Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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The Challenge of Rehabilitating Relocated Listed Heritage Buildings: Requirements, Current Standards and Opportunities

Master's thesis in Civil and Environmental Engineering
Supervisor: Bjørn Petter Jelle
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Preface

This study is carried out as our master's thesis and is a part of the course *TBM4900 - Master's Thesis in Civil and Environmental Engineering* at the Norwegian University of Science and Technology (NTNU). It was written during the spring of 2023 by three students majoring in building technology: Helga Margaretha Hognestad, Malin Pedersen and Ronja Helle.

Our thesis explores the challenge of relocating and rehabilitating listed heritage buildings according to current standards and is a case study for Ørland Municipality. It demonstrates the culmination of years of hard work and dedication, and marks the end of our master's program. We are grateful for the opportunity to pursue this research.

We would like to acknowledge our thesis advisor, Bjørn Petter Jelle, for guidance throughout this study. We would also like to thank Ørland Municipality for the opportunity to take part in this exciting project. Finally, we would like to express sincere appreciation to all the helpful people working at NTNU and SINTEF for answering our questions throughout the semester.

Trondheim, 2023.

Helga Margaretha Hognestad, Malin Pedersen and Ronja Helle.

Thesis description

This master's thesis consists mainly of a scientific article, which will be submitted for publication, concerning the rehabilitation of three listed heritage buildings. The article first gives an overview of the case situation involving the location, the three selected farmhouses, as well as national and regional requirements and regulations. Secondly, a literature review of relevant information is given, followed by possible solutions for rehabilitation within the given requirements. The literature review focuses prominently on thermal insulation materials and building integrated photovoltaics (BIPV). Lastly, the following research questions (RQ) are answered in a conclusion:

RQ1: What can be possible solutions for the rehabilitation of listed heritage buildings while preserving their cultural significance?

RQ2: What are the most suitable thermal insulation materials for the rehabilitation of the heritage buildings in Ørland Municipality?

RQ3: How can building integrated photovoltaics (BIPV) be implemented in the building envelope concerning applicable and possible solutions for heritage buildings?

RQ4: Is it possible to achieve today's Norwegian energy standard for listed traditional farmhouses while preserving their cultural heritage?

To evaluate if listed cultural heritage buildings can meet today's standards after rehabilitation, the applied method used findings in literature and results from simulations, described further below. This was used to evaluate the most suitable building technical solutions, which measures gave the most savings in the net energy demand, and how to preserve cultural heritage.

The first step was to choose buildings for the study in cooperation with Ørland Municipality. Three different farmhouses in varying conditions were selected: Trøa (bad condition), Grande (better condition) and Viken (best condition).

The second step was to document the current condition and energy consumption of the three buildings. Therefore, existing documents from the Municipality were read, concerning the project in general and evaluations of conditions for the specific farmhouses. In addition, building surveying had already been conducted by Ørland Municipality and architect students for these buildings. Then the current net energy demand was determined by using SIMIEN, i.e., the leading Norwegian simulation tool for energy calculations.

The third step was to determine how the buildings were going to be compared and evaluated. It was decided to use the simulation tools SIMIEN (energy), THERM (U-value) and WUFI (moisture). Data was gathered through scientific papers, Norwegian regulations, manufacturer websites, and the SINTEF research design guides, and examined. From these findings, possible solutions for the foundation, external wall and roof were created and illustrated in the BIM tool ArchiCad. Meanwhile, possible energy-saving measures were formed and tested in SIMIEN individually and in various combinations. This was used to determine whether technical energy requirements were fulfilled or not.

The fourth step was to evaluate the results from the simulations and calculations. First, results from WUFI, THERM and SIMIEN were plotted into graphs using Excel for easy and visible comparison between the different solutions. The solutions' feasibility, U-value and relative humidity were assessed, together with the reduction in net energy demand. Even though cultural heritage preservation has been a priority, it is also attempted to challenge and expand the understanding of what preservation of cultural heritage buildings means using modern methods and materials.

Additionally, the master's thesis includes appendixes for details concerning the calculations and simulations that were carried out. In the article, a somewhat abridged version of some of the appendixes are presented, as parts of the content is considered too extensive and detailed for a scientific article. The following appendixes are included in the master's thesis:

Appendix A: Details on input values and results from THERM and WUFI

Appendix B: Details on rehabilitation measures, associated risks, and results from energy simulations carried out in SIMIEN

Appendix C: Estimated U-value for exterior walls post-insulated with vacuum insulated panels

Sammendrag (Norwegian abstract)

Som følge av klimaendringer er det knyttet nye og forsterkede utfordringer til bevaringen av bygninger og bygningsmiljøer. Til tross for disse utfordringene er rehabilitering av eksisterende bygninger et viktig grep for å spare energi og redusere miljøpåvirkningen fra bygg- og anleggsbransjen. I denne sammenhengen er vern av bygningers kulturhistoriske verdi gjennom bruk et vesentlig prinsipp for forvaltningen av kulturminner. Disse byggene møter imidlertid sjeldent kravene og standardene som stilles til energi og komfort. Denne studien evaluerer tre vernede trønderlån i Ørland kommune som skal flyttes og dermed også rehabiliteres i henhold til dagens norske krav og standarder. Følgelig evaluerer denne studien mulige løsninger og utfordringer knyttet til energioppgradering og bevaringen av byggenes kulturhistoriske verdier.

Studien legger frem løsninger til rehabiliteringen av de tre trønderlånene basert på litteraturstudier, fukt- og varmesimuleringer, samt energisimuleringer. Løsningene inkluderer etterisolering av yttervegger og kalde loft med mineralull, vakuumisolasjonspanel (VIP) og aerogel. I tillegg vurderes mulighetene for renovering av vinduene, samt implementeringen av bygningsintegrerte solceller (BIPV). Til slutt simuleres potensialet for energibesparelser ved ulike rehabiliteringstiltak på hvert av de tre husene.

Et nytt fundament grunnet flytting, og etterisolering av det kalde loftet er gjennomførbare rehabiliteringstiltak som samtidig bevarer det arkitektoniske utrykket og autentisiteten. Når det gjelder etterisolering av ytterveggene er utvendig isolering fordelaktig med tanke på fukt og plassbesparelse, men det er da viktig å vurdere eventuelle tap av kulturhistoriske verdier. Alternativt kan innvendig isolering med aerogelmatter være en gjennomførbar løsning, blant annet på grunn av liten tykkelse. Å utbedre de gamle originalvinduene med innvendige varevinduer kan være en like god løsning som å bytte ut alle vinduene med nye, samtidig som det er anbefalt for kulturhistorisk bevaring. Implementering av BIPV kan bidra til at byggene møter dagens krav til netto energibehov. Dersom BIPV benyttes, er det anbefalt at de etterligner en akseptert taktekking fra gjeldene reguleringsplan for å imøtekomme bygningenes arkitektoniske estetikk og autentisitet, som for eksempel skifer.

Denne studien gir en innsikt i og anbefalinger til rehabiliteringen av vernede trønderlån ved å adressere deres energieffektivitet samtidig som kulturminner bevares. Funnene viser at det er mulig å oppnå dagens energikrav når vernede bygninger rehabiliteres, men det er essensielt å merke seg at hvert bygg er unikt og at hvert tilfelle må vurderes individuelt. Likevel kan funnene være egnet for lignende prosjekter.

Table of Contents for Master's Thesis

The Challenge of Rehabilitating Relocated Listed Heritage Buildings: Requirements and Opportunities

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Abstract

Climate change presents new and intensified challenges for the preservation of buildings and built environments. Despite these challenges, rehabilitation of existing buildings remains a viable solution to save energy and to reduce the environmental impact from the building sector. In this context, protecting the cultural and historic value of buildings through use is a significant principle in cultural environment management. However, listed historic buildings often fall short of current standards for energy and comfort. This study evaluates three listed farmhouses in Ørland Municipality which are going to be relocated and rehabilitated according to current Norwegian standards and requirements. Accordingly, the study assesses possible solutions and challenges regarding energy upgrading and restoration while preserving their historic features and cultural heritage.

The study suggests solutions for the rehabilitation of the three farmhouses based on literature studies, and both hygrothermal and energy simulations. These solutions include post-insulation of external walls and above the framework of joists against the cold attic with mineral wool, vacuum insulation panels (VIP), and aerogel blankets. Additionally, fenestration renovation options and the potential for implementation of building integrated photovoltaics (BIPV) are reviewed. Lastly, simulations of multiple energy-saving measures for each of the farmhouses are conducted.

A new foundation due to the relocation, together with post-insulation of the cold attic are feasible measures considering the preservation of the architectural appearance and authenticity. Regarding the external walls, post-insulating externally is preferable considering moisture and space savings. However, it is important to consider any possible loss of cultural heritage value. Alternatively, internal insulation with aerogel blankets may be a feasible solution due to its small thickness. Enhancing old original windows with secondary glazing may be an equally good solution compared to total windows replacement, and is recommended for cultural preservation. Implementation of BIPV can help meet the net energy demand requirement. Nevertheless, it is recommended that the BIPV resembles an accepted roofing material from the regulatory requirements, e.g., slates, to accommodate the building's architectural aesthetics and authenticity.

This study provides insight and recommendations for the rehabilitation of three listed traditional farmhouses in Trøndelag County, addressing energy efficiency while preserving their cultural significance. The findings show that it is possible to achieve today's energy requirements when rehabilitating listed heritage buildings, but it is essential to note that each building is unique, and a case-by-case approach is needed. Nevertheless, the findings can be applicable for a general energy upgrading of heritage buildings.

Keywords: Rehabilitation, heritage, building, energy efficiency, building integrated photovoltaics, BIPV, vacuum insulation panel, VIP, aerogel.

Table of Contents

1 Introduction

The United Nations General Assembly created 17 Sustainable Development Goals (SDGs) in 2015 as a guideline to restore the natural world by the end of this decade (United Nations, 2021). The building sector alone is responsible for about 40 % of the total energy consumption and greenhouse gas emissions globally (United Nations, 2022). As a result, the building sector has a significant environmental impact, making it a crucial task to adopt measures to improve the sustainability of the built environment (Munarim & Ghisi, 2016). In relation to this, reuse and energy rehabilitation of already existing buildings can be a feasible solution to decrease the environmental impacts from the building industry. According to Kynbraten and Larsstuen (2015) approximately 70-80 % of the buildings that will be in use by 2050 have already been constructed. Rehabilitation can provide benefits regarding the SDGs, in contrast to demolition and new constructions.

Climate change poses new and intensified challenges for the preservation of buildings and built environments (Ministry of Climate and Environment, 2021). A more humid and warmer climate can increase the risk of rot and insect damage, while acute events such as floods, landslides, fires and heavy rainfalls also pose a growing threat. Despite these challenges, the rehabilitation of existing buildings remains a viable solution to reduce the environmental impact from the building sector. The adoption of a circular economy is crucial for the construction industry to achieve sustainability, which involves reusing both buildings and materials to optimize resource utilization. In this context, protecting the cultural and historic value of buildings through use is a significant principle in cultural environment management.

Cultural heritage provides a baseline for understanding societal changes over decades, thereby having the potential of being a positive resource concerning societal development (Mittet, 2022). This is relevant to achieving SDG no.11: “Sustainable cities and communities” (United Nations, 2021). Additionally, continuous use, relocation and recycling of existing constructions and materials can help reduce greenhouse gas emissions and energy consumption (Mittet, 2022), contributing to the attainment of SDG no.12: “Responsible consumption and production” (United Nations, 2021). Townscape character and urban spaces are often created by historic buildings (Cabeza et al., 2018). Their visual appearance, materials, and construction techniques may be protected by law to preserve cultural heritage and local building traditions (Cabeza et al., 2018; Polo López & Frontini, 2014). Such houses undergo the term *listed heritage buildings.*

Listed heritage buildings rarely meet the current standards considering energy and comfort (Polo López & Frontini, 2014). Energy rehabilitation and retrofitting of the building envelope in these houses need to be done with respect to historic features and the protection of cultural heritage. Passive energy measures such as well-insulated surfaces, high-performance windows, and techniques for heating and cooling will affect the aesthetic appearance if not carried out with great care. In other words, every approach to the cultural heritage building mass has to combine the architectural conservation principles, and the environmental and economic aspects, whereas the SDGs play a substantial role (Cucco et al., 2023).

In a life cycle assessment (LCA) view, a rehabilitated heritage building will have an environmental, social and economic advantage (Munarim & Ghisi, 2016). When comparing a new building and a rehabilitated heritage building, the rehabilitated one will have much lower total emissions as there are no new emissions connected to the building’s footprint, i.e., production of materials, distribution and rising the building (Flyen et al., 2019). This is because the building has already been built. However, the rehabilitation work itself will have an environmental load, and some of the performance-improving solutions may even have a negative impact on the environment (Munarim & Ghisi, 2016). Also, when looking at the use phase, a new building will have lower emissions connected to operation (Flyen et al., 2019). Therefore, a key point of rehabilitation is improving the buildings’ energy efficiency to obtain a lower energy demand (Munarim & Ghisi, 2016). Munarim & Ghisi (2016) refer to several studies comparing rehabilitation of historic buildings with replacement of buildings. They found that rehabilitating historic buildings resulted in reduced energy consumption, fewer CO_2-emissions, and lesser disruption of the environment “related to climate change, human health, quality ecosystems and natural resources depletion”.

The social value of rehabilitation can be found when solutions preserve the built heritage (Munarim & Ghisi, 2016). Sjöholm (2017) explains the definition of built heritage as a socially constructed "product of the present, purposefully developed in response to current needs or demands for it, and shaped by those requirements". In areas where built heritage no longer can be preserved at the situated site, one option is relocation. This particularly applies to heritage buildings (Heesom et al., 2020). However, relocation should only be an option when all other possibilities have been considered and the structure is in danger. The original location of a building is part of its cultural heritage. Therefore, when relocating, it is essential that "the new site should provide a setting that is compatible with the heritage". On the other hand, it is also important to consider the current and future issues concerning the environmental and social aspects when relocating built heritage (Martínez, 2022). Furthermore, Munarim & Ghisi (2016) emphasises the importance of providing the building with an active role in the community to which it belongs. Structures established by relocated heritage buildings may lead to a growing interest in history and culture (Martínez, 2022). Through literature studies, Martinez (2022) finds that the relocation of buildings is "associated with social modernisation, urban development, and heritage appreciation".

The main objective of this study is to assess miscellaneous possible solutions for the rehabilitation of three relocated listed residential farmhouses in Ørland Municipality in Norway while preserving their cultural heritage and fulfilling today's energy requirements. Possible solutions are introduced in this work, including alternatives for post-insulation of external walls and cold attics, fenestration renovation, and air tightening. Additionally, an evaluation is carried out to determine the most suitable thermal insulation materials for the three heritage farmhouses. Furthermore, the possibilities for implementation of building integrated photovoltaics (BIPV) concerning applicable and feasible solutions for heritage buildings are investigated. Lastly, whether the three farmhouses may achieve today's Norwegian energy standard while preserving their cultural heritage are evaluated.

2 Case studies: rehabilitating relocated listed heritage buildings in Ørland Municipality

2.1 Location: Ørland Municipality

Ørland Municipality is located at Fosenhalvøya in Trøndelag County (Haugen, 2023). Most of the population in Ørland Municipality lives near the northern coastline, in Brekstad and on the outer west peninsula, called Ørlandet. Ørlandet is a flat area characterized by agriculture and a military airport. In 2012 it was decided to establish a main combat aircraft base at Ørlandet for The Royal Norwegian Airforce (The defence sector's properties, 2014). This development will not only expand the existing base but also bring new aeroplanes. The increased noise levels from these aeroplanes will have an impact on the environment, including potential harm to both people and animals living in the area. As a result, The Norwegian Defence Estates Agency has designated a "red zone" around the base that will be most affected by noise, see Figure 2.1.

To prevent the buildings located within the red zone to decay, the aim is to relocate them. Several of these buildings are listed heritage buildings. This change will greatly alter the landscape, and the municipality is now faced with the challenge of preserving historic buildings, including residences, barns, sheds, and garages, amidst the demolition of homes.

Figure 2.1: Part of Ørland Municipality, showing Ørlandet and Brekstad. The red line represents the red noise zone, and the yellow line represents the yellow noise zone. The current location of the three assessed farmhouses (Trøa, Grande and Viken) and the recently designated Brekstad Bay area are also indicated. Drawn on the map from norgeskart.no.

Relocating budlings is an old tradition in Trøndelag (ALM, 2021). Many of the buildings in Ørland Municipality were previously moved there from other locations in Norway. By again moving the listed heritage buildings, the historic tradition continues, and the cultural heritage can be preserved. The listed heritage buildings at Ørlandet will be relocated to a new area in Brekstad Bay (Brekstadbukta), where the coastline has been expanded with filling compounds. This new area will contain a combination of approximately 55 new and relocated buildings (Mittet, 2022). Twenty-six of these are listed heritage buildings, whereas 17 are farmhouses/residences, seven are storehouses and two are firehouses/carriage sheds.

2.2 National and regional requirements and regulations

New buildings in Norway must follow requirements stated in the building code (TEK17) and other regulatory requirements given by the municipality or the county. Regarding existing buildings, the requirements are vague and subject to interpretation. The Norwegian Plan and Building Act § 31-2 states that measures on existing buildings should be designed and executed in accordance with requirements given or authorized by law (The Planning and Building Act, 2008, secs 31–2). This implies that relocated and renovated cultural heritage buildings should adhere to the same standards as new buildings. However, when handling listed buildings, it is more common to deviate from technical requirements rather than fulfilling them (Kynbraten & Larsstuen, 2015). It is the municipality that approves if a deviation is acceptable or not. Kynbraten and Larstuen (2015) state that most exceptions from technical requirements can be permitted, except fire safety measures.

The regulatory plan for Brekstad Bay provides information regarding requirements in the area (Ørland Municipality, 2022). It is aimed at preserving cultural heritage while ensuring that new buildings meet the necessary standards. Table 2.1 presents the requirements that will have an impact on the relocation and rehabilitation of listed buildings.

Table 2.1: Requirements from the regulatory plan that affect which changes can be made to the listed buildings and specifications regarding noise (Ørland Municipality, 2022).

Information	Details
New extensions and façade changes	New extensions must be adapted to the main building's size, shape, and style. The façade material must mainly consist of vertical wooden cladding, stone/plastered masonry, and glass. Reflective materials must be avoided as much as possible.
Roofing	Only gable roofs and shed roofs are permitted. New roofing on listed buildings should preferably be slate, alternatively, traditional turf roof, chipped roof or wooden cladding can be accepted.
Colour restrictions	Buildings must be coloured with traditional red tones, ochre, dark green, brown shades, and off-white. White should be avoided as the main colour. Grey is not considered as a traditional colour. Window frames, doors and gates should be in a contrasting colour to the building.
Noise zone	Assumed noise level is 53 dB for the entire plan area due to aircraft noise. This marginally exceeds the requirement of 52 dB and results in a yellow noise zone. Grande will be relocated within the yellow zone for traffic noise.
Height restrictions	The height of the upper side of the internal ground floor shall be no lower than +3.5 m above sea level, i.e., basements are not permitted.
Universal design	The relocated buildings are exempt from requirements for universal design.
Energy solution	Connection to an external district heating system is not required. Alternative energy sources should be considered when assessing security measures in the event of a power outage.
Preservation and restoration	The exterior of listed buildings must be preserved or restored according to antiquarian principles and in consultation with the cultural heritage authorities. There is no requirement for authentic interior preservation.

2.3 Selected buildings

For this study, three listed traditional farmhouses from Trøndelag County (trønderlån) in various conditions from the farms Trøa, Grande and Viken are chosen (Table 2.2). Hereafter, when referring to Trøa, Grande and Viken, it is only referred to the specific farmhouses and not the entire farm. Traditional farmhouses from Trøndelag County are characterised by being long and narrow, as a result of gradual extension in the ends to make room for new generations or to satisfy new housing standards (Gunnarsjaa, 2021). Usually, this type of building has no more than two floors, which is the case for Trøa, Grande and Viken.

In a recent report by Johansen (2022), a restoration program was presented to address some of the challenges associated with relocating and renovating cultural heritage buildings in Ørland Municipality. The program involved categorizing buildings based on their condition, antiquarian value, and previous renovations. There are three categories described in the report and each of the selected buildings belongs to a different category, see description in Table 2.2.

Table 2.2: Overview of the three selected buildings for the case studies.

Name	**Trøa**	**Grande**	**Viken**
Photo		 Source: (Taftø Petersen & Johansen, 2016).	
Address	Ulriksborgveien 53	Grandveien 350	Nordgrandveien 4
Category	1	2	3
Description of category	Highest antiquarian value due to few changes over time and some original surfaces. Focus on material conservation.	Exterior from newer time that does not reflect the time period in which the building was built. Focus on visual restoration.	Well maintained building in line with the old building practice.

2.3.1 Trøa

Trøa was established in the late 19th century and today the construction consist of both logs (laft) and framework (Taftø Petersen, 2015). A log construction is a wall construction where horizontal timber logs lay with the root end and top end alternately to each side (Thue, 2021). The logs are held in place by the joint ends in corners and/or transverse walls. It is assumed that Trøa's log construction was moved to the site and is most likely from the 18th century (Taftø Petersen, 2015). The farmhouse rests on a foundation of natural stone and cement, has two floors, and a cold attic. The roof construction is purlins over the logs, and roof trusses over the framework. Originally, the house had a traditional turf roof, but this was replaced with slates in the mid-20th century (Wærnes & Solgård, 2019). The façades have original board-on-board cladding, except the north façade which is post-insulated and therefore has newer cladding. Consequently, the window framings are removed, and the windows do not longer flush with the cladding at this façade. Thus, the north façade is of lower esthetical quality than the other façades. The windows originate from different time periods, and there are both single- and double-glazed windows with and without grids.

The log construction is generally in good condition, except for the southeast corner where water leakages from the roof have caused damages (Wærnes & Solgård, 2019). The roof needs repairing and upgrading; however, the slates can be reused. Despite their age, some windows are in good condition, although some need replacement. In general, the cladding is in great state, but specific rot-damaged cladding needs to be changed. The farmhouse has two chimneys that are recommended replaced with new ones when relocating the building.

2.3.2 Grande

It is uncertain when Grande was constructed, yet it is confirmed to be prior to 1895 as someone was born inside the house this year (Taftø Petersen & Johansen, 2016). The construction consists mainly of logs, but also some framework and half-timbered wood. Additionally, Grande has a cold roof with purlins and rafters as load-bearing elements. At the west end of the house, there is an unfurnished storage shed (torvbu), which has exposed logs and a framework made of airport planks.

The two-story farmhouse was moved a few meters in 1951, hence some major changes occurred: cast new concrete foundation and basement under parts of the building, a framework of joists was installed, cladding was changed, a porch and storage shed (torvbu) was built, and the traditional turf roof was torn down and replaced with steel plates. The façades have board-on-board cladding, as well as awning windows and two-section casement windows from varying time periods. The southwest façade has been post-insulated with mineral wool. While Grande is mostly in adequate condition, there is moisture damage around a second-floor window on the northeast façade (Hesthol Løvik et al., 2022). This stems from a hole in the roof due to corroded steel plates. Water has come down inside the wall, gathering around the window and on the floor. Therefore, mould has developed in the window frame, as well as fungal growth in the wall under the interior panelling and in the floor. On the outside, the paint around this area is flaked off. According to Ørland Municipality, the fungal growth has been stopped (Ørland Municipality, n.d.).

2.3.3 Viken

Viken was originally constructed in Skaudalen in Rissa, but underwent relocation to Ørlandet at the end of the 19th century (Taftø Petersen & Johansen, 2015). The wall construction consists mainly of logs, but some newer parts are half-timber (Feragen et al., 2016). The roof has purlins and rafters as load-bearing elements with original slates as roofing. The foundation is of natural stone and plaster under the log construction, and concrete underneath the half-timber. The house has two floors, but there is a non-heated basement under parts of the building.

The exterior of the building has undergone various changes and renovations over time, nevertheless, its traditional and distinctive character has been effectively maintained. Facing south, a glass veranda was added in 2005 to extend the dining area, replacing an old extension from the 1960s (Feragen et al., 2016). In 2005 it was also added 50 mm of thermal insulation to the external walls and most of the windows were changed around the same time (Taftø Petersen & Johansen, 2015). The building is well preserved and holds high functional value, as well as cultural and historic value.

2.3.4 Placement in Brekstad Bay

Today, the three selected farmhouses are rurally located at some distance from the coast. Trøa is located near Uthaug, north of Ørlandet, while both Grande and Viken are situated in the southern part of Ørlandet, see Figure 2.1. In the new residential area, the buildings' orientations and climate stresses will change. For instance, the proposed site for Viken is situated along the coast, resulting in significant alterations in the weather exposure the building will be subjected to. The farmhouse will be rotated approximately 220º based on cardinal directions (north being 0º and east being 90º etc.). Trøa will be somewhat protected from climate stresses by surrounding buildings, and the proposed orientation remains roughly the same. Grande will be situated farthest away from the coast but close to the road, causing issues concerning noise. Grande will be rotated about 50º from its original orientation. Figure 2.2 show the new placement of the buildings in Brekstad Bay.

