Master's thesis

NTNU
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Faculty of Architecture and Design
Department of Architecture and Technology

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Template for architectural and energy advice for retrofitting heavyweight non-residential heritage buildings in Norway

A trial demo using an ARV (Climate Positive Circular Communities) project case as reference

Master's thesis in Sustainable Architecture
Supervisor: Inger Andresen
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Abstract

An increase in greenhouse gas emissions has led to a climate change concern, triggering different spheres of society to lead a transformation of their usual functioning. The Norwegian building industry has embraced sustainable practices to diminish energy consumption, but the energy demand remained high compared to other countries. While efforts have focused on new buildings, a large portion of the existing building stock, particularly cultural heritage buildings, poses challenges for energy refurbishments due to their unique characteristics and legal protections. There is existing customised advice for the traditional residential lightweight buildings, but little about the remaining heritage buildings typologies that also require tailored assessment and retrofitting approaches, leading to calls for a comprehensive framework to address their complexity and energy efficiency needs.

This research focuses on the challenges associated with energy retrofitting of non-residential and heavyweight materials heritage buildings in Norway. The main objectives were to develop an advice template that effectively presents retrofitting measures, gathers necessary information, standardise data compilation, and structures a recommendation report. The research employed a systematic approach to categorise and classify retrofitting interventions, providing a framework for clear communication and implementation. Extensive data collection from Norwegian case studies and literature reviews ensured specific and suitable advice measures that consider the unique characteristics and requirements of each building. The complexity of the Norwegian building stock was managed through a methodical strategy, grouping buildings by shared features in an archetype system. The template incorporates technical, energy, architectural, and heritage recommendations to facilitate decision-making and execution of retrofitting projects. The results, shown through a selected archetype, trends related to retrofitting advice, emphasising the need to balance energy goals with heritage preservation, successfully identifying its strengths, shortcomings, and further development.

KEYWORDS:

Assessment guideline, cultural heritage buildings, renovation, energy retrofitting, non-residential buildings, heavyweight materials, building fabric, energy efficiency.

Sammendrag

En økning i klimagassutslippene har ført til bekymring for klimaendringer, noe som har fått ulike samfunnsområder til å legge om sin virksomhet. Den norske byggebransjen har tatt i bruk bærekraftig metoder for å redusere energiforbruket, men energibehovet er fortsatt høyt sammenlignet med andre land. Selv om innsatsen har fokusert på nye bygninger, utgjør en stor del av den eksisterende bygningsmassen, særlig kulturarvbygninger, utfordringer for energirenovering på grunn av deres unike egenskaper og juridiske beskyttelse. Det finnes skreddersydde råd for de tradisjonelle lette boligbygningene, men lite om de gjenværende typologiene av kulturarvbygninger som også krever skreddersydde vurdering- og oppgraderingstilnærminger, noe som fører til krav om et omfattende rammeverk for å håndtere deres komplekset og behov for energieffektivitet.

Denne forskningen fokuserer på utfordringene knyttet til energirenovering av yrkesbygg og verneverdige bygninger i tunge materialer i Norge. Hovedmålet var å utvikle en rådgivningsmal som effektivt presenterer oppgraderingstiltak, samler inn nødvendig informasjon, systematiserer datainnsamlingen og strukturer en anbefalingsrapport. Forskningen benyttet en systematisk tilnærming for å kategorier og klassifisert oppgraderingstiltak, noe som gir et rammeverk for tydelig kommunikasjon og gjennomføring.

Omfattende datainnsamling fra norske casestudier og litteratur-gjennomganger sikret spesifikke og egnede råd som tar hensyn til de unike egenskapene og kravene til hver enkelt bygning. Kompleksiteten i den norske bygningsmassen ble håndtert gjennom en metodisk strategi som grupper bygninger etter felles egenskaper i et arketypesystem. Malen inneholdt tekniske, energimessige, arkitektoniske og kulturhistoriske deler for å lette beslutningstaking og gjennomføring av oppgraderingsprosjekter. Resultatene, vist gjennom en utvalgt arketype, trender knyttet til råd om ettermontering, understreker behovet for å balansere energimål med bevaring av kulturer, og identifiserer styrker, mangler og videre utvikling.

Preface

This preface functions as an introduction and recognition of the journey embarked upon in the development of this master's thesis. It signifies the culmination of extensive investigation, critical analysis, and scholarly inquiry conducted. The purpose of this preface is to offer readers insights into the origins, motivations, and objectives that guided the author throughout the process.

The inspiration for this master's thesis arose from a profound enthusiasm for historic structures and their particular conditions to be preserved throughout time. The educational concepts acquired during the master’s program and personal experiences have nurtured a strong fascination with exploring the complexities, obstacles, and potential solutions related to energy retrofitting in these buildings.

This thesis is divided into several parts, each developing and explaining distinct aspects of the research. The introduction opens (1) the investigation with the problem description research topic, outlines the research questions and objectives and justifies the main reason for the study. The background section (3) offers a comprehensive understanding of the studies and policies that recommend investigating the current matter. The methodology and theory chapter (4) elaborates on the research methodology employed, providing a detailed explanation of data collection, analysis, and interpretation and an extensive literature review for supporting the later decisions. The result chapter (5) presents the research findings, followed by a critical discussion and analysis in the discussion section (6). Finally, the conclusion chapter (7) presents a diagnosis drawn from the research, recommendations for future studies and potential areas of further exploration.

I want to express my most profound appreciation and gratitude to all those who have contributed to the successful completion of this thesis.

First, I sincerely thank my supervisor Inger Andresen and my co-supervisor Sladjana Lazarevic for their guidance, expertise, and support throughout this research endeavour. Their insightful input, constructive feedback, and dedication shaped the direction and quality of this thesis.

Thanks to the staff and administration of NTNU and the Sustainable Architecture master's program for their support throughout the entire degree and this research.

I extend my heartfelt appreciation to the leaders and representatives of the projects assessed during this study for their willingness to share their information and perspectives. Without their active involvement, this research would not have been possible. I also want to acknowledge the countless researchers, scholars, and authors whose seminal works have laid the foundation for this study. Their contributions to the field have shaped and informed my research, and I deeply appreciate their commitment to advancing knowledge.

Most importantly I praise my entire family, especially, my parents, Jorge and Luz Marina, my brothers and sisters-in-law Jorge, Luis, Giovanny, Diana, Isabel, and Marcela and their children for the encouragement, understanding and support throughout this challenging journey in the distance. Their love, support, and belief in my abilities have constantly motivated and inspired me. I also thank my friend Francy in Colombia, who helped me overcome all the difficulties and share good moments during the last two years.

And finally, to my beloved friends and classmates from this master's program Åsmund, Bianca, Camilo, Galina, Ingrid, Irene, Sara, Steinar, Roya, and Theresa. What a beautiful family we are; we encouraged and supported each other to give the best of ourselves. Without them, it would have been impossible to finish this journey successfully. All the best for your future errands.

Although it is impossible to mention everyone who has played a role in this undertaking, I am genuinely grateful for the collective support, guidance, and encouragement I have received. Thank you all for being an integral part of this journey and helping me achieve this desired goal.

This master's thesis results from hours of dedication and scholarly exploration. I expect this research to contribute to the body of knowledge and trigger further discussions and investigations. May the findings presented in this thesis inspire future researchers, practitioners, and enthusiasts to delve deeper into retrofitting heritage buildings.

Jesús

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List of Abbreviations

ARV	Climate Positive Circular Communities project
BCC	Building criteria characterisation
BREEAM	Building Research Establishment Environmental Assessment Methodology
CPCCs	Climate Positive Circular Communities
DATAHOLZ.EU	Catalogue of wood and wood-based materials, building materials, components, and component connections for timber construction.
EPS	Expanded polystyrene
GWP	Global Warming Potential
HiBERAtlas	Historic Building Energy Retrofit Atlas
HVAC	Heating, ventilation, and air conditioning
ICA-SHC Task 59	Renovating Historic Buildings toward Zero Energy
IEQ	Indoor environment quality
KPIs	Key Performance Indicators
Kulturmminesøk	Cultural memory database
LCA	Life-cycle assessment
PE	Polyethylene
PET	Polyethylene terephthalate
Riksantikvaren	Norwegian Directorate for Cultural Heritage
SINTEF	The Foundation for Industrial and Technical Research
TEK 17	Byggteknisk forskrift – Norwegian Building code
U-Value	Thermal transmittance
VIOLET	Preserve traditional buildings through energy reduction – European project.
VIP	Vacuum Insulation panels
ZEB	Zero Emission Buildings
ZNEB	Nearly Zero-energy building

1 Introduction

1.1 Problem description

Recent natural events that have been disastrous for humanity are linked to human activity [1], increasing global temperatures which destabilize the delicate balance of the environment, triggering droughts, floods, landslides and other phenomena with more frequency and lethality [2]. One of the activities that contribute the most to global emissions is the construction industry [3]. For instance, in Europe, carbon emissions in the construction industry, account for approximately 36% of GHG emissions [4]. There is a commitment of world nations to reach the Paris Agreement and restricting the increase in average global temperature 1.5 °C by 2030, in which Norway's attempts are based on some compromises such as reducing its GHG emissions by 55% by 2030 compared to 1990 levels [4].

Norway belongs to a selected list of countries that consumes more resources on the planet. In fact, in 2021 energy use per person in Norway was 105148 kWh, almost double the average of high-income countries (55860 kWh), nearly three times more than the European Union average (37519 kWh) and five times more than the World average (20902 kWh) [5]. One of the reasons behind this trend is its geographical location; the harsh weather and dark days during most of the year skyrocket the use of electricity and heating in buildings [6].

In an attempt to overcome this tendency, the Norwegian building industry has rapidly adapted to recent efforts in transitioning from traditional construction methods to a sustainable approach for new buildings under strict environmental benchmarks; ZEB (Zero Emission Buildings) guidelines and BREEAM standards helped the transition to diminish the impact of buildings during their lifetime [7]. And, although it is vital to minimize the energy consumption in newly constructed buildings, still the embodied emissions of materials used to reach those benchmarks rise sharply (55-87% of embodied GHG emissions) [8]. Meanwhile, the building stock of the country grows rapidly with new buildings, the investment for the construction of new public buildings has been rising sharply since 2017 [9] and still, 62% of the building stock of residential buildings was built before 1990 [9]. These buildings built before 1990 usually have a high energy consumption due to the lack of energy measurements at their construction [10] and it is demonstrated that in most cases refurbishing these buildings, could bring significant environmental and social benefits [11], hence fostering the efforts in achieving the GHG reduction goals.

However, there is part of the building stock which has some particularities that could have obstacles to executing energy refurbishments in a habitual manner. These are the cultural heritage buildings, constructions that have a historical, architectural or aesthetical significance [12]. This distinctiveness difficult the implementation of standardised energy retrofitting solutions because each building is required to be evaluated as a single case, prioritizing the historic values that are under a legal framework "manoeuvre" rather than the possible energy savings that might bring a deep renovation [13].

Therefore, some related Norwegian entities such as Riksantikvaren (Norwegian Directorate for Cultural Heritage (National Antiquities), SINTEF (The Foundation for Industrial and Technical Research) and others have advised a procedure plan on the refurbishment of cultural heritage buildings under an energy retrofitting premise [14]. It is important to highlight that these recommendations are mostly related to traditional timber Norwegian houses [15]. Their similarities in scale and materiality facilitate the development of general guidelines on this building typology [15]. On the contrary, the rest of the cultural heritage building stock (mostly non-residential buildings) has a different level of heritage protection and it is diverse in its, use, scale, fabric, and energy benchmarks [16], which difficult the creation of a general framework for retrofitting them.

Consequently, there are some petitions from different actors related to cultural heritage management on having a more profound assessment of non-residential buildings with larger complexity in their fabrics, systems, and energy consumption benchmarks [17]. This could open the possibility of searching for a method on how to appraise Norwegian building actors about the correlation between heritage protection and energy retrofitting, and how to proceed with efficient and long-lasting refurbishments according to the building characteristics and environmental circumstances.

1.2 Research question

How to inform designers about adequate measures for energy refurbishment of heavyweight non-residential buildings in Norway that are under heritage protection through an appropriate template that contains a set of measures based on previous successful retrofitting cases?

1.3 Complementary questions

- How to present in an organized and clear manner effectively proved retrofitting measures to the aimed building stock?
- What is the information that needs to be collected from buildings and support literature to give specific and a suitable set of advice measures?
- How to systemise a strategy to compile information collected from the abundant and complex Norwegian building stock that is manageable for the timespan of the research.?
- How to structure an adequate template for a recommendation report that adjust to the conditions to the building typology selected?
- How ARV project contributes to the advice report from their assessment criteria developed in their involved projects?

1.4 Main objectives

- Utilise ARV (Climate Positive Circular Communities) project key performance indicators demo case in Oslo (Voldsløkka school) and the as main reference for setting parameters for a database.
- Create a reliable database of retrofitting cases in Norway that can compile the most common building components and their intervention.
- Develop a selection criterion for evaluating heritage building references based on ARV project key performance indicators.
- Classify all the relevant building components to facilitate a cross reference study of them to ensure a correct functioning of the database.
- Cross reference different cultural heritage levels with building components to set a general advice for the most prominent typologies and component interventions.
- Set a parameter of interventions and pros and cons of any measure considering the level of heritage protection.
- Test the feasibility of the measures for completing a broader guideline that can be shared publicly.

1.5 Justification

Heritage buildings with heavyweight materials, such as stone, brick, and concrete, are valuable cultural assets that often pose challenges when it comes to energy efficiency improvements [18]. Retrofitting these buildings to enhance their energy performance while preserving their historical and architectural significance requires careful consideration and specialized guidelines [19]. This research project aims to analyse successful intervention in Norwegian and global cases for energy retrofitting of heritage buildings with heavyweight materials, considering their unique characteristics and conservation requirements.

Energy retrofitting interventions must be carried out in a manner that respects the cultural value and historical significance of heritage buildings [20]. Any modifications should not compromise the original materials, architectural integrity, or authenticity [20]. Therefore, a guide is necessary to ensure that the measures chosen in a decision-making process aligns with conservation principles.

Improving energy efficiency in heritage buildings is important for diminishing incidence of building industry on climate change [21]. However, the application of conventional retrofitting techniques usually largely described for residential wood constructions (lightweight) [16] [22] can be challenging due to the distinctive properties and limitations of heavyweight materials. Therefore, tailored guidelines could be required to address thermal characteristics and constraints of these materials.

The first part of the study aims to create optimal conditions for giving architectural and energy recommendations. This means, developing a structure of data sources and research that support any measure or intervention.

The second part of the research will investigate strategies to optimize the thermal performance of heritage buildings with heavyweight materials. This includes assessing different aspects of a construction. The main component are building fabric elements, where is important to suggest both insulation techniques and insulation systems or materials, while considering their impact on the building's aesthetics and moisture management [23].

Heavyweight materials have different moisture absorption and release properties compared to lightweight materials. Retrofitting measures must consider moisture management to prevent issues such as dampness, mould growth, and deterioration of building materials [24].

The second component that is evaluated are the building systems. The selection and integration of heating, ventilation, air conditioning (HVAC) and lighting, may have a higher effect in retrofitting heritage buildings [25]. The research project will just cover the analysis of the necessary elements and factors that might be important from buildings. Advice will not be provided about the building systems as with the fabric, since there are gaps left on what is the pertinent data that is required for giving precise recommendations about systems, factors not explored in depth during the study.

The last component assessed is the users' and building management behaviour towards energy reduction and renovation processes to reach energy goals. Similarly, The study will only recommend a template for data collection about users' behaviour towards retrofitting interventions [26].

To validate the proposed guidelines, the research will include a comprehensive analysis of Norwegian case studies involving heritage buildings with heavyweight materials that have undergone energy retrofitting, representing the context of the study; and cases form literature of successful and innovative renovations, embodying a broad perspective and new technologies. The performance of the retrofitted buildings measures will be finally summarized by performance indicators highlighted in ARV project as main part of their assessment criteria.

The conclusions of this study will strengthen heritage conservation and sustainable building practices. The template for recommendations and the advice itself will provide valuable insights for architects, engineers, heritage preservation organizations, and policymakers involved in retrofitting heritage buildings with heavyweight materials as well of a glimpse of the necessary aspects that should be included for a holistic and general guideline report for energy retrofitting of heritage buildings in Norway.

By undertaking this research project and establishing guidelines for energy retrofitting of heritage buildings with heavyweight materials, we can bridge the gap between energy efficiency goals and the preservation of historical structures, ensuring a sustainable future while maintaining our architectural heritage.

2 Thesis structure

The following illustration (Figure 1) shows how the thesis is structured, later explaining the reasons through the importance of having quality support information for any suggestion or recommendation on renovation processes.

Background	1. Norwegian policies and recommendations 2. Literature and standards 3. ARV project framework
Methodology and theory	1. Research design 2. Thesis scope 3. Norwegian and literature cases 4. Data collection and analysis 5. ARV Framework
Results	1. Guideline structure 2. Example of data collection process 3. Retrofitting advice example
Discussion	1. Method approach 2. Research output 3. Uncertainties and improvements 4. Bases for further research
Conclusions	
Bibliography	
Appendixes	

Figure 1 Summary of the thesis document structure (Own illustration)

3 Background

This research presents a concise background section focusing on research, projects and standards issuing energy retrofitting in heritage buildings. The following paragraphs outline the most related literature and guidelines on this topic, identify research gaps, and highlight the importance of further investigating this area. An in-depth literature review is presented later in the methodology section as part of the assessment of research support for retrofitting advice.

3.1 Norwegian policies and recommendations retrofitting historical buildings. RIKSANTIKVAREN and SINTEF

Riksantikvaren (Norwegian Directorate for Cultural Heritage) is responsible for safeguarding and promoting Norway's cultural heritage, including historic buildings. In a joint study with SINTEF (The Foundation for Industrial and Technical Research), they acknowledge the importance of reducing energy consumption while preserving their historical significance and architectural integrity [16]. According to SINTEF, 1.95 million tonnes of waste come from the building sector, representing 25% of Norway's waste [27]. Hence, different governmental and private entities focused on updating ageing buildings, accounting for the overall energy demand of all building stock [28].

Historic buildings often pose unique challenges in terms of energy efficiency due to their construction methods, materials, and architectural features [16]. Retrofitting these structures to meet modern energy standards requires careful consideration to minimise any negative impact on their heritage value. Riksantikvaren suggests a set of recommendations as an essential method for guiding communities on balancing energy efficiency and heritage conservation on their properties [16].

It covers insulation, windows, ventilation, heating systems, and renewable energy options for traditional residential units in Norway [28]. The content emphasises the importance of understanding the specific characteristics of historic buildings and tailoring energy-saving measures accordingly.

It provides practical recommendations and considerations, such as conducting energy audits, using insulation materials compatible with traditional construction, preserving original windows, optimizing heating systems, and integrating renewable energy sources discreetly [28]. It also highlights the significance of involving professionals with expertise in energy efficiency and heritage preservation to ensure the best outcomes.

The guidance aligns with several theoretical frameworks and principles related to energy efficiency in historic buildings. However, there is an intention to transfer a similar theoretical framework to other building typologies. Strategies such as retrofitting old residential buildings are essential to diminish the impact; the effort must extend to non-residential buildings. There are numerous cases where strict regulations apply over non-residential buildings such as churches, museums, governmental buildings, or mixed structures located at historical centres of towns.

In that case, SINTEF and RIKSANTIKVAREN suggest the extent of research emphasising non-residential buildings through in-depth comparisons between the level of protection of heritage buildings, the materials, and their large variety in typologies [27].

There are many reasons to create a standard advice structure for retrofitting non-residential buildings in Norway. The first is the more significant embodied emissions of the materials that compose their building fabric [29]. Most non-residential buildings have more material proportions in their fabric, such as brick, concrete, and steel, than traditional residential units [30]. Similarly, these human-made materials have a lower reusability rate than wood, making it complicated to reuse them due to their physical aspects and the technique used to merge them in the building [31].

3.2 Current research about retrofitting guidelines

The main reference as a national standard in Norway that addresses the requirements related to improving the energy performance of historical buildings is NS-EN 16883:2017 [32]. The standard outlines a method for choosing suitable actions to enhance the energy efficiency of a specific historic structure, presenting overall factors to be considered and followed before implementing the process [33].

It highlights crucial points, such as the importance of enough research to base any suggestion since each building must be assessed as a single study [33]. It mentions four primary areas of intervention, among them building fabric and systems, considering them the cornerstone of the analysis. Finally, it essentially explains methods for developing a building survey and assessment [33]. This is essential for the undergoing research as a guide to correctly identify the cases and avoid inaccuracies during decision-making phases.

Different projects have been developed at a European level related to retrofitting guidelines. Interreg Europe developed VIOLET (Preserve traditional buildings through energy reduction), an initiative to address a common challenge faced by European Union (EU) regions that possess significant traditional building stocks.

The primary objective of the VIOLET project is to is to enhance the energy efficiency of conventional buildings by refining public policies. while simultaneously incorporating actions that promote low carbon emissions and cultural preservation [34]. The project emphasizes the importance of considering the specific context of each region and tailoring solutions accordingly [34]. This measure needs to be explicitly considered in the Norwegian context. The difference in climate conditions and the particular characteristics of their preservation features embrace the idea of having a guide promoting specific solutions for the context.

At a more practical level, Interreg also has developed HiBERAtlas. This database contains comprehensive records that offer insights into the building's characteristics, construction details, heritage evaluation, specifications of building materials, energy efficiency measures, building services, comfort considerations, refurbishment options and recommended products [35]. The output of HiBERAtlas is an online tool, easily accessible and graphical, that shows the different measures depending on several factors pre-selected during an identification phase [35]. However, all the measures are presented from each building's perspective, using their experience and simulations in the retrofit process as references for describing advantages and disadvantages. This research wants to explore additional data support from an external perspective, to avoid biased conclusions when only taking own experiences.

3.3 ARV goals and references for current study

The ARV Green Deal EU project (Climate Positive Circular Communities) is an ambitious initiative to drive sustainable development, foster green innovation, and address climate change challenges within the European Union (EU) [36]. It aims to showcase and confirm practical, durable, cost-effective approaches that incentivise deep energy renovations in distinct European climate zones [36]. Additionally, the project aims to promote the adoption of energy and climate measures in the construction and energy sectors [36]. This project has six demo projects located at different locations: Norway, Spain, Netherlands, Czech Republic, Italy, and Denmark. The case studies were selected, representing an overall picture of the European climate [36].

The projects are embedded in areas called Climate Positive Circular Communities (CPCCs). CPCCs are urban areas aiming for zero greenhouse gas emissions, energy flexibility, circular economy, and social sustainability [36].

ARV project has designed an assessment framework for designing and evaluating these urban areas, where it is considered the interaction between buildings, users, and energy systems, facilitated by ICT, to create attractive and affordable solutions. It emphasises the neighbourhood-based approach, architectural qualities, and circularity [36].

Figure 2 ARV illustration representing demo projects and Key performance indicators (Taken from ARV project)

The framework includes established and emerging EU indicators and introduces additional KPIs (Key Performance indicators) to assess the energy, environmental, economic, well-being, and social impacts of CPCCs (Figure 3). The main categories of KPIs are energy, environment, social, architecture, circularity, and economics [36].

Architecture	Social	Environmental
Aesthetics and Visual qualities Flexibility and adaptability Sufficiency and adequacy of space Indoor Air Quality Thermal Comfort Overheating risk Solar and Daylight access Acoustic Comfort Outdoor Comfort	Affordability of Energy Energy and environmental consciousness Democratic Process Social Inclusion Social Engagement Demographic Composition Social Interaction and Cohesion Safety and Security Energy and Environmental consciousness Affordability of Housing Acess to Sustainable Mobility Access to Services and Amenities	Life-cycle GHG Emissions in CPCC Air Pollution from the Energy Consumption Dust during Retrofiting Noise during Retrofiting

Economics	Energy	Circularity
Construccion Time Reduction Global Cost Energy Renovation Rate Number of Jobs created	Non-renewable Primart LifeCycle Energy in the Built environment Renewable Energy Ratio Grid Delivered Facotr Net Energy/Net Power	▪ Materials from Cycled Sources ▪ Reusability

Figure 3 ARV project Key Performance Indicators. (Own illustration, taken from ARV project)

These indicators are an optimal opportunity to contribute to any criteria evaluation process, and they have the necessary support to analyse various measures and decision-making within projects. However, in the case of the current demos, two are heritage-protected buildings. Following the characteristics explained by Riksantikvaren, the challenges that bring protected buildings make them suitable to have specific indicators that adjust to their features. For the current study, these indicators could work as a tool to illustrate the suitability of different interventions, proving that perhaps additional indicators are necessary to assess listed buildings specifically.

