UiA University of Agder

Master

Preserving the Past, Powering the Future: Energy Efficiency and Renewables in Norway's Wooden Churches

A Master's Thesis on Strategies for Improved Energy Efficiency and Renewable Integration in Three Historic Wooden Churches: Preserving Cultural Heritage and Paving the Way for a Greener Future

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Happy reading!

Thomas Tømte

Abstract

This master's thesis explores the potential for energy efficiency in three wooden churches built in the 19th century in the southern part of Norway. Specifically, the thesis focuses on the three churches Eide, Landvik, and Grimstad, all owned and operated by the Grimstad Church Council. Each church presents its own unique set of challenges related to heating and overall energy efficiency, largely due to their varying sizes. The thesis examines the impact of various energy efficiency measures and explores the possibilities of implementing renewable energy systems such as solar panels and geothermal energy.

At Eide church, three different configurations of solar panel systems have been studied, and the thesis also considers how the implementation of a battery can increase self-consumption of the church's electricity production. PVsyst has been used to simulate these alternatives. The thesis highlights potential energy savings in the range of 30-50% by lowering the temperature, making simple structural upgrades, and upgrading the heating control system in an annex adjacent to the church. A combination of solar panels and energy efficiency measures could make the church energy positive.

In Landvik church, the energy calculation program Simien has been used to assess the effects of various energy efficiency measures. Among the measures mentioned are retrofitting of roof, wall, and floor insulation, window replacement, lighting system upgrades, and temperature reduction. The results show that the church can achieve annual energy savings of up to 40% of the current energy consumption by combining multiple measures.

Furthermore, this master's thesis suggests that implementing a 25.5 kW liquid-to-water heat pump in Grimstad church, supplied from two energy wells, could cover 90% of the church's energy consumption and thus save an equivalent proportion of biofuel oil, over 13 000 liters annually.

The thesis identifies a significant need to educate and inform the church's staff about energy efficiency and points out that too much responsibility is placed on those working for the church's daily operations.

Based on the large number of churches in Norway, the results of this study have significant transferability, and the potential for energy savings at a national and Nordic level is considerable. In conclusion, the thesis emphasizes that the approach requires a balance between advanced technologies, awareness, and basic practices.

Sammendrag

Denne masteroppgaven utforsker potensialet for energieffektivisering av tre trekirker bygget på 1800-tallet i Sør-Norge. Mer spesifikt tar oppgaven for seg de tre kirkene Eide, Landvik og Grimstad, alle eid og driftet av Grimstad kirkelige fellesråd. De tre kirkene er av ulik størrelse og med unike utfordringer knyttet til oppvarming og generell energieffektivisering. Oppgaven ser på effekten av en rekke energieffektiviseringstiltak, i tillegg til å utforske mulighetene for implementering av fornybare energisystemer som solcelleanlegg og bergvarme.

Det er ved Eide kirke utforsket tre ulike konfigurasjoner av solcelleanlegg, og det er også sett på hvordan implementeringen av et batteri kan øke egenforbruket av strømproduksjonen ved kirken. PVsyst har blitt brukt for å simulere disse alternativene. Oppgaven peker på potensielle energibesparelser i området 30-50% ved å senke temperaturen, utføre enkle bygningsmessige oppgraderinger, samt oppgradere varmestyringssystemet i et anneks i nær tilknytning til kirken. En kombinasjon av solcelleanlegg og energieffektivisering vil kunne gjøre kirken til en plusskirke.

I Landvik kirke har energiberegningsprogrammet Simien blitt benyttet for å vurdere effekten av ulike energieffektiviseringstiltak. Av ulike tiltak nevnes blant annet etterisolering av tak, vegger og gulv, utskifting av vinduer, oppgradering av belysningssystem til LED og senking av temperatur. Resultatene viser at kirken kan oppnå årlige energibesparelser tilsvarende opp mot 40% av dagens energiforbruk ved å kombinere flere tiltak.

Videre peker denne masteroppgaven på at implementeringen av en 25,5 kW væske-til-vann varmepumpe i Grimstad kirke, forsynt fra 2 180 meter dype energibrønner, vil kunne dekke 90% av kirkens energiforbruk, og dermed spare en tilsvarende andel biofyringsolje, over 13 000 liter årlig.

Oppgaven identifiserer et betydlig behov for å opplyse og utdanne kirkens ansatte i energieffektivisering, og peker på at et for stort ansvar legges på de som arbeider med den daglige driften av kirken.

Med utgangspunkt i det store antallet kirker i Norge, kan resultatene ha stor overføringsverdi, og potensialet for energibesparelser på et nasjonalt, og også et Nordisk nivå, er betydelig. Avslutningsvis konkluderer oppgaven med at tilnærmingen krever en balanse mellom avanserte teknologier, bevisstgjøring og grunnleggende praksis.

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Chapter 1

Introduction

1.1 Background

As climate change increasingly impacts our world, the global community – nations and organizations alike – is intensifying the quest for energy efficiency and sustainability. Norway, in particular, has been actively addressing its energy consumption, which totaled 235 terawatt-hours (TWh) in 2018 [68], with buildings accounting for 84 TWh or 36% of this figure [88]. Norway's ban on fossil fuel heating in buildings, instituted before 2020, led to a significant decline in greenhouse gas emissions from heating, now representing less than 2% of the total emissions [67]. However, to achieve the climate targets by 2030 [64], further reductions in building energy consumption are necessary, enabling renewable energy to be redirected towards lowering emissions in other sectors, such as transportation and industry. Consequently, enhancing energy efficiency in buildings is essential for meeting climate objectives and has become a key focus in Norway's efforts.

The Church of Norway has recognized the urgency of addressing climate change and is committed to reducing its transport-related emissions by 60% while achieving climate neutrality by 2030 [18]. This pledge aligns with the United Nations Sustainable Development Goals 7 and 11, emphasizing affordable and clean energy and sustainable cities and communities, respectively. With around 1,620 churches spread across the nation, the Church of Norway holds a distinctive position to make a substantial contribution to energy efficiency and sustainability.

A report published in 2012 highlighted that a staggering 67% of the Church of Norway's total emissions originated from church buildings [19]. This finding accentuates the importance of energy efficiency in Norwegian churches for both environmental and economic reasons. The dual motivations of climate and economy have become particularly relevant in light of the recent spike in energy prices, which has led to the closure of several churches due to financial challenges [3].

This master's thesis explores the potential for energy efficiency improvements, as well as the implementation of local renewable energy sources, in three Norwegian churches. The thesis offers a comprehensive analysis of the measures that can be implemented to achieve the climate and economic goals established by the Church of Norway and the international community at large. By evaluating the current state of energy usage in Norwegian churches, pinpointing areas for improvement, and proposing energy efficiency strategies, this research aims to contribute to ongoing efforts to secure a more sustainable and economically viable future for these treasured historical and cultural landmarks.

1.2 Research Problem and Objectives

Grimstad church council (Grimstad kirkelige fellesråd) faces challenges related to high electricity and heating costs in their historical and culturally significant buildings, which often suffer from poor energy efficiency. There is a need to explore environmentally friendly solutions that can reduce these costs while preserving the architectural and cultural heritage of these churches.

> **What is the potential for energy conservation and economic savings in three Norwegian wooden church buildings through the implementation of specific energy efficiency measures, while maintaining their architectural and cultural heritage?**

Research Objectives:

- To identify and analyze the current technological possibilities for improving energy efficiency in Norwegian wooden church buildings.
- To assess the economic feasibility of various energy measures and determine which ones can provide cost-effective solutions for churches.
- To review various case studies and projects, identifying and extracting valuable insights and best practices that can be applied to a broader range of similar church initiatives.
- To explore the potential future possibilities for energy efficiency improvements in wooden church buildings through new research and technological developments.

To accomplish these objectives, the study will investigate various energy measures, including solar energy, retrofitting with additional insulation, examining alternative lighting options, exploring potential changes in usage patterns, implementing geothermal systems utilizing heat pumps, among other energy efficiency strategies. The outcomes of this research may possess applicability and transferable value to other churches in Norway as well as the broader Nordic region.

Moreover, this study aims to address the more general day-to-day challenges related to preserving cultural heritage while ensuring energy efficiency. The findings can contribute to understanding the importance of the relation between advanced technology and simple energy efficiency measures.

1.3 Significance and Motivation

The significance of this master's thesis lies in its examination of energy efficiency measures for Norwegian wooden church buildings, an underexplored topic in academic literature. By focusing on the economic feasibility of energy measures, this study fills a critical gap in existing research, as the cost implications have not been thoroughly investigated. The findings will contribute to global sustainability efforts, climate action, and the preservation of cultural heritage.

This study also addresses societal challenges related to preserving cultural heritage while implementing energy-saving measures. The findings may have transferable value to churches in Norway and other Nordic countries, broadening its impact.

The motivation for this thesis stems from the desire to work with historically significant buildings that require special considerations and a personal interest in preserving cultural heritage while contributing to climate action and sustainability. The recent surge in energy prices necessitates a fresh look at energy efficiency measures and their financial implications, making this research timely and crucial.

1.4 Scope and Limitations

The scope of this master's thesis is focused on three wooden church buildings under the management of Grimstad Church Council (Grimstad kirkelige fellesråd). These churches were selected based to their common characteristics: wood construction, similar coastal climate, and 1800s construction period. While the council oversees other facilities, this study is limited to the three churches Eide, Landvik and Grimstad.

Limitations include time constraints, as the master's thesis duration is only half a year, which impacts the depth of research especially on temperature, humidity, and usage patterns.

Lastly, the uniqueness of each church building may limit the generalizability of the findings. Variations in architectural details and current usage patterns may impact the applicability of specific energy efficiency measures, and findings may not be universally applicable to all church buildings.

1.5 Structure

This master's thesis is organized into six chapters. The structure of the rest of the thesis is as follows:

Chapter 2: Theory and Literature Review
The second chapter combines both the theoretical framework and literature review. Initially, it presents the key concepts, principles, and theories associated with energy efficiency, building preservation, and cost implications. Subsequently, it reviews existing literature on energy efficiency measures in historical buildings, particularly wooden churches, identifying gaps that this thesis intends to fill.

Chapter 3: Methods
In this chapter, the research methodology is described, including the selection of the three churches, data collection methods, and analytical techniques employed. The chapter also discusses the limitations and assumptions associated with the chosen methods.

Chapter 4: Results
This chapter presents the findings of the research, including the analysis of energy usage in the three selected churches, the identification of potential energy efficiency measures, and the evaluation of their economic feasibility. The results provide insights into the potential for energy conservation and cost savings in the context of the three examined church buildings.

Chapter 5: Discussion
In this chapter, the results are discussed in light of the research objectives, theoretical framework, and existing literature. The implications of the findings for energy efficiency, building preservation, and cost implications are explored, along with the potential transferability of the results to other churches.

Chapter 6: Conclusions
This chapter summarizes the main findings of the research and draws conclusions about the potential for energy efficiency improvements in the three wooden church buildings. Recommendations for future research, as well as practical suggestions for the Church of Norway and Grimstad Church Council are provided.

Chapter 2

Theory & Literature Review

In this chapter, different theories and existing literature related to energy efficiency and heating of churches will be explored. This chapter forms the theoretical foundation that is important for understanding and justifying the assumptions made in the subsequent parts of the thesis.

2.1 Heating of Churches

2.1.1 History

The establishment of the first Norwegian churches traces back to the end of the Viking age, in the late 11th century [21] [60]. Yet, it wasn't until approximately 800 years later, deep into the 19th century, that the first attempts to heat the churches were made [42]. The evolution of heating methodologies within these churches broadly followed the advancements of technology, transitioning from wood-burning stoves and coke heating to the use of oil, electricity, heat pumps, and biofuels. Nevertheless, the shift towards heated churches did not go unchallenged [95]. As early as 1875, prior to the installation of heating in Kongsberg church, the parish priest expressed his concerns that the church was too big to be effectively heated. He suggested constructing a smaller chapel for heating purposes. Despite this, four stoves were eventually installed in Kongsberg church in 1877. These stoves could raise the temperature inside the church to approximately 10°C during winter days – a comfort level that was well-received by the congregation. This early resistance to heating technologies may very well represent one of the first instances of energy efficiency concerns within the context of Norwegian churches. Fast forward nearly 150 years, to 2023, the principle of energy efficiency is more important than ever [3].

2.1.2 Intermittent Heating

Intermittent heating is defined as the strategy in which heating is applied in a periodic manner, providing an optimal balance between energy usage, comfort levels and preservation environment [59].

The Church of Norway's employer organization, known as KA, assists church owners in building-related matters [44]. KA has compiled several detailed reports providing recommendations on topics such as heating, energy efficiency, and church preservation. A recurring figure in these reports is KA's recommendation of an installed heating power between 27 and 35 W/m^3 of heated air [45]. This power range, according to KA, ensures short heating periods. Furthermore, KA recommends maintaining a resting temperature (the temperature when the church is not in use) between 5 and 8°C, and an operational temperature (temperature during use) between 16 and 19°C [42] [90]. These recommendations are mainly shaped by the idea that lower temperatures increase relative humidity, beneficial for preserving building materials and other artifacts, along with energy-saving considerations [46]. The concept of relative humidity, and the effects of this value being too high or too low, will be elaborated later in the chapter.

A 2014 master's thesis from Lund University in Sweden concluded that there is no clear consensus in existing research regarding the optimal heating methods [71]. The thesis emphasizes that numerous aspects must be accounted for when considering church heating, often necessitating compromises. Balancing comfort, preservation environment, and energy usage exemplifies such a situation. From an energy perspective, the most efficient solution would be to completely shut off the heating in the churches. However, this would lead to a very uncomfortable environment for both the church workers and visitors. Moreover, such a drastic measure would result in a high-humidity environment, thus negatively impacting the preservation conditions. Conversely, a constant comfortable indoor temperature, such as 22°C, would lead to excessive energy consumption and a poor preservation environment due to low relative humidity.

The thesis also highlights the effectiveness of localized and zone-adjusted heating. The study specifically investigates electric pew heaters, concluding that they represent a good heating solution as they concentrate the majority of the heat where people are seated. Intermittent heating is also acknowledged as a useful strategy to maintain a good preservation environment, maintaining a resting temperature between 5 and 10°C, and an operational temperature between 15 and 19°C. The thesis suggests a potentially more cost-effective approach of adjusting the resting temperature according to the relative humidity. This approach could allow the resting temperature to drop as low as 4°C on the driest winter days, yielding significant energy savings. Nonetheless, this method would probably require more proactive temperature management, as extended heating periods might be necessary during specific seasons. The thesis also notes that despite the use of intermittent heating, damage due to improper preservation conditions still occurred. The key takeaway from the thesis suggests that intelligent temperature control is one of the most effective methods for maintaining ideal church conditions.

Several other studies and guides highlight the advantages of intermittent heating, and KA's recommendations of a resting temperature between 5-8°C and an operational temperature between 16-19°C seem to be a recurring suggestion, primarily aimed at ensuring a good preservation environment and conserving energy [15] [56] [16] . The Directorate for Cultural Heritage in Norway (Riksantikvaren), responsible for the management of cultural heritage, has also drafted a guide for Heating Control Systems in Churches [79]. This guide suggests that the maximum operational temperature should be 16°C and that the resting temperature should be "as low as possible". The guide further recommends temperature control based on humidity levels, maintaining the relative humidity within the range of 40-60%. Solutions such as remote management and calendar system integration are proposed to guarantee appropriate heating for scheduled events. Such systems has demonstrated notable success in some churches in Drammen and Trøndelag [42] [5].

2.1.3 Heat Sources

As mentioned in the previous subsection, the first heated Norwegian churches were typically heated with wood-burning stoves. As electricity became widely available in Norway at the beginning of the 20th century, these stoves were gradually replaced with electric heating systems [93].

Electric floor mounted tube heaters, once common in Norwegian churches, are now being used less and less, though some traces of them remain. These tube heaters were usually mounted on the floor along walls or directly underneath pews. They tended to have a very high surface temperature, therefore burning some dust. These inefficient heat sources have gradually been replaced with more efficient bench heaters [78]. Bench heaters are often mounted directly under church benches and are designed to provide a comfortable temperature for the congregation. Thermography results reveal that the bench heaters maintain an even, comfortable heat near the seating area, although they tend to make the leg area feel slightly warmer [71] [75].

In 2014, a relatively new type of heating sytem was installed in Eide church. This heating system consisted of infrared heating panels mounted in the ceiling and underneath the pews. The system was referred to as "biogenetic infrared heating". This involves heating panels that, instead of emitting convection heat, rely on infrared heat. This means that the air is not directly heated, but rather the surfaces of the surroundings are heated, which in turn heat up the air. A very detailed report published by KA shows that this new system performs very well [75]. The report indicates that the organ got significantly better operating conditions, and the organ tuner could note that the organ appeared much more stable both mechanically and musically. The report also shows that even temperatures down to 16°C provide good thermal conditions for users, due to the heating panels' operation and placement. It is clear from the report that lowering the resting and operational temperatures from 10 and 19°C, respectively, to 6 and 16°C, would not only improve the preservation environment but could also reduce energy consumption by up to 40%.

In some cases, particularly in large churches, it may not always be cost-effective to install or upgrade the capacity of an electric heating system. This is because the increased power can carry significant costs associated with power tariffs and contributions to upgrading the local power grid. This was something Risør church experienced in 2013 when it was considered that the heating system had to be upgraded[74]. The heating system had too low power to perform intermittent heating, resulting in high energy costs. It was estimated that if the electric heating system was upgraded from 16 and 20 W/m^3 to 39 W/m^3, this would result in an annual cost increase of 70-80 000 NOK, and an investment cost associated with upgrading the power grid of 50-100 000 NOK. The decision was therefore made to replace the electric heating system with a hydronic heating system with radiators mounted under the benches. Connected to the new heating system was a liquid-to-water heat pump supplied from 2 energy wells with a depth of 150 meters. In addition, two 1000-liter accumulator tanks were installed to increase the power in the system. A report prepared by KA in the period after this installation shows a total energy saving of 50%, and a reduction in greenhouse gas emissions equivalent to 18-20 tons of CO_2 per year [74].

Another church that does not have electricity as its primary heating source, but instead bases its heating on a hydronic heating system is Grimstad church, one of the largest wooden churches in Norway. This church is equipped with wall-mounted radiators supplied with hot water from an oil burner in a technical room in the basement. This system thus relies on burning bio oil to heat up water that in turn circulates in the radiators. As of 2020, the use of fossil fuel as a source of heating in buildings is banned, and the equipment is therefore adapted to be used with bio oil [34].

Hydronic heating systems are versatile, as they can use various heat sources [97]. However, the typical hydronic heating systems utilizes heat pumps. There are typically three kinds of heat pumps: air-to-air, air-to-water, and liquid-to-water. Despite their differences, all these heat pumps operate on the same basic principle: a heat pump, in its simplest form, operates on the principles of thermodynamics, utilizing a refrigeration cycle to transfer heat energy. It absorbs heat from a low-temperature source, like the ground, air, or water, and transfers it to a high-temperature recipient. This transfer is enabled through a working fluid, often a refrigerant, which circulates through the system, alternately evaporating and condensing as it absorbs and releases heat. The overall effectiveness of this process, commonly noted as COP and SCOP (Coeffecient of Performance and Seasonal Coefficient of Performance) is largely determined by the temperature difference between the source and recipient, and the performance characteristics of the heat pump system itself [40].

In colder climates like Norway, one of the most effective methods of heating is through the use of geothermal energy, as exemplified by Risør Church [94]. This technique involves Ground Source Heat Pumps (GSHPs), which harness the heat stored in the ground.

A closed-loop GSHP system works by circulating a mixture of water and antifreeze through a network of underground pipes [37]. This mixture absorbs heat from the ground, which is then transferred to the heat pump. The heat pump raises the temperature of the absorbed heat to a level suitable for warming the building. Once cooled, the water is returned to the underground pipes, reabsorbing heat from the ground in a consistent cycle. The typical rate of heat extraction for such a system ranges from 20 to 80 Watts per every meter of well [97]. The typical depth of such wells range from 100-300 meters.

2.2 Thermal Performance, Temperature and Relative Humidity

2.2.1 Heat Transfer

Heat transfer is a fundamental concept in building physics, as it directly affects the indoor climate and energy efficiency of buildings. When a building is heated, heat is transferred from the heat source (for example a radiator) to (usually) the surrounding air and then to the walls, floor, and ceiling. Conversely, when a building is cooled, heat is transferred from the indoor air to the outdoor environment. In this section, the three types of heat transfer that are relevant to building physics will be described [35] [2].

1. **Conduction** is the transfer of heat through a material without any movement of the material itself. Examples of conduction in buildings include the transfer of heat through walls, floors, and ceilings. The rate of heat transfer through a material is given by Fourier's Law:

   $$Q = -kA\frac{dT}{dx} \tag{2.1}$$

   where Q is the heat transfer rate, k is the thermal conductivity of the material, A is the surface area, T is the temperature, and x is the distance.

2. **Convection** is the transfer of heat through the movement of fluids, such as air or water. In buildings, examples of convection include the flow of warm air rising from a heater and the circulation of water in a radiator. The rate of heat transfer through convection is given by Newton's Law of Cooling:

   $$Q = hA(T_s - T_a) \tag{2.2}$$

   where Q is the heat transfer rate, h is the heat transfer coefficient, A is the surface area, T_s is the surface temperature, and T_a is the ambient temperature.

3. **Radiation** is the transfer of heat through electromagnetic waves. In buildings, examples of radiation include the transfer of heat from the sun through windows and the emission of heat from a fireplace. The rate of heat transfer through radiation is given by the Stefan-Boltzmann Law [36]:

   $$Q = \sigma A(T_s^4 - T_a^4) \tag{2.3}$$

   where Q is the heat transfer rate, σ is the Stefan-Boltzmann constant, A is the surface area, T_s is the surface temperature, and T_a is the temperature of the surrounding environment.

These fundamental types of heat transfer play a significant role in the thermal performance of buildings. Later on in this thesis, these calculations will be performed by the software Simien.

2.2.2 Thermal Transmittance

Thermal transmittance, commonly referred to as the U-value, is a measure of the rate of heat transfer through a building element, such as a wall, roof, or window. It is expressed in watts per square meter per degree Celsius (W/m^{2}K) and indicates the effectiveness of a material in insulating against heat loss or gain. A lower U-value represents better insulating properties, while a higher U-value indicates less efficient insulation [91][57].

The U-value of a building element is determined by the thermal conductivity and thickness of the materials that make up the element. The thermal transmittance (U-value) can be found using the following formual(s) [9]:

$$U = \frac{1}{R_{\text{total}}} \tag{2.4}$$

where R_{total} is the total thermal resistance of the structure. The thermal resistance R of a homogeneous layer is given by:

$$R = \frac{d}{k} \tag{2.5}$$

where d is the thickness of the layer and k is the thermal conductivity of the material. For multiple layers, the total thermal resistance is the sum of the thermal resistances of each layer:

$$R_{\text{total}} = R_{\text{surface, in}} + R_1 + R_2 + \ldots + R_n + R_{\text{surface, out}} \tag{2.6}$$

In this formula, $R_{\text{surface, in}}$ and $R_{\text{surface, out}}$ are the surface resistances of the internal and external surfaces respectively, and $R_1, R_2, ..., R_n$ are the thermal resistances of the individual layers.

For a structure with multiple layers, the thermal resistance of each layer can be found by adding them up, and then use the total in the U-value formula.

The table below shows the minimum requirements for U-values in different building components, according to the building regulations TEK97 and TEK17, the latter being the most recent [12] [11]. TEK, which translates to "Technical Regulations under the Planning and Building Act", represents a comprehensive set of rules guiding the Norwegian construction industry [10]. The Norwegian Building Authority (Direktoratet for byggkvalitet) is responsible for implementing and overseeing these regulations. The core objective of these codes is to ensure that buildings are safe, accessible, and energy-efficient. Over the years, the TEK regulations have been periodically updated to reflect contemporary standards for sustainability and quality, with the versions being named after the year of their release. For instance, TEK97 and TEK17 were released in 1997 and 2017 respectively.

TEK Version	**Roof (W/m^{2}K)**	**Floor (W/m^{2}K)**	**Walls (W/m^{2}K)**	**Windows (W/m^{2}K)**
TEK97	0,15	0,15	0,22	1,6
TEK17	0,13	0,10	0,18	0,8

Table 2.1: Minimum Requirements for some U-Values Specified by TEK97 and TEK17

2.2.3 Infiltration

In the context of building physics, infiltration refers to the unintentional introduction of outside air into a building, typically through cracks, joints, and gaps in the building envelope. The infiltration rate measures the amount of this outdoor air that enters a building, and it has a significant impact on the thermal efficiency of a structure. Even if building components are properly insulated, a high infiltration rate can lead to substantial heat loss, making the building thermally inefficient [96].

An essential parameter in measuring the infiltration rate is the N50 parameter, also known as air change rate or air leakage rate. The N50 value is the number of times the entire volume of air inside a building is replaced by outdoor air in an hour (expressed as h^{-1}) under 50 Pascals pressure difference across the building envelope. This pressure difference is created using a fan pressurization or depressurization test, such as a blower door test.

The blower door test is a standard method for measuring the air tightness of a building [63]. In this test, a powerful fan is mounted into the frame of an exterior door. The fan pulls air out of the building, lowering the air pressure inside. The higher outside air pressure then flows in through all unsealed cracks and openings. The rate of inflow of air is measured and used to calculate the building's air tightness.

A lower N50 value signifies a more airtight building, contributing to improved thermal efficiency. Conversely, a high N50 value indicates significant air leaks and potentially substantial heat loss, indicating a need for better sealing or insulation to improve the building's thermal efficiency. The N50 parameter forms an integral part of energy efficiency building standards, such as the Passive House standard, which requires an N50 value of no more than 0.6 air changes per hour at 50 Pa [81] [76].

Determining the exact air leakage rate in old buildings, especially unique buildings like churches, can be challenging without performing tests like the blower door test. Such tests performed in older, logged buildings show results of air leakage rates up to 10-15h^{-1} [86].

2.2.4 Temperature, Relative Humidity and Dew Point

Relative humidity (RH) is a measure of the amount of moisture in the air relative to the maximum amount the air can hold at a given temperature. It is expressed as a percentage, with 100% representing the maximum amount of water vapor the air can hold at that temperature [33]. The relative humidity can be calculated using the following formula:

$$\mathrm{RH} = \frac{\text{actual humidity}}{\text{humidity at saturation}} \times 100\% \tag{2.7}$$

Temperature and relative humidity are interdependent. As the temperature increases, the air can hold more moisture, causing the relative humidity to decrease, while a decrease in temperature reduces the air's capacity to hold moisture, resulting in an increase in relative humidity.

In churches, maintaining a stable relative humidity is essential for preserving the integrity of the structure and its contents, including wooden elements, artworks and musical instruments like organs. Wood is a hygroscopic material, meaning it can absorb and release moisture from the surrounding air. Fluctuating humidity levels can cause wood to expand and contract, leading to warping, cracking, and even structural damage [62].

Musical instruments such as organs are particularly sensitive to changes in humidity. The wood, leather, and metal components of an organ can react differently to changes in humidity, leading to misalignment, tuning issues, and reduced lifespan of the instrument. Considering that many musical instruments are made entirely or partly from wood, modern buildings designed for music, such as the Norwegian Academy of Music and the Oslo Concert Hall, consistently control the humidity levels. These buildings use ventilation systems to maintain a relative humidity of 45 ± 5% [46].

The dew point is the temperature at which air becomes saturated and water vapor begins to condense into liquid water [13]. When the temperature drops to the dew point, the relative humidity reaches 100%. The dew point temperature can be calculated using the following equation:

$$T_{\text{dew}} = \frac{243.04 \times (\ln(RH/100) + \frac{17.625 \times T}{243.04+T})}{17.625 - (\ln(RH/100) + \frac{17.625 \times T}{243.04+T})} \tag{2.8}$$

where T_{dew} is the dew point temperature in degrees celsius, RH is the relative humidity in percentage, and T is the air temperature in degrees Celsius.

Low humidity levels can negatively impact the preservation environment, whereas high levels of relative humidity equally can be just as bad, causing mildew, rot, and other damages to buildings [61]. This is especially harmful in church buildings, rich with wooden structures and artworks. Moreover, mold and mildew growth, resulting from high humidity, can pose health risks to occupants and visitors. This underscores the importance of effectively managing temperature and humidity levels in these buildings to avoid rot.

2.3 Solar Energy

2.3.1 Photovoltaic Systems

Photovoltaic (PV) systems are technological innovations that convert sunlight directly into electrical energy. These systems rely on solar cells most commonly made from semiconducting materials, such as silicon. When sunlight hits the solar cell, its semiconductive material absorbs the light's energy. This process moves electrons and creates an electric current, which then can be used in an electric circuit [14].

A PV system consists of several components: solar panels, an inverter, a charge controller, a battery for energy storage, and other electrical accessories such as wiring and mounting equipment. The solar panels capture sunlight and convert it into direct current (DC) electricity. This DC electricity is then transformed by the inverter into alternating current (AC) electricity, which is compatible with most appliances and can be connected to the electrical grid. The charge controller, manages the flow of electricity to and from the battery, ensuring optimal charging and discharging to extend battery life. In recent times, PV panels equipped with Passivated Emitter and Rear Cell (PERC) technology have gained popularity. PERC technology enhances the efficiency and output power of solar cells by adding a passivation layer that reduces electron recombination and improves light absorption [85].

The efficiency of PV panels, the main performance measure, is defined as the quotient of the panel's electrical output to the solar energy it receives. This efficiency largely depends on the type of solar cell material and the specific design of the panel. As of 2023, under Standard Test Conditions (STC), the efficiency range for commercially available PV panels, most commonly monocrystalline cells, are found to be between 15% and 22% [17]. However, due to ongoing advancements in science and technology, even higher efficiencies could possibly be seen in the future, leading to better performing PV systems.

Building-integrated photovoltaics (BIPV) represent an unique design approach that incorporates PV panels directly into the building, taking the form of roof tiles, facade materials, or window glazing. While BIPV systems offer aesthetic and functional benefits, their efficiencies are typically lower than traditional PV panels due to design limitations and the necessity to find a balance between visual appeal and energy production. The efficiency range for BIPV systems generally lies between 10% and 15%, around half of ordinary PV panels [25].

In the past ten years, the cost of PV systems has dropped significantly. This change has been driven by improvements in technology, larger-scale manufacturing, and more competition in the market. This trajectory is projected to continue, making PV systems progressively more accessible and cost-effective across a wide array of applications. As technology evolves, it is possible that future PV systems will achieve higher efficiencies, leading to further reductions in the cost of solar energy [41].

If the power generated by a PV system surpasses the building's electricity consumption, the surplus can be stored in a battery for later use or sold back to the electrical grid. This sell-back capability offers an additional income stream, helping to offset the initial investment cost in the PV system.

It is also worth to mention that PV and BIPV panels generally experience an annual degradation rate ranging from 0.5% to 1%. This indicates a gradual decrease in their annual energy production. Nevertheless, panels of high quality can maintain considerable performance levels for many years, with some models continuing to operate at 80-90% of their initial capacity after 25 years [84].

As of 2023, only two churches in Norway have embraced this technology: Strand church and Sarpsborg church. Globally, in as early as 2014, there were already over 2, 000 churches equipped with solar panels [69]. The delayed adoption in Norwegian churches, compared to other types of buildings, can be attributed to how solar cells majorly affect the aesthetic appearance of the churches. A report compiled by KA, based on experiences from Strand Church, demonstrates that the solar panels have performed remarkably well [43] [55].

2.4 Energy Efficiency

Energy efficiency in buildings is defined as the optimized use of energy resources to provide necessary functions, such as heating, cooling, and lighting, while minimizing waste [28]. It represents a balance between the energy consumed by a building and the services it provides, with the goal of reducing overall energy consumption without compromising comfort or functionality. A classic example of energy efficiency is the use of LED bulbs, which produce the same amount of light as traditional incandescent bulbs, yet consume significantly less energy.

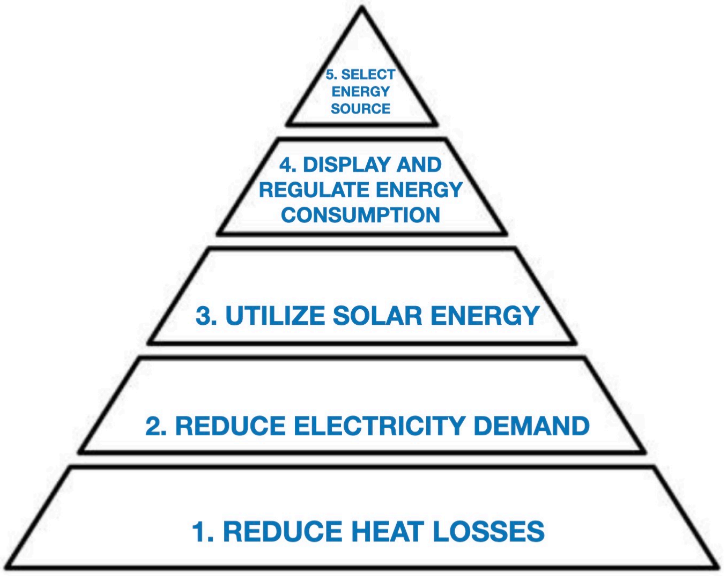


Figure 2.1: The Kyoto Pyramid

2.4.1 Kyoto Pyramid

The Kyoto Pyramid is a visual guide for reducing energy consumption in buildings, featuring five layers each representing a different priority [20]. It encourages starting with reducing heat losses, then ascending through the layers to sustainable heat sources, enabling a cost-effective and impactful approach to energy efficiency. The five layers are described below:

1. **Reduce Heat Losses:** The base layer of the pyramid emphasizes the importance of minimizing heat losses in buildings through insulation, air sealing, and thermal bridging reduction. These measures can significantly improve the overall energy performance of a building and reduce heating costs.

2. **Reduce Electricity Consumption:** The second layer of the pyramid focuses on minimizing electricity consumption by using energy-efficient appliances, lighting, and equipment. This includes the use of LED lights, energy-saving appliances, and energy management systems to monitor and control electricity usage.

3. **Take Advantage of Solar Energy:** The third layer of the pyramid promotes the utilization of solar energy in buildings through the use of solar thermal collectors and photovoltaic (PV) systems. These technologies can help generate renewable energy, reduce electricity costs, and decrease greenhouse gas emissions.

4. **Show and Control the Energy Consumption:** The fourth layer of the pyramid highlights the importance of monitoring, displaying, and controlling energy consumption in a building. This can be achieved through the use of smart meters, energy management systems, and building automation systems that allow occupants and building managers to track and optimize energy usage.

5. **Choose Source of Heat:** The top layer of the pyramid emphasizes the selection of efficient and sustainable sources of heat for a building, such as heat pumps, district heating, or biomass heating systems. By choosing environmentally friendly and energy-efficient heat sources, buildings can further reduce their greenhouse gas emissions and energy consumption.

2.4.2 LED Lighting

LED lighting is a highly energy-efficient lighting technology that offers numerous advantages for churches, which often require substantial lighting due to their size and architectural features. Traditional incandescent light bulbs, while still used in some churches, are less energy-efficient and have shorter lifespans, making them less desirable for long-term use in these buildings.

LED lights consume significantly less energy, typically using 75-90% less power than incandescent bulbs to produce the same amount of light [29]. This energy-saving attribute results in reduced electricity consumption and lower energy bills. For example, a 60-watt incandescent bulb can in a best case scenario be replaced by a 6-watt LED bulb to produce the same amount of light, highlighting the efficiency gains provided by LED lighting.

In addition to their energy efficiency, LED lights offer greater versatility in terms of color temperature, which can enhance the appearance and ambiance of the church. Color temperature is measured in Kelvins (K) and can range from warm white (2700K) to cool white (5000K) or even higher [58]. This variety allows churches to customize their lighting to suit the desired atmosphere and purpose of different spaces within the building.

LED lights also have a significantly longer life expectancy compared to traditional incandescent bulbs. LED bulbs can last up from 15 000 to 50 000 hours, which is up to 25 times longer than incandescent bulbs [7]. This longevity results in lower maintenance and replacement costs, further contributing to energy and cost savings.

2.5 Cost of Energy

For years, Norway has benefited greatly from affordable and renewable electricity, primarily produced by the numerous hydroelectric power plants [26]. However, in recent years, energy prices, with a particular emphasis on electricity, have become a hot topic for debates and political disagreements [22]. The energy market is incredibly intricate, with many attributing the recent spike in energy prices to factors such as interconnections, war, and political instability.

Much like other goods and services, the cost of electricity is dictated by the principle of supply and demand [4]. Prices shift from hour to hour, reaching their peak when the demand is high and supply is low, and conversely, they drop when the supply is high and demand is low. This means that the energy use during cold winter mornings and evenings is often more expensive compared to the warm summer days or nights.

In an attempt to ease the load on the power grid, a new tariff, known as a power tariff, has been introduced [23]. This tariff imposes a penalty for excessive energy use. It is typically determined by averaging the three highest monthly power measurements (kWh/h).

Predicting future energy prices with accuracy is nearly impossible. However, numerous reports hint that high energy prices in the foreseeable future should be expected [66]. For many, this acts as a powerful motivator to focus more on energy efficiency and other cost-reducing measures.

2.6 Preservation

In Norway, the Directorate for Cultural Heritage, also known as Riksantikvaren, bears the primary responsibility for ensuring the appropriate management of cultural monuments and cultural environments [39]. To fulfill this mandate, the Directorate can employ various strategies, the most powerful of which is a preservation order. The implementation of a preservation order means any changes beyond routine maintenance on a building must be authorized by the government. However, this does not mean that alterations to technical systems are prohibited. All buildings built before 1537 are automatically protected under preservation orders.

However, the rules for churches, are even more stringent, distinguishing between two types of protection: fully preserved churches and listed churches. All churches built before 1650 are automatically placed under preservation orders. There are also some churches that are under preservation orders despite being built after 1650. The other category of protection status, known as a listed churches, includes all churches that were constructed between 1650 and 1850. Furthermore, several churches built even after 1850 are classified as listed churches. This status means these churches are deemed culturally significant and with national value. The Directorate of Cultural Heritage states these churches "must be treated with the same respect as fully preserved churches".

In summary, one cannot freely make alterations to the exterior or interior appearance of churches [38]. Consequently, most modifications must be done in consultation with the authorities, aiming to preserve the churches' aesthetic and architectural expression.

Chapter 3

Methods

3.1 Church Buildings Description

The focus of this master's thesis, prepared in consultation with Grimstad Church Council, is an analysis of three church buildings within their operational jurisdiction: Eide church, Landvik church, and Grimstad church. These churches were chosen based on factors such as construction materials and building year.

Wood is the primary structural material in approximately 65% of all churches in Norway [54], making it an essential aspect to consider when performing this study. The age of the churches also plays a significant role in determining their preservation requirements. As a result, this research targets wooden churches, as findings from these type of churches are expected to have the highest transferability value.

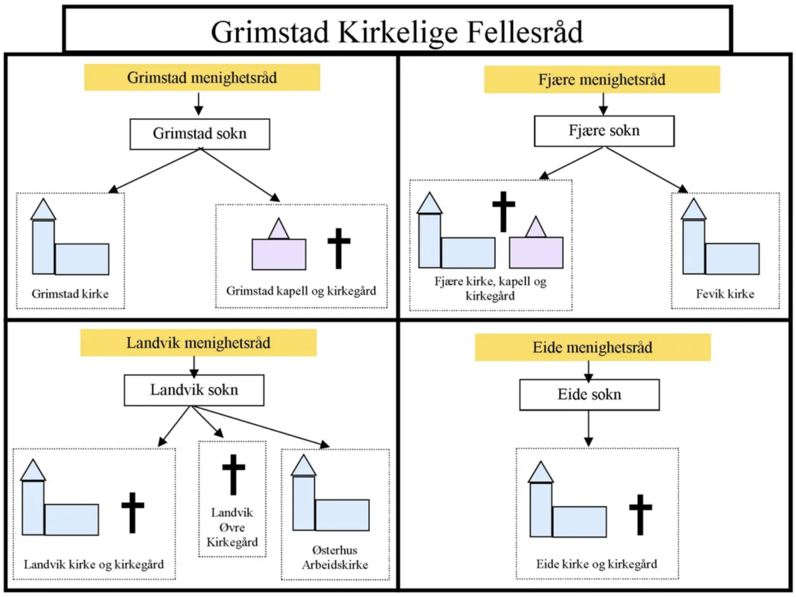
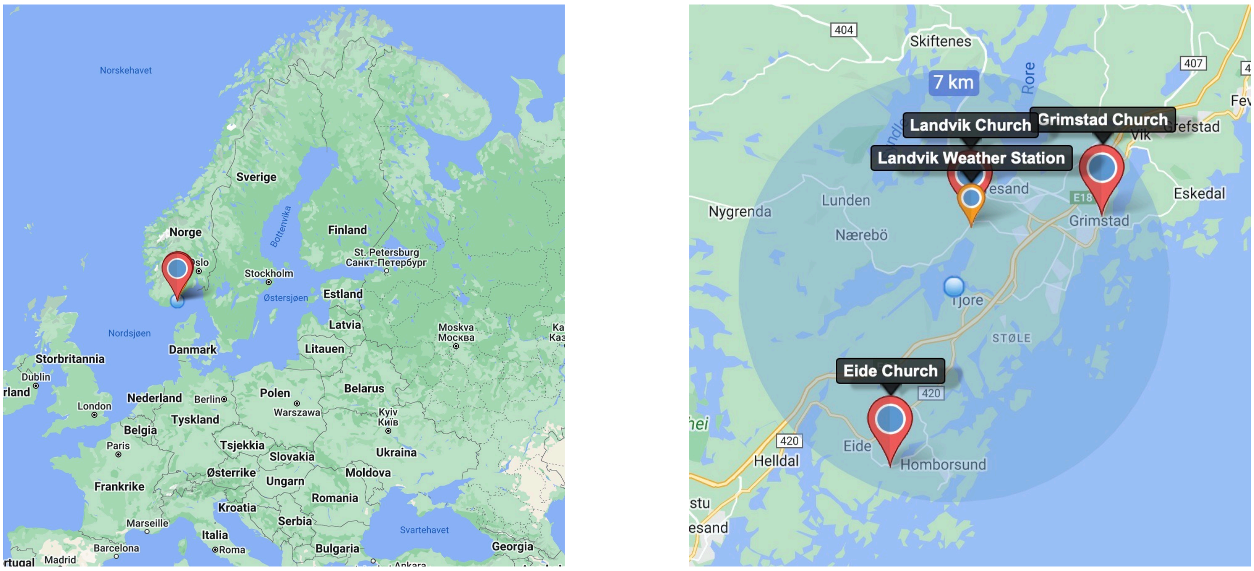


Figure 3.1: Grimstad Church Council Operational Responsibility [32]

It is important to note that Grimstad Church Council is responsible for a diverse range of buildings, including a total of five church buildings, one working church, two chapels, five cemeteries, and two kindergartens as shown in Figure 3.1 [32]. However, this thesis does not look into all of these structures. For example, Fjære Church, which is built of stone, and Fevik Church, constructed in 1978 with more modern building practices, are not part of the study.

The three churches are situated within a close geographical range, all located in the southern region of Norway, specifically in the municipality of Grimstad as shown in Figure 3.2. In the following sections of this subchapter, a general analysis of the individual characteristics and unique features of each church will be presented. The main aspects are found in Table 3.1, which provides an overview of the key parameters of all three churches.



(a) Map of Europe showing selected churches

(b) Zoomed-in map of the three churches

Figure 3.2: Selected Churches and Weather Station: Map of Europe and Zoomed-in View

The close proximity of the three church buildings allow for a better comparison of their energy requirements, not only in terms of the buildings experience roughly the same temperature and therefore the same heating requirement, but also in terms of daylight and therefore energy consumption for lighting. Visible in the map in Figure 4.16b, the position of the weather station in Landvik is shown. This weather station continuously collects numerous meteorological data, some of which will be examined later in the thesis [89].

Specifications	**Eide Church**	**Landvik Church**	**Grimstad Church**
Construction Year	1795 / 1807	1825	1881
Seating Capacity	250	400	1000
Building Material	Wood	Wood	Wood
Construction Technique	Log Building	Log Building	Timber Framing
Heating Source	Electricity	Electricity	Biofuel Oil
Heated Area [m^2]	221	430	750
Heated Volume [m^3]	909	2 154	6 584
Electric Energy Consumption (2022) [kWh]	26 559	62 520	41 246
Fuel Consumption (2022) [L]	-	-	15 000
Installed Heating Capacity [kW]	28,4	47,1	-
Heating Capcity per Area [W/m^2]	124	110	-
Heating Capacity per Volume [W/m^3]	31	21	-
Lighting	LED	Incandescent	LED
Preservation Status	Automatically Listed	Automatically Listed	Listed

Table 3.1: Church Spesification Overview

3.1.1 Eide Church

With a seating capacity of 250 people, Eide church is the smallest of the three churches examined in this thesis. Initially constructed in 1795 but not completed until 1807, Eide Church is not only the smallest but also the oldest of the three [51] [48]. Like all other churches built between 1650 and 1850, Eide church is automatically listed by the Directorate of Cultural Heritage as a building of national, cultural, and historical value. According to the Directorate, such buildings should be treated with the same respect as fully protected churches [77].

The cruciform church is constructed with logged timber and consists of a narthex (våpenhus) at the western end, a sacristy at the eastern end, and the main seating area, including the nave, altar, and choir in the center. The organ is located in the western gallery, while two additional galleries can be found in the northern and southern ends of the church, displayed with the grey areas in Figure 3.5.

The ceiling in the main seating area is insulated with 10-15 cm of mineral wool. However, a report from 2016 mentions heat losses due to unevenly laid insulation. The floor is reportedly not insulated and consists of relatively thick floorboards and timber framing above a crawl space. The exterior walls are not insulated but have been later clad with vertical paneling. As for the windows, the original single-pane windows have been complemented with secondary glass mounted on the inside to reduce heat losses. The church underwent restoration in the 1960s and 1970s, with the aim of returning it to its original form and appearance.

Nearly all traditional incandescent light bulbs in Eide have been replaced with energy saving LED bulbs.


(a) Exterior View from South


(b) Exterior View from West


(c) Exterior View from East


(d) Interior View

Figure 3.3: Eide Church

Located only a few meters from the western entrance of the church are two smaller buildings: a heated annex (kirkestue) and a cold shed. The annex, built in 1997, consists of a living room and bathroom facilities and is used for various less space-demanding activities. The shed is used for equipment storage.

(a) Pew-mounted Heating Panels

(b) Ceiling-mounted Heating Panels

Figure 3.4: IR Heating Panels in Eide church

In 2014, Eide Church underwent a major upgrade of its heating system. All floor-mounted tube heaters were replaced with pew-mounted infrared heating panels, accompanied by infrared heating panels mounted in the ceilings underneath the galleries shown in Figure 3.4. All the heating panels are shown in red in Figure 3.5. This heating system has a total installed capacity of 28.4 kW. Considering the total area of 221 m^2 and the total volume of 909 m^3, the heating system can deliver 31 W/m^3, supposedly enough to intermittently heat the church, as per KA's recommendation [45].

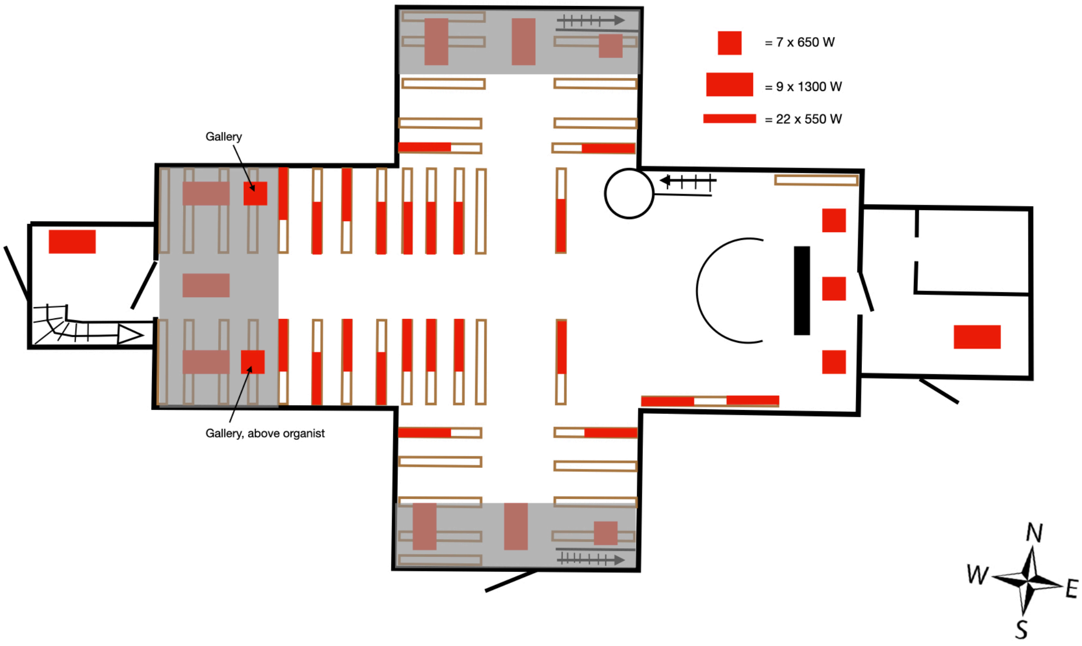


Figure 3.5: Eide Church Floorplan and Heating Panel Placement

3.1.2 Landvik Church

Constructed in 1825, Landvik Church is the second oldest church examined in this thesis and is automatically listed by the Directorate of Cultural Heritage. With a heated volume of over 2000 m^3, Landvik is more than twice the size of Eide church in terms of volume. Landvik Church has a seating capacity of 400 people, 150 more than Eide church [53] [50].

Similar to Eide church, Landvik is built as a cruciform structure using logged timber. The church comprises a narthex in the western end, a sacristy in the eastern end, a southern entrance/windshield, a northern sacristy, the main seating area, the choir and altar, and a handicap-accessible toilet, only accessible from the outside. A heated annex, built in 1999/2000 on top of an existing cold garage, is located to the northeast of the church. The northern sacristy and handicap toilet were constructed at the same time as the annex; therefore, these are assumed to follow stricter regulations regarding insulation levels (TEK97).

As for the rest of the church, the insulation level is relatively low. Similar to Eide church, Landvik's walls are not insulated, with only a layer of vertical paneling mounted on the exterior walls. The ceiling in the main seating area is insulated with 10-15 cm of mineral wool. Though not insulated, there are several layers of flooring. In the 1940s and 50s, the church underwent restoration: the windows received an additional layer of glass, and an electrical heating system was installed. The church has three galleries, with the organ situated on its own gallery behind the altar.

The lighting in Landvik Church primarily consists of incandescent bulbs.

(a) Exterior View from Southeast

(b) Exterior View from West

(c) Annex (Kirkestue)

(d) Interior View

Figure 3.6: Landvik Church

(a) Pew-mounted Bench Heater, 250W

(b) Heating Panels Hanging from Ceiling, 1700W

Figure 3.7: Heating System in Landvik Church

The current heating system predominantly features bench heaters discretely mounted underneath the benches shown in Figure 3.7a. Additionally, there are a few infrared ceiling-mounted heating panels similar to those found in Eide church, as well as some tube heaters mounted low on the wall by the choir and around the altar. In the narthex and northern sacristy, ceiling-hung heating panels as shown in Figure 3.18b are used. All heat sources in the church are marked with red in Figure 3.8. The church has a total installed heating capacity of nearly 43 kW. With an area of 377 m^3 and a volume of 2012 m^3, the church's heating capacity is 21.3 W/m^3, insufficient for adequately heating the church intermittently according to KA's guidelines [45].

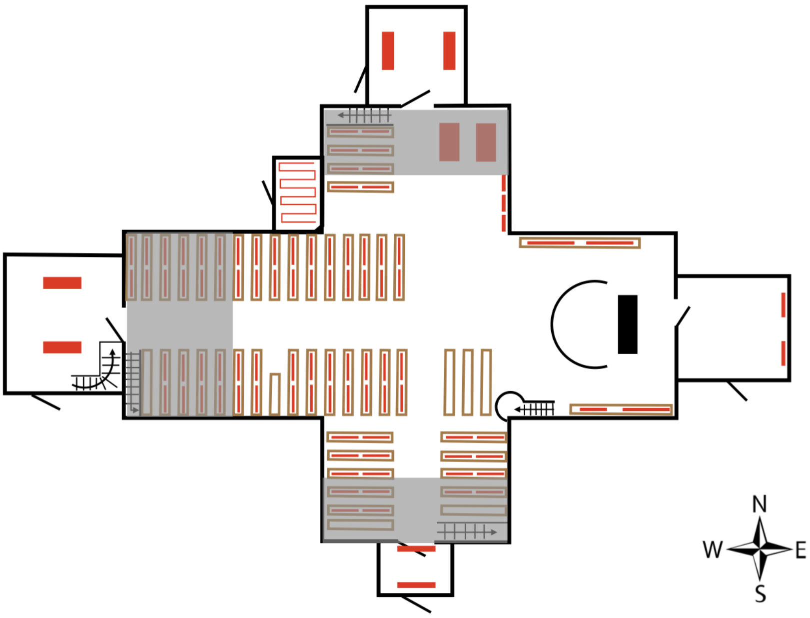


Figure 3.8: Landvik Church Floorplan and Heat Source Placement

3.1.3 Grimstad Church

Grimstad Church is not only the largest of the three churches examined in this thesis, but it is also the third-largest wooden church in Norway, with a capacity of 1 000 people [52] [49]. Although it is built in 1881, the church has been granted the same level of protection as the other two churches, highlighting its historical and cultural significance.

In addition to the main seating area, altar, and choir, the church features three galleries, sacristies, a western entrance hall, a handicap-accessible toilet, and a basement. The basement houses a living room, toilet facilities, and a technical room. The organ is situated on the western gallery.

Unlike Eide and Landvik church, Grimstad church is not built with logged timber but rather with a more modern wooden framework and vertical paneling on the exterior walls. With a height of up to 13 meters from floor to ceiling, Grimstad church boasts a heated volume of over 6500 m^3, making it significantly larger than both Eide and Landvik church combined.

Another notable difference between Grimstad church and the other two churches is the heating system. Grimstad church utilizes a hydronic heating system, featuring wall-mounted radiators. The system derives its heat from a boiler burning bio-fuel oil. The burner itself is rated at 178 kW, while the boiler is rated for 160 kW.

The church has primarily opted for LED lighting, providing energy-efficient illumination throughout the building.

(a) Exterior View from West

(b) Exterior View from South

(c) Exterior View from North

(d) Interior View

Figure 3.9: Grimstad Church

3.2 Electric Energy Consumption and Power

Figure 3.10: Smart Energy Meter (AMS)

In order to assess the energy efficiency of the churches, it is essential to examine their historical energy consumption. Analyzing energy consumption can provide valuable insights into the usage patterns, identify inefficiencies, and serve as a basis for comparing the effectiveness of potential energy efficiency measures. Since January 1st, 2019, all Norwegian electricity customers have been required to have a smart electricity meter installed, known as AMS meters as shown in Figure 3.10 [73]. All the churches examined in this thesis have these smart energy meters installed. These meters continuously and automatically report hourly energy consumption values to the transmission system operator. For all the churches in this thesis, this transmission system operator is Glitre Nett (formerly Agder Energi Nett).

Smart electricity meters also feature a HAN (Home Area Network) port, which can be made accessible to the customer. Through this port, one can obtain precise instantaneous values of consumption (power), voltage levels, and any surplus power generated, for instance, from PV systems [73]. However, in this thesis, data obtained through the HAN port has not been used or evaluated. The historical hourly energy consumption data is available for download in Excel format through the transmission system operator's web portal shown in Figure 3.11 on the next page. Long-term data has been extracted from this source and further processed and plotted in Python. It is worth noting that if one goes far enough back in time, hourly data is not available, but annual totals can still be obtained.

Despite identical operations from year to year, variations in energy consumption may be caused due to different yearly outdoor temperatures. In years with lower outdoor temperatures, energy consumption will be higher than in years with higher outdoor temperatures [31] [30]. To represent energy consumption independently of the temperature variable, all annual energy consumption numbers have been degree-day corrected, i.e., temperature-corrected. This has been achieved using temperature data from Landvik weather station to find the average annual sum of degree-day numbers for the period from 1991 to 2020. The relationship between the sum of degree-day numbers for the year to be corrected and the sum of degree-day numbers for the reference year can then be multiplied by the energy consumption in the year of interest. The method to find the sum of degree-day numbers will be discussed in the next chapter.

Let E_Y be the energy consumption in a year Y, G_Y be the sum of degree-day numbers for the year Y, and G_{ref} be the sum of degree-day numbers for the reference year. The degree-day corrected energy consumption, E_{corr}, can be calculated as follows:

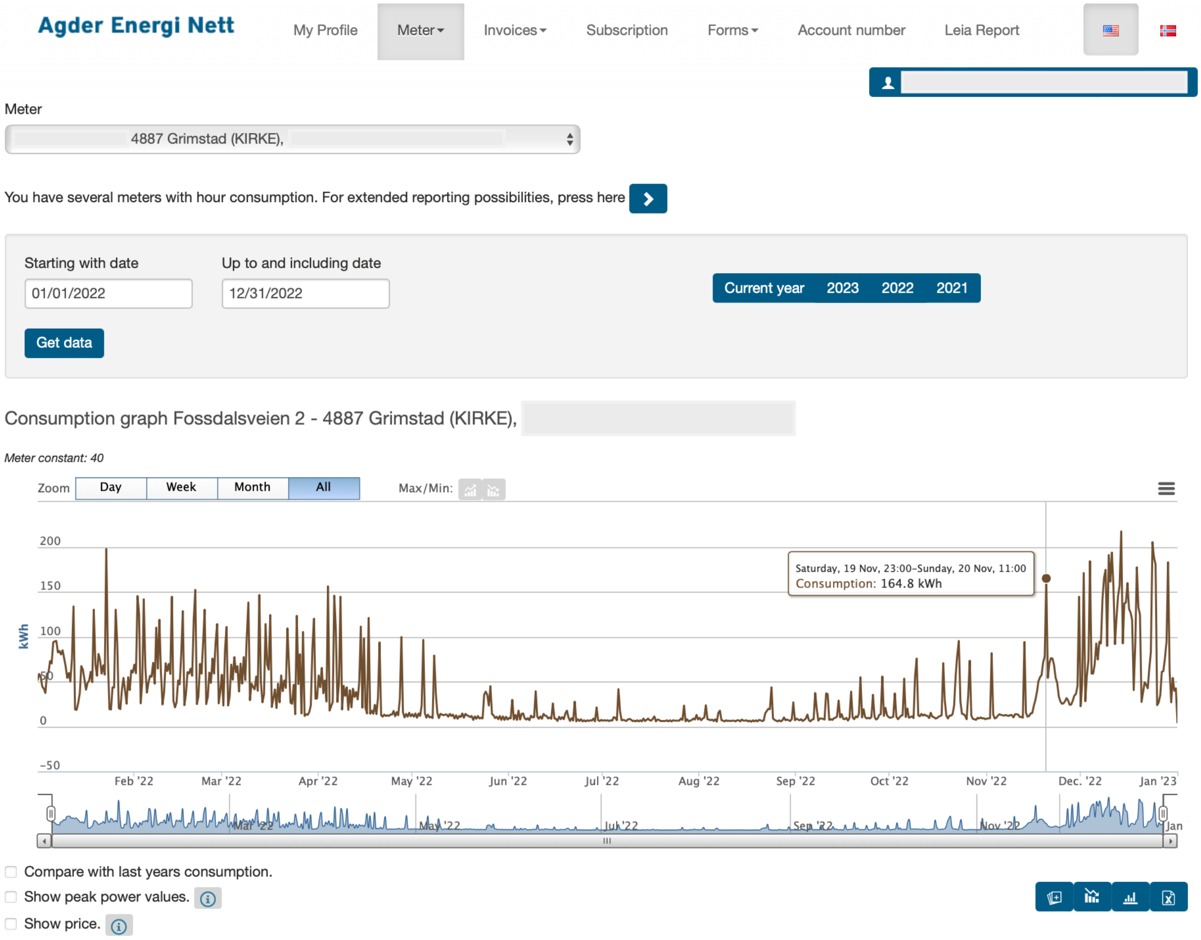
$$E_{corr} = E_Y \frac{G_Y}{G_{ref}} \tag{3.1}$$

Later in the thesis, the maximum power consumption during a year is briefly addressed. As the electricity meters only display hourly consumption values, the power consumption will not be shown with perfect accuracy. However, it is considered that the values of the power consumption, found by dividing the hourly energy consumption in kWh by one hour, will provide an average power consumption for that hour. Since the largest power consumption is related to heating and there are no large motors or similar devices with high starting currents, this method for determining maximum power is deemed satisfactory [83].

To find the power, P, in kilowatts (kW), the following equation can be used:

$$P = \frac{EnergyConsumption(kWh)}{(h)} = kW \tag{3.2}$$

Figure 3.11 shows the interface from the customers perspective. Personal identifiers have been removed from the print screen.



[redacted]

Meter

[redacted] 4887 Grimstad (KIRKE), [redacted]

You have several meters with hour consumption. For extended reporting possibilities, press here

Starting with date: 01/01/2022

Up to and including date: 12/31/2022

Current year | 2023 | 2022 | 2021

Get data

Consumption graph Fossdalsveien 2 - 4887 Grimstad (KIRKE), [redacted]

Meter constant: 40

Saturday, 19 Nov, 23:00–Sunday, 20 Nov, 11:00
Consumption: 164.8 kWh

☐ Compare with last years consumption.
☐ Show peak power values.
☐ Show price.

Figure 3.11: Print Screen of Transmission Operator's Web Portal

3.3 Temperature and Relative Humidity Data

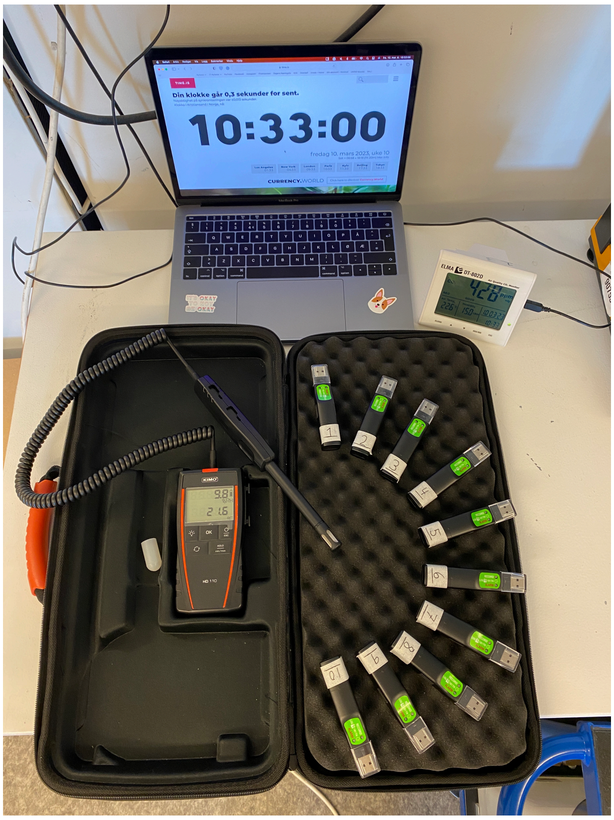


Figure 3.12: Data Logger Test Setup

In this study, temperature and relative humidity data play an essential role in understanding the heating and cooling processes, as well as relative air humidity and heat distribution within the three churches. To obtain accurate data, ten ElmaLOG 181TH sensors from Elma Instruments have been placed in each church. These data loggers record both temperature and relative humidity, and have also been used to verify the reported resting and operating temperatures of the churches.

As shown in Figure 3.12, all data loggers were tested against a reference sensor, a KIMO HD 110, which is a highly accurate measuring instrument, previously calibrated for precise temperature and humidity readings. The test was conducted over a one-hour period, with a measurement interval of 30 seconds. The average of these measurements is compiled in Table 3.2. It is important to note that all measurements were performed in the same room with very similar temperature and humidity conditions throughout the test. The reference sensor (KIMO HD 110) consistently displayed a temperature of 21.6°C, except for one measurement showing 21.5°C. The ElmaLOG sensors demonstrated a slightly larger variation, but still a very low amplitude in fluctuations. Considering all loggers as a whole (Average (Logger 1-10)), the temperature was only 0.43°C above the reference measurement. Regarding relative humidity measurements, larger variations were observed, with Logger 7 displaying the most significant deviation. It should be mentioned that the test measurements were performed under very dry conditions. The calibration certificate for the ElmaLOG sensors indicates that, at 23°C and 50% relative humidity, the sensors have a deviation of ±0.5°C and ±3%, respectively.

Data Logger	**Temperature (°C)**	**Relative Humidity (%)**
KIMO HD 110 (Reference)	*21,60*	*9,89*
Average (Logger 1-10)	*22,03*	*11,32*
Logger 1	21,5	12,3
Logger 2	21,7	11,0
Logger 3	22,6	8,7
Logger 4	22,3	12,6
Logger 5	21,6	13,8
Logger 6	22,3	9,9
Logger 7	21,8	14,2
Logger 8	22,2	8,8
Logger 9	22,4	11,2
Logger 10	21,9	10,7

Table 3.2: Data Loggers vs Reference

Figures 3.13 and 3.14 illustrate how the data loggers respond to rapid temperature (and relative humidity) changes in a domestic environment. The loggers were first placed on a tray next to each other at room temperature, then moved to a refrigerator set at 4°C, followed by a freezer set at -18°C, back to the refrigerator at 4°C, and finally returned to the kitchen counter at room temperature. The graphs indicate that the data loggers generally perceive temperature and relative humidity similarly. Despite some deviations, the data is considered suitable for the intended purpose.

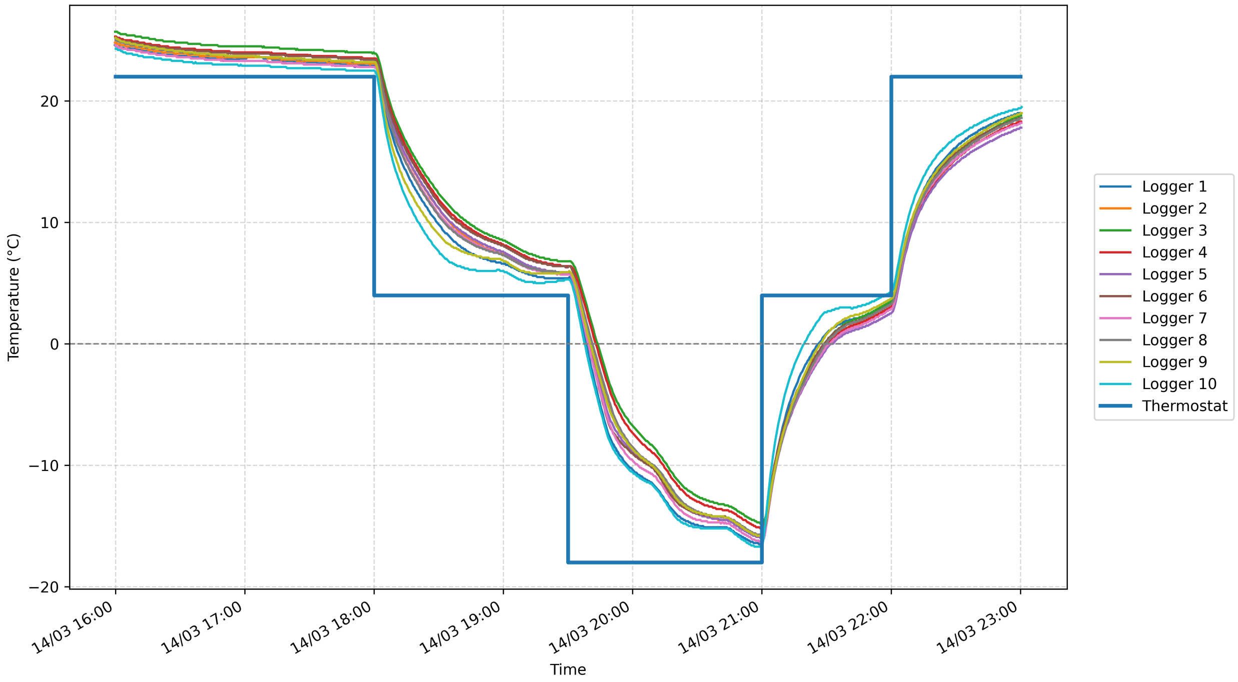


Figure 3.13: Home Environment Temperature Testing

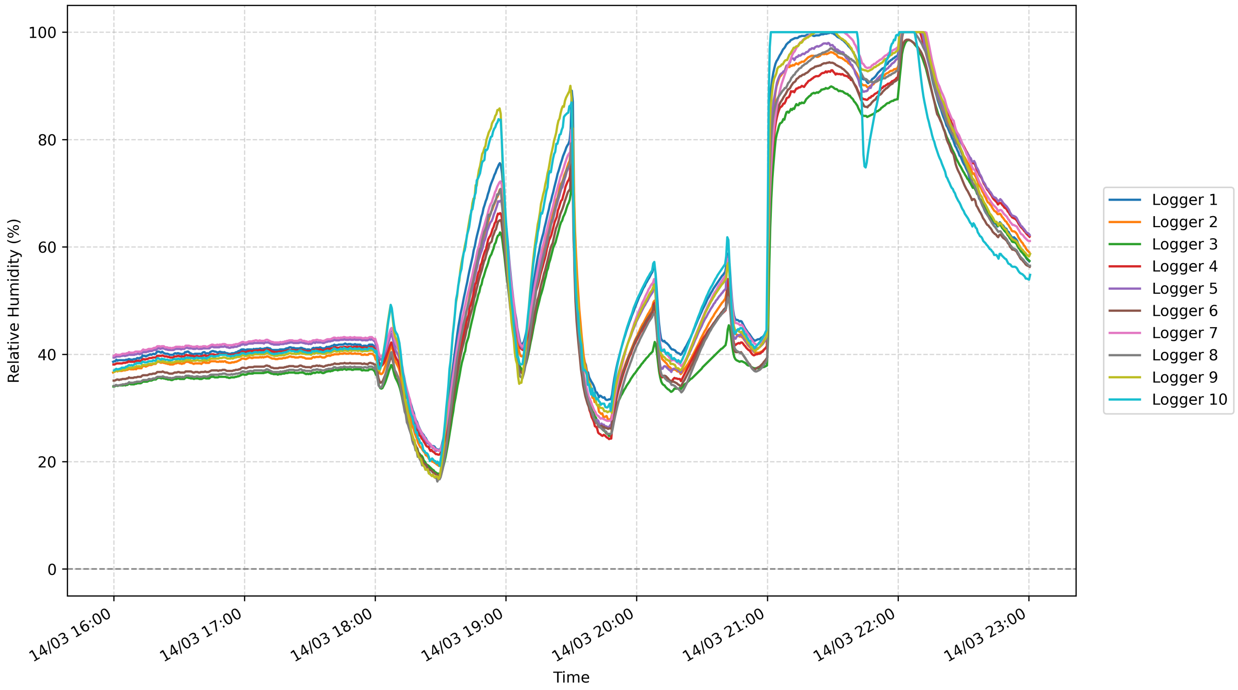


Figure 3.14: Home Environment Relative Humidity Testing

Due to the temperature and humidity loggers not being waterproof, the outdoor logger (always Logger 1) has been protected by a rain jacket made from a cut-off plastic bottle shown in Figure 3.15. Figure 3.16 further demonstrates how the outdoor logger, in this demonstration placed on the north-facing wall of Landvik church, correlates with the temperature measured at the weather station only around a hundred meters away. These values are also considered adequate for the context in which the data is used.

Figure 3.15: Rain Protected Outdoor Logger

In addition to the ten temperature and humidity loggers, surface temperature measurements have been performed using a Fluke Ti400 thermal imaging camera and a handheld Raytek Raynger ST laser thermometer. Both the thermal imaging camera and the laser thermometer were set to an emissivity of 0.85, as there is some reflection in the painted surfaces that mainly were measured. The thermal imaging camera also allowed for background temperature adjustment, set to the actual temperature in the church during the thermal imaging process (e.g., 19°C during church operation and 10°C during idle temperatures). The thermal imaging files were imported into Fluke's proprietary software, where the images were cropped and exported as standard JPG files.

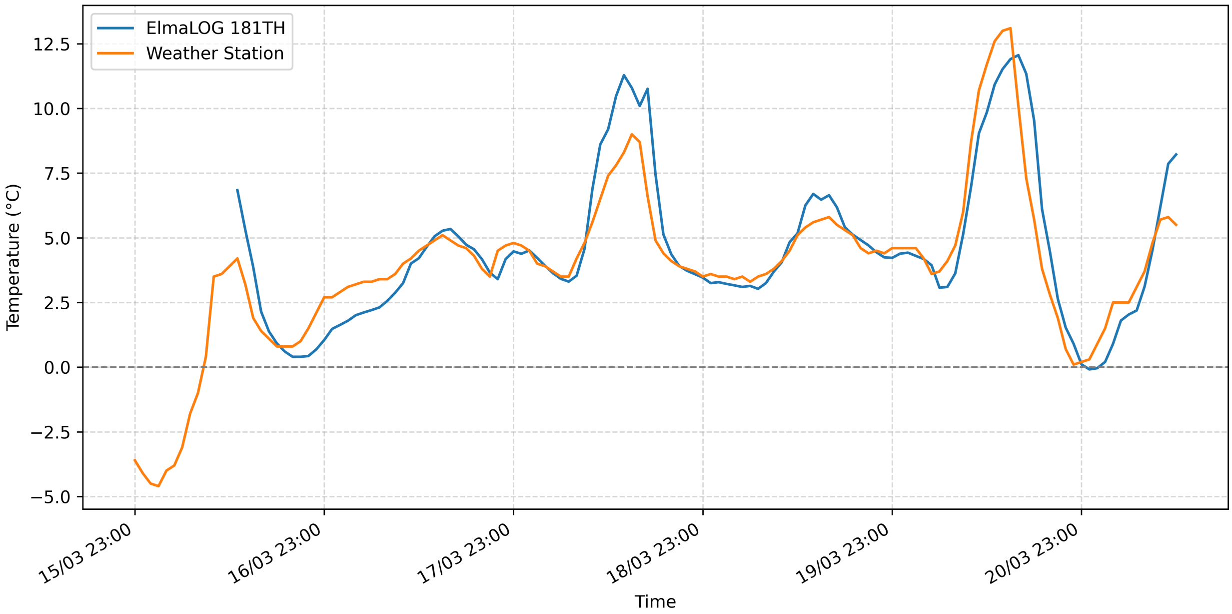


Figure 3.16: Logger 1 (Landvik Outdoor) vs. Landvik Weather Station

As mentioned in the previous chapter on energy consumption, the annual energy consumption data of the churches has been adjusted to account for annual variations in outdoor temperature. The temperature data that serves as the foundation for this adjustment, comes from the weather station in Landvik, in close distance to all of the churches as shown in Figure 3.2. From this weather station, daily mean temperatures were collected from the years 1991 to 2020.

The concept of energy degree-days and degree-day normals forms the basis for the degree-day correction of the churches energy consumption data. In a typical heated building, the interior temperature generally ranges from 21 to 23°C. However, a fraction of the heating comes from incidental sources such as lighting, machinery, and human occupants. When these factors are isolated, the heating requirement approximates to around 17°C, which is therefore used as a base temperature for calculations[31] [30].

The method for adjusting temperature and location incorporates energy degree-days, which quantify the heating requirement. This metric is derived from the difference between the daily average temperature and the base temperature of 17°C. To illustrate, if the daily average temperature happens to be 8°C, the degree-day for that specific day would be 17 - 8 = 9. Any negative values are disregarded and set to zero.

By summing all degree-days within a particular year, the energy degree-days for that year can be determined. While the application of a 17-degree base temperature is suitable for a standard residential building maintaining a steady temperature, it may not be entirely fitting for a church with variable operational and resting temperatures, and sporadic heating. Yet, it is seen as a satisfactory representation of the correlation between the annual energy consumption and the outdoor temperature.

The degree-day, G_{day}, for a specific day can be calculated using the daily average temperature, T_{avg}, and the base temperature, T_{base} (17°C) as follows:

$$G_{day} = max(0, T_{base} - T_{avg}) \tag{3.3}$$

The energy degree-days for a particular year, G_{year}, can then be computed by summing all degree-days within that year:

$$G_{year} = \sum_{i=1}^{365} G_{day,i} \tag{3.4}$$

To carry out the degree-day calculations and adjust the energy consumption, a Python script was used. The script interprets daily average temperature data from a CSV file, computes degree-days for each year included in the dataset, and determines the average degree-days over the period 1991-2020. Subsequently, it corrects the actual energy consumption for a specific year based on the ratio of degree-days for that year to the average degree-days in the period 1990-2020. In this exercise, it is assumed that 100% of the energy consumption contributes to heating.

The summarized results from this temperature-correction for all churches can be found in Appendix E.

3.4 Solar Energy Simulations and Calculations

As previously outlined in Chapter 2.3, solar panels are a rare sight on Norwegian church rooftops. To date, only two churches in Norway have embraced this technology. The primary reason for this is the difficulty in obtaining approval for such a modification, as it often significantly alters the architectural expression of the building. However, it is important to remember that solar technology is evolving rapidly, and much can change in a matter of a few decades. Maybe in the future, it could be that solar cell roof tiles will become indistinguishable from ordinary roof tiles, making PV systems available to all churches?

This changing landscape makes exploring the potential of PV installations on church buildings interesting for two key reasons. Firstly, it *shines light* on potential benefits churches may miss out on due to strict rules around preserving their architectural style and historical appearance. Secondly, it encourages to think about the possibilities that might open up in the future if BIPV become as efficient as today's conventional solar modules.

For the purpose of this exercise, the focus will be on Eide church, examining how solar panels could potentially influence its energy balance. Like most churches, Eide's altar faces east, offering large south-facing roof surfaces, which - in the northern hemisphere - are ideal for harnessing solar energy. The church, located in open terrain with minimal shading and a low horizon in the south, presents a good case for solar installation. It must be noted, however, that this study does not consider the aesthetic or architectural implications, nor does it account for the significant roof loads that a solar installation might impose. The outcome of this exercise is not intended as a direct recommendation, but aims to highlight the potential opportunities for utilizing solar energy at Eide church.

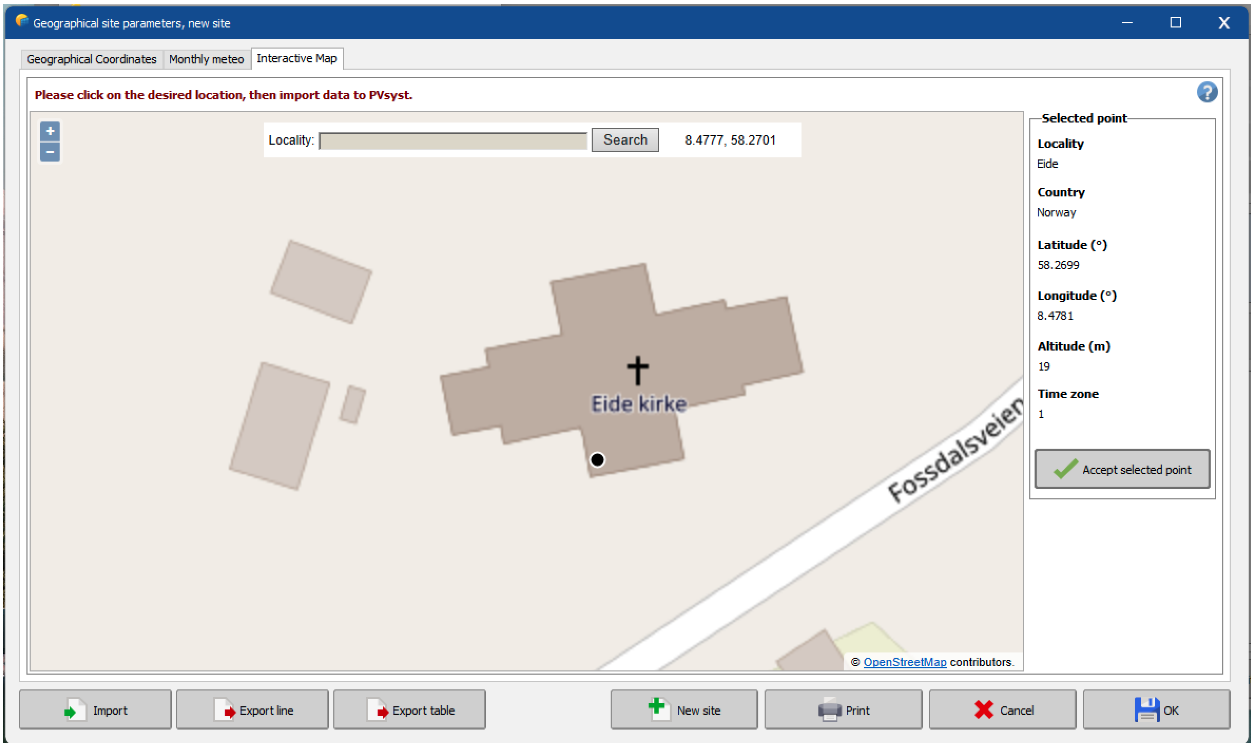
This study presents a detailed analysis of three specific configurations of solar panels. These configurations, referred to as alternatives, are described as follows:

- **Alternative 1:** This configuration includes solar panels mounted on all of the most sun-exposed roofs of the church, in addition to the east-facing roof of the annex and the south-facing roof of the shed.
- **Alternative 2:** This configuration focuses solely on solar panels on the church's most sun-exposed roof surfaces.
- **Alternative 3:** This configuration includes solar panels only on the annex and the shed, thus excluding the main church building.

Each of these alternatives follows the same simulation procedure as further described in the following pages.

In order to calculate and simulate the solar energy potential in Eide church, the software PVsyst has been utilized. More specifically, the trial version of PVsyst 7.3.3. PVsyst is a Swiss made software designed for the study, sizing, simulation, and data analysis of complete PV systems [70]. This includes a detailed database of meteorological data and PV system components like PV modules and inverters. It is widely used by researchers, engineers, and PV system designers to optimize the layout and performance of solar energy installations. It allows users to simulate the energy production of a PV system under different climatic and installation conditions, providing a comprehensive understanding of how a particular system would perform over time.

In this simulation, the project choice "New grid-connected project" was selected in PVsyst. The software then prompts the user to select both the "Site File" and the "Meteo File". The "Site File" was set to the exact location of Eide church, selected from the interactive map in the PVsyst menu, as shown in Figure 3.17. Specifically, the latitude is set to 58.2699°N and longitude to 8.4781°E, at 19 meters above sea level. Based on this location, a synthetic weather file in the Meteonorm 8.1 format was obtained, providing various meteorological data, including temperature and solar irradiance. This weather data is recorded on an hourly basis.



Please click on the desired location, then import data to PVsyst.

Locality:

8.4777, 58.2701

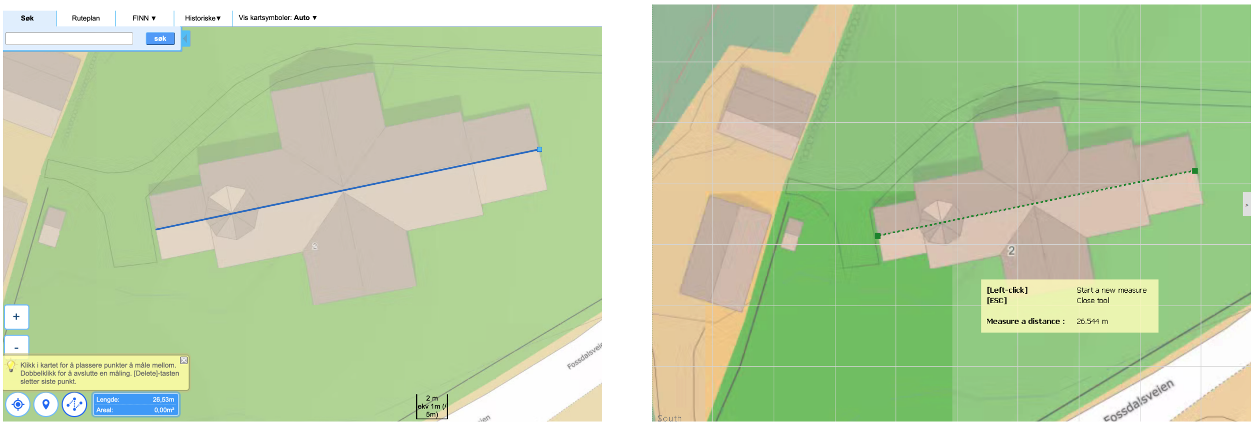
Selected point

Locality: Eide
Country: Norway
Latitude (°): 58.2699
Longitude (°): 8.4781
Altitude (m): 19
Time zone: 1

Figure 3.17: Geographical Parameters of Eide Church in PVsyst

There are two main parameters in the software that must be filled out for any simulation to take place: "Orientation" and "System". However, two optional parameters, "Horizon" and "Near Shadings", were also utilized. The previously selected location allows for the addition of horizon data to enable more detailed simulations. Under the "Horizon profile", the horizon data was imported from "PVGIS Horizon from web, version 5.2", as this is assumed to provide a more accurate result, given the lack of measured horizon data. This model does not take into account nearby buildings or other potential sources of shade. However, it is worth noting that the church is located in a very open area, with few direct obstructions to sunlight.

To better visualize the different alternatives and to more easily determine the available roof area, a 3D model of the church and the two nearby buildings was created under the "Construction / Perspective" menu of the "Near Shadings" parameter. To ensure that the size of the 3D model corresponds to the actual size of the church, a screenshot of a map of the church area was used as a reference. This screenshot was obtained from the map service of finn.no, which was chosen due to the ease of measuring distances with the tool in the service. The lengths and widths of the church were first measured on the map, and the screenshot in PVsyst was measured using PVsyst's measuring function to ensure the same size. Figure 3.18 on the following page shows the measurement of the length of the church in both the map and in PVsyst.



Klikk i kartet for å plassere punkter å måle mellom. Dobbelklikk for å avslutte en måling. [Delete]-tasten sletter siste punkt.

Lengde: 26,53m
Areal: 0,00m²

[Left-click] Start a new measure
[ESC] Close tool

Measure a distance : 26.544 m

(a) Length Measurement in Map (b) Length Measurement in PVsyst

Figure 3.18: Size Matching PVsyst 3D Model to Realistic Size

Once the size ratio in PVsyst was verified to match the real world, a simple 3D model of the buildings was created on top of the outline of the buildings on the map. The primary uncertainty regarding the 3D model lies in the actual height of the model. The height of the church was not measured, but height data from hoydedata.no was used to roughly determine the church's height. Hoydedata.no displays two different heights: ground height and surface height. By subtracting the ground height from the surface height, an approximate height was determined for use in specifying the various heights of the church. These different heights were further assessed using common sense. Incorrect height of the church can have a minor impact on the simulation because an unrealistically high roof will have more hours of sunlight and less shade over the year than a low roof. The angle of the church roof was measured to be 40°, based on a digital protractor over an image of the church in profile, as shown in Figure 3.19. The roofs of the two other buildings were measured to be 30°.

Figure 3.19: Roof Angle Measurement Eide Church

Proceeding in the simulation setup, the type of solar modules have been determined. In PVsyst, 395-watt solar panels from the brand JA Solar have been selected, specifically the JAM72-S09-395 PR type. The solar panel has a stated efficiency of 22.36% based on the cell area of the panel, or 20.06% if the entire module area is considered. The solar panel is made of monocrystalline cells and uses PERC technology. It is assumed that the solar module is a good average of what can be expected from modern solar panels, and it is therefore further assumed that the panel will provide a representative result. The total area of the solar module, 1.971m^2, has been automatically considered when integrating the modules into the 3D model.

In the 3D model, the panels have been placed parallel to the roof angle, and an effort has been made to accommodate as many panels of the given type as possible. It is worth noting that building-integrated photovoltaics (BIPV) could be more area-efficient if laid as, for example, solar roof tiles. In the 3D model, the solar modules have been placed in a total of five different orientations: three on the church building and two on the two other buildings. A complete overview of the angle and azimuth for the different orientations can be found in Table 3.3.

Orientation	**Description**	**Roof Angle / Panel Tilt**	**Azimuth**
Orientation #1	South-facing Church Roofs	40°	-11,5°
Orientation #2	East-facing Church Roof	40°	-101,5°
Orientation #3	West-facing Church Roof	40°	78,5°
Orientation #4	East-facing Annex Roof	30°	-73.9°
Orientation #5	South-facing Shed Roof	30°	20,9°

Table 3.3: PV Module Orientations in PVsyst

After the solar modules have been placed in the 3D model, the "Orientation" and "System" tabs have been updated to match the given parameters. In the "System" tab, one inverter per orientation has been selected. The inverters have been selected so that their rated power matches the combined peak output power under standard test conditions (STC) for the different orientations. If the peak output power from the solar modules falls between two inverter sizes, the smaller inverter has been selected. Table 3.4 shows the number of solar modules in the different orientations, area, output power, and the chosen inverter size.

Orientation	**Number of PV Modules**	**Area of PV Modules (m^2)**	**Output Power (kWp)**	**Inverter Size (kW)**
Orientation #1	32	63	12,6	10
Orientation #2	8	16	3,2	3
Orientation #3	8	16	3,2	3
Orientation #4	12	24	4,7	4,2
Orientation #5	6	12	2,4	3

Table 3.4: PV System Sizing for Different Orientations

Before the simulation could start, a "Shading Factor Table" had to be generated in the "Near Shadings" tab. Three different simulations have been run, one simulation per alternative. In addition to PDFs with all simulation results, a CSV file per simulation has been generated. This CSV file contains hourly values of energy production throughout a whole year. It is possible in PVsyst to have this CSV file contain all sorts of data, but it is only the value "E_grid" that is included here. Since no load is defined in the system, "E_Grid" will solely show the energy production. These CSV files have been imported into Python for further analysis and plotting.

The hourly energy production data from the various PV alternatives have then been evaluated against the church's hourly energy consumption. Consumption data from the year 2021 was used as the basis for this evaluation as it was found to be very similar to the temperature-corrected annual consumption. Thus, it can be said that the annual consumption in 2021 closely represents a "normal" year of consumption.

The analysis of the church's energy use and production focuses on understanding two main aspects: firstly, the proportion of the energy consumed by the church that comes from the PV system versus how much needs to be purchased from the grid; and secondly, how much of the energy produced by the PV system is consumed on-site by the church versus how much is sold to the grid. These are aspects that greatly influence the economy of such a PV system, and will be further described later in this chapter.

The energy sold to the grid in any given hour (E_{sold}) is calculated when the energy production from the PV system exceeds the energy consumption of the church. This is represented by the following equation:

$$E_{\text{sold}} = E_{\text{produced}} - E_{\text{consumed}} \quad \text{if } E_{\text{produced}} > E_{\text{consumed}} \tag{3.5}$$

Where E_{produced} is the amount of energy produced by the PV system in a given hour, and E_{consumed} is the amount of energy consumed by the church in that same hour.

The energy purchased from the grid in any given hour ($E_{\text{purchased}}$) is calculated when the church's energy consumption is greater than the energy production from the PV system. This is represented by the following equation:

$$E_{\text{purchased}} = E_{\text{consumed}} - E_{\text{produced}} \quad \text{if } E_{\text{consumed}} > E_{\text{produced}} \tag{3.6}$$

Where E_{consumed} is the amount of energy consumed by the church in a given hour, and E_{produced} is the amount of energy produced by the solar PV system in that hour.

These hourly values are then summed up over the course of an entire year to provide a comprehensive understanding of the church's annual energy consumption and production balance.

In most instances, it is economically favorable to consume the energy produced by the PV system directly within the building, rather than selling it to the grid [82]. Given that the typical energy production of a PV system tends to be inversely proportional to the typical energy consumption, (often referred to as a duck curve [87]) it is interesting to examine how the introduction of an energy storage system, specifically a battery, could affect the energy balance. More precisely, how much larger a share of the produced energy could be directly utilized in the building, rather than being sold, with the implementation of a battery? Additionally, how does this change the energy mix?

In light of this, a fourth solar energy configuration, hereafter referred to as "Alternative 1 w/ Battery", will be presented. The solar energy production will be identical to that of Alternative 1, comprising solar panels on all of the most sun-exposed church roofs, in addition to the roofs of the annex and shed. The same energy production file and the same energy consumption data from 2021 have been imported into Python. However, in this new alternative, a battery with an energy storage capacity of 100 kWh has been incorporated.

This battery size was selected based on its typical physical dimensions, a typical battery size found in several larger electric vehicles. Imagining such a repurposed EV battery, it would likely be flat enough, and with a small enough footprint, to potentially be buried just below the ground. This setup could also potentially reduce fire hazards by not storing the battery inside the church.

Technical solutions for the integration of the battery into the PV system have not been considered in this exercise. Neither degradation of the battery nor the battery's maximum depth of discharge (DoD) have been accounted for. It is therefore assumed that the battery could repeatedly deliver its full capacity of 100 kWh.

Various algorithms exist for charging and discharging such a battery, some aiming to optimize self-consumption, others to maximize lifespan. Some algorithms may also use day-ahead electricity prices to further optimize charging and discharging [1]. However, the battery logic used in this exercise is straightforward, with the sole goal of maximizing on-site consumption of energy produced by the PV system, thereby minimizing sales to the grid. The flowchart shown in Figure 3.20 on the following page illustrates how the battery behaves in different scenarios.

In Python, this is achieved by comparing the energy production from the PV system with the energy consumption in the church for each hour. The production, consumption, and available energy in the battery for each hour are each represented in a column in a dataframe. Two additional columns indicate energy sold and purchased to and from the grid. If the energy production in a given hour exceeds the energy consumption, the excess energy is stored in the battery until the battery is fully charged (100 kWh). Once the battery is fully charged, any surplus energy must be sold to the grid. When energy consumption exceeds energy production, the system draws energy from the battery to cover the difference until the battery is depleted (0 kWh). Beyond this point, energy is purchased from the grid. The battery state of charge data in the battery column of the dataframe is later used as the basis for plotting the battery's state of charge throughout the year. In the simulation the battery has an initial state of charge of 0%.

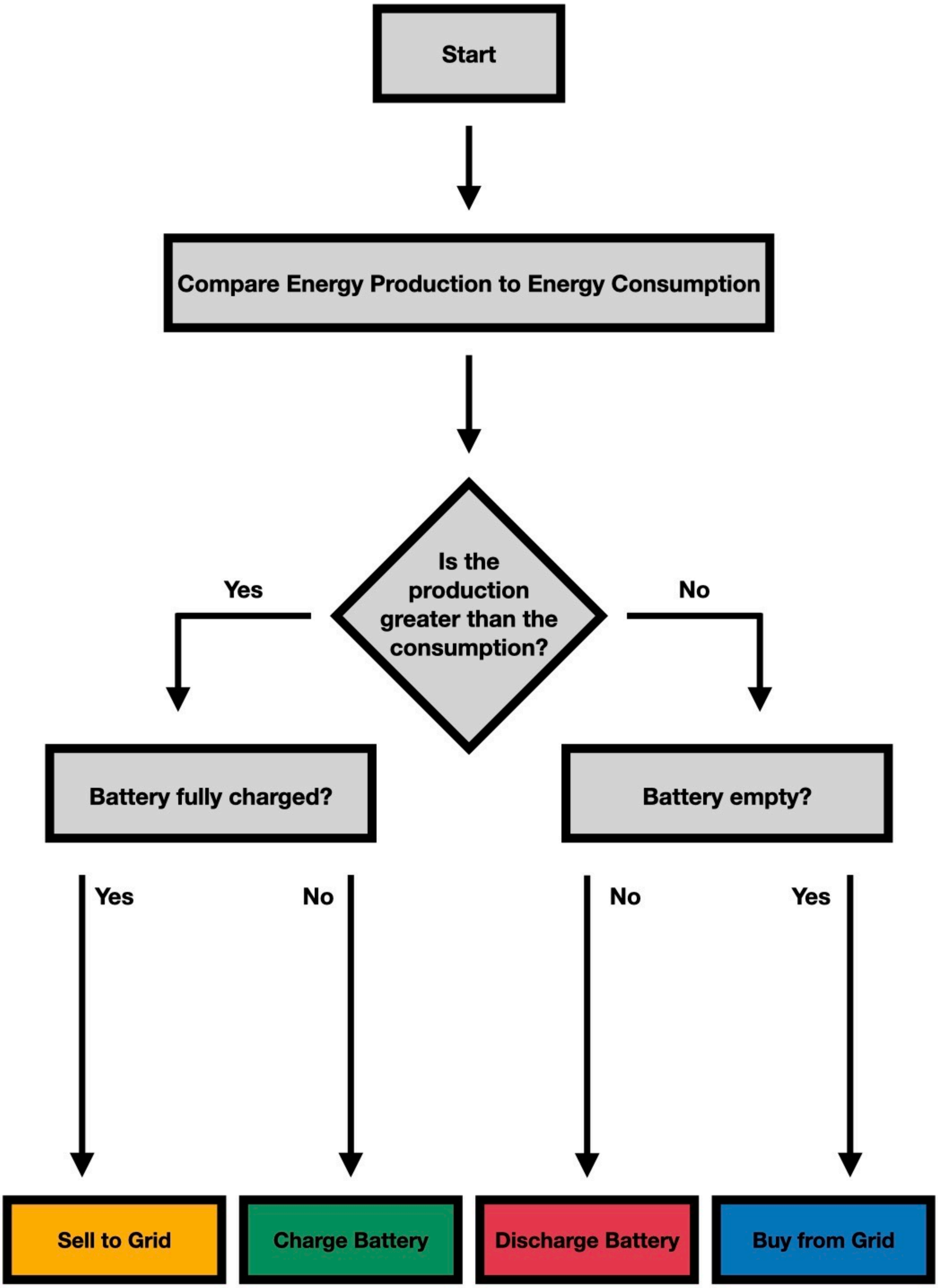


Figure 3.20: Flowchart of Battery Charging and Discharging Logic

3.5 SIMIEN Simulations

Energy efficiency in buildings often starts with considering upgrades to the building envelope. Simulating various energy efficiency measures, such as enhancing insulation, window replacement, or lowering temperature settings, provides a practical approach to assess the impact of these modifications. This concept is central to the use of the energy calculation software Simien in this master's thesis, which focuses on Landvik church. The software provides the means to simulate how different measures can affect the annual energy consumption, and to identify the strategies offering the most substantial savings.

Simien, developed by Programbyggerene, is a versatile tool for energy efficiency simulations in buildings. Its detailed modelling capabilities allow for a comprehensive understanding of a building's energy performance under a variety of conditions. To yield an in-depth view of the church's indoor climate and relative humidity, every room in the church is modelled individually in Simien. This approach aligns with the software's user guide recommendation for obtaining optimal results [80].

The creation of the model of Landvik church in Simien requires four essential parameters: the area and volume of the various rooms/zones and their building components, the U-values of different building parts of the rooms/zones, the installed heating power for each room, and the operational schedule, which includes the standby and operating temperatures. The climate location in Simien was set to Kristiandsand (Kjevik), as this is the option closest to Grimstad.

The task of measuring all distances within the church was performed using a Bosch PLR 50 C laser distance meter. This device has a measuring range from 0.05 to 50 meters, with an accuracy of ± 2.0 millimeters. In addition to measuring the lengths and widths of the various rooms and zones within the church, ceiling heights were also measured to calculate volume. Given that most of the church's ceilings are not flat, calculating ceiling area and room volume presented a tedious challenge. To address this, a basic 3D model of the church's rooms was created using the 3D design software Sketchup. Sketchup's feature that easily displays the area or volume of a surface or space was utilised, simplifying the measurement process while maintaining high precision. The thickness of the walls, along with the areas of windows and doors, was measured using a conventional tape measure.

The next step in the model involves defining the thermal transmittance, also known as the U-value, for each building component. Different approaches have been utilized to determine these values. For structures such as the annex, the northern sacristy, and the handicap toilet, which were constructed around 1999/2000, it's presumed that the minimum requirements outlined in TEK97 were adhered to. This assumption has been validated through visual inspections to ensure its plausibility. However, it's important to note that documentation detailing the construction process of these building extensions is not readily available, making it challenging to estimate the U-values accurately. For instance, it's uncertain whether the concrete base under the handicap toilet is insulated, and if so, to what extent. Consequently, only the minimum values outlined in TEK97, the building regulations applicable when these extensions were constructed, have been considered.

Other building elements, such as the church's outer walls, are reported to be uninsulated. Thus, their U-values are based on the thickness and material of the walls. Visual inspection of the floor indicates that it's not insulated but comprises numerous layers, up to seven in some areas. The naves roof has been visually inspected, and it's assumed to be insulated with 10-15 cm of mineral wool with paper. Other U-values employed in the simulation are based on visual inspection, thickness, and/or available information about insulation levels.

They have been determined in consultation with this thesis' main supervisor. All U-values used in the simulations for various building parts in different rooms are specified in Table 3.5.

Room/Zone	**Building Element**	**U-value**	**Area (m^2)**
Nave	Floor	0,5	276,9
	Ceiling	0,3	304,1
	Walls (N, E, S, W)	0,68	397,1
	Windows	2,8	28,3
Northern Sacristy	Floor	0,4	17,6
	Roof/Ceiling	0,2	24,6
	Walls (N , E, W)	0,28	34,3
	Windows	1,36	4,4
	Door	1,9	3
Eastern Sacristy	Floor	0,2	20,7
	Ceiling	0,3	20,3
	Walls (N, E, S)	0,68	30,2
	Windows	3	3,1
	Door	2,4	1,7
Southern Entrance	Floor	0,5	7
	Roof/Ceiling	0,7	11
	Walls (E, S, W)	0,68	22,3
	Window	4,7	0,6
	Door	2	2,8
Narthex	Floor	0,5	26,5
	Roof/Ceiling	0,7	40,6
	Walls (N, S, W)	0,68	49,1
	Windows	3	1,2
	Door	2,4	2,8
Handicap Toilet	Floor	0,33	7,1
	Ceiling	0,2	8,2
	Walls (N, W)	0,28	12,4
	Windows	1,36	0,6
	Door	1,9	1,9
Basement / Toilet	Floor	0,5	20,7
	Walls (E)	0,5	9,6
	Door	2,4	0,9
Annex	Floor	0,4	53,4
	Ceiling/Roof	0,2	69,6
	Walls (N, E, S, W)	0,28	59
	Windows	2	8,2
	Doors	2	1,9

Table 3.5: U-values for SIMIEN Simulations

The installed heating capacity in various rooms has been primarily determined through visual inspection, such as reading rating plates and counting the number of heat sources. In cases where a heat source did not have a rating plate indicating its power, the manufacturer's website and data sheets were consulted. For instance, the bench heaters lacked a rating plate, but the manufacturer's logo was clearly imprinted, allowing the power to be determined through the manufacturer's resources.

There is some uncertainty regarding the actual installed power in three instances: in the southern vestibule, two heating panels are installed on the northern and southern walls at about 2 meters height. It's unclear whether these panels have a power of 550 or 600 watts. However, for the purpose of the simulation, a power of 550 watts has been assumed. This minor difference is likely to have an insignificant impact on the results. Furthermore, there's uncertainty regarding the underfloor heating in the handicap toilet and the entrance area of the annex. It's not clear how many meters of underfloor heating were installed and at what power per meter. It's assumed that 80 W/m^2 have been installed.

The installed heating power in the various rooms and zones is clearly presented in Table 3.6.

Room/Zone	**Heat Source**	**Power (W)**	**Number**	**Capacity (W)**	**Rest/Operation (°C)**
Nave	Beanch Heater	250	84	21 000	10/19
	IR Heating Panels	1300	2	2 600	
	Finned tube heater	775	3	2 325	
	Tube heater	1000	1	1 000	
	Tube heater	1500	3	4 500	
	Total			31 425	
Northern Sacristy	Heating Panel	1700	2	3 400	10/19
Eastern Sacristy	Panel Oven	750	2	1 500	10/19
Southern Entrance	Heating Panel	550	2	1 100	17/17
Narthex	Heating Panel	1700	2	3 400	10/19
Handicap Toilet	Underfloor Heating	569	-	569	15/15
Basement / Toilet	Panel Oven	500	3	1 500	15/15
Annex	Panel Oven	4	750	3 000	10/19
	Underfloor Heating	1220	-	1 220	
	Total			4 220	
Total				**47 114**	

Table 3.6: Heating Capacity in Landvik Church

Another crucial aspect of the simulation is the set temperature during operational hours and resting hours in the church, as well as the number of days and hours of operation. The temperature during non-operational hours, or resting temperature, is set to 10°C, while the operating temperature is set to 19°C. These settings have been validated through control measurements. Some rooms maintain a constant temperature. The resting and operating temperatures for each room are provided in Table 3.6 on the previous page.

Table 3.7 outlines various activities and the number of these activities for the year 2022. As shown, there are a total of 134 activities, each assumed to last an average of 3 hours, during which the church must maintain its operating temperature. This data was obtained from the church's logbook via the janitor of the church.

Activity	**Number**	**Number per Month**	**Average Duration**	**Total Hours**
Religious Services	46	3,8	3	138
Funerals	13	1,1	3	39
Wedding Ceremonies	12	1,0	3	36
Choir Activities	41	3,4	3	123
Confirmation Classes	22	1,8	3	66
Total	**134**	**11,2**	**3**	**402**

Table 3.7: Types and Numbers of Activities in Landvik 2022

The distribution of activities throughout the year is not provided, only the total count. Based on typical seasonal events in the Norwegian churches, an estimated distribution of these activities is presented in Table 3.8. For example, it is reasonable to assume that more church activities occur in the lead-up to Christmas, Easter, and typical confirmation periods than during the summer holidays.

Month	**Assumed Number of Activities**	**Justification of Activity Number**
January	11	
February	11	
March	16	Easter
April	12	
May	14	Confirmations
June	8	
July	1	Summer Holidays
August	7	
September	12	
Ocotber	12	
November	14	Advent
December	16	Advent and Christmas
Total	**134**	

Table 3.8: Assumed Monthly Distribution of Activities in Landvik 2022

Another variable influencing the church's energy consumption is the duration of the heating periods. That is, the time it takes to heat the church to its operating temperature before an activity. In reality, these times are manually set by the janitor and are temperature-dependent. For example, heating will start earlier when the outdoor temperature is -20°C than when it is +5°C. In the simulation, the heating time is set to 11.5 hours, meaning heating starts at 00:30 and ends at 12:00.

In addition to the above parameters, other factors were included in the Simien model, such as "thermal storage in the interior layer" of walls, floors and ceilings. The closest match to reality from the dropdown menu in the software was chosen. For instance, "Massive wood (thickness over 40mm)" was chosen for the timber walls as it was the closest match. The building's facade orientation was also specified to match reality. Orientations are rounded to the nearest whole 90°. For example, even if a facade doesn't face exactly north, it's set to do so in the model. Internal loads, i.e., equipment that consumes energy for purposes other than direct heating, were included: light output for each room, hot water, and other technical equipment were based on visual inspection of the number and type of equipment, along with reading rating plates.

The final parameter with significant influence on the annual energy consumption is associated with the infiltration in various rooms, specified in Simien as "Leakage number (N50) [1/h]", or "number of air changes at a pressure difference of 50 Pa across the climate screen". This parameter carries the most uncertainty, but it's set to be 5.00 in all church rooms and 4.00 in the annex in consultation with the thesis' supervisor.

After completing the model, various simulations were run: annual simulation, winter simulation, and summer simulation. When simulating the effect of different energy-saving measures, the measure was implemented in the model, and the simulations were rerun. The results were then compared with the original results. For instance, to determine the effect of insulating the floor, the U-value of the relevant floor was adjusted to match the minimum requirements of TEK17, the latest available building regulation, and the simulation was rerun. The difference between the new and old annual energy consumption thus represents the annual savings for the measure. Many different measures were considered to explore various alternatives.

A comprehensive table containing various information specific to the simulation can be found in Appendix D.

3.6 Ground Source Heat Pump Calculations

Given the significant consumption of biofuel oil in Grimstad church, and considering that the church already have a hydronic heating system in place, it is interesting to explore alternative and more efficient heat sources. A hydronic heating system is flexible in terms of heat sources. However, due to the size of the church, this study only considers a liquid-to-water heat pump with energy wells as the heat source. This choice is based on the good results from a similar project in Risør church, previously described in Chapter 2.1.3.

It is further assumed that the heat pump will not replace the existing oil furnace but instead will be designed to function as a base load, with the oil furnace handling peak loads on the coldest days. This not only ensures a lower investment cost as the heat pump can be designed for lower power requirements, but also ensures redundancy in the heat supply. This provides a backup in case one of the heat sources ceases to function or needs service or repairs.

To make better assessments of the dimensioning of the heat pump, it is useful to examine what proportion of the annual energy consumption could be covered by a base load of X% of the total heat power requirement. For instance, in a building with a total installed heating capacity of 100 kW, how much of the annual energy consumption could be covered by a base load of 50 kW, i.e., 50% of the maximum power demand. There are no exact figures related to power and heating energy needs in Grimstad church, so data from Landvik church is used as a basis. It is assumed that these two churches have a relatively similar usage pattern in a very similar climate, and that data from Landvik, therefore, will be the best available basis for use in Grimstad.

Energy consumption data from Landvik church for the year 2021 has been analyzed to understand the power demand over time. This data, consisting of hourly energy consumption values, was arranged in descending order, revealing the highest to lowest energy usage throughout the year.

Next, a duration curve was plotted from this data. In this context, a duration curve visualizes the descending power demand over the course of a year. It helps in determining the number of hours in a year when the power demand exceeds a certain percentage of the total installed heating capacity.

By reviewing the duration curve, one can gain a clear understanding of the proportion of the total energy consumption that a base load can cover, given a certain percentage of the total heating power demand. This method provides a way to visualize how effectively a base load can cover the annual energy consumption and how often the peak load capacity would need to be used.

Based on this analysis, it is possible to determine the optimal relative size of the heat pump, i.e., the size of the heat pump as a percentage of the total heat power demand.

Next, the energy consumption of Grimstad church was estimated, but there is a degree of uncertainty as it was difficult to determine the exact annual consumption and maximum power output from the system. Table 3.9 shows the recorded amount of purchased biofuel. However, as the biofuel oil was introduced in 2020, it's challenging to establish the exact annual consumption. For instance, of the 17 298 liters purchased in 2022, 4 529 liters were purchased in December, meaning that some of the purchased fuel were not used until 2023. Therefore, for the purposes of this study, an annual consumption of 15 000 liters worth of biofuel oil is assumed.

Month and Year	**Volume of Biofuel Oil Purchased (Liters)**
November 2020	4 500
January 2021	1 089
February 2021	4 904
May 2021	3 000
November 2021	4 737
Total 2021	**13 730**
January 2022	4 898
Mars 2022	2 652
August 2022	5 219
December 2022	4 529
Total 2022	**17 298**

Table 3.9: Volume of Biofuel Oil Purchased

The conversion of energy content from megajoules per kilogram (MJ/kg) to kilowatt-hours per kilogram (kWh/kg) is essential for this study. The equivalence of 1 MJ to 0.277778 kWh is utilized for this conversion. Thus, the energy content of the bio fuel oil, containing approximately 37.1 MJ/kg [47], is obtained in terms of kWh/kg using the formula:

$$37.1\,\mathrm{MJ/kg} \times 0.277778\,\mathrm{kWh/MJ} = 10.3\,\mathrm{kWh/kg} \tag{3.7}$$

Considering the known density of the fuel, the energy per volume (kWh/L) can also be found. This is achieved by multiplying the energy per mass unit (kWh/kg) with the density (kg/L).

$$10.3\,\mathrm{kWh/kg} \times 0.883\,\mathrm{kg/L} = 9.09\,\mathrm{kWh/L} \tag{3.8}$$

Therefore, the fuel has an energy density of approximately 9.09 kilowatt-hours per liter (kWh/L).

When the system operates at maximum power, an efficiency of 90% is assumed, and an efficiency of 80% is considered for the entire year.

The nominal power of the boiler implies a power of 160 kW. However, Newton's law of cooling (as shown in Equation 3.9) has been used to demonstrate that this probably do not correspond with the actual, delivered power.

$$Q = hA(T_s - T_a) \tag{3.9}$$

where:

- Q is the heat transfer,
- h is the heat transfer coefficient,
- A is the surface area,
- T_s is the surface temperature,
- T_a is the ambient temperature.

Furthermore, it has been assumed that a better approach to find the maximum fuel consumption per day is by dividing the annual consumption by 200. A heating time of 12 hours has been assumed to find the maximum average consumption per hour.

For the heat pump, a Coefficient of Performance (COP) factor of 3.5 and a Seasonal Coefficient of Performance (SCOP) factor of 4 have been used [27]. An extraction rate of 50 W/m, the average of the expected 20-80 W/m [97], was assumed for the energy wells in the calculations.

The calculations presented in the results chapter are done step by step, making it easier to see the underlying assumptions without having to refer back to this chapter.

3.7 Economic Calculations

In order to evaluate the profitability of an energy-saving measure, the energy prices are a crucial factor. For some of the economic calculations in the results chapter, the energy prices of the different churches were used. These are shown in Table 3.10 and are exclusive of VAT. These figures were provided by Grimstad church council and represent the actual energy prices experienced in 2022.

Church	**Electricity Price 2022 (NOK/kWh)**	**Bio Fuel Oil Price 2022 (NOK/L)**
Eide	2,1919	-
Landvik	1,9854	-
Grimstad	1,7204	17,47

Table 3.10: Energy Prices for Different Churches in 2022

It is important to note that energy prices can change suddenly and are dependent on a multitude of factors.

In the calculation of the profitability of the PV system at Eide Church, it was assumed that the generated electricity could be sold at 70% of the average annual electricity price. This is based on the fact that most of the electricity sales will take place during the day when electricity prices are generally lower than the daily average[87]. This is possibly a somewhat unfortunate simplification, but due to the very costly data sets from Nordpool, such assumptions unfortunately had to be made.

In the part of the results chapter about the PV system at Eide, the Return on Investment (ROI) is mentioned. This is calculated using the formula:

$$ROI = \frac{Net\ Profit}{Cost\ of\ Investment} \times 100 \tag{3.10}$$

The investment costs associated with the PV system include all costs related to installation as well as any maintenance, which are incorporated into this price.

Further explanations of economic calculations can be found in association with the results.

Extensive economic aspects for the three different PV alternatives can be found in Appendix A, B and C.

Chapter 4

Results

In this chapter, the results of the conducted measurements, simulations, and calculations will be presented. The chapter is structured in such a way that the results from Eide, Landvik, and Grimstad churches will be presented sequentially. Results from temperature and humidity measurements, as well as energy consumption, will be addressed first, followed by results from the PV system, the Simien simulation, and the heat pump dimensioning. The intention of this chapter is to present the findings in a clear and objective manner before these findings are further discussed and evaluated in the discussion chapter.

4.1 Eide Church

4.1.1 Temperature and Humidity

As mentioned in Chapter 3.3, a total of 10 temperature and humidity loggers have been placed in the churches to verify the stated resting and operating temperatures, as well as to examine the relative humidity. Figure 4.2 on the next page shows the placement of the various loggers in Eide church, while Figure 4.1 presents the measured temperatures during the measurement period. The blue boxes marked with a number inside in Figure 4.2 correspond to "Logger 1" through "Logger 10" in the legend of Figure 4.1. The blue boxes indicate where the logger was placed in the church, with loggers hidden under grey areas suggesting that the logger is located underneath a gallery.

Measurements in Eide church started around 12:00 on March 10, 2023, and ended approximately four days later, on March 14, 2023. During the measurement period, the church was heated to operating temperature once, for a church service on Sunday, March 12, starting at 11:00. This service hosted slightly more visitors than usual, as there was a baptism in conjunction with the service.

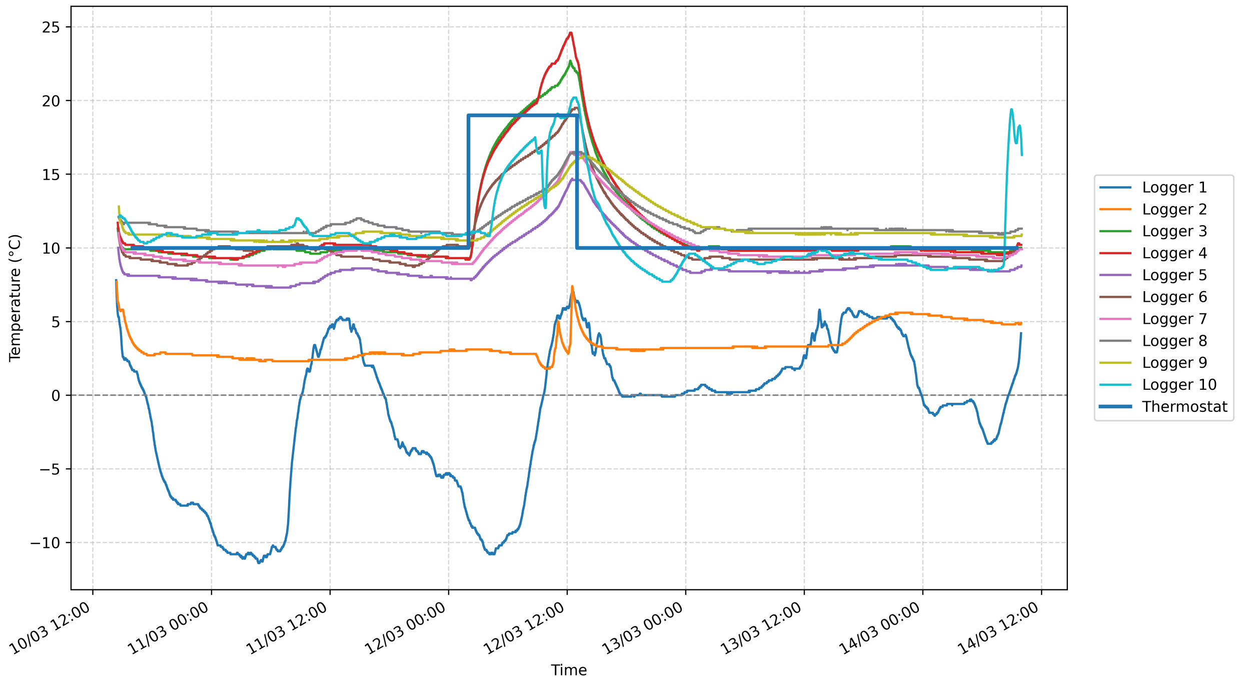


Figure 4.1: Measured Temperature during Heating in Eide

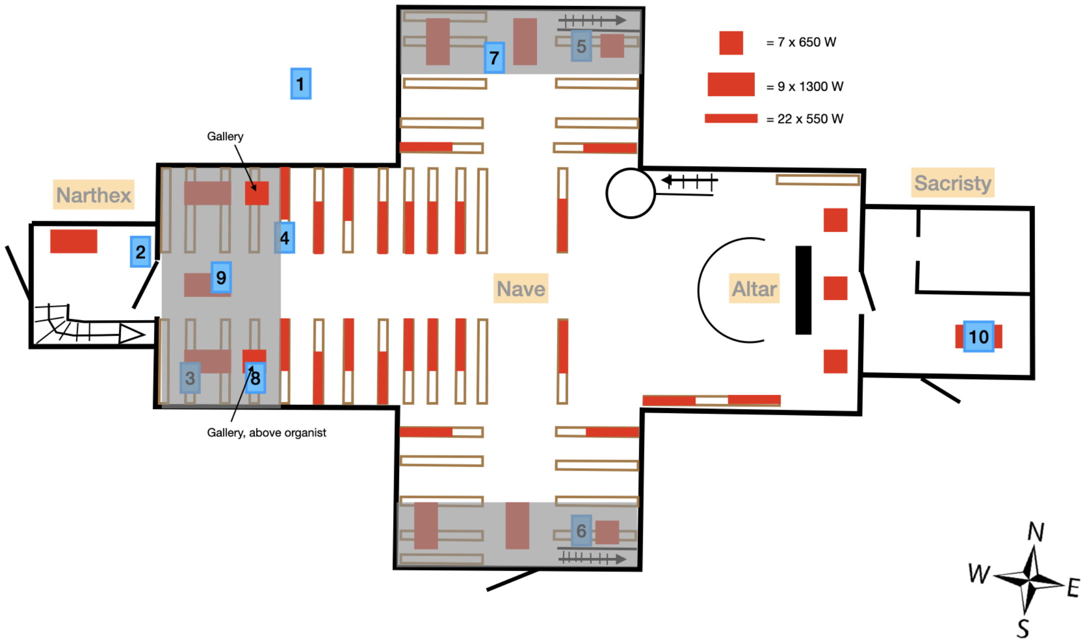


Figure 4.2: Temperature/Humidity Logger Placement Eide

The outdoor temperature during the measurement period, represented by Logger 1, shows a varying temperature between +5°C and -10°C. The "Thermostat" graph among the measurements indicates the desired temperature in the church at different times. Just after midnight before the church service, the heat is increased from 10°C to achieving an operating temperature of 19°C. The heat is then reduced towards the end of the service at around 12:30. The temperature in the narthex, represented by Logger 2, shows a significantly lower temperature than the rest of the church, only a few degrees at its coldest.

The remaining measurements, represented by Logger 3 to 10, show a relatively stable resting temperature around 10°C. During the heating period, it is evident that there are greater variations, and Loggers 3 and 4, in particular, show very rapid heating, reaching a temperature well above the desired level, up to 25°C. This is likely due to the placement of these loggers under the western gallery, where they experience heat contributions from both the bench heaters and the ceiling-mounted panels.

Logger 5 and 7 show the opposite trend, with a significantly longer heating period, and they do not reach the desired temperature. It is worth noting that the ceiling-mounted heating panels under the northern sacristy were likely out of operation this day. Similarly, the heating panel in the narthex or the heating panel above the organist was probably not turned on. Temperature measurements of these surfaces show that the panels were cold, which should be looked into to ensure a more even temperature in the church.

Logger 10 appears to have a sudden dip during the heating period; it is uncertain what caused this, but since it was placed close to the sacristy entrance door, this is likely the cause. Logger 6, marked in brown and placed underneath the southern gallery, seems to achieve the exact desired temperature. Logger 9, located inside the organ, reaches a temperature just above 15°C. A common feature for all temperature loggers on this relatively cold winter day is that the average temperature inside the church does not reach the operating temperature by the time the service starts at 11:00. On the other hand, the majority of the congregation sat near the western sacristy, which quickly maintained a comfortable temperature. The author, who was present at the service near Logger 4, can report a pleasant temperature throughout the session.

Figure 4.3 shows the energy consumption during the heating period. These values are hourly, unlike the temperatures which are measured at every minute. The energy consumption correlates very well with the outdoor temperature, and naturally also with the desired indoor temperature. The highest hourly value of the energy consumption appears to reach about 19 kWh/h, significantly lower than the total installed power of 28.4 kW, despite at least five of the heating panels (5.2 kW) being out of operation that day.

Figure 4.4 shows the relative humidity in the church during the measurement period. Measurements of relative humidity were made parallel to the temperature measurements. The relative humidity varies somewhat depending on where in the church the measurement is obtained, but appears to remain relatively stable between 40 and 50%, in the lower end of the recommended levels. The relative humidity in the narthex is somewhat higher, which makes sense given that the temperature is significantly lower there. As expected, the relative humidity drops slightly as the temperature in the church increases.

During the church service, the humidity seems to make a slight jump of a few percentage points. This can likely be explained by the gathering of more people in the church, contributing to increased humidity. The humidity appears to rise to between 50 and 60% after the heating period. This is probably due to an increase in outdoor humidity (rain), represented by Logger 1.

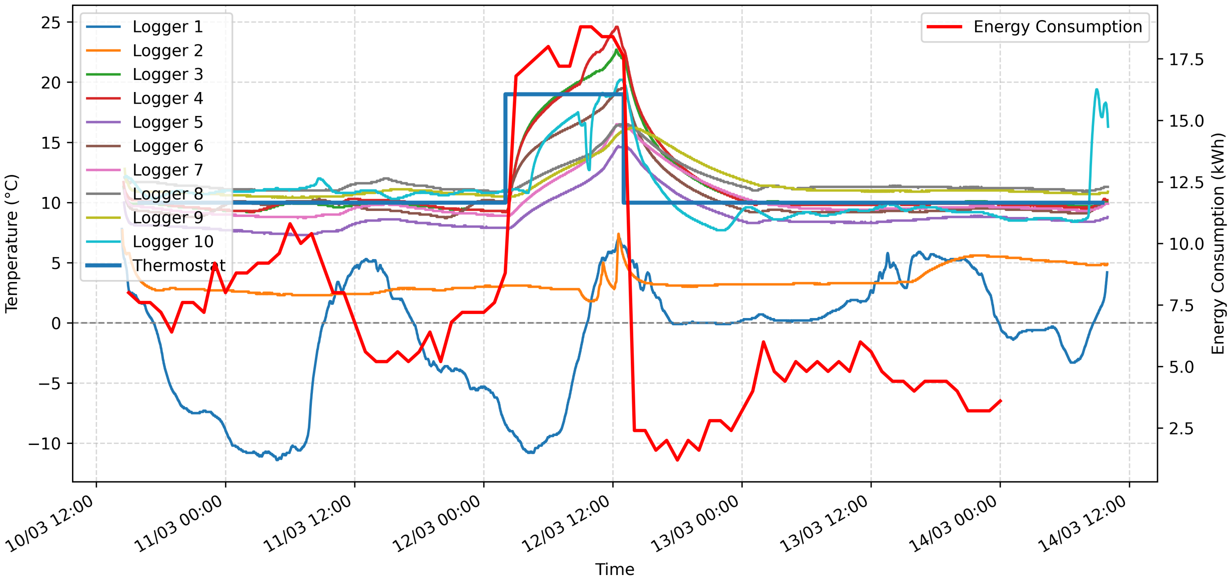


Figure 4.3: Energy Consumption during Heating in Eide

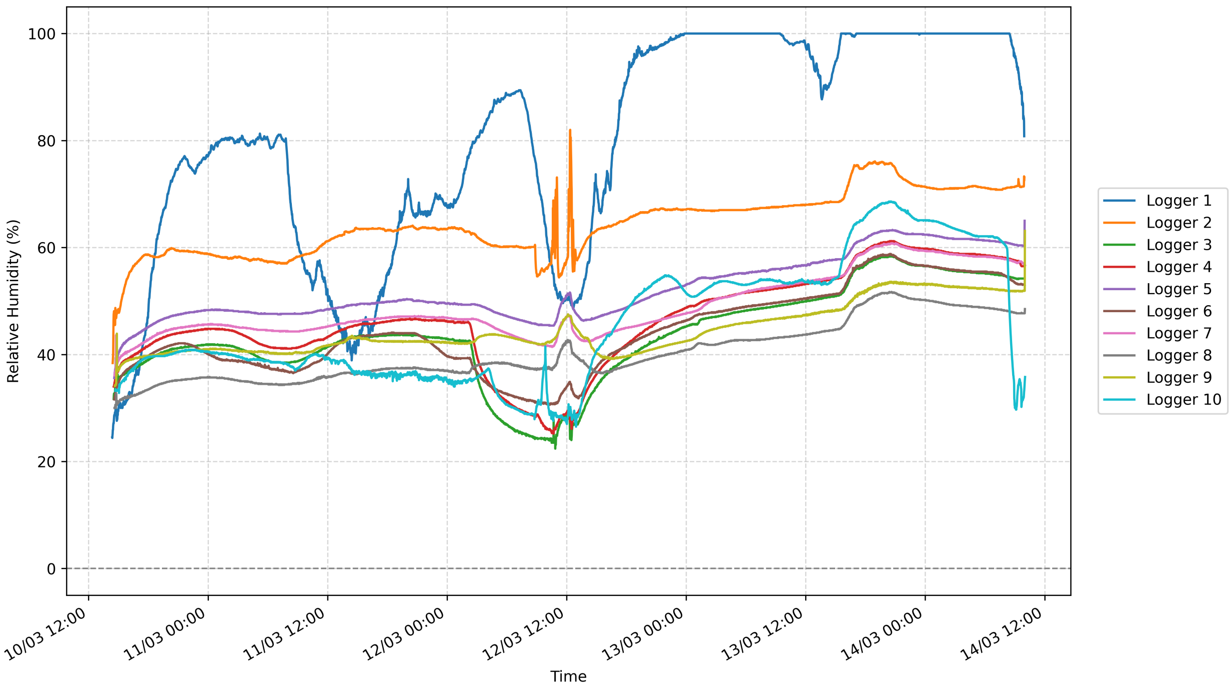


Figure 4.4: Measured Relative Humidity during Heating in Eide

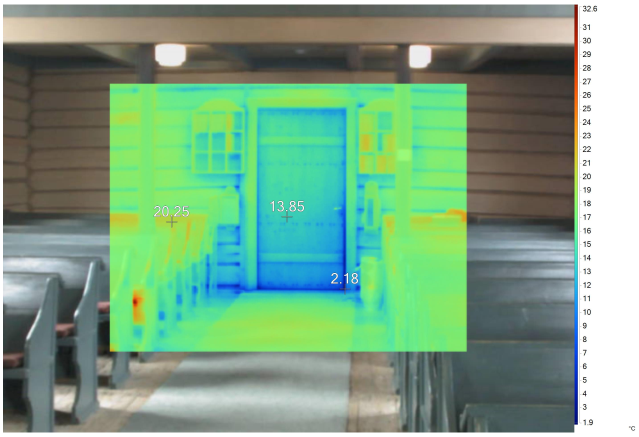
Further on, measurements of surface temperatures in the church were carried out, both with a thermal imaging camera and a handheld laser thermometer.

Figure 4.5 shows images taken with the thermal imaging camera. Figure 4.5a presents the door under the eastern gallery towards the narthex, and it is evident that there are significant temperature differences on and around the door. While the top of the benches maintain a temperature of around 20°C, it is barely above 2°C at the bottom of the door frame.

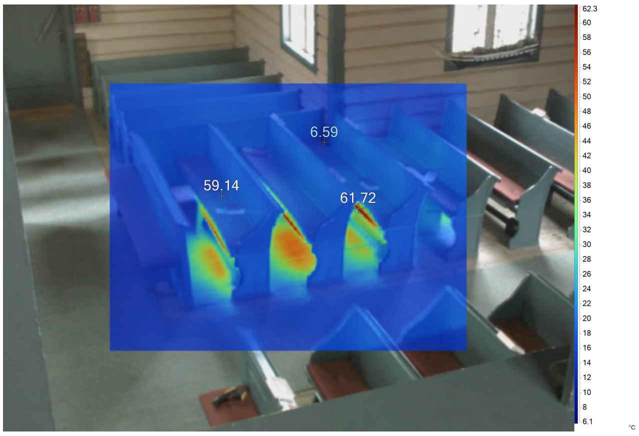
Figure 4.5b displays the heat distribution from the bench heaters. The heat is highly concentrated: on the floor right around the bench, it is around 60°C, while it is only slightly above 6°C on the wall right next to it.

Figure 4.5c further highlights this phenomenon, where it is significantly colder in the joint of the walls than in the middle of the wall. There appears to be a rather substantial heat loss effect right where the logs intersects.

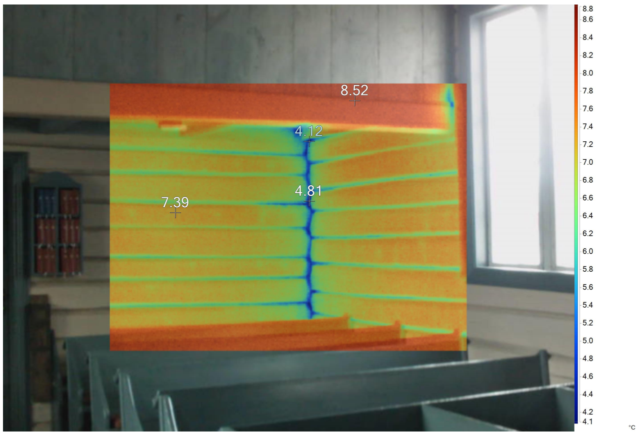
The ceiling-mounted heating panels were measured to have a surface temperature between 130°C and 162°C. The highest temperature was measured on one of the heating panels behind the altar. The surface temperature of the bench heaters was measured to be between 115°C and 120°C, with the highest measurement at 123°C. This is a number worth noting and will be discussed in more detail later.



(a) Heat Loss Around Door Frame



(b) Heat Distribution from Pew Heaters



(c) Heat Loss in Corner of Logged Walls

Figure 4.5: Thermal Imaging of Eide

4.1.2 Historical Energy Consumption

Figure 4.6 shows actual and temperature-corrected yearly energy usage from 2010 to 2022 in Eide. The green dashed line symbolizes the annual average temperature at Landvik weather station. The figure illustrates a significant energy consumption drop from in the period 2010-2012, mainly due to a electricity meter restructuring, where a local wastewater system got its own meter. Consumption steadily decreased from 2014, the heating system replacement year, until 2020. The substantial 2020 reduction is probably tied to the COVID-19 pandemic lockdown [72]. The actual energy consumption in 2021 mirrors the temperature-corrected consumption for that year.

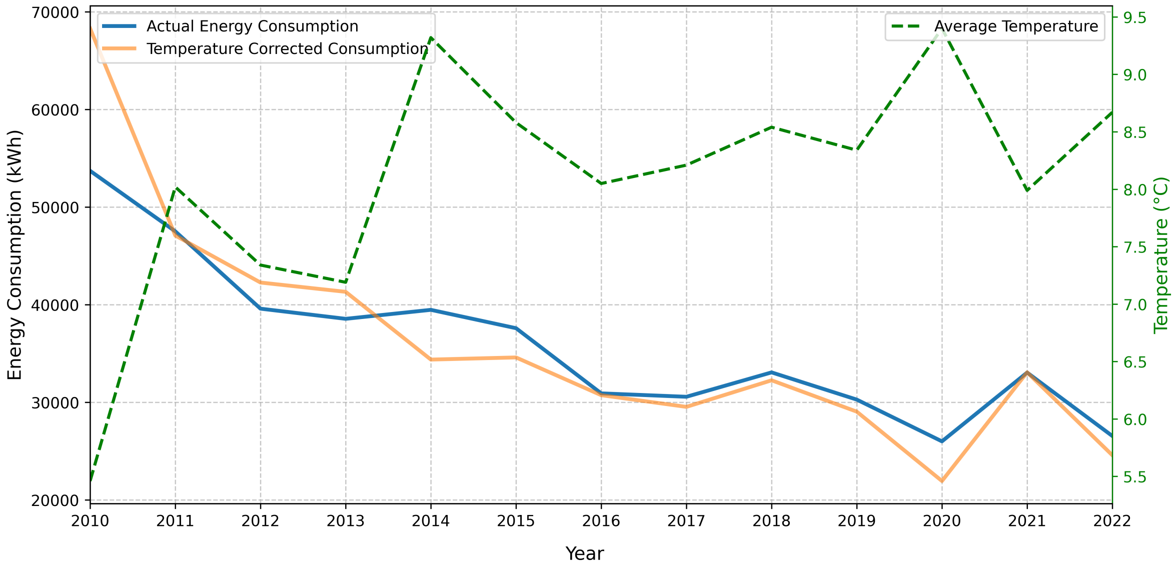


Figure 4.6: Temperature Correction of Energy Consumption Eide 2010-2022

Figure 4.7 shows the temperature-corrected annual energy consumption in Eide from 2016 to 2022. The average of these seven years is marked with the red dashed line. Energy consumption during these years has typically been around 30 000 kWh per year. There is a relatively large decrease in consumption from 2021 to 2022, which cannot be easily explained.

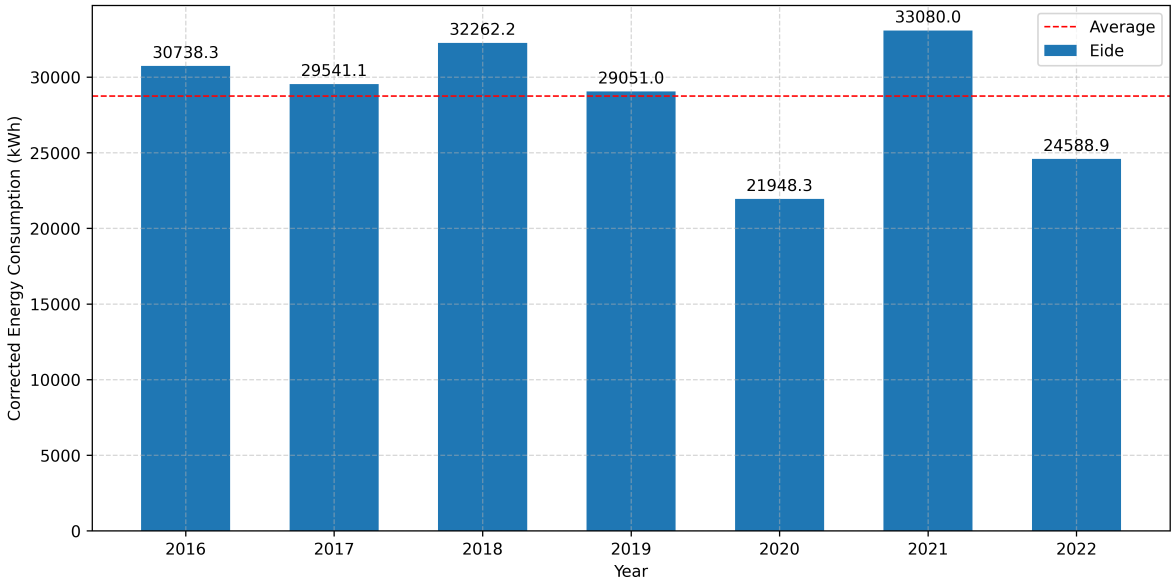


Figure 4.7: Temperature Corrected Energy Consumption Eide 2016-2022

4.1.3 Solar Energy

In this subsection, the results from the PVsyst simulation for the different PV alternatives will be presented. The focus will be primarily on the results from Alternative 1 and Alternative 1 with battery. The various alternatives and their results in terms of annual energy production will be discussed in more detail throughout this chapter.

Described in Chapter 3.4, mainly three different alternatives have been looked into. Alternative 1 includes PV modules on all of the most sun-exposed roof surfaces of the church, as well as on the annex and the shed. Alternative 2 includes PV modules only on the church, thus excluding the annex and the shed, while alternative 3 considers PV modules only on the annex and the shed, thus excluding the church. The three alternatives are shown in Figure 4.8

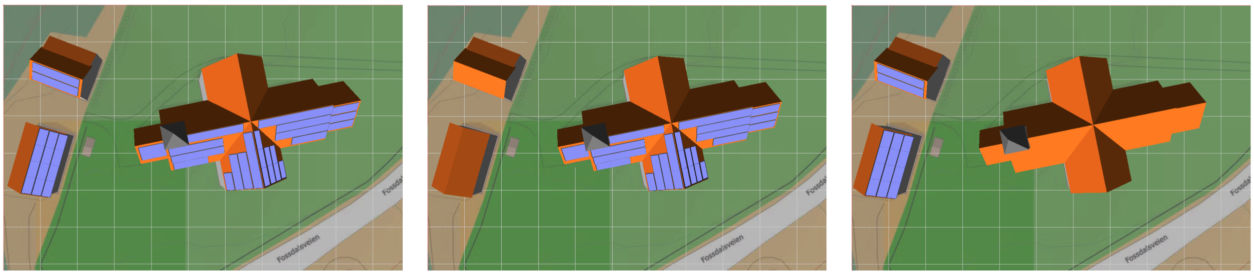
Energy consumption data from 2021 is used as a basis in the simulation, as these figures are very close to the temperature-corrected energy consumption. The actual energy consumption in Eide church in 2021 was 33 053 kWh. Table 4.1 shows the sizing of the different PV systems.

Alternative	**Number of Panels**	**Output Power**	**PV Module Area**
Alternative 1	66	26,1 kWp	130 m^2
Alternative 2	48	19,0 kWp	95 m^2
Alternative 3	18	7,1 kWp	35 m^2

Table 4.1: Sizing of Different PV Alternatives

The main results in terms of annual energy production for the three alternatives are as follows:

- **Alternative 1:** Annual energy production of 24 019 kWh, corresponding to a specific yield of 920 kWh/kWp.
- **Alternative 2:** Annual energy production of 17 562 kWh, corresponding to a specific yield of 925 kWh/kWp.
- **Alternative 3:** Annual energy production of 6 457 kWh, corresponding to a specific yield of 908 kWh/kWp.



(a) PV Alternative 1 (b) PV Alternative 2 (c) PV Alternative 3

Figure 4.8: The Three Different PV Alternatives

Figure 4.9 displays the 3D model designed in PVsyst for Alternative 1 with PV modules on all of the most sun-exposed roof surfaces, both on the church, the annex, and the shed.

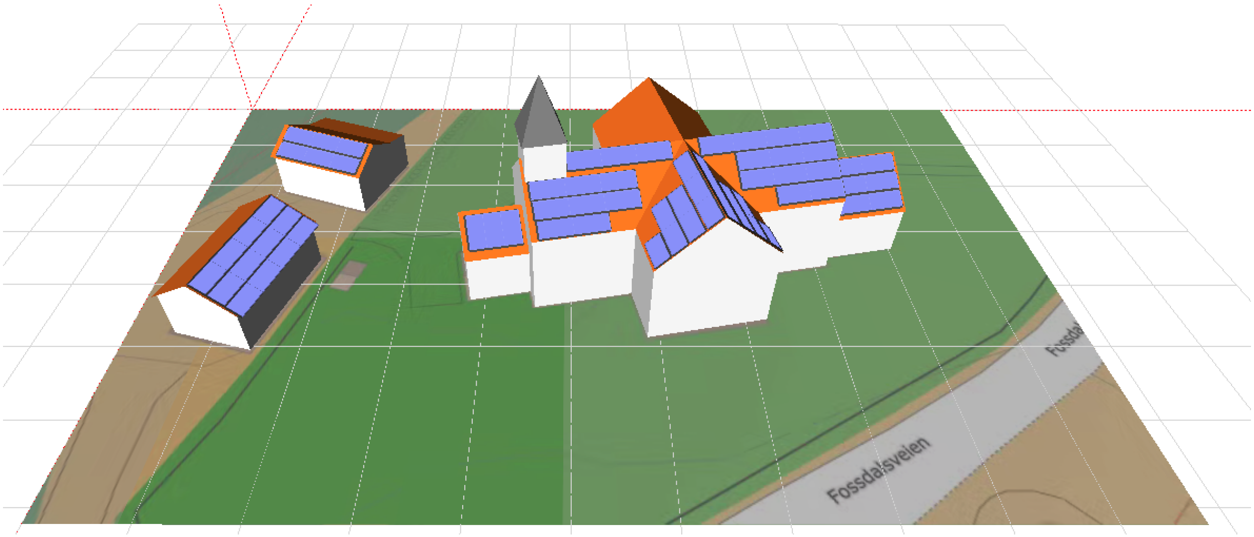


Figure 4.9: 3D Model of PV Alternative 1

Figure 4.10 shows monthly values of Eide church's energy consumption as well as the PV system's monthly energy production. From the graph, it is evident that the energy production is at its lowest when the energy consumption is at its greatest, a phenomenon previously described with the duck curve [87].

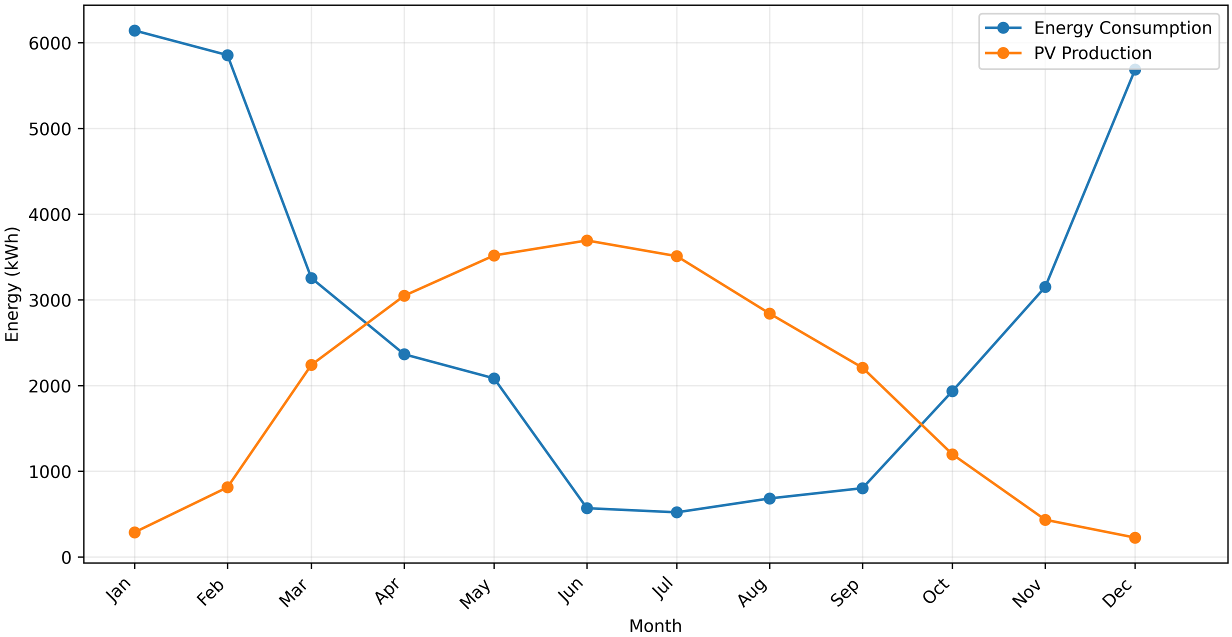


Figure 4.10: Energy Consumption and PV Energy Production

Figure 4.11 and 4.12 show the monthly energy production from the PV system and the proportion of the produced energy that is consumed in the church and the proportion that must be sold to the grid, for the system without and with the 100 kWh battery, respectively. When comparing the graphs, it becomes apparent that a larger share of the produced energy can be used locally in the system with a battery. The difference seems to be the greatest in spring and autumn. For instance, in April, 63.2% of the energy produced will be sold to the grid in the system without a battery, while only 27.2% of the energy will be sold in the system with a battery. From November to February, 100% of the produced energy will be used locally in the church, and thus nothing will be sold to the grid in the system with the battery.

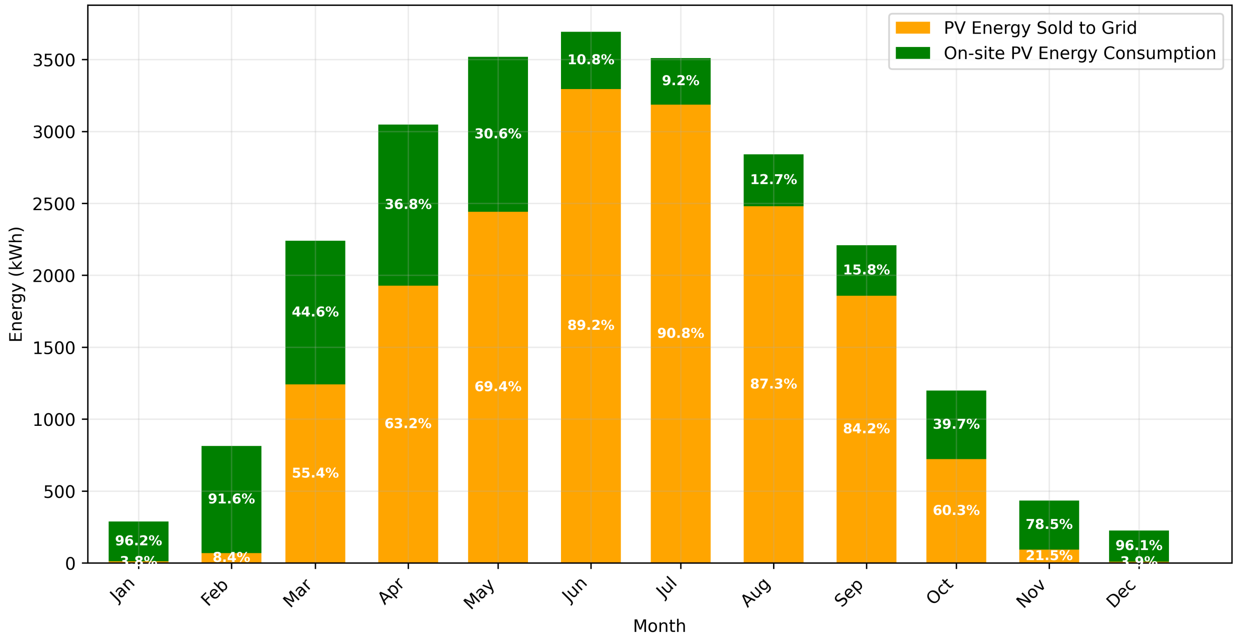


Figure 4.11: Alt 1: Monthly PV Energy Production, On-site Consumption and Grid Sales

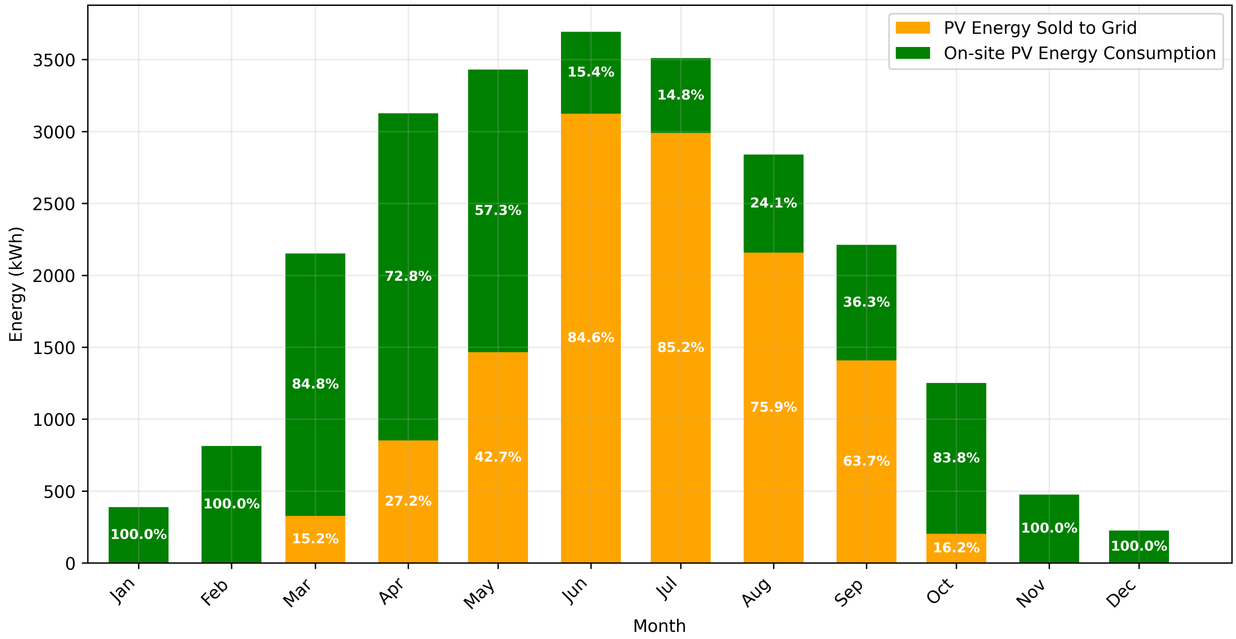


Figure 4.12: Alt 1 w/ Battery: Monthly PV Energy Production, On-site Consumption and Grid Sales

Figure 4.13 and 4.14 show the monthly energy consumption in the church, and the energy mix for the system with and without a battery. When comparing the graphs, it is clear that a significantly larger share of the consumed energy must be purchased from the grid in the system without a battery, despite the PV system having a relatively high annual energy production compared to the annual energy consumption. For the system with the battery, almost 100% of the consumed energy from May to September will come from the PV system. This proportion is significantly lower in the system without the battery.

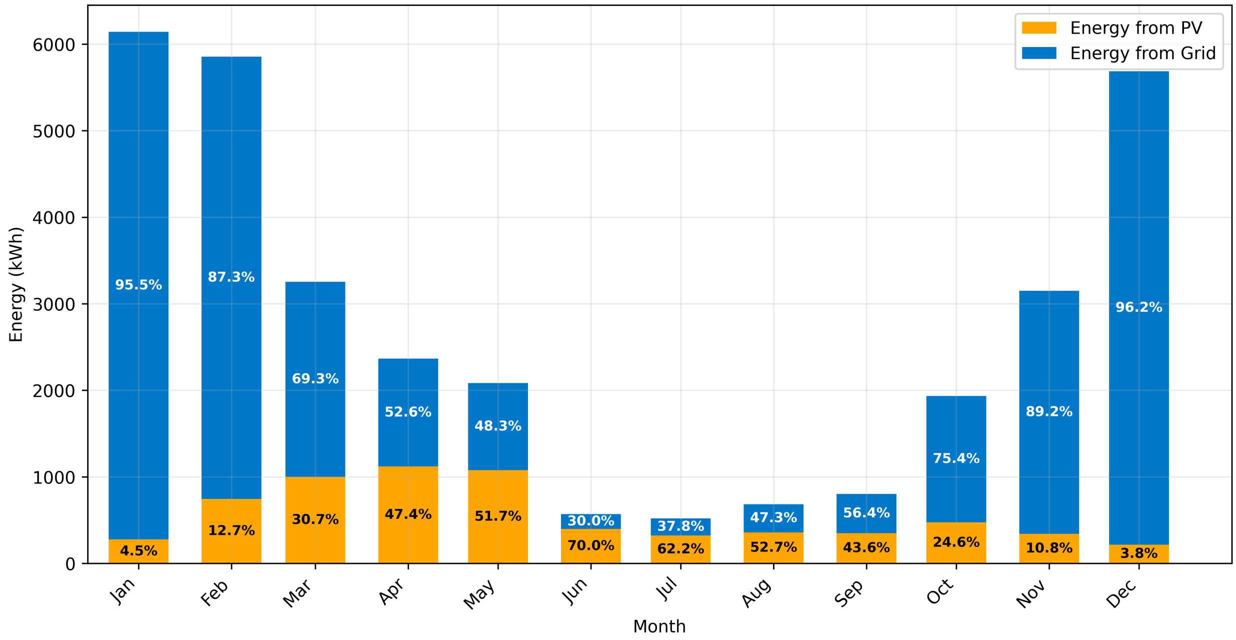


Figure 4.13: Alt 1: Monthly Energy Consumption and Energy Mix

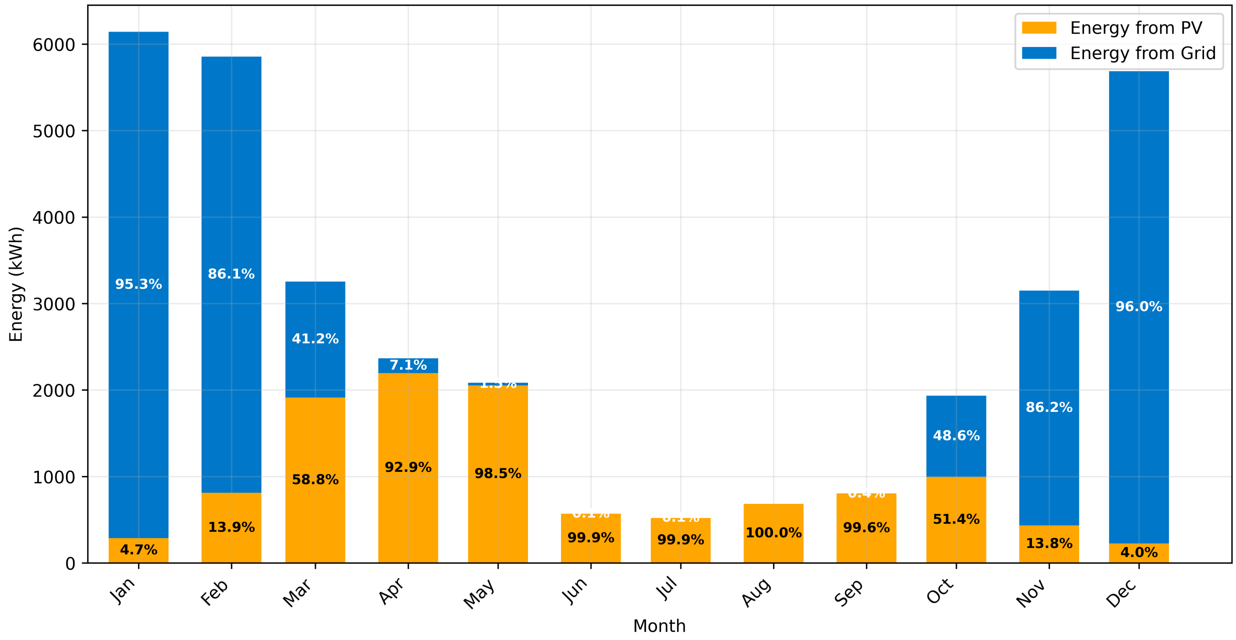


Figure 4.14: Alt 1 w/ Battery: Monthly Energy Consumption and Energy Mix

Figure 4.15 shows the battery's state of charge, as a percentage of its total capacity, throughout an entire year. The graph shows that the battery hardly discharges more than to 95% of total capacity in the months from June to August, while in the months from January to March, and November to December, it hardly charges over 20%. Therefore, there will be long periods during the year when the battery capacity is not utilized optimally.

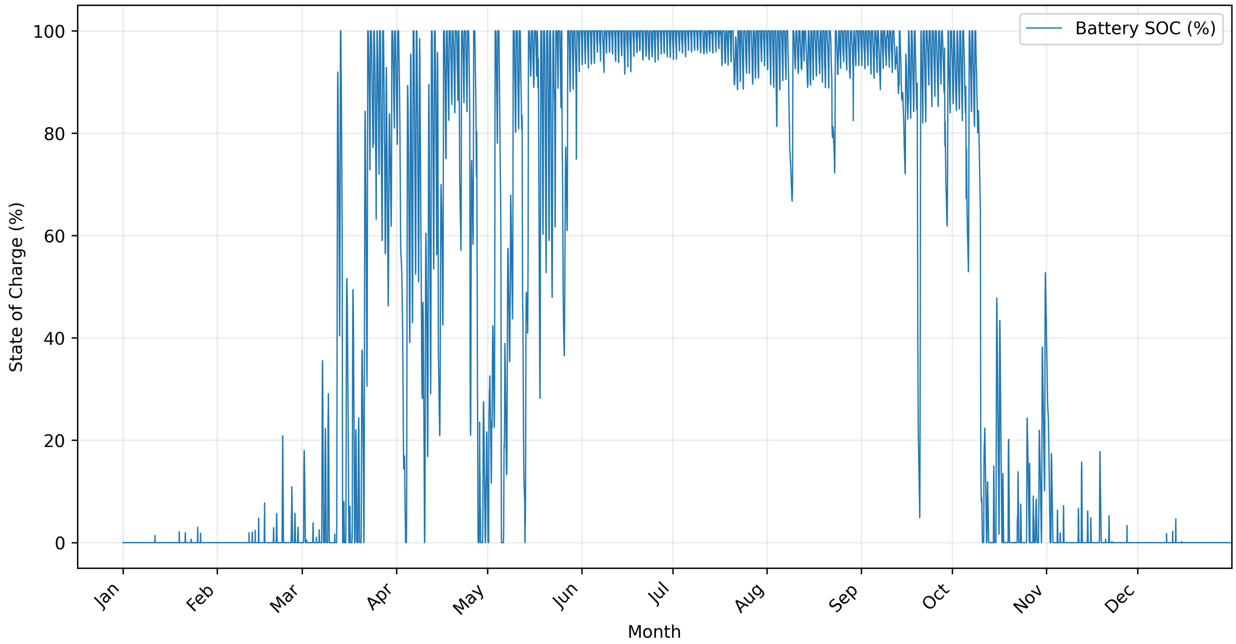
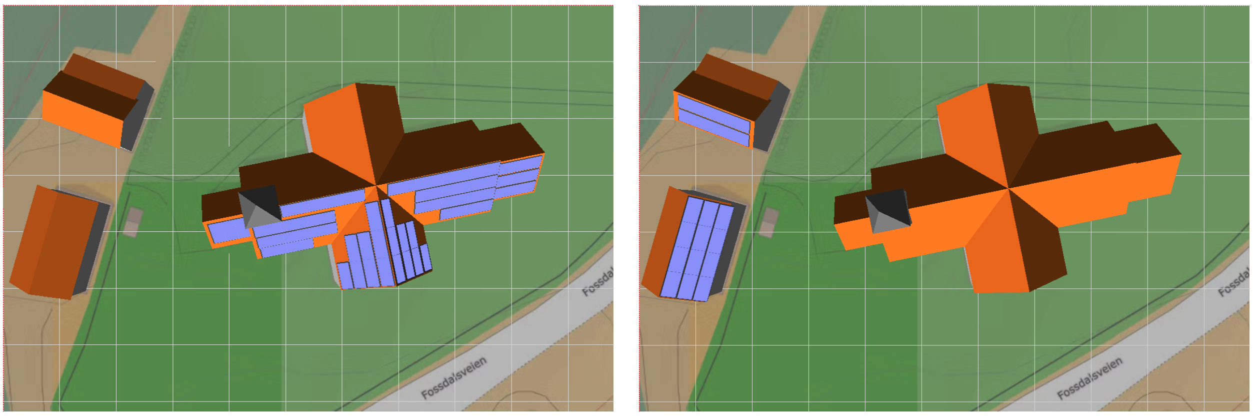


Figure 4.15: Alt 1 w/ Battery: Battery State of Charge

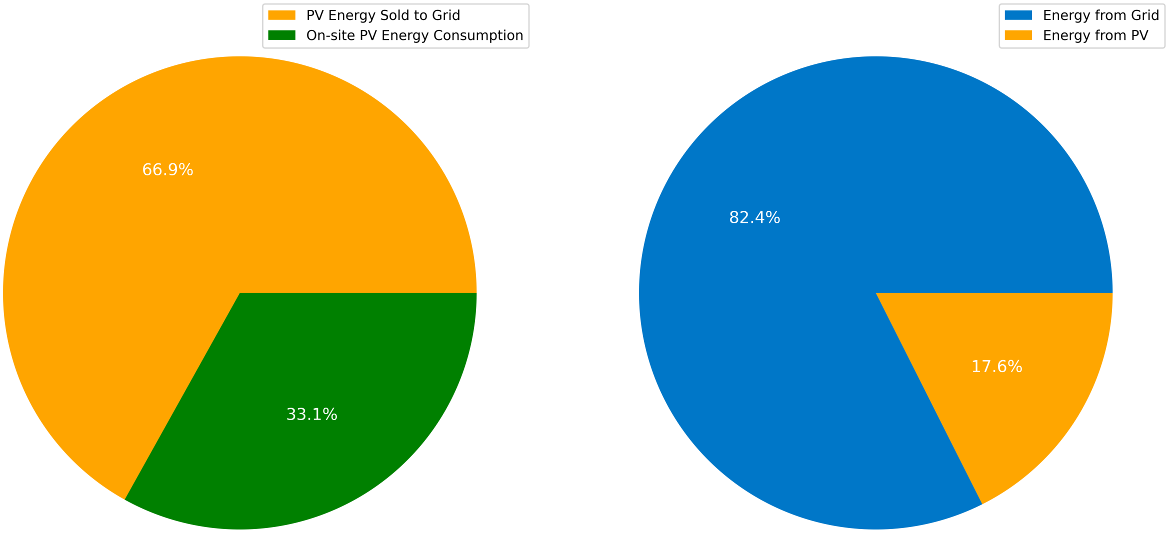
Further on, the results for alternative 2 and 3 are presented. The layout for the two alternatives are once again shown in Figure 4.16. Note that none of these alternatives include a battery.



(a) Alt 2: PV on Church Only

(b) Alt 3: PV on Annex and Shed Only

Figure 4.16: Alternative 2 and 3: 3D Models Top View

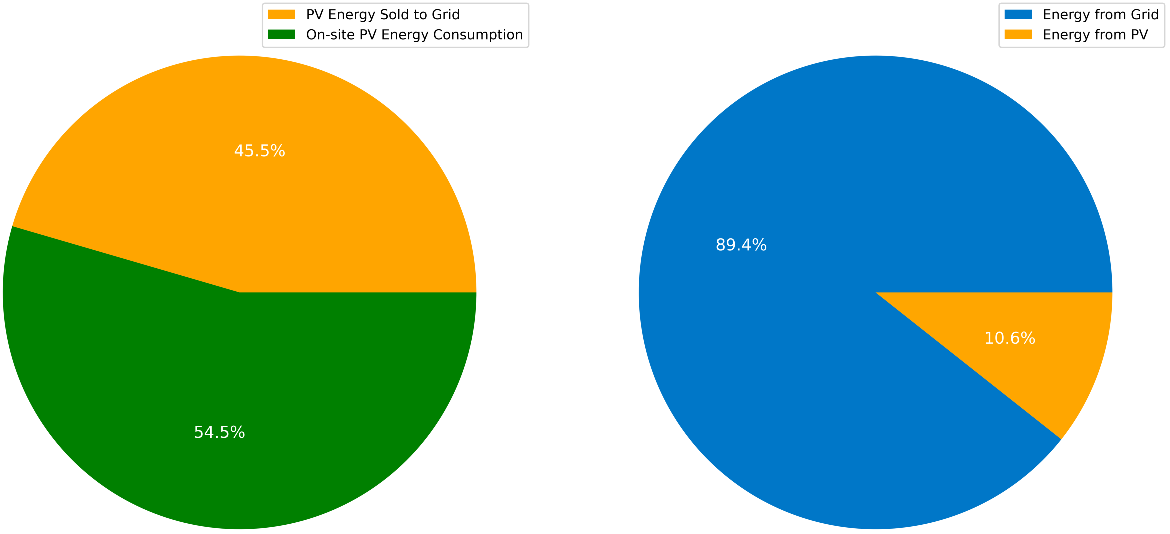


(a) Alt 2: PV Energy Distribution (b) Alt 2: Energy Mix

Figure 4.17: Alternative 2: PV Production Distribution and Energy Mix

For alternative 2, it is clear from Figure 4.17a that nearly 70% of the annual energy produced by the PV system is sold to the grid, and just over 30% is used locally in the church. The PV system in this alternative has an annual energy production of 17 562 kWh, equivalent to 53% of the total energy consumption, yet it is clear from Figure 4.17b that energy from the PV system in reality only covers 17.6%, and thus the remaining 82.4% must be purchased from the grid.

Alternative 3 has an annual energy production of 6 457 kWh, and thus has the smallest energy production of the three alternatives. This corresponds to 19.5% of the total annual energy consumption. However, as shown in Figure 4.18b, the system only covers 10.6% of the annual energy consumption. Compared to alternative 2, a smaller proportion of the produced energy must be sold to the grid, shown in figure 4.18a.



(a) Alt 3: PV Energy Distribution (b) Alt 3: Energy Mix

Figure 4.18: Alternative 3: PV Production Distribution and Energy Mix

A summary of the results from the four different alternatives is presented in Figure 4.19 and 4.20.

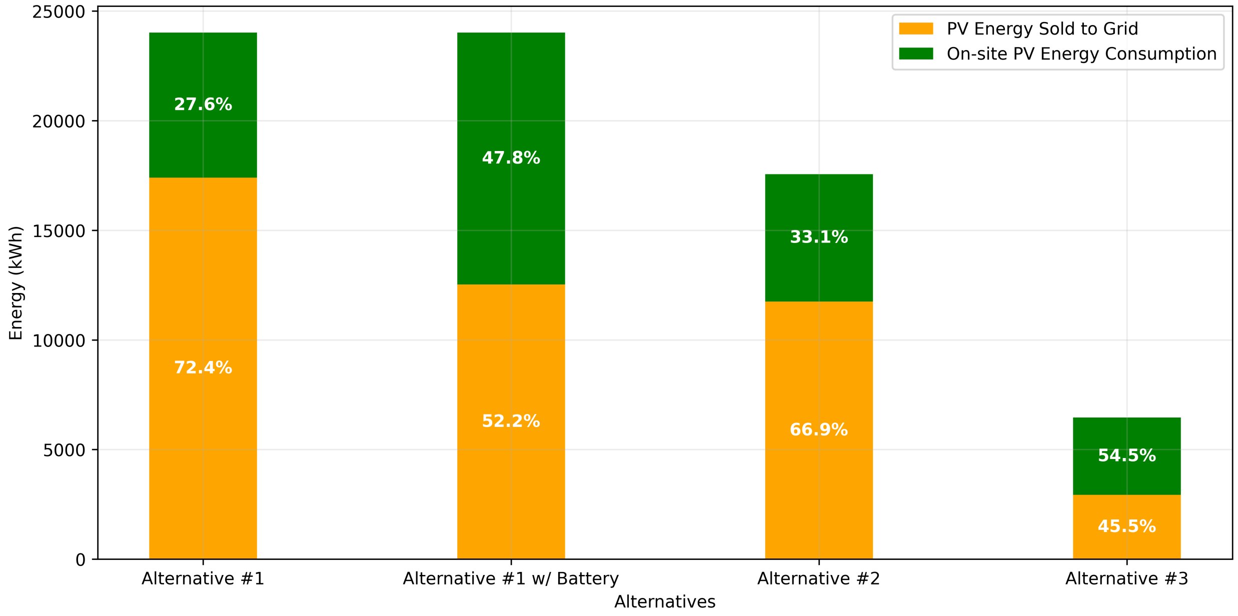


Figure 4.19: PV Energy Production: Comparison of Alternatives

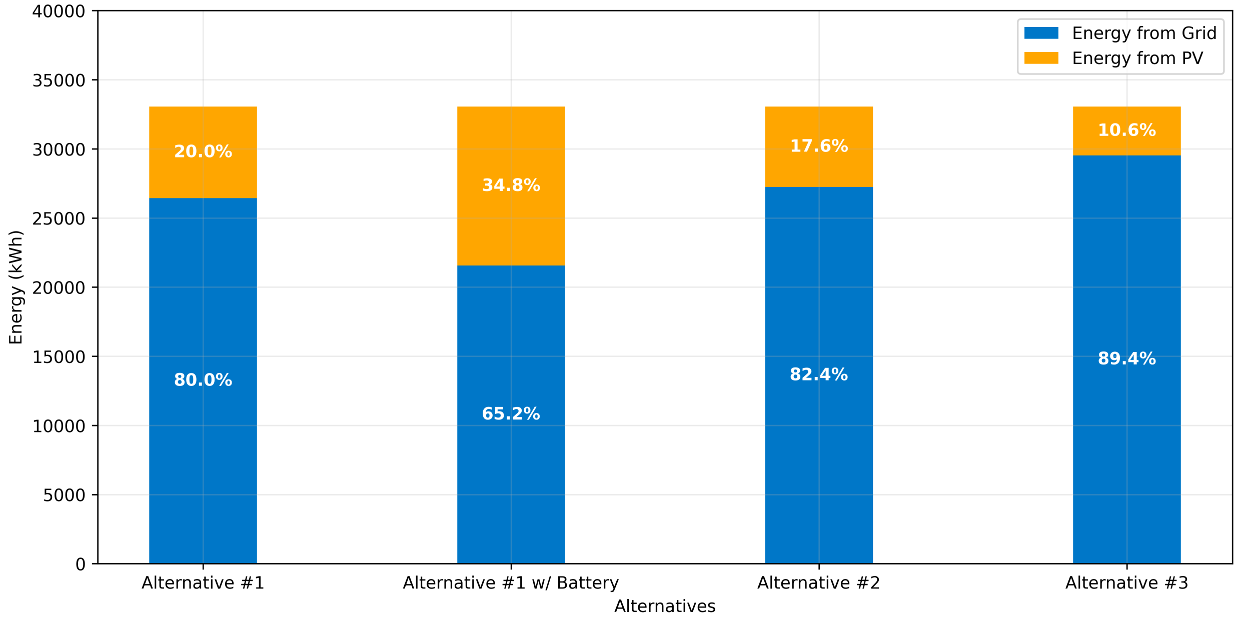


Figure 4.20: Energy Mix: Comparison of Alternatives

4.1.4 Solar Energy Economics

In this subsection, some of the economic aspects of Alternative 1 without battery will be presented. The data basis for economic aspects for all alternatives can be found in Appendix A, B and C. A wide range of investment costs, from NOK 5000/kWp to NOK 25000/kWp, are presented in the graphs to clarify how this affects the overall picture. Note that the investment cost includes all costs associated with the PV system throughout its entire lifetime, to simplify the calculations.

Figure 4.21 shows the payback time at different electricity prices for the PV system in alternative 1 without battery. Marked on the y-axis is a repayment time of respectively 25 and 30 years. 25 years is the typical minimum lifespan of PV systems, but 30 years is equally realistic. If the payback time for a PV system with a lifespan of 25 years, is over 25 years, the system will thus be a bad investment. The shorter the payback time, the better. The average electricity price for Eide church in 2022 was NOK 2.19/kWh. Assuming that this electricity price remains constant throughout the system's lifespan, and assuming an investment cost of NOK 15000/kWp, this will result in a payback time of just under 10 years. Thus, such a system, given a lifespan of 25 years, will produce "free" electricity for over 15 years.

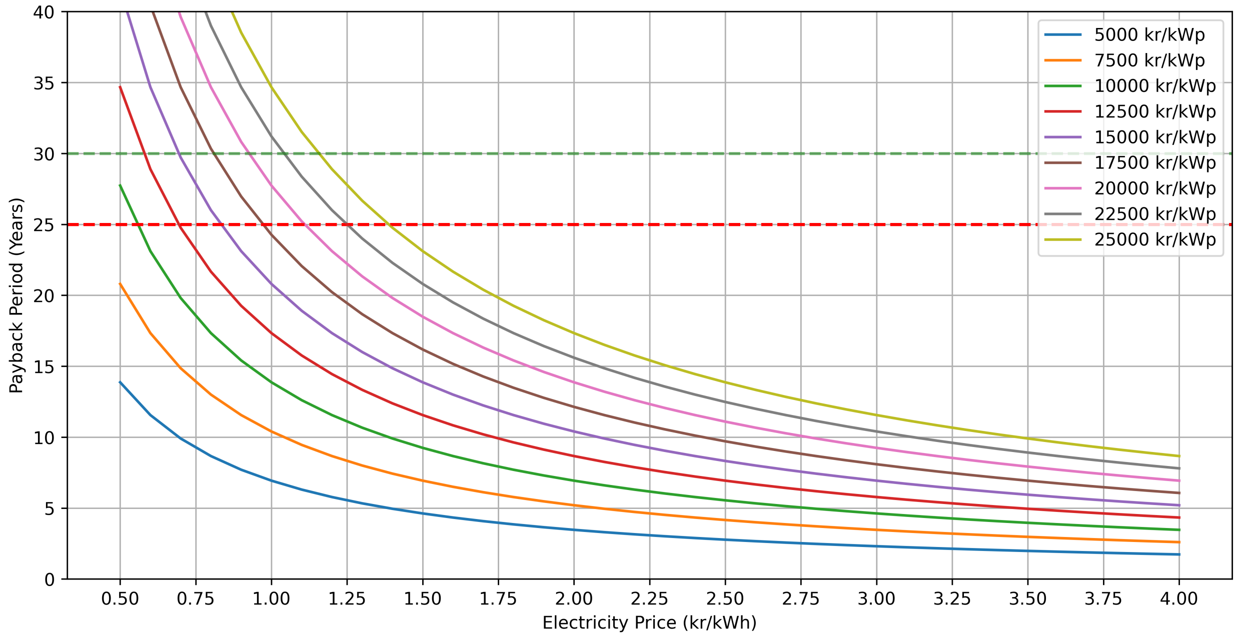


Figure 4.21: Alternative 1: Payback Period vs. Electricity Price for Various Investment Costs

Figure 4.22 shows the cost per produced kWh for the PV system, given a lifespan of 25 or 30 years and with different investment costs. An annual degradation of the PV system of 0.5% has been assumed. Assuming a lifespan of 25 years and an investment cost of NOK 15000/kWp, this system will produce electricity at a cost of approximately NOK 0.7/kWh.

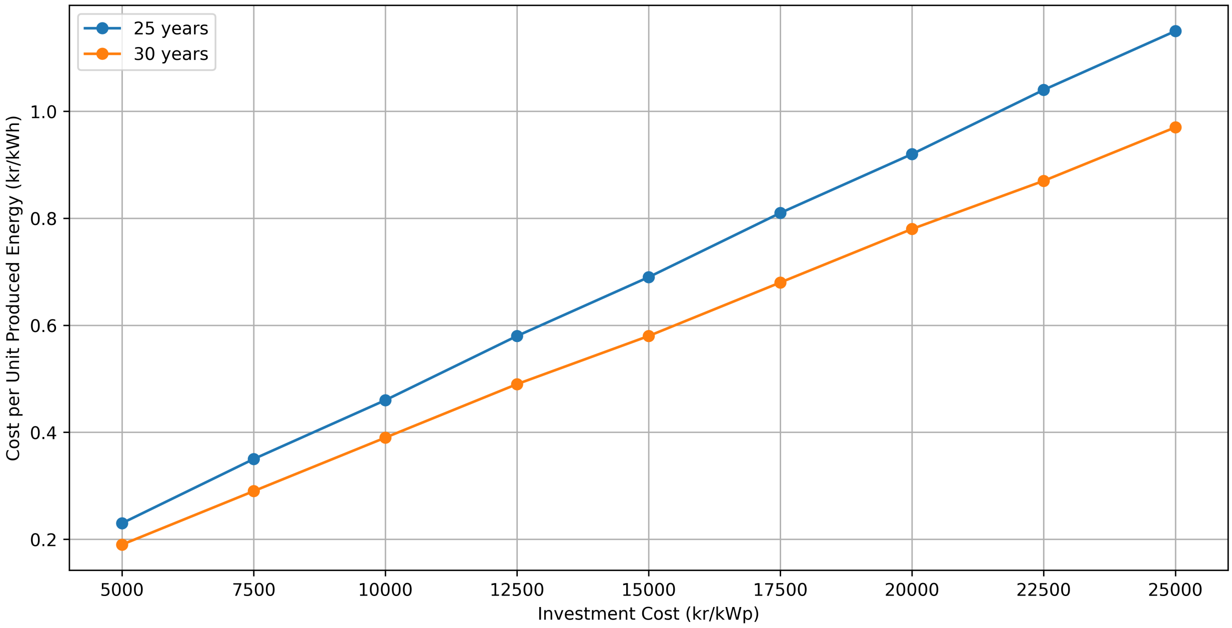


Figure 4.22: Alternative 1: Cost per kWh

Figure 4.23 shows the return on investment (ROI) in percent of the total investment cost for the PV system in Alternative 1 at different investment costs (kr/kWp). Furthermore, an electricity price corresponding to that in 2022, of NOK 2.19/kWh, has been assumed. With such a high electricity price, it is seen that even in the worst scenario, that is, with an investment cost of NOK 25000/kWp, and a lifespan of 25 years, the ROI is still over 50%.

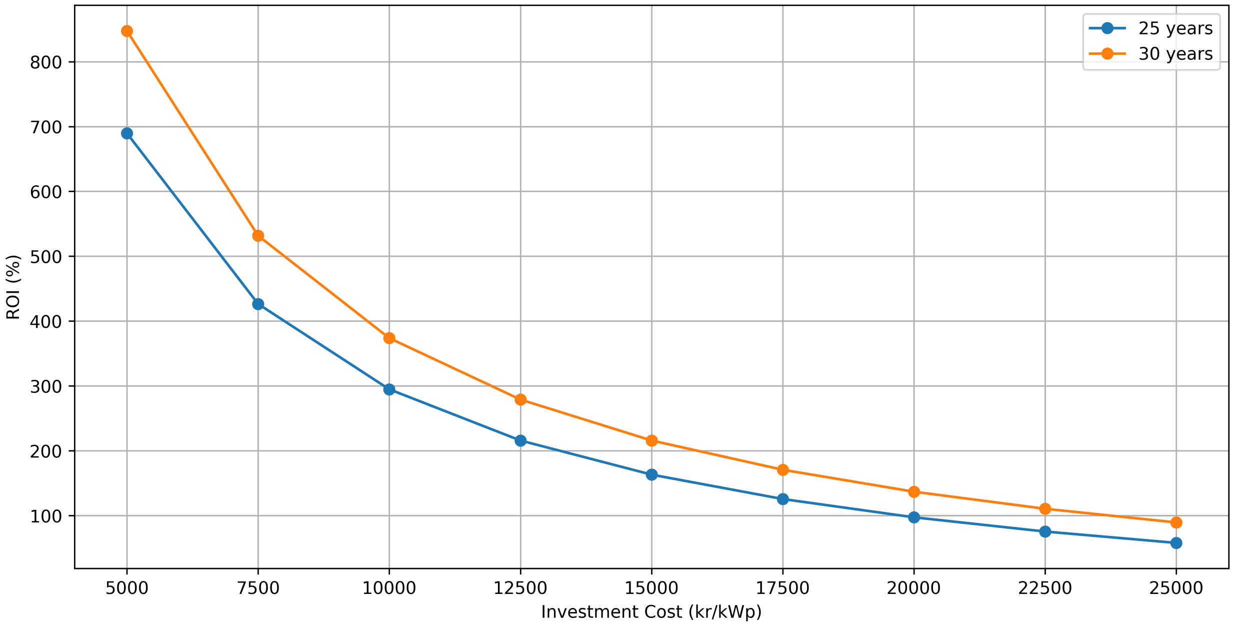


Figure 4.23: Alternative 1: Return on Investment (%)

Figure 4.24 also shows the return on investment (ROI) as a function of investment cost, but this time as an absolute return measured in millions of kroner (MNOK).

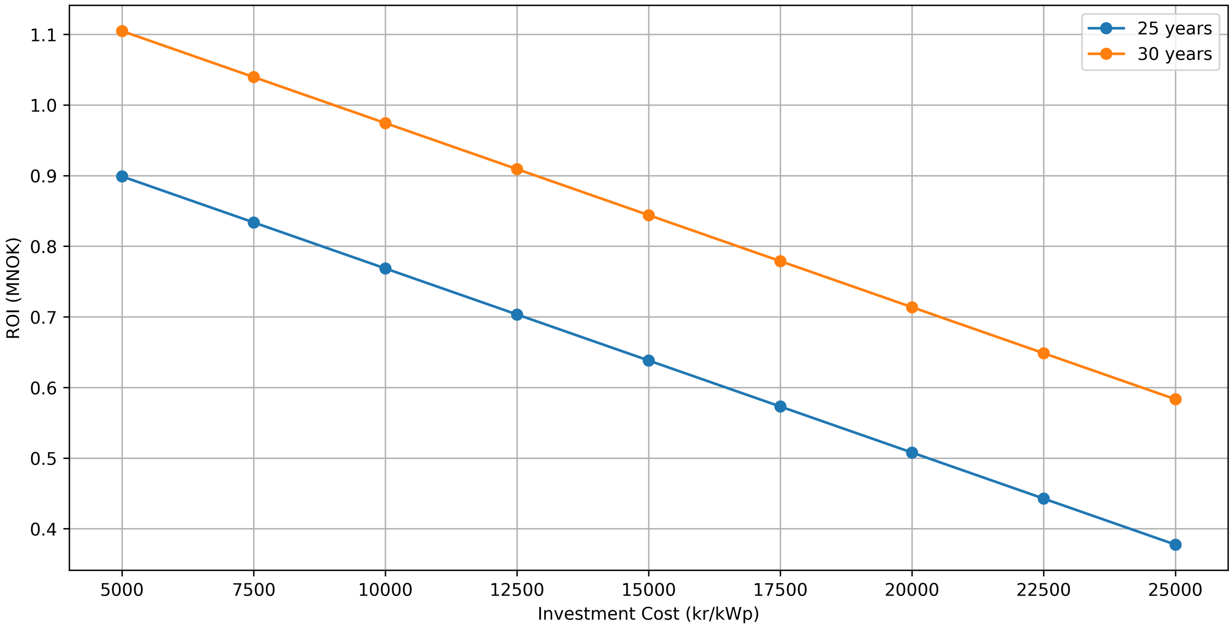


Figure 4.24: Alternative 1: Return on Investment (MNOK)

4.2 Landvik Church

4.2.1 Temperature and Humidity

In this chapter, the findings and results from Landvik church will be presented. First, results from temperature and humidity measurements, in addition to energy consumption, will be presented. Then, the results from the Simien simulations will be presented.

Just like in Eide church, 10 temperature and humidity loggers have been deployed in Landvik church to gain a better insight into the indoor climate of the church. Figure 4.26 on the following page shows where in the church the different loggers have been placed, and the temperature measurements are shown in Figure 4.25. The measurements were made over a period of approximately 4 days, from March 17, 2023, to March 21, 2023. During the measurement period, there were a total of 3 heating events, but only the heating for the service on March 19 is shown in its entirety. At the very beginning, and also at the end of the measurement period, there were choir rehearsals in the church, and the heating for these activities are visible in the graph.

The service on March 19 started at 11:00, and the heat seems to have been turned on shortly after midnight before the service. The outdoor temperature during the measurement period, represented by Logger 1, shows a temperature between 0°C and 10°C. Particularly Logger 3, marked in green, shows apparent large changes in temperature without the remaining loggers showing it. This is most likely due to the logger's location near a window, where direct sunlight is the cause of this. Logger 7, marked in pink, also shows very sudden changes. This is probably due to the logger's placement directly under the heating panel in the northern sacristy.

Beyond this, it is quite clear that the resting temperature is set to 10°C, while the operating temperature is set to 19°C. Some of the loggers show that the temperature actually exceeded 19°C. During the actual service, proximity to logger 2 allowed for the first-hand experience of a comfortable temperature throughout the ceremony. It is worth noting that the church is divided into different heating zones, which may be the reason for different temperatures in different parts of the church. For example, one can see from the graph that the temperature in the northern sacristy (Logger 7) is turned on later than in the rest of the church. In addition, the eastern sacristy maintains a higher temperature over a longer period than the rest of the church, to ensure good working conditions for the staff.

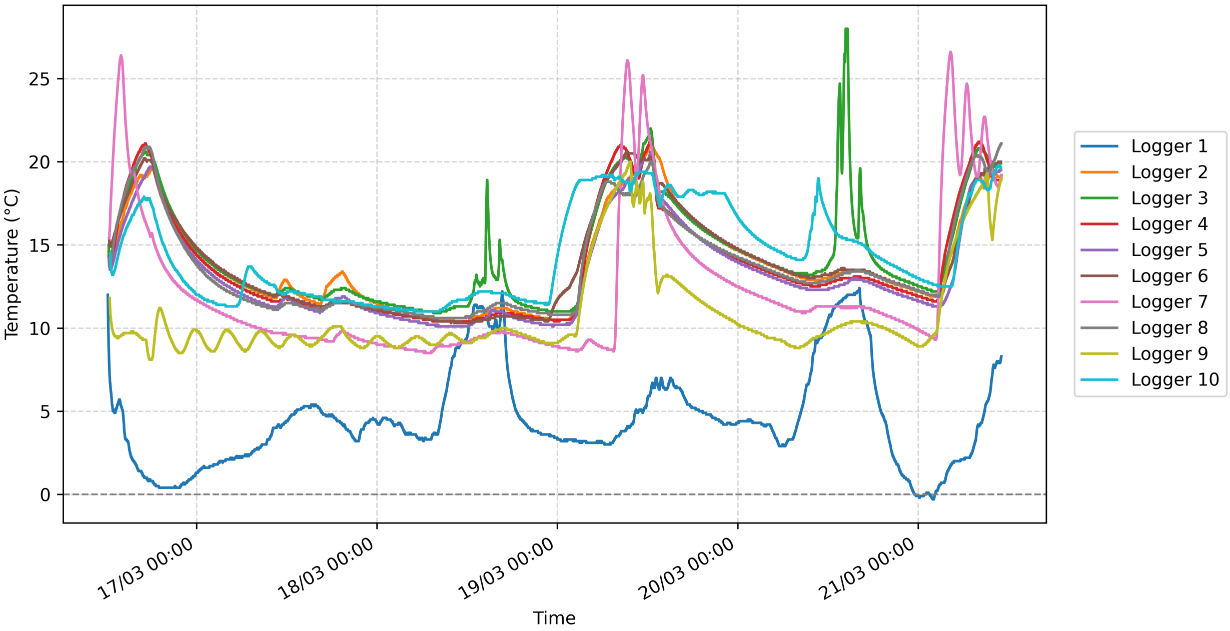


Figure 4.25: Measured Temperature during Heating in Landvik

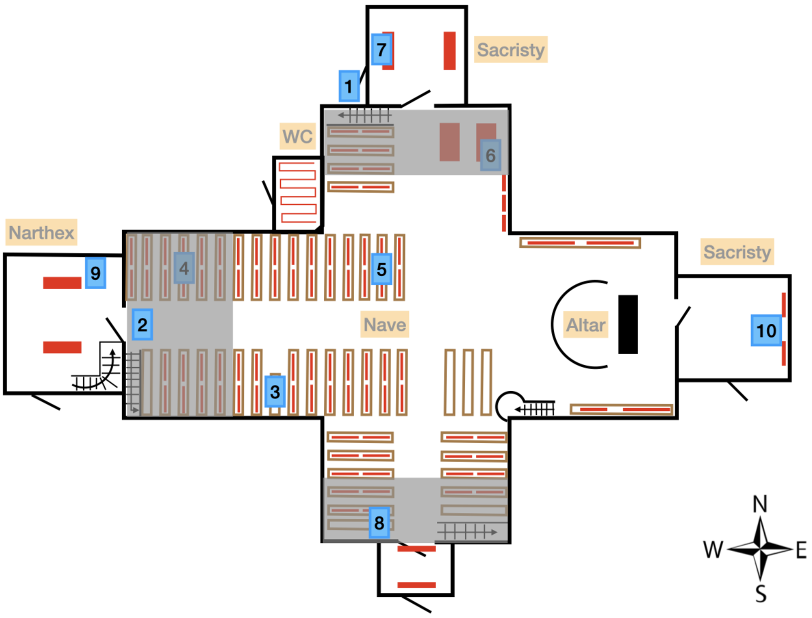


Figure 4.26: Placement of Temperature and Humidity Loggers in Landvik

The entire measurement period is characterized by precipitation and otherwise very high outdoor humidity represented by Logger 1 as shown in Figure 4.27. Logger 9, placed in the narthex, also shows a significantly higher relative humidity than the rest of the church, up to 80%. Otherwise, it appears from the graph that the humidity increases as a result of the decreasing indoor temperature at the start of the measurement period, before the humidity again decreases when the temperature rises. Most places in the church experience a relative humidity between 40 and 60% during the measurement period. The unnatural changes in relative humidity for Logger 3 are also likely related to the logger's position sometimes in direct sunlight. Logger 7 in the northern sacristy shows a very sudden change in relative humidity from 60 to around 35% as the temperature in the room quickly increases. When the heat is turned off, the humidity quickly rises again.

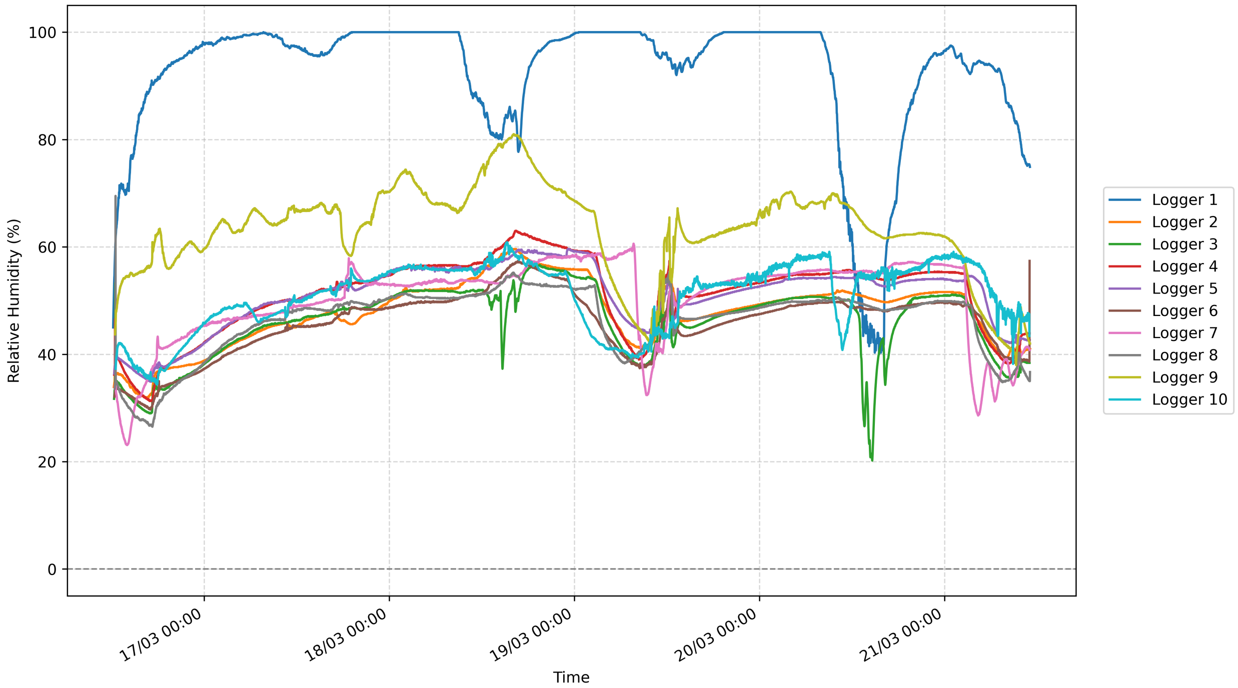


Figure 4.27: Relative Humidity during Heating Period Landvik

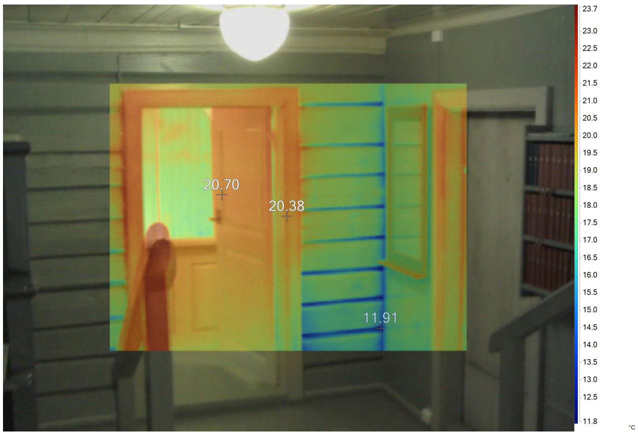
In addition to measuring air temperature and relative humidity, surface temperatures were measured using a thermal imaging camera and a handheld laser thermometer. Figure 4.28 shows images taken with the thermal imaging camera in Landvik church, shortly after the service on March 17.

Figure 4.28a shows the wall and windows directly behind the choir, facing east. The colors in the image are somewhat disturbed due to the warm light bulbs just being within the camera's sensor, but annotations around the window in particular show large temperature differences. While the wall itself appears to maintain almost 19°C, the window has a temperature of 15°C, while the lower part of the window has a temperature of just over 8°C.

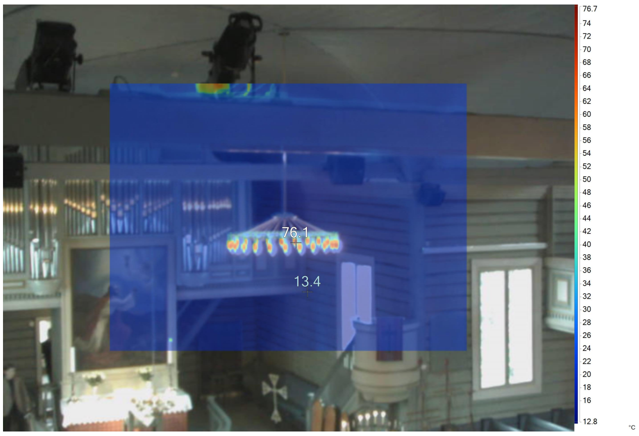
Figure 4.28b shows some of the same tendency seen in the thermal images from Eide church, namely how the logs seem to maintain a significantly lower temperature where they are connected with other rooms or walls. This image shows the wall between the nave and the narthex on the second floor, on the gallery. To the right of the image, one can see the entrance door to the room that leads further up to the bell tower.

Figure 4.28c shows the largest chandelier in the church, and how the old-fashioned light bulbs emit a lot of heat, close to 80°C.

(a) Heat Loss around Window Frame



(b) Heat Loss in Log Intersections



(c) Hot Incandescent Bulbs

Figure 4.28: Thermography of Landvik

In addition to this, measurements made with the thermometer show the following surface temperatures: Temperature on the surface of the bench heaters: 100-110°C. Surface temperature on the heating panels in the narthex: 320-330°C. Surface temperature on the heating panels in the northern sacristy: 160-170°C. Temperature on stage lights: 130°C.

4.2.2 Historical Energy Consumption

Figure 4.29 shows the actual and temperature-corrected annual energy consumption in Landvik church from 2010 to 2022, with the annual average temperature at Landvik weather station also displayed. As with Eide church, the temperature-corrected consumption in Landvik Church for 2021 closely matches the actual consumption.

Figure 4.30 displays the temperature-corrected energy consumption for the years 2016-2022. The red dashed line shows the average annual energy consumption for this period. A notable decrease in energy consumption in 2020 is likely due to the COVID-19 pandemic. The energy consumption varies significantly from year to year, with a 28% decrease (over 20 000 kWh) observed from 2021 to 2022 without an evident explanation.

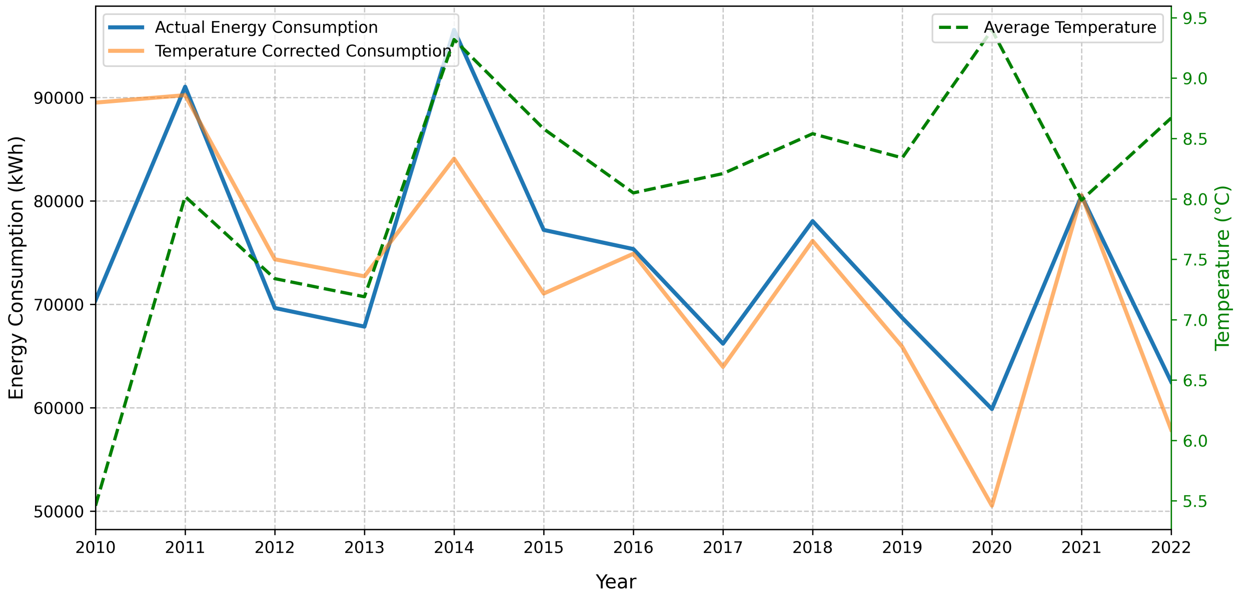


Figure 4.29: Historical Energy Consumption and Temperature Correction Landvik 2010-2022

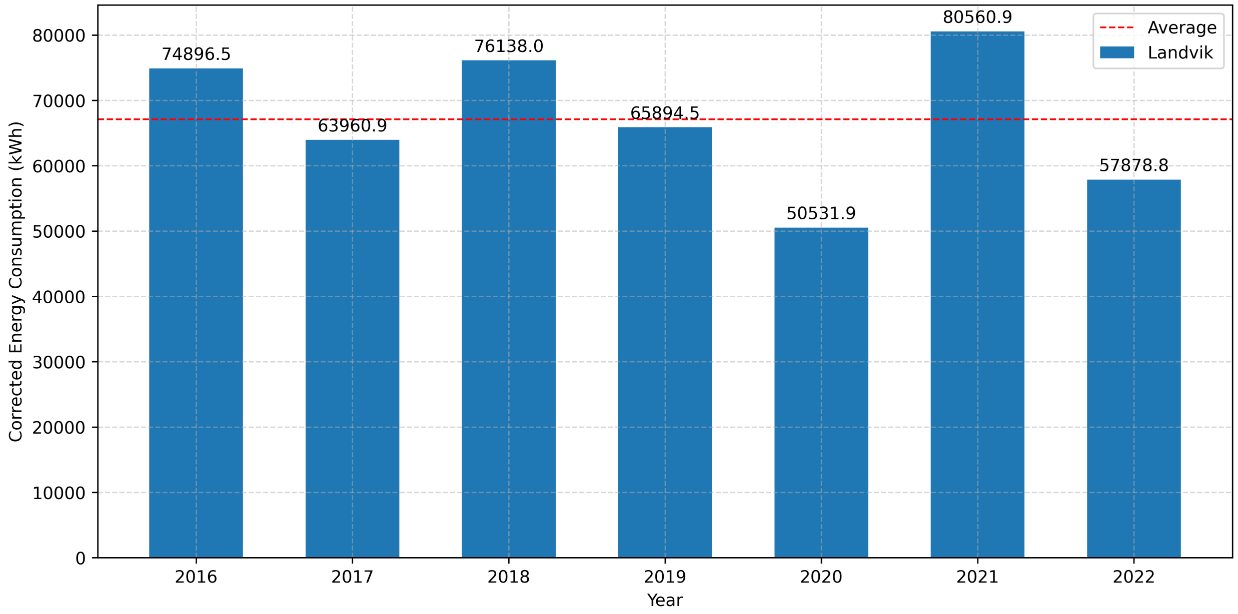


Figure 4.30: Temperature Corrected Energy Consumption Landvik 2016-2022

4.2.3 SIMIEN Simulations

In this subsection, the results from the Simien simulations will be presented. The simulation of the annual energy consumption shows a result of 65 309 kWh. Excluding the unusually low consumption in 2020, the average of the annual temperature-corrected energy consumptions in Figure 4.30 shows a consumption of 69 888 kWh. This is approximately 7% higher than the simulated consumption.

Figure 4.31 shows that 89% of the energy consumption goes to heating, 8.6% goes to lighting, and 1.1% and 1.2% go to technical equipment and hot water, respectively. Furthermore, Figure 4.32 shows the heat losses. The largest losses occur through the outer walls and through infiltration, which together account for nearly 60% of the total heat losses.

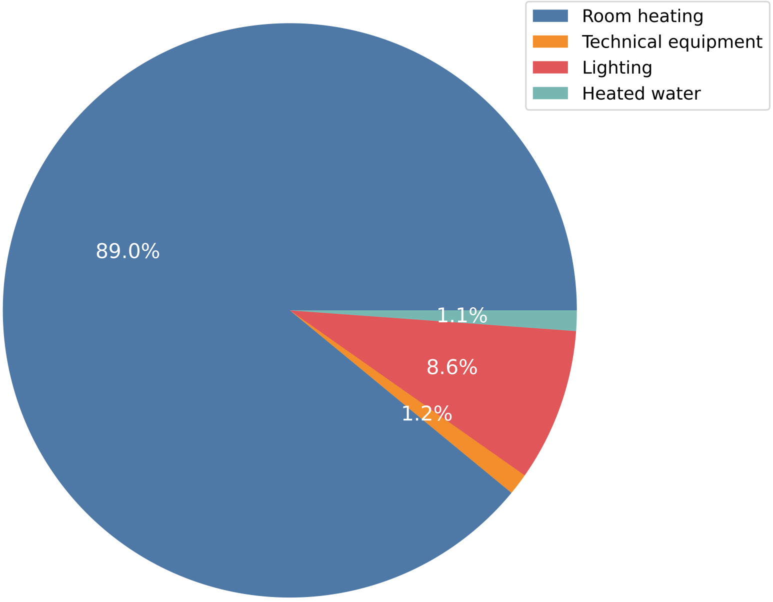


Figure 4.31: Energy Budget Landvik Church

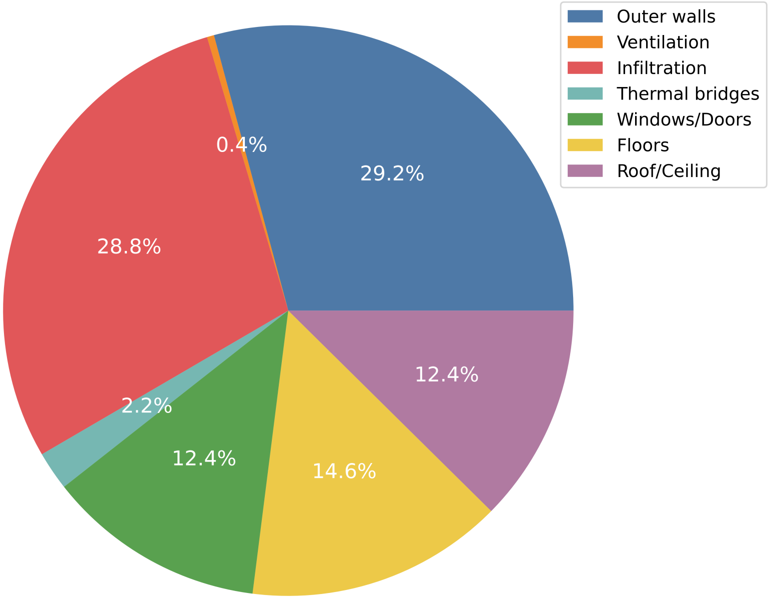


Figure 4.32: Heat Loss Distribution Landvik Church

As mentioned in the Chapter 3.5, the effect of various energy efficiency measures in Landvik church has been simulated in Simien. In this exercise, 18 different measures have been evaluated. The effects of the various measures are shown in Figure 4.33, where the annual energy consumption with the measure implemented is shown on the y-axis. The percentage inside the bars represents the energy savings for the different measures compared to the energy consumption without measures. In the figure, the measures are sorted from least to greatest energy saving.

Table 4.2 on the next page describes the different measures and shows even more precisely the energy savings they bring. The table correlates with Figure 4.33, and also in the table, the measures are sorted from least to greatest energy savings. "Church room" in the description of the measures refers to the nave of the church, i.e. the entire "room" available to the congregation during, for example, a service. Where TEK17 is in parentheses after the description of the measure, it means that the measure meets what is considered the minimum insulation requirement in TEK17.

The measure describing the removal of all the choir rehearsals is calculated by comparing the energy consumption without measures with the energy consumption where a resting temperature of 10°C is maintained throughout the year. The difference of these energy consumptions is further divided by the number of annual activities in the church, and then multiplied by the number of choir rehearsals (41).

In the table, a measure that involves lowering the resting and operating temperatures to 8°C and 17°C, respectively, while increasing the heating power is described. In this measure, the installed heating power in the church room has been increased to about 33 W/m^3, in accordance with KA's recommendation on power per volume for efficient, intermittent heating.

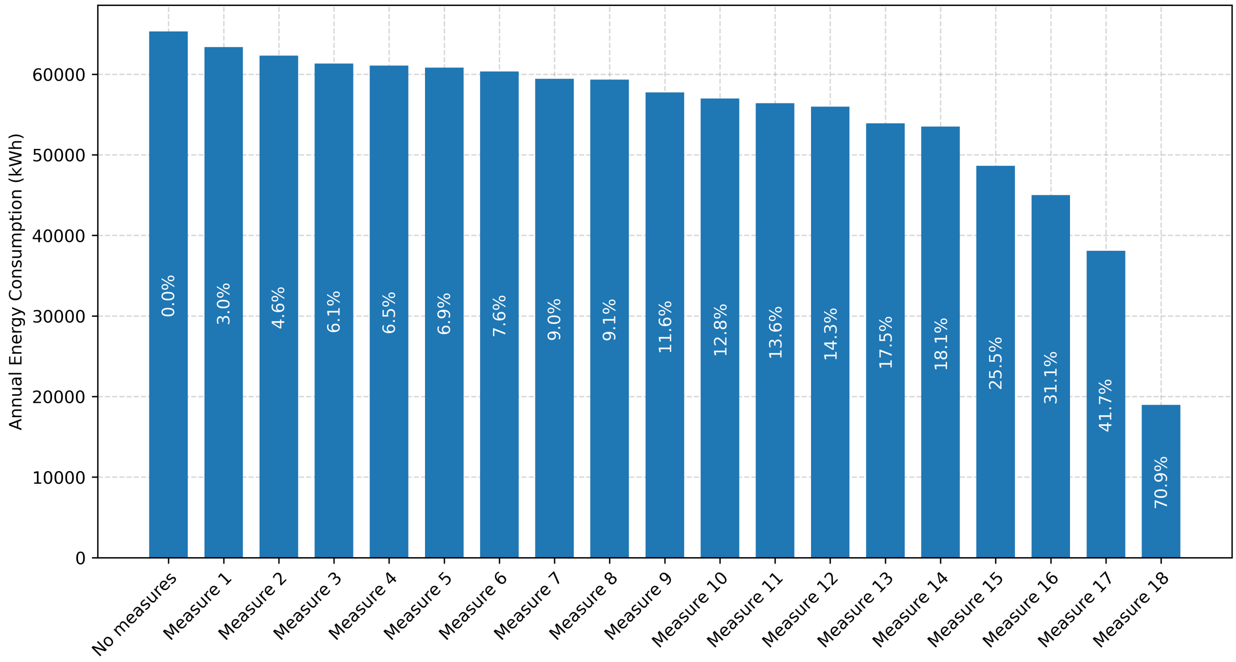


Figure 4.33: Annual Energy Savings with Various Measures

Measure #	**Description**	**Consumption (kWh)**	**Savings (kWh)**
No Measure	No measures	65 309	0
Measure 1	Insulate ceilings in church room to U-value 0.13 (TEK17)	63 375	1 934
Measure 2	Replace all windows in church room to U-value 0.8 (TEK17)	62 303	3 006
Measure 3	Insulate all roofs to U-value 0.13 (TEK17)	61 338	3 971
Measure 4	Insulate floor in church room to U-value 0.1 (TEK17)	61 082	4 227
Measure 5	Replace all windows to U-value 0.8 (TEK17)	60 824	4 485
Measure 6	Switch from incandescent bulbs to LED lighting	60 348	4 961
Measure 7	Lower idle and operating temperatures to 9 and 18°C (-1°C)	59 445	5 864
Measure 8	Insulate all floors to U-value 0.1 (TEK17)	59 340	5 969
Measure 9	Change leakage rate in church room from 5 to 2.5 (TEK17)	57 744	7 565
Measure 10	Remove all choir rehearsals (41 rehearsals)	56 981	8 328
Measure 11	Insulate outer walls in church room to U-value 0.18 (TEK17)	56 403	8 906
Measure 12	Change leakage rate in all rooms from 4 and 5 to 2.5 (TEK17)	55 988	9 321
Measure 13	Lower idle and operating temperatures to 8 and 17°C (-2°C)	53 903	11 406
Measure 14	Insulate all outer walls to U-value 0.18 (TEK17)	53 509	11 800
Measure 15	Lower idle and operating temperatures to 7 and 16°C	48 632	16 677
Measure 16	Lower idle and operating temperatures to 8 and 17°C (increased power)	45 010	20 299
Measure 17	Constant idle temperature at 10°C	38 089	27 220
Measure 18	Constant idle temperature at 6°C	18 973	46 336

Table 4.2: Various Energy Saving Measures in Landvik Church

From Table 4.2, it is clear that the most effective energy-saving measure is to turn off all lights, shut down the church, and set a constant temperature of 6°C to avoid frost damage and too high levels of relative humidity. This would result in an annual saving of 70.9%, corresponding to over 46 000 kWh. However, it is worth noting that even with this approach, the church will still have an annual energy consumption of nearly 19 000 kWh, an energy consumption greater than the average Norwegian household [24]. Assuming an average electricity price of about 2 kroner per kWh, this would still result in an annual energy cost of nearly 40 000 kroner.

Measure 16, which involves replacing the current 250 watt bench heaters with 550 watt bench heaters, while reducing the heating time from 11.5 to 5 hours, as well as reducing the resting and operating temperatures to 8°C and 17°C respectively, shows an annual energy saving of over 30%. It is very important to note that such a change would result in an increase in maximum power of 25 200 watts. In a 230 volt low voltage system, such an increase in power would mean an increase in maximum current of nearly 110 amps. This could cause significant implications not only in the church's electrical system, but potentially in the upstream transformer and power grid.

Landvik church is the only church in this study that still uses incandescent bulbs for lighting. Energy saving measure number 6, which involves switching from traditional incandescent bulbs to LED bulbs with 90% lower power but the same lighting effect, results in an annual saving of nearly 5 000 kWh. This measure is one of the "low hanging fruits" seen in this simulation, and the measure can be easily implemented by a single, unskilled person.

Insulation of various building parts has varying effects, and insulating the roof of the church room is, according to the simulation, the measure with the least effect. On the other end of the spectrum, insulating the outer walls to today's TEK17 standard could have a greater impact on the energy consumption.

Further, it is worth noting that some of the measures in practice cannot be done alone. For example, assuming the work is properly done, it would be difficult to insulate the outer walls of the church room (measure 11) without simultaneously making the church room more airtight with fewer air changes (measure 9).

Common for all the measures mentioned in the table is the importance of evaluating each measure against the cost-benefit value of the measure. For example, insulating the roof of the church room may not yield the largest savings, but if the measure can be implemented as a community effort in the congregation, it will still have a high cost-benefit value.

In the follow page, the economic savings of two of the measures, measures 6 and 16, will be evaluated.

Measure 6, which involves switching from traditional incandescent bulbs to LED bulbs, shows an annual energy saving of 7.6%, equivalent to 4 961 kWh. In 2022, Landvik church experienced an average electricity price of 1.9854 kroner. If this electricity price is used as a basis, the introduction of energy-saving measure 6 represents an annual cost saving of 9 850 kroner.

In the simulation, it is assumed, and also verified by visual inspection, that Landvik church has an installed lighting capacity of 10 090 watts. This particularly high wattage is partly due to the presence of 14 relatively large stage lights. If it is further assumed that equivalent LED lighting only needs 10% of the power to provide the same perceived light effect, this corresponds to a new lighting capacity of:

$$10090\,\mathrm{W} \times 10\% = 1009\,\mathrm{W} \tag{4.1}$$

Based on the prices of typical LED bulbs with E14 and E27 sockets from a number of retailers, it appears that it costs an average of 12.165 kroner per watt of LED lighting. This results in a total investment cost of:

$$12.165\,\mathrm{kr/W} \times 1009\,\mathrm{W} = 12274\,\mathrm{kr} \tag{4.2}$$

Given the annual saving of 9 850 kroner, this will result in a payback time of:

$$\frac{12274\,\mathrm{kr}}{9850\,\mathrm{kr/year}} \approx 1.25\,\mathrm{years} \tag{4.3}$$

Over 5 years, this will save:

$$-12274\,\mathrm{kr} + (5\,\mathrm{years} \times 9850\,\mathrm{kr}) = 36976\,\mathrm{kr} \tag{4.4}$$

Over 10 years, this corresponds to:

$$-12274\,\mathrm{kr} + (10\,\mathrm{years} \times 9850\,\mathrm{kr}) = 86226\,\mathrm{kr} \tag{4.5}$$

Given Landvik church's 402 operating hours in 2022 as a basis for further calculations, and the average LED bulb's minimum lifespan of 15 000 hours, this gives a minimum lifespan of:

$$\frac{15000\,\mathrm{hours}}{402\,\mathrm{hours/year}} = 37.3\,\mathrm{years} \tag{4.6}$$

In summary: LED bulbs pay off quickly.

A counter-argument to this could be that the traditional light bulbs generate a lot of heat in the church. However, this has been taken into account in the Simien simulation, and the heat emitted from the light bulbs probably does not have such a big influence due to being installed high above the floor.

Measure 16 showed the greatest energy savings, without having to significantly affect the church's activity. As previously described, the measure includes the following points:

- Replace all 84 of the 250W bench heaters with new, 550W IR bench heaters of the same type installed in Eide church.
- Lower resting and operating temperatures from 10°C and 19 °C to 8°C and 17°C, respectively. This also applies to rooms that previously had a constant temperature.
- Shorten heating time from 11.5 to 5 hours.

Such an upgrade of the heating system in the nave will result in an increase in installed power of 25 200 watts, from 31 425 watts to 56 625 watts. This again corresponds to an increase from 18.4 W/m^3 to 33.2 W/m^3. This is now within KA's recommendation of 27-35 W/m^3 to be able to perform efficient, intermittent heating. This also means that all rooms in the church have an installed heating capacity between 27 and 35 W/m^3.

According to the simulation in Simien, this upgrade can provide an annual energy saving of approximately 20 300 kWh, or around 31% of the annual consumption. Using the electricity price that Landvik church experienced in 2022 as a basis, i.e., 1.9854 kr/kWh, this will provide an annual cost saving of about 40 000 kr.

The company who supplied the heating system to Eide church in 2014 provide these prices when asked about costs associated with 550W bench heaters of the same type as in Eide:

- Price estimate per heat source: 5500-6500 kr, excluding VAT and shipping.
- Installation per heat source: 500 kr
- Control system: 70-80 000 kr excluding VAT
- In addition, there is electrical work etc.

Given a worst-case scenario in terms of price, where shipping accounts for 7% of the cost per heater and electrical work accounts for 10% of the cost per heater, this will result in a total cost of:

$$\begin{gathered}\text{Investment cost} = 84\,(\text{heaters}) \times [6500\,(\text{kr/heater}) + 500\,(\text{installation}) + \\ 455\,(\text{shipping}) + 650\,(\text{electrical work})] + 80,000\,(\text{control system}) = 760,820\,\text{kr}\end{gathered} \tag{4.7}$$

This may sound reasonable, but for comparison, the total cost of the heating system in Eide church in 2014 ended up costing 535,528 kroner. This was for a total of 38 heating panels, though of slightly different types, but with a clear majority of bench heaters (22 pcs). With an inflation of 25.45% from 2014 to 2022 [6], this corresponds to a cost today of:

$$535,528\,\text{kr} + 25.45\% = 671,832\,\text{kr} \tag{4.8}$$

If we then subtract the cost of the control system (90 000 kr) and divide by the 38 panels in Eide, we find that with today's value of the krone, the cost per heating panel will be:

$$\frac{671,832\ \text{kr} - 90,000\ \text{kr}}{38\ \text{panels}} = 15,311\ \text{kr/panel} \tag{4.9}$$

Multiplied by the necessary number of bench heaters in Landvik church, in addition to adding the control system at 90 000 kr, we find a total cost of:

$$15,311 \text{ kr/panel} \times 84 \text{ panels} + 90,000 \text{ kr control system} = 1,376,124 \text{ kr} \tag{4.10}$$

This corresponds to a cost that is 80% higher than what was found in the first calculation shown in Equation 4.7.

If we further calculate 760 820 kr as a minimum value and 1 376 124 kr as a maximum value, we find that the shortest payback time will be:

$$\text{Payback time, minimum investment cost} = \frac{760,820 \text{ kr}}{40,000 \text{ kr/year}} \approx 19 \text{ years} \tag{4.11}$$

And for the largest investment cost:

$$\text{Payback time, maximum investment cost} = \frac{1,376,124 \text{ kr}}{40,000 \text{ kr/year}} \approx 34 \text{ years} \tag{4.12}$$

In addition to the costs mentioned above, it is very important to be aware that a power increase of 25 200 watts, in a 230-volt electrical system, will lead to an increased maximum current of:

$$\frac{25,200 \text{ W}}{230 \text{ V}} \approx 110 \text{ A} \tag{4.13}$$

Such an increase will almost certainly lead to a necessary upgrade of the main fuse, and there is a good chance that the intake cable will also have to be replaced with a thicker diameter. In the worst case, such a change could lead to higher connection charges if both the upstream transformer and the power grid in general need to be upgraded. Such costs could make the total calculation significantly worse.

Figure 4.34 and 4.35 on the next page show the simulated temperature in the nave during heating. Figure 4.34 shows the temperature rise under "normal" conditions, i.e., as the church appears today, with a resting temperature of 10°C and an operating temperature of 19°C. The heating time is 11.5 hours, from 00:30 to 12:00. The outside temperature in the simulation is set to −3°C. The green line shows the air temperature in the room, while the blue line shows what in Simien is called "Operational temperature in the zone", which refers to the perceived temperature and also includes radiation from surfaces.

It shows from the graph that the air temperature is higher than the perceived temperature during the entire heating period. The perceived temperature seems to reach a peak at around 18°C. Compared to the measured temperatures, previously shown in Figure 4.25, the measurements show a higher indoor temperature compared to the simulated ones. On the basis of this, it is important to remember that these figures only show a theoretical curve.

Figure 4.35 shows the simulated temperature in the nave during heating, but this time with the upgraded heating system (33.2 W/m^3), and with a shorter heating time of 5 hours, and a lower rest and operating temperature. It is clear that heating happens quite a lot faster compared to the current heating system. The operational temperature does not seem to reach quite 18°C, but rather seems to reach a maximum at 16°C. Because the heat comes from right under the benches, this may still be good enough to provide a comfortable temperature for the congregation.

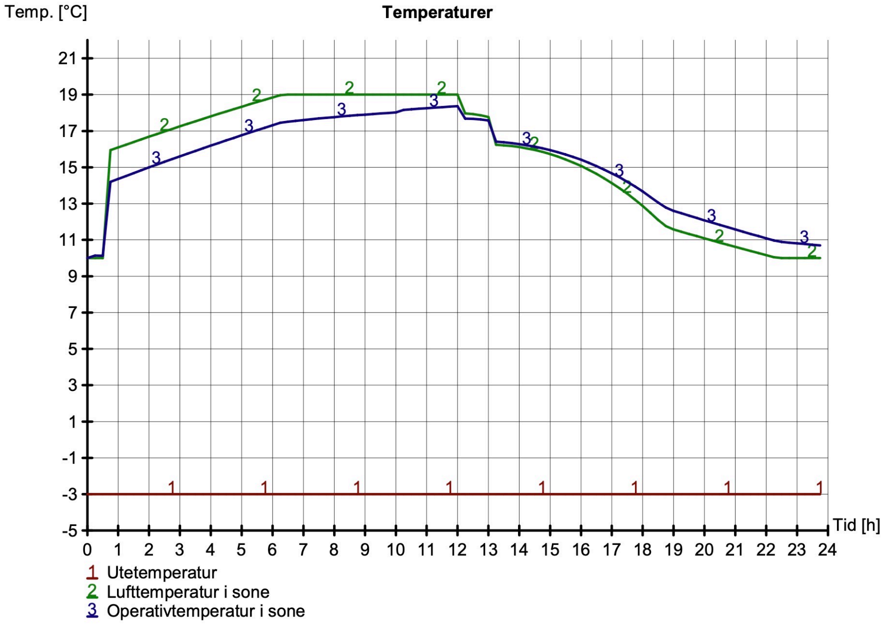


Figure 4.34: Simulated Temperature Rise under Current Operating Conditions

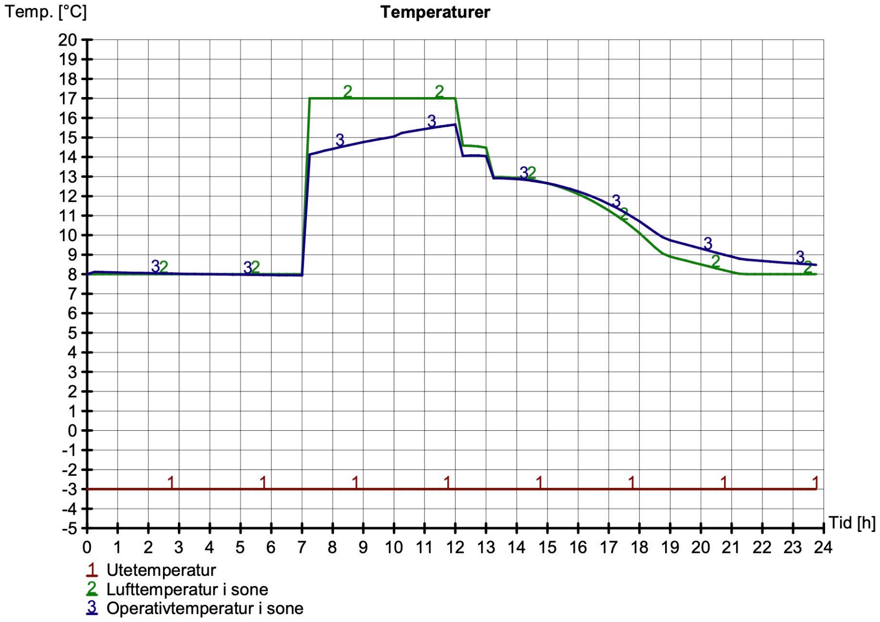


Figure 4.35: Simulated Temperature Rise with increased Heating Capacity

Furthermore, Figure 4.36 and 4.37 show the simulated relative humidity in the nave during the heating shown in the two previous figures. Figure 4.36 shows the relative humidity during heating with today's installed heating system, while Figure 4.37 shows the relative humidity with the new heating system with increased power.

By comparison, it is clear that such a upgraded heating system will provide much shorter periods with reduced humidity, which can be positive for the preservation environment. In addition, by lowering the resting temperature to 8°C, it is seen that the relative humidity in the church is somewhat higher, from 52% to 60%.

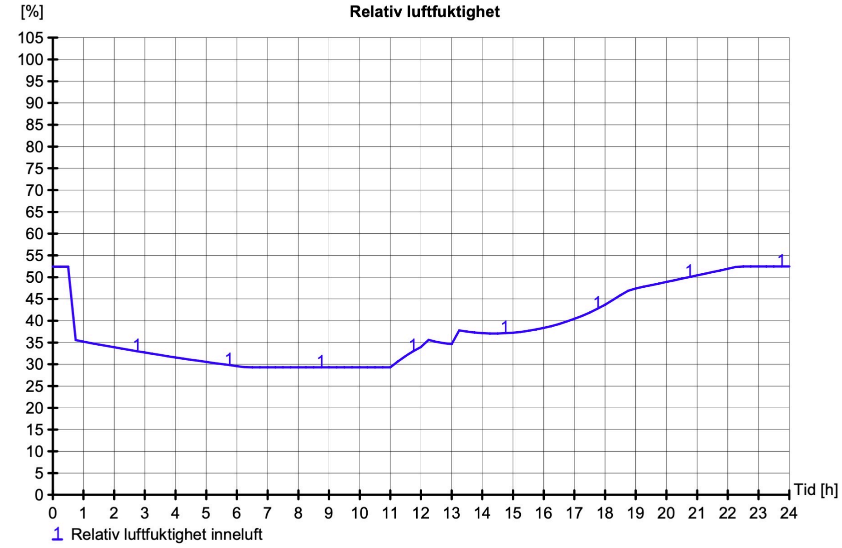


Figure 4.36: Simulated Relative Humidity during the Heating Period

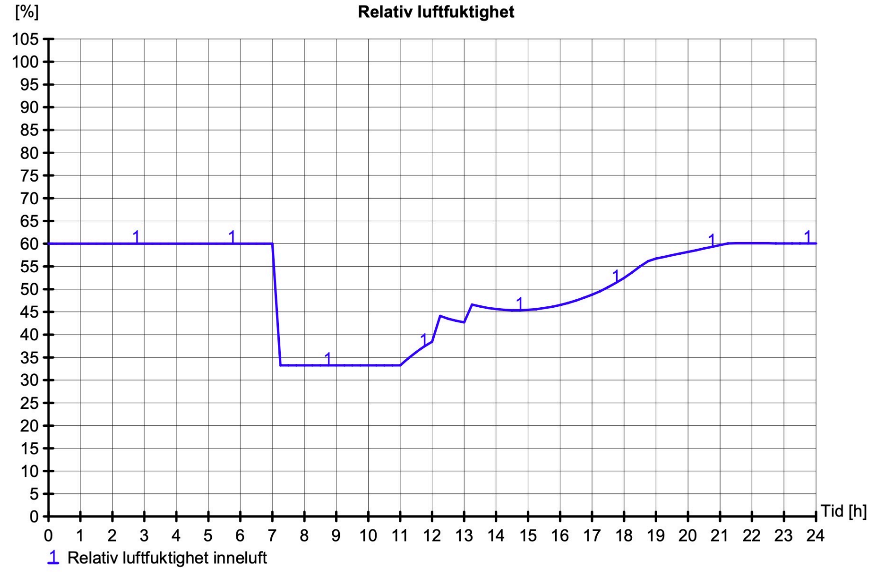


Figure 4.37: Simulated Relative Humidity during the Heating Period with increased Heating Capacity

4.3 Grimstad Church

4.3.1 Temperature and Humidity

In this subchapter, the results from Grimstad church will be presented. First, the data on temperature and relative humidity, as well as energy consumption, will be presented, followed by calculations made on the energy wells and heat pump for the church. The subchapter thus has the same structure as the previous result chapters about Eide and Landvik church.

Figure 4.38 on the next page shows the measured temperatures in the church during the measurement period, while Figure 4.39 shows the placement of the data loggers in the church. The measurement period mainly lasted for 6 days from March 22, 2023, to March 28, 2023. However, from the figure, it appears that one of the loggers, Logger 4, did not stop taking measurements until March 30, two days after the other loggers. This was due to a misunderstanding among one of the church visitors, and the logger was moved from its original position shown in Figure 4.39, to a drawer near the altar just before the remaining loggers were collected. This did not have any impact on the final result.

During the measurement period, the outdoor temperature, represented by Logger 1, varied between approximately 10°C and 0°C. Logger 10, placed in the narthex, shows a lower temperature than the rest of the church. This result was also seen in the narthexes of both Eide and Landvik church. It can be seen that Logger 3 and 7, marked in green and pink respectively, show sudden changes in temperature, beyond what the other measurements show. This is most likely due to the loggers' placement right in front of the large south-facing windows.

During the measurement period, two different heating periods were logged. Only the heating in connection with an activity on March 26 is fully visible. The graph shows that the resting temperature was stable just above 10°C, and achieved an operating temperature of around 19°C. The operating temperature was maintained for a relatively long period, far beyond the duration of the activity. Logger 9, positioned directly next to the organ, displays the highest temperature amongst the loggers during the heating on March 26. Logger 5, placed underneath the southern gallery, on the other hand, shows the lowest temperature.

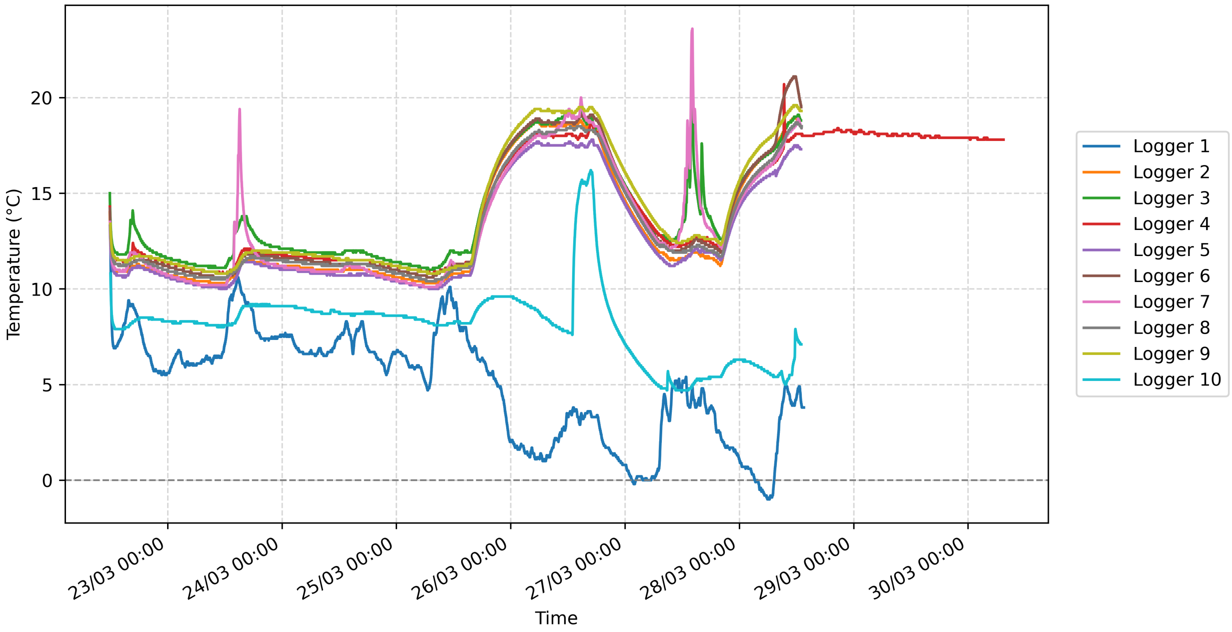


Figure 4.38: Measured Temperature during Heating in Grimstad

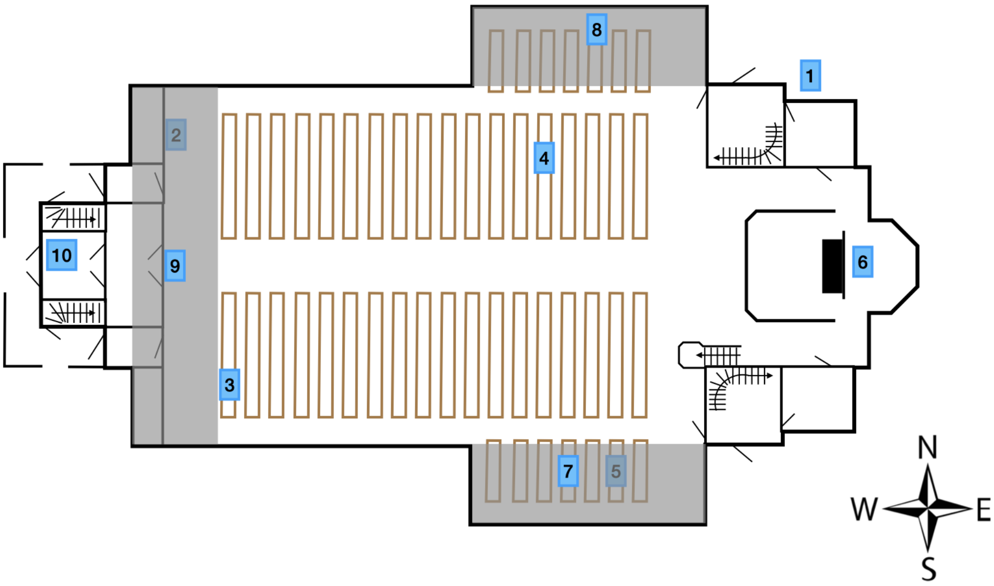


Figure 4.39: Placement of Temperature and Humidity Loggers in Grimstad

Figure 4.40 shows the relative humidity during the measurement period. The relative humidity measured outdoors has been quite high throughout the period, between 60 and 90%. As seen in the other churches, the relative humidity in the narthex is higher than in the rest of the church. This is likely due to the lower temperature in this room. The other loggers in the church have measured a relative humidity between 50 and 60% at 10°C, before it dropped to about 40% during heating. After the heating period, the humidity rises again.

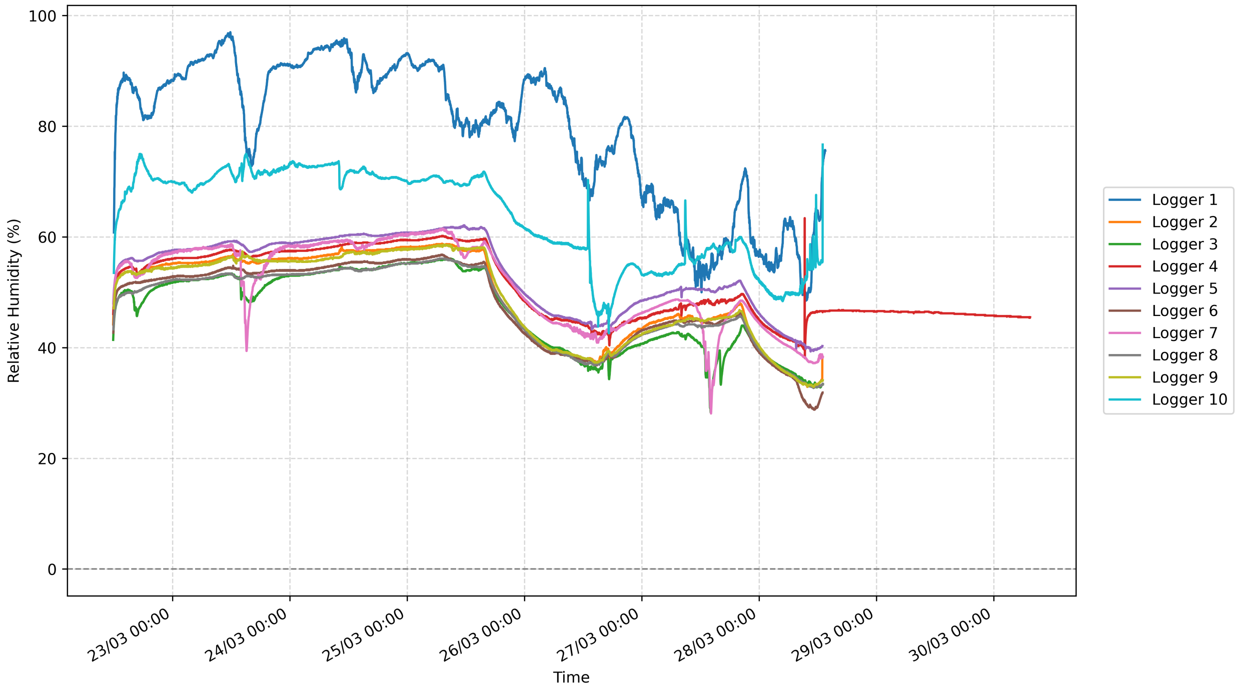


Figure 4.40: Relative Humidity during Heating Period Grimstad

Thermography of Grimstad church, unlike Eide and Landvik, has not been performed. However, surface measurements of the wall-mounted radiators in the church during heating have been conducted, which showed a temperature of 60°C.

4.3.2 Historical Energy Consumption

Figure 4.41 shows the actual and temperature-corrected electrical energy consumption in Grimstad church from 2010 to 2022. The annual average temperature at Landvik weather station is shown with the green dashed line. From 2010 to 2012, a significant decrease can be seen, particularly in the temperature-corrected energy consumption. The reason for this decrease is unclear. From 2012 to 2022, no very specific trend is discernible, and the energy consumption remains relatively stable between 35 000 and 50 000 kWh.

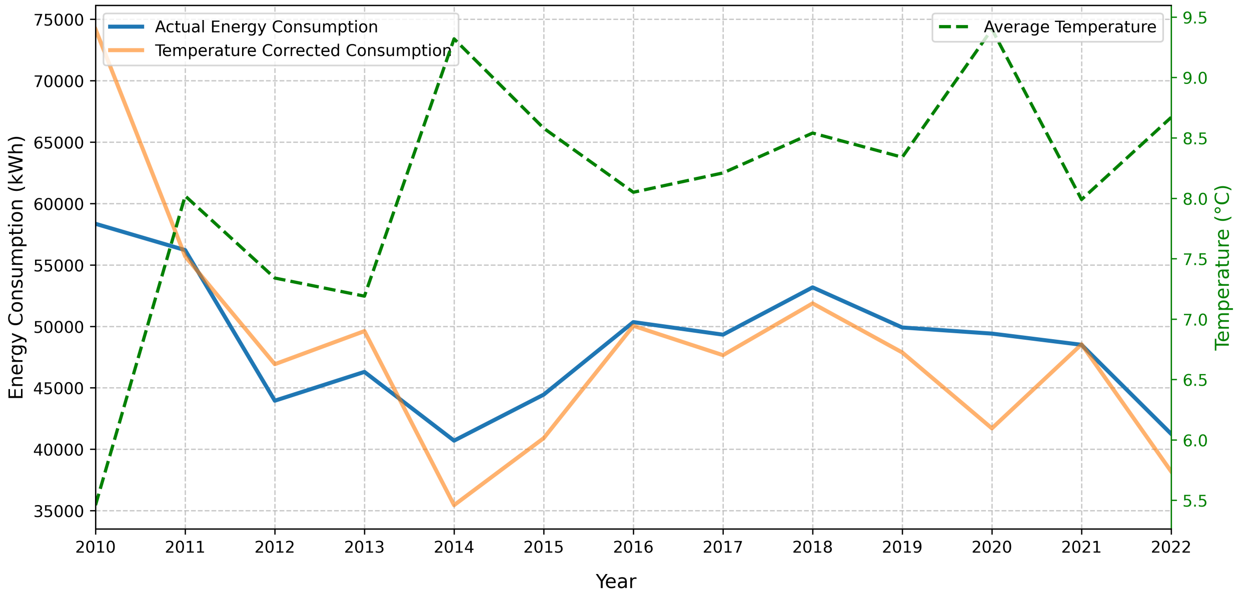


Figure 4.41: Historical Energy Consumption and Temperature Correction Grimstad 2010-2022

Figure 4.42 shows the temperature-corrected electrical energy consumption in Grimstad church from 2016 to 2022. The average of the measurements is shown with the red dotted line. If the year 2020 is excluded, the church has had an annual temperature-corrected average electrical energy consumption of just over 47 000 kWh. In addition, there is an annual consumption of biofuel oil of about 15 000 liters.

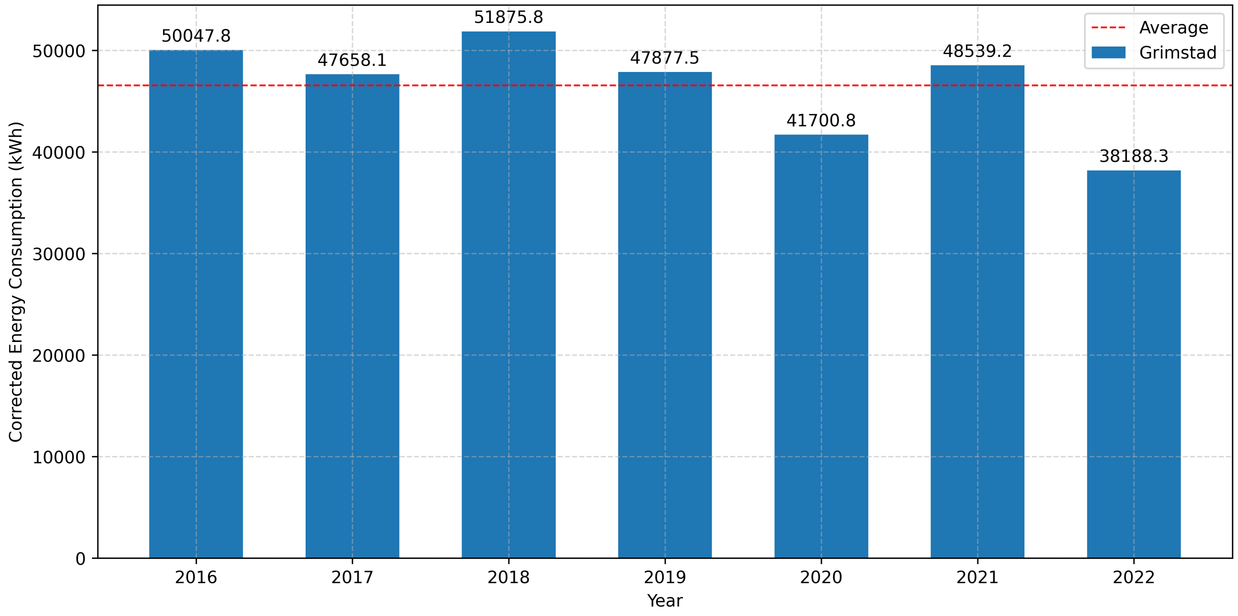


Figure 4.42: Temperature Corrected Energy Consumption Grimstad 2016-2022

4.3.3 Ground-Heat and Heat Pump Calculations

In this subsection, the calculations and results of the geothermal wells and the heat pump in Grimstad church will be presented.

As mentioned in Chapter 3.6, from an economic perspective, it is not cost-effective to design the heat pump to match the entire power demand. The lower the power of the heat pump, the lower the cost. By not replacing, but rather implementing the heat pump as an addition to the oil furnace, redundancy in the heating system is ensured. Thus, the heating system is not as vulnerable to downtime during repairs or other services that may occur.

Figure 4.43 shows the correlation between the capacity of the heat pump and the proportion of the annual energy consumption it covers. The data in the graph is based on numbers from Landvik church, but it is assumed that these are highly applicable to Grimstad church as the churches have a relatively similar activity pattern in almost identical climates.

From the plot, it can be seen that even a heat pump with a capacity of only 10% of the maximum power requirement can cover more than 40% of the annual energy consumption. A heat pump with a capacity of 30% can further cover approximately 75% of the energy consumption. From the graph, it can be seen that the increase in the contribution to energy consumption is minimal when the heat pump's capacity goes from 50 to 100% of the maximum power demand. A heat pump that will cover the entire maximum power demand (100%) will only cover 10% more of the energy consumption than a heat pump with a capacity of 50% of the maximum power demand. Based on this, it is further assumed that a heat pump with a capacity of 50% of the maximum power requirement is the most optimal solution from an economic perspective.

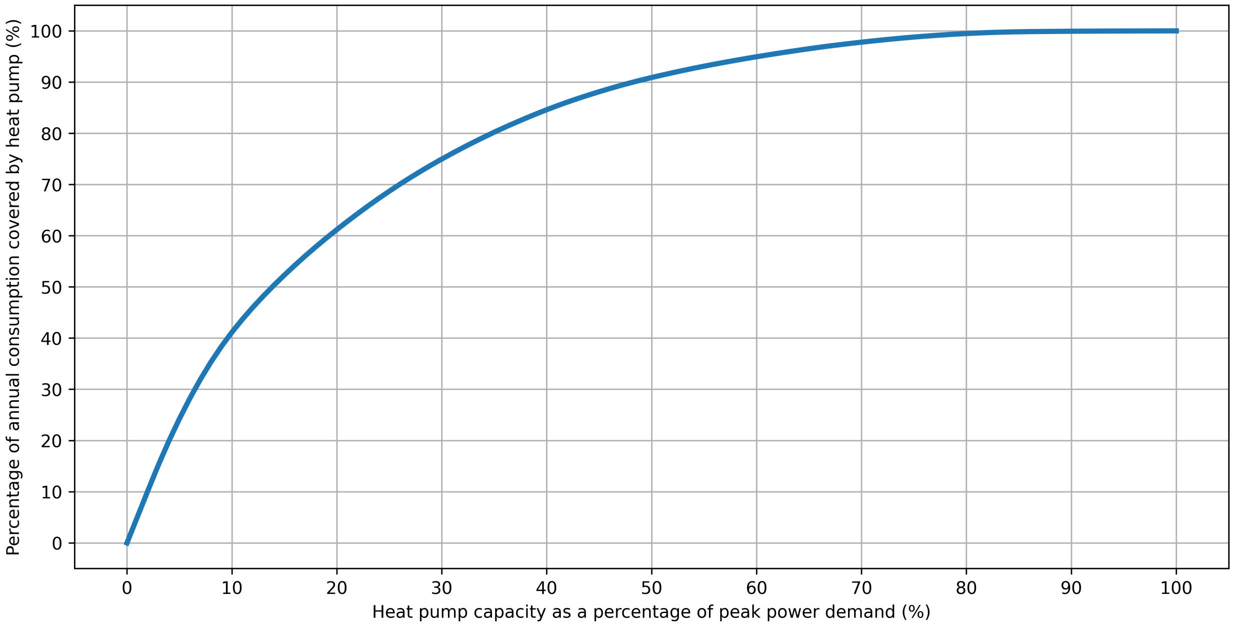


Figure 4.43: Correlation between Heat Pump Capacity and Annual Consumption Coverage

Figure 4.44 shows the hourly-based power consumption (kWh/h) in decreasing order for a whole year. The heat pump, covering 50% of the maximum power demand, is considered as a base load (marked in blue) and the oil furnace is considered as a peak load (marked in orange). It becomes clear how rarely the oil furnace actually would be in operation. In this case, only 817 hours per year. This corresponds to less than 10% of the time. The area under the graph corresponds to the annual energy consumption. An interesting observation is that in over 4000 hours per year, the heat pump, which is designed to deliver 50% of the total power requirement, will only need to deliver 20% or less. A heat pump that covers 50% of the power requirement will thus cover a total of 90.89% of the annual energy consumption. This further means that 90.89% of the annual consumption of bio heating oil can be cut.

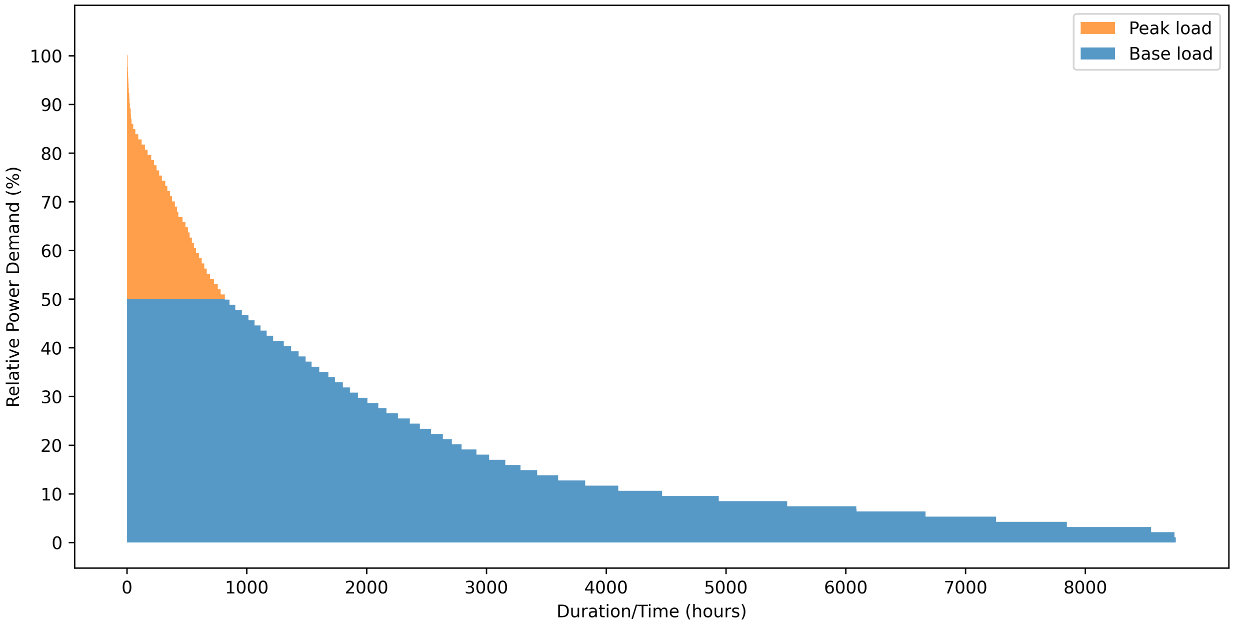


Figure 4.44: Load Duration Curve, Base and Peak Load

To further dimension the heat pump, and later also the energy wells, the actual power requirement in Grimstad church must be determined.

The rating plates on the boiler and burner display a power of 160 kW and 178 kW, respectively. Given the hydronic heating system in the church, consisting of around 30 old-fashioned and relatively small single-layer radiators, such a high output power seems unlikely.

Assuming that there are 30 radiators in the church, each of these has an area of 1.5 m^2, with a heat transfer coefficient assumed to be 10 $\mathrm{W/m^2K}$ (although this is temperature dependent), the radiators would in that case need to have a surface temperature of:

$$Ts = \frac{Q}{hA} + Ta = \frac{160,000\,\mathrm{W}}{10\,\mathrm{W/m^2K} \times 45\,\mathrm{m}^2} + 10\,^{\circ}\mathrm{C} \approx 365.56\,^{\circ}\mathrm{C} \tag{4.14}$$

Even doubling the heat transfer coefficient h to 20 $\mathrm{W/m}^2K$ results in a temperature of over 180°C.

This seems very unlikely, considering that the surface temperature of the radiators has been measured at 60°C, and because the radiators are mounted without any form of protection.

This would have posed a significant risk of burns.

The exact number of radiators in the church is not known, and this is therefore a very inaccurate way of calculating the power requirement. The ideal way to do this would have been to gauge the oil level in the oil tank before and after heating. This has not been possible to do. Further in the calculations, the rule of thumb saying that the annual consumption divided by 200 will give an approximate estimate of consumption on the coldest day of the year, will be used.

This gives a daily maximum consumption of bio fuel oil corresponding to:

$$\frac{15,000 \text{ L}}{200} = 75 \text{ L} \tag{4.15}$$

Given that the heating time is as measured in Figure 4.38, that is 12 hours, this will give an hourly value of:

$$\frac{75 \text{ L}}{12 \text{ h}} = 6.25 \text{ L/h} \tag{4.16}$$

1 liter of bio heating oil has an energy equivalent to 9.09 kWh, so 6.25L corresponds to 56.8 kWh/h = 56.8 kW. It can further be assumed that the burner has an efficiency of 90% under these conditions. This will be taken into account in further calculations.
From the previous findings, it was determined that a heat pump with a rated output equivalent to 50% of the maximum power requirement could cover over 90% of the annual energy demand. Thus, an appropriate heat pump in this case would be calculated as follows:

$$P_{\text{heat pump}} = P_{\text{max}} \times \eta_{\text{eff}} \times \text{ratio} = 56.8 \text{ kW} \times 90\% \times 50\% \approx 25.5 \text{ kW} \tag{4.17}$$

In order to further calculate the required depth of the energy wells, the COP factor of the heat pump must be considered. The COP factor is dependent on the temperature on the inlet side (i.e., from the fluid circulating in the well). In this context it is set to 3.5, which corresponds well with the data sheet of a 24 kW ground source heat pump from the well-known heat pump manufacturer NIBE.
Assuming a ground source heat pump of 25.5 kW, with a COP factor of 3.5, this means that the power that must be obtained from the energy well(s) is equivalent to:

$$P_{\text{well}} = P_{\text{heat pump}} - \frac{P_{\text{heat pump}}}{\text{COP}} = 25,500 \text{ W} - \frac{25,500 \text{ W}}{3.5} \approx 18,000 \text{ W} \tag{4.18}$$

The remaining power, around 7500 W, must be supplied from the grid.

One can expect a power output between 20-80 watt per meter of energy well [97]. Taking the average of this, i.e., 50 W/m, the required well depth can be found:

$$L_{\text{well}} = \frac{P_{\text{well required}}}{P_{\text{well W/m}}} = \frac{18,000 \text{ W}}{50 \text{ W/m}} = 360 \text{ m} \tag{4.19}$$

This could further be divided up into two wells of 180 meters each.

In the existing heating system, approximately 15 000 liters of bio fuel oil is consumed per year. Assuming 9.09 kWh/L, and an annual efficiency of 80% in the boiler, this corresponds to an annual energy consumption of:

$$E_{\text{annual}} = V_{\text{oil}} \cdot E_{\text{oil per L}} \cdot \eta_{\text{boiler}} = 15,000 \, \text{L} \cdot 9.09 \, \text{kWh/L} \cdot 80\% = 109,080 \, \text{kWh} \tag{4.20}$$

To find the annual electrical energy consumption of the heat pump, the SCOP factor and the delivered energy from the heat pump must be considered. The SCOP factor is typically a little higher than the COP factor. Further assuming a SCOP factor of 4.

It was previously assumed that a heat pump with a rated output 50% of the maximum power requirement could cover 90.89% of the annual energy consumption. Thus, in Grimstad church, a heat pump with a rated output of 25.5 kW will cover a total of 99 143 kWh. With a SCOP factor of 4, this corresponds to an annual electrical energy consumption of:

$$E_{\text{electric}} = \frac{E_{\text{total}} \times \text{coverage}}{\text{SCOP}} = \frac{109,080 \text{ kWh} \times 90.89\%}{4} \approx 25,000 \text{ kWh} \tag{4.21}$$

At the same time, 90.89% of the bio fuel oil can be saved. This corresponds to an annual saving of:

$$V_{\text{oil saving}} = V_{\text{oil}} \times \text{coverage} = 15,000 \text{ L} \times 90.89\% \approx 13,600 \text{ L} \tag{4.22}$$

In summary, a ground source heat pump with a rated output of 25.5 kW, supplied from two energy wells each 180 meters deep, will presumably be able to cover 90.89% of the church's energy needs for heating, thus saving 13 600 liters of bio fuel oil annually. This solution will result in an increased annual electrical energy consumption of approximately 25 000 kWh. The two wells could be drilled in the parking lot outside the church, as shown in Figure 4.45, with pipes coming into the church in the existing technical room in the basement.

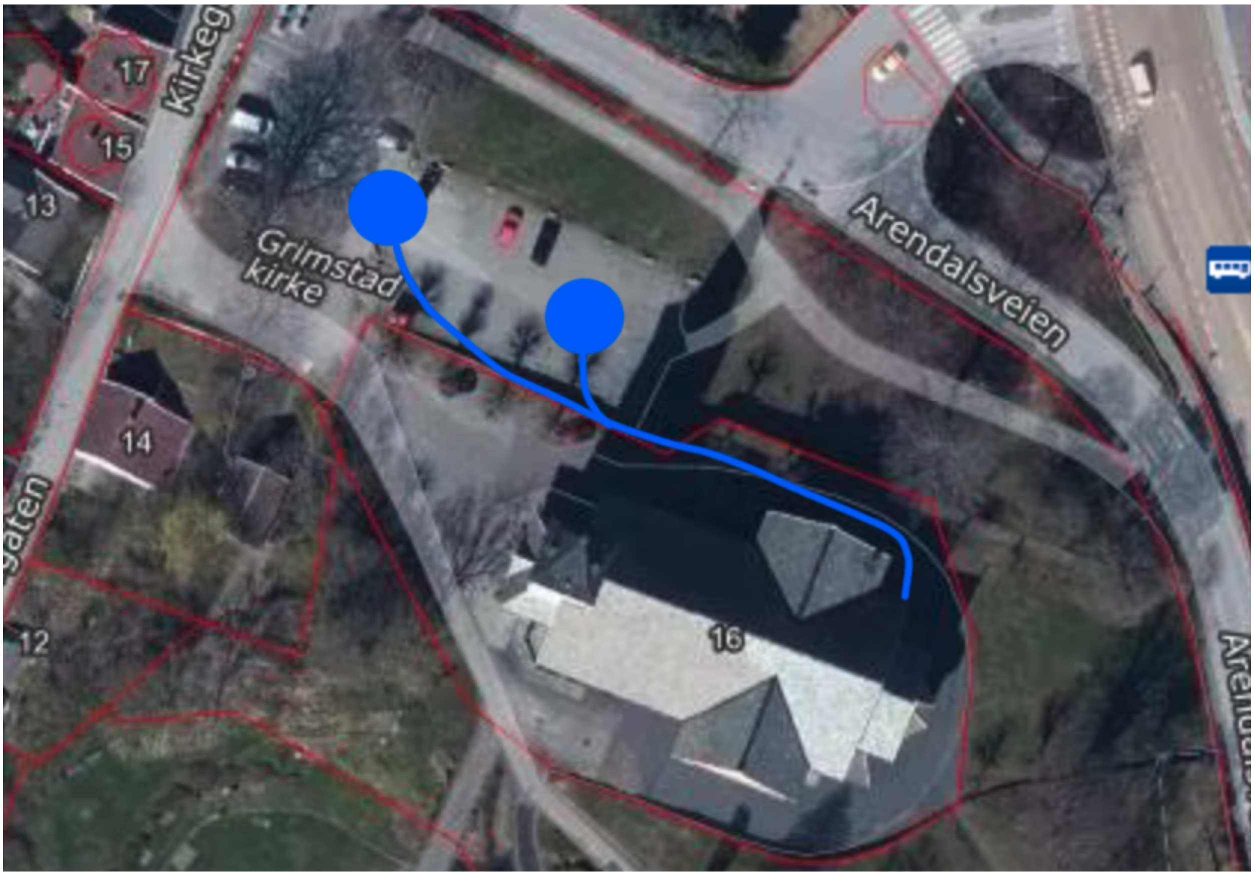


Figure 4.45: Potential Placement of Energy Wells in Existing Parking Lot Grimstad Church

4.3.4 Heat Pump Economy and Potential Savings

As summarized in the previous subsection, the heat pump will provide annual fuel oil savings of 13 600 liters, and an increased consumption of electrical energy equivalent to about 25 000 kWh. In 2022, Grimstad church experienced an average electricity price of 1.7204 NOK/kWh, and an average oil price of 17.47 NOK/L.

Therefore, the cost savings would be:

$$\text{Cost savings} = 17.47\ \text{NOK/L} \times 13,600\ \text{L} - 1.7204\ \text{NOK/kWh} \times 25,000\ \text{kWh} = 194,582\ \text{NOK} \tag{4.23}$$

This calculation does not take into account the likely increased power tariff or other potentially necessary upgrades due to the increased power. The increased electrical power requirement is approximately 7500W, which in a 230-volt electrical system corresponds to an increase in maximum current of:

$$\text{Current increase} = \frac{7500\ \text{W}}{230\ \text{V}} = 32.6\ \text{A} \tag{4.24}$$

In the worst case, this could lead to the need to replace the main fuse and the intake cable. These aspects are not considered in the calculation, and it is unclear how these will in reality affect the total calculation.

With an annual cost saving of nearly 200 000 NOK, a ground source heat pump system would have to be extremely expensive to install for it not to be profitable. The total cost of installing a ground source heat pump is dependent on many factors, and determining the exact price is difficult, but an attempt can be made:

The cost can be divided into three parts: the drilling and mounting of the casing and collector (i.e., everything that is hidden underground), the heat pump itself, and the installation cost, i.e., getting everything connected.

The range of available prices for energy well drilling is relatively small, but some sources indicate that a 150-meter energy well costs between 37 500 and 45 000 NOK and that a 200-meter well costs between 50 000 and 70 000 NOK [8] [92]. For two wells of 180 meters, it should therefore not be unreasonable to assume 55 000 NOK per well, totaling 110 000 NOK.

For a ground source heat pump, it can cost between 100 000 and 250 000 NOK depending on the size. In this case, where a relatively large heat pump of 25.5 kW is considered, it is reasonable to assume that this will be in the upper range, and a price of 250 000 NOK is assumed [65].

Finding the installation cost, in this case without more information, is very difficult, but for simplicity, an installation cost of 100 000 NOK can be assumed, including trenching with an excavator etc.

The total price then sums up to 460 000 NOK. If one assumes that the annual savings of almost 200,000 NOK is more or less correct, it almost doesn't matter whether the ground source heat pump installation costs 460 000 or 1 000 000 NOK - the system will anyway be paid off within very few years, given that energy prices remain at a 2022 level.

Chapter 5

Discussion

In this chapter, the key aspects of the results will be further summarized and discussed, with an effort to put them into a broader context in line with the thesis's framework. The outcomes from each of the three churches will initially be addressed on an individual basis. However, the summarizing subsection will compare the findings across all three churches.

5.1 Eide Church

During the four-day measurement period at Eide church, the rest and operational temperatures were confirmed to be 10°C and 19°C respectively. This was also verified by discussions with the sexton at Eide church, who is responsible for the heating and management of the premises. Despite exterior temperatures decreasing to lows of -10°C during the heating period, the data suggested that the heating system was efficient, ensuring comfortable temperatures in areas where occupants were seated.

The most considerable deviation in temperature measurements was recorded in the narthex, which barely maintained a temperature above 0°C. It is assumed that this relatively low temperature would probably affect the overall temperature within the rest of the church. The placement of the heating panel close to the ceiling in the narthex appears to be inefficient, with the panel reportedly rarely being in use due to perceived low heat output. Another contributing factor to the narthex' low temperature likely stems from the poorly sealed exterior door. A substantial gap is visibly present between the door and its frame, likely leading to unnecessary heat losses. This could potentially be easily fixed with door adjustments and/or the application of sealing strips.

Results from the thermography clearly highlight the issue of significant heat loss around the doors. The thermography also revealed heat loss at the joints between exterior walls. It remains uncertain if this is a constant issue or an occurrence specifically associated with the drying of the timber in the spring, especially closer to the end grain. A potential solution could involve sealing the walls from the inside using sheep's wool, according to KA, a method reportedly yielding promising results. Additionally, the thermography revealed that the bench warmers provide adequate warmth for those seated, thereby proving to be an effective heating method.

A 2016 report on the heating system in Eide church, published by KA, makes it clear that the surface temperature of the bench heaters far exceeded the maximum permitted limit within regulation [75]. According to the report, regulation IEC 60335-2-30, which governs electric heating products, specifies that the surface temperature of heating panels installed in church benches cannot exceed $70K$, or 70°C above the ambient temperature. At 20°C, this translates to a surface temperature of 90°C. The 2016 report documented the surface temperature at a staggering 150°C, and seven years later, this temperature has been recorded at approximately 120°C, still far above "legal" limits. In a worst-case scenario where the heating panels cause a fire, an insurance company could demand considerable compensation, especially since the flaw had already been previously identified. This should be addressed immediately, despite the potentially significant impact on heating efficiency.

The relative humidity remained mostly within the range of 40% to 60% throughout the entire measurement period. The exception was the narthex, which experienced a humidity level of over 60% towards the end of the measurement period, a likely result of particularly humid outdoor weather.

One of the most significant findings at Eide church involves a comparison of temperatures from the 2016 report and measurements conducted in this project. The 2016 report clearly indicated that it is entirely feasible to lower the resting and operating temperatures to 6°C and 16°C respectively, without negatively affecting church users or staff in any significant way. The report further stated that this temperature reduction could nearly halve the heating time, subsequently reducing energy consumption by between 30% and 40%, equivalent to between 10 000 and 11 000 kWh. There is no evidence to suggest that this proposed measure has been implemented, judging by the measurements conducted in this thesis. Assuming the proposed measure would have produced the suggested results, it implies that the church has missed out on energy savings equivalent to nearly 80 000 kWh over the last seven years.

The heating in the annex at Eide church also shows signs of inefficiency. This is somewhat understandable given that only standard wall-mounted convection heaters are installed. A cheap and easily implementable solution would be to install smart plug sockets with a thermostat on the heaters, so they can be connected to the existing internet in the church, and thus be remotely controlled and automated, contributing to additional energy savings. The door to the handicap toilet in the annex is also noted to be difficult to close, potentially resulting in heat losses. This should be looked into, in is probably a quick fix.

It is reasonable to assume that the church faces significant potential energy savings, up to 50% from today's level, by lowering the temperature in the church, adjusting and sealing doors, attempting to seal the exterior walls with sheep's wool, and upgrading the heating control system in the annex. All of these are measures come with very minimal to no investment costs and should absolutely be feasible.

Results from the simulation of PV modules on the church show that this is definitely something to consider as the technology matures and the price of solar energy continues to drop. Such projects have yielded good results in two other churches, but there are still significant challenges associated with the architectural change due to the solar panels. The simulations conducted in this thesis show that by covering the most sun-exposed roofs of the church, the annex, and the shed with ordinary PV modules, one could produce energy equivalent to 98% of the energy consumption the church experienced in 2022. If one could additionally implement the energy saving measures mentioned above, Eide church would become a net-positive church, meaning it would produce more energy than it would consume. Simulations including a battery in the PV system also show that this can significantly increase self-consumption of the produced energy, which could further strengthen the economic conditions for the system.

Even the implementation of the smallest proposed PV system, represented by PV alternative 3, could cover between half and a third of consumption, assuming the implementation of the above-mentioned energy saving measures, without directly changing the appearance of the church itself. With the high electricity prices Eide has experienced over the past year, almost any solar panel system would be profitable. However, it is very difficult to draw conclusions about the economy of the mentioned system, as future energy prices are impossible to predict, and the costs associated with such a special type of system are difficult to estimate.

5.2 Landvik Church

Temperature measurements in Landvik church confirm a resting temperature of 10°C and an operational temperature of 19°C. This was also verified during inspections of the church. The sexton (kirketjeneren) adjusts the church's temperature across various heating zones, as clearly indicated in the graphs, striving to manage it as efficiently as possible. Despite the heating system in the church being far from fulfilling KA's recommendation of 27-35 W/m^3, heating appears to occur relatively efficiently with an outdoor temperature between 0°C and 10°C. This situation is said to be different when the outdoor temperature drops significantly, and this must be taken into account by the sexton responsible for the heating. The heating system in the annex relies on simple, manually adjustable convection heaters. It would be worth considering the installation of smart plug sockets with a thermostat to remotely control the heat and thus save energy.

Results from the thermography of the church indicates significant heat losses, especially around windows and at the joints of the exterior walls. Just like proposed in Eide church, sheep's wool could be a possible measure to reduce heat loss and infiltration.

Measurements of the relative humidity show values between 40% and 60%, with slightly higher measurements made in the narthex. It is worth noting that the climate was very humid throughout the entire measurement period.

A model of the church made in the energy calculation program Simien shows that nearly 90% of the energy goes to heating the building, where again the most significant heat loss occurs through the exterior walls and as a result of infiltration. Eighteen different measures have been simulated to estimate which ones are worthwhile and which ones are less important.

For example, it seems that replacing all the windows in the nave with more modern windows that meet the insulation requirements of TEK17 will only result in an annual energy saving of around 4.5%. This is likely a a very low percentage considering the cost and efforts of replacing the windows. On the other end of the scale, unsurprisingly, closing off the church and lowering the temperature to a preservation temperature of 6°C would provide the most significant saving of over 70%. A more realistic approach, however, would be to lower the temperature by one or two degrees, which could provide an annual energy saving of 9% and 18% respectively. This should be considered to be quite good, especially since the investment cost is zero to none. Thus, it would be worth considering whether it is possible to ask the congregation to dress more warmly in cold periods.

Using the total number of activities in 2022 (134) as a basis, and comparing the energy consumption at normal operation with the energy consumption at a constant 10°C, which is the church's resting temperature, each activity "costs" approximately 203 kWh. This is equivalent to around 400 kroner per activity with 2022 electricity price levels. By relocating the 41 choir practices that are assumed to occur in the church each year, an estimated 12.8% of the annual energy consumption could potentially be conserved.

Landvik church is also the only church in this study still using traditional incandescent light bulbs. Considering a best-case scenario where LED bulbs with 10% of the power of traditional bulbs provide the same light, this would result in an annual saving of 7.6%, equivalent to around 5 000 kWh. With electricity prices equivalent to the 2022 level, this adds up to to nearly 10 000 kroner in annual savings, and a payback period of just over one year. Regardless of whether it is a best-case scenario or not, LED bulbs will almost always be a no-brainer, with the installation being easily performed by one person without specialized competence.

The simulation looks at possible savings by upgrading the heating system to one with higher power, thus being able to lower the temperature and therefore the heating time. The simulations show excellent results with an annual saving of approximately 30%. However, it is highly uncertain whether this will be feasible in a real world scenario, as the increased power will likely require other necessary upgrades to the electrical grid. In addition, there are significant uncertainties associated with the costs of implementing such a new system, and this must be carefully examined before a conclusion can be drawn. The simulation nonetheless indicates that by reducing the heating time, the duration of the humidity being too low would be decreased, thereby improving the preservation environment in the church.

By combining various of the mentioned measures, such as lowering the resting and operating temperatures by 2°C, switching from incandescent bulbs to LED bulbs, relocating choir rehearsals, and attempting to seal walls window frames, these combined measures could lead to annual energy savings of up to 40%.

5.3 Grimstad Church

Similar to the other churches, Grimstad church maintains a resting and operational temperature of 10°C and 19°C, respectively. The relative humidity was in the measuring periode measured to be relatively stable, mainly between 40% and 60%, with the exception of the narthex, which showed elevated levels. Despite the church being primarily heated with biofuel oil, the electric energy consumption remains relatively high, between 40 000 and 50 000 kWh per year. It may be beneficial to thoroughly examine all electricity consumers to ensure that nothing is drawing an unnecessary amount of power.

When it comes to sizing the energy wells and the heat pump, it is challenging to draw any clear conclusions due to a thin data basis. What appears certain, however, is that even a relatively small heat pump could cover a substantial portion of the energy consumption, drastically reducing the consumption of biofuel. Further, it has been found that with the church's usage pattern, a heat pump with a capacity of 50% of the maximum power demand could cover approximately 90% of the church's energy consumption. It is thus likely not cost-effective to size the heat pump for any higher power than about half of the specific demand. By preserving the oil furnace as a peak load, high supply security in the church can be ensured.

The uncertainty in the calculation lies mainly in how much power the current system actually delivers. Although the boiler is designed for delivering up to 160 kW, it is unlikely that this is the actual heating power delivered, based on the number of radiators and their measured temperature.

To ensure accurate calculations of the heat pump and energy wells, it is essential to use the actual power requirement as the basis. A better approach to this would have been to gauge the oil tank before and after heating on one of the coldest winter days. There has not been an opportunity to do this in this project.

A similar project was carried out in Risør church, and this project shows very promising results and should be looked at closely if considering geothermal heating in Grimstad church. It is worth mentioning that Risør church has status as fully protected, a stricter preservation status than Grimstad church. Thus, it should be reasonable to assume that such a project should be feasible in Grimstad church, from a preservation perspective.

Actual costs of the drilling of energy wells, the cost of the heat pump itself, and the costs on installation are very difficult to determine as this can vary enormously from project to project. Despite uncertainties in the calculations made around the heat pump, it is clear that the potential for saving is enormous, as the annual consumption of biofuel oil is around 15 000 liters. In this context, it is also important to remember that a heat pump will increase electricity consumption, with the potential increased costs that it will entail.

5.4 Limitations

It is important to acknowledge that the results presented in this thesis may hold various levels of uncertainty, which could impact the overall significance of the findings. In other words, the quality of the results is no better than the quality of the data they are based on. The various physical investigations and measurements conducted in relation to this project represent in reality only a snapshot of the situation in the churches. A good example of this is measurements of temperature and relative humidity. Although the measurements show that, for example, the relative humidity is entirely in line with the recommendations given by the Directorate for Cultural Heritage and KA, the same values might be completely off in another part of the year when the climate, for example, is drier.

Ideally, there are several measurements that should have been carried out and followed up over a longer period of time, ideally over a year, but this has not been possible given the format of the master's thesis. In simulations and calculations, too, it has been necessary to make some simplifications and assumptions, which are described in detail in the Chapter 3. It is important to remember that such simplifications and assumptions can be a significant source of error, even though they have been largely attempted to be avoided.

5.5 Summary

All three churches examined in this thesis employ the strategy of intermittent heating, which is beneficial for energy savings and preservation environments. All the churches maintain a resting temperature of 10°C and an operating temperature of 19°C. This is slightly above the recommended resting temperature of between 5°C and 8°C, as well as an operating temperature between 16°C and 19°C. However, this provides a good basis for future energy savings.

Results from this thesis show that the following annual energy savings should be possible:

- Eide Church: annual energy savings of between 30% and 50% by lowering the resting and operating temperature to 6°C and 16°C, respectively, as well as attempting to seal doors and walls, in addition to upgrading the heating control system in the annex. The results also reveal that by harnessing solar energy from the most sun-exposed roofs of the church, annex, and the shed, the church has the potential to generate more energy than it consumes, consequently becoming energy positive.
- Landvik Church: by combining various of the mentioned measures, such as lowering the resting and operating temperatures by 2°C, switching from incandescent bulbs to LED bulbs, relocating choir rehearsals, and attempting to seal walls and window frames, these combined measures could lead to annual energy savings of up to 40%.
- Grimstad Church: by implementing a ground source heat pump of 25.5 kW, supplied from two 180-meter deep energy wells, results from this thesis show that the church can save over 13 000 liters of bio oil per year equivalent to about 90%. This could lead to tens of thousands of kroner in annual savings.

A widely shared benefit of these measures is their ability to enhance the preservation environment within churches by increasing relative humidity. Additionally, most of these measures come with little or no investment costs, making them highly profitable.

The potential for energy savings with minimal investment is significant, yet it is questionable why these opportunities have not been explored earlier. One reason for this could be the perceived "gap" between those who hold the knowledge and those tasked with implementing it. For example, if skilled engineers and advisors at the employer organization KA develop intricate reports about appropriate heating, those reports may not achieve their intended purpose if those who actually manage the heating systems do not engage with them. It seems that there is a disconnect where those with direct control over energy consumption may lack the necessary understanding to utilize these strategies effectively.

In addition, it seems that the energy consumption of a church is not solely determined by the tools available, but also by the commitment and focus of the church staff towards energy conservation. While this thesis does not explore the potential energy savings on a national level, the significant scale of the opportunity is evident with over 1600 churches in existence. It is crucial to note that the taxpayers ultimately bear the final cost, making it a matter worthy of serious consideration.

One possible solution to address this issue is for multiple church councils to collaborate and hire an engineer, or someone with relevant technical expertise, to oversee energy related matters. The cost of this employment could for example be divided among the councils based on the size of the buildings they manage. Let's say three councils jointly own 1000 m^2 of church property. If one council owns 300 m^2, they would then be responsible for 30% of the hiring cost.

It is important to acknowledge the extensive expertise and knowledge acquired by certain employees in KA. As these key individuals approach retirement, it is crucial to establish an effective method of knowledge transfer to ensure the preservation of valuable insights.

Chapter 6

Conclusions

This thesis has illustrated considerable potential for energy conservation and economic savings in three Norwegian wooden church buildings, through the implementation of renewable energy systems and through the implementation of energy efficiency measures. These strategies have the potential to reduce energy consumption by 30% to 50%, all while maintaining the architectural and cultural heritage of these historical landmarks.

The research has also revealed a disconnect between the entities holding the technical knowledge and those tasked with the day-to-day operation of these buildings. To bridge this gap, the study proposes collaborative efforts such as the joint hiring of technical experts by church councils. Ensuring effective knowledge transfer, especially with the impending retirement of key experts, was also identified as a critical need.

Figure 6.1: Blue Skies and (unnecessary) Bright Light

The findings indicate a potentially scalable opportunity that could be applicable to a considerable portion of Norway's network of over 1,600 churches, potentially leading to significant economic and environmental impacts. This thesis stresses the need for church staff to not only possess, but also comprehend and use energy-saving tools effectively, thereby emphasizing the importance of heightening awareness around energy conservation.

In conclusion, the potential for energy savings in Norwegian churches is vast, and requires the balance of advanced technologies and basic practices. Amidst our climate crisis, all conservation efforts count, whether it is the installation of a high-efficiency heat pump or – as not shown in Figure 6.1 – simply remembering to just switch off the lights in broad daylight.

Further Work

This thesis has established a foundation for further exploration of energy efficiency in Norwegian churches. Several promising directions for future research have emerged.

A significant area to investigate is the detailed feasibility of implementing ground source heat pumps in these historical buildings. While this technology has been considered within the scope of this thesis, a comprehensive exploration could uncover new insights about its potential efficiency gains, cost-effectiveness, and impacts on the architectural integrity of the churches.

Creative alternatives to PV systems should also be considered for further investigation. Given the architectural preservation considerations of these historical buildings, unconventional and less intrusive solutions may be more suitable. For instance, solar window films or solar thermal systems could be explored as potentially less disruptive yet effective energy efficiency measures – at least in the future.

Additionally, exploring the potential advantages of digital tools and smart systems for energy conservation could be of great value. The integration of Internet of Things (IoT) devices or energy management systems may result in more automated and efficient control of energy usage in these buildings.

To conclude, this thesis has contributed to the understanding of potential energy savings within Norwegian churches, yet the area of study remains wide and full of opportunities. Each advancement in research represents progress towards a more sustainable future, with a clear focus on honoring and maintaining our cultural heritage. As we delve further into this field, we strive to maintain a careful equilibrium - preserving the past while powering the future.

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Appendix A

PV Alternative 1

Investment Cost (kr/kWp)	Investment Cost (kr/m^2)	Total Investment Cost (kr)	Lifespan (Years)	Total Production (kWh)	Cost per kWh (kr/kWh)	Annual Savings (kr)	Payback Period (Years)	Return on Investment (kr)
5000	1002,03	130350	25	565790,4	0,23	41170,47	3,17	898911,67
7500	1503,04	195525	25	565790,4	0,35	41170,47	4,75	833736,67
10000	2004,06	260700	25	565790,4	0,46	41170,47	6,33	768561,67
12500	2505,07	325875	25	565790,4	0,58	41170,47	7,92	703386,67
15000	3006,09	391050	25	565790,4	0,69	41170,47	9,5	638211,67
17500	3507,1	456225	25	565790,4	0,81	41170,47	11,08	573036,67
20000	4008,12	521400	25	565790,4	0,92	41170,47	12,66	507861,67
22500	4509,13	586575	25	565790,4	1,04	41170,47	14,25	442686,67
25000	5010,15	651750	25	565790,4	1,15	41170,47	15,83	377511,67
5000	1002,03	130350	30	670686,42	0,19	41170,47	3,17	1104764,01
7500	1503,04	195525	30	670686,42	0,29	41170,47	4,75	1039589,01
10000	2004,06	260700	30	670686,42	0,39	41170,47	6,33	974414,01
12500	2505,07	325875	30	670686,42	0,49	41170,47	7,92	909239,01
15000	3006,09	391050	30	670686,42	0,58	41170,47	9,5	844064,01
17500	3507,1	456225	30	670686,42	0,68	41170,47	11,08	778889,01
20000	4008,12	521400	30	670686,42	0,78	41170,47	12,66	713714,01
22500	4509,13	586575	30	670686,42	0,87	41170,47	14,25	648539,01
25000	5010,15	651750	30	670686,42	0,97	41170,47	15,83	583364,01

Table A.1: PV Alternative 1 Economy

Appendix B

PV Alternative 2

Investment Cost (kr/kWp)	Investment Cost (kr/m^2)	Total Investment Cost (kr)	Lifespan (Years)	Total Production (kWh)	Cost per kWh (kr/kWh)	Annual Savings (kr)	Payback Period (Years)	Return on Investment (kr)
5000	1002,03	94800	25	413689,62	0,23	38368,77	2,38	901466,04
7500	1503,04	142200	25	413689,62	0,34	38368,77	3,57	854066,04
10000	2004,06	189600	25	413689,62	0,46	38368,77	4,76	806666,04
12500	2505,07	237000	25	413689,62	0,57	38368,77	5,95	759266,04
15000	3006,09	284400	25	413689,62	0,69	38368,77	7,14	711866,04
17500	3507,1	331800	25	413689,62	0,8	38368,77	8,33	664466,04
20000	4008,12	379200	25	413689,62	0,92	38368,77	9,52	617066,04
22500	4509,13	426600	25	413689,62	1,03	38368,77	10,7	569666,04
25000	5010,15	474000	25	413689,62	1,15	38368,77	11,89	522266,04
5000	1002,03	94800	30	490386,56	0,19	37777,93	2,4	1091531,46
7500	1503,04	142200	30	490386,56	0,29	37777,93	3,6	1044131,46
10000	2004,06	189600	30	490386,56	0,39	37777,93	4,79	996731,46
12500	2505,07	237000	30	490386,56	0,48	37777,93	5,99	949331,46
15000	3006,09	284400	30	490386,56	0,58	37777,93	7,19	901931,46
17500	3507,1	331800	30	490386,56	0,68	37777,93	8,39	854531,46
20000	4008,12	379200	30	490386,56	0,77	37777,93	9,59	807131,46
22500	4509,13	426600	30	490386,56	0,87	37777,93	10,79	759731,46
25000	5010,15	474000	30	490386,56	0,97	37777,93	11,99	712331,46

Table B.1: PV Alternative 2 Economy

Appendix C

PV Alternative 3

Investment Cost (kr/kWp)	Investment Cost (kr/m^2)	Total Investment Cost (kr)	Lifespan (Years)	Total Production (kWh)	Cost per kWh (kr/kWh)	Annual Savings (kr)	Payback Period (Years)	Return on Investment (kr)
5000	1002,03	35550	25	152100,78	0,23	23274,41	1,49	560065,49
7500	1503,04	53325	25	152100,78	0,35	23274,41	2,24	542290,49
10000	2004,06	71100	25	152100,78	0,47	23274,41	2,98	524515,49
12500	2505,07	88875	25	152100,78	0,58	23274,41	3,73	506740,49
15000	3006,09	106650	25	152100,78	0,7	23274,41	4,48	488965,49
17500	3507,1	124425	25	152100,78	0,82	23274,41	5,22	471190,49
20000	4008,12	142200	25	152100,78	0,93	23274,41	5,97	453415,49
22500	4509,13	159975	25	152100,78	1,05	23274,41	6,71	435640,49
25000	5010,15	177750	25	152100,78	1,17	23274,41	7,46	417865,49
5000	1002,03	35550	30	180299,85	0,2	23057,18	1,5	675783,68
7500	1503,04	53325	30	180299,85	0,3	23057,18	2,25	658008,68
10000	2004,06	71100	30	180299,85	0,39	23057,18	3	640233,68
12500	2505,07	88875	30	180299,85	0,49	23057,18	3,75	622458,68
15000	3006,09	106650	30	180299,85	0,59	23057,18	4,5	604683,68
17500	3507,1	124425	30	180299,85	0,69	23057,18	5,25	586908,68
20000	4008,12	142200	30	180299,85	0,79	23057,18	6	569133,68
22500	4509,13	159975	30	180299,85	0,89	23057,18	6,75	551358,68
25000	5010,15	177750	30	180299,85	0,99	23057,18	7,5	533583,68

Table C.1: PV Alternative 3 Economy

Appendix D

Landvik Church Measurments

Rom / Sone	Kirkerom (Hovedskip)	Kirkerom (Sideskip N)	Kirkerom (Sideskip S)	Kirkerom (Totalt)	Våpenhus	Toalettrom	Dåpssakristi	Prestesakristi	Toalettkjeller	Vindfang Syd	Totalt Kirke	Kirkestue	Totalt
Lengde (Øst-Vest)	24,1	7,9	7,9		4,7	2,3	4,1	4,7	4,7	3,1		9,8	
Bredde (Nord-Sør)	7,9	5,5	5,5		5,6	3,1	4,3	4,4	4,4	2,3		5,5	
Takhøyde 1	5,1	5,1	5,1	5,1	2,7	2,0	2,4	2,2	2,2	2,6		1,5	
Takhøyde 2	6,7	6,7	6,7	6,7	5,9	3,3	4,4			4,4		3,8	
Gulvareal	190,0	43,5	43,5	276,9	26,5	7,1	17,6	20,7	20,7	7,0	376,4	53,4	429,8
Takareal	208,7	47,7	47,7	304,1	20,3	8,2	12,3	20,7	20,7	5,5	391,7	34,8	426,4
Veggareal N			111,1	131,1	12,5	6,1	13,9	10,3	10,3	10,7	175,0	15,0	
Veggareal Ø			95,2	104,8	24,1	10,3	10,2	9,6	9,6	5,8	164,8	14,5	
Veggareal S			120,4	131,1	12,5	6,1	13,9	10,3	10,3	10,7	184,3	15,0	
Veggareal V			70,4	104,8	24,1	6,3	10,2	9,6	9,6	5,8	136,0	14,5	
Volum				1 705,1	113,7	19,1	59,7	45,2	45,2	24,2	2 012,1	142,3	2 154,4
Total Varmeeffekt				31 425,0	3 400,0	569,2	3 400,0	1 500,0	1 500,0	1 100,0	42 894,2	4 220,0	47 114,2
Varmeeffekt / m^2				113,5	128,4	80,0	193,0	72,6	72,6	158,0	114,0	79,0	109,6
Varmeeffekt / m^3				18,4	29,9	29,9	57,0	33,2	33,2	45,5	21,3	29,6	21,9
Total Lyseffekt				8 380,0	420,0	20,0	270,0	140,0	140,0	90,0	9 460,0	630,0	10 090,0
Lyseffekt / m^2				30,3	15,9	2,8	15,3	6,8	6,8	12,9	25,1	11,8	23,5
Internlaster Hvile				10,0	0,0	4,0	0,0	150,0	0,0	0,0	164,0	50,0	214,0
Internlaster Drift				300,0	0,0	4,0	0,0	500,0	0,0	0,0	804,0	50,0	854,0
Internlaster Hvile / m^2				0,0	0,0	0,6	0,0	7,3	0,0	0,0	0,4	0,9	0,5
Internlaster Drift / m^2				1,1	0,0	0,6	0,0	24,2	0,0	0,0	2,1	0,9	2,0

Table D.1: Landvik Church Measurements

Appendix E

Temperature Corrected Energy Consumption

Year	Grimstad	Landvik	Eide	Årlig Middeltemperatur	Grimstad Korrigert Forbruk	Landvik Korrigert Forbruk	Eide Korrigert Forbruk
2010	58354,8	70400	53720	5,46	74198,32722	89513,8401	68305,16322
2011	56211,6	91050	47520	8,02	55708,22461	90234,64641	47094,45796
2012	43951,2	69650	39600	7,34	46923,09714	74359,60146	42277,67721
2013	46297,2	67850	38560	7,19	49617,81987	72716,47266	41325,67702
2014	40699,2	96550	39480	9,32	35448,4143	84093,65297	34386,50875
2015	44446,8	77200	37600	8,58	40905,10131	71048,39541	34603,8817
2016	50350,8	75350	30924,4	8,05	50047,791	74896,54687	30738,29826
2017	49328,4	66202,5	30576,4	8,21	47658,14015	63960,88305	29541,08296
2018	53179,2	78051	33072,8	8,54	51875,81011	76138,0174	32262,20576
2019	49911,6	68694	30285,2	8,34	47877,54838	65894,50765	29050,9847
2020	49414,8	59879,5	26008,4	9,4	41700,79056	50531,87483	21948,29972
2021	48504	80502,5	33056	7,99	48539,17858	80560,8862	33079,97459
2022	41247,6	62515,5	26558,8	8,67	38188,28474	57878,75451	24588,94619

Table E.1: Temperature Corrected Energy Consumption