Figure 2.2: Placement of Trøa, Grande and Viken in Brekstad Bay (Brekstadbukta). Drawn on site plan received from Ørland Municipality.

3 Rehabilitation measures for improving energy efficiency in relocated heritage buildings

3.1 New foundation and floor construction

The three selected buildings will need a new foundation and floor construction, because they are going to be relocated. The regional requirement, presented in Table 2.1, gives hight restrictions that will affect the foundation. The height of the upper side of the internal ground floor shall be no lower than +3.5 m above sea level, i.e., basements are not permitted. This results in three possible foundation techniques, namely, slab-on-grade foundation with a concrete stem wall, ring wall with crawl space, or open foundation (SINTEF 521.011, 2005). It is generally advised against utilizing ring wall with crawl space for permanent residential dwellings due to the high risk of moisture damage. The use of an open foundation leads to an outdoor climate under the joist layer and may result in cold floors, draft problems, and increased energy consumption. Additionally, an open foundation does not align with the architectural design of a traditional farmhouse in Trøndelag County (trønderlån). Therefore, a slab-on-grade foundation with a concrete stem wall will be the most suitable option.

Insulation of the floor construction will be done according to new building technical regulations and standards. As Brekstad Bay is situated along the coastline, it is imperative to utilize insulation materials that are capable of withstanding high levels of moisture, such as expanded polystyrene (EPS) and extruded polystyrene (XPS).

In Norway, the building code (TEK17) stipulates requirements for radon, which means that the majority of new constructions must be equipped with both a radon membrane and a radon well (SINTEF 520.706, 2018). To use a membrane as both a radon and moisture barrier, as well as protect it against puncture during construction work, it should be placed below the concrete slab and 50 mm of insulation. However, there is a risk that the insulation layer between the membrane and the overlying concrete may become permanently wet, thereby decreasing its insulation properties. To mitigate this risk, the membrane can be placed between the concrete and the insulation layer. In this case, a protective and sliding layer of 0.8 mm thick plastic or an equivalent material with similar strength must be placed above the membrane to safeguard it against puncture.

3.2 Post-insulation of the building envelope

In Norway, all post-insulation of listed buildings has to be approved by the cultural heritage authority (SINTEF 723.511, 2004). Post-insulating of façades can either be done on the external or the internal part of the wall (Polo López & Frontini, 2014). In addition, half-timber frames can be insulated inside the cavity. External post-insulation with traditional insulation materials is a favourable method for minimizing heat loss and ensuring adequate moisture control when using traditional insulation materials (SINTEF 723.511, 2004). For example, insulating with plates or mats of mineral wool eliminates thermal bridges. Choosing an exterior cladding that resembles the original one and moving the windows out into the wall is recommended to avoid water leaks and moisture damage. Reuse of old cladding is also a possibility. If the intention is to refrain from installing a new vapour barrier, it is commonly observed that this approach is well-suited for older wooden structures. This is because old timber walls, such as logs, framework and old half-timber, are often so massive compared to newer light half-timber walls. The rationale for avoiding the installation of a new vapour barrier may stem from the desire to maintain the interior of the wall in its current condition (e.g., to avoid additional renovation work) or to achieve a visible timber/log. The design of a traditional farmhouse in Trøndelag County allows for external insulation without changing the visible exterior of the building since cladding covers the log walls. This presents a significant benefit, as the usable area on the interior of the building can be maintained while also improving its energy-efficiency through post-insulation.

Internal post-insulation with traditional insulation materials is only relevant if the façades are in great condition and should be preserved (SINTEF 723.511, 2004). When adding additional insulation on the inside, the original wall's ability to dry out will be reduced, and it will become more humid. Kalnæs and Jelle (2014) point to the risk of low exterior surface temperatures, which can lead to an increased frequency of freezing and thawing cycles. In addition, there is a risk of condensation forming, which can cause damage to the building and promote the growth of mould. Therefore, it is critical to approach internal post-insulation with care and take measures to mitigate these potential issues.

All three farmhouses in this study have a roof construction of purlins and a cold attic. Analogous to the process of post-insulating the external walls, either the roof construction or the joists in the attic can be thermally insulated on the upper side (externally) or on the underside (internally) (SINTEF 725.403, 2005). However, insulating the roof construction itself would be unfortunate due to limited headroom and inapplicable living space. Additionally, post-insulation on the underside of the joists is not a viable alternative due to height restrictions in the building code (TEK17) for habitable rooms. To circumvent changes in ceiling height, insulation may therefore be added to the upper side of the joists against the cold attic. A continuous layer of insulation across the roof's entire width is recommended to reduce thermal bridges. Moreover, a cold ventilated roof is advantageous concerning BIPV since they are most efficient when cold.

Hansen (2019) found that small differences in the air change rate in the attic could affect the hygrothermal performance and is consequently a very important factor in whether the cold ventilated roof works or not. Furthermore, when having a non-insulated roof construction, the attic could either be ventilated or not (SINTEF 525.106, 2020). For weather-beaten areas along the coast, such as Ørlandet, a non-ventilated attic would be beneficial regarding entering snow, lashing rain, and cold air into the insulation. Moreover, a non-ventilated attic will have two continuous layers of air tightening; wind and vapour barrier, whereas a ventilated attic only will have one; vapour barrier. Concerning fire safety, the non-ventilated solution results in less hazard for fire spreading through the attic.

3.3 Airtightness of the building envelope

To improve a building's energy efficiency through rehabilitation, one measure is to increase the airtightness of its envelope (Svensson et al., 2012). This is important to prevent cold air from entering the thermal insulation and consequently reducing the insulation properties, and hindering water vapour and humid indoor air from entering the construction. Additionally, increasing airtightness will improve thermal comfort and soundproofing. For the case at Ørlandet, air-tightening of log walls and old frameworks, together with wooden roofs, are of interest. This can be done by installing a wind barrier and a vapour barrier, and seal around openings such as windows and doors. It is essential to consider the moisture levels and use a wind barrier with low vapour resistance to enable the wall structure to dry out. The roofs should be air tightened by using an external wind barrier and an internal vapour barrier (SINTEF 725.403, 2005). Additionally, it is important to assess the ceiling's ventilation and moisture levels to avoid condensation, plus seal around openings for ducts, pipes, and attic hatches. Moreover, if the continuous thickness of the thermal insulation in the walls or roofs exceeds 200 mm, using a convection barrier is necessary (SINTEF 573.344, 2020). The convection barrier will hinder internal natural convection in the insulation, and further reduce thermal losses and redistribution of moisture.

3.4 Fenestration renovation

Original windows in old buildings contribute to a large part of the building's energy losses due to their low thermal performance, thermal bridging and air leakage (Homb & Uvsløkk, 2012). Hence, energy savings can be achieved by restoring or replacing the building's fenestration. Total windows replacement is currently the most applied fenestration upgrade, also in historic buildings, even though other options exist (Litti et al., 2018). This is partly due to technical simplicity, affordability and high energy-saving potential, but also window products producers and suppliers influence this through compelling lobbying activity. Furthermore, it is noticeable that total windows replacement is not always the only and better solution for fenestration renovation. Restoration and/or installation of internal secondary glazing may lead to similar or more energy savings, according to Litti et al. (2018). Moreover, windows replacement is not always compatible with preservation of heritage buildings and their cultural value. This is applicable for the case in Ørland Municipality, where there are regulatory requirements about preserving the exterior façades, something that must be accounted for when considering fenestration renovation. The original windows in listed buildings are an important part of building history and traditional craftmanship (Korsaksel & Stige, 2014). Also, there are multiple reasons to preserve old windows, e.g., historic cultural value, lifetime and quality, economy, and environmental considerations. Figure 3.1 shows an example of an old window which is improved with an energy-efficient secondary glazing.

Figure 3.1: Installation of a secondary glazing improving the window's U-value from 4.6 W/(m^{2}K) to 1.6 W/(m^{2}K). Photo: Marte Boro (Directorate for Cultural Heritage, n.d.).

It is important to preserve the original windows in heritage buildings and assess whether they can be repaired and improved according to current requirements for comfort, thermal performance, and airtightness, rather than just replacing them with new windows (Homb & Uvsløkk, 2012). This is especially significant when both the windows and façades are in generally good condition. A possible solution is internal storm windows with panes with good thermal performance. Litti et al. (2018) studied five options for fenestration renovation in a historic building: fenestration maintenance, fenestration drought proofing, internal storm glazing addition (both single- and double-glazed), glass pane replacement, and total windows replacement. Within a time interval of 100 years, the building life cycle operating energy reduction was greatest when replacing the windows, but not substantially more than installing secondary glazing or replacing the glass panes. Nevertheless, the study did not grant a clear result for the best and most performing windows retrofitting option, since this depends on the relation between materials' durability and building preservation. Furthermore, they point out the importance of exploring alternatives and not just relying on traditionally effective measures, especially when dealing with heritage buildings.

Homb and Uvsløkk (2012) investigated the performance of an old heritage window upgraded with a secondary glazing with various configurations of panes and positions. Four different solutions were tested: single and double glazing, each with a cavity between the panes of 74 mm and 174 mm, see Figure 3.2. The research included both calculations and measurements in the laboratory, e.g., thermal transmittance (U-value), air tightness and soundproofing. The best results were obtained in both positions with a double-glazed windowpane.

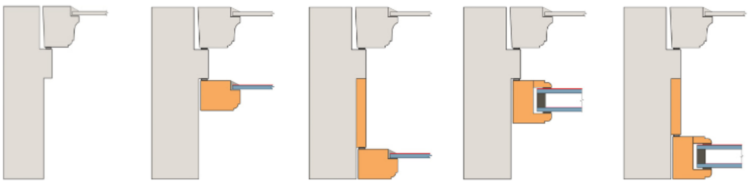


Figure 3.2: Possible solutions for upgrading an old single-glazed window with an internal storm window of single or double glaze (Homb & Uvsløkk, 2012).

A study conducted by Harrestrup and Svendsen (2015) carried out a holistic energy renovation on a heritage building in Copenhagen, Denmark. Concerning the windows, the municipality accepted windows replacement despite the façades being of heritage value, because a test apartment in the building showed that this was the most cost and energy-efficient option. To preserve the exterior of the building, the new windows were constructed aesthetically as the old ones, only with energy-efficient three-layered glazing. Out of the energy-saving measures that were applied in this building (insulation, mechanical ventilation and windows replacement), the fenestration retrofitting provided the highest savings.

As mentioned, improving windows' thermal transmittance affects the building's energy use. Additionally, the thermal improvement can lead to a longer service lifetime due to less condensation problems (SINTEF 733.161, 2016). Table 3.1 presents the thermal transmittance for old single-glazed windows that have been improved with different types of secondary glazing, and for comparison, normal thermal transmittance for new triple-glazed windows.

Table 3.1: Indicative thermal transmittance (U-value) for old single-glazed wooden windows improved with secondary glazing, and indicative thermal transmittance (U-value) for new triple-glazed windows (Enova, 2012; SINTEF 733.161, 2016).

Window type	U-value ($W/(m^2K)$)
Old window with single glazing and wood frame	4.1-4.5
Secondary single glazing	2.0-2.1
Secondary single glazing, heat reflective coating	1.5-1.6
Secondary double glazing, air-filled cavity	1.5-1.6
Secondary double glazing, heat reflective coating on both panes, air-filled cavity	1.0-1.1
Secondary double glazing, heat reflective coating on both panes, gas-filled cavity	0.9-1.1
New triple-glazed window, heat reflective coating on two panes, gas-filled cavity	0.9-1.1
New triple-glazed window, heat reflective coating on two panes, gas-filled cavity, insulated frame	0.7-0.9

4 Thermal insulation materials

4.1 A comparison of thermal insulation materials

Proper thermal insulation is a critical component for energy-efficient buildings. Cabeza et al. (2018) have found that most studies concerning improving energy performance of historic buildings have agreed that improving the building's climate insulation is one of the most impactful measures. Listed cultural heritage buildings often have limitations regarding the thickness of their building envelope due to architectural constrains, making it impractical to add a thick layer of insulation. Therefore, selecting insulation materials that makes the building energy-efficient while maintaining its historic character is important. Table 4.1 provides an overview of relevant insulation materials, including traditional materials that have been used for many years, as well as state-of-the-art materials that are emerging in the market.

Table 4.1: Insulation materials comparison: properties, performance data, and estimated insulation thickness for a generic external wall with 6" logs and a U-value of 0.22 $W/(m^2K)$.

Materials	Possible site adaptation [a]	Load-bearing capabilities [a]	Fire resistance [b]	Thermal conductivity [b] (W/(mK))	Estimated thickness [c] (mm)	Typical area of use [b]
Traditional thermal building insulation						
Mineral wool	Yes	No	Yes	0.032-0.043	142	Moisture-protected building parts, such as floor dividers, walls and roofs.
Cellulose	Yes	No	Yes	0.037	154	Moisture-protected building parts, such as floor dividers, walls and roofs.
Wood fibre	Yes	No	Yes	0.038	157	Moisture-protected building parts, such as floor dividers, walls and roofs.
EPS	Yes	No	No	0.031-0.041	93	Floors on the ground and ring walls.
XPS	Yes	No	No	0.027-0.039	81	Floors on the ground and ring walls.
PUR	Yes	No	No	0.023-0.038	69	Factory-made wall and ceiling elements with panels on each side.
State-of-the-art thermal building insulation						
VIP	No	No	Dependent on product type	0.007-0.010	21	Moisture-protected building parts, such as floor dividers, walls and roofs [d]
Aerogels	Yes	No	Yes	0.015	45	Moisture-protected building parts, such as floor dividers, walls and roofs, and translucent or transparent building parts, e.g., windows [e]

EPS: expanded polystyrene; XPS: extruded polystyrene; PUR: polyurethane; VIP: vacuum insulation panel; a: (Jelle, 2011); b: (SINTEF 573.344, 2020); c: calculations based on a simplified U-value calculation; d: (SINTEF Certification, 2019); e: (Baetens et al., 2011).

In Norway, mineral wool is a prevalent insulation material used for walls and roofs, and includes glass and rock wool (Vetlejord, 2019). Mineral wool is non-organic, which is beneficial because it maintains its thermal properties over time and does not rot (SINTEF 573.344, 2020). Both glass and rock wool are considered fire-resistant, but rock wool has a higher melting point. Additionally, glass wool can be compressed to 20 % of its original volume, making it easier to transport and store (Vetlejord, 2019). However, cellulose and wood fibre insulation are also used today, but they have a higher thermal conductivity and need to be handled as hazardous waste due to additives used in their production (SINTEF 573.344, 2020). They are also more susceptible to rotting over time, which may lead to changes in thermal properties. Plastic-based insulation materials can contain substances that need to be handled as hazardous waste. Polyurethane (PUR) is a plastic-based insulation material that is mainly used where the insulation is protected from moisture. Additionally, during a fire, PUR can release hydrogen cyanide and isocyanates, which are highly toxic. Furthermore, extruded polystyrene (XPS) and PUR can experience an increase in thermal conductivity over time due to the diffusion of gas between the pores. This will not be the case for expanded polystyrene (EPS) which has an open pore structure.

Regarding moisture-technical properties, mineral wool, plastic insulation, aerogel insulation and VIPs will absorb little or no moisture from the air (SINTEF 573.344, 2020). Mineral wool will, however, retain water if exposed to it. Cellulose and wood fibre insulation are hygroscopic and have an equilibrium humidity approximately the same as other wood materials. There is not necessarily a need to use a vapour barrier when using hygroscopic insulation because it carries water away instead of retaining it. This results in a more "breathable" construction. EPS and XPS have high compressive strength and absorb little moisture, i.e., they are suitable for insulation in moist areas. XPS has higher compressive strength and is more moisture resistant than EPS, but has a cost three times higher (Vetlejord, 2019). XPS insulation is typically the preferred choice for insulating constructions that require high pressure resistance, such as foundation walls.

Traditional insulation materials are well known, but the introduction of newer materials has opened new avenues of possibilities. Hence, the state-of-the-art insulations VIP and aerogel are two examples of materials that could be interesting to explore further regarding their condition of use and effect.

4.2 Vacuum insulation panels

A vacuum insulation panel (VIP) is formed of a core of porous material enclosed by an airtight foil, from which the air is pumped out forming a vacuum (SINTEF 573.344, 2020). VIPs have very low thermal conductivity, in fact, the insulation performance is 5-10 times better, dependent on ageing, compared to conventional thermal insulation (Kalnæs & Jelle, 2014). This technology represents one of the most up-and-coming building insulation materials for commercialization today. Information about the construction of VIPs, and different types, can be found in Kalnæs and Jelle (2014). Figure 4.1 displays the components of a VIP.

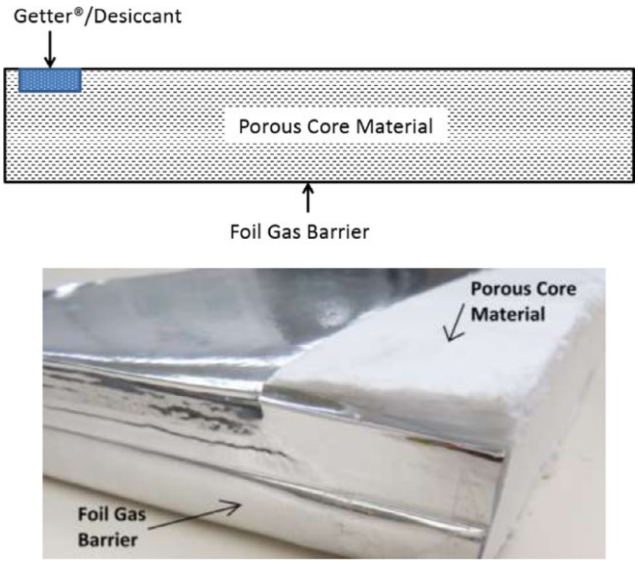


Figure 4.1: VIP components (Molleti et al., 2018).

VIPs make it possible with highly insulated floors, walls and roofs, especially when rehabilitating old buildings with limited space (Kalnæs & Jelle, 2014). However, it is crucial with thorough planning with regards to durability, lifetime expectations, thermal bridges, and lack of flexibility, to integrate VIPs effectively. Due to their modest thickness, VIPs may be a great choice for internal post-insulation in existing buildings. This can be very beneficial for listed buildings where the exterior needs to be preserved (Uriarte et al., 2019), just like the case in Ørland Municipality. Compared to traditional thermal insulation, VIPs can offer the same thermal performance but with a much slimmer construction that utilizes significantly less of the indoor area. However, there are some downsides with VIPs, such that they cannot be cut on-site, they have a risk for loss of vacuum over time, and they can easily be damaged which will reduce their thermal performance. This has held back the use of VIPs in the construction sector.

Throughout their studies, Uriarte et al. (2019) discovered that one of the main issues to make the installation process fast and smooth are the VIPs' tolerances. Nevertheless, the use of VIPs seems promising with regards to space heating energy savings, with a reduction of 23 % and 36 % in the respective study. Sallée et al. (2014) studied the use of VIPs for internal thermal insulation in existing buildings with façades with high architectural character, as an alternative to external thermal insulation systems. They found that the use of VIPs can yield a 30 % reduction of the whole U-value, while external thermal insulation systems can give a reduction of 50 %. This study was carried out on a mock-up of a connection between an external wall and a partition wall both made of concrete. A study conducted by Sveipe et al. (2011) investigated the use of VIPs for retrofitting half-timber frames, both on the cold (exterior) and warm (interior) side. The study concludes that "timber frame buildings thermally insulated with 100 mm mineral wool, might be retrofitted at the exterior side by adding 30 mm VIPs in a continuous layer", based on the results from the experiments, the simulations, and the condensation controls (Sveipe et al., 2011). On the other hand, the condensation calculations highlighted the importance of preventing puncturing of the VIPs and to account for the VIPs' qualities in aged conditions. The solution with VIPs for interior retrofitting showed the best results concerning moisture, i.e., no condensation occurred during the test. Examples of VIPs used for external and internal insulation are shown in Figure 4.2.

Figure 4.2: External ventilated façade retrofitting with VIPs in Malmö (two left photos) and internal installation of VIPs in KUBIK by Tecnalia (two right photos) (Uriarte et al., 2019).

In a study conducted by Yuk et al. (2023), retrofitting with VIPs on a wooden roof in a historic building was investigated. A VIP with a thermal condutivity of 0.0034 W/(mK) was developed for this specific retrofitting case, accordingly, allowing a thickness of only 0.015 m to obtain the same thermal performance as conventional insulation materials. The study confirmed that applying VIPs only to the roof, reduced the roof thermal transmittance by 88 % and consequently the heating and cooling energy usage was lowered by 55 %. However, Yuk et al. (2023) emphasizes that historic buildings need to be preserved and that the use of passive technologies should be studied with regard to possible damages. Nevertheless, they conclude that "the conservation of historic buildings was possible through the application of advanced insulation materials" (Yuk et al., 2023).

On the façades, an uninterrupted insulation layer that will reduce the impact of thermal bridges can be fulfilled with VIPs (Kalnæs & Jelle, 2014). Retrofitting with VIPs at the inside will not eliminate thermal bridging between construction elements such as two floors, unlike retrofitting at the outside

(Sveipe et al., 2011). Accordingly, exterior thermal insulation is advantageous seen from a thermal insulation point of view.

The service life of VIPs is an important factor to account for when using VIPs in buildings (Fantucci et al., 2019). Given that a building should be dimensioned with a service lifetime in a range of 50-100 years, the VIPs' lifetime should have an equally long-term performance (Kalnæs & Jelle, 2014). An increase in internal gas pressure and water content over time will lead to an increase in thermal conductivity. The time until the thermal conductivity in the centre of a panel reaches a critical level is the functional lifetime. Nevertheless, the VIP will still function when the critical value is reached, but the U-value and the heat loss will continuously increase. Currently, there are still uncertainties around the lifetime of VIPs in use, consequently, there is some scepticism about the implementation of VIPs in the building sector.

4.3 Aerogels

Aerogels are materials with high porosity and very low thermal conductivity, made of dried gels (Baetens et al., 2011). In addition, aerogels have other beneficial properties for building application, such as vapour diffusion openness, strong hydrophobicity, and good fire resistance (Ganobjak et al., 2020). Currently, aerogel-based insulation materials are niche products which are quite costly. Space savings, reduction in operation cost, longevity and chemical resistance are reasons why aerogels can be worth the investment according to Koebel et al. (2012). Due to their high thermal performance, aerogels are considered an innovative alternative to conventional thermal insulation materials (Baetens et al., 2011).

There are three different types of aerogels: silica, carbon and alumina, whereas silica is the most common (Cuce et al., 2014). Silica aerogel can be used in both opaque and translucent building parts, e.g., roofs, walls and windows (Baetens et al., 2011; Cuce et al., 2014). The process of creating aerogels is described thoroughly by Baetens et al. (2011) and Cuce et al. (2014). Aerogels come in different product types, e.g., blankets (see Figure 4.3), render and boards (Ganobjak et al., 2020). Due to low thermal conductivity, the products are slim and ideal when space saving is crucial (Cuce et al., 2014). By using aerogel materials instead of conventional thermal insulation materials, a given insulation performance is achievable with about half the thickness (Ganobjak et al., 2020). Hence, aerogel materials may be suitable for the rehabilitation of cultural heritage buildings. Furthermore, this was investigated by Ganobjak et al. (2020) with respect to a historic building's authenticity, integrity, reversibility and compatibility. The projects presented in the mentioned article are mainly quarry and brick walls retrofitted with exterior aerogel render. Ganobjak et al. (2020) conclude that heritage requirements, as well as a decrease in energy demand, can be obtained with aerogel-based insulation for retrofitting preserved heritage buildings. However, additional insulation can cause moisture problems, especially internal thermal insulation must be carefully evaluated. Elshazli et al. (2022) performed full-scale experimental tests to study the performance of aerogel insulation blankets used as internal insulation in a student residential apartment. The study showed a reduction in energy usage by 23 % and 38 % for single and double layers of aerogel, respectively. Anyhow, Elshazli et al. (2022) emphasizes that type of building, type of building envelope and thickness, type of thermal insulation, and windows and configurations will affect the energy-saving percentages. More studies about building retrofit with aerogel have been conducted by (Cuce & Cuce, 2016; Ibrahim et al., 2015; Koebel et al., 2012; Koh et al., 2022).

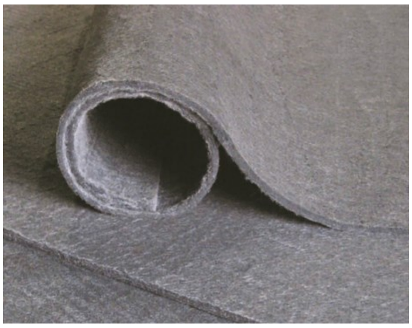


Figure 4.3: Spaceloft® Aerogel insulation blanket developed by Aspen Aerogels, Inc. (Glava AS, 2013).

High costs are one of the main challenges of using aerogel in building application (Ganobjak et al., 2020). Additionally, with the thin insulation thickness of aerogel materials, the effect of thermal bridging can be more critical compared to conventional insulation materials. On the other hand, the small thickness and low thermal conductivity are beneficial when it comes to feasible solutions for energetic retrofitting and at the same time preservation of heritage values. Good energy performance and thermal comfort can be achieved with aerogel materials.