4 Methodology and theory

Building a decision-making recommendation tool for energy renovation of heritage buildings is an adopted measure based on organisational and executive processes usually adopted by different social spheres such as governmental entities, academia, and the building industry [37]. The approach of many of these institutions is to gather data related to buildings under the heritage spectrum to find patterns where advice can be formulated.

One key challenge of advising building interventions is that the scope needs to be designed accordingly to the community expertise and possibilities, therefore including traditional measures and materials. However, it must also be expanded outside of conventional parameters, including global and innovative interventions, thereby expanding practices commonly constrained by the success of local interventions. Hence, it is essential to find both buildings in the study region that have successful experiences with retrofitting and alternative interventions that might fit in local building typologies. Both research pillars require an output that assesses credible criteria that designers, clients, and other actors from the industry can understand and incorporate into their cases.

To have a functional guideline report, it is necessary to identify and analyse all variables influencing heritage buildings, which is an enormous scope out of the reachability of the current research. Thus, the structure of this thesis aims to fit as a demo test based on the general perspective of the suggestion of both the ARV project and Riksantikvaren previously mentioned for a future guideline tool.

This methodology section is explained through five main aspects:

- The research design and approach methodology.
- The thesis scope: how to get to control a manageable spectrum of data for the given timespan.
- Explanation of the “Norwegian case studies and literature cases” approach
- Data collection and analysis and literature review
- ARV Framework as template for summary of the advice

4.1 Research design

The thesis focuses mainly on quantitative and qualitative research that circumnavigates a case study approach with the support of a literature review. This focus fits an optimal strategy of guideline development, where for the current research, it is necessary to address the two main components that are part of the discussion for retrofitting: an improvement in the energy and environmental performance and the protection of heritage buildings. Hence, quantifiable data is usually related to energy savings, thermal performance, measures, and proportions; and non-quantifiable data is expressed usually on descriptions, qualities, flaws, and pertinence of a retrofit action.

4.2 Thesis scope

Following the ARV project and Riksantikvaren's suggestions, a suitable output that encloses both visions relate closer to a report or project that describes a Norwegian guideline for retrofitting heritage buildings. Undeniably, the level of difficulty and the amount of data necessary to be realistic surpasses the goals of the thesis. The expertise and spent time resources can be compared with similar regional projects. One is Historic England, a guideline project encompassing advice on the most relevant building elements in several reports [38]. Nevertheless, from a research perspective, the current study can be an initial step of a much-desired project from both entities; therefore, it is important to reduce the thesis scope (Figure 4).

There is a general goal following the conclusions from the background study about the gaps remaining in the area. It is to create a guideline that advice about energy retrofitting of heritage buildings representing all Norwegian protected building stock typologies. To reduce the scope, the subject concentrates on the areas still not covered by other institutions in Norway. If ignoring traditional wood houses, that stands as a much more covered topic, the research focuses on opposite sides, with non-residential buildings built with heavy materials. The depth of research and analysis is still out of range at this stage, meaning focusing on distinctive materials and building elements is necessary to give a manageable and reliable recommendation. Furthermore, it is known how buildings are complex entities to study, and many factors and components need to be analysed [39]. Hence, the current research will focus more on the aspect of the fabric, where most actions are taken. The limited timeframe for this study, limits the capacity to suggest advice on very intricate elements as building systems or the users' role on energy retrofitting.

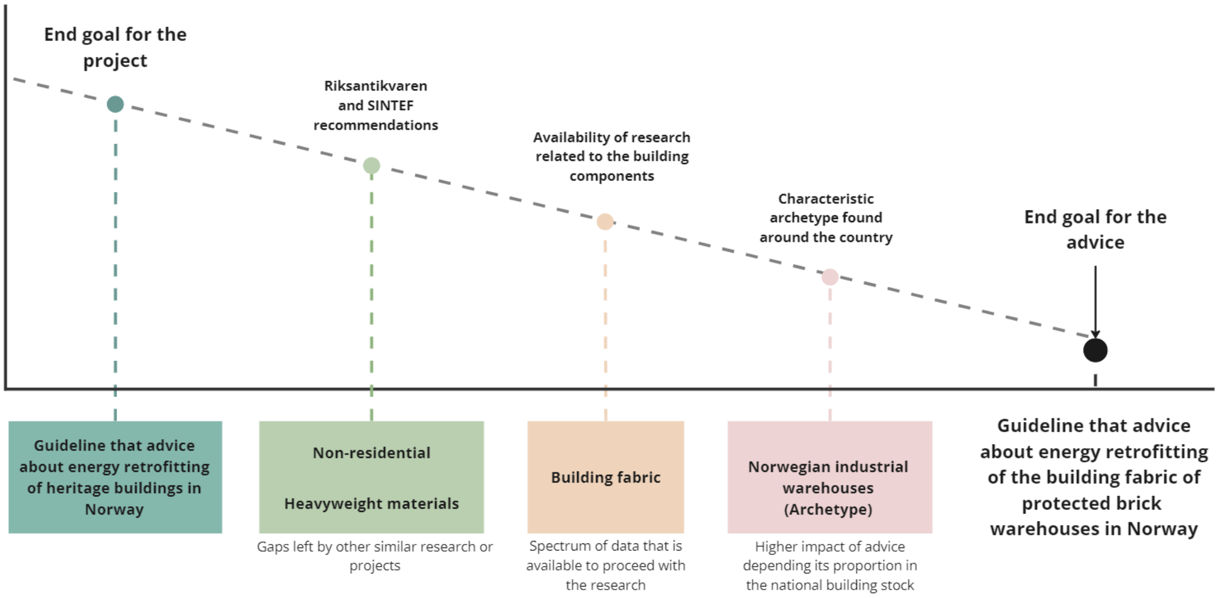


Figure 4 Process of minimizing the scope from a project level to a thesis output.

Still, covering the building fabric of a wide range of typologies and architectural styles is a task that requires a significant amount of research to support any decision-making guide. Heritage buildings in Norway are selected from the Viking Age (6th century) to postmodernist buildings in the 1970s, with a broad range of materials, styles and uses [40]. Therefore, it is planned to analyse several Norwegian case studies to highlight different archetypes where buildings are categorised by their physical and use aspects; and select one to proceed with a more manageable research process. The current research selects Norwegian industrial warehouses as archetype for basing the advice.

All the decisions taken during the thesis scope are explained largely during the current chapter.

4.3 Norwegian and literature case studies

4.3.1 Local-Regional interventions (Norwegian case studies)

Developing general advice for optimal refurbishment creates the necessity of having a database of heritage-protected buildings in Norway that have been refurbished following environmental goals regarding energy consumption reduction [10]. The most optimal approach resides in looking for governmental or related institutions' databases to have reliable data to support the choice of buildings under the study spectrum. During the research, buildings selected with the mentioned characteristics are named the "case studies".

4.3.1.1 Voldsløkka school – Demo from ARV project

As mentioned, the ARV project has six projects that have done or are currently undertaking retrofitting processes. Voldsløkka School is one of the projects that have initiated first, starting operations during the autumn semester of 2023 [41]. The Voldsløkka project comprises two areas: to build a new school structure and improve the energy efficiency of the Heidenreich building, a protected cement factory used as a cultural area [41]. The project was chosen as the first case study and as a sample for selecting other buildings. Many aspects are behind the decision, but three fundamental aspects are that the construction is located in Norway (on the geographical study spectrum); it has a close involvement from academic entities related to the ARV project as NTNU and SINTEF [41]; thus, resources and data are more reachable for the undergoing study, and finally, that it meets the criteria for the thesis scope (Heritage non-residential building made in heavy materials).

4.3.1.2 Buildings database selection process

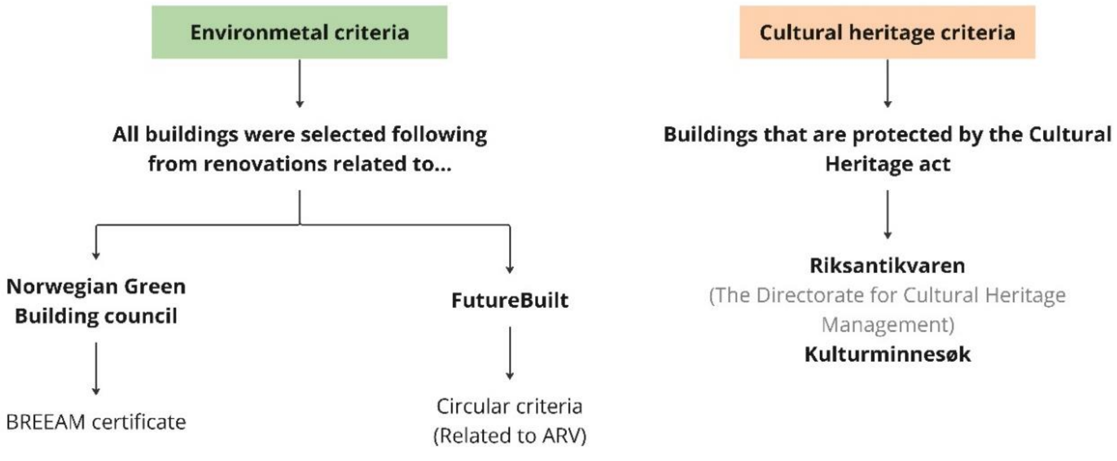


Figure 5 Selection process of buildings that have heritage status and energy renovations were performed (own illustration)

1. The first criteria to fulfil was that the buildings were non-residential and that their main fabric composition was heavyweight materials such as brick, concrete or stone.

2. Secondly, the criteria regarding environmental and energy concerns: Buildings that integrate the database were selected following the BREEAM certificate, a rated base assessment that is used in Norwegian buildings by Grønn Byggallianse (Norwegian Green Building Council) that desire to be retrofitted under an energy and environmental assessment. The other benchmark is FutureBuilt, used to evaluate buildings around their contribution to GWP (Global warming

potential), establishing an improvement parameter—the latest, used by the ARV project as a framework for project renovations.

3. Thirdly, conservation and heritage protection: Buildings were selected following a mapping process found in the Riksantikvaren (Norwegian Directorate for Cultural Heritage Management) platform that shows all heritage buildings in the country and their level of protection.

Due to the large heritage building stock in the country [42], the selection process started with the environmental and energy criteria since the information about energy renovation of brick or concrete buildings is minor in comparison to all the historical constructions in a database that does not filter buildings by materiality or if they had renovations.

Both Grønn Byggallianse [43] and FutureBuilt [44] databases mention when a renovated building is considered historic; hence, filtering in the selection process in the Riksantikvaren database worked as a confirmation of their protected status. “Expanded” interventions (Literature cases). Similar conditions need to be applied for more global and general retrofitting cases. Unfortunately, cases outside the Norwegian scope are more intricate to manage since not many worldwide databases enclose energy retrofitting of heritage buildings. Examples include HiBERAtlas [22], but usually with European cases and not expanding them outside the continent.

Moreover, building retrofit data is given as a whole by construction but not by the type of intervention or a specific element intervened. In such an extensive research scale, using a resource that already specifies those characteristics is more beneficial. Therefore, the most reliable resource scheme is literature. Literature databases filter information by using keywords related to the topic. Hence, words were suggested based on their relevance to the subject from energy and heritage perspectives. Table 1 shows the selected keywords from different categories.

Category	Keywords
Architecture preservation	cultural heritage building; listed building; historic building
Process	renovation; refurbishment; retrofit
Typology	non-residential, school, hospital, office
Materials	concrete, brick, heavyweight
Components or strategies	walls, roof, windows, floor, heating, lighting, behaviour, consumption, operational energy
Goal	energy efficiency, sustainable, NZEB, Zero Energy Buildings, passive house

Table 1 Keywords suggested for literature research.

4.4 Data collection and analysis

4.4.1 Norwegian case studies

4.4.1.1 Collection

During the collection process eighteen (18) buildings were confirmed (including Voldsløkka school) as they fulfilled with all the three criteria mentioned (Figure 6). Buildings were identified mainly in Oslo and some in Trondheim and Rjukan.

1

Voldsløkka school, Oslo

2

Katedral skole, Trondheim

3

Skur 38, Oslo

4

Kristian Augusts gate 23, Oslo

5

Wergelandsveien 7, Oslo

6

Bratørkaia 13 B, Trondheim

7

Kongens gate 21, Oslo

8

Akersgata 35-39, Oslo

9

Skippergata 3, Oslo

10

Berg gård, Oslo

11

Dronning Mauds gate 11, Oslo

12

Kongens gate 8, Mercursenteret, Trondheim

13

Gjerdrums vei 12, Oslo

14

Skippergata 22, Bygårdsanleg, Oslo

15

Sophus Bugges hus, UiO, Oslo

16

St. Olavs Plass 5, Oslo

17

Stortorvet 7, Oslo

18

Mannheim, Rjukan

1. Kontur Arkitektur, 2. Wikipedia, 3. FutureBuilt, 4. KA23, 5. Byggeindustrien, 6. Entra, 7. Grønn byggallianse, 8, Computas, 9, Wikipedia, 10, ReiseKick, 11, Byggeindustrien, 12, Wikipedia, 13, DARK Arkitekter, 14, Wikipedia, 15, GoogleMaps, 16, Byggeindustrien, 17, EstateNyheter, 18, Radio Rjukan

Figure 6 Database of Norwegian case studies that fulfilled selected criteria (photos taken from diverse online sources)

4.4.1.2 Analysis

4.4.1.2.1 Classifying

To reduce the research scope, it is necessary to direct efforts on specific patterns that the selected buildings have to group them to structure advice around the available database. To classify case studies around similar aspects, the evaluation criteria were divided into five categories:

- Architecture style
- Building original use
- Building fabric composition
- Heritage level of protection

1. Architecture style

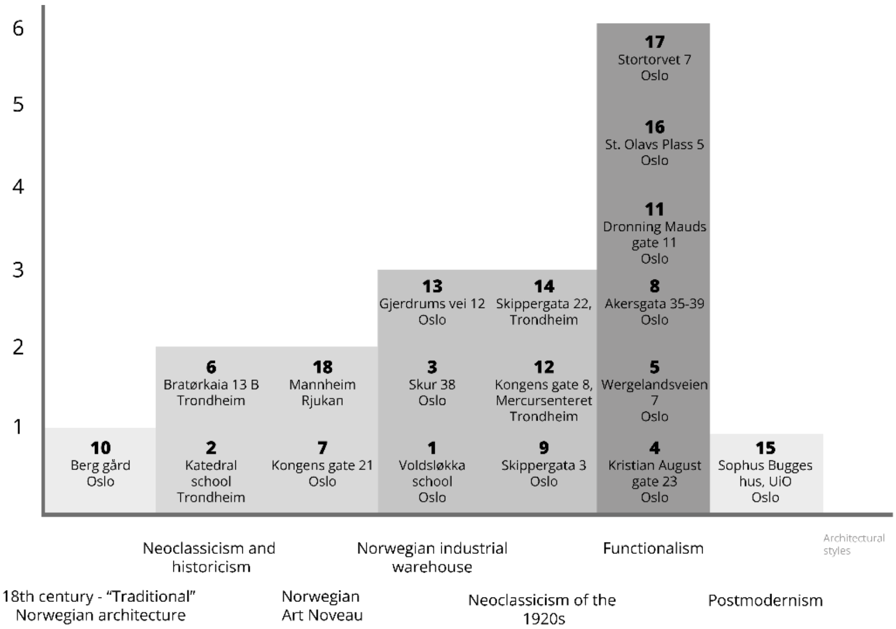


Figure 7 shows a large number of functionalist buildings built between 1950 – 1970. There is a little account of buildings that have been energy retrofitted from styles from before the 20th century and before 1960. *Analysis was done by observation and following general historic guidelines.*

Figure 7 Classification of case studies by architectural style

2. Building original use

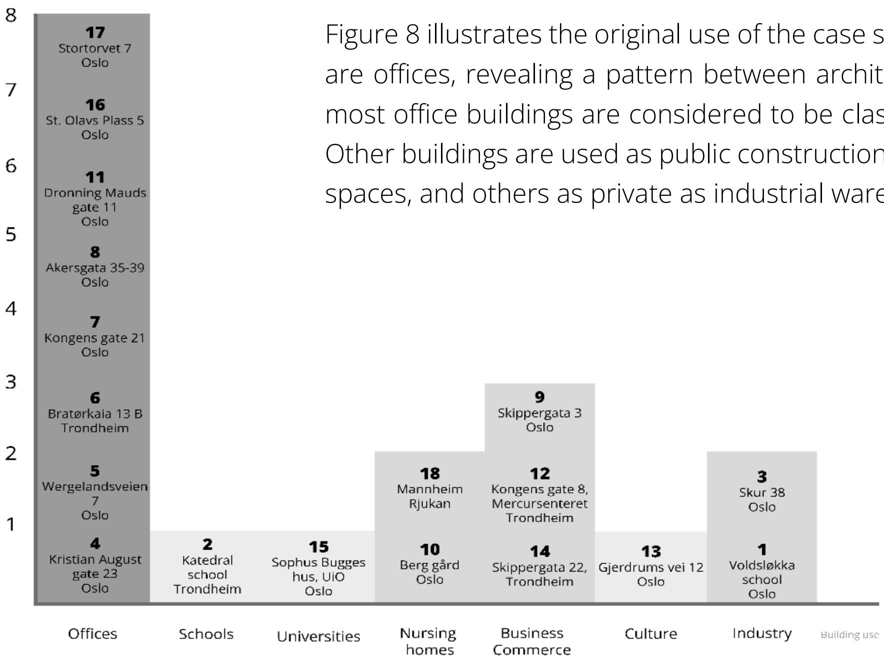


Figure 8 illustrates the original use of the case studies. Half of the buildings are offices, revealing a pattern between architectural style and use since most office buildings are considered to be classified as functionalist style. Other buildings are used as public constructions as educational or cultural spaces, and others as private as industrial warehouses and commerce.

Figure 8 Classification of case studies by their original use

3. Building fabric composition

External wall	
Assessment: *Technical drawings and online data*	
Brick	1. Voldsløkka school, Oslo 2. Katedral skole, Trondheim 5. Wergelandsveien 7, Oslo 8. Akersgata 35-39, Oslo 9. Skippergata 3, Oslo 12. Kongens gate 8, Trondheim 13. Gjerdrums vei 12, Oslo 14. Skippergata 22, Bygårdsanleg, Oslo 16. St. Olavs Plass 5, Oslo 17. Stortorvet 7, Oslo 18. Mannheim, Rjukan
Wood	10. Berg gård, Oslo
Concrete	3. Skur 38, Oslo 4. Kristian Augusts gate 23, Oslo 11. Dronning Mauds gate 11, Oslo 15. Sophus Bugges hus, UiO, Oslo
Stone	6. Bratørkaia 13 B, Trondheim 7. Kongens gate 21, Oslo

Roofing	
Assessment: *Technical drawings and online data*	
Concrete (Flat)	4. Kristian Augusts gate 23, Oslo 5. Wergelandsveien 7, Oslo 8. Akersgata 35-39, Oslo 11. Dronning Mauds gate 11, Oslo 15. Sophus Bugges hus, UiO, Oslo 16. St. Olavs Plass 5, Oslo 17. Stortorvet 7, Oslo
Tiles (Slopped)	1. Voldsløkka school, Oslo 2. Katedral skole, Trondheim 3. Skur 38, Oslo 6. Bratørkaia 13 B, Trondheim 7. Kongens gate 21, Oslo 9. Skippergata 3, Oslo 10. Berg gård, Oslo 12. Kongens gate 8, Trondheim 13. Gjerdrums vei 12, Oslo 14. Skippergata 22, Bygårdsanleg, Oslo 18. Mannheim, Rjukan

Ground floor	
Assessment: *Assumptions based on architecture style*	
Concrete slab	1. Voldsløkka school, Oslo 2. Katedral skole, Trondheim 3. Skur 38, Oslo 4. Kristian Augusts gate 23, Oslo 5. Wergelandsveien 7, Oslo 8. Akersgata 35-39, Oslo 9. Skippergata 3, Oslo 11. Dronning Mauds gate 11, Oslo 12. Kongens gate 8, Trondheim 13. Gjerdrums vei 12, Oslo 14. Skippergata 22, Bygårdsanleg, Oslo 15. Sophus Bugges hus, UiO, Oslo 16. St. Olavs Plass 5, Oslo 17. Stortorvet 7, Oslo
Stone-gravel	10. Berg gård, Oslo 18. Mannheim, Rjukan 6. Bratørkaia 13 B, Trondheim 7. Kongens gate 21, Oslo

Window frame	
Assessment: *Assumptions based on architecture style*	
Wood	1. Voldsløkka school, Oslo 2. Katedral skole, Trondheim 3. Skur 38, Oslo 4. Kristian Augusts gate 23, Oslo 5. Wergelandsveien 7, Oslo 8. Akersgata 35-39, Oslo 9. Skippergata 3, Oslo 11. Dronning Mauds gate 11, Oslo 12. Kongens gate 8, Trondheim 13. Gjerdrums vei 12, Oslo 14. Skippergata 22, Bygårdsanleg, Oslo UiO, Oslo 16. St. Olavs Plass 5, Oslo 17. Stortorvet 7, Oslo 18. Mannheim, Rjukan
Aluminium, PVC, other synthetic	6. Bratørkaia 13 B, Trondheim 7. Kongens gate 21, Oslo 10. Berg gård, Oslo 15. Sophus Bugges hus,

Table 2 Classification of cases by building fabric composition.

Table 2 shows the main components of the building fabric of the case studies. The predominant materials were brick for external walls, tiles for slopped roofing, concrete slab on the ground floor and wood frames for windows. The results illustrate that addressing the most common characteristics on a recommendation report will cover more of the current trend of the heritage building stock.

4. Heritage protection level

Finally, case studies are classified by their protection level. Table 3 shows that selected buildings mostly belong to B and C levels, meaning that cases have regional protection or are enclosed in a protected environment. Few buildings belong to the A level of high protection, a predicted trend since energy retrofitting could affect building fabric to the point that is not allowed by the building authorities.

A	B	C
Assessment was based on the Cultural Heritage map levels described by Byantikvaren		
Very High conservation status National or regional heritage value Unique or monumental [45]	**High** conservation status Regional heritage value High architectural value Decoration in the exterior [45]	Individual objects or embedded in a protected environment. Part of a regional character or a cultural landscape [45]
Very limited intervention to exterior elements	Limited intervention to exterior elements	Changes are assessed individually depending on the context

2. Katedral skole, Trondheim 6. Bratørkaia 13 B, Trondheim 7. Kongens gate 21, Oslo	1. Voldsløkka school, Oslo 3. Skur 38, Oslo 9. Skippergata 3, Oslo 10. Berg gård, Oslo 12. Kongens gate 8, Trondheim 13. Gjerdrums vei 12, Oslo 14. Skippergata 22, Bygårdsanleg, Oslo 18. Mannheim, Rjukan	4. Kristian Augusts gate 23, Oslo 5. Wergelandsveien 7, Oslo 8. Akersgata 35-39, Oslo 11. Dronning Mauds gate 11, Oslo 15. Sophus Bugges hus, UiO, Oslo 16. St. Olavs Plass 5, Oslo 17. Stortorvet 7, Oslo

Table 3 Classification of cases by heritage protection level

4.4.1.3 Selection

After the analysis results, there was a common pattern to follow for giving the advice that covers most of the building stock and relates the most to Voldsløkka school, which is the main reference for the guideline. Hence, an archetype strategy was followed to classify buildings and select the most suitable. An archetype classification aids in creating general and standard features for complex and large types and building characteristics. Three archetypes were built to choose the most notable cases with more specific advice scenarios.

Archetype		1. By local context	2. By architectural style	3. By façade-detail
Buildings		1. Voldsløkka school, Oslo 3. Skur 38, Oslo 13. Gjerdrums vei 12, Oslo	4. Kristian Augusts gate 23, Oslo 5. Wergelandsveien 7, Oslo 8. Akersgata 35-39, Oslo 11. Dronning Mauds gate 11, Oslo 16. St. Olavs Plass 5, Oslo 17. Stortorvet 7, Oslo	9. Skippergata 3, Oslo 12. Kongens gate 8, Trondheim 14. Skippergata 22, Bygårdsanleg, Oslo 18. Mannheim, Rjukan
Architectural style		Norwegian industrial warehouses	Functionalism	Neoclassicism and Art Noveau
Building original use		Industry	Offices	Public use
Building fabric	*External wall*	Brick w/wo plaster	Concrete	Brick with plaster
	Roof	Slopped roof - Tiles	Flat roof - Concrete	Slopped roofs - Tiles
	Ground floor	Concrete slab	Concrete slab	Concrete slab
	Windows	Wood frame	Wood frame	Wood frame
Heritage protection level		B level	C level	B level

Table 4 Identified archetypes of the case studies.

According to Table 4, archetypes were distinguished first by **local contex**t, meaning that it has features that are related to the Norwegian context and that they are situated in different parts of the country despite the location; in these case, warehouses, buildings that need transformation or reuse due to the current needs of society for habitable spaces.

Second, by **architectural style**, buildings with very similar architectural features are based on a style that was a trend during a period of time, such as functionalist buildings, where offices operate and are concrete base constructions.

And third, buildings with **façade external features** as main preservation characteristics, in this scenario, constructions in city centres that belong to a joint heritage context at an urban level.

After the analysis, archetype by **local context** was selected to carry on the advice guideline for the Norwegian case studies part of the research, as it is predominant in different parts of the country and is the one where the Voldsløkka project is embedded, knowing the advantages described previously.

After surveying and gathering data process with designers and actors involved in the two other projects *(Skur 38 and Gjerdrums vei 12)*, it was decided to carry with Skur 38 as a second case study since available information was more compatible with what the Voldsløkka project provides.

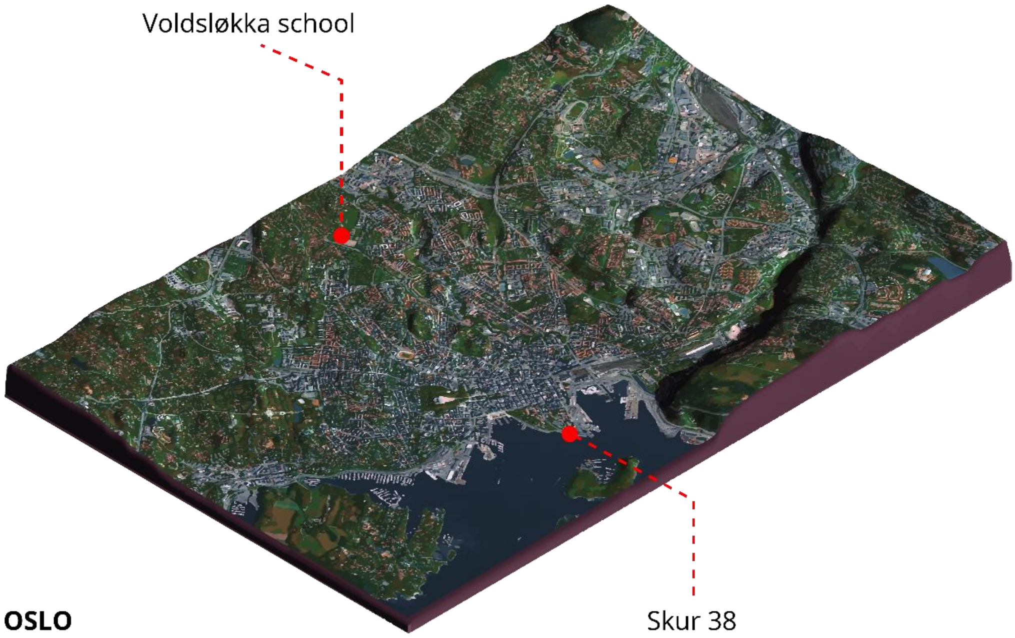


Figure 9 3D of Oslo area that contains both study cases selected (from 3D Mapping Photoshop)

4.4.2 Literature cases

4.4.2.1 Collection

Databases used during the data collection process were SCOPUS and WEB of SCIENCE, cross-referencing different keywords and filtering the results by peer-reviewed articles or conference papers and with published data after 2010. The search for articles resulted in a database of 133 documents that matched the used keyword combinations. There were two filtering stages, firstly a repetition check since there were two sources, and repetitions might have happened.

The second filtering step related to revising the abstract and introduction parts of each of them and rejecting papers that were not closely related to either energy retrofitting or cultural heritage buildings (Appendix 1). An extensive review is necessary if developing a general advice report to encompass larger building singularities. Articles were numbered and sorted by search identification (Appendix 1).

4.4.2.2 Mapping

1. Building Fabric	2. General Assessment		3. Heritage concerns
Exterior wall Roof Ground floor Windows and doors	Approach to a guideline (Framework characteristics)		Explicit heritage concerns
4. Energy efficiency	**5. Building systems**		**6. Health concerns**
No explicit energy target. NZEB, ZEB, Passive house, and others	Heating Cooling Ventilation	Lighting Energy generation	Explicit health concerns

Figure 10 Six spheres to classify literature for the ease of the referencing and advice process. - Adapted from Energy-efficiency measures for heritage buildings: A literature review)

To have a straight-forward process when using literature, a classification map was made to separate articles depending on their content and their relation to the current research [37].

The map was divided into six spheres (Figure 10), with aspects that are essential for the study, such as building fabric, general assessment (literature that focuses on the structure for heritage retrofit advice), heritage protection, energy efficiency and benchmarks, building systems and health/risks concerns.

4.4.3 Literature cases review

Retrofitting heritage buildings under an energy efficiency improvement is a complex task that balances the historical significance and the energy and environmental benchmarks [46]. This literature review explores different interventions in heritage buildings following the six spheres classification previously mentioned. By studying the literature, the current review aims to identify the necessary data that can be referenced for retrofitting advice from a broad and innovative perspective (Figure 11).

The first sphere analysed was literature on building fabric and renovation processes involving interventions on the fabric elements. A common trend suggested in the literature is based on external wall renovations [47]. Most literature on retrofitting measures concerns walls and their particular heritage [32]. Most heat losses are produced through these elements [48], considering their proportion in comparison with other building elements in terms of area. Several interventions are explained, with a high incidence of action of internal insulation, specifically in cold climates [49].

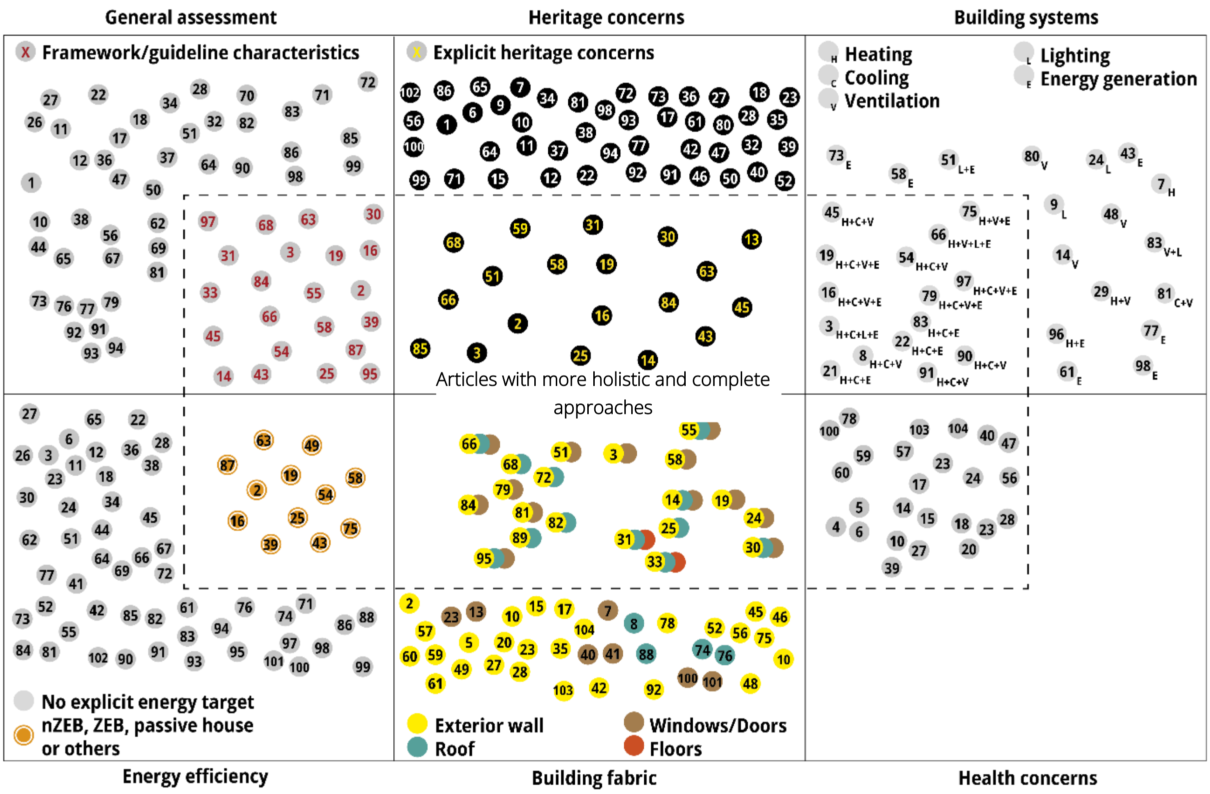


Figure 11 Mapping of literature and classification in 6 spheres as backing for the advice in the guidelines. (Own illustration, adapted from Energy-efficiency measures for heritage buildings: A literature review)

This measure is popular among heritage buildings due to the usual protection restrictions on the external side of the façade. Therefore, these articles focus on innovative materials [50], new technologies [51] and techniques [52] for making internal insulation more effective and less damaging to heritage [53]. Little, authors adventure to describe alternate measures for insulation of external walls, knowing the risk of modifying the appearance or not gaining sufficient benefits for energy demand reduction [54], with few articles mentioning external, cavity or reversible measures.

Regarding roof and floor renovations, there is little connection between heritage building retrofitting and energy efficiency as a general trend on research [55]. Many papers address these elements as a significant part of the retrofitting concern. Most of them focus on new techniques to intervene without damaging elements on the interior of roofs, such as wood battens and structures or finishing floor layers as ceramic tiles that are worthy of protection or have an essential aesthetic feature [55]. Conversely, windows have a more in-depth assessment of literature since the technology of glass and frames advance rapidly to have high energy efficient materials [56] that help to decrease affecting factors such as thermal bridges and air tightness, common on window systems [56].

The second sphere concerns a general assessment structure. These articles are a convenient base for the current research template. Most examples include authors that study governmental and building industry entities reports [28, 33, 34] developed at a regional and national level to give designers and inhabitants a technical but understandable guide on how to retrofit their buildings. Most descriptions refer to existing European assessment tools or EU databases [13]. Some articles specify explicitly throughout the research methods on structuring a recommendation tool [30], and others are mentioned implicitly in case study analysis [57].

The third sphere categorises articles that relate to direct heritage concerns. Across the literature review, several articles highlight their particular heritage protection level or concern; from there, they base their research on implementing a technique or new material by analysing the intervention's impact on specific protected elements [55]. Others have heritage protection as the case study context, but specific characteristics are not illustrated or entirely related to the research proposal or topic. Most of the concerns are related to external features of the fabric: material prevenance, façade details, window frames or roof tiles [32].

The fourth sphere involves energy efficiency goals and benchmarks within the literature. Articles categorised in this sphere thoroughly explain case studies that their intervention has a benchmark purpose, being prevalent passive house standards [58] or Nearly Zero Energy Buildings [59]. Results and discussions are highly related to how each measure affects the road to reaching mentioned goals. On the other hand, some research uses energy benchmarks as a remark on the extent of retrofitting heritage buildings, evaluating the suitability of the benchmarks on different protection levels [60].

The fifth sphere connects articles mentioning building systems as target interventions. Most of the literature focuses on improving current heating, cooling or ventilation systems that are outdated for new technologies, considering their replacing impact on protected elements [61]. A higher prevalence of information relates to heating systems, specifically their distribution or emitter elements, to be upgraded [62]. Little information was found about the correlation between lighting systems and listed buildings.

Finally, the sixth sphere contains health concerns of building elements, and this is a common trend among papers since the impact of hygroscopic issues on ageing buildings is significant [63]. Therefore, the issue is usually present when formulating or analysing a new measure and how it could affect or prevent damaging treads such as moulding, moisture, and other risks [24].

In conclusion, academic research has focused on building fabric and different strategies to improve energy efficiency whilst preserving the element according to the protection status. Other aspects, such as health and heritage concerns and energy efficiency benchmarks, usually gravitate around building fabric interventions supporting realistic and feasible findings. Hence, it is foreseeable that this research will follow a similar trend to complement what is available.

The main reason is that the advice given needs to be supported by quality references with enough reliability to base suggestions. Other spheres, such as the building systems, are less documented and referenced; therefore, recommendations on the matter must be handled carefully and at a more general level to avoid grave mistakes or misinterpretations of different measures that affect decision-making processes.

On the contrary, this research will aim extensively to fill the gaps left by scattered articles that centre on the structure of an advisory report, specifically on how to create a reliable, structured, and understandable output that is both technical enough for designers to follow and also informative and impactful for clients to decide to retrofit their properties.

4.5 ARV framework

4.5.1 ARV KPI's (Key performance indicators) considered for advice

Since it is necessary to have a clear advice output, that facilitates the decision-making for the actors involved, the ARV project KPIs appear as an opportunity to visualise the final conclusions of the analysis of different measures. All five aspects are addressed in a way to have a wholesome perspective of the advice, and for clients to make comparisons on where the intervention will have more affectation or benefits. For the research were selected the indicators that adjust the most to the conditions of the study. However, some aspects are not included that are related to heritage concerns, which affect different areas of the study. Therefore, the suggestion is to create a singular category special for the use of buildings under a protection condition (Figure 12). The category includes elements found common in the literature research, such as the adaptability to different building regulations and restrictions, the level of affectation of the fabric aesthetics and the hygroscopic affectation or improvement on the elements.

Architecture	Environmental	Circularity
▪ Aesthetics and Visual qualities ▪ Flexibility and adaptability ▪ Indoor Air Quality ▪ Thermal Comfort ▪ Overheating risk	▪ Life-cycle GHG Emissions in CPCC	▪ Reusability

Economics	Energy	Heritage
▪ Construccion Time Reduction	▪ Non-renewable Primart LifeCycle Energy in the Built environment	▪ Variance with the building and planning regulations ▪ Affectation of the historic fabric appearance ▪ Hygroscopic affectation on buidling elements

Figure 12 ARV project KPI's that adjusted to the research output with the inclusion of a new category for the use of protected buildings (Own illustration, adapted from ARV project)

5 Results

Findings in this report have three sections. The first section (5.1) relates to the creation of the template for data collection and advice, following the methods applied. The second section (5.2) exemplifies the data collection template through the two Norwegian case studies selected. Finally, the third section (5.3) of the results illustrates a retrofitting advice applied to the archetype selected.

5.1 Guideline structure

The guideline structure exploration divides in two sections. The first focus (5.1.1) is on how to structure a question-based model to collect all the indispensable information from the building for later advice. And the second (5.1.2) is that using the template for data collection creates a structure for retrofitting advice for building fabric solely.

5.1.1 Data collection procedure and template

Evaluating the building and its characteristics is essential to suggest a suitable measure for a specific building. To be closely relatable to the archetypes identified in the Norwegian cases, it is necessary to have knowledge of the building features to be related closely to one archetype and have more specific advice instead of general advice that lacks background information to suggest. The data collected will be cross-referenced with the case studies and the literature.

For classifying the building data, a three-step data collection is created to have an overall picture of the case sufficient for exact recommendations. A test of this structure will be later exemplified by the two Norwegian case studies selected (Voldsløkka School and Skur 38).

1. STEP 1 - IDENTIFIERS: Construct the identity of the selected building.

The first step is called Identifiers because it is a characterization of the general data of the building. This data is entered by the constructors, designers, clients, or actors involved in the renovation process. The information will categorize the building and work as the first filter of renovation measures [22]. The structure of the first step is based on the database created by Interreg and ICA-SHC Task 59, called HiBERAtlas [22].

Identifiers	Description
Region	Here the information stored will give an insight into the geographical and climate conditions of the building.
City or town	
Current building use	The information will define and help to categorize buildings by use, which goes along with the energy benchmarks of each building typology.
Area of the building	The area, occupants, number of floors and height will establish a range of scale of the project, which will determine factors such as energy demand, number of materials and the scale of the systems.
Number of occupants (expected)	
Number of floors / Height of the building	
Date, year, period of construction	The construction date will give an insight into the possible building conditions, materials, and suitability for certain retrofitting measures.

Table 5 Identifiers for classifying buildings

2. STEP 2 - DEFINERS: Define the building characteristics concerning heritage and the building elements.

The second step is the Definers, aiming to characterise the construction according to the heritage status and the main building element composition. Filtering the information in this stage will provide only measures according to the protection level and the materials and systems used in the building [13]; hence, actors interested will have more focused efforts and reduce the possibility of giving nonsensical or misguided measures.

Finally, the energy goals are established according to the needs of the designers. This is because the measures should be classified by the possible impact on energy reduction and the intervention [13]. Therefore, there is a cross-reference analysis of heritage protection and energy goals. For instance, a retrofitting measure could significantly impact energy reduction. Still, it might be invasive to a building fabric to the extent that it collides with the heritage characteristics of the element and therefore is excluded.

Definers	Questions	
Conservation	Which is the heritage protection level of the building?	*(The assessment tool should provide a pre-saved range for this data to have easier management)*
	What is the condition/health of the building	
Energy goals	What is the energy reduction goal wanted with the renovation?	

Table 6 Questions to define the conservation and building elements status.

3. STEP 3: BUILDING CRITERIA CHARACTERISATION

After having all information on the building collected and filtered for the use of the database, it is essential to characterise each building's criteria for giving the most helpful advice. The building criteria will be divided into three categories: fabric, services, and behaviour.

Implementation measures		
Fabric	Services	Behaviour
Wall Roof Ground floor Windows and doors	Heating Cooling Ventilation Lighting	User's interaction with retrofitting processes

Figure 13 Main categories for advice and alternative measures.

Each criteria have specific options to filter the information according to their qualities. Although the advice template example will only show the building fabric results, in this step of creating the template, Considering the other components of buildings: systems and behaviour is vital for further research development and to keep a record of the existing gaps and necessary information that is needed to provide suggestions.

- Building fabric

For the current research, the **building fabric** is the criterium that defines the archetypes; hence, most of the elements analysed in both buildings (Voldsløkka school and Skur 38) are the same. Three areas are submitted to gather information about the building fabric: First, the material composition that aims to have a general idea of the materials and how they are layered in the element. Second, the question around heritage protection points to what extent the component is protected and, finally, the element's affectation by external agents, seeking to illustrate the level of risk the element has for hygroscopic issues.

FABRIC	SELECTION
EXTERNAL WALL	
What is the **materiality composition** of the building element? *Have an idea of the materials and techniques that compose the element*	Exposed brick
	Exposed concrete
	Brick covered with plaster
To what extend the building element has a **heritage protection**? *Characteristics of the element that are protected or not*	External and internal finishing protection
	Only external finishing protection
	Only internal finishing protection
	No heritage protection to the façade
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.? *Usually categorised as hygroscopic issues caused by rain, wind, or humidity*	Higher risk of affectation of building element
	Lower risk of affectation of building element
ROOF	
What is the **materiality composition** of the building element? *Have an idea of the materials and techniques that compose the element*	Slopped roof (tiles, wood)
	Flat roof (concrete)
What is the level of **heritage protection**? To what extend the building element has a **heritage protection**? *Characteristics of the element that are protected or not*	External and internal finishing protection
	Only external finishing protection
	Only internal finishing protection
	No heritage protection to the roof
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.? *Usually categorised as hygroscopic issues caused by rain, wind, or humidity*	Higher risk of affectation of building element
	Lower risk of affectation of building element
GROUND FLOOR	
What is the **materiality composition** of the building element? *Have an idea of the materials and techniques that compose the element*	Concrete slab direct contact to soil
	Additional foundation layer between slab and soil (e.g., stone)
What is the level of **heritage protection**? To what extend the building element has a **heritage protection**? *Characteristics of the element that are protected or not*	Finishing layer of ground floor protected
	No heritage protection to finishing layer
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.? *Usually categorised as hygroscopic issues caused by rain, wind, or humidity*	Higher risk of affectation of building element
	Lower risk of affectation of building element
WINDOWS AND DOORS	
What is the level of **heritage protection**?	Windows and doors located in a façade that is protected

To what extend the building element has a **heritage protection**? *Characteristics of the element that are protected or not*	Windows and doors located in a section of the building that is not protected
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.? *Usually categorised as hygroscopic issues caused by rain, wind, or humidity*	Good condition of the glass and/or frame
	Poor condition of the glass and/or frame

Table 7 Template criteria selection for building fabric

It is found that. For elements of the fabric, such as walls, roofs, and ground floors, it is vital to know the material composition of the element. However, the window designs are always transparent glass layers embedded in a frame, and the frame material and the type of glass could vary. Still, the characterisation of the building is not primary since advice for windows and doors is related more to heritage concerns and energy goals.

- Building systems

In the case of building systems, it is a much more complex criterium, and in practice, there is scarce data to conclude similarities between buildings. Then, it is sensitive to use systems as an evaluation aspect to be englobed in a general archetype definition. However, it will be helpful to have an idea of what could be the provided data for the creation of future advice templates.

First of all, heating is usually a conditioned system in buildings since their functioning highly depends on external factors, such as energy sources and carriers throughout the surroundings. There are different parts and components, but it could be divided into four main aspects that directly concern the current needs. Heating methods, heat generators, distribution grids, and emitters [64]. These aspects represent the distribution process, from how the energy is produced to the element that transmits the heat into rooms.

The ventilation system is the type of ventilation that affects the rest of the elements [65]. Depending on the type of system, different methods of how the air is distributed or extracted are selected [64].

Finally, the data needed for lighting is more generalised, seeking the type of lighting used to know how inefficient it is for later suitable upgrade advice.

SYSTEMS	SELECTION
HEATING	
What is the **heating method** used in the building? *How energy is produced or used for heating purposes*	**Local heating**
	Stove
	Solid, liquid or gas fuel
	Electricity
	Central heating
	Heat carrier – water, steam, air
	Solid, liquid, or gas fuel
	Electricity
What is/are the **heat generator/s** in the building? *Elements that are used to generate energy for heating*	**Boiler Plant**
	Combustion
	Electric
	District heating
	Direct system

	Indirect system (user substation, heat exchanger)
	Heat pump
	Water – sea/lake, ground water, sewage drain
	Air – outdoor air, exhaust air
	Ground
	Solar radiation
	Solar collector or air as heat carrier
What is the **distribution grid** system used? *Pipe system that is used to carry the heat*	One pipe system
	Two pipe system
What are the **heat emitters** used? *Elements that are heat transmitters to building spaces*	Radiators
	Heating panels
	Floor heating
	Ceiling heating
VENTILATION	
What is the ventilation system used in the building? *Main ventilation strategy that the building uses*	Natural ventilation
	Mechanical exhaust ventilation
	Balanced mechanical ventilation
	Hybrid systems
What is the solution for air conditioning system?	Constant air flow (CAV)
	Variable air flow (VAV)
What is the type of ventilation system in the rooms? *How ventilation is delivered to building rooms*	Mixing ventilation
	Displacement ventilation
	Piston flow
	Demand control ventilation (DCV)
What is the type of heat recovery unit for ventilation air?	Cyclic (regenerative)
	Static (recuperative)
LIGHTING	
What is the main artificial light resource?	Incandescent
	Fluorescent
	LED (Light-emitting diode)

Table 8 Template criteria selection for building systems

- Behaviour

The last component assessed is the behavioural aspect; the range could be significantly extended compared to other elements. A behavioural assessment is related to the practices of users that have some effect on the buildings' energy performance or heritage values. The data collected here is generalised since aspects here are usually non-quantifiable and very subjective, making every building a particular case [35].

Some research references the user's awareness of energy reduction with optimal consumption behaviours or knowledge of the systems to be used properly. The other aspect relates to maintaining both the fabric and the system [65].

BEHAVIOUR	SELECTION
What is the extend of users' awareness for energy reduction? *How people relate to energy reduction strategies*	High awareness of users of the building fabric composition and control and operation of the system
	Medium awareness of users of the building fabric composition and control and operation of the system

	Low awareness of users of the building fabric composition and control and operation of the system
How often the building fabric and system are maintained or repaired?	Optimal maintenance at regular periods of the fabric and the systems
	Correct maintenance at regular periods of the fabric and the systems
	Lack of maintenance at regular periods of the fabric and the systems

Table 9 Template criteria selection for behaviour aspect

5.1.2 Advice (retrofitting measures) structure –

The second step is to discover how the advice needs to be presented to the designers about which measure can be considered, according to the information given of the building on the previous step.

It is important to illustrate both advantages and disadvantages of the interventions [65], apart from some alternatives that can give a wholesome approach when retrofitting the building. Hence, the retrofitting measures of the archetypes (case studies) in which the building-in-case fits will be subject to assessment and comparison.

The goal is to analyse the advantages and disadvantages of each measure, supported by journal articles. The pros and cons will be divided into two main categories. Energy and technical considerations, heritage, and architectural considerations, ultimately suggesting alternatives specially selected for that building-in-case also referenced from research papers.

5.1.2.1 Advice structure for building fabric

The advice contains different measures that better fit with the characteristics of the building fabric after research filters, and it is divided into measures and materials. The measures are the types of renovations that can be done to a building element; illustrating to designers a general idea of each measure provides a set of options to be comparable for an optimal decision-making process. Secondly, equally important, the materials used by different interventions have a significant impact; hence, the advice report provides a material selection that matches the intervention to select and the building heritage characteristics and environmental goals.

1. Measures or techniques

   The current research uses different techniques or measures from the study cases and literature review. Since the scope of the research is reduced, the number of measures taken from study cases is limited (4.4.1). In this case, two measures (knowing there are just two buildings by an archetype) are analysed from the case studies perspective with the support of a literature review.

   Having two possible measures among a handful of options available on the market nowadays does not provide a wholesome and realistic picture of the different options for intervention [33]. For the sake of the current research, this needs to be complemented with other measures found only in articles but from a more general perspective.
   Ideally, for future implementation of a complete guideline, it is necessary to include Norwegian case studies and literature for all the measures.

   - Based in Norwegian case studies and literature.

This advice structure is the ideal scenario for a future assessment tool. To have a holistic approach to advice measures, it is necessary to have both Norwegian cases where the measure is applied successfully to improve energy performance and literature that support the case studies. Ideally, the referred literature comes from interventions or research on Norwegian retrofitting; however, it is visible that the number of papers based in the country building stock will not be enough to establish the measures.

- *Technical solution in the case study*
  Showcasing the intervention's technical detail, including a drawing of the element and the description of the layers, thicknesses, and location.
- *Visual documentation*
  If available, visual documentation from working documents from the projects illustrates the measure.
- *Advantages and disadvantages*
  After displaying the features of the measure of the case study, it is necessary to show the advantages and disadvantages of the technique. This is supported by the literature selected from the review process.

- Based solely in literature.
  The second part of the advice structure of the measures is supported solely by a literature review due to the complexity of composing several measures with the previous structure. This is complementary advice to demonstrate diverse interventions apart from the case studies with a general and concise approach.

  - *Visual documentation*
    Visual interventions are taken from the article or paper referenced and online databases.
  - *General description*
    It is provided a short description of the technique and how is adapted to the building element characteristics.

2. Alternative materials
   Apart from the techniques, it is important to illustrate different insulation materials that are more suitable to the composition of the building element. The advice is divided into technical data and impact, a general description and visual documentation.

- Technical data and impact range
  It is essential to show average data of its insulation, environmental and heritage performance to provide designers with a coherent and realistic approach to materials, along with which technique or measure the material is more compatible. All the aspects must be assessed together to have an overall result of which material could adapt better to all situations. A colour range will simplify the suitability of the material for the current case.

  - *Thermal conductivity*

The thermal conductivity parameter gives an idea of the insulation performance of the material and its impact on a building element. There is not a generalized range for all materials since their properties and uses differ from one to another. [66].

Lower conductivity	Medium conductivity	High conductivity
Lower conductivity than the average of available products on the market (Standardised values) (W/mK)-	Lower conductivity than the average of available products on the market (Standardised values) (W/mK)-	Lower conductivity than the average of available products on the market (Standardised values) (W/mK)-

Table 10 Thermal conductivity of materials and its insulation performance (Taken from Green Material Guide: Guide in environmentally sound material selection)

- *Embodied emissions*

The embodied emissions of the materials illustrate the environmental impact. This can be contrasted with thermal conductivity since a material can have good insulation properties. Still, its embodied emissions could be higher; therefore, it is a matter of balance and what to trade off and prioritize in the selection. Depending on the material, embodied emissions are assessed by either kg or m^2 [66].

Lower emissions	Medium emissions	High emissions
Lower emissions than the average of materials on the market (Standardised values) (kg CO_2e)	Similar emissions than the average of materials on the market (Standardised values) (kg CO_2e)	Lower emissions than the average of materials on the market (Standardised values) (kg CO_2e)

Table 11 Embodied emissions of materials and its environmental impact (Taken from Green Material Guide: Guide in environmentally sound material selection)

- *Adaptability to heritage concerns*

Good adaptability	Medium adaptability	Minimal adaptability
Installation of material adapts smoothly to the heritage conditions of the building element	Installation of material might risk the aesthetics of the protected building element.	Installation of material changes the aesthetics of the element and needs reparation to keep its previous condition

Table 12 Level of adaptability of the materials t the heritage characteristics (Taken from Green Material Guide: Guide in environmentally sound material selection)

- *Applicability*

The applicability description relates to how a material can be used in each building element depending on the measures explained before. Some materials do not fit specific techniques.

5.1.2.2 Advice structure for building systems

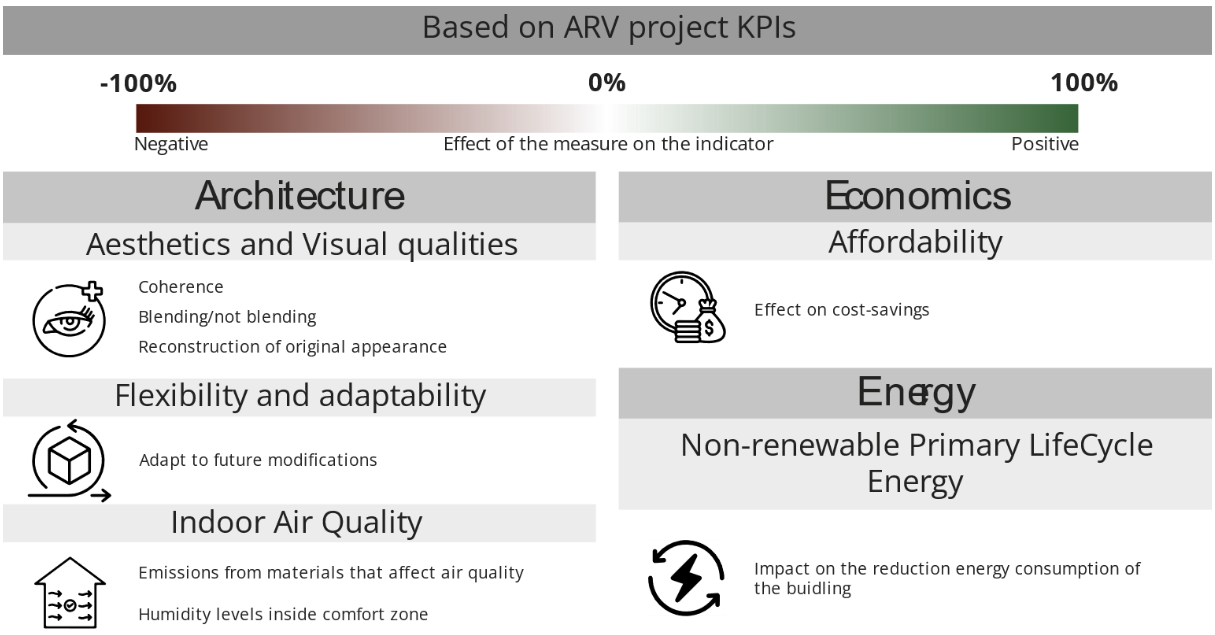
Building systems are very complex and varied within themselves, and their functioning varies significantly from building to building [64]. Since the case studies did not provide most of the data required for the system might have inaccuracies, it was decided not to include them in the advice results, which means that the current research will only briefly explain the possible conditions that are necessary to have a complete map of the functioning of the systems. For decision-making, it seems impossible to provide any specific advice or suggestion with the current available information for the research. When an energy benchmark is set, upgrading, or completely changing systems might contribute positively to reaching the goals [37]. However, it is important that the decision must rely primarily on software simulations [62, 67] that give a more accurate insight into the current energy performance and, from there, select a solution that substantially improves energy efficiency with minimal affectation on what is existing.

5.1.2.3 Advice structure for behaviour concerns

A similar situation to the building systems occurs with behaviour scenarios. Information about how users relate to changes in their habitable spaces is complex and often non-quantifiable data in the case of Voldsløkka school [35]. The project has not started operations; therefore, there is no input from users about the retrofitting measures designers took. This report will not give behaviour advice as well as the systems.

5.1.3 Summary of the measures assessed by Key Performance Indicators

To summarise, the retrofitting advice supported by ARV project KPIs is implemented as a scale representing each measure's effect on a positive or negative percentage. Illustrating the impact of the measures on different areas with a quantifiable portrayal gives the possibility for interested actors to compare and select actions that adjust better to their needs or individual requirements. Each indicator has a series of criteria assessed based on the advice given and general assumptions. (Figure 14).



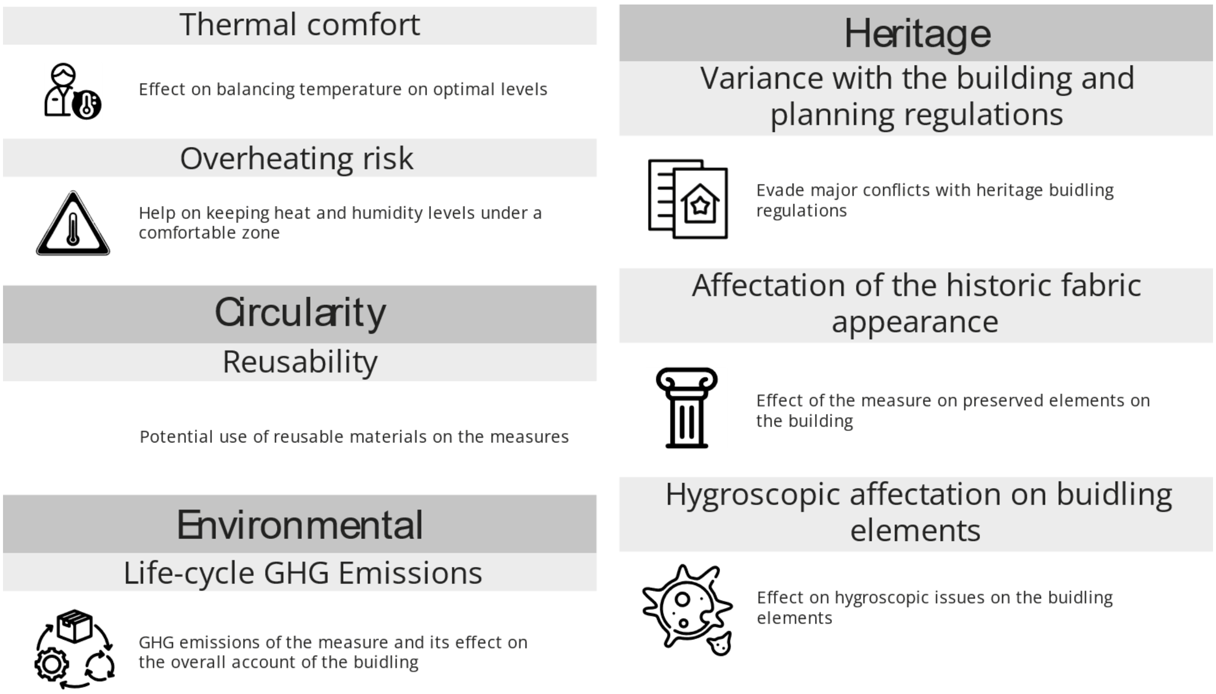


Figure 14 Adaptation of ARV project KPIs for the use as a summary for the advice report and their assessed criteria (own illustration)

5.2 Example of the use of the identification of buildings template

CASE 1: VOLDSLØKKA SCHOOL IDENTIFICATION

STEP 1 – IDENTIFIERS

For the information collected, actors involved in Voldsløkka from the ARV project provided access to a shared folder that contained drawings and reports about the refurbishment of the building [68]. In this case, next to the data, there is an insight section (Table 13) to illustrate several characteristics that can be extracted from the data collected to aid the classification to scale down the scope of any retrofitting suggestion.

Identifiers	Data provided [68]	Convenient insights for the assessment	
Region	Oslo	Dfb (Warm-summer humid continental climate) (Temperatures) Wind direction Radiation	*(The assessment tool will provide a pre-saved range for this data to have easier management)*
City or town	Oslo		
Current building use	Concrete fabric (Industry)	Yearly and hourly energy demand for each use Energy and emission benchmarks Energy profile consumption (behaviour) *(All of these numbers can be more precise if using simulation tools or estimations if following standards)*	
Area of the building (BRA) Usable area	2331 m2		
Number of occupants (expected)	1750 weekly users		
Number of floors / Height of the building	2 floors / 6,12m (to the ceiling)		
Date, year, period of construction	1919	Building fabric composition Frailty (possible condition) of the building elements and systems according to the time period.	

Table 13 Voldsløkka school identification

STEP 2: DEFINERS

The data collected for the definers step, was provided, or searched from different sources. For the conservation related questions, data was found in Kulturmminesøk map [42] establishing the level of heritage protection. For the health condition of the building, there was no information provided from the project actors, but there is visual documentation from before the retrofitting that made possible to assess the condition of the building fabric.

The energy benchmark for the refurbishment was provided in the building program report of the project [68]. However, there is no description of the energy demand previous the retrofitting. Different options are shown in (Table 14) but selected data are highlighted in red.

Definers	Questions	Possible range of results and selection
Conservation	Which is the heritage protection level of the building?	Level A: Buildings assessed as having a significantly high conservation value. Level B: Municipality wants to regulate the building for conservation. Level C and D: Buildings with less conservation value and major adaptability to retrofitting measures.

	What is the condition/health of the building	**Poor condition:** Building fabric presents heavy deterioration and it might need an imminent intervention to be habitable. **Medium condition:** The building is in use, but the fabric presents some deterioration which affects the energy performance of the building. **Good condition:** Building fabric is well preserved, with recent renovations and minor interventions are needed.
Energy goals	What is the energy reduction goal wanted with the renovation?	**FutureBuilt:** Reduction of energy demand in 50% compared to the actual demand. **TEK17:** Depending on the building use, there is a maximum of energy demand. **NZEB** **Passive House**

Table 14 Voldsløkka school status related to heritage, building elements and energy goals.

STEP 3: BUILDING CRITERIA CHARACTERISATION

- Building fabric

Building fabric information was obtained by the building program report [68] and architectural and technical drawings. The data provides an insight on the specific set of measures needed for the building.

FABRIC	SELECTION
EXTERNAL WALL	
What is the **materiality composition** of the building element?	Brick covered with plaster
To what extend the building element has a **heritage protection**?	**Only** external finishing protection
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.?	**Higher** risk of affectation of building element
ROOF	
What is the **materiality composition** of the building element?	Slopped roof (tiles, wood)
To what extend the building element has a **heritage protection**?	**Only** external finishing protection
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.?	**Higher** risk of affectation of building element
GROUND FLOOR	
What is the **materiality composition** of the building element?	Concrete slab direct contact to soil
To what extend the building element has a **heritage protection**?	**No** heritage protection to finishing layer
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.?	**Lower** risk of affectation of building element
WINDOWS AND DOORS	
What is the **materiality composition** of the building element?	Windows and doors located in a façade that is protected

To what extend the building element has a heritage protection?	Good condition of the glass and/or frame

Table 15 Voldsløkka school characterisation of building fabric elements.

- Building system and behaviour

Following previous explanations, building system and behaviour gathered information was not enough to provide clear advice; therefore, it is not classified in the suggested template shown in the previous chapter (5.1.1).

CASE 2: SKUR 38 IDENTIFICATION

STEP 1 – IDENTIFIERS

Information is collected from Michael Lommertz [69] (Leader architect of the renovation project) and the FutureBuilt database [70]. In this case, next to the data, there is an insight section (Table 16) to illustrate several characteristics that can be extracted from the data collected to aid the classification to scale down the scope of any retrofitting suggestion.

Identifiers	Data	Convenient insights for the assessment	
Region	Oslo	Dfb (Warm-summer humid continental climate) (Temperatures) Wind direction Radiation	*(The assessment tool will provide a pre-saved range for this data to have easier management)*
City or town	Oslo		
Current building use	Offices	Yearly and hourly energy demand for each use Energy and emission benchmarks Energy profile consumption (behaviour) *(All of these numbers can be more precise if using simulation tools or estimations if following standards)*	
Area of the building (BRA) Usable area	3333 m2		
Number of occupants (expected)	155		
Number of floors / Height of the building	4 floors / 18,2m		
Date, year, period of construction	1915	Building fabric composition Frailty (possible condition) of the building elements and systems according to the time period.	

Table 16 Skur 38 identification

STEP 2: DEFINERS

The data collected about the conservation level was extracted from Kulturmminesøk map [42] and FutureBuilt report Rehabilitating Skur 38 [70]. The energy related question gather data from SIMIEN files extracted in FutureBuilt database. (Selected answers are highlighted in red)

Definers	Questions	Possible range of results and selection
Conservation	Which is the heritage protection level of the building?	Level A: Buildings assessed as having a significantly high conservation value. Level B: Municipality wants to regulate the building for conservation. Level C and D: Buildings with less conservation value and major adaptability to retrofitting measures.

	What is the condition/health of the building	**Poor condition:** Building fabric presents heavy deterioration and it might need an imminent intervention to be habitable. **Medium condition:** The building is in use, but the fabric presents some deterioration which affects the energy performance of the building. **Good condition:** Building fabric is well preserved, with recent renovations and minor interventions are needed.
Energy goals	What is the energy reduction goal wanted with the renovation?	**Current energy demand:** 220 kWh/m2/year **FutureBuilt:** Reduction of energy demand in 50% compared to the actual demand. **TEK17:** Depending on the building use, there is a maximum of energy demand. **NZEB:** **Passive House: 108 kWh/m2/year** passive house standard

Table 17 Skur 38 status related to heritage, building elements and energy goals.

STEP 3: BUILDING CRITERIA CHARACTERISATION

- Building fabric

Information is collected following FutureBuilt database from technical details and visual documentation [70].

FABRIC	SELECTION
EXTERNAL WALL	
What is the **materiality composition** of the building element?	Concrete covered with plaster
To what extend the building element has a **heritage protection**?	**Only** external finishing protection
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.?	**Higher** risk of affectation of building element
ROOF	
What is the **materiality composition** of the building element?	Slopped roof (tiles, wood)
To what extend the building element has a **heritage protection**?	**Only** external finishing protection
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.?	**Higher** risk of affectation of building element
GROUND FLOOR	
What is the **materiality composition** of the building element?	Concrete slab direct contact to soil
To what extend the building element has a **heritage protection**?	**No** heritage protection to finishing layer
What is the risk of the building element to have affectations by **external agents** as moulding, moisture etc.?	**Lower** risk of affectation of building element
WINDOWS AND DOORS	
What is the **materiality composition** of the building element?	Windows and doors located in a façade that is protected

To what extend the building element has a **heritage protection**?	**Good** condition of the glass and/or frame

Table 18 Skur 38 characterisation building fabric elements.

- Building system and behaviour

Following previous explanations, building system and behaviour gathered information was not enough to provide clear advice; therefore, it is not classified in the suggested template shown in the previous chapter (5.1.1).

5.3 Retrofitting advice example

The following section illustrates the implementation of the advice template explained in the first result section (5.1).

5.3.1 Advice for building fabric retrofitting

5.3.1.1 External wall

Conditions:

Element composition	Heritage protection	Element condition
Brick covered with plaster	Only external finishing protection	Higher risk of element affectation

1. MEASURE 1: INTERNAL INSULATION

CASE STUDY: Voldsløkka school

No energy benchmark achieved

Previous U-value	After intervention U-value
0.30 W/(m^2K)	0.21 W/(m^2K)

Inside	Plywood board	12mm
	Plasterboard	13mm
	Timber elements	50mm
	Steel profiles with insulation 0.037 W/(mK).	95mm
	Air gap	10-40mm
	Existing wall (brick covered with plaster)	250mm
Outside	No intervention on the outside	

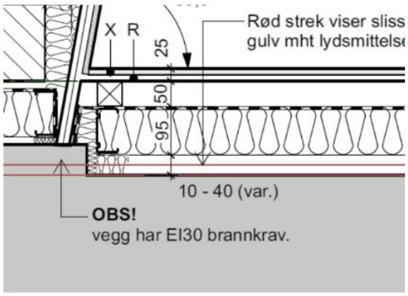


Figure 15 Technical detail external wall of the intervention at Voldsløkka school (Taken from ARK documents from Voldsløkka school project)

The intervention of the external walls at Voldsløkka school consisted in an internal insulation retrofitting. The existing wall did not have any intervention, and it was considered as an outer layer. After an air gap, the insulation was installed with steel profiles and then covered by plasterboard and wood board elements.

ADVANTAGES

Technical / energy related	Literature review
High thermal efficiency: On paper, U-values can be easily improved with internal insulation [52]	*19. Evaluation of natural-based internal insulation systems in historic buildings through a holistic approach (Article) [52]*
Convenience of installation: Installation of internal insulation can be done by rooms, at a	*02. Evaluating the impact of indoor insulation on historic buildings: A multilevel approach involving heat and moisture simulations (Article) [67]*

different pace, depending on the need and current use. [67]	
Easier reversibility: Depending on the insulation, it can be removed without a troublesome process if compared with other solutions. [51]	*25. Climate resilience of internally insulated historic masonry assemblies: Comparison of moisture risk under current and future climate scenarios (Article) [51]*

Architecture / heritage related	Literature review
More relatable with more common conservation status: Availability of materials are broad and can be chosen depending on the requirements (e.g., capillary active insulation materials or vapour retarder) [53] [71]	*68. Reconciling energy and heritage: Retrofit of heritage buildings in contexts of energy vulnerability (Article) [53]* *96. EFFESUS methodology for assessing the impacts of energy-related retrofit measures on heritage significance (Article) [71]*
Preservation of original aspect on the exterior: If done correctly, no energy retrofitting is needed for the exterior layer. [57]	*58. Balancing Trade-offs between Deep Energy Retrofits and Heritage Conservation: A Methodology and Case Study (Article) [57]*

DISADVANTAGES

Technical / energy related	Literature review
Condensation: Liquid water within a building element due to condensing water vapour. [51]	*25. Climate resilience of internally insulated historic masonry assemblies: Comparison of moisture risk under current and future climate scenarios (Article) [51]* *114. Responsible Retrofit Guidance Wheel [65]*
Trapped moisture: Liquid or gas that is confined within the structure of a building due to alterations in either material layers or the ventilation circumstances. [65]	
Thermal bridges: Higher thermal conductivity of the bridging element leads to increased heat loss. [72]	*32. Overheating Risks and Adaptation Strategies of Energy Retrofitted Historic Buildings under the Impact of Climate Change: Case Studies in Alpine Region (Article) [72]*
Overheating: Fabric energy efficiency measures can exacerbate problems with higher temperature. [72]	
Installation quality: Product or material needs to be installed according to a set high standard of quality. [73] [65]	*11. Visual documentation process of historic building refurbishment "Improving energy efficiency by insulating walls on the interior" (Article) [73]* *114. Responsible Retrofit Guidance Wheel [65]*

Architecture / heritage related	Literature review
Use of sympathetic materials: The materials designated do not align with the current structure, whether it be in terms of visual appeal,	*68. Reconciling energy and heritage: Retrofit of heritage buildings in contexts of energy vulnerability (Article) [53]* *114. Responsible Retrofit Guidance Wheel [65]*

origin, or performance of the building materials. [65]	
Original internal detail lost: Loss of the building's inherent character may occur either temporarily or permanently, involving the disappearance of its original internal details. [65]	*44. Influence of envelope properties on interior insulation solutions for masonry walls (Article) [74]* *114. Responsible Retrofit Guidance Wheel [65]*
Loss of internal space: To achieve energy goals, larger thickness of insulation is used, reducing the usable area of a space. [75]	*83. Beyond cultural and historic values, sustainability as a new kind of value for historic buildings (Article) [75]*

2. MEASURE 2: EXTERNAL INSULATION - AEROGEL

CASE STUDY: Skur 38

Element composition	Heritage protection	Element condition
Concrete covered with plaster	Only external finishing protection	Higher risk of element affectation

Passive House benchmark achieved

Previous U-value	After intervention U-value
0.35 W/(m^2K)	0.14 W/(m^2K)

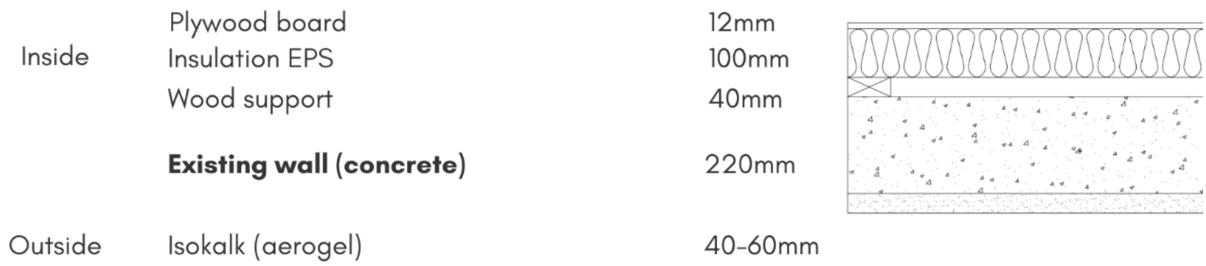


Figure 16 Technical detail external wall of the intervention at Skur 38 (Taken and adapted from shared information in FutureBuilt webpage of Skur 38 intervention)

Measures used for retrofitting external walls at Skur were related to external insulation. Despite regulations about the aesthetic of the outer layer of the building, the use of aerogel insulation that mimic the original layer, was found optimal for energy demand reduction and the achievement of Passive House standards.

ADVANTAGES

Technical / energy related	Literature review
Lower condensation: Lower risk of condensation and damaging agents as fungi on the interior. [52]	*19. Evaluation of natural-based internal insulation systems in historic buildings through a holistic approach (Article) [52]*
Reduction of thermal bridges: Levelled and uninterrupted insulation on the exterior, reduces the chance of major thermal bridges. [76]	*99. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study (Article) [76]*

Thermal comfort: Reduces the chance of having overheating or colder temperatures. [30]	*59. A Review on Technical Challenges and Possibilities on Energy Efficient Retrofit Measures in Heritage Buildings (Article) [30]*

Architecture / heritage related	Literature review
Save Floor Space: Takes up no internal floor space since intervention is done from the exterior. [53] [71]	*68. Reconciling energy and heritage: Retrofit of heritage buildings in contexts of energy vulnerability (Article) [53]* *96. EFFESUS methodology for assessing the impacts of energy-related retrofit measures on heritage significance (Article) [71]*
Increase Lifespan of Building Fabric: This measure covers the entire outer surface of a structure, enveloping it with a shield that safeguards element from the effects of weather.[57]	*58. Balancing Trade-offs between Deep Energy Retrofits and Heritage Conservation: A Methodology and Case Study (Article) [57]*

DISADVANTAGES

Technical / energy related	Literature review
Trapped moisture: Liquid or gas that is confined within the structure of a building due to alterations in either material layers or the ventilation circumstances. [63] [65]	*22. Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: A cultural properties case study (Article) [63]* *114. Responsible Retrofit Guidance Wheel [65]*
Installation quality: Product or material needs to be installed according to a set high standard of quality. [65] Adaptability and reversibility: Insulation on the outside is treated as a whole, difficulty in its reversibility and change. [77]	*81. Making good decisions: avoiding alignment problems and maladaptation in retrofit and construction (Article) [77]* *114. Responsible Retrofit Guidance Wheel [65]*
Affect frames: Windows and doors frames can be affected by the increase of thickness on the exterior. [48]	*36. Energetic refurbishment of historic brick buildings: Problems and opportunities [48]*

Architecture / heritage related	Literature review
Planning consent within conservation area: Proposals for approval by the local authority conservation officer can be rejected due to the possible changes to the exterior aesthetics. [78]	*95. A method to assess the potential for and consequences of energy retrofits in Swedish historic buildings (Article) [78]*
Original external detail lost: Provisional or constant absence of distinctive external features, such as traditional stonework, ornamental stonework details, horizontal	*58. Balancing Trade-offs between Deep Energy Retrofits and Heritage Conservation: A Methodology and Case Study (Article) [57]* *114. Responsible Retrofit Guidance Wheel [65]*

decorative bands, and the sills of windows and doors. [57] [65]	
Use of sympathetic materials: The materials designated do not align with the current structure, whether it be in terms of visual appeal, origin, or performance of the building materials. [47] [65]	*64. Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building (Article) [47]* *114. Responsible Retrofit Guidance Wheel [65]*

3. MEASURE 3: REVERSIBLE EXTERNAL FAÇADE SYSTEMS

Reversible façade element installed on the outside or wooden panelling using straw insulation.

This intervention is a façade element installed over the existing wall, with soft wood fibre and a render to mimic the original plaster layer on the façade. Installing an element in mostly on the outside, diminish the impact on the usable area on the inside, and if the materials are low emission carbon as wood mostly, it can counter traditional external insulation measures such as aerogel, that might have higher embodied emissions *[79]*.

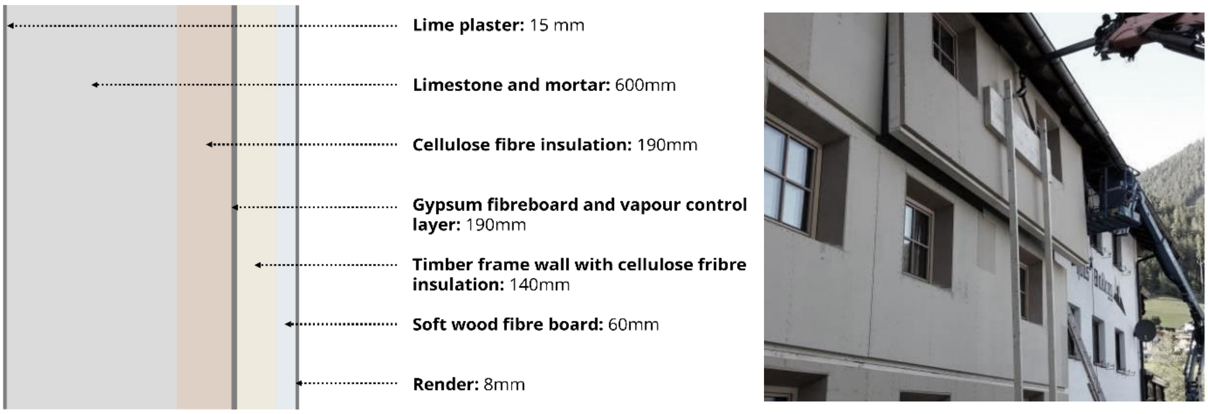


Figure 17 Example of reversible external facade system in (Mayrhof) in Trins (Taken from https://www.hiberatlas.com/smartedit/projects/40/Bauernhof%20Trins_Projektbeschreibung_Fotodokumentation.pdf)

4. MEASURE 4: CAVITY INSULATION

Can be done from the interior if the exterior is worthy of preservation.

The brick heritage building in question was intervened with a cavity insulation measure. The insulation material is a water blown foam. This type of interventions diminishes the risk of damaging delicate structures, since the foam expands equally and also gives breathability to the interior, controlling the moisture. Since is it done from the inside, the exterior wall can be kept with its original features [73].

Figure 18 Example of cavity insulation of an 18th century house in Scotland. (Taken from Visual documentation process of historic building refurbishment "Improving energy efficiency by insulating wall cavity")

ALTERNATIVE MATERIALS: Utilize different innovative materials that can be applied to the different techniques analysed previously.

1. AEROGEL *(Average data)*

Aerogel is a very flexible material available in the market in different forms; it can either be a panel in its compacted form or used simply as an applicable material similar to plaster or concrete [80]. Its facility to mimic textures makes it especially useful when protected facades have some textured plaster on the outer layer. It is an insulation material and a finishing component, reducing the use of additional materials.

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.020 W/mK [80]	0.51 (kg CO_2e/kg) [81]	Mimic texture of plaster of original facades	External insulation

Table 19 Aerogel characteristics for retrofitting in historic buildings

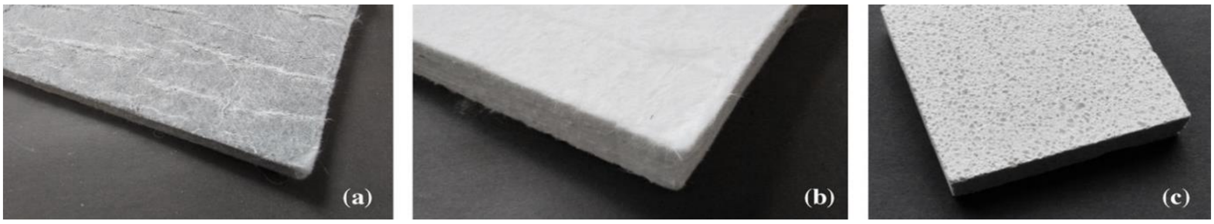


Figure 19 Available aerogel (a) Spaceloft blanket, (b) Heck AERO board, (c) Fixit 222 render (Taken from Aerogel materials for heritage buildings: Materials, properties, and case studies)

2. WOOD-FIBRE BOARDS *(Average data)*

Wood fibre boards can be composed by several layering options, but still remains as lightweight based material, which makes easier to reverse in any case [82]. Since it is a prefabricated component, its installation depends on the façade area. Its finishing layer might replicate plaster or tiles finishing, and still aiding to reduce energy demand.

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.043 W/mK [83]	0.37 (kg CO_2e/kg) [82]	Lightweight possibilities with limited affectation on existing elements	Internal or external insulation

Table 20 Wood-fibre characteristics for retrofitting in historic buildings

Figure 20 Process of rehabilitation of a wall with wood-fibre insulation (Taken from Developing of an Internal Insulation System made of wood-fibre boards for energy-efficient retrofitting of heritage buildings in Vienna)

3. PERLITE AND PUMICE *(Average data)*

These two materials that come from volcanic minerals, are really flexible in its usage stage. They can be applied to any insulation technique. Since it needs a finishing layer, it adapts to either internal, external or cavity insulation. They are used for reaching optimal thermal resistance, while being thin and with low density [82].

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.047 W/mK [82]	0.52 (kg CO_2e/kg) [84]	Not exposed element that can be applied in different ways.	Internal, external and cavity insulation

Table 21 Perlite insulation characteristics for retrofitting in historic buildings

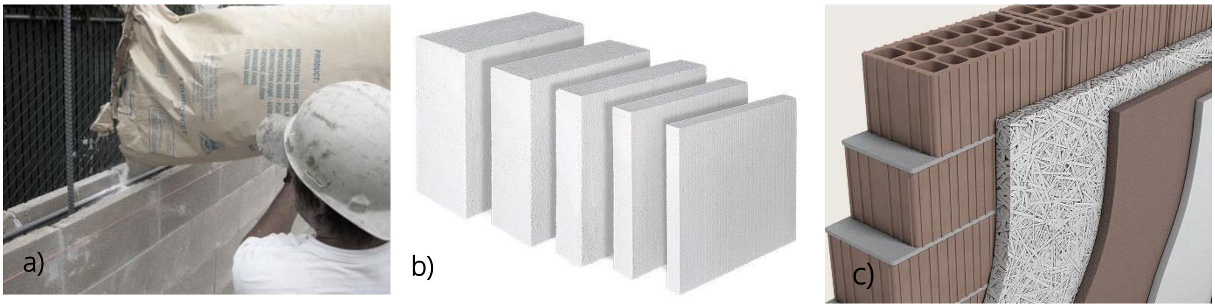


Figure 21 Perlite characteristics. a) Applicability (Taken from https://www.perlite.org/insulation/) b) Board form of Perlite (Taken from https://www.xeral.com/en/Insulating-boards/Interior-wall-insulation/XERAL-GB-046---PERLITE-INSULATING-BOARDS) c) Use of Perlite in brick buildings (Taken from https://www.dicalite.com/2019/01/perlite-functional-fillers-for-use-in-cementitious-composites)

5.3.1.2 Roof

Conditions:

Element composition	Heritage protection	Element condition
Slopped roof (tiles, wood)	Only external finishing protection	Higher risk of element affectation

1. MEASURE 1: INSIDE RETROFITTING - NEW INSULATION AND UPGRADE WOODEN BATTENS

CASE STUDY: Voldsløkka School

Passive House standard achieved.

Previous U-value	After intervention U-value
Not mentioned	0.13 W/(m^2K)

Board cladding and covering		
Roof trust		19 mm
NEW Wooden lath / battens		36 mm
NEW Wooden loops (support)		36 mm
Vapor barrier in Polyethylene (PE) foil		
Plywood truss	**NEW** Insulation	121 mm
Steel profile	**NEW** Insulation	210 mm
Heavy plate - stone wool		50 mm

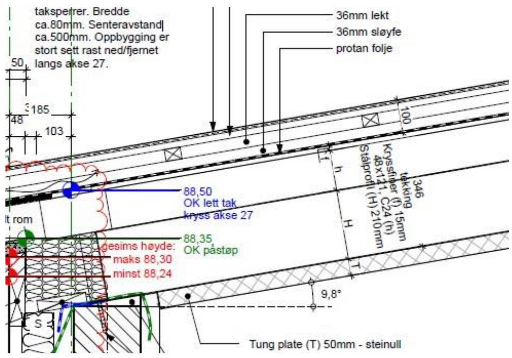


Figure 22 Technical detail of the roof intervention at Voldsløkka school (Taken from ARK documents from Voldsløkka school project)

Structure of the roof at Voldsløkka school is made in wood, with an external layer of board cladding. Roof retrofitting was doing from the interior, where a new insulation layer, vapour barrier and wooden battens were installed. Structural supports were preserved and then covered by a new heavy plate layer.

ADVANTAGES

Technical / energy related	Literature review
Thermal bridging: Changing the roof support structure might solve thermal bridges occurred by material degradation or failures caused by aging [85].	*106. Retrofit room in Room Insulation: Guide to best practice [85]*
Insulation effectiveness: Renewing the insulation might avoid degradation of the material, accumulation of dust, moulding and moisture that could be present by non-effective installations [85] [86].	*106. Retrofit room in Room Insulation: Guide to best practice [85]* *51. Historic building energy conservation with wooden attic using vacuum insulation panel retrofit technology [86]*
Airtight layer: Airtightness can be improved if changing the different layers of the roofing and	*107. From "16 to 1"– Retrofitting airtightness of roofs in existing buildings from the inside [87]*

the air layer is renewed, especially when done it from the inside [87].	
Long-term energy reduction: Although replacing layers of the roofing could signify a higher embodied emission, if installed properly in the long term the lifespan of the roof would considerably be increased, hence an optimal energy performance [88].	*108. Aligning historic preservation and energy efficiency: legal reforms to support the greenest buildings [88]*

Architecture / heritage related	Literature review
Conservation of original aspect of the roof: No risk in affecting the outer layer of the roof in its aesthetics and performance.	
Structural changes: Usually retrofitting is planned to change the use of the building, and some adjustments to the structure could affect joints to the roof battens, especially if they are wood structures [85].	*106. Retrofit room in Room Insulation: Guide to best practice [85]*

DISADVANTAGES

Technical / energy related	Literature review
Embodied emissions: Replacing several layers of the roofing increases the embodied emissions of the materials. It has to be compensated with lower energy consumption during the building lifetime or energy production [88].	*108. Aligning historic preservation and energy efficiency: legal reforms to support the greenest buildings [88]*

Architecture / heritage related	Literature review
Planning and consideration of systems: If not planning correctly there is a risk of not implementing accordingly inlets or outlets for ventilation through the roof [85].	*106. Retrofit room in Room Insulation: Guide to best practice [85]*
Use of sympathetic materials: The materials designated do not align with the current structure, whether it be in terms of visual appeal, origin, or performance of the building materials. [47].	*64. Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building (Article)* *114. Responsible Retrofit Guidance Wheel [65]*

2. MEASURE 2: INSIDE RETROFITTING - Reuse insulation and outer layer treatment

CASE STUDY: Skur 38

Passive House standard achieved

Previous U-value	After intervention U-value
Not mentioned	0.13 W/(m^2K)

Standing seam metal roof	12 mm
Self-adhered membrane	
TREATED Roof sheeting	15 mm
Vapor barrier in Polyethylene (PE) foil	
Insulation Baffle	36 mm
RE-USED Insulation	300 mm
RE-USED rigid insulation	30 mm
Gypsum board	12 mm

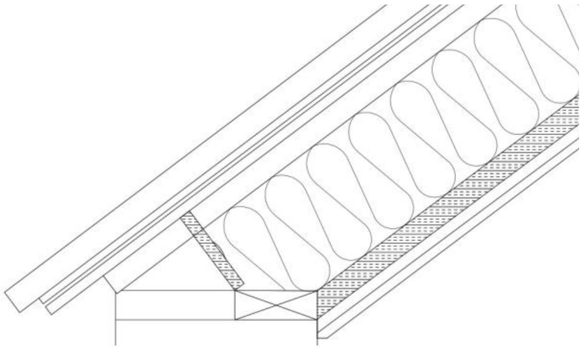


Figure 23 Technical detail of the roof intervention at Skur 38 (Taken and adapted from shared information in FutureBuilt webpage of Skur 38 intervention)

The solution for the renovation of the roof at Skur 38 consisted in an approach of re-using materials instead of replacing them. Insulation was reused, and the rest of the roof structure was repaired where needed. The outer layer of the roof, which is a metal sheeting, was treated to prolong its lifespan.

ADVANTAGES

Technical / energy related	Literature review
Emission reductions: Emissions can be saved by preserving most of the layers of the roof. If minor retrofitting is done correctly, both embodied emissions and operational energy are improved [85].	*106. Retrofit room in Room Insulation: Guide to best practice [85]*
Decrease risk of water filtrations: Treating thoroughly the metal sheeting can prevent water leakages that can affect the insulation or other layers of the roof [88].	*109. Aligning historic preservation and energy efficiency: legal reforms to support the greenest buildings*

Architecture / heritage related	Literature review
Return to original aesthetics of the roof: Roofing colour has been changed several times during past renovations and treating a material as steel can give back the original aesthetic of the roof [85].	*106. Retrofit room in Room Insulation: Guide to best practice [85]*

DISADVANTAGES

Technical / energy related	Literature review
Affectation of insulation: Not replacing the old insulation can cause a misconception of the original thermal conductivity of the material and	*51. Historic building energy conservation with wooden attic using vacuum insulation panel retrofit technology [86]*

the one that could be after several years, thus, affecting the U-value of the entire roof [86].	
Airtight layer: Conserving almost all layers of the roof, could affect the air tightness if only the external layers are changed. Installation processes could damage the materials [85].	*106. Retrofit room in Room Insulation: Guide to best practice [85]*

Architecture / heritage related	Literature review
Use of sympathetic materials: The materials designated do not align with the current structure, whether it be in terms of visual appeal, origin, or performance of the building materials. [47] [65]	*64. Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building (Article) [47]* *114. Responsible Retrofit Guidance Wheel [65]*

3. MEASURE 3: REPLACE TRADITIONAL THICK INSULATION MATERIALS WITH THINNER PANELS

Using thick insulation materials on wood composed roofs can affect their aesthetic value [86]. It is part of the flexibility aspect of a construction to be able to remove ceilings without affecting the insulation performance of the roofing component. Therefore, utilizing efficient and thinner insulation layer can reduce the overall change in appearance of external and internal layers. In this building reference, energy for heating could be reduced by almost a fifth compared to previous insulation *[86]*.

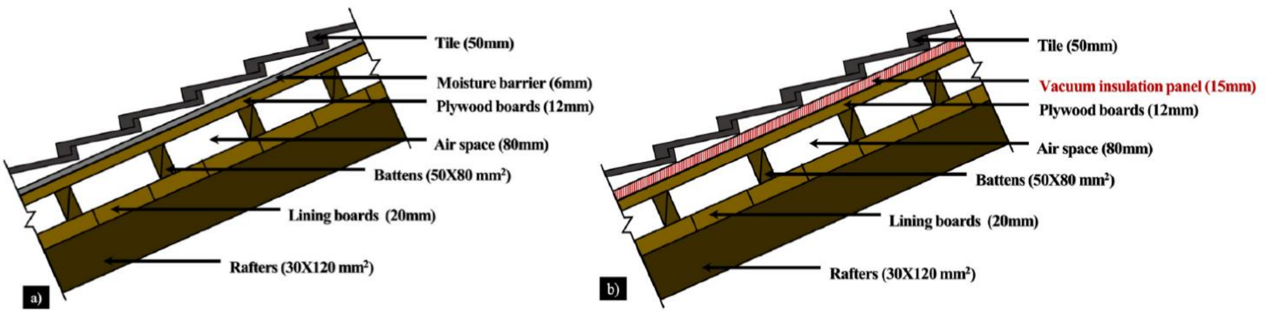


Figure 24 Wooden roof layer in historic building case, a) Before applying retrofit technology, b) After applying retrofit technology. (Taken from *Historic building energy conservation with wooden attic using vacuum insulation panel retrofit technology*)

4. MEASURE 4: DEEP RETROFITTING ENERGY GENERATION TECHNOLOGIES (WHERE POSSIBLE):

Perhaps an alternative not contemplated for heritage buildings, but a thorough assessment could allow the use of renewable energy systems in the building, referring specifically to solar energy. Standard EN-16883:2007 mentions predominantly aspects related to material, visual and spatial risks [89] [90], among other criteria to evaluate.

As a general rule for the heritage aspects, for the current archetype (roof with external heritage protection), solar panels should not be visible from the ground, otherwise, they should merge with the existing roofing in terms of symmetry, colour matching, coplanarity and others [90]. If an intervention as such is pertinent, then it needs to be analysed together with its energy generation potential and other design and economic matters to be implemented.

ALTERNATIVE MATERIALS

Figure 25 Solar panels implementation in Villa Castelli (Bellano), Italy. (Taken from *Historic Building Energy Retrofit Atlas – HiBERatlas)*

1. VACUUM INSULATION PANELS (VIP) *(Average data)*

Insulation panels are one of the most convenient options for roof retrofitting either for inside or outside executed renovations. One of the materials that could benefit a low impact renovation are VIPs. According to building market and research, VIP compared to other insulation materials performance is the thinnest [86]. Thermal conductivity and embodied emissions factors can vary within the measure, due to the large extent of materials that could form the core layer and the envelope of the panel [86] [91].

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.007 W/mK [91]	6.4 (kg CO_2e/kg) [91]	Optimal thickness for a low-impact retrofitting.	Inside and outside retrofitting

Table 22 VIP Vacuum Insulation Panel characteristics for retrofitting in historic buildings

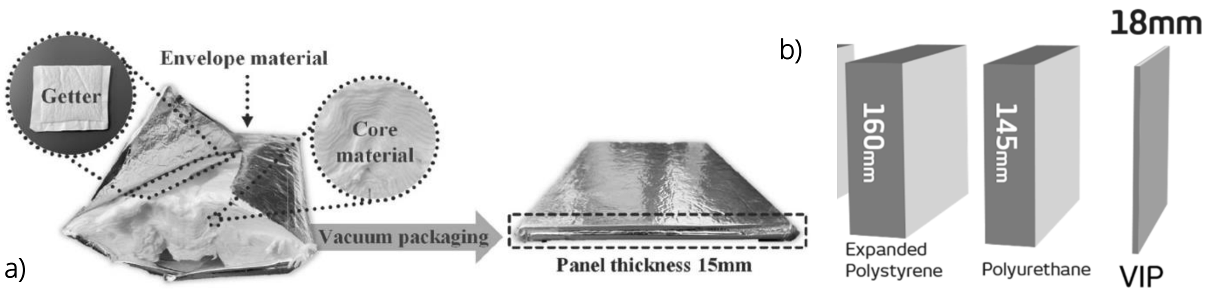


Figure 26 a) Composition of Vacuum Insulation Panels. *(Taken from Historic building energy conservation with wooden attic using vacuum insulation panel retrofit technology)* b) Thickness comparison between VIP and other insulation layers . *(Taken from Vacuum Insulation Panels used in Buildings https://vipa-international.org/vacuum-insulation-panels-used-in-buildings/)*

2. RECYCLED PET (POLYETHYLENE TEREPHTHALATE) *(Average data)*

Using recycled materials diminish embodied emissions of the overall building element. In this case recycled PET comes from daily-use bottles which are transformed with external additions to create insulation panels. Its thermal conductivity is low, and it might become an alternative material for conventional roof interventions [92] [93].

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.037 W/mK [92]	1.78 (kg CO_2e/kg) [92]	Easily adjusted to non-damaging interventions but needs vapour barrier	Inside and outside retrofitting

Table 23 Recycled PET characteristics for retrofitting in historic buildings.

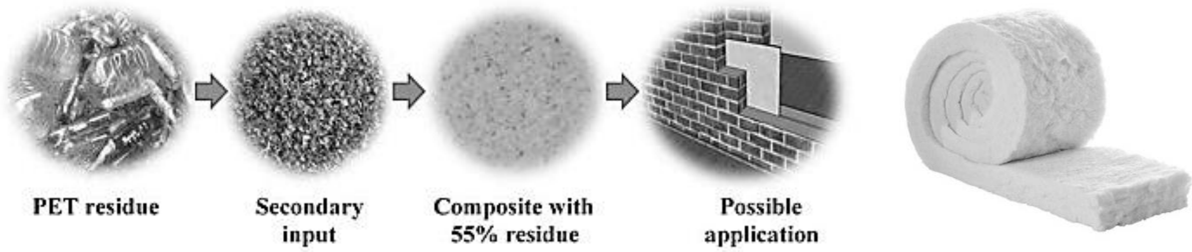


Figure 27 Process of recycled PET from its residue stage, to become insulation panels suitable for retrofit measures *(Taken from Recycled polyethylene terephthalate-based boards for thermal-acoustic insulation).*

5.3.1.3 Ground floor

Conditions:

Element composition	Heritage protection	Element condition
Concrete slab	No heritage protection to finishing layer	Lower risk of element affectation

1. MEASURE 1: NEW SLAB – INSULATION BELOW SLAB- (SIMPLE RETROFITTING)

CASE STUDY: Voldsløkka School

No energy benchmark achieved.

Previous U-value	After intervention U-value
Not mentioned	0.23 W/(m^2K)

Outer later dependable on the room use Vinyl, Linoleum, Concrete, Wood etc.	-
Rockwool plate	50 mm
EPS Insulation	100 mm
Crushed Stone support	150 mm
Drainage layer	-

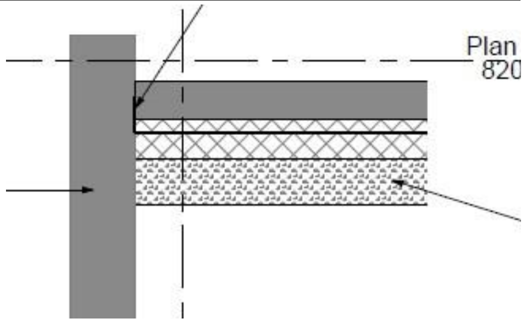


Figure 28 Technical detail ground floor of the intervention at Voldsløkka school (Taken from RIB documents from Voldsløkka school project)

There are different retrofitting scenarios to consider depending on the need of the designers, but a common approach for ground floors is to update or install new insulation systems. In the case of Voldsløkka school, the intervention is basically a replacement of the original layer, and further installation of insulation and a new concrete slab on top, with various finishes depending on the use. The insulation used in the floor is a conventional EPS board. In the case of Voldsløkka school there is a unheated basement that was also treated, with a similar measure.

ADVANTAGES

Technical / energy related	Literature review
Thermal mass: Heat can be collected in the element if the concrete slab is exposed, helping to regulate temperature. [94]	*113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors [94]*
Loads: When the slab is over the insulation, the floor layering loads are spread throughout the slab. [95]	*Housing Retrofit: Ground floor insulation [95]*
Thermal comfort: Having thermal mass can facilitate to control indoor temperatures if correctly receiving enough radiation. [94]	*113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors [94]*

Architecture / heritage related	Literature review

No advantage recorded

DISADVANTAGES

Technical / energy related	Literature review
Hidden services: Having to remove the existing slab might have potential affectation on old plumbing or other installations that are usually not accounted on floor plans due to the age of the building. [94]	*113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors [94]*
Trapped moisture: Original slabs might have been built over soil with no damp membrane, removing floor layers could cause trapped moisture to affect the element or the surroundings. [94]	
Slower heating process: Opposite to the potential of using thermal mass, this process slows the heating process, particularly difficult to manage if there is not enough heat to collect, decreasing indoor temperatures. [60]	*1. Refurbishment concepts for a student housing at the Otto Wagner Areal in Vienna under the aspects of sustainability, energy efficiency and heritage protection [60]*
Higher demolition rate of the existing flooring: Changing the flooring, means more materials that have to be disposed, especially concrete, that although could be recycled, it is not easy to reuse in a project, hence, increasing emissions during the demolition phase. [94] [95]	*113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors [94]* *Housing Retrofit: Ground floor insulation [95]*

Architecture / heritage related	Literature review
Risk of damage of internal aesthetics of adjacent elements: Removing floor layers can undermine any aesthetic value of elements attached to it, such as walls or the structure. [53]	*68. Reconciling energy and heritage: Retrofit of heritage buildings in contexts of energy vulnerability (Article) [53]*
Inefficient reversibility: Using conventional concrete slabs affects possible future repairing, making arduous and inefficient to for instance change installations. [95]	*Housing Retrofit: Ground floor insulation [95]*

2. MEASURE 2: NEW SLAB – INSULATION BELOW SLAB (DEEPER RETROFITTING)

CASE STUDY: Skur 38

Passive house benchmark achieved.

Previous U-value	After intervention U-value
Not mentioned	0.09 W/(m^2K)

150 mm FutureCEM concrete cover	150 mm
Half reinforcing mesh	-
EPS insulation	150 mm
Radon prevention	-
EPS insulation	200 mm
Crushed stone / drainage	

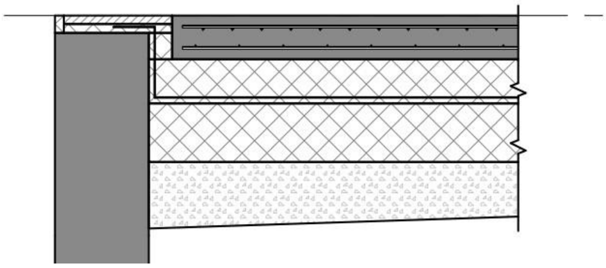


Figure 29 Technical detail ground floor of the intervention at Skur 38 (Taken from FutureBuilt documents https://www.futurebuilt.no/Forbildeprosjekter#!/Forbildeprosjekter/Skur-38)

In Skur 38 an innovative material was used. Clay-based concrete. A lower embodied emission material (FutureCEM) compared to traditional concrete (36% emission savings), where burnt clay replaces some of the clinker [96]. Being the first building in Norway to use such material, evidence that despite the building being protected, elements as the ground floor, that in this case are not, can be more manageable and have deeper and more impactful renovations. The new material is complemented with two traditional EPS insulation boards [97].

Figure 30 Visual documentation of Skur 38 intervention to the ground floor

ADVANTAGES

Technical / energy related	Literature review
Thermal mass: Heat can be collected in the element if the concrete slab is exposed, helping to regulate temperature. [94]	*113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors [94]*
Loads: When the slab is over the insulation, the floor layering loads are spread throughout the slab. [95]	*Housing Retrofit: Ground floor insulation [95]*
Emission savings: Reduction in emissions in concrete, a material that is highly use in construction is highly valued. [96]	*FutureCEM® cement CEM II/B-M (Q-LL) 52,5 N Aalborg Portland A/S [96]*

Architecture / heritage related	Literature review

Visual aspect: Having the clay-concrete with the traditional aggregate varies the grey colour of traditional concrete and it might be more visually appealing to leave it as external layer- [97]	*Leirebetongen kommer - Skur 38 [97]*

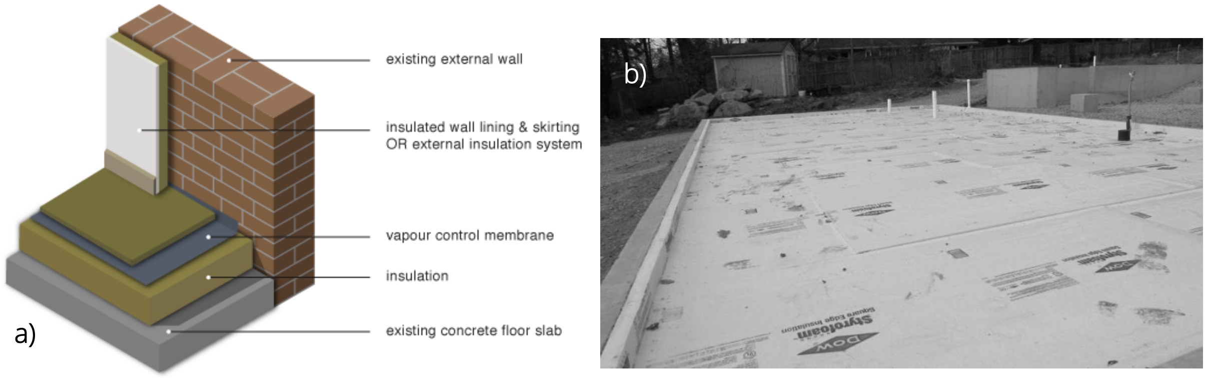
DISADVANTAGES

Technical / energy related	Literature review
Hidden services: Having to remove the existing slab might have potential affectation on old plumbing or other installations that are usually not accounted on floor plans due to the age of the building. [94]	*113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors [94]*
Trapped moisture: Original slabs might have been built over soil with no damp membrane, removing floor layers could cause trapped moisture to affect the element or the surroundings. [60]	
Market availability for repairing: Clay based concrete is still not exceptionally popular, which might have consequences if reparations are needed, adding emissions of possible transportation process. [60]	*1. Refurbishment concepts for a student housing at the Otto Wagner Areal in Vienna under the aspects of sustainability, energy efficiency and heritage protection [60]*

Architecture / heritage related	Literature review
Risk of damage of internal aesthetics of adjacent elements: Removing floor layers can undermine any aesthetic value of elements attached to it, such as walls or the structure. [53]	*68. Reconciling energy and heritage: Retrofit of heritage buildings in contexts of energy vulnerability (Article) [53]*
Inefficient reversibility: Using conventional concrete slabs affects possible future repairing, making arduous and inefficient to for instance change installations. [95]	*Housing Retrofit: Ground floor insulation [95]*

3. MEASURE 3: UPGRADING AN EXISTING SLAB

For concrete slabs if there is no existing insulation, the more straightforward technique is adding insulation on top, keeping the slab [95]. Other than emission reduction benefits in not demolishing the existing slab, proceeding with this measure might not be sufficient to reach certain energy benchmarks and it could provoque some design limitations and adaptations, since the current level of the floor increases, meanwhile doors, instalations and other elements remain the same [95]. This measure is efficient for basements with lower risk of moisture affectation or when already compromising radical changes in other parts of the envelope and also if just structural strenghten of the slab is needed.



4. MEASURE 4: NEW SLAB – INSULATION ABOVE SLAB

Figure 32 a) Technical detail of a usual upgrading of a concrete slab with insulation (Taken from Housing Retrofit: Ground floor insulation b) Image of an insulation installation in a former garage to become a habitable space. (Taken from How to Insulate an Existing Concrete Slab https://todayshomeowner.com/insulation/guides/how-to-insulate-an-existing-concrete-slab/)

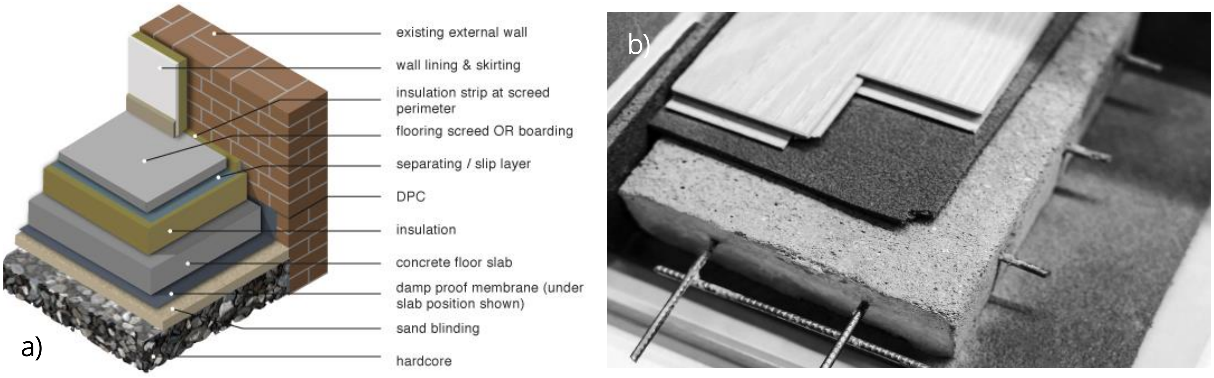


Figure 31 a) Technical detail of new slab installation with insulation above (Taken from Housing Retrofit: Ground floor insulation b) Trial casting of a concrete slab with insulation (Taken from How to Insulate A Floor Over Concrete https://www.oxfordshireconcrete.co.uk/how-to-insulate-a-floor-over-concrete/)

Replacing the concrete slab entirely and installing the insulation above the new, might be effective if there is a floor heating system. Moreover, temperatures rise rapidly because of the location of the lower thermal conductivity layer on above [95]. However, on the contrary to the insulation-below-the-slab measure, structurally is not as efficient and then control temperatures might be more challenging [95].

ALTERNATIVE MATERIALS

1. RECYCLED FOAMED CELLULAR GLASS *(Average data)*

Foamed cellular glass is common to use as replacement of heavy traditional concrete slabs since it can be used also as a load bearing element but being light and thin at the same time [98]. These panels can be produced with the addition of recycled porous minerals, as clay or wasted bricks making the material even lighter. Using these aggregates lower use of concrete, plaster or resin, common elements on the foamed glass [98].

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.036 W/mK [98]	0.68 (kg CO_2e/kg) [99]	If outer layer protected can be removed and	New slab retrofitting

		located over the foamed glass, but with reinstallation risks.	

Table 24 Recycled Foamed cellular glass characteristics for retrofitting in historic buildings.

Figure 33 a and b) Foam glass installation and visual appearance of it (Taken from Foamglas https://www.foamglas.com/en/references/netherlands/walterboscomplex-apeldoorn) c) Example of installation of Foam glass (Taken from On the Jobsite with Foamglas https://www.greenbuildingadvisor.com/article/on-the-jobsite-with-foamglas)

2. RIGID PHENOLIC FOAM *(Average data)*

Phenolic foams are mostly composed by two elements. A blown material that is a chemical called pentane and covered in in aluminium foil or glass, and gas tight, similar to a VIP. Usually, it has optimal insulation characteristics, and it is highly resistant to moisture [100]. However, it has some mechanical issues that makes it uneven and possibly unstable. Installation does not affect possible surrounding protected elements [101].

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.020 W/mK [100]	7.021 (kg CO_2e/kg) [102]	If outer layer protected can be removed and located over but with reinstallation risks.	New slab retrofitting

Table 25 Phenolic foam characteristics for retrofitting in historic buildings.

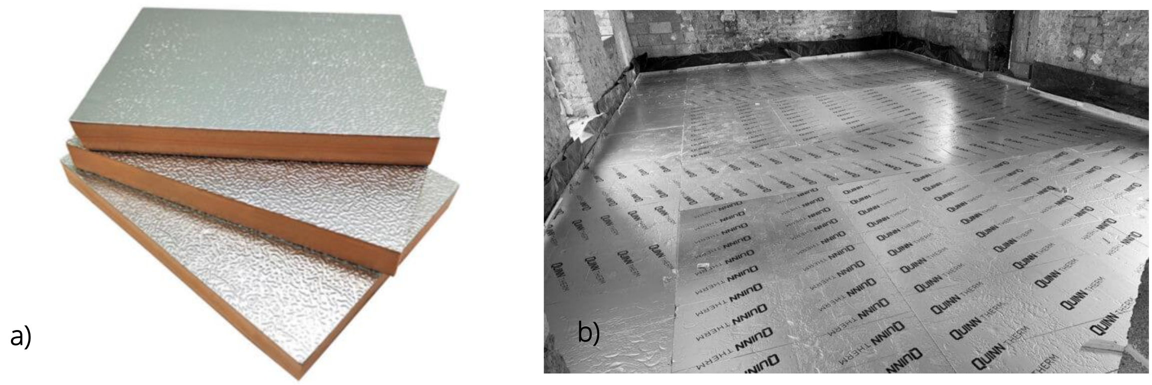


Figure 34 a and b) Visual aspect of phenolic foam and its installation as floor insulation (Taken from VENTECH https://www.chinaventech.com/factory-hot-selling-duct-insulation-materials-phenolic-pre-insulated-duct-sheet-board-foam-pir-air-p-6083.html and ASCUS Screeding https://www.ascusscreeding.co.uk/floor-insulation.html)

5.3.1.4 Windows and doors

Conditions:

Element composition	Heritage protection	Element condition
Wood frame windows, with double layer Different type of doors (wood, glass)	Windows and doors located in a façade that is protected	Good condition of the glass and/or frame

1. MEASURE 1: WINDOWS: BOX-TYPE WINDOWS (OLD PRESERVED WINDOWS AND NEW WINDOWS)

CASE STUDY: Voldsløkka School

Passive house standard achieved

Previous U-value	After intervention U-value
Not mentioned	Windows: 0.80 W/(m^2K)

Windows

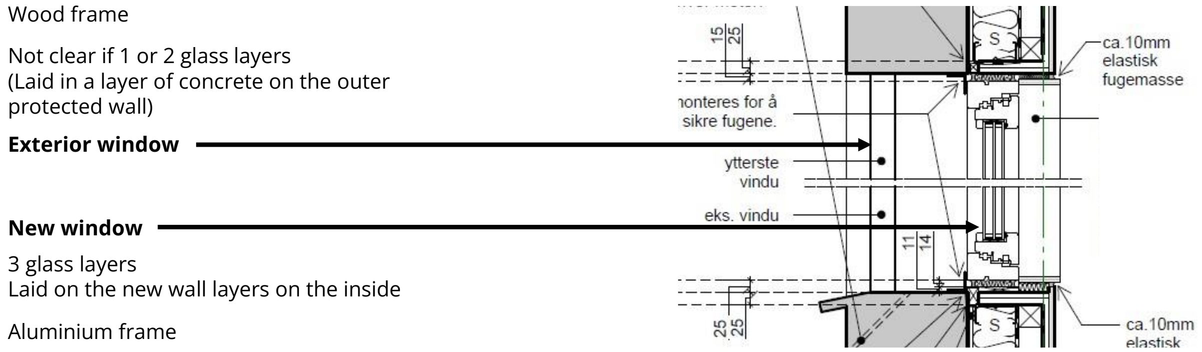


Figure 35 Technical detail of windows at Skur 38 intervention (Taken from ARK documents from Voldsløkka school project)

For the retrofit of windows in Voldsløkka school, it was used the box-type window concept. The exterior windows were protected and could not be replaced in its entirety. Considered that new interior layers were installed in the internal part of the exterior wall, giving extra depth, created a perfect scenario to mount a new window on the interior, respecting the original without any damaging intervention and reducing heat losses through the windows.

ADVANTAGES

Technical / energy related	Literature review
Reduction in heat losses: Heat losses can be reduced considerably by having tow windows and a cavity, hence helping to reduce the energy demand of the building. [103]	*15. Energetic refurbishment of the historic windows of the listed heritage building Alte Schäfflerei and its influence on the overall energy balance [103]*
No risk on seals: Seals of the new window will not be corroded, increasing the lifespan of the material. [104]	*Energy Efficiency and Historic Buildings: Secondary Glazing for Windows [104]*

Avoid thermal bridges: Thermal bridge between the frame and the glass is reduced drastically, due to the original window working as a first filter. [104]	
Solar gain: The heat transmitted through the two windows is larger if compared to a double glass layer glazing. [104]	
Embodied emissions: Keeping the original window, reduces embodied emissions of disposal of the glass, since regardless the glass has to change if the original is updated. [105]	*16. Simulation aided optimization of a historic window's refurbishment [105]*

Architecture / heritage related	Literature review
Conservation of the original window: With this technique the original frame and glass can be preserved if they are in good conditions satisfying heritage restrictions. [103]	*15. Energetic refurbishment of the historic windows of the listed heritage building Alte Schäfflerei and its influence on the overall energy balance [103]*

DISADVANTAGES

Technical / energy related	Literature review
Ventilation: If the original window is sealed, natural ventilation is excluded as mechanism to regulate temperature and exhaust air. Moreover, the internal window is restricted to have certain opening mechanism that does not interfere with the external. [104]	*Energy Efficiency and Historic Buildings: Secondary Glazing for Windows [104]*
Maintenance: Access to the box or cavity either from inside or outside could be compromised for cleaning reasons or fixings. [104]	

Architecture / heritage related	Literature review
Visual impact: There is a risk that poor installation process could create obtrusive views either on the interior or exterior. Careful design needs to be implemented to avoid any visual impact. [104]	*Energy Efficiency and Historic Buildings: Secondary Glazing for Windows [104]*
Increased thickness of the wall: To mount the new window system need some mounting space on the wall. If the thickness of the wall is insufficient, this method might not be optimal. [103]	*15. Energetic refurbishment of the historic windows of the listed heritage building Alte Schäfflerei and its influence on the overall energy balance [103]*

DOORS

Previous U-value	After intervention U-value
Not mentioned	Doors: 1.20 W/(m^2K)

New exterior doors

Different types of doors
Wood
Wood + Glass

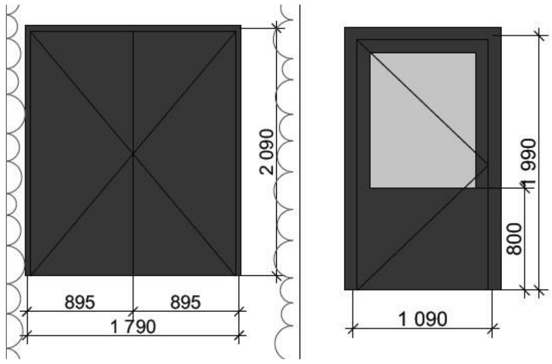


Figure 36 Typologies of doors and their replacement in the façade at Skur 38 intervention (Taken from ARK documents from Voldsløkka school project)

No information available from the case study and from literature to describe advantages or disadvantages of the measure.

2. MEASURE 2: WINDOWS: COMPLETE REPLACEMENT

CASE STUDY: Skur 38

Passive house standard achieved.

Previous U-value	After intervention U-value
Not mentioned	Windows: 0.77 W/(m^2K)

There was no availability of a technical drawing to show the new window system.

Figure 37 Intervention on the façade of Skur 38, with previous windows and the new installation. (Taken from FutureBuilt Skur 38 https://www.futurebuilt.no/Forbildeprosjekter?municipal%5B%5D=oslo#)

High U-value of windows made designers aware that they have to be replaced, therefore they were dismantled and later reused in other projects. New windows were installed following the same size and visual aspect of the original ones [70]. Regarding the colour, the façade did not have a heritage restriction, since it was not the original, then the windows frame colour was adjusted to the design along the new façade colour palette [69].

ADVANTAGES

Technical / energy related	Literature review
Improve overall lifespan of the envelope: Replacing old windows that might reached or will reach their end of life soon, generally lengthen lifespan of the façade, avoiding near repairs. [38]	*Traditional Windows: Their Care, Repair and Upgrading [38]*
Avoid thermal bridges: A replace of the entire window element can prevent thermal bridges that might be ignored when just replacing glazing or repairing the element. [65]	*114. Responsible Retrofit Guidance Wheel [65]*

Architecture / heritage related	Literature review
In-depth visual matching: Complete replacement of windows can favour visual matching with the entire façade if there is a colour or texture change. [38]	*Traditional Windows: Their Care, Repair and Upgrading [38]*

DISADVANTAGES

Technical / energy related	Literature review
Embodied emissions: Replacing might have the highest embodied emissions percentage out of other interventions if using new materials for the new windows and also the disposal of the old materials. [38]	*Traditional Windows: Their Care, Repair and Upgrading [38]*

Architecture / heritage related	Literature review
Change in glazing bars: Old wood windows have small glazing that is supported by wooden bars. New windows come in larger sizes, making unnecessary to use bars, although those can be embedded in the glazing with just decorative function. [38]	*Traditional Windows: Their Care, Repair and Upgrading [38]*
Building consent from authorities: In order to dismantle window elements in protected facades, it is necessary to have consent from the heritage and planning authorities, which might be approved depending on the new proposal and the conservation level of the building. [65]	*Responsible Retrofit Guidance Wheel [65]*

DOORS

Previous U-value	After intervention U-value
Not mentioned	Doors: 0.77 W/(m^2K)

No information available from the case study and from literature to describe advantages or disadvantages of the measure.

3. MEASURE 3: DOUBLE AND TRIPLE GLAZING UPGRADE

Upgrading window profiles with double or triple glazing in heritage buildings is considered when the profile is strong enough to bear larger thickness and weight that more panels suppose or if the is worthy of preservation and there is desire to improve the overall thermal transmittance of the element [38]. However, the main issue is related to the installation and all the damage and risk that the frame can have, leading to the increase of thermal bridges. Therefore, this measure needs to prioritise an optimal sealing intervention to prevent air and moisture [38] [106].

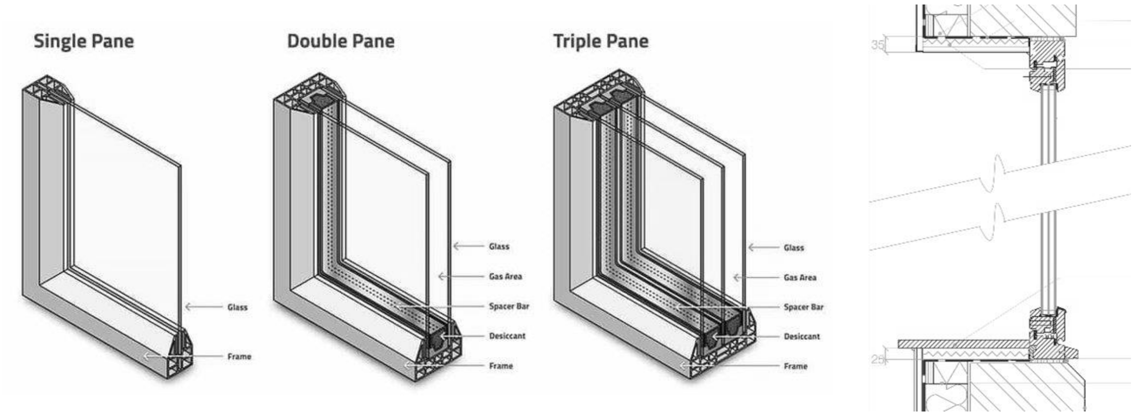


Figure 38 Differences between single, double, and triple panels and a technical detail of a 3-layer window. (Taken from A short review on passive strategies applied to minimise the building cooling loads in hot locations [150] and IWI to new triple/double glazed window https://retrofit.support/detail/46/)

4. MEASURE 4.: DRAUGHT PROOFING

Usually, a common repair method for windows, this measure could be less invasive and damaging to the element if compared to double or triple glazing upgrade. Draught proofing works for both windows and doors, and the goal is to airtight the element to prevent possible leakages and thermal bridges between the frame and glazing [107]. There are different of products but the main are compression and wiper seals, with their advantages and disadvantages depending on what needs to be sealed [107]

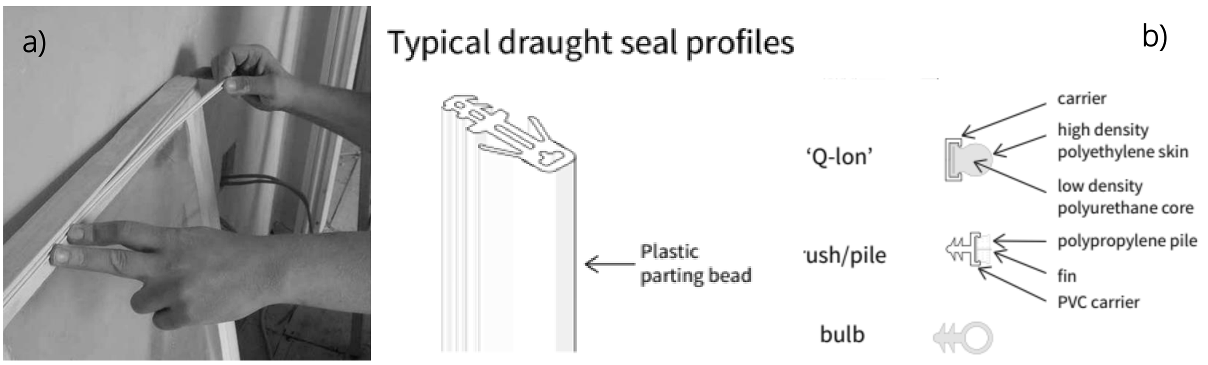


Figure 39 a) Visual example of a draught proofing technique for a window frame b) Drawings of typical draught seal profiles (Taken from Energy Efficiency and Historic Buildings: Draught-proofing Windows and Doors [151])

ALTERNATIVE MATERIALS

FRAME

1. FIBERGLASS OR COMPOSITE - WINDOWS OR DOORS

Fiberglass is a material that works optimally both in the mechanical and the heat transmittance aspect [108]. It is highly competitive in the market despite higher costs than other options. It is lighter and has high insulation performance [108]. In terms of the visuals, its texture and colours can replicate wood finishing, if the protected façade requires it. Apart from that, its properties allow to adapt to different shapes [108].

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Λ = 0.3 W/mK [108]	84 (kg CO_2e/m^2)	Lightweight material with low impact on the wall and visually can replicate original elements	Complete replacement or secondary glazing

Table 26 Fibreglass as window frame: characteristics for retrofitting in historic buildings.

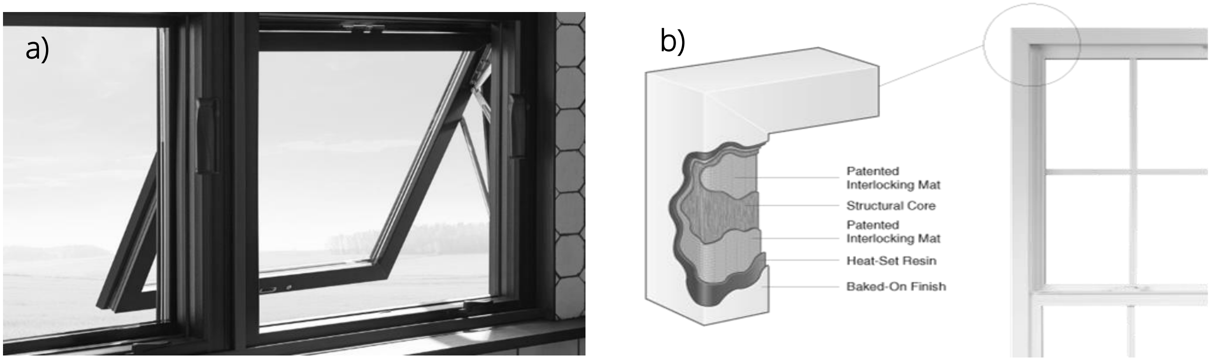


Figure 40 a) Visual example of a fibreglass frame (Taken from Exploring Window Materials https://www.pellabranch.com/windows-doors/windows/vinyl-windows/exploring-window-materials-vinyl-fiberglass-and-wood/ b) Fibreglass composition (Taken from Products: Fiberglass Window Frames https://pqnk.com/blog/product-fiberglass-windows/)

GLAZING

2. LOW-EMISSIVITY COATING WITH GASES (DOUBLE/TRIPLE GLAZING)

Low-e coating glass purpose is to reduce the emissivity of glass surfaces [109]. In combination with gas infills as argon or xenon could reduce its overall u-value to a passive house standard [109]. It has benefits on reducing glare but if there is need to have heat gain as passive strategy through windows, the effect can be diminished by the coating [109], but optimal to prevent overheating. Some issues may appear in terms of similar visual appearance to old glazing to protected facades, if it is a coloured coating.

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Glass Λ = 0.68 W/mK Gas Λ = 0.018 W/mK [109]	30 (kg CO_2e/m^2) [110]	Challenging element to install in existing frames	Upgrading existing window or complete replacement

Table 27 Low -e coating glass and gas in-fillers: characteristics for retrofitting in historic buildings.

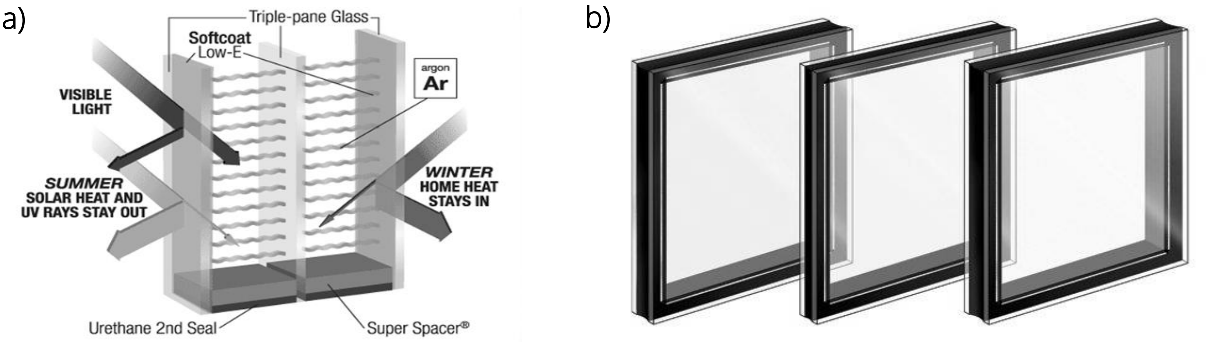


Figure 41 a) Low-e coating window incidence factors (Taken from What is Low-E Glass https://www.stanekwindows.com/what-is-low-e-glass-and-does-it-make-windows-more-energy-efficient.aspx) b) Visual example of coatings for low -e windows (Taken from Low-E Windows vs. Clear Glass Windows https://www.chinanorthglass.com/news-low-e-windows-vs-clear-glass-windows-which-one-to-choose.html)

3. VACUUM GLAZING (DOUBLE/TRIPLE GLAZING)

Vacuum glazing is a double glazing where the air was extracted between, leaving a vacuum. Since there are not many air particles, the heat transmittance is minimal, hence, the space between glazing is smaller than conventional double glazing an d reduced condensation as well [111]. One of the downsides relates to minor availability on the market, resulting in high prices.

Thermal conductivity	Embodied carbon emissions	Adaptability to heritage concerns	Applicability
Glass Λ = 0.68 W/mK Vacuum Λ = 0.003 W/mK [111]	64 (kg CO_2e/kg) [110]	Optimal thickness for a low-impact retrofitting.	Complete replacement

Table 28 Vacuum glazing system: characteristics for retrofitting in historic buildings.

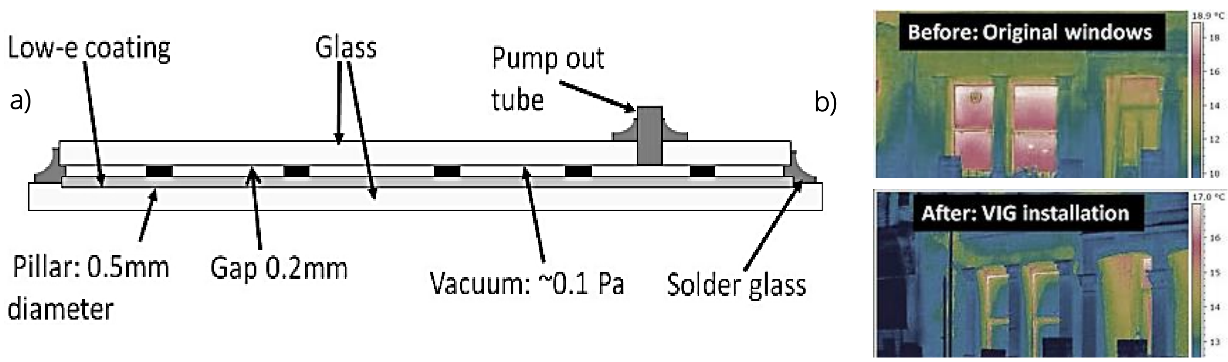


Figure 42 a) Common composition of a vacuum glazing window. b) Thermal image contrasting original glass and Vacuum glazing (Taken from Properties and performance of vacuum insulated glazing [154])

5.3.1.5 Example of summary based on ARV project KPIs

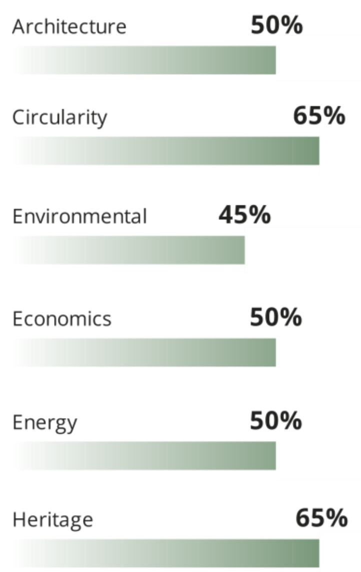
This summary based on the ARV project KPIs solely represents how the data should be provided in a simple manner that allows comparison between measures. The summary of this research is based on the suggestions given earlier in the results chapter (5.3.1.1), considering the advantages and disadvantages shown and the technical data from measures and materials. Although it is not the thesis focus, it illustrates the importance of having a clear summary for any advice template; therefore, it is recommended to follow reliable methods, such as the benchmarks used in the Assessment Framework of CPCC of ARV project [36], that rely on calculations, simulations, and other aspects.

Following the indicators selected during the guideline structure chapter, there is a percentage of how positive or negative is the impact of the measure on each indicator. The current summary, Table 29, only illustrates the external façade measures.

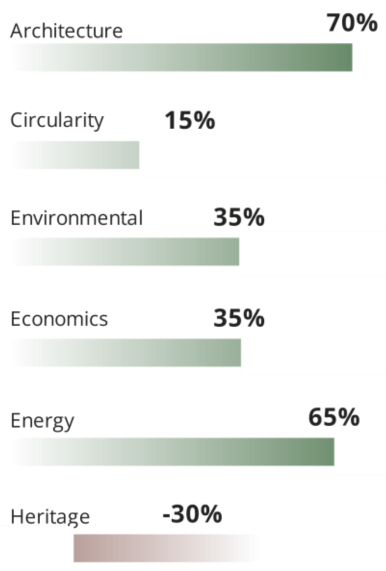
Building fabric

External façade measures

Internal Insulation



External Insulation



The results show a higher positive impact on the Circularity and Heritage indicators. This is because internal insulation usually uses reversible techniques and has a lower affectation on heritage protection, especially when only the external side of the façade is protected.

Furthermore, it has a balanced impact towards the oth indicators, making this measure the most used in energ retrofitting for heritage buildings.

The external insulation has a high positive incidence in tl architectural indicators, predominating its bett performance for avoiding thermal bridges aı overheating. As well as the Energy indicator, the resı follows the trend of being more efficient in reduciı operational energy.

However, it negatively impacts the Heritage aspects sin most buildings are protected in their façade, making complex to install without affecting the original aesthetic

Reversible external facade

Cavity Insulation

Architecture **35%**	Architecture **65%**
Circularity **45%**	Circularity **50%**
Environmental **50%**	Environmental **40%**
Economics **-30%**	Economics **-20%**
Energy **60%**	Energy **40%**
Heritage **-20%**	Heritage **10%**
The reversible external façade system positively impac the Energy indicator due to the similarities improvements that give insulation on the exterior sic However, its cost can be high compared to othe depending on the scale and complexity of the installatic Also, it might harm the Heritage aspects since the origir aesthetics are intervened.	The cavity insulation technique disturbs minimu external or internal insulation, preserving the aesthetic However, depending on the material used, it is a cos intervention and could not be feasible.

Table 29 Example of the summary of external façade measures on assessment indicators.

6 Discussion

The discussion aims to address the research question which is: *How to inform designers about adequate measures for energy refurbishment of heavyweight non-residential buildings in Norway that are under heritage protection through an appropriate template that contains a set of measures based on previous successful retrofitting cases?*

This chapter will be divided into four main sections. Firstly, details of the method used and its suitability to retrofitting advice processes. Secondly, an overview of the three-result output (5.1, 5.2, 5.3) from the research, reviewing the main aspects of each to describe later the connection and co-dependence of the template and the data provided, also explaining how this research gears into a more complex advice picture. Thirdly, the exploration of all the uncertainties that affect the output and the suitability of the research and alternatives that could facilitate the processes developed during the study. Finally, a discussion of the areas where further research could focus on having a solid base for an additional guideline report.

6.1 Method approach

6.1.1 Structure

One of the most challenging steps during the research was reducing the thesis scope from a broad and complex general guideline to a master thesis output. This is vital to acknowledge since most of the references used to create retrofitting advice are academic research with a smaller timeframe than the wingspan of a project, which is usually used to develop a general guideline [13]. Therefore, the current study is expected to move towards a different scope of research papers and regional-based projects. The spectrum of articles is very much specific and centred on a particular intervention [51], material [50], or an overview of general guidelines and projects [112], usually focusing on policies and standards necessary to follow to become real. The current study wanted to collect factors from both scopes to develop an advice template, but still at a manageable range that could be reflected in a next-level project approach.

For example, by analysing both outputs in this research, the data collection template, and the retrofitting advice for the specific archetype, it is noticeable that they result solely from the selected methodology of choosing the necessary information support. In this case, having two separate sources for the data was successful in terms of the aspects considered. The literature cases and the Norwegian case studies reflect the two worlds mentioned previously, and both were essential for having a holistic based output.

To illustrate the latter, the method used for mapping the literature cases gave an overview of where articles focus the most when discussing retrofitting processes and identify instantly the flaws and inconsistencies of the advice in elements that are not studied thoroughly as others. The literature case review (4.4.3) also helped organise the literature for selecting the more wholesome articles and covering as many aspects as possible.

Conversely, several issues could be addressed following this procedure. First, handling all the building elements involved in retrofitting is a challenging task to follow. There are many aspects to evaluate and several variables that need extensive information support to be reliable. It was visible during the selection process of case studies that the information collected for identifying the archetypes was neither clear nor general enough to be encompassed in fluctuating and vague parameters. For instance, when classifying case studies by fabric composition (3), such as identifying elements of external wall and just categorizing them only by their primary material (brick, concrete etc.), differs significantly from how building elements are composed, thus allowing wrong classifications since there are aspects that are not considered such as wall thickness or their current insulation material. This is also related to the information found by the research design method. Attempts were made to have more profound knowledge of all eighteen cases identified, but there was reluctance or no answer for sharing this detailed information, and in other cases, there was no existing information whatsoever.

Furthermore, during the advice structure phase (5.1.2.1), it was explained that the current research had to base measures on different methods, some interventions for instance, contain both support from Norwegian case studies and literature and others just in literature. It was also mentioned that the timeframe and extent of data necessary to support all measures by both were limited to make it possible. It could be questioned that, despite the mentioned reasons, it did not follow the same structure of presenting the data, meaning having both a system to portray advantages and disadvantages and technical advice.

During the data collection process, it was evident that the data gathered was insufficient to follow the discussed structure. For instance, the Norwegian case studies have technical drawings of their intervention, but that was not the case in all literature cases. It is essential to highlight that for an optimal development of a guideline, all measures should be supported by a technical database like DATAHOLZ.EU to exemplify each measure and some parameters. The main issue is that for heavyweight materials, there is no database with the extent that Dataholz has for wood-based elements.

Using two sources for support might seem to interfere with the equality and consistency an advice report should have. But this research, as the link between research and implementation projects, needs variety and heterogeneous data to bring a holistic perspective.

6.1.2 Archetypes

As explained in the methodology chapter (4.4.1.2.1), archetype identification is an essential step to recognise the main characteristics of the Norwegian building stock. However, the criteria and aspects to evaluate are far from defined in each building. Elements such as architectural style are particularly vague since different interpretations can be made about them. Despite this, a clear pattern was found for functionalist buildings, which in contrast to other architectural styles in Norway, have a prominent aesthetic condition that define them. Different styles vary significantly from their classification, especially with buildings categorised as neoclassicism or historicism. Their features differ significantly, making them difficult to label. Something similar occurs with the building use and the fabric composition. Taking each assessment alone does not aid in creating archetypes.

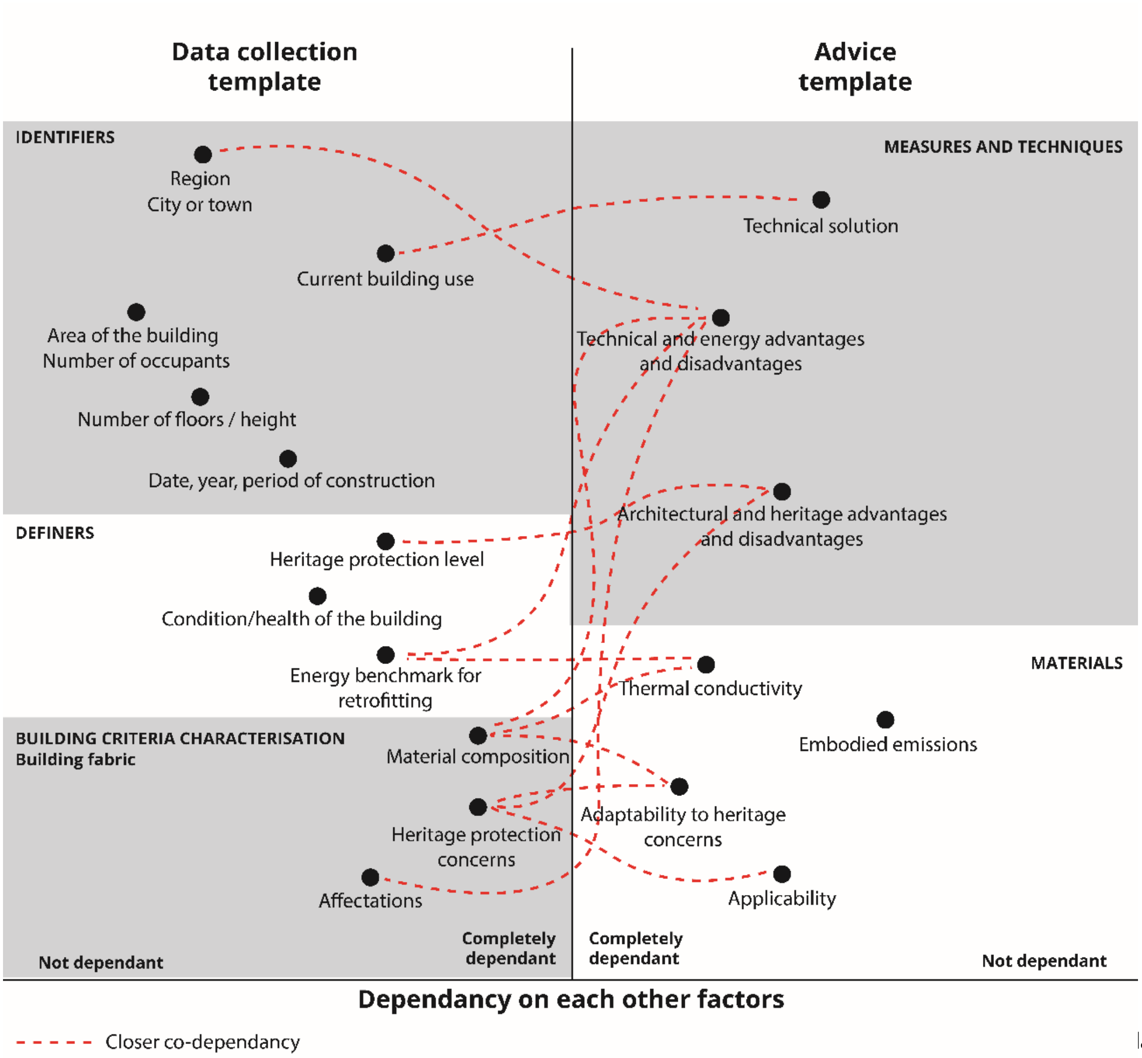
When selecting the archetype to proceed with the data collection and advice template, it was vital to acknowledge that some categories significantly impact decision-making measures more than others. It could be argued that the archetype with more similarities in the more impactful aspects, or the one with a more significant number of buildings representing it, will be selected for further recommendations. In that scenario, the chosen option would have been the archetype by architectural style that englobes concrete modern structures.

This archetype is representative by containing the higher number of cases and share more similarities, but it was important to acknowledge the Norwegian context. Apart from the capital Oslo, settlements in the country are small in comparison [113]. The number of modern concrete buildings in these areas is much smaller, conditioning the study to a more local status than regional. It may increase the accuracy of the advice since there are more similarities between buildings. However, this archetype is not highly represented in the overall Norwegian context, which is why the actual archetype (Norwegian industrial warehouses) was selected. Despite major inaccuracies and differences in their characteristics, it covers better the picture of the Norwegian heritage building stock.

6.2 Research output

6.2.1 Guideline structure

Creating a template for such complex matters as retrofitting heritage buildings needs more than a handful of support information to have a reliable structure that enables advice to be given understandably [13]. As explained in 5.1, separate efforts were made to create a template for data collection and another for retrofitting advice. In a sense, this is a thread due to the complexity required to develop both structures. However, after completing the templates, they some aspects were found to be more connected in between than others. Figure 43 shows how closely related the different aspects considered between the templates are.



lates

For instance, if technical or energy advice for retrofitting a wall is given, the building that uses the advice needs to provide information about the element material composition, its heritage protection status, and the general energy benchmark to decrease the scope of the advice and more precise information will be given. Conversely, when recommending an alternative material, the heritage and energy data collected from the building are essential to identify the most suitable materials with thermal conductivity and other factors that adapt better to the particular conditions of the building element.

Since the data collection process was a separate gathering mechanism on its own, it was foreseeable to find some data that was provided rapidly and others that had limitations due to being undisclosed information for the public or unavailable. The impact of the IDENTIFIER information in the advice could classify climate information, the scale of the project and insights about the conditions of the buildings. In a future application, this needs to be connected to external mediator databases linking, for instance, the city location of the project to a weather file (EPW) that later, in an advice tool, select the measures that relate the most to the climate conditions.

Concerning the DEFINER information collected from the case studies, it is visible that the data collected is the one that condition primarily the overall state of the building. The level of protection gives the depth of the retrofitting measures to be analysed in the literature review. If the building has a high level of protection, the database should filter those interventions or materials that would not be compatible with this protection. Conversely, the health of the building gives an insight into the general condition of the whole construction, but just as an identification, not really conditioning the later advice (Figure 43). But it is when assessing the state or risk by each element the literature reviews are filtered, focusing more on articles that prioritise hygrothermal issues.

After, the energy goals criteria at this stage, only set the parameters for the energy benchmark the renovation is going to be done. However, is necessary to clarify, that for further research specific goals in the decrease of energy demand or U-value benchmarks to obtain should be provided. It is demonstrated on the example of advice retrofitting for the building fabric that not having information about previous energy demand data and clear goals, hinder the advice prospect, since it could seem vague and generalized.

In addition, the energy goals criteria at this stage only set the parameters for the energy benchmark to base how the renovation will be done. However, it is necessary to clarify that specific goals in decreasing energy demand or U-value benchmarks should be provided for further research and should be included in the template as question. It is demonstrated in the example of advice retrofitting for the building fabric that not having information about previous energy demand data and clear goals hinders the advice prospect since it could seem vague and generalized recommendations that do not apport a clear view for decision-making processes.

Finally, the BUILDING CRITERIA CHARACTERISATION (BCC) query specific parameters of the building elements. It follows an equal pattern for all building fabric elements based on material composition, heritage protection level and health risks. It was seen that elements were less compatible with each other during the exemplification of the structure with the case studies. The main reason refers to their composition. For instance, walls, roofs, and floors follow a similar layer system, and their assessment is similar energy and heritage related, and the literature approach usually assesses the element altogether. But windows are elements composed of frame and glazing, typically separately analysed unless it is a double/triple glazing unit. It is imperative to have a different template for the windows. Despite this, the three areas assessed are the ones that relate the most to the advice data (Figure 43). One of the reasons is their relation in terms of scope with the literature. For this stage, the questions must address a similar spectrum of the literature, focusing on the elements' specifications and their composition.

6.2.2 Example of the template for buildings' identification through case studies

Knowing the similarities, the case studies have since they were grouped by archetype, it could be argued that too many similarities in their components could lead to gathering the same measures, ignoring the purpose of comparing options. According to Figure 44, it illustrates what information collected in both Voldsløkka and Skur 38 resembles in its majority to each other. IDENTIFIERS' data is much more different, given that it is the personal identification of the building.

The DEFINERS stage shows that only the energy goals are other, being more ambitious than the ones in Skur 38. But for the BUILDING CRITERIA CHARACTERISATION (BCC), all the elements assessed have the same pattern, except the walls made of brick in Voldsløkka and concrete in Skur. It might be adduced that having building components with similar characteristics will give similar measures for all. By contrast, a similar technique was used only for the ground floors, even though it has a different depth in its renovation impact.

It is essential to recognize then that if having too different data from the BCC, the measures would not be compatible to the extent of buildings and will merely sink into just addressing particular characteristics of the building. The DEFINER stage information should remain similar except for the energy goals because various energy benchmarks will help extend the impact and effectivity of different measures. However, the IDENTIFIERS are the aspects that have a real say in differentiating the measures since the scale, the use, or the date of construction of the building might have changed perspectives on the designers to choose one intervention.

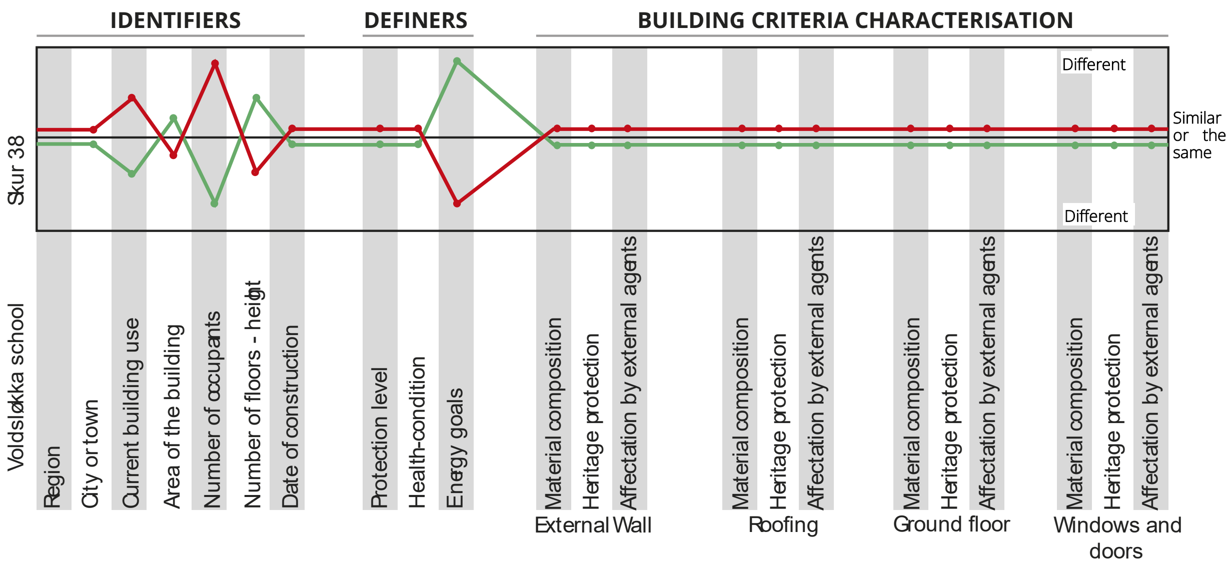


Figure 44 Similarities and differences of data collected from Voldsløkka School and Skur 38

6.2.3 Retrofiting advice example – Building fabric

One first description of the different trends of the result section related to the interventions concerns the technical descriptions and the energy goals of the building. In the result section (5.3.1), the advice gives a specific description if the element manages to reach a benchmark by decreasing the U-value of the fabric component. However, from Voldsløkka school, there is no gathered information on the previous energy demand before retrofitting, making it difficult to know the real impact of a retrofitting measure to reach specific goals. Therefore, for the projects that require the advice, it is necessary to have insight into the energy demand compared to what actual energy goal could be reached by selecting a specific retrofitting measure and how the element contributes to that goal.

Furthermore, it is visible that the availability of data from the literature support affects the number of advantages and disadvantages of information to base the given measures. An insight from an overall sum of all the building elements (Figure 45) shows that external wall data is more available, following the already-mentioned trend. It can be highlighted that, in general, there are more benefits and drawbacks from the technical and energy perspective than the architectural and heritage. This is because many articles solely relate to either new materials and their implementation process or the impact on thermal comfort or building health causing heritage characteristics such as originality or material provenance to be overwhelmed.

Although there is no clear trend, there seem to be more disadvantages than advantages in the research. All these tendencies might affect giving a balanced perspective of the different measures. That is why it could be recommended to have an external source from material databases, which often showcase more material benefits. However, it needs to be handled carefully since material databases might not have the accuracy of technical reports, which forward again the view towards specialised databases similar to DATAHOLZ.EU.

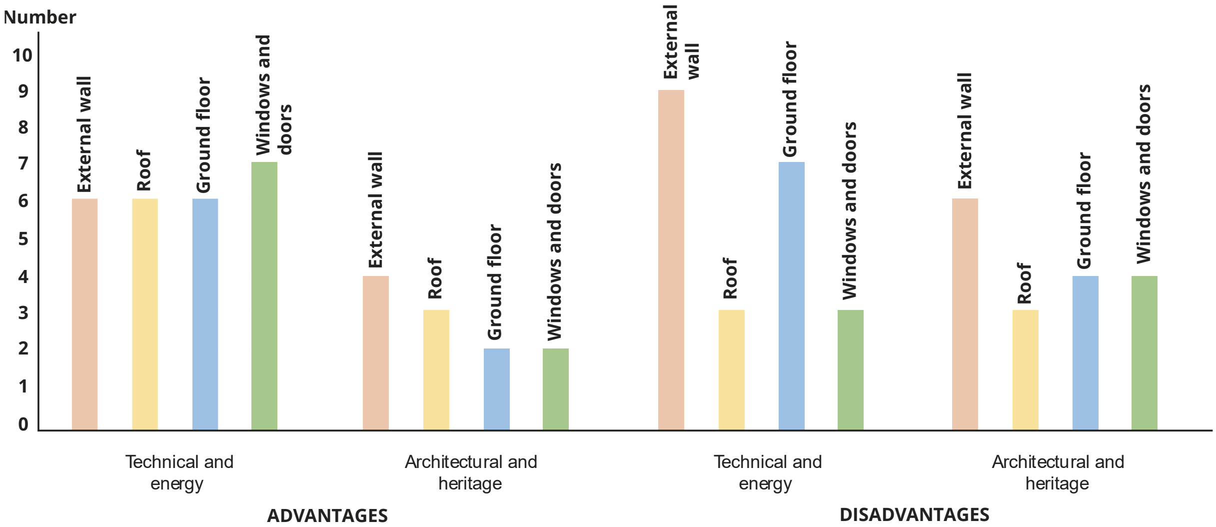


Figure 45 Advantages and disadvantages account per number of advice given on each building fabric element.

6.2.3.1 Retrofitting advice assumptions

As a diagnosis of the retrofitting advice for the archetype selected and its conditions it can be argued that many of the measures contemplated, can fit into several other archetypes. However, the selection mechanism for the advice is not made to give specific indications on how to proceed to do a renovation but to dismiss those measures that are not compatible with the heritage condition of the element. Therefore, the current results show a range of measures that in an overview could fit in a more or less suitable manner.

When reviewing the advice from all the building fabric components, it is important to state that the measures and the materials suggested were simply a result of the literature found. Perhaps another literature review mechanism, would have described several others. Meanwhile, it is possible to summarize the interventions following an adapted version of a research that shows literature support as tool for decision-making [114] by selecting which measures are more suitable to the parameters stablished during the results chapter. The chosen measures and materials were selected depending on the number benefits and drawbacks extracted from literature (measures) and technical aspects (materials).

There are many trends observed in Table 30. First, it illustrates that the technical and energy parameters, the most convenient measures, were the ones studied in the Norwegian cases (Measures 1 and 2). At the same time, for the architectural and heritage aspects, two out of four belong to the other suggestions from the literature (Measures 3 and 4). There is no clear conclusion since the measures have different templates, given their previously explained constraints in the study. However, it could be mentioned that the measures opted for by both cases were really beneficial for their energy performance and comfort aspects. In both cases, the measures were applicable enough for heritage concerns but with a higher risk of affecting it when prioritizing energy goal achievements.

Secondly, the measures and materials differ for the parameters for walls, roofing, and ground floor elements, a trend that does not occur in the windows. Although windows are, together with the walls, the most visible aspect of heritage protection, within the suggested box, type windows (secondary glazing system) have a balanced supported from literature, remaining within the literature gathered the best performance and option for protected buildings.

More suitable interventions for protected Norwegian industrial warehouses (heavy materials covered with plaster)					
PARAMETERS		EXTERNAL WALLS	ROOFING	GROUND FLOOR	WINDOWS AND DOORS
Architectural and heritage	Measures or techniques	Measure 1 Voldsløkka Internal insulation	Measure 3 Literature Replace traditional thick insulation materials with thinner panels	Measure 3 Literature Upgrading an existing slab	Measure 1 Voldsløkka Box type windows
	Materials	Wood fibre boards	Vacuum insulation panels (VIP)	Recycled foamed cellular glass	Vacuum glazing
Technical and energy	Measures or techniques	Measure 2 Skur External insulation	Measure 1 Voldsløkka New insulation and upgrade wooden battens	Measure 2 Skur Insulation below slab	Measure 1 Voldsløkka Box type windows
	Materials	Aerogel	Vacuum insulation panels (VIP)*	Rigid phenolic foam*	Vacuum glazing

Table 30 Selection of the most suitable measures and materials by assessment parameters.

Two specific materials' selection unveils a possible flaw in how the materials are assessed by their technical and energy performance. For the advice structure, technical and energy advice contains aspects related to energy demand, embodied emissions, and comfort. However, when analysing the materials and their thermal conductivity or embodied emissions, some patterns suggest that their performance in those areas could be contrasting (*). For instance, the roofing material that performs well on the technical and energy aspects is the Vacuum Insulation Panels (VIP). It has an excellent thermal conductivity that makes it efficient for energy reduction. However, its embodied emissions are significantly higher than other materials. Therefore, it is a matter of choosing what aspects to prioritise, but the template structure should reflect the differences.

6.2.3.2 Summary based on ARV Key performance indicators

The summary presented in the result section based on indicators used in assessment framework in the ARV project gave an insight of the aspects considered there and the possible further development of them as a graphical output that accompanies the advice. For the current research the data linked to the percentages given for impact of the measures were based on the literature, however, it is advisable to use instead the assessment methods employed by the ARV project [36] to have reliable and technical data support.

6.3 Limitations and improvement

Many aspects have further implications in creating an advice template or for the data collection process. Many assumptions must be made to develop an initial outline for retrofitting recommendations. One of them is that grouping several buildings through general qualities diminishes the precision with which advice can be given. This is important to acknowledge since other approaches use case studies. One of them is to utilise a similar method for searching cases in energy and heritage-related databases, pick the most distinctive buildings, link them to worldwide databases such as HiBERAtlas [22] or Historic England, and find a similar project in similar conditions. This could be an arduous search process, but it could ensure more reliable and specific advice.

Another assumption was that with only one archetype selected, it was expected to have usable results enough. However, this could be argued, knowing that measures could vary significantly from archetype to archetype, and a template structure would change if including aspects from buildings that do not appear in the ones selected initially.

However, it is in the energy benchmark where the assessment needs to be precise. Some benchmarks or regulations focus more on the technical aspects of the building elements that help achieve energy efficiencies, like the Passive House standards [115] or TEK 17 [116]. And others are fixed more on the result of the diminished energy demand in the building as NZEB or FutureBuilt. It is vital to have a broad perspective of all aspects. Therefore, adapting the data collection and advice templates to technical aspects and the final energy efficiency improvement could be beneficial.

A facet that was not defined when constructing the template was to set how many measures and materials are necessary to cover a general picture of the current market availability. This study had four measures and two or three material descriptions. Although a larger number of interventions and materials can be given, that depends on the transcendence of the literature and their perspective on different measures. It is impossible to compare external wall interventions to the ground floor since the first usually has a more significant impact on decreasing energy demand, and it has been studied much further.

A final aspect to consider for future guideline development is how updating measures from technological advancements and market availability will affect any templates suggested. These should also be flexible and adaptable to unique circumstances from either new literature or new local case studies that could be included.

6.4 Bases for further research

While the current research on energy retrofitting advice for a specific archetype of heritage buildings in Norway provides valuable insights, there are several avenues for further research that were not addressed in the study, but that can enhance our understanding and inform practical interventions.

First, and perhaps the most important, the economic viability of the measures. It is necessary to investigate the economic viability of diverse energy retrofitting measures. For instance, analyse the costs and benefits of different retrofitting strategies, considering long-term energy savings, maintenance expenses, and potential revenue generation [117]. Additionally, mention financing mechanisms within the Norwegian and European context, such as green bonds, public-private partnerships, and tax incentives [118].

A second aspect that was considered briefly in different sections of the technical aspects but not in the overall of each measure is an LCA (Life-cycle assessment). Two parts of the process is to evaluate retrofitting interventions' environmental impacts throughout their life cycle, and compare the environmental performance of various materials, technologies, and energy sources used in retrofitting projects [11]. This process should occur after analysing the heritage concerns and selecting the suitable measure for further LCA assessment information [11].

Furthermore, the behaviour advice template was explored vaguely, a particular perspective might be needed: Stakeholder engagement and social acceptance. It might be beneficial to assess the attitudes, motivations, and barriers faced by building owners, tenants, architects, conservation authorities, and local communities [119] and how that will impact the development of strategies to promote awareness, collaboration, and active participation in retrofitting initiatives [120].

Finally, one aspect quickly mentioned in a measure was the integration of renewable energy sources, specifically solar energy. Since it is a significant debate on where this system should be considered for heritage buildings and their protected facades and roofs, it is eventually a matter of trading off the needs and the visual aspects [121]. There needs to be a conscious assessment of integrating renewable energy systems while respecting the architectural integrity of heritage buildings.

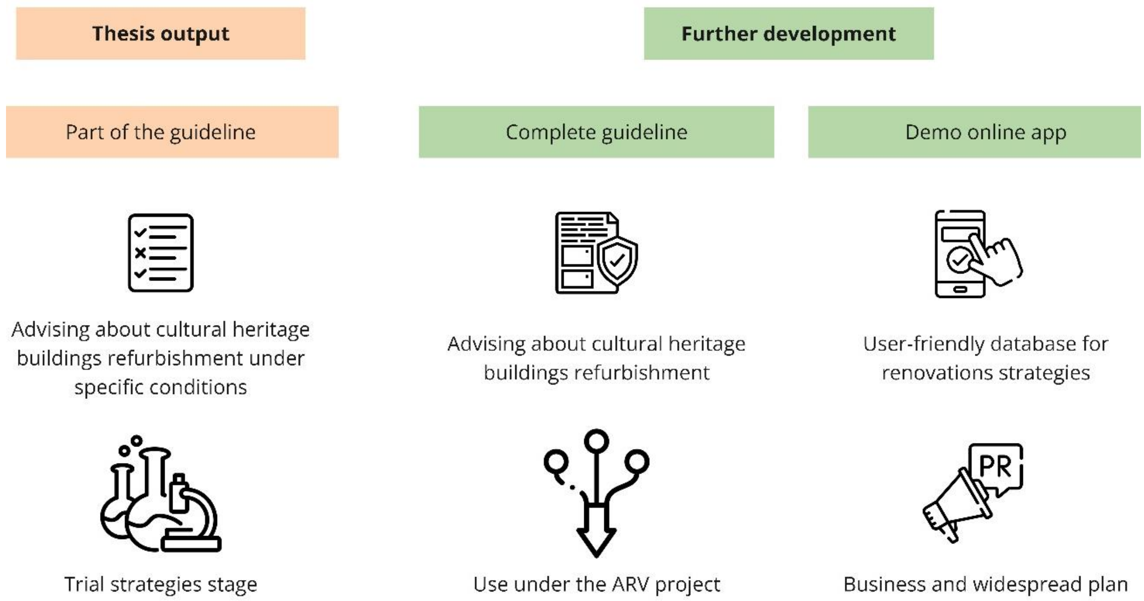


Figure 46 Further development scheme of the current research (own illustration)

As explained in the methodology section, this study is part of more extensive research about guidelines for energy retrofitting in heritage buildings. Figure 46 summarises the thesis output's goal, which can be condensed as a trial demo research of renovation advice under specific circumstances (one archetype analysis and just building fabric).

If pursuing to have a project that englobes all the aspects to consider, it is necessary to have complementary studies with a similar depth of investigation on the remaining elements that were not analysed, such as the building systems, the behaviour concerning renovations and expand the advice to other archetypes identified.

The end goal for this research is that it could be adaptable to an online database and advice tool, using a user-friendly interface that has a reach outside the academic community to be used in the building industry as well.

7 Conclusion

In conclusion, this research addresses the challenges associated with energy retrofitting on non-residential and heavyweight materials (such as stone, brick, and concrete) heritage buildings in Norway. The main objectives were to develop an advice template that effectively presents retrofitting measures, identifies necessary information from buildings and support literature, systemises a strategy for compiling data from the diverse Norwegian building stock, and structures an appropriate template for a recommendation report. The objectives were continuously assessed under the energy benchmarks and unique preservation requirements of protected buildings.

The research has employed a systematic approach to presenting retrofitting measures in an organised and precise manner. By categorising and classifying retrofitting actions given by successful Norwegian case studies and literature reviews, the advice template provides a streamlined framework for communicating recommendations. This ensures that building owners and stakeholders can easily understand and implement the proposed measures, leading to tangible energy efficiency improvements.

Extensive information collection from buildings and support literature was conducted to provide specific and suitable advice measures. This involved analysing the existing energy retrofitting process and its benchmark and historical significance of the targeted building stock. By considering these two aspects, the research ensures that the advice measures are tailored to the unique characteristics and requirements of each building, maximising the potential for successful retrofitting outcomes.

The complexity and abundance of the Norwegian building stock presented a significant challenge in compiling information for the research within a manageable timespan. To address this, a systematic strategy was devised to prioritise and gather relevant data from a representative sample of buildings. This approach allows for a comprehensive understanding of the building stock while ensuring that the research remains feasible and practical within the given timeframe. The method was to classify buildings by some characteristic features (archetypes) to later focus on one more representative among the building stock and create an advice template based on them.

After acknowledging the Norwegian case studies to be used, the investigation gathered data from literature reviews. The process relied on a cluster approach, mapping articles by their content in categories related to the desired advice output. By having this, advice was given more accurately based on specific research from each article category.

Developing an adequate template for a recommendation report was critical to this research. By selecting an appropriate building typology, the template was tailored to the specific needs and conditions of the targeted heritage buildings. For a reliable outline, creating a data collection template was first necessary to ensure the support data for advice was suitable to the archetype conditions. From the data collected, then, generate the recommendation outline.

The template structure incorporates two relevant sections: technical, energy, and architectural and heritage to base the retrofitting measures. This ensures that the recommendation report provides a comprehensive framework for decision-making and facilitates the smooth execution of retrofitting projects.

The most influential trends in the results were related to the diagnosis of retrofitting advice for the selected archetype, suggesting that many measures can be applied to multiple archetypes. Still, the focus is on eliminating incompatible measures based on heritage conditions. The results also provide a range of measures that may be more or less suitable overall. The suggested interventions and materials were based on literature and selected, considering benefits, drawbacks, and technical considerations. Trends indicate that technical and energy parameters were prioritised in Norwegian cases, while architectural and heritage aspects drew from other literature suggestions. The chosen measures benefited energy performance and comfort but posed a higher risk to heritage preservation when prioritising energy goals.

It is highlighted that the advice template is not intended as a one-size-fits-all solution but rather as a flexible framework that can be adapted to the unique characteristics of each building. It encourages a holistic approach considering the context, building typology, and stakeholder requirements.

Given the assumptions taken, the research has some expected uncertainties and threats. The study explored various aspects of creating an advice template. Still, it highlighted the potential loss of precision when grouping buildings based on general qualities. It proposed an alternative approach using case studies and energy/heritage databases for more reliable advice. The study also emphasised the need to carefully select archetypes, as different building types may require varying measures and affect the template structure.

It was acknowledged then, that following the results from the advice, the primary aim was to perform a trial demonstration of renovation advice despite knowing that areas not covered should also be addressed to have a complete guideline structure.

Finally, it is worth mentioning that this study left valuable insights, but more research is required. It is crucial to examine other aspects related: First, the economic feasibility of retrofitting measures and investigating various funding options. Second, to perform life-cycle assessments that can aid in evaluating environmental consequences and comparing different materials and technologies. Third, emphasizing stakeholder engagement and societal acceptance is vital to promote involvement in retrofitting projects, and lastly, integrating renewable energy sources like solar power should be approached cautiously to maintain a balance between architectural integrity and energy efficiency. These considerations are needed to continue developing a reliable guideline that contains the investigated in the current research and expands it, and spreads throughout other archetypes identified but not addressed yet.

Overall, this research has successfully addressed the research questions and achieved its objectives by creating an advice template for energy retrofitting on non-residential and heavyweight materials heritage buildings in Norway. The template offers an organised and clear presentation of retrofitting measures from a complex and intricate set of information, utilising comprehensive information collection, implementing a manageable strategy for data compilation, and structuring an adequate recommendation report. This research contributes to the sustainable preservation and energy efficiency improvement of Norway's heritage building stock by providing practical guidance and facilitating informed decision-making.

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8 Bibliography

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9 Appendices

Appendix 1 Literature cases database

Discarded articles are highlighted in yellow

1. Refurbishment concepