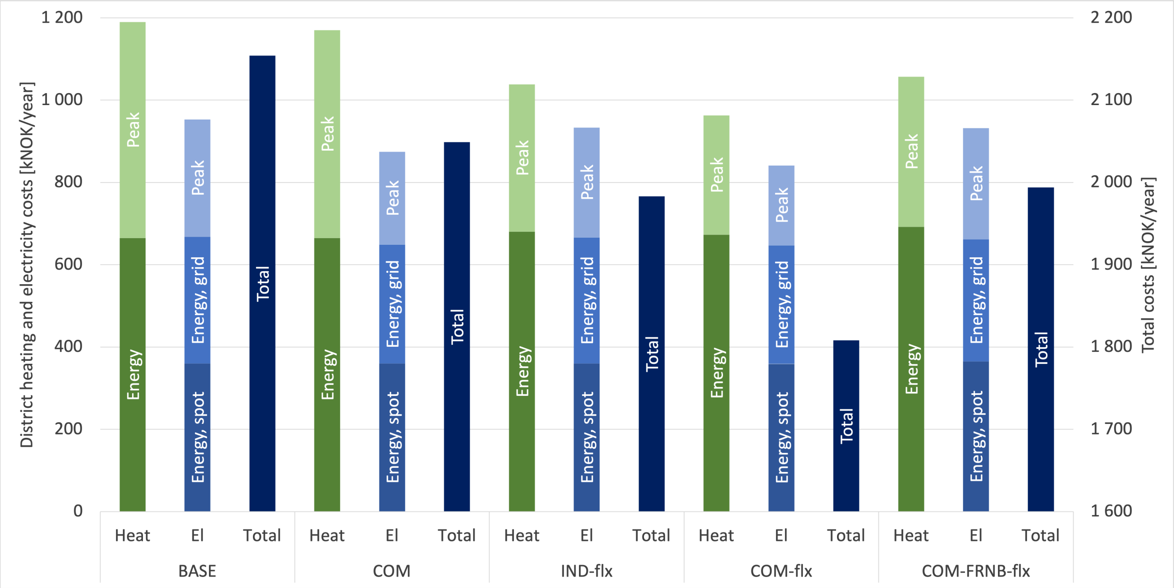

Figure 7.15: District heating and electricity cost displayed on primary axis, and total costs displayed on secondary axis

8 Discussion

This chapter discusses the results. The discussion is mainly based on Table 7.11. When referring to a percentage difference, BASE is the comparison.

Discussing the results
The results reveals that COM-flx performs best on most KPIs. In terms of total cost, peak load reduction, PV self-consumption, electricity grid cost and electricity consumption, it has the best results. The only KPIs where it does not perform best are electricity market cost, heating energy consumption and heating energy cost. This makes sense as the heating needs to be increased earlier at night to reduce the peak load in the morning. However, the peak heating load is reduced to almost half, both in terms of cost and consumption. This supports the findings from previous studies [43], that the use of rule-based schedule control is effective in reducing peak load but may increase energy consumption. However, in this case, energy consumption is increased so little that total cost is still significantly reduced, making COM-flx a satisfactory operational strategy.

An interesting aspect is that the total cost is reduced by nearly 5% only by changing the metering from individual to common. As Table 7.11 displays, this is mainly caused by the increase in PV self-consumption and the reduction in peak electricity load, which are +16% and -20.1%, respectively. As for the peak load, it is not the actual peak load that is reduced. The peak loads of the respective buildings do not coincide, so that when they are all registered behind the same energy meter, the maximum peak load that occurs in one hour is significantly reduced. The peak load for heating is not reduced as much, only 3.8%. This is probably because all the buildings´ heating peak load occur approximately at the same time of the day. These findings illustrate the economic benefits of having common metering instead of individual metering. For the specific case of Oksenøya, the billing practice regarding common metering may be solved easier as all buildings have the same owner. In a neighbourhood consisting of different building owners, a common energy meter may pose a greater challenge to billing practices. To this end, a regulatory framework may need to be established to avoid economic conflicts.

Adding flexibility measures to reduce each building's peak load (IND-flx) reduces total cost more than using a common energy meter with no flexibility (COM). This shows that implementing flexibility measures is cost effective regardless of the energy metering. The cost reduction is mainly caused by the reduction of the peak heating load, which is reduced by 31.7% compared to the baseline. The district heating peak load cost is reduced correspondingly with 31.8%. For electricity, the peak load is not reduced very much, and this is true for all individual metering scenarios. This proves that with individual metering it is difficult to exploit the full potential of the battery. With an extensive reduction in the heating peak load and a minor reduction in the electricity peak load, IND-flx shows the second best performance in terms of total cost reduction, although it only reduces the total cost by 7.9%. IND-flx illustrates that it is profitable to install energy flexibility measures even though buildings are individually metered for energy.

COM-FRNB-flx is the flexibility scenario with the highest cost. Although it includes flexibility services, cost reduction is not the main objective. Interestingly, it still reduces the total cost more than not implementing flexibility measures. Heating flexibility contributes most to the reduction, where the peak heating load is reduced by 30.6% compared to the baseline. Peak electricity load and electricity consumption increase, so electricity costs are higher. These results suggests that shifting heating loads in a building contributes more than having such a small battery in the grid. Heating flexibility proves effective in shifting the load profile. However, since Oksenøya is so small, it does not show a significant change in Fornebu´s load profile. It might be interesting to run other districts at Fornebu in the same way to see what the results are. If the same results can be found for other neighbourhoods, it can be assumed that Fornebu´s peak load, in both electricity and district heating, can be reduced noticeably. This assumption supports the findings from the literature review [42] that the amount of energy that can be curtailed from a single building is limited, but when aggregated to the level of a district it can be more significant. Since one of Bærum's main goals is to establish the whole of Fornebu as a ZEN by 2027, it can be considered feasible that with several building clusters like Oksenøya, it is indeed possible to reduce the peak energy use at Fornebu. Furthermore, since it is expected that the peak load grid tariffs will also apply to residential customers soon, this will provide a good incentive for residential customers to reduce their peak load.

Regarding PV self-consumption, the scenarios with common metering perform best in general. This is probably because the energy consumption associated with the available PV production is higher. Thus, if PV can be used by anyone who needs it, the surplus production of one building does not have to be sold to the grid, but can be used by one of the other buildings. Increasing self-consumption at Oksenøya is beneficial since there is no feed-in tariff in Norway, so the price paid for electricity from the grid is higher than the price for sold PV. If the operation of the battery had been optimized, the PV self-consumption might have been increased even further, as the rules for charging the battery could have been different. The battery is modeled to primarily use PV generation, but when there is both a surplus and the battery capacity is full, it must sell PV. The model is relatively simply, and only considers the state of the previous hour and the current hour. The battery does not take into account any forecast of expected PV production for the next day when it is charged at night. By using weather forecasts, it is possible to predict how much PV will be produced the next day and aim that all the PV is self-consumed.

Electricity market costs appear to vary little in the different scenarios, with a maximum change of +1.5% from the baseline. A possible explanation for the little variation in market costs may be that the decrease in electricity consumption from the grid roughly corresponds to the increase in PV self-consumption. In scenarios where less electricity is purchased from the grid, less PV production surplus is sold to the grid. It appears that this offsets the costs for most scenarios. The exception is COM-FRNB-flx, which can be explained by the fact that the battery stores a higher share of electricity from the grid than in the other scenarios. A clear trend is that the electricity grid cost is reduced more with common metering than with individual metering. This is also true for energy consumption, but not for electricity market costs. This can be explained by the fact that the energy market cost is offset by the PV production sold, while the electricity grid cost is only affected by the actual consumption. The consumption appears lower in common metering scenarios. However, since consumption is what is drawn from the grid, it just means that more PV is being used.

The results confirm that it is possible to reduce peak loads and thus reduce energy costs with a conventional rule-based control of a space heating system and a battery. The fact that peak load reduction increases energy consumption is not a major problem in any of the scenarios. Heating consumption increases a little, but only by 4.1% in the worst scenario. Electricity consumption actually decreases slightly. It can therefore be assumed that the implementation of a battery reduces both peak load and energy consumption, and may therefore be an efficient measure when battery costs are further reduced. It is also interesting to note that although heating energy consumption increases slightly, the peak load is reduced to such an extent that heating makes the largest contribution to reducing total costs.

Uncertainties

Some information may have been lost in the simplification of the building envelope in the models. Since accurate models exist, these would preferably have been used. However, since they could not be implemented in IDA ICE, they had to be created from scratch and simplified to save time. Windows and zones are merged, and the building envelope is not entirely accurate, so it must be taken into account that the actual energy consumption of the buildings can change slightly. However, as all scenarios are derived from the same baseline, the percentage differences in consumption are likely to remain roughly the same. Another important aspect of the modeling is that in the method used in this thesis, the load profiles of each building are extracted from IDA ICE and then combined in Excel. This is done to make the buildings work together, as they have to be modeled individually in IDA ICE. For this reason, using a BPS tool to model a neighbourhood may not have been the best solution as the tool itself does not take into account the interaction of the buildings. However, the BPS tool does provide a detailed modeling of the energy use in the respective buildings.

There are uncertainties regarding the prices used. For electricity, the average spot price from 2013-2020 is used, which is an adequate approach, but it can be assumed that prices in 2030 will be slightly higher, and with more daily fluctuations, as mentioned in subchapter

3.3. Due to more daily fluctuations in spot prices, the occurrence of energy consumption may have a greater impact than today, so the ability to shift energy could be more valuable. The development of grid tariffs will depend on how the power system evolves and whether severe and expensive changes or expansions need to be made. If enough energy flexibility measures are implemented, there may be no need for expansion. As far as district heating prices are concerned, there is no indication that there will be a free market soon, so they can be expected to evolve with average annual electricity prices. Despite the price change, the percentage cost difference is expected to remain the same.

Even though optimal control is not used in this thesis, all scenarios show a significant reduction in both cost and peak load consumption by using energy flexibility. Even the use of flexibility for Fornebu, where cost reduction is not the main objective, results in cost reduction compared to not having flexibility. This shows that even with a conventional control algorithm, as is the case with rule-based control, there are economic benefits. Since managing energy flexibility is a serious issue, utilising simple control strategies can at least be a starting point. Complex optimal control strategies may not be mature yet, but this thesis shows that, for starters, it is both feasible and profitable to work with the control strategies that already exist.

Since this thesis is limited to using only space heating and a battery for flexibility, the true flexibility potential of the ZEN is likely to be even more evident. Other loads that can be operated flexibly include lighting systems or ventilation systems. In addition, there is the possibility of electric vehicles being charged in the buildings at certain times, which can be controlled as a battery depending on when they are connected in order to utilise the energy storage. However, as the cost reduction is adequate with the two flexibility measures selected, the implementation of other measures will bring about the cost reduction to a greater extent. In the case of the ventilation system, the control of the heating coil can help to reduce the heating energy consumption even further. The need for this is particularly evident in COM-FRNB-flx where it is impossible to completely reduce heating during Fornebu's peak hours, as heat is required for the heating coil to maintain the desired ventilation supply temperature. The airflow of the ventilation system can also be reduced at certain times, such as during mid-day for the school when pupils are likely to be outside. Reducing ventilation airflow can reduce energy consumption for pumps and fans. For the lighting system, a suggestion for energy saving from Veidekke is to implement it with presence sensors. This is not modeled in the simulations and is not necessarily a flexibility measure, but a measure that can reduce energy consumption for lighting and thus reduce energy costs even further.

Fornebu's load profile for electricity is created assuming that electric vehicles are charged by an unintelligent charging pattern. This results in a peak load in the afternoon. The battery flexibility has hence been modeled with the assumption in mind that all EV´s are charged in the afternoon. The uncertainty is that the assumption may not be correct. Smart chargers for EVs already exist, and with more knowledge and a prediction of more daily fluctuations in spot prices, the likelihood that EVs will still have a dumb charging pattern in ten years' time can be considered relatively low. It must therefore be considered that the shape of the load profile, and therefore the modeling of the battery for use at Fornebu, could change.

Further work

Even though this thesis has proved that energy flexibility for peak load reduction reduces costs, there are still many unanswered questions. The main query is perhaps how much the energy cost can really be reduced. Therefore, another study with more focus on optimization is proposed to find the optimal operation strategy for space heating and battery. To develop a complete picture of the flexibility capacity of the buildings, additional studies are needed that examine other loads or load combinations. One suggested study for further work is to implement all load types in an optimization solver such as Python, rather than using a BPS tool. More research should consider modeling the loads to find the optimal common operating point, with the goal of either minimizing cost or minimizing peak load during grid peak hours. As the buildings are due to be completed soon, conducting in-use studies with MPC may be interesting, especially as this field has a gap in the literature.

9 Conclusion

In this thesis, the target was to assess the flexibility potential of Oksenøya, which is a ZEN-pilot project located at Fornebu. The second aim was to utilize this flexibility to reduce operational costs, as well as to utilize it to avoid grid expansion.

The study has used Rule-Based control by scheduling to obtain an operating strategy that reduces energy costs for a neighbourhood consisting of a school, a nursing home and a kindergarten. Flexibility measures have been applied to reduce peak loads by space heating flexibility in the district heating system, and by utilising a stationary battery in the electricity system.

The study has found that generally, implementing flexibility measures will reduce energy costs. This is in spite of not using optimal control algorithms like Model Predictive Control, but rather algorithms that are already in use and widely known, like Rule-Based control. This highlights the importance of utilizing flexibility with the available technology, and that implementing flexibility does not require advanced monitoring.

Utilizing flexibility measures in a ZEN proves that shifting consumption to avoid distribution grid peak hours works. The contribution from Oksenøya to the distribution grid at Fornebu is relatively small, for both district heating and electricity. However, if aggregated to more neighbourhoods it will have an actual contribution in reducing the distribution peak load.

The proposed operational strategy is having common metering, for both electricity and district heating, and controlling flexible loads with the objective of reducing the total peak load. This gives a peak load reduction of 44.7 % and 33.0% in district heating and electricity, respectively. Peak load reduction is what mainly contributes to the 16.1% reduction in total costs. Even though the study has proved capable of reducing the energy costs, it is possible that if an optimization model was used instead of a "what-if" approach, the costs could have been further reduced.

For further work, the operation strategy should be optimized to investigate the full cost reduction of heating flexibility and battery implementation. Further research should also investigate more flexible loads to find the full flexibility potential of the buildings. When the buildings are completed, in-use experiments should be carried out to establish the actual building operation.

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Appendix

A Details of electricity costs

Table A1: Electricity costs, BASE

Component		**Cost [NOK]**
Grid cost	Fixed annual	12 240
	Energy tariff	65 804
	Peak load tariff	284 797
	Electricity tax	229 668
Market cost	Electricity purchased	380 301
	Electricity sold	20 367

Table A2: Electricity costs, COM

Component		**Cost [NOK]**
Grid cost	Fixed annual	4080
	Energy tariff	63 778
	Peak load tariff	225 387
	Electricity tax	221 442
Market cost	Electricity purchased	368 139
	Electricity sold	8 204

Table A3: Electricity costs, IND-flx

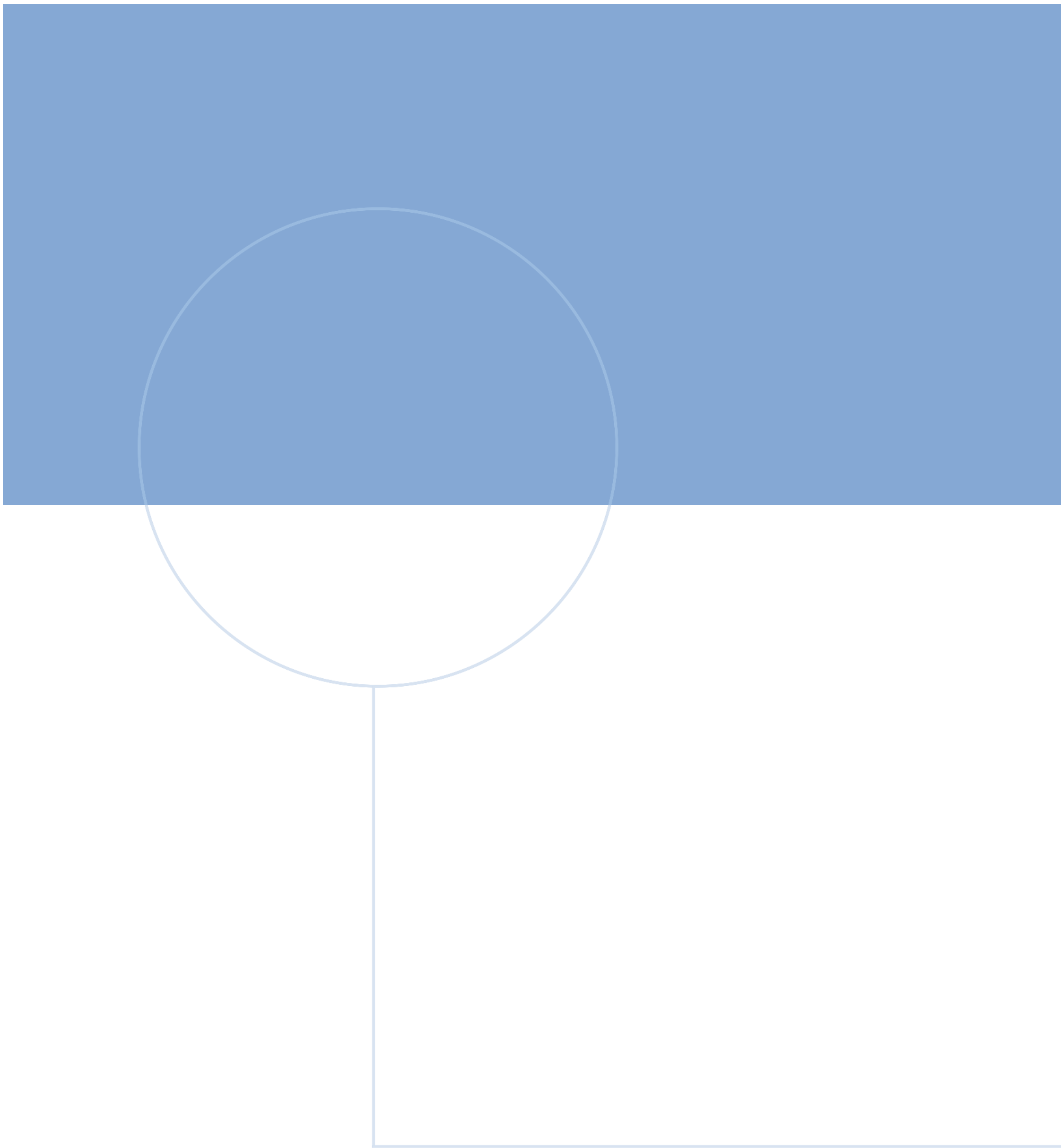
Component		**Cost [NOK]**
Grid cost	Fixed annual	12 240
	Energy tariff	65 457
	Peak load tariff	267 243
	Electricity tax	228 016
Market cost	Electricity purchased	376 253
	Electricity sold	16 442

Table A4: Electricity costs, COM-flx

Component		**Cost [NOK]**
Grid cost	Fixed annual	4 080
	Energy tariff	63 564
	Peak load tariff	194 263
	Electricity tax	219 982
Market cost	Electricity purchased	360 900
	Electricity sold	2 191

Table A5: Electricity costs, COM-FRNB-flx

Component		**Cost [NOK]**
Grid cost	Fixed annual	4 080
	Energy tariff	65 584
	Peak load tariff	269 978
	Electricity tax	227 742
Market cost	Electricity purchased	370 509
	Electricity sold	5 261



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