5 Building integrated photovoltaics

5.1 Building integrated photovoltaics in historic buildings

The integration of solar energy in historic buildings can be difficult (Cabeza et al., 2018) and in the recent past, this was not recommended (Polo López et al., 2020). Now, it is increasingly possible due to the high compatibility of new products. The integration of photovoltaics (PV) in historic buildings will challenge both the preservation of heritage and the need to adapt to provisions concerning energy improvement by using renewable energy (Polo López et al., 2021).

Considering aesthetics and function, building integrated photovoltaics (BIPV) can satisfy strict requirements governing heritage conservation, whereas standard building applied photovoltaics (BAPV) would be prohibited (Novak & Vcelak, 2019). Not only does BIPV contribute to generating electricity, but they are also a constructive part of the building envelope (Polo López et al., 2021). Using BIPV as cladding or roofing could lead to less material usage and potentially reduced costs compared to BAPV (Bunkholt et al., 2021). New product designs allow better integration of BIPV in historic buildings due to similarities towards traditional building elements (Polo López et al., 2021), for instance: “crystalline silicon modules, thin films, coloured solar cells, homogenised black appearance and integration of high-resolution images” (Pelle et al., 2020).

The market is receptive to new solar products that will satisfy regulations and requirements (Frontini et al., 2012). Polo López et al. (2021) emphasize that coloured PV recently has been considered a necessity for gaining market acceptance, as they allow better integration in historic buildings and landscapes. The colour in BIPV or BAPV appears from “coloured glass, pattern coatings or printing on front glazing treatments or coverings”. According to Pelle et al. (2020), coloured PV modules seems to be the best alternative to create a balance between conservation and energy issues in architecturally sensitive areas. There exists a wide range of possible colours and the PV can be applied to for example roofs, façades and shading systems. Also, the finishing layer can portray miscellaneous textures, uneven surfaces, fouling and time-related performance decay. The technology of coloured BIPV hides the original material of the PV cells behind coloured patterns. However, the colouring works as a “shade” over the PV cells, resulting in a consistent reduced energy production compared to regular PV cells (Polo López et al., 2021). In addition, the colour can also hinder the PV by reflecting solar radiation which could otherwise be used to generate electricity (Pelle et al., 2020). Another drawback is often high cost (Polo López et al., 2020).

Pelle et al. (2020) find in their study that integration of BIPV in historic buildings consists of three integration levels: (i) aesthetic integration, i.e., the capability to include PV in a building's architectonic rules; (ii) technological/functional integration, i.e., the PV system’s potential to substitute traditional building components; and (iii) energy integration, i.e., the PV’s ability to efficiently integrate to the applicable energy system to maximise self-consumption and contribute to the implementation of energy-efficient communities. To visualize this; during an energy upgrade of an 1859 rural farmhouse in Switzerland (Figure 5.1), terracotta-coloured PV modules were used to meet requirements (Polo López et al., 2021). These solar panels are integrated in the building, and they have anti-reflective glass, cover a 250 m^2 area and produce 16 500 kWh per year.

Figure 5.1: Rural farmhouse in Switzerland from 1859 with terracotta coloured BIPV (right picture). The left photo shows the building before the energy upgrade. Photos from (Polo López et al., 2020).

The Italian company Dyaqua Invisible Solar has taken it one step further and recently launched an invisible solar roofing tile that realistically resembles a traditional terracotta roofing tile (Dyaqua, n.d.), as shown in Figure 5.2. The PV cells are hidden underneath a low molecular polymeric compound surface which is opaque to human eyes, but transparent for sun rays. These tiles have a peak power of 7.5 Wp and weigh 2 kg per tile. The same company are also developing PVs that realistically look like other building materials, such as wood, stone and concrete, see Figure 5.3, which can be applied to roofs, walls and pavements. However, the three last-mentioned products are not on the market yet. Still, they are worth a mention to show where the development of PV technology is headed. Such realistic PV tiles could be of great importance for the integration and acceptance of PV in general, and especially for cultural heritage buildings and areas.

Figure 5.2: Dyaqua Invisible Solar terracotta roofing tile (Dyaqua, n.d.).

Figure 5.3: PV-technology under development from Dyaqua (Dyaqua, n.d.). PV with realistic-looking wood (left), stone (middle) and concrete (right) surface.

5.2 Building integrated photovoltaics in Norway

Over the past few years, the accumulated capacity of solar power plants has increased in Norway (Kvalbein & Stensrud Marstein, 2018). Typical for Norway is to apply the PV panels to existing buildings as BAPV, and not installed as ground-mounted systems or BIPV. Nevertheless, the country has a growing interest for BIPV (Bunkholt et al., 2021), and they are highly applicable due to low temperatures and low sun angle, especially on south-facing façades (Kvalbein & Stensrud Marstein, 2018). However, there are few agreed-upon and recommended solutions for building structures with BIPV, and this is not included in the "SINTEF Building Research Design Guides" (Byggforskserien) (Bunkholt et al., 2021), which is an important national information channel, knowledge base and quality standard used by builders, contractors, engineers, and architects (*SINTEF Information*, n.d.). Still, BIPV can be found in several Norwegian buildings, e.g., Powerhouse Brattørkaia, Telemark and Kjørbo (Powerhouse, n.d.), ZEB Laboratory in Trondheim (ZEB Laboratory, 2022), and several others shown in (Bunkholt et al., 2021; Kvalbein & Stensrud Marstein, 2018). Some of the aforementioned buildings with BIPV are depicted in Figure 5.4.

Figure 5.4: Powerhouse Telemark (left) (Powerhouse, n.d.). Two Norwegian houses with BIPV roofs (middle and right) (Bunkholt et al., 2021).

The production of energy generated by a PV system is impacted by climate and weather conditions (Bunkholt et al., 2021). Coastal areas, topography, and elevation above sea level heavily influence the Norwegian climate, which is known for its significant geographic disparities and significant yearly fluctuations in temperature and solar radiation. Façades and roofs are often subject to freeze-thaw cycles, temperature variations and stresses caused by wind and precipitation, especially snow and wind-driven rain. Therefore, Norway has strict rules for constructing buildings, including BIPV installations (Bunkholt et al., 2021) which must fulfil the same building-technical requirements and exhibit equivalent performance as the elements they replace (SINTEF, 2023).

Due to the Norwegian climate, special requirements for rain tightness and ventilation of solar panels appear, to provide resistance towards moisture and secure efficiency (SINTEF, 2023). During periods of much sunlight, it is crucial to ensure proper ventilation to keep the temperature of the PV cells low, i.e., enhanced production. According to Bunkholt et al. (2021) the efficiency of solar cells is reduced by approximately 0.5 % per °C temperature increase, i.e., areas of lower temperatures, such as Ørlandet, given adequate solar radiation, could be beneficial. Proper ventilation is also needed to dry out condensation on the PVs backside and to reduce deterioration (Bunkholt et al., 2021). Therefore, diagonal roofs with BIPV are often built as ventilated roofs with an air gap in the underside of the panels. Simulations of installation method and the geometry of the air gap has demonstrated that the height and angle of the air gap impacts the temperature and thus the efficiency of the panels. Increasing the slope of the roof and hight of air gaps, while decreasing the length of air gaps can provide improved efficiency due to reduced temperatures. However, steeper roof angles and larger air gaps can generate increased air circulation through natural convection in the gap.

During winter, snow and ice could potentially cover the entire or a portion of the roof, i.e., shadowing the BIPV and impend an efficient energy production (Bunkholt et al., 2021). Additionally, this could affect the service lifetime. Moreover, snow is highly reflective, meaning that a thin layer of snow could reduce the radiation significantly. If the layer exceeds 10 cm, the energy production will be nearly zero. Also, with BIPV roofs there are challenges associated with runoff of rain and snow (SINTEF, 2023). Snow and ice sliding off the roof could pose a threat to humans and equipment on the ground (Bunkholt et al., 2021). While snow traps eliminate this threat, they can cause snow and ice to accumulate on parts of the BIPV roof, thus also reducing the energy production. To prevent snow and ice accumulation, Bunkholt et al. (2021) suggests a combination of active and passive measures. An active measure could for instance be heating, while passive measures could be using special material surfaces, e.g., (i) self-cleaning surfaces where snow, ice, dust and other contaminants do not stick to the panels; (ii) hydrophilic surfaces that attracts water; (iii) hydrophobic surfaces that repels water; and (iv) rough surfaces with micro/nanostructure which impacts the hydrophobic properties.

5.3 Possible building integrated photovoltaics for heritage buildings at Ørlandet

Ørlandet, being a coastal region in the mid-northern part of Norway, is especially exposed to rain and snow, so the mentioned challenges in Chapter 5.2 are important if BIPV is incorporated into the three farmhouses. Further barriers arise with strict regulatory requirements for façade and roofing materials and colours, see Table 2.1. Here, coloured BIPV could be a fitting solution. One permitted roofing material is slate, which can be resembled by anthracite or grey-green colour (Pelle et al., 2020). The

British company GB-Sol offers a product called PV Slate, which looks like slate stones (GB-Sol, 2022). They claim the PVs will work seamlessly with natural slates, see Figure 5.5. This could be an option for Ørlandet to satisfy regulations; incorporating both natural slate and PV slate. The PV slates come in different shades, are lightweight compared to natural slate, and have an output of 132-138 Wp/m^2 depending on dimension. Alternatively, they could be used on the entirety of the roof, as they offer edge-to-edge solutions.

Figure 5.5: PV Slates from GB-Sol (GB-Sol, 2023).

The Dutch manufacturer Kameleon Solar offer coloured PV, called ColorBlast, with a variety of 4000+ colours, and customizable shapes and glass finishes (Kameleon Solar, n.d.-b). The output is colour dependant, but they have the potential to reach 168 Wp/m^2. In addition, they offer several other types of PVs, e.g., with design/image print, as well as metallic and matte surfaces. However, these have a lower output between max 150-168 Wp/m^2. Kameleon Solar uses metric patterns of hexagons to create a homogenous colour/image from a distance, while allowing light to pass through the gaps. This is beneficial as colour works as a shade for solar radiation. See Figure 5.6. For Trøa, Grande and Viken, a green PV could, for instance, resemble a turf roof (permitted roofing material), alternatively a turf-print could be applicable. Furthermore, woodprint PVs could be incorporated into the façades.

Figure 5.6: Hexagon coloured pattern on ColorBlast PVs (left). Kuijpers - Helmond with ColorBlast PVs in orange shades from a distance, appearing as homogenous colours (right). Both images are retrieved from (SolarLab, n.d.).

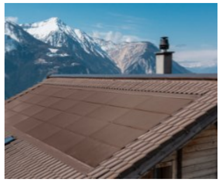
Wienerberger is a Dutch manufacturer producing PVs which resemble roofing tiles, named Alegra 10 Wevolt solar roof tile (Wienerberger, 2022). Regular roofing tiles are not permitted according to regulatory requirements; however, Alegra 10 Wevolt solar roof tiles are still considered an applicable option as they do not appear as PVs, but rather standard roofing tiles as shown in Figure 5.7. These solar roofing tiles are combined with a traditional ceramic roofing tile, making them easy and flexible to lay (Wienerberger, 2023a). They have an output of 106 Wp/m^2. Further BIPV options are presented in Table 5.1.

Figure 5.7: Alegra 10 Wevolt solar roofing tiles by Wienerberger (Wienerberger, 2023b).

Table 5.1: Possible BIPV for heritage buildings: product name, manufacturer, and properties (not comprehensive list).

Product name	Manufacturer	Photo	Output (Wp/m^2)	Efficiency (%)	Service lifetime (year(performance))	Dimensions l x w (mm x mm)	Weight (kg)	Colour/ finish	Application	Source
Alegra 10 Wevolt solar Roof Tile	Wienerberger AG Mail: office@wienerberger.com Web: https://www.wienerberger.com/en.html		106	17.1	≤ 12 (90 %) 12-25 (85 %)	304 x 477	49.29 kg/m	Black	Roof	(Wienerberger, 2023a) (Wienerberger, 2022) (Wienerberger, 2023b)
HanTile solar roofing tiles	Haenergy Thin Film Power Mail: businessdevelopment@hanergy.eu Web: https://www.hanergy.eu/		105	25.1	≤ 30 (100 %)	721 x 500	6.5	Black	Roof	(Hanergy, 2020) (Sangsolar, 2021) (Sangsolar, 2021) (Thoubboron, 2019)
Pixasolar – Fully coated solar panel	Hermans Technisolar Mail: info@hermanstechnisolar.nl Web: https://hermanstechnisolar.com/		100-160		≤ 30 (80 %)	600-2400 x 600-1200	28 kg/m^2	Customizable	Façade, wall, signage	(Hermans Technisolar, 2023) (Hermans Technisolar, 2022) (Caminogroup, 2021)
PV Slate 500 x 250 500 x 300 600 x 300	GB-Sol Mail: info@gb-sol.co.uk Web: https://www.gb-sol.co.uk/		138 138 132		≤ 10 (90 %) 10-25 (80 %)	1009 x 200 906 x 200 906 x 250	3.2 3.0 3.8	Light grey, blue-grey, black	Roof	(GB-Sol, 2023) (GB-Sol, 2022)

Table 5.1 (*continued*)

Product name	Manufacturer	Photo	Output (Wp/m^2)	Efficiency (%)	Service lifetime (year(performance))	Dimensions l x w (mm x mm)	Weight (kg)	Colour/finish	Application	Source
BiSolar roofing tile	BiSolar Mail: info@rooftilestechnology.com Web: https://www.bisolarroof.com/		173	17.3		300 x 445 Customizable	5.7	Dark grey	Roof	
Suncol Façade	Sunage Mail: info@sunage.ch Web: https://sunage.ch/en/			11-16.5	≤ 25 (80 %)	Customizable		Customizable	Façade	(Sunage, 2021a) (Sunage, 2021b) (Sunage, 2023a) (EURAC RESEARCH, n.d.-b)
Suncol Tile	Sunage Mail: info@sunage.ch Web: https://sunage.ch/en/			11-16.5	≤ 25 (80 %)	Customizable	20 kg/m^2	Customizable	Roof	(Sunage, 2023b) (Sunage, 2021c) (Sunage, 2021a) (EURAC RESEARCH, n.d.-b)
ColorBlast	Kameleon Solar Mail: info@kameleonsolar.com Web: https://kameleonsolar.com/		≤ 168 (depending on colour)		≤ 30 (80 %)	Customizable	~24 kg/m^2	Customizable	Façade, roof, balustrades, sun shading	(Kameleon Solar, n.d.-a) (SolarLab, n.d.)
Soluxa Solar Panels	Soluxa Contact: https://www.soluxa.solar/contact/ Web: https://www.soluxa.solar/#intro		≤ 190 (depending on colour)					Customizable	Façade	(Stultiens, 2021) (Soluxa, n.d.)

6 Exploring possible rehabilitation solutions within given requirements

6.1 Recommended new foundation and floor construction

As addressed in Chapter 3.1, a new slab-on-grade foundation with a concrete stem wall is the best option for the new foundation and floor construction for the three buildings. Considering the high moisture levels present at the coast, XPS has been identified as the most suitable thermal insulation material. Furthermore, insulation thickness is not a concern due to the foundation being remade and ample space being available in the ground. Figure 6.1illustrates the composition of the floor construction.

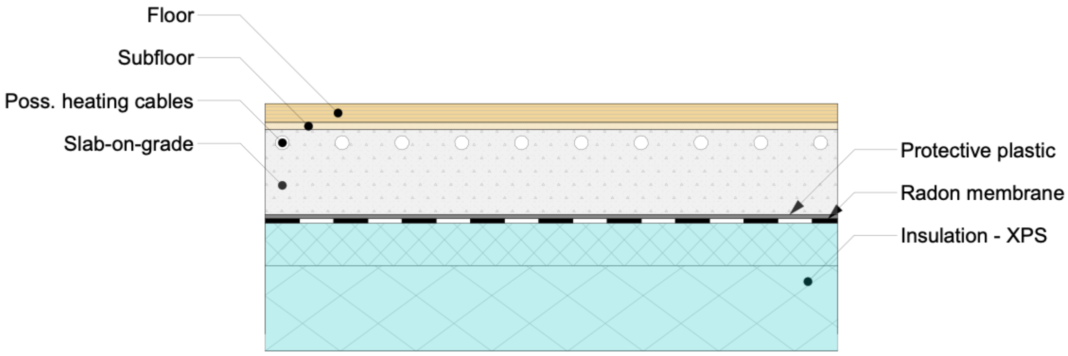


Figure 6.1: Illustration of suggested new floor composition.

The U-values for the floor construction was determined in THERM (THERM - Berkeley Laboratory, 2019). Two simulations for the foundation were performed, one with 200 mm XPS and one with 400 mm XPS. This gives a U-value of 0.16 W/(m^{2}K) and 0.08 W/(m^{2}K), respectively. As the foundation will be built according to today's requirements the risk of moisture accumulation within the floor construction and how moisture will move through the construction, was not deemed problematic. Therefore, no WUFI simulations (WUFI - Fraunhofer IBP, 2023) were carried out.

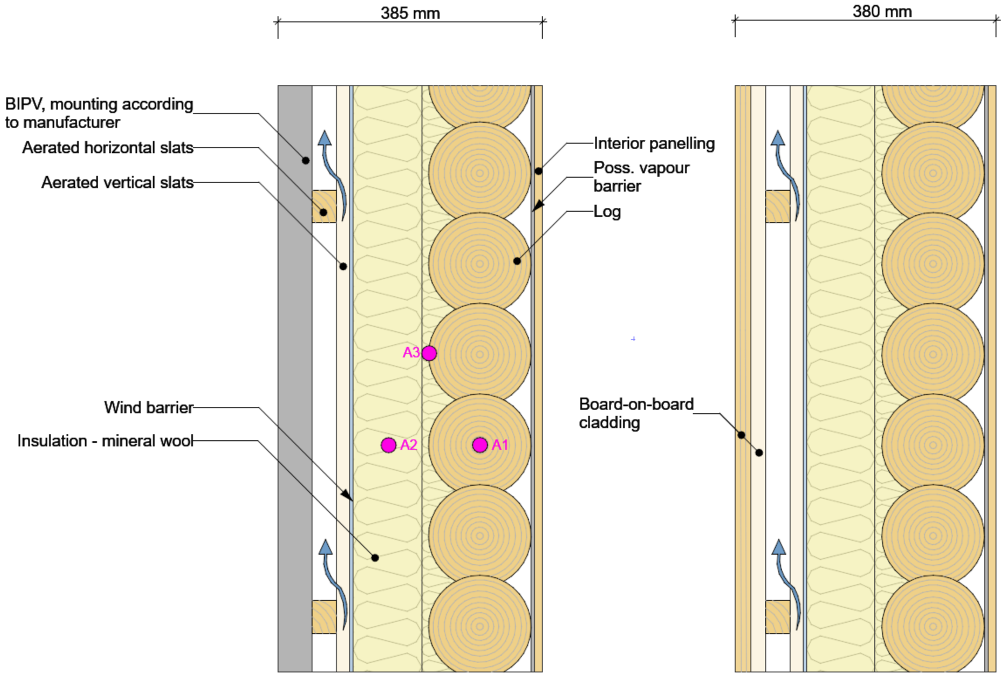
The concrete stem wall must be designed for each case dependent on the final thickness of the wall construction to ensure architectural authenticity. The surface treatment can be altered based on the desired aesthetic effect. Today, both Grade and Viken have a mix of natural stone with a protective coat of render and concrete with render. This is fairly easy to replicate the appearance of when relocating the buildings. Trøa, on the other hand, have natural stone with some mortar of gravel and silt. To replicate the appearance of this, a stamped concrete finish or natural stone veneers could be applied to the surface of the stem wall.

6.2 Possible solutions for external walls

In Norway, if the external wall of a building consists of 6'' logs or thicker there is no additional requirement for the U-value. This is the case for all three buildings in the study. However, to meet the required net energy demand, insulating the external walls is advantageous since 6'' logs only give a U-value of approximately 0.84 W/(m^{2}K) (SINTEF 471.431, 2013). In comparison, the minimum requirement for other types of wall constructions in Norway is 0.22 W/(m^{2}K). Table 4.1 highlights that when considering insulation material for wall constructions, the most advantageous options in terms of thickness are mineral wool, aerogel, and VIP, when looking at both traditional and state-of-the-art materials. Cellulose and wood fibre could be an option, but they result in a thicker wall construction compared to mineral wool to achieve the same U-value. Therefore, there will not be presented solutions with these materials. Regarding placement, aerogel and VIP could both be placed externally and internally, while mineral wool should only be placed externally to avoid compromising the inside area considerably.

For the following solutions (A-F), only the changed layers are named in the figures. Also, BIPV is suggested as a possible cladding for all wall solutions, but traditional board-on-board cladding is still an option. Figure 6.5 shows a summary of the simulated U-values from THERM and the total wall thicknesses. Figure 6.6, Figure 6.7 and Figure 6.8 illustrates the relative humidity (RH) in wall solutions A-F, simulated in WUFI both with and without vapour barrier.

Figure 6.2 presents a solution of a wall construction externally post-insulated with 150 mm mineral wool (solution A), which gives a U-value of 0.26 W/(m^{2}K). The mineral wool is placed in a framework and fills the gaps in the logs. While obtaining an adequate U-value, the drawback of solution A is a total thickness of ca. 385 mm which will affect the eaves and window placement in the wall, and consequently the building's architectural appearance. Moreover, deeper window posts also result in less daylight inside. WUFI revealed that the centre of the logs (A1) will dry out well with this solution, see Figure 6.6. In the centre of the mineral wool (A2), the graph (Figure 6.7) demonstrates that the relative humidity (RH) fluctuates stably and gradually downward sloping. The peaks are during autumn and the troughs are during spring, meaning the insulation dries out during winter. In the junction between the mineral wool and the logs (A3), Figure 6.8, solution A displays the best results out of all the solutions (A-F). Adding a vapour barrier gives slightly better results over time in all positions, than without vapour barrier, i.e., using a vapour barrier results in lower RH in solution A.



Solution A

Figure 6.2: Wall construction post-insulated with external mineral wool. The left wall suggests BIPV as exterior cladding, and the right wall illustrates traditional board-on-board cladding. Monitor positions and names for WUFI simulations are shown as pink dots.

Figure 6.3 illustrates how to post-insulate with 20 mm VIP externally (solution B) and internally (solution C). VIP results in a slimmer construction than mineral wool, approximately a total thickness of 300 mm. The VIPs are connected to the logs in a 23-36 mm framework, where the log gaps are filled with up to 50 mm mineral wool. Both external and internal VIP will provide a U-value of 0.25 W/(m^{2}K). In both centre log (B1, C1, Figure 6.6) and the junction between logs and insulation (B3, C3, Figure 6.8), the VIP solutions causes a rather high relative humidity in the wall. Solution B with vapour barrier hardley decreases from 80 % RH over 7 years in the log-centre and increases somewhat in the junction. This is because VIP is vapour diffusion tight and works as a vapour barrier, resulting in a vapour tight layer on both sides of the log. Therefore, post-insulating externally with VIP (solution B) cannot be combined with a vapour barrier since the moisture will be "trapped" inside the construction. An RH of 80 % together with the right temperature (25-30 ºC) could cause mould growth and rot in the logs (SINTEF 701.401, 2005). However, solution B without vapour barrier will give the logs an opportunity to dry out more. Solution C, both with and without vapour barrier also decreases marginally from 80 % RH over seven years in both the centre log (Figure 6.6) and the junction between logs and insulation (Figure 6.8), i.e., this is not a good solution.

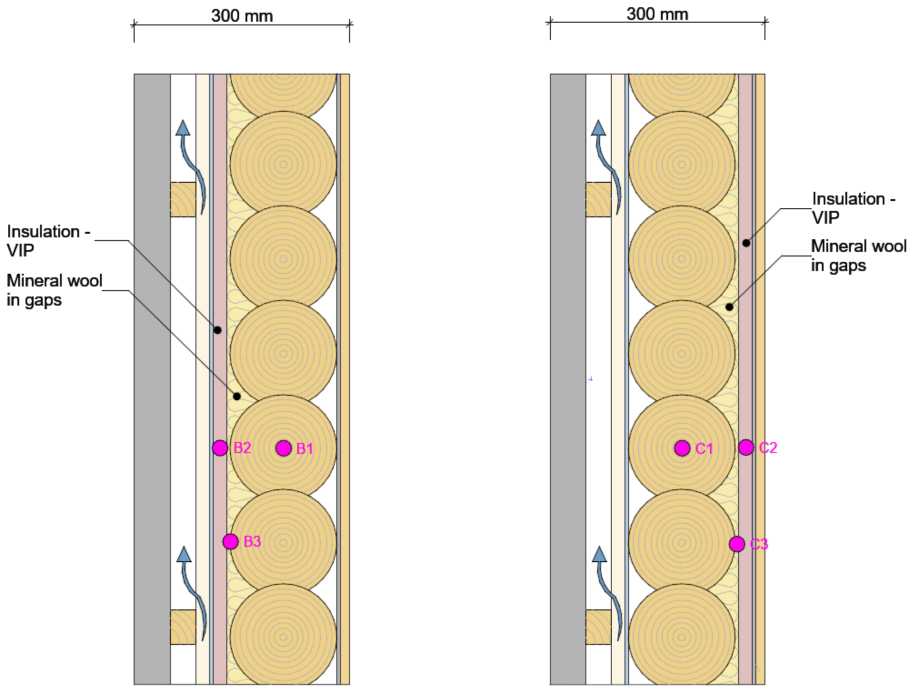
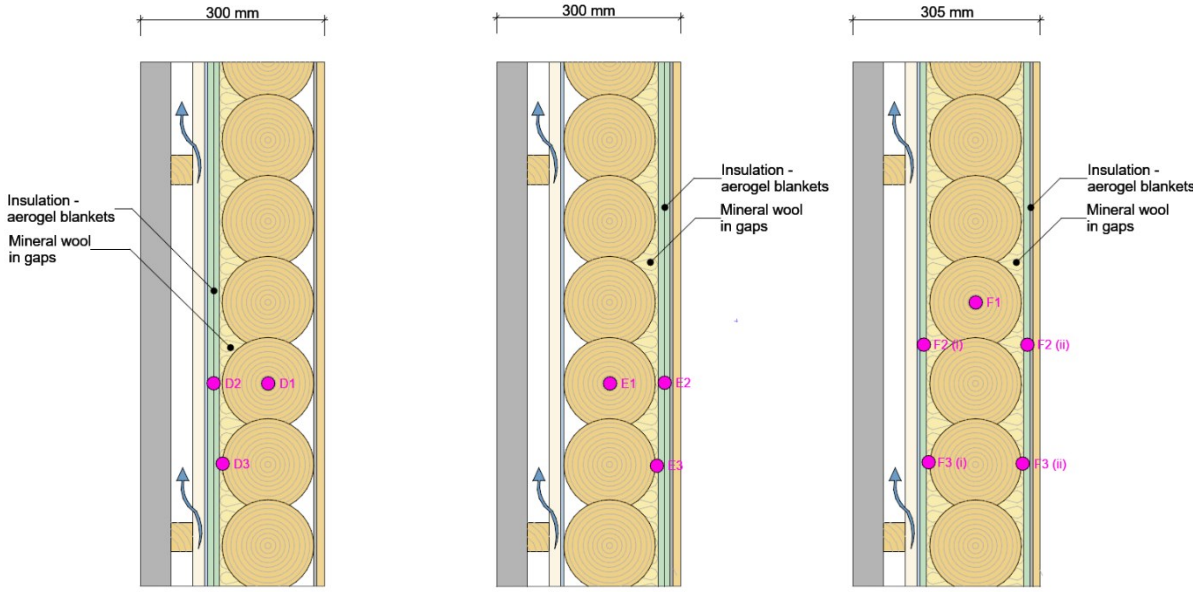


Figure 6.3: Wall construction post-insulated with external VIP (B), and internal VIP (C). Monitor positions and names for WUFI simulations are shown as pink dots.

Figure 6.4 shows three solutions for post-insulating with aerogel blankets. According to Table 4.1, it would be necessary to use five layers of aerogel blankets to achieve a U-value of 0.22 W/(m^{2}K). Because aerogel is an expensive product, it is not a feasible alternative to use five aerogel blankets to achieve a U-value which isn't required. Therefore, it is only suggested to use two aerogel blankets of 10 mm each, either placed externally (solution D), internally (solution E), or both (solution F). Like the alternative with VIP, the total wall thickness is estimated to be 300 mm. The aerogel blankets are connected to the logs with screws, and the log gaps are filled with up to 50 mm mineral wool. With two layers of aerogel the U-value is 0.33 W/(m^{2}K) for solution D, 0.32 W/(m^{2}K) for solution E and 0.30 W/(m^{2}K) for solution F. The aerogel blankets used for these simulations are hydrophobic, yet breathable, i.e., repelling liquid water, but allowing vapour to pass thorough (Aspen Aerogels, 2017).

Measurements from the log centre (Figure 6.6) and between the logs and the insulation (Figure 6.8) shows that external aerogel gives the best result out of the three solutions. Both with and without vapour barrier result in low RH in the log, but over time the solution with vapour barrier will be the best by decreasing the most. Combined external and internal aerogel gives tolerable results by reducing the RH in the centre log (F1, Figure 6.6) both with and without vapour barrier. In the junction between logs and insulation (F2 (i) and (ii), Figure 6.8) the solution with vapour barrier gives more RH on the internal side than the external. It is the opposite case for the solution without vapour barrier. Also, the RH is higher. Internal aerogel insulation gives a relatively high RH both with and without vapour barrier in the log centre (E1, Figure 6.6) and the junction between logs and insulation (E3, Figure 6.8), but somewhat lower RH without vapour barrier. In the centre of the insulation (Figure 6.7), the internal aerogel in solution F has the lowest RH when combined with a vapour barrier, but the appurtenant external insulation contains more moisture. Solution E with a vapour barrier has the second-lowest RH, while the same solution without a vapour barrier is higher. Solution D has approximately the same high RH with and without vapour barrier.



Solution D Solution E Solution F

Figure 6.4: Wall construction post-insulated with external aerogel insulation (D), internal aerogel insulation (E), and both (F). Monitor positions and names for WUFI simulations are shown as pink dots.

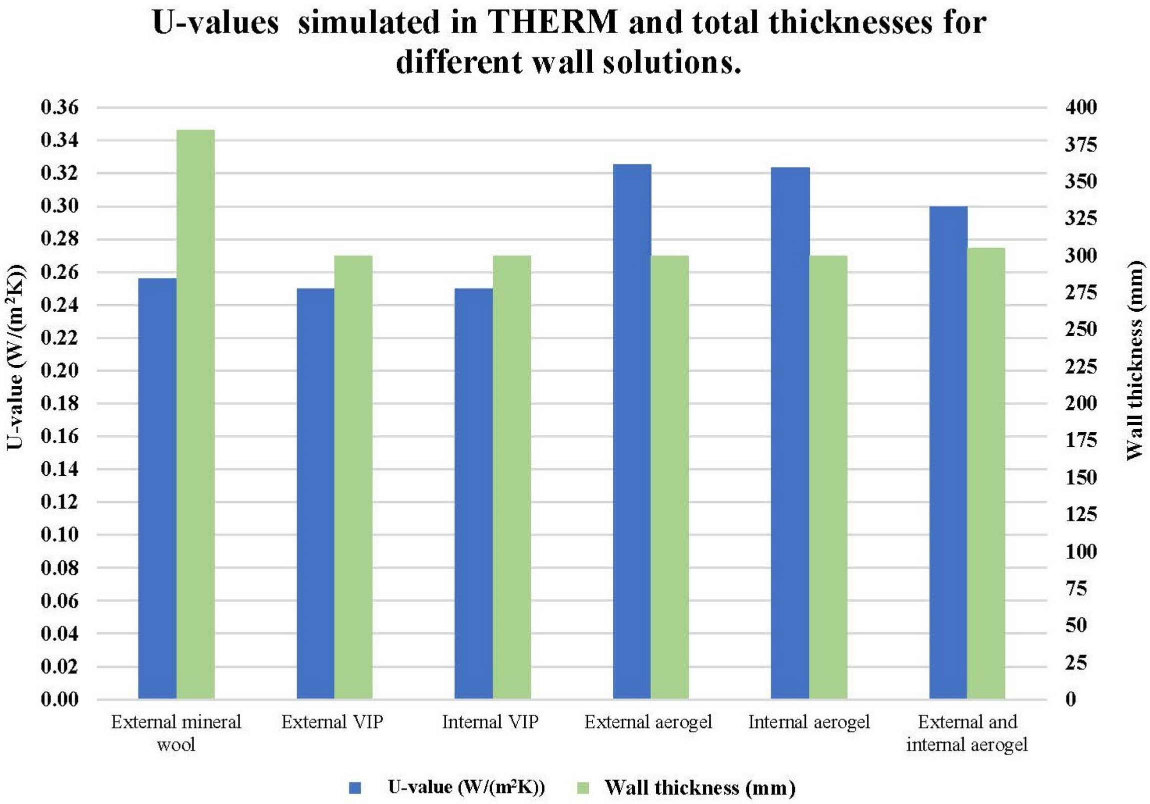
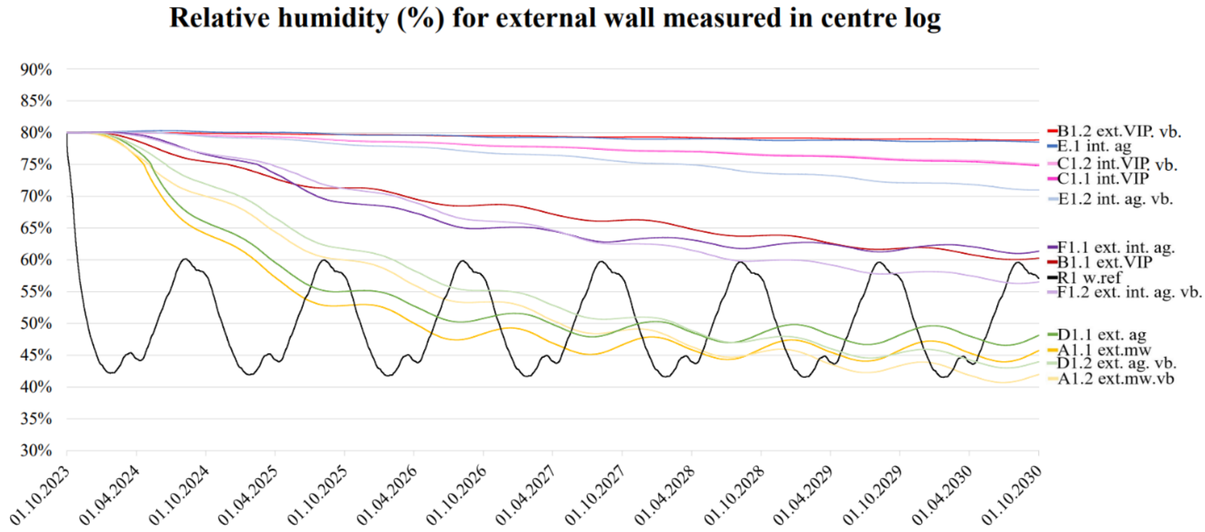
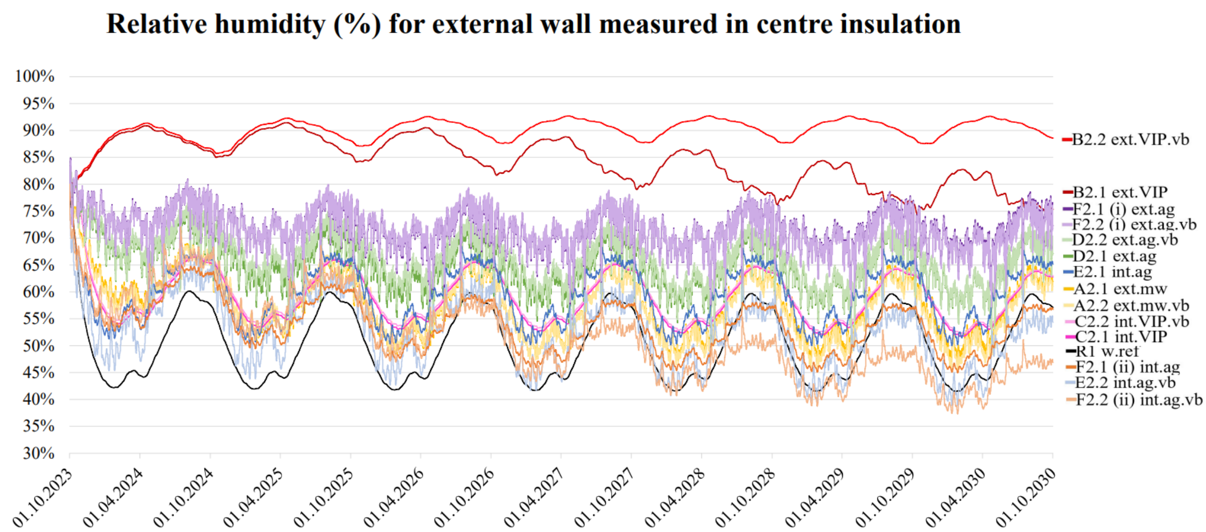


Figure 6.5: U-values simulated in THERM and total thicknesses for different wall solution.



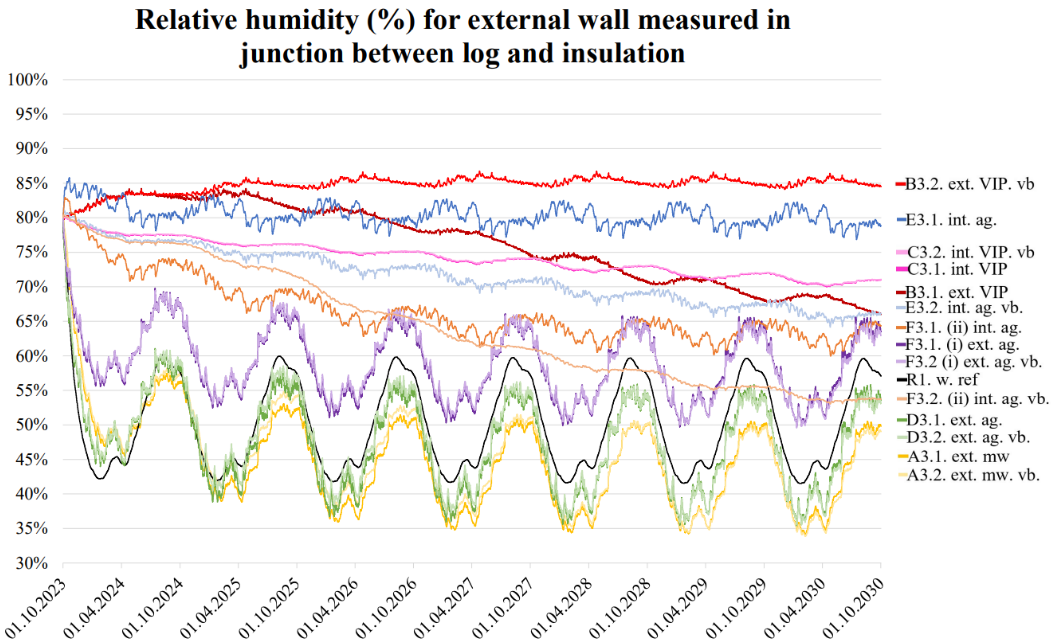
VIP. vb.: Solution C internal VIP with vapour barrier; D1.1. ext. ag.: Solution D external aerogel; D1.2. ext. ag. vb.: Solution D external aerogel with vapour barrier; E1. 1. int. ag.: Solution E internal aerogel; E1.2. int. ag. vb.: Solution E internal aerogel with vapour barrier; F1.1. ext. int. ag.: Solution F external and internal aerogel; F1.2. ext. int. ag. vb.: Solution F external and internal aerogel with vapour barrier; R1. w. ref.: Wall reference measured on interior surface.

Figure 6.6: Relative humidity (%) for external wall measured in centre log (monitor position 1) for solution A-F.



A2.1. ext. mw.: Solution A external mineral wool; A2.2. ext. mw. vb.: Solution A external mineral wool with vapour barrier; B2.1. ext. VIP.: Solution B external VIP; B2.2. ext. VIP. vb.: Solution B external VIP with vapour barrier; C2.1. int. VIP: Solution C internal VIP; C2.2 int. VIP. vb.: Solution C internal VIP with vapour barrier; D2.1. ext. ag.: Solution D external aerogel; D2.2. ext. ag. vb.: Solution D external aerogel with vapour barrier; E2.1. int. ag.: Solution E internal aerogel; E2.2. int. ag. vb.: Solution E internal aerogel with vapour barrier; F2.1. (i) ext. ag.: Solution F external aerogel; F2.2. (i) ext. ag. vb.: Solution F external aerogel with vapour barrier; F2.1. (ii) int. ag.: Solution F internal aerogel; F2.2. (ii) int. ag. vb.: Solution F internal aerogel with vapour barrier; R1. w. ref.: Wall reference measured on interior surface.

Figure 6.7: Relative humidity (%) for external wall measured in centre insulation (monitor position 2) for solution A-F.



A3.1. ext. mw.: Solution A external mineral wool; A3.2. ext. mw. vb.: Solution A external mineral wool with vapour barrier; B3.1. ext. VIP.: Solution B external VIP; B3.2 ext. VIP. Vb.: Solution B external VIP with vapour barrier; C3.1. int. VIP.: Solution C internal VIP; C3.2. int. VIP. Vb.: Solution C internal VIP with vapour barrier; D3.1. ext. ag.: Solution D external aerogel; D3.2 ext. ag. vb.: Solution D external aerogel with vapour barrier; E3.1 int. ag.: Solution E internal aerogel; E3.2. int. ag. vb.: Solution E internal aerogel with vapour barrier; F3.1. (i) ext. ag.: Solution F external aerogel; F3.1. (ii) int. ag.: Solution F internal aerogel; F3.2 (i) ext. ag. vb.: Solution F external aerogel with vapour barrier; F3.2. (ii) int. ag. vb.: Solution F internal aerogel with vapour barrier; R1. w. ref.: Wall reference measured on interior surface.

Figure 6.8: Relative humidity for external wall measured in the junction between log and insulation (monitor position 3) for solution A-F.

6.3 Possible solutions for the roof construction

Concerning the roof construction, possible solutions for the three farmhouses are to insulate above the joists against the cold attic, either with mineral wool, VIPs or aerogel blankets. The floor framework in the attic is assumed uninsulated in the three farmhouses, and there is a mix of raftered and panelled ceiling on the underside. A solution could be to insulate the joists, but in cases with raftered ceiling and limited headspace this would not be feasible. Placing the vapour barrier under the floor framework becomes necessary if the joists are insulated. This can complicate the installation process or require dismounting of the panelled ceiling. If it is desired to preserve the panelled ceiling this may not be an optimal solution. The simulations are based on a raftered ceiling; hence the floor framework is not included as an insulating layer in the U-value simulations performed in THERM.

The proposed solutions (G-I) are illustrated in Figure 6.9, and the only difference between them is the insulation layer. All the studied solutions satisfy the minimum requirement of 0.18 W/(m^{2}K), see Figure 6.10. Solution G has a thick layer of mineral wool, hence more of the attic space is used but the obtained U-value is relativly low; 0.11 W/(m^{2}K). The large thickness could be a disadvantage if the space is limited and are going to be used for storage, e.g., for ventilation and BIPV equipment. In this case, solution H using VIPs may be more suitable since it takes up very little space. However, this solution has a higher U-value; 0.16 W/(m^{2}K). Solution I is a combination of aerogel blankets and mineral wool. To meet the technical energy requirements by only using aerogel blankets would require about seven layers, hence a combination with aerogel and mineral wool is studied. This solution consumes more of the attic space compared to the VIPs but is about half the thickness compared to the alternative with mineral wool alone. Nevertheless, the U-value for this solution is 0.18 W/(m^{2}K).

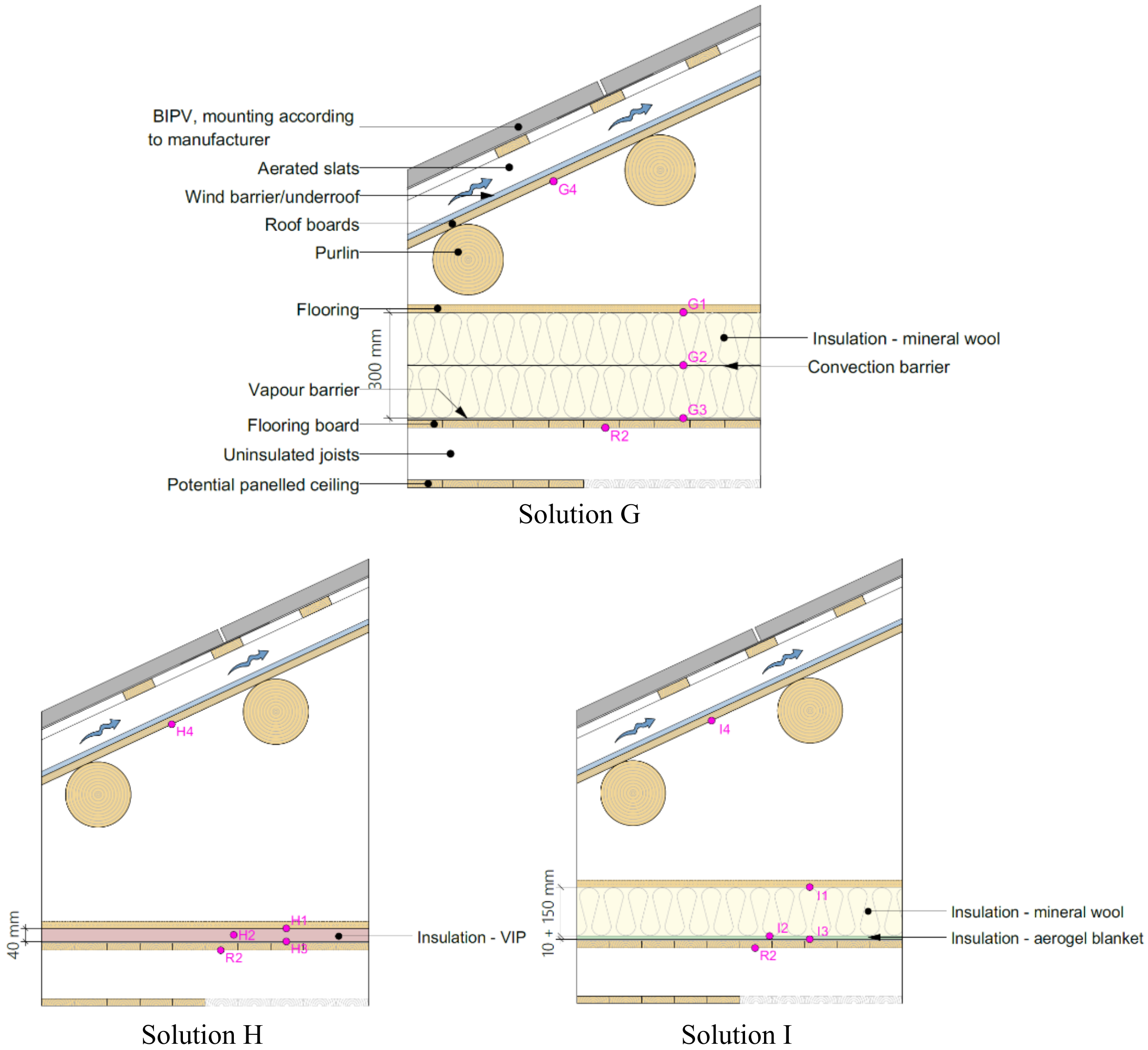


Figure 6.9: Three possible solutions for post-insulating above the joists against the cold attic: Solution G with mineral wool, Solution H with VIPs, and Solution I with aerogel and mineral wool. Monitor positions and names for WUFI simulations are shown as pink dots.

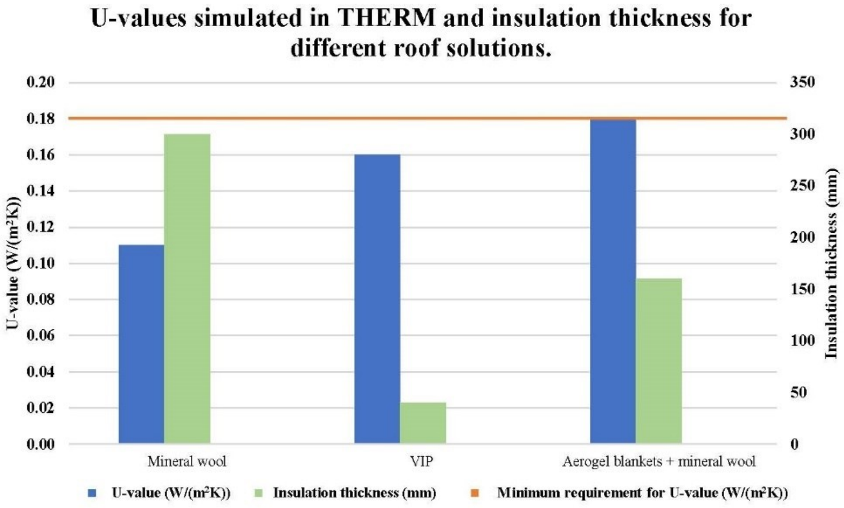
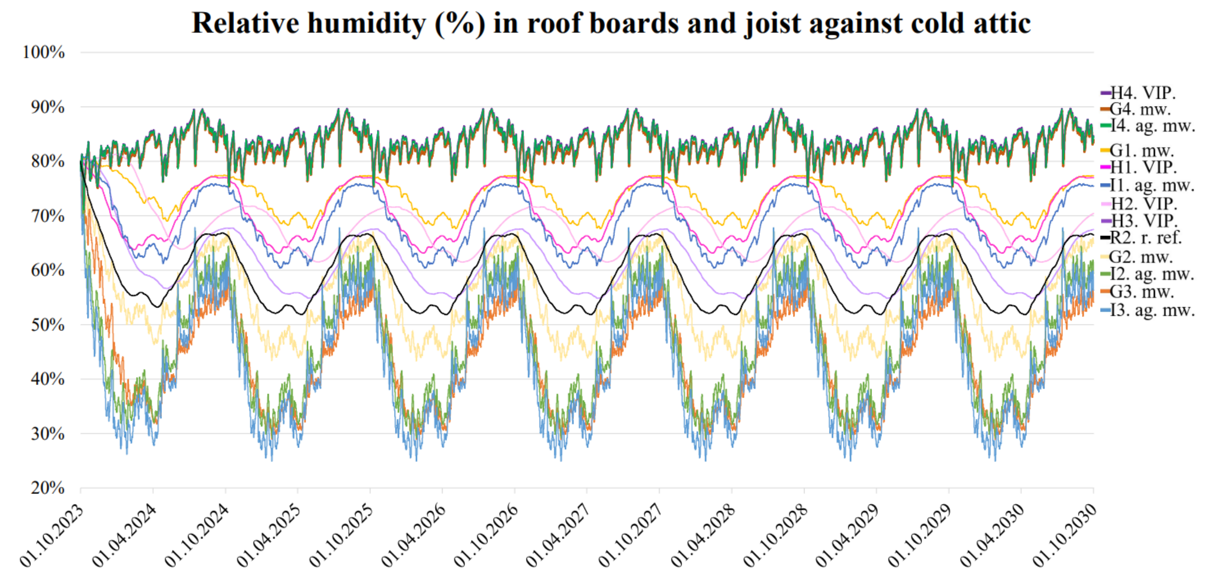


Figure 6.10: U-values and insulation thickness for three different roof solutions for post-insulation above the joists against the cold attic simulated in THERM.

A vapour barrier is necessary underneath the insulation to prevent warm and humid air from entering the insulation. Although the VIP itself is vapour tight, a vapour barrier is also included in this alternative to ensure a consistently air and vapour tight layer, especially in the joints between the VIPs. Figure 6.11 shows the relative humidity (RH) in four measuring points for each solution. On the underside of the roof boards, i.e., in measuring points G4, H4 and I4, the RH is alarmingly high (> 80 %) in all the suggested solutions. The post-insulation will cause cooler temperatures and consequently a higher RH in the attic. Moreover, the underside of the roof boards is likely cooler than the air in the attic, and the RH is even higher here. With the right temperature, for example during the summer, this can cause rot and mould growth. To avoid this, it is crucial with sufficient aeration in the attic to lower the RH. The remaining measuring points have lower RH that fluctuates evenly through the simulated years with peaks during the autumn and troughs during the spring. The moisture levels are increasing from the interior side to the attic side of the joists, but the RH is never higher than 80 %.



G1-4. mw.: Solution G, monitor position 1-4, mineral wool; H1-4. VIP.: Solution H, monitor position 1-4, VIP; I1-4. ag. mw.: Solution I, monitor position 1-4, aerogel and mineral wool; R2. r. ref.: Roof reference measured on interior panelled ceiling.

Figure 6.11: Relative humidity (%) in roof boards and joist against cold attic (monitor position 1-4) for solution G, H, and I.

The presented alternatives have BIPV as roofing, despite it not being a part of the regulatory requirements. To optimize the efficiency of the BIPV, a relatively large, aerated slat-layer is necessary as this will secure sufficient ventilation and cooling. Dependent on the product type for BIPV, they must be mounted according to the manufacturer. In addition, a combination of active and passive measures presented in Chapter 5.2 should be incorporated to prevent snow and ice accumulation on the roof. To secure an airtight envelope, a dual-purpose underroof and wind barrier is needed outside the roof boards. Ideally, the wind barrier in the external walls should overlap with the wind barrier on the roof to avoid any air leakages. This results in a cold non-ventilated attic with two air-tightening layers.

6.4 Possible solutions for fenestration renovation

The windows in the three buildings, Trøa, Grade and Viken, have been evaluated regarding their energy-efficiency and suitability for preservation. Trøa was found to have a number of old windows in relatively good condition, which could be repaired and reused, making it ideal to use internal storm windows that preserve the building's historic appearance externally. This is in line with the regulatory requirements for the area, which states that the exterior of listed buildings must be preserved or restored according to antiquarian principles. The remaining windows in Trøa are not original and therefore suggested replaced by new energy-efficient windows that resemble the original ones with slats. Figure 6.12 shows some of the current windows in Trøa.

Figure 6.12: The pictures show an old original slatted window on the first floor and a newer two-section window on ground floor. Photos: (Taftø Petersen, 2015).

Grande have both awning windows and two-section casement windows from varying time periods, see Figure 6.13. Especially the awning windows do not fit the antiquarian principles from the construction period. However, some slatted windows were discovered at the farm, which are believed to be old windows from Grande. Although they are in bad condition, they can serve as a template for designing new windows that replicate the old ones. The aim for Grande is to restore the windows in line with antiquarian principles by recreating the slatted windows found at the farm.

Figure 6.13: Left: Old slatted window found at the farm held over an awning window. Middle: two-section casement window. Right: Awning windows on the southwest and southeast façades. Photos: (Hesthol Løvik et al., 2022).

Viken has mostly newer windows which both meet today's building requirement in terms of insulation-properties and are in line with antiquarian principles, see Figure 6.14. Therefore, the focus is to take care of the existing windows and compensate with post-insulation in other parts of the climate shell to achieve required energy efficiency.

Figure 6.14: The east (left) and north (right) façade of Viken illustrating the current windows (Taftø Petersen & Johansen, 2015).

6.5 Energy-saving measures and recommended solutions

6.5.1 General energy-saving measures and results

To assess the most energy-efficient measures for the three buildings, various measures were set up for analysis. Table 6.1 presents 17 individual measures and three combinations of measures that were simulated in SIMIEN (SIMIEN, n.d.). The individual measures include post-insulation, fenestration renovation, air-tightening and use of BIPV, and are the same for all three buildings. The three different combinations of measures are meant to reflect three different solutions: (no. 18) conservation of cultural heritage; (no. 19) most energy-efficient; and (no. 20) the recommended solution. Note that the combination of measures is different for each of the three buildings. For a more detailed explanation and risks associated with each measure see Appendix B.

Table 6.1: Energy-saving measures and combinations of measures for Trøa, Grande and Viken.

No.	Building part	Description
1	Foundation/floor	New foundation with 200 mm XPS.
2	Foundation/floor	New foundation with 400 mm XPS.
3	External wall	Post-insulation with 100-150 mm mineral wool.
4	External wall	Post-insulation with 20 mm VIP.
5	External wall	Post-insulation with 20 mm aerogel.
6	External wall	Post-insulation with 10 mm aerogel both externally and internally.
7	Roof	Post-insulation above frame of joists against cold attic with 300 mm mineral wool.
8	Roof	Post-insulation above frame of joists against cold attic with 40 mm VIP.
9	Roof	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool.
10	Windows	Fenestration renovation with new triple-glazed energy-efficient windows.
11	Windows	Improve the old windows with secondary glazing.
12	Windows	Fenestration renovation with new doors and new energy-efficient windows on the ground floor, and improvement of the old windows on the first floor with secondary glazing (only applicable for Trøa).
13	Building envelope	Air tightening from an infiltration of 10 h^{-1} to 6 h^{-1} (n50) (requirement for log constructions. Estimated leakage with new foundation and post-insulation of the roof).

Table 6.1 (*continued*)

No.	Building part	Description
14	Building envelope	Air tightening from an infiltration of 10 h^{-1} to 4 h^{-1} (n50) (estimated leakage with some additional air tightening)
15	Building envelope	Air tightening from an infiltration of 10 h^{-1} to 1.5 h^{-1} (n50) (requirement for non-log constructions).
16	Roof	BIPV with 18 % efficiency for the relevant roof surface.
17	Facade	BIPV with 18 % efficiency for the relevant façade.
18	Combination	Preserve cultural heritage.
19	Combination	Most energy-efficient.
20	Combination	Recommended solution.

The impact of each measure for all three buildings are compared as a reduction in percentages of the net energy demand and presented in Figure 6.15. Which measure that has the greatest impact on the net energy demand varies between the buildings, e.g., measures one and two have a much greater impact on Viken than on Trøa and Grande. Not surprisingly, the largest energy savings for the combined measures can be accomplished in Trøa, due to its poor present condition compared to Grande and Viken. Later, individual graphs for the three buildings will be presented to show the resulting net energy demand for each individual measure and how they compare to the requirement specified in the Norwegian technical requirements. When implementing BIPV, it should be noted that the requirement increases by 10 kWh/m^2 due to the production of self-generated energy.

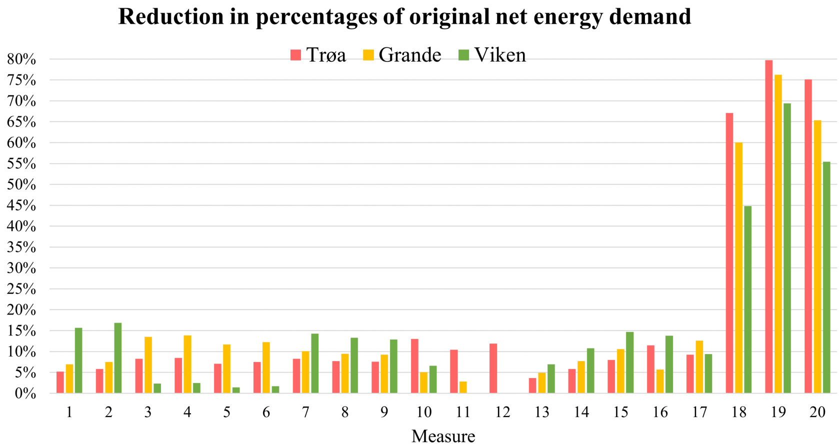


Figure 6.15: Reduction in percentages of original net energy demand for all three buildings.

For all three buildings, the difference in energy savings with 200 mm insulation versus 400 mm insulation in the foundation is just 1 % at the most, consequently it is recommended to only use 200 mm to minimize the material usage and costs. Generally, post-insulating the wall with VIP gives the greatest reduction in net energy demand, closely followed by mineral wool. However, mineral wool is not an ideal solution due to the required thickness. For the roof construction, mineral wool gives up to 1 % more reduction than VIP and aerogel for all three buildings. Even though this requires a thick insulation layer, it is considered the best solution due to its affordability and availability of sufficient space in the attic. Utilising a combination of blown in insulation along the eaves and batt insulation on the remaining area gives both advantages with sealing tiny cracks and crevices and easy removal for future inspection of the joists.

Air-tightening of the building envelope is recommended to lower the energy demand for all three buildings. Generally, by implementing a vapour barrier in the roof construction together with a new foundation, a 4-7 % reduction is achieved (no. 13). With some additional air sealing around windows and doors, this number goes up to 8-11 % (no. 14). With a new vapour and wind barrier in the external wall it is assumed that air-tightening of infiltration can reach 1.5 h^{-1} (n_{50}) (no. 15), resulting in a reduction up to 15 %. However, a too tight building envelope would require a ventilation system to achieve a good indoor climate.

Regarding the implementation of BIPV, it is not in line with cultural heritage preservation. For the façade, it will alter the appearance in various amounts depending on the type of BIPV used. Despite the availability of coloured BIPV with flat finish, a façade covered in BIPV may be more reflective than original wooden cladding. This contradicts the regulatory requirements that states that reflective materials must be avoided as much as possible. Moreover, the use of BIPV on the façade does not provide the same superficial structure as traditional board-on-board cladding. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look. Nevertheless, the use of BIPV that simulates conventional roofing and cladding materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.

6.5.2 Results and suggested solution for Trøa

Each different measure (no. 1-17) has about the same impact on Trøa's net energy demand, a reduction in a range of 4-13 % according to the simulations, see Figure 6.16. Measure no. 18-20 are combinations of the individual measures, thus resulting in a high reduction in the net energy demand (67-80 %). The combination, aiming at preserving the cultural heritage (no. 18), includes post-insulation of the external walls with aerogel both externally and internally. Since it is most likely necessary to dismount the existing board-on-board cladding and the interior panelling, this is viewed as the most optimal choice considering moisture, U-value, air tightness and preservation. Additionally, measure no. 18 includes a new foundation, insulating above the joists against the cold attic, and improving the airtightness of the building from 10 to 1.5 h^{-1} (n_{50}). It is assumed that it is possible to achieve such good airtightness by installing a new vapour barrier and a new wind barrier in continuous layers around the building envelope.

Concerning Trøa's windows, the suggested solution for cultural preservation is measure no. 12: a combination of window restoration with secondary glazing and window replacement with new energy-efficient windows that resemble the old original ones. Compared to replacing all the windows with new ones (no. 10 and no. 19), the suggested solution results in only 1 % lesser savings in the net energy demand. The fenestration renovation is the measure alone that will have the greatest impact on the net energy demand.

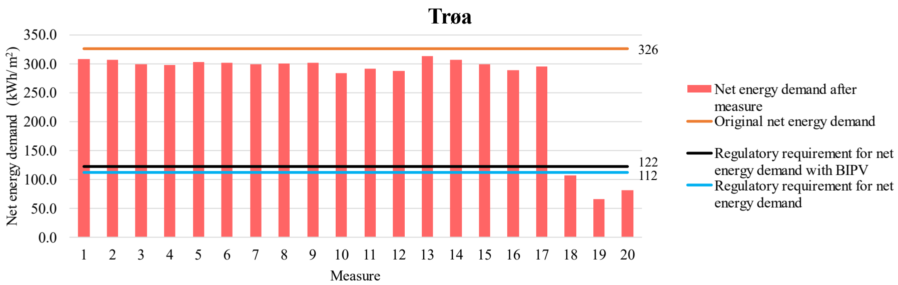


Figure 6.16: Trøa's net energy demand after each individual measure and the combined measures, as well as original net energy demand and regulatory requirement for net energy demand with and without BIPV.

The suggested combined measures that preserve the cultural heritage in the best possible way reduce the net energy demand by 67 %, i.e., from 326 kWh/m^2 to 107 kWh/m^2, hence the regulatory requirement for net energy demand of 112 kWh/m^2 is accomplished. Combined with a solution including BIPV on the roof, the net energy demand is reduced by 75 %. This is the recommended solution, i.e., measure no. 20. BIPV on the façade is not recommended as it probably would change the appearance of the building, and the energy requirement is fulfilled without it. Measure no. 19 represent the most energy-efficient measures combined, hence an 80 % reduction in Trøa's net energy demand. This combination does not take the cultural value or hygrothermal aspects into consideration and is therefore not recommended as the final solution.

6.5.3 Results and suggested solution for Grande

Grande currently has a net energy demand of 305 kWh/m^2. Figure 6.17 shows that after performing the individual measures (no. 1-17), there is a slight reduction in the net energy demand: all being between 250-300 kWh/m^2. However, the combined measures (no. 18-20) show a significant reduction.

For the combined measures focusing on preserving cultural heritage, it is only included measures that best ensure architectural integrity and authenticity. Therefore, 20 mm of external aerogel insulation is preferred as insulation for the external walls, as it gives a slimmer construction and shows good results regarding moisture. Since it is unnecessary to tear down both exterior cladding and interior panelling in Grande, this alternative will be without a vapour barrier. When not installing a vapour barrier, the building envelope probably won't fulfil the Norwegian airtightness demand of 1.5 h^{-1} and is consequently thought to be reduced from the original 10 h^{-1} to 4 h^{-1}. Yet, it is assumed that exterior cladding, wind barrier, insulation, and the log itself provide sufficient air tightness. Because Grade currently has a blend of windows in different styles from different time periods, retaining the windows as they are do not restore the structure's original architectural integrity. Hence, it is desired to change the old windows and doors into new triple-glazed energy-efficient windows and new doors which both resemble the originals. Also, the foundation is insulated with 200 mm XPS and there is mineral wool above the framework of joists against the cold attic. These combined measures resulted in a net energy demand of 122 kWh/m^2, i.e., a reduction of 60 %. However, this does not fulfil the energy requirement for Grande which is 110.8 kWh/m^2.

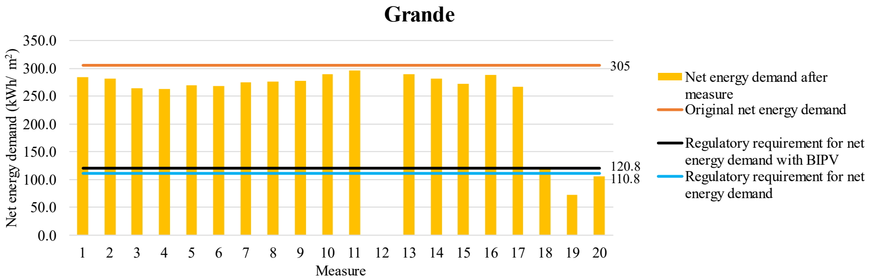


Figure 6.17: Grande's net energy demand after each individual measure and the combined measures, as well as original net energy demand and regulatory requirement for net energy demand with and without BIPV.

For the most energy-efficient combined measures (no. 19), cultural heritage preservation and feasibility are not considered. Therefore, only the most net energy demand reducing measures are simulated, i.e., 400 mm XPS, insulating the wall with VIP, mineral wool above the framework of joists, new doors and triple-glazed energy-efficient windows, a presumed airtightness of 1.5 h^{-1}, and BIPV on both the whole roof and on the west and south façade. Only these façades are deemed fitting for BIPV, because they are more exposed to sun radiation. These energy-efficient measures result in a net energy demand of 73 kWh/m^2, i.e., a reduction of 76 % fulfilling the demand. When including BIPV, the energy requirement becomes 120,8 kWh/m^2 for Grande. Although this solution is the most energy-efficient, it is not recommended due to the lack of cultural preservation. The recommended solution of combined measures (no. 20) is therefore similar to the cultural heritage solution, with the addition of BIPV on the roof. This combination of measures results in a net energy demand of 106 kWh/m^2, which fulfils the demand and constitutes a reduction of 65 %.

6.5.4 Results and suggested solution for Viken

For Viken, a new foundation has the greatest impact closely followed by post-insulating the roof and improving the overall airtightness of the building envelope (Figure 6.18). Based on the results from the simulation, post-insulating the external walls further, have little to no effect on the overall energy demand (no. 3-6). Regarding the integration of BIPV the reduction in the overall net energy demand is around 14 % for BIPV on the roof and 9 % for BIPV on the east façade. Adding BIPV on the remaining façades was considered excessive and inefficient due to the location of the building in the new residential area.

When constructing the combinations of measurements for preserving cultural heritage (no. 18), only measures that would not alter the exterior appearance of the building envelope were selected. The result was a 45 % reduction in net energy demand, which gives an annual net energy demand of 138 kWh/m². This is higher than the requirement of 106 kWh/m². The most energy-efficient solution (no. 19) involves taking apart the exterior walls to add new insulation together with a new wind and vapour barrier. This is considered a significant additional workload in accordance with its level of necessity, considering the current condition of both the interior and exterior surfaces in the wall. Nevertheless, a reduction of 69 % can be achieved which gives an annual net energy demand of 77 kWh/m².

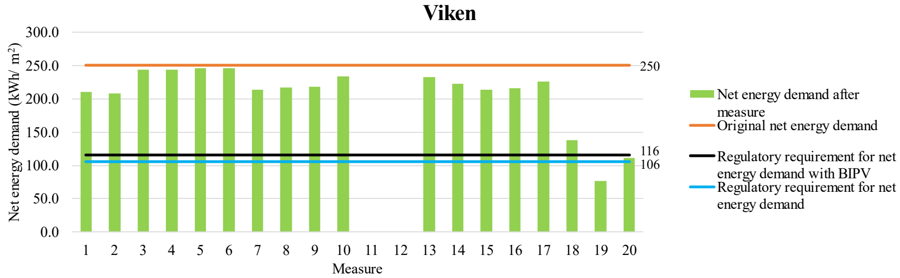


Figure 6.18: Viken's net energy demand after each individual measure and the combined measures, as well as original net energy demand and regulatory requirement for net energy demand with and without BIPV.

For the recommended solution (no. 20), the exterior walls were considered sufficient regarding both energy efficiency and architectural expression in their current state. The suggested measures are post-insulating the roof, a new foundation, a more airtight building envelope and BIPV on the roof. It is not recommended to install BIPV on the façade since it produces less energy than BIPV on the roof. Also, integrating BIPV on both the roof and the façade results in a negligible difference in energy reduction. The combined measures result in a 55 % reduction in the original net energy demand. Since the recommended solution includes BIPV, the building technical requirement for energy efficiency is fulfilled, as shown in Figure 6.18. The annual net energy demand will be 111 kWh/m².

7 Future perspectives

Energy rehabilitation and reuse of existing buildings have the potential to contribute to sustainable heritage conservation while embracing new energy efficiency principles. Reducing energy consumption aligns with several of the United Nations Sustainable Development Goals. Additionally, considering the building sector's large impact on total energy consumption globally, energy rehabilitation presents a feasible solution to mitigate these environmental impacts. Incorporating sustainable solutions that not only prioritize energy reduction but also safeguard cultural heritage is imperative. This is particularly significant considering that many of the existing buildings possess historical value, cultural heritage, or architectural traditions. Energy-generating systems such as BIPV need further development to secure affordable and efficient integration. Additional options for BIPV that accommodate cultural heritage and architectural authenticity are needed in the nearest future. The implementation of smart technologies within energy rehabilitation projects could also enhance energy efficiency and optimize energy consumption. By embracing energy rehabilitation, the industry can make progress towards achieving the SDGs, reducing energy consumption, and preserving our cultural heritage. Promoting and recognizing the importance of engagement and education are factors to succeed in sustainable development.

Further development of this research is essential to fully make the project feasible. This would involve enhancing the level of detail pertaining to building components and their junctions. Exploring additional possibilities for post-insulation, such as utilizing combinations of different materials, could be of great interest. Regarding the BIPV, a detailed analysis concerning irradiance and energy production potential, as well as mounting and architectural appearance, needs to be performed. The rehabilitation measures need to satisfy requirements to fire safety, hence a fire safety assessment would be required. The environmental impact from the relocation and rehabilitation also needs addressing, for example by conducting a life cycle assessment (LCA). Moreover, it would be necessary to do a comprehensive economic analysis to evaluate the total costs related to the project.

8 Conclusions

Rehabilitation of listed heritage buildings while preserving their cultural significance includes adaptive reuse and restoration. To balance modern energy efficiency with architectural cultural integrity, a combination of new and old materials is recommended. Where it is possible, e.g., exterior cladding, interior panelling and load-bearing elements, the original materials should be used if they are in good condition. New materials, such as thermal insulation and wind and vapour barrier, will provide better air-tightening and hygrothermal properties. When choosing specific solutions, the building's unique situation must be considered as different approaches will have varying impacts on each individual building, i.e., the available options must be carefully considered for the respective case.

For the three listed heritage buildings in Ørland Municipality, the simulated results show that different individual energy-saving measures have about the same impact in reducing their net energy demand. The exception is where measures previously have been implemented, such as Viken where the external wall is post-insulated, a new wind barrier is installed, and the windows are changed. As a result, further improvements to these building parts on Viken only reduce the total net energy demand by 1-2 %. However, if elements significant to the building's architectural expression have been lost during previous renovations, a major part of the rehabilitation process will involve restoring the building to its original architectural expression. One example is Grande where there is installed awning windows that do not fit the original building style, i.e., a good opportunity to get new energy-efficient windows that resemble the originals. Due to the relocation, the three farmhouses will receive a new foundation that will benefit the energy consumption and moisture properties. The new foundations will lower the buildings' net energy demand by 5-16 %. In addition, the implementation of coloured BIPV technology on the roof contributes to renewable power generation, i.e., lowering the buildings' net energy demands, while also maintaining the traditional look of an original roofing material.

Regarding the most suitable thermal insulation material for rehabilitation of the listed heritage buildings in Ørland Municipality, the results shows that aerogel and mineral wool is best suited. High moisture levels and poor adaptability on-site are reasons why VIPs are not recommended as a solution in this case. Generally, the choice of thermal insulation material is dependent on various factors such as available space, desired U-value, moisture transport and costs. State-of-the-art thermal insulation materials with a much lower thermal conductivity than traditional materials offer the advantage of adding thinner layers of insulation that do not compromise the architectural expression of the building. Hence, aerogel blankets appear to be a promising material due to its ability to breathe, thinness, water-repellent properties, and adaptability on-site. However, if there is sufficient space to lay a thick insulation layer, it can be advantageous to use traditional insulation materials such as mineral wool since it is more readily available and costs significantly less.

The development of high-quality and aesthetically pleasing solar panels has made it possible to integrate BIPV in a seamless manner. It is essential to embrace the advancements in technology and move forward towards a sustainable future. The integration of BIPV can be done on the roof and the façades of the buildings, with a focus on maintaining the appearance of the original building material. Coloured BIPV can be customized to match the original building material. However, there is a need for further development to make it more feasible and universal to combine BIPV with the architectural authenticity of heritage buildings. It is crucial to take a proactive approach and not resist change but find ways to preserve the cultural and essential values of heritage buildings while also incorporating sustainable solutions.

It is evident that rehabilitating culturally and historically protected buildings to meet today's energy standards is a complex and challenging task, but it is achievable. This work has identified several possible solutions, focusing on rehabilitation measures guaranteeing energy efficiency while also preserving cultural heritage. Through simulations it is demonstrated that the net energy demand can be lowered by 75 %, 65 % and 55 % for Trøa, Grande and Viken, respectively, and thereby satisfy the current Norwegian standard. These results provide a basis for future projects, but it is essential no note that each building is unique, and a case-by-case approach is needed.

Appendixes

A - Material properties for THERM and WUFI simulations

Table A1: Relevant material properties for the components used in the floor construction [a].

Material	Thickness (mm)	Thermal conductivity (W/(mK))	Thermal resistance ((m²K)/W)
R_{si}	-	-	0.17
Floor	22	0.13	0.17
Moisture-resistant subfloor	22	2.3	0.22
Concrete	100	2.5	0.04
Plastic	0.8	2.3	0.0003
Radon membrane	0.4	0.5	0.0001
Thermal insulation - XPS	200/400	0.034	5.88/11.76
R_{se}	-	-	0.04

a: For the foundation, it has not been an area of interest to control the moisture content or movement since it is selected as a modern pre-accepted solution which is commonly used in Norway. The input data in Table is therefore only relevant for the THERM simulations.

Table A2: Relevant material properties for THERM and WUFI simulations for the exterior wall [a].

Material		Thickness (mm)	Thermal conductivity (W/(mK))	Thermal resistance ((m²K)/W)	Density (kg/m³)	Water vapour diffusion resistance factor (-)
R_{se} horizontal (R_{se} and ventiladed cladding)				0.04 (0.13)		
Cladding		22 + 22			420	50
Aerated horizontal slats		36			1.3	0.32
Aerated vertical slats		19			1.3	0.32
Wind barrier		15	2.3	0.30	280	144
Thermal insulation	Mineral wool	100	0.034 (0.046 [b])	2.94 (2.17 [b])	60	1.3
	VIP	20	0.007	2.86	200	1 500 000
	Aerogel	10 + 10	0.015	1.33	146	4.7
Log		150	0.13	1.15	510	50
Vapour barrier		1	2.2	0.01	130	70 000
Interior panelling		12	0.12	0.10	420	50
R_{si} horizontal			0.13			

a: The wall is simulated with board-on-board cladding. It is assumed the results will be approximately the same when using BIPV due to ventilated air slats; b: Combined thermal conductivity for mineral wool and timber-frame where it is assumed 13% framework and 87% mineral wool (SINTEF 471.401, 2012): $\lambda_{(t+mw)} = A_t \cdot \lambda_t + A_{mw} \cdot \lambda_{mw}$.

Table A3: Relevant material properties for THERM and WUFI simulations for the roof [a].

Layer	Material		Thickness (mm)	Thermal conductivity (W/(mK))	Thermal resistance ((m²K)/W)	Density (kg/m³)	Water vapour diffusion resistance factor (-)
	R_{se} (upwards) + R_u [b]			30	0.04 + 0.20		
1 [c]	Roof membrane		1	0.5		2 400	100 000
2 [c]	Roof boards (particle board)		19	0.14		610	50
3	Fibre building board		22	0.14		610	50
4	Thermal insulation	Mineral wool (convection barrier)	300 (1)	0.034 (0.42)		60 (120)	1.3 (3 000)
		VIP	40	0.007		200	1 500 000
		Mineral wool + Aerogel	M: 150 A: 10	M: 0.034 A: 0.015		M: 60 A:146	M: 1.3 A: 4.7
5	Vapour barrier		1	2.2	0.01	130	70 000
6	Flooring boards		15	0.13		420	50
7 [c]	Air		150	0.94		1.3	0.07
8 [c]	Ceiling boards		15	0.13		420	50
-	R_{si} (upwards)				0.13		

a: The roof is simulated with a roof membrane as the exterior surface and it is assumed the results will be approximately the same when using BIPV due to ventilated air slats.; b: Value only included in simulations in THERM.; c: Layers only included in moisture simulations in WUFI.

B – Energy-saving measures, combinations of measures and associated risks

Table B1: Trøa – rehabilitation measures, results from SIMIEN and associated risks,

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
1	New foundation with 200 mm XPS	Foundation/floor	0.96	0.15	309.0	5 %	No risk.	No risk.	Easy to implement.
2	New foundation with 400 mm XPS	Foundation/floor	0.96	0.08	307.0	6 %	No risk.	No risk.	Easy to implement.
3 [a]	Post-insulation with 100-150 mm mineral wool	External wall	0.84	0.26	299.0	8 %	High risk for changed architectural appearance; reduced eaves, new windows placement in wall	Low risk of high relative humidity.	Labour intensive. Requires more work due to new window placement.
4 [a]	Post-insulation with 20 mm VIP	External wall	0.84	0.25	298.4	8 %	Low risk for reduction of heritage value.	Varying risk of high relative humidity depending on internal or external insulation and with or without vapour barrier.	Labour intensive.
5 [a]	Post-insulation with 20 mm aerogel	External wall	0.84	0.32	302.9	7 %	Low risk for reduction of heritage value.	Some risk of high relative humidity when applied internally without vapour barrier.	Labour intensive.
6 [a]	Post-insulation with 10 mm aerogel both externally and internally	External wall	0.84	0.30	301.6	7 %	Low risk for reduction of heritage value.	Low risk of high relative humidity.	Labour intensive. Both external and internal insulation will affect both interior and exterior surfaces.
7	Post-insulation above frame of joists against cold attic with 300 mm mineral wool	Roof	0.96	0.11	299.1	8 %	No risk.	Low risk of high relative humidity.	Easy to implement.
8	Post-insulation above frame of joists against cold attic with 40 mm VIP	Roof	0.96	0.16	300.8	8 %	No risk.	Risk of high relative humidity.	Can be challenging to implement since VIP cannot be altered at the building site.
9	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool	Roof	0.96	0.18	301.4	8 %	No risk.	Low risk of high relative humidity.	Easy to implement.
10 [b]	Fenestration renovation with new doors and triple-glazed energy-efficient windows	Windows	4.5	0.8	283.7	13 %	Some risk.	Low risk of window condensation.	Requires a template for imitating the old windows found at the farm.
11 [b]	Fenestration renovation with new doors and improvement of the old windows with secondary glazing	Windows	4.5	1.5	292.0	10 %	Some risk.	Low risk of window condensation.	Requires precise measurements and evaluation of each case to ensure that there is adequate space within the current window frame, potentially adapt to new wall thickness.
12 [b]	Fenestration renovation with new doors and new energy-efficient windows on ground floor, and improvement of the old windows on first floor with secondary glazing	Windows	4.5	0.8 / 1.5	287.3	12 %	Low risk.	Low risk of window condensation.	Combination of measurement no. 10 and 11.

Table B1 (*continued*)

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
13	Air tightening from an infiltration of 10 to 6 h^{-1} (n50) (requirement for log constructions)	Building envelope			314.0	4 %	No risk.	No risk.	Presumed satisfied by implementing a new foundation and post-insulating the roof.
14	Air tightening from an infiltration of 10 to 4 h^{-1} (n50) (Estimated leakage with sealing of roof and new foundation)	Building envelope			307.0	6 %	Low risk due to possible changes when sealing around doors and windows.	No risk.	Presumed that some additional air sealing around windows and doors will be needed in addition to new foundation and post-insulation of the roof.
15	Air tightening from an infiltration of 10 to 1.5 h^{-1} (n50) (requirement for non-log constructions)	Building envelope			300.0	8 %	Some risk. To achieve this level of air tightening, a new wind and vapour barrier must be installed for the building envelope. This may entail changes in the architecture of the building.	An assessment of the implementation of ventilation systems must be carried out to ensure sufficient air supply.	Labour intensive. Would require a new vapour and windproof layer to be implemented for the entire building envelope, as well as new windows and doors.
16 [c]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Roof			288.7	11 %	High risk. Not in line with cultural heritage preservation. The use of BIPV that simulates conventional roofing materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.	No risk.	Somewhat labour intensive.
17 [c]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Façade (south)			295.9	9 %	High risk. Not in line with cultural heritage preservation. Will alter the appearance of the façade in various amounts depending on the type of BIPV used. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look.	No risk.	Given that the façade is required to be replaced or dismantled for repair, the additional effort required to install BIPV will not be substantial.
18	Combined measures: 1, 6, 7, 12 and 15 (preserve cultural heritage)				107.3	67 %			
19	Combined measures: 2,4,7,10,15, 16 and 17 (most energy-efficient)				66.1	80 %			
20	Combined measures: 1, 6, 7, 12, 15 and 16 (recommended solution)				81.1	75 %			

a: The U-value of 0.84 W/(m²K) is for the log construction. After the measure it is assumed that all exterior walls will have equivalent U-values. Assuming the new insulation will replace the existing post-insulation on the north façade; b: Trøa currently has a blend of windows in different styles from different time-periods. Retaining the windows as they are do not restore the structure's original architectural integrity. New windows may not be an exact replica of the originals but can resemble the structure's original design; c: Net energy demand with BIPV: Total calculated energy demand minus energy delivered to the building from the BIPV (kWh/m² NIA) (NIA=138.7 m²).

Table B2: Grande– rehabilitation measures, results from SIMIEN and associated risks,

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
1	New foundation with 200 mm XPS	Foundation/floor	0.96	0.15	284	7 %	No risk.	No risk.	Easy to implement.
2	New foundation with 400 mm XPS	Foundation/floor	0.96	0.08	282	7 %	No risk.	No risk.	Easy to implement.
3 [a]	Post-insulation with 100-150 mm mineral wool	External wall	0.84	0.26	264	14 %	High risk for changed architectural appearance; reduced eaves, new windows placement in wall	Low risk of high relative humidity.	Labour intensive. Requires more work due to new window placement.
4 [a]	Post-insulation with 20 mm VIP	External wall	0.84	0.25	263	14 %	Low risk for reduction of heritage value.	Varying risk of high relative humidity depending on internal or external insulation and with or without vapour barrier.	Labour intensive.
5 [a]	Post-insulation with 20 mm aerogel	External wall	0.84	0.32	269	12 %	Low risk for reduction of heritage value.	Some risk of high relative humidity when applied internally without vapour barrier.	Labour intensive.
6 [a]	Post-insulation with 10 mm aerogel both externally and internally	External wall	0.84	0.30	268	12 %	Low risk for reduction of heritage value.	Low risk of high relative humidity.	Labour intensive. Both external and internal insulation will affect both interior and exterior surfaces.
7	Post-insulation above frame of joists against cold attic with 300 mm mineral wool	Roof	0.96	0.11	274	10 %	No risk.	Low risk of high relative humidity.	Easy to implement.
8	Post-insulation above frame of joists against cold attic with 40 mm VIP	Roof	0.96	0.16	276	9 %	No risk.	Risk of high relative humidity.	Can be challenging to implement since VIP cannot be altered at the building site.
9	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool	Roof	0.96	0.18	277	9 %	No risk.	Low risk of high relative humidity.	Easy to implement.
10 [b]	Fenestration renovation with new doors and triple-glazed energy-efficient windows	Windows	2.3	0.8	290	5 %	Low risk.	Low risk of window condensation.	Requires a template for imitating the old windows found at the farm.
11 [b]	Fenestration renovation with new doors and improvement of the old windows with secondary glazing	Windows	2.3	1.5	296	3 %	High risk.	Low risk of window condensation.	Requires precise measurements and evaluation of each case to ensure that there is adequate space within the current window frame, potentially adapt to new wall thickness.
12 [c]	Fenestration renovation with new doors and new energy-efficient windows on ground floor, and improvement of the old windows on first floor with secondary glazing	Windows							

Table B2 (*continued*)

No.	Description	Building part	Original U-value ($W/(m^2K)$)	U-value after measures ($W/(m^2K)$)	Net energy demand after measure ($(kWh)/m^2$)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
13	Air tightening from an infiltration of 10 to 6 h^{-1} (n50) (requirement for log constructions)	Building envelope			290	5 %	No risk.	No risk.	Presumed satisfied by implementing a new foundation and post-insulating the roof.
14	Air tightening from an infiltration of 10 to 4 h^{-1} (n50) (Estimated leakage with sealing of roof and new foundation)	Building envelope			282	8 %	Low risk due to possible changes when sealing around doors and windows.	No risk.	Presumed that some additional air sealing around windows and doors will be needed in addition to new foundation and post-insulation of the roof.
15	Air tightening from an infiltration of 10 to 1.5 h^{-1} (n50) (requirement for non-log constructions)	Building envelope			273	11 %	Some risk. In order to achieve this level of air tightening, a new wind and vapour barrier must be installed for the building envelope. This may entail changes in the architecture of the building.	An assessment of the implementation of ventilation systems must be carried out to ensure sufficient air supply.	Labour intensive. Would require a new vapour and windproof layer to be implemented for the entire building envelope, as well as new windows and doors.
16 [d]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Roof			288	6 %	High risk. Not in line with cultural heritage preservation. The use of BIPV that simulates conventional roofing materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.	No risk.	The entire roof must be replaced anyways and integrating BIPV will therefore not entail much additional work.
17 [d]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Façade (south)			267	13 %	High risk. Not in line with cultural heritage preservation. Will alter the appearance of the façade in various amounts depending on the type of BIPV used. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look.	No risk.	Installation of BIPV for the entire west and south façade will entail additional work, because the current west and south façade are in good condition.
18 [e]	Combined measures: 1, 5, 7, 10 and 14 (preserve cultural heritage)				122	60 %			
19	Combined measures: 2, 4, 7, 10, 15, 16 and 17 (most energy-efficient)				73	76 %			
20	Combined measures: 1, 5, 7, 10, 14 and 16 (recommended solution)				106	65 %			

a: The U-value of 0.84 $W/(m^2K)$ is for the log construction. After the measure it is assumed that all exterior walls will have equivalent U-values. Assuming the new insulation will replace the existing post-insulation on the south-west façade. However, further insulation of the external wall results in the destruction/alteration of interior and/or exterior surfaces which are mostly in good condition; b: Grande currently has a blend of windows in different styles from different time-periods. Retaining the windows as they are do not restore the structure's original architectural integrity. New windows may not be an exact replica of the originals, but can resemble the structure's original design; c: Not applicable for Grande; d: Net energy demand with BIPV: Total calculated energy demand minus energy delivered to the building from the BIPV (kWh/m^2 NIA) (NIA=148 m^2); e: External aerogel gives a slim construction and is better than VIP regarding moisture in the wall. Also, it will preserve the inside panelling.

Table B3: Viken– rehabilitation measures, results from SIMIEN and associated risks,

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
1	New foundation with 200 mm XPS	Foundation/floor	0.96	0.16	211	16 %	No risk.	No risk.	Easy to implement.
2	New foundation with 400 mm XPS	Foundation/floor	0.96	0.08	208	17 %	No risk.	No risk.	Easy to implement.
3 [a]	Post-insulation with 100-150 mm mineral wool	External wall	0.42	0.26	244	2 %	High risk for changed architectural appearance; reduced eaves, new windows placement in wall	Low risk of high relative humidity.	Labour intensive. Significant additional workload in accordance with its level of necessity (reduction in net energy demand).
4 [a]	Post-insulation with 20 mm VIP	External wall	0.42	0.25	244	2 %	Low risk for reduction of heritage value.	Varying risk of high relative humidity depending on internal or external insulation and with or without vapour barrier.	Labour intensive.
5 [a]	Post-insulation with 20 mm aerogel	External wall	0.42	0.32	246	1 %	Low risk for reduction of heritage value.	Some risk of high relative humidity when applied internally without vapour barrier.	Labour intensive.
6 [a]	Post-insulation with 10 mm aerogel both externally and internally	External wall	0.42	0.30	246	2 %	Low risk for reduction of heritage value.	Low risk of high relative humidity.	Labour intensive.
7	Post-insulation above frame of joists against cold attic with 300 mm mineral wool	Roof	0.96	0.11	214	14 %	No risk.	Low risk of high relative humidity.	Easy to implement.
8	Post-insulation above frame of joists against cold attic with 40 mm VIP	Roof	0.96	0.16	217	13 %	No risk.	Risk of high relative humidity.	Can be challenging to implement since VIP cannot be altered at the building site.
9	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool	Roof	0.96	0.18	218	13 %	No risk.	Low risk of high relative humidity.	Easy to implement.
10 [b]	Fenestration renovation with new doors and triple-glazed energy-efficient windows	Windows	1.5	0.8	234	7 %	No risk.	Low risk of window condensation.	Easy to implement, but a lot of work and high cost in relation to the reduction in energy demand.
11 [c]	Fenestration renovation with new doors and improvement of the old windows with secondary glazing	Windows							
12 [c]	Fenestration renovation with new doors and new energy-efficient windows on ground floor, and improvement of the old windows on first floor with secondary glazing	Windows							

Table B3 (*continued*)

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
13 [d]	Air tightening from an infiltration of 10 to 6 h^{-1} (n50) (requirement for log constructions)	Building envelope			233	7 %	No risk.	No risk.	Presumed satisfied by implementing a new foundation and post-insulating the roof.
14 [d]	Air tightening from an infiltration of 10 to 4 h^{-1} (n50) (Estimated leakage with sealing of roof and new foundation)	Building envelope			223	11 %	Low risk due to possible changes when sealing around doors and windows.	No risk.	Presumed that some additional air sealing around windows and doors will be needed in addition to new foundation and post-insulation of the roof.
15 [d]	Air tightening from an infiltration of 10 to 1.5 h^{-1} (n50) (requirement for non-log constructions)	Building envelope			213	15 %	Some risk. In order to achieve this level of air tightening, a new wind and vapour barrier must be installed for the building envelope. This may entail changes in the architecture of the building.	An assessment of the implementation of ventilation systems must be carried out to ensure sufficient air supply.	Labour intensive. Would require a new vapour and windproof layer to be implemented for the entire building envelope, as well as new windows and doors.
16 [e]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Roof			215	14 %	High risk. Not in line with cultural heritage preservation. The use of BIPV that simulates conventional roofing materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.	No risk.	Labour intensive.
17 [e]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Façade (south)			227	9 %	High risk. Not in line with cultural heritage preservation. Will alter the appearance of the façade in various amounts depending on the type of BIPV used. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look.	No risk.	Labour intensive.
18 [e]	Combined measures: 1, 7 and 14 (preserve cultural heritage)				138	45 %			
19	Combined measures: 2, 4, 8, 10, 15, 16 and 17 (most energy-efficient)				77	69 %			
20	Combined measures: 1, 7, 14 and 16 (recommended solution)				111	55 %			

a: The U-value of 0.84 W/(m²K) is for the log construction. After the measure it is assumed that all exterior walls will have equivalent U-values. Assuming the new insulation will replace the existing post-insulation. Note that further insulation of the external wall results in the destruction/alteration of interior and/or exterior surfaces which are mostly in good condition; b: Most of the windows are from the early 2000s and fit the architectural expression; c: Not applicable for Viken; d: In reality, Viken already has a relatively new wind barrier and windows. As a result, Viken most likely have a better infiltration than 10 h^{-1}; e: Net energy demand with BIPV: Total calculated energy demand minus energy delivered to the building from the BIPV (kWh/m² NIA).

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Appendix A:
Details on input values and results from THERM and WUFI

Floor construction

For the floor construction, it has not been an area of interest to control the moisture content or movement since it is selected a modern pre-accepted solution which is commonly used in Norway. The input data in Table A1 is therefore only relevant for the THERM simulations. Table A2 shows the composite results from these THERM simulations.

Table A1: Material properties for the components used in the floor construction.

Material	Thickness (mm)	Thermal conductivity (W/(mK))	Thermal resistance ((m^2K)/W)
R_{si}	-	-	0.17
Floor	22	0.13	0.17
Moisture-resistant subfloor	22	2.3	0.22
Concrete	100	2.5	0.04
Plastic	0.8	2.3	0.0003
Radon membrane	0.4	0.5	0.0001
Thermal insulation - XPS	200/400	0.034	5.88/11.76
R_{se}	-	-	0.04

Table A2: U-values from simulations in THERM for the floor construction.

Description	U-value (W/(m^2K))
Floor construction with 200 mm XPS	0.16
Floor construction with 400 mm XPS	0.08

External wall

Table A3 gives relevant material properties for simulation in THERM and WUFI. In WUFI, the wall is simulated with board-on-board cladding. It is assumed the results will be approximately the same when using BIPV due to ventilated air slats. Table A4 shows the composite results from these THERM simulations. Figure A1, Figure A2 and Figure A3 show the results from the WUFI simulations in three different monitor positions for the different solutions given in the article.

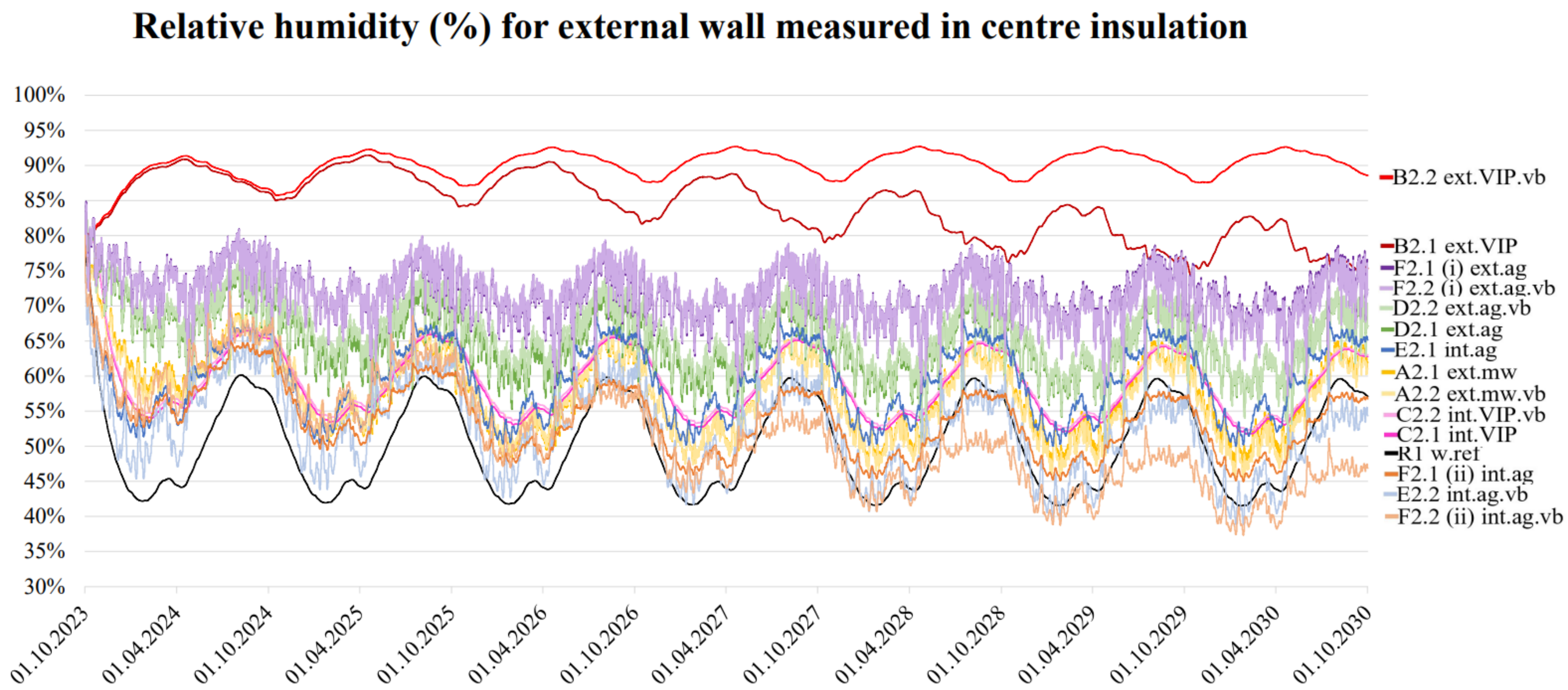
Table A3: Relevant material properties for THERM and WUFI simulations for the external wall.

Material		Thickness (mm)	Thermal conductivity (W/(mK))	Thermal resistance ((m^2K)/W)	Density (kg/m^3)	Water vapour diffusion resistance factor (-)
R_{se} horizontal (R_{se} and ventilated cladding)				0.04 (0.13)		
Cladding		22 + 22			420	50
Aerated horizontal slats		36			1.3	0.32
Aerated vertical slats		19			1.3	0.32
Wind barrier		15	2.3	0.30	280	144
Thermal insulation	Mineral wool	100	0.034 (0.046 [a])	2.94 (2.17 [a])	60	1.3
	VIP	20	0.007	2.86	200	1 500 000
	Aerogel	10 + 10	0.015	1.33	146	4.7
Log		150	0.13	1.15	510	50
Vapour barrier		1	2.2	0.01	130	70 000
Interior panelling		12	0.12	0.10	420	50
R_{si} horizontal			0.13			

a: Combined Thermal conductivity for mineral wool and timber-frame where it is assumed 13% framework and 87% mineral wool (471.401): $\lambda_{(t+mw)} = A_t \cdot \lambda_t + A_{mw} \cdot \lambda_{mw}$.

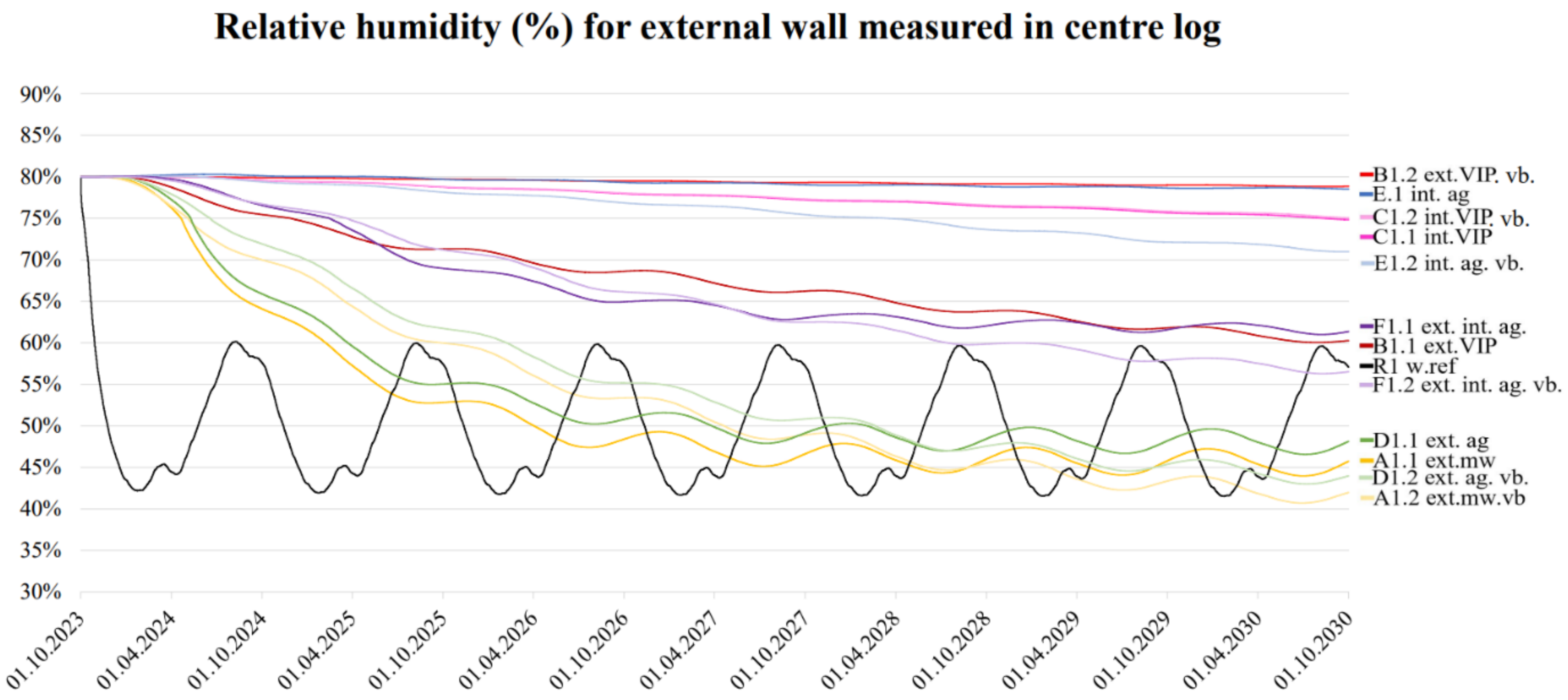
Table A4: U-values from simulations in THERM for the extrnal wall.

Description	U-value (W/m^2K)
Ext. mw.	0.26
Ext. ag.	0.33
Ext. VIP	0.25
Int. ag.	0.32
Int. VIP.	0.25
Int. ext. ag.	0.30



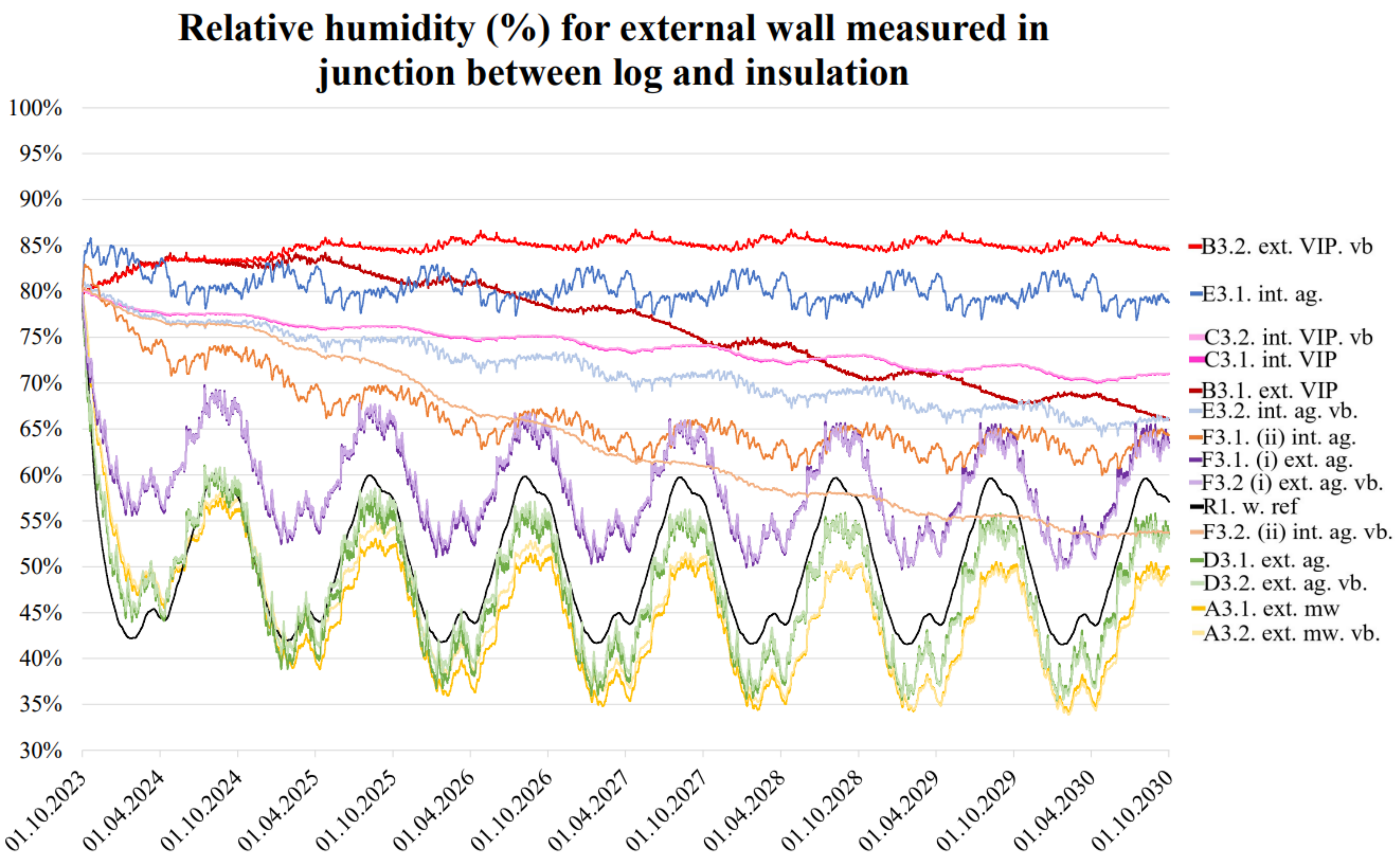
A2.1. ext. mw.: Solution A external mineral wool; A2.2. ext. mw. vb.: Solution A external mineral wool with vapour barrier; B2.1. ext. VIP.: Solution B external VIP; B2.2. ext. VIP. vb.: Solution B external VIP with vapour barrier; C2.1. int. VIP: Solution C internal VIP; C2.2 int. VIP. vb.: Solution C internal VIP with vapour barrier; D2.1. ext. ag.: Solution D external aerogel; D2.2. ext. ag. vb.: Solution D external aerogel with vapour barrier; E2.1. int. ag.: Solution E internal aerogel; E2.2. int. ag. vb.: Solution E internal aerogel with vapour barrier; F2.1. (i) ext. ag.: Solution F external aerogel; F2.2. (i) ext. ag. vb.: Solution F external aerogel with vapour barrier; F2.1. (ii) int. ag.: Solution F internal aerogel; F2.2. (ii) int. ag. vb.: Solution F internal aerogel with vapour barrier; R1. w. ref.: Wall reference measured on interior surface.

Figure A1: Relative humidity (%) for external wall measured in centre insulation (monitor position 2) for solution A-F.



A1.1. ext. mw.: Solution A external mineral wool; A1.2. ext. mw. vb.: Solution A external mineral wool with vapour barrier; B1.1. ext. VIP.: Solution B external VIP; B1.2. ext. VIP. vb.: Solution B external VIP with vapour barrier; C1.1. int. VIP: Solution C internal VIP; C1.2 int. VIP. vb.: Solution C internal VIP with vapour barrier; D1.1. ext. ag.: Solution D external aerogel; D1.2. ext. ag. vb.: Solution D external aerogel with vapour barrier; E1. 1. int. ag.: Solution E internal aerogel; E1.2. int. ag. vb.: Solution E internal aerogel with vapour barrier; F1.1. ext. int. ag.: Solution F external and internal aerogel; F1.2. ext. int. ag. vb.: Solution F external and internal aerogel with vapour barrier; R1. w. ref.: Wall reference measured on interior surface.

Figure A2 Relative humidity (%) for external wall measured in centre log (monitor position 1) for solution A-F.



A3.1. ext. mw.: Solution A external mineral wool; A3.2. ext. mw. vb.: Solution A external mineral wool with vapour barrier; B3.1. ext. VIP.: Solution B external VIP; B3.2 ext. VIP. Vb.: Solution B external VIP with vapour barrier; C3.1. int. VIP.: Solution C internal VIP; C3.2. int. VIP. Vb.: Solution C internal VIP with vapour barrier; D3.1. ext. ag.: Solution D external aerogel; D3.2 ext. ag. vb.: Solution D external aerogel with vapour barrier; E3.1 int. ag.: Solution E internal aerogel; E3.2. int. ag. vb.: Solution E internal aerogel with vapour barrier; F3.1. (i) ext. ag.: Solution F external aerogel; F3.1. (ii) int. ag.: Solution F internal aerogel; F3.2 (i) ext. ag. vb.: Solution F external aerogel with vapour barrier; F3.2. (ii) int. ag. vb.: Solution F internal aerogel with vapour barrier; R1. w. ref.: Wall reference measured on interior surface.

Figure A3: Relative humidity for external wall measured in the junction between log and insulation (monitor position 3) for solution A-F.

Roof

Table A5 gives relevant material properties for simulation in THERM and WUFI. In WUFI, the roof is simulated with a roof membrane as the exterior surface. It is assumed the results will be approximately the same when using BIPV due to ventilated air slats. Table A6 shows the composite results from the THERM simulations. Figure A4 show the results from the WUFI simulations in four different monitor positions for the different solutions given in the article.

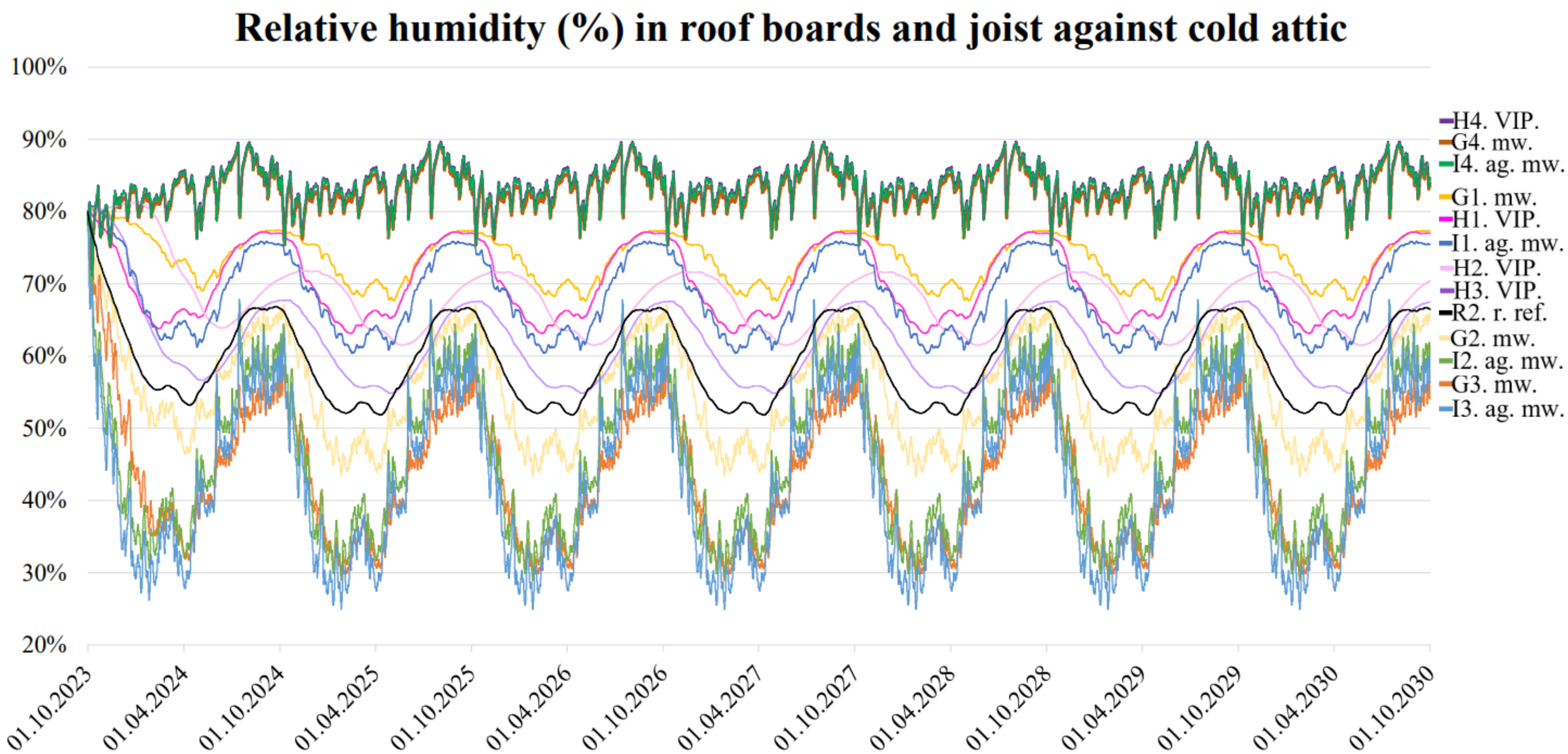
Table A5: Relevant material properties for THERM and WUFI simulations for the roof.

Layer	Material		Thickness (mm)	Thermal conductivity (W/(mK))	Thermal resistance ((m^2K)/W)	Density (kg/m^3)	Water vapour diffusion resistance factor (-)
	R_{se} (upwards) + R_u [a]			30	0.04 + 0.20		
1 [b]	Roof membrane		1	0.5		2 400	100 000
2 [b]	Roof boards (particle board)		19	0.14		610	50
3	Fibre building board		22	0.14		610	50
4	Thermal insulation	Mineral wool (convection barrier)	300 (1)	0.034 (0.42)		60 (120)	1.3 (3 000)
		VIP	40	0.007		200	1 500 000
		Mineral wool + Aerogel	M: 150 A: 10	M: 0.034 A: 0.015		M: 60 A:146	M: 1.3 A: 4.7
5	Vapour barrier		1	2.2	0.01	130	70 000
6	Flooring boards		15	0.13		420	50
7 [b]	Air		150	0.94		1.3	0.07
8 [b]	Ceiling boards		15	0.13		420	50
-	R_{si} (upwards)				0.13		

a: Value only included in simulations in THERM.; b: Layers only included in moisture simulations in WUFI.

Table A6: U-values from simulations in THERM for the roof.

Description	Insulation thickness (mm)	U-value (W/(m^2K))
Mineral wool above joist against cold attic	300	0.11
VIPs above joist against cold attic with	40	0.16
Aerogel and mineral wool above joist against cold attic	A: 10 M: 150	0.18



G1-4. mw.: Solution G, monitor position 1-4, mineral wool; H1-4. VIP.: Solution H, monitor position 1-4, VIP; I1-4. ag. mw.: Solution I, monitor position 1-4, aerogel and mineral wool; R2. r. ref.: Roof reference measured on interior panelled ceiling.

Figure A4: Relative humidity (%) in roof boards and joist against cold attic (monitor position 1-4) for solution G, H, and I.

Appendix B:
Details on rehabilitation measures, associated risks, and results from energy simulations carried out in SIMIEN.

Table B1, B2 and B3 show rehabilitation measures executed in SIMIEN for Trøa, Grande and Viken, respectively. The original and the new U-value for the different building components are given. New net energy demand and reduction in percentages of original net energy demand after each measure are also given. Lastly, risks associated with each measure concerning reduction of heritage value and building physical damage, and necessary workload are evaluated.

Table B1: Trøa – rehabilitation measures, results from SIMIEN and associated risks.

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
1	New foundation with 200 mm XPS	Foundation/floor	0.96	0.15	309.0	5 %	No risk.	No risk.	Easy to implement.
2	New foundation with 400 mm XPS	Foundation/floor	0.96	0.08	307.0	6 %	No risk.	No risk.	Easy to implement.
3 [a]	Post-insulation with 100-150 mm mineral wool	External wall	0.84	0.26	299.0	8 %	High risk for changed architectural appearance; reduced eaves, new windows placement in wall	Low risk of high relative humidity.	Labour intensive. Requires more work due to new window placement.
4 [a]	Post-insulation with 20 mm VIP	External wall	0.84	0.25	298.4	8 %	Low risk for reduction of heritage value.	Varying risk of high relative humidity depending on internal or external insulation and with or without vapour barrier.	Labour intensive.
5 [a]	Post-insulation with 20 mm aerogel	External wall	0.84	0.32	302.9	7 %	Low risk for reduction of heritage value.	Some risk of high relative humidity when applied internally without vapour barrier.	Labour intensive.
6 [a]	Post-insulation with 10 mm aerogel both externally and internally	External wall	0.84	0.30	301.6	7 %	Low risk for reduction of heritage value.	Low risk of high relative humidity.	Labour intensive. Both external and internal insulation will affect both interior and exterior surfaces.
7	Post-insulation above frame of joists against cold attic with 300 mm mineral wool	Roof	0.96	0.11	299.1	8 %	No risk.	Low risk of high relative humidity.	Easy to implement.
8	Post-insulation above frame of joists against cold attic with 40 mm VIP	Roof	0.96	0.16	300.8	8 %	No risk.	Risk of high relative humidity.	Can be challenging to implement since VIP cannot be altered at the building site.
9	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool	Roof	0.96	0.18	301.4	8 %	No risk.	Low risk of high relative humidity.	Easy to implement.
10 [b]	Fenestration renovation with new doors and triple-glazed energy-efficient windows	Windows	4.5	0.8	283.7	13 %	Some risk.	Low risk of window condensation.	Requires a template for imitating the old windows found at the farm.
11 [b]	Fenestration renovation with new doors and improvement of the old windows with secondary glazing	Windows	4.5	1.5	292.0	10 %	Some risk.	Low risk of window condensation.	Requires precise measurements and evaluation of each case to ensure that there is adequate space within the current window frame, potentially adapt to new wall thickness.
12 [b]	Fenestration renovation with new doors and new energy-efficient windows on ground floor, and improvement of the old windows on first floor with secondary glazing	Windows	4.5	0.8 / 1.5	287.3	12 %	Low risk.	Low risk of window condensation.	Combination of measurement no. 10 and 11.

Appendix B

Table B1 (*continued*)

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
13	Air tightening from an infiltration of 10 to 6 h^{-1} (n50) (requirement for log constructions)	Building envelope			314.0	4 %	No risk.	No risk.	Presumed satisfied by implementing a new foundation and post-insulating the roof.
14	Air tightening from an infiltration of 10 to 4 h^{-1} (n50) (Estimated leakage with sealing of roof and new foundation)	Building envelope			307.0	6 %	Low risk due to possible changes when sealing around doors and windows.	No risk.	Presumed that some additional air sealing around windows and doors will be needed in addition to new foundation and post-insulation of the roof.
15	Air tightening from an infiltration of 10 to 1.5 h^{-1} (n50) (requirement for non-log constructions)	Building envelope			300.0	8 %	Some risk. To achieve this level of air tightening, a new wind and vapour barrier must be installed for the building envelope. This may entail changes in the architecture of the building.	An assessment of the implementation of ventilation systems must be carried out to ensure sufficient air supply.	Labour intensive. Would require a new vapour and windproof layer to be implemented for the entire building envelope, as well as new windows and doors.
16 [c]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Roof			288.7	11 %	High risk. Not in line with cultural heritage preservation. The use of BIPV that simulates conventional roofing materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.	No risk.	Somewhat labour intensive.
17 [c]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Façade (south)			295.9	9 %	High risk. Not in line with cultural heritage preservation. Will alter the appearance of the façade in various amounts depending on the type of BIPV used. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look.	No risk.	Given that the façade is required to be replaced or dismantled for repair, the additional effort required to install BIPV will not be substantial.
18	Combined measures: 1, 6, 7, 12 and 15 (preserve cultural heritage)				107.3	67 %			
19	Combined measures: 2,4,7,10,15, 16 and 17 (most energy-efficient)				66.1	80 %			
20	Combined measures: 1, 6, 7, 12, 15 and 16 (recommended solution)				81.1	75 %			

a: The U-value of 0.84 W/(m²K) is for the log construction. After the measure it is assumed that all exterior walls will have equivalent U-values. Assuming the new insulation will replace the existing post-insulation on the north façade; b: Trøa currently has a blend of windows in different styles from different time-periods. Retaining the windows as they are do not restore the structure's original architectural integrity. New windows may not be an exact replica of the originals but can resemble the structure's original design; c: Net energy demand with BIPV: Total calculated energy demand minus energy delivered to the building from the BIPV (kWh/m² NIA) (NIA=138.7 m²).

Appendix B

Table B2: Grande – rehabilitation measures, results from SIMIEN and associated risks.

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
1	New foundation with 200 mm XPS	Foundation/floor	0.96	0.15	284	7 %	No risk.	No risk.	Easy to implement.
2	New foundation with 400 mm XPS	Foundation/floor	0.96	0.08	282	7 %	No risk.	No risk.	Easy to implement.
3 [a]	Post-insulation with 100-150 mm mineral wool	External wall	0.84	0.26	264	14 %	High risk for changed architectural appearance; reduced eaves, new windows placement in wall	Low risk of high relative humidity.	Labour intensive. Requires more work due to new window placement.
4 [a]	Post-insulation with 20 mm VIP	External wall	0.84	0.25	263	14 %	Low risk for reduction of heritage value.	Varying risk of high relative humidity depending on internal or external insulation and with or without vapour barrier.	Labour intensive.
5 [a]	Post-insulation with 20 mm aerogel	External wall	0.84	0.32	269	12 %	Low risk for reduction of heritage value.	Some risk of high relative humidity when applied internally without vapour barrier.	Labour intensive.
6 [a]	Post-insulation with 10 mm aerogel both externally and internally	External wall	0.84	0.30	268	12 %	Low risk for reduction of heritage value.	Low risk of high relative humidity.	Labour intensive. Both external and internal insulation will affect both interior and exterior surfaces.
7	Post-insulation above frame of joists against cold attic with 300 mm mineral wool	Roof	0.96	0.11	274	10 %	No risk.	Low risk of high relative humidity.	Easy to implement.
8	Post-insulation above frame of joists against cold attic with 40 mm VIP	Roof	0.96	0.16	276	9 %	No risk.	Risk of high relative humidity.	Can be challenging to implement since VIP cannot be altered at the building site.
9	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool	Roof	0.96	0.18	277	9 %	No risk.	Low risk of high relative humidity.	Easy to implement.
10 [b]	Fenestration renovation with new doors and triple-glazed energy-efficient windows	Windows	2.3	0.8	290	5 %	Low risk.	Low risk of window condensation.	Requires a template for imitating the old windows found at the farm.
11 [b]	Fenestration renovation with new doors and improvement of the old windows with secondary glazing	Windows	2.3	1.5	296	3 %	High risk.	Low risk of window condensation.	Requires precise measurements and evaluation of each case to ensure that there is adequate space within the current window frame, potentially adapt to new wall thickness.
12 [c]	Fenestration renovation with new doors and new energy-efficient windows on ground floor, and improvement of the old windows on first floor with secondary glazing	Windows							

Appendix B

Table B2 (*continued*)

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
13	Air tightening from an infiltration of 10 to 6 h^{-1} (n50) (requirement for log constructions)	Building envelope			290	5 %	No risk.	No risk.	Presumed satisfied by implementing a new foundation and post-insulating the roof.
14	Air tightening from an infiltration of 10 to 4 h^{-1} (n50) (Estimated leakage with sealing of roof and new foundation)	Building envelope			282	8 %	Low risk due to possible changes when sealing around doors and windows.	No risk.	Presumed that some additional air sealing around windows and doors will be needed in addition to new foundation and post-insulation of the roof.
15	Air tightening from an infiltration of 10 to 1.5 h^{-1} (n50) (requirement for non-log constructions)	Building envelope			273	11 %	Some risk. In order to achieve this level of air tightening, a new wind and vapour barrier must be installed for the building envelope. This may entail changes in the architecture of the building.	An assessment of the implementation of ventilation systems must be carried out to ensure sufficient air supply.	Labour intensive. Would require a new vapour and windproof layer to be implemented for the entire building envelope, as well as new windows and doors.
16 [d]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Roof			288	6 %	High risk. Not in line with cultural heritage preservation. The use of BIPV that simulates conventional roofing materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.	No risk.	The entire roof must be replaced anyways and integrating BIPV will therefore not entail much additional work.
17 [d]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Façade (south)			267	13 %	High risk. Not in line with cultural heritage preservation. Will alter the appearance of the façade in various amounts depending on the type of BIPV used. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look.	No risk.	Installation of BIPV for the entire west and south façade will entail additional work, because the current west and south façade are in good condition.
18 [e]	Combined measures: 1, 5, 7, 10 and 14 (preserve cultural heritage)				122	60 %			
19	Combined measures: 2, 4, 7, 10, 15, 16 and 17 (most energy-efficient)				73	76 %			
20	Combined measures: 1, 5, 7, 10, 14 and 16 (recommended solution)				106	65 %			

a: The U-value of 0.84 W/(m²K) is for the log construction. After the measure it is assumed that all exterior walls will have equivalent U-values. Assuming the new insulation will replace the existing post-insulation on the south-west façade. However, further insulation of the external wall results in the destruction/alteration of interior and/or exterior surfaces which are mostly in good condition; b: Grande currently has a blend of windows in different styles from different time-periods. Retaining the windows as they are do not restore the structure's original architectural integrity. New windows may not be an exact replica of the originals, but can resemble the structure's original design; c: Not applicable for Grande; d: Net energy demand with BIPV: Total calculated energy demand minus energy delivered to the building from the BIPV (kWh/m² NIA) (NIA=148 m²); e: External aerogel gives a slim construction and is better than VIP regarding moisture in the wall. Also, it will preserve the inside panelling.

Table B3: Viken – rehabilitation measures, results from SIMIEN and associated risks.

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
1	New foundation with 200 mm XPS	Foundation/floor	0.96	0.16	211	16 %	No risk.	No risk.	Easy to implement.
2	New foundation with 400 mm XPS	Foundation/floor	0.96	0.08	208	17 %	No risk.	No risk.	Easy to implement.
3 [a]	Post-insulation with 100-150 mm mineral wool	External wall	0.42	0.26	244	2 %	High risk for changed architectural appearance; reduced eaves, new windows placement in wall	Low risk of high relative humidity.	Labour intensive. Significant additional workload in accordance with its level of necessity (reduction in net energy demand).
4 [a]	Post-insulation with 20 mm VIP	External wall	0.42	0.25	244	2 %	Low risk for reduction of heritage value.	Varying risk of high relative humidity depending on internal or external insulation and with or without vapour barrier.	Labour intensive.
5 [a]	Post-insulation with 20 mm aerogel	External wall	0.42	0.32	246	1 %	Low risk for reduction of heritage value.	Some risk of high relative humidity when applied internally without vapour barrier.	Labour intensive.
6 [a]	Post-insulation with 10 mm aerogel both externally and internally	External wall	0.42	0.30	246	2 %	Low risk for reduction of heritage value.	Low risk of high relative humidity.	Labour intensive.
7	Post-insulation above frame of joists against cold attic with 300 mm mineral wool	Roof	0.96	0.11	214	14 %	No risk.	Low risk of high relative humidity.	Easy to implement.
8	Post-insulation above frame of joists against cold attic with 40 mm VIP	Roof	0.96	0.16	217	13 %	No risk.	Risk of high relative humidity.	Can be challenging to implement since VIP cannot be altered at the building site.
9	Post-insulation above frame of joists against cold attic with 10 mm aerogel and 150 mm mineral wool	Roof	0.96	0.18	218	13 %	No risk.	Low risk of high relative humidity.	Easy to implement.
10 [b]	Fenestration renovation with new doors and triple-glazed energy-efficient windows	Windows	1.5	0.8	234	7 %	No risk.	Low risk of window condensation.	Easy to implement, but a lot of work and high cost in relation to the reduction in energy demand.
11 [c]	Fenestration renovation with new doors and improvement of the old windows with secondary glazing	Windows							
12 [c]	Fenestration renovation with new doors and new energy-efficient windows on ground floor, and improvement of the old windows on first floor with secondary glazing	Windows							

Appendix B

Table B3 (*continued*)

No.	Description	Building part	Original U-value (W(/m²K))	U-value after measures (W/(m²K))	Net energy demand after measure ((kWh)/m²)	Reduction in percentages of original net energy demand (%)	Risk for reduction of heritage value	Risk for building physical damages	Necessary workload and scope of intervention
13 [d]	Air tightening from an infiltration of 10 to 6 h^{-1} (n50) (requirement for log constructions)	Building envelope			233	7 %	No risk.	No risk.	Presumed satisfied by implementing a new foundation and post-insulating the roof.
14 [d]	Air tightening from an infiltration of 10 to 4 h^{-1} (n50) (Estimated leakage with sealing of roof and new foundation)	Building envelope			223	11 %	Low risk due to possible changes when sealing around doors and windows.	No risk.	Presumed that some additional air sealing around windows and doors will be needed in addition to new foundation and post-insulation of the roof.
15 [d]	Air tightening from an infiltration of 10 to 1.5 h^{-1} (n50) (requirement for non-log constructions)	Building envelope			213	15 %	Some risk. In order to achieve this level of air tightening, a new wind and vapour barrier must be installed for the building envelope. This may entail changes in the architecture of the building.	An assessment of the implementation of ventilation systems must be carried out to ensure sufficient air supply.	Labour intensive. Would require a new vapour and windproof layer to be implemented for the entire building envelope, as well as new windows and doors.
16 [e]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Roof			215	14 %	High risk. Not in line with cultural heritage preservation. The use of BIPV that simulates conventional roofing materials can be appropriately incorporated to achieve desirable outcomes perceived from afar.	No risk.	Labour intensive.
17 [e]	Building integrated photovoltaics (BIPV) with 18 % efficiency	Façade (south)			227	9 %	High risk. Not in line with cultural heritage preservation. Will alter the appearance of the façade in various amounts depending on the type of BIPV used. The visibility of the issue is enhanced by the proximity of viewers to the façade, which allows for a more detailed look.	No risk.	Labour intensive.
18 [e]	Combined measures: 1, 7 and 14 (preserve cultural heritage)				138	45 %			
19	Combined measures: 2, 4, 8, 10, 15, 16 and 17 (most energy-efficient)				77	69 %			
20	Combined measures: 1, 7, 14 and 16 (recommended solution)				111	55 %			

a: The U-value of 0.84 W/(m²K) is for the log construction. After the measure it is assumed that all exterior walls will have equivalent U-values. Assuming the new insulation will replace the existing post-insulation. Note that further insulation of the external wall results in the destruction/alteration of interior and/or exterior surfaces which are mostly in good condition; b: Most of the windows are from the early 2000s and fit the architectural expression; c: Not applicable for Viken; d: In reality, Viken already has a relatively new wind barrier and windows. As a result, Viken most likely have a better infiltration than 10 h^{-1}; e: Net energy demand with BIPV: Total calculated energy demand minus energy delivered to the building from the BIPV (kWh/m² NIA).

Appendix C:
Estimated U-value for exterior walls post-insulated with vacuum insulated panels

Manual calculations

The calculation is done according to NS-EN ISO 6946. This method will not provide a realistic U-value when dealing with such thin layers and significant differences in thermal conductivity between the materials. However, it gives a reference point for the simulations done in THERM. Table C1 shows values for calculation for the upper limit and Table C2 shows values for calculation for the lower limit for the thermal resistance. These are used in the estimation of the total thermal resistance calculated below. The following is applied in the calculations:

- Field a: vacuum insulation panel (proportion = 91 %).
- Field b: timber (proportion = 9 %).
- It is assumed that 36 mm furring with 600 mm spacing is used.

Table C1: Upper limit value, $R_{tot;upper}$

Layer		Surface resistance, R (m^2K/W)	
		Field a, VIP $F_a = 0.91$	**Field b, timber $F_b = 0.09$**
External ventilated cladding	R_{se} + R1 + R2	0.13	0.13
Asphalt wind barrier, 12 mm	R3	0.17	0.17
VIP, 20 mm	$R4_a$	2.86	-
Framework, 23 mm timber	$R4_b$	-	0.19
Vapour barrier	R5	0.03	0.03
Internal cladding, 13 mm timber	R6	0.10	0.10
Internal transitional resistance	R_{si}	0.13	0.13
Total thermal resistance		**3.42**	**0.75**

$$R_{tot;upper} = \frac{1}{\frac{fa}{R_{tot;a}} + \frac{fb}{R_{tot;b}}} = \frac{1}{\frac{0.91}{3.42} + \frac{0.09}{0.75}} = 2.59\ m^2K/W$$

Table C2: Lower limit value, $R_{tot;lower}$

Layer		Surface resistance, R (m^2K/W)
External ventilated cladding	R_{se} + R1 + R2	0.13
Asphalt wind barrier, 12 mm	R3	0.17
Equivalent thermal resistance for layers with VIP and framework.	R4 [a]	1.04
Vapour barrier	R5	0.03
Internal cladding, 13 mm timber	R6	0.10
Internal transitional resistance	R_{si}	0.13
Total thermal resistance, $R_{tot:lower}$		**1.60**

a: $R4 = \frac{1}{\frac{0.91}{2.86} + \frac{0.09}{0.19}} = 1.04$

$$Thermal\ resistance = R_{tot} = \frac{R_{tot:upper} + R_{tot:lower}}{2} = \frac{2.59 + 1.60}{2} = 2.10\ m^2K/W$$

→ U-VALUE = $\frac{1}{R_{tot}} = \frac{1}{2.10} \approx$ **0.48 W/(m²K)**

Option 1 for simulation in THERM: timber fasteners not included

Figure C1 shows an excerpt from THERM including the results and illustration of the simulation. When using this method, there are certain advantages and disadvantages to consider. One advantage is that it allows to get an impression of the best U-value the wall can achieve in its optimal section. This provides valuable insights into the potential thermal efficiency of that specific area. However, a significant drawback is that this method may not provide an accurate representation of the overall U-value performance of the entire wall construction. It might give an artificially good U-value, as it does not account for other factors and variations in different sections of the wall. Therefore, while this approach provides valuable information, it should be used alongside a comprehensive analysis of the wall's U-value considering all relevant factors to obtain a more accurate assessment.

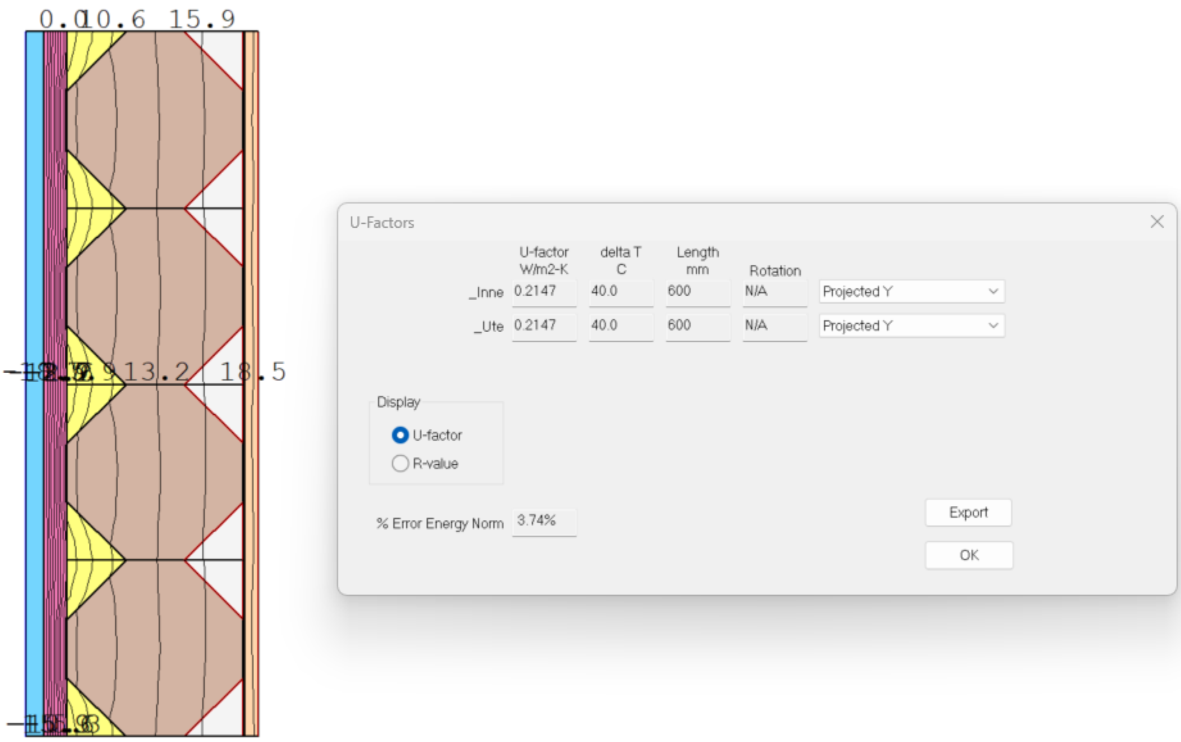


Figure C1: Excerpt from THERM that shows an illustration of the simulated wall and the results for Option 1 for simulation in THERM.

→ U-VALUE = 0.2147 W/(m^{2}K) ≈ **0.21 W/(m^{2}K)**

Option 2 for simulation in THERM: Does not take into account mineral wool in cavities in log construction

Figure C2 presents an excerpt from THERM, showcasing both the simulation results and an illustrative representation. This approach has several advantages and disadvantages that should be considered. One advantage of using this method is that it provides a more realistic impression of the worst-performing section of the wall. It allows for a better understanding of the U-value in that specific area, giving insights into potential thermal weaknesses. Additionally, the proportion of all materials, excluding mineral wool in the cavities between the logs, will be accurately represented. However, there are some drawbacks to consider. This method does not account for the presence of mineral wool in the cavities, resulting in a slightly underestimated performance. Furthermore, the thermal bridging contribution from the fastenings may appear higher than reality. THERM assumes continuous furring or timber against the logs throughout the height of the wall, which can lead to an artificially high thermal bridging estimate. It is worth noting that if parts of the logs were replaced with mineral wool to achieve the correct proportion of mineral wool and logs, the representation of thermal bridging would not be realistic.

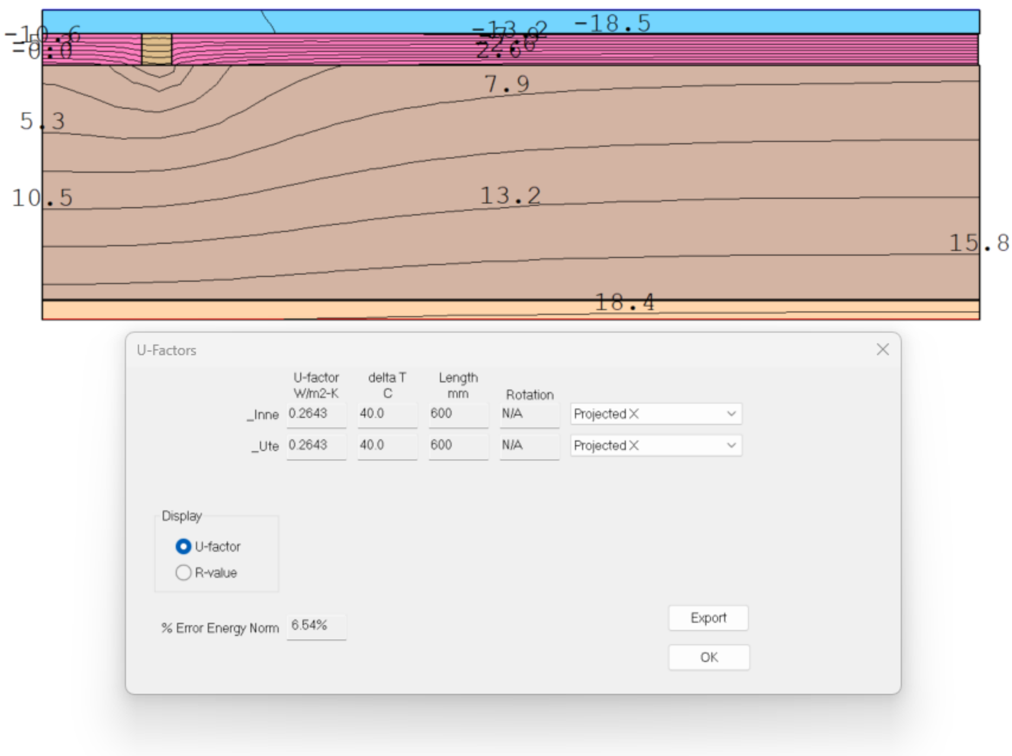


Figure C2: Excerpt from THERM that shows an illustration of the simulated wall and the results for Option 2 for simulation in THERM.

→ U-VALUE = 0.2643 W/(m^{2}K) ≈ **0.26 W/(m^{2}K)**

Option 3 for simulation in THERM: representative material share

Figure C3 presents an excerpt from THERM, showcasing both the simulation results and an illustrative representation. One advantage of using this method is that it accurately represents the approximate percentage of logs and mineral wool (in the cavities within the logs). This ensures that the calculated proportion of all materials in the wall construction is representative of the actual composition. However, there are a couple of drawbacks to consider. Firstly, the thermal bridging contribution from the fastenings will appear higher than reality. THERM assumes continuous furring or timber against the logs throughout the height of the wall, leading to an artificially elevated thermal bridging estimate. Secondly, it is worth noting that the orientation of the logs in the illustration is incorrect, which only affects the visual aspect and does not impact the performance analysis.

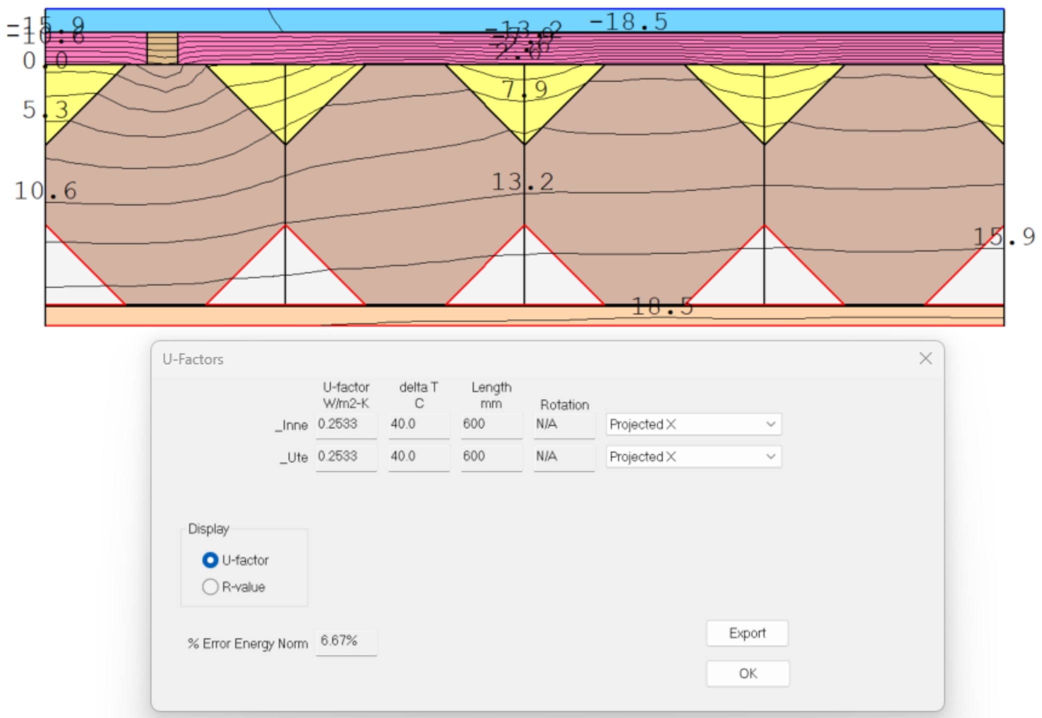


Figure C3: Excerpt from THERM that shows an illustration of the simulated wall and the results for Option 3 for simulation in THERM.

→ U-VALUE = 0.2533 W/(m^{2}K) ≈ **0.25 W/(m^{2}K)**

Option 4 for simulation in THERM: Representative material share and an approximate percentage for thermal bridging

Figure C4 presents an excerpt from THERM, including both the simulation results and an illustrative representation. One advantage of using this method is that it accurately represents the approximate percentage of logs and mineral wool, ensuring the correct proportion of all materials in the calculation. As the fastening is positioned partly above the mineral wool and logs, the thermal bridging contribution will not be as significant as in Option 1 and Option 2. However, there are a couple of drawbacks to consider. Firstly, the percentage of furring that meets the logs is only assumed and not precisely defined. Secondly, it is worth noting that the orientation of the logs in the illustration is incorrect, which only affects the visual aspect and does not impact the performance analysis.

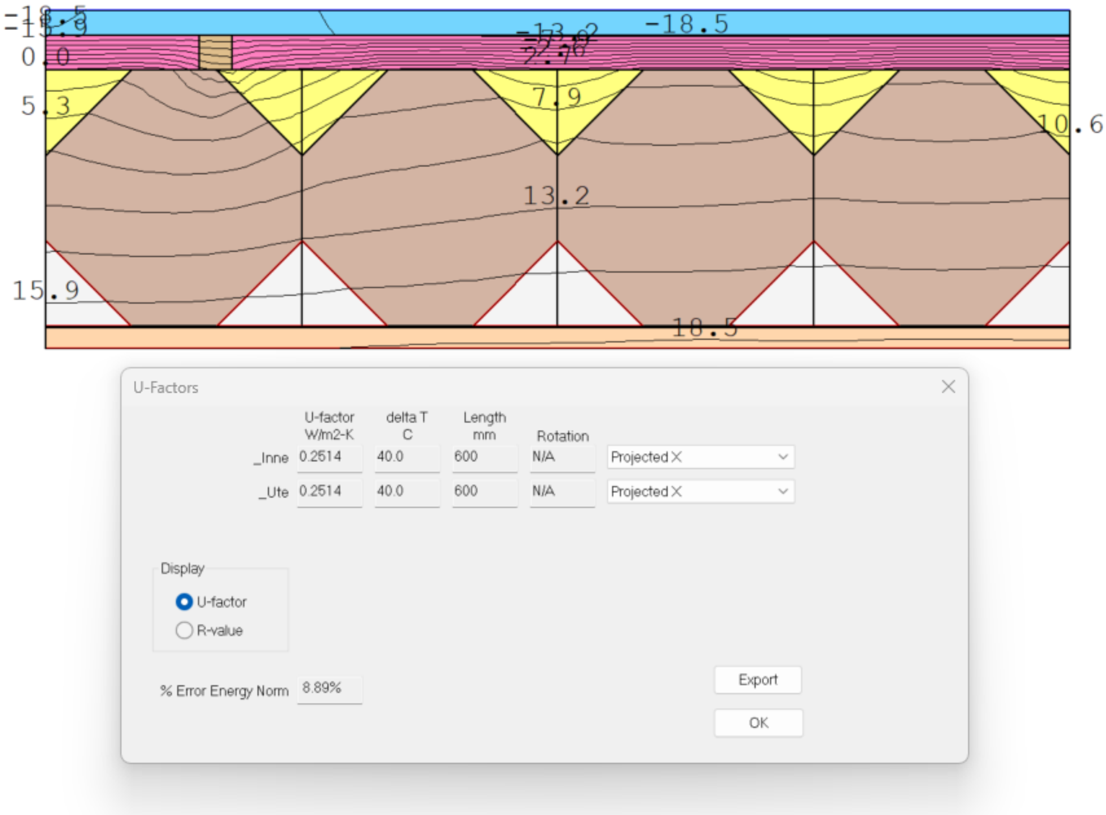


Figure C4: Excerpt from THERM that shows an illustration of the simulated wall and the results for Option 4 for simulation in THERM.

→ U-VALUE = 0.2514 W/(m^{2}K) ≈ **0.25 W/(m^{2}K)**

Summary of results

Table C3 summarizes the manual calculations and the simulations preformed in THERM. Regarding the manual calculations it is pertinent to mention once again that these should not be included in the estimate due to the applied method. The average of all four simulations is 0.24 W/(m^{2}K), but since Option 1 yields an artificially low U-value, it significantly influences the overall result and brings the value down slightly more than necessary. Option 3 and 4 are nearly identical and represent a solution that closely resembles the actual situation. Based on this, the estimated U-value for post-insulation with VIP is 0.25 W/(m^{2}K) for both internal and external post-insulation.

Table C3: Summary of results from manual calculations and simulations in THERM regarding wall constructions with vacuum insulated panels.

Method	U-value (W/(m^{2}K))	Comment
Manual calculations	0.48	The method is inadequate for layers with significant variations in thermal conductivity (λ) between materials.
Option 1 for THERM	0.21	Does not take into account the framework/fastening of the VIP insulation and gives an artificially low U-value.
Option 2 for THERM	0.26	Artificially high thermal bridging and absence of mineral wool in cavities gives a worst-case simulation for the U-value.
Option 3 for THERM	0.25	Representative material share, but artificially high thermal bridging and not representative illustration.
Option 4 for THERM	0.25	Representative material share and an approximate percentage for thermal bridging, but not representative illustration.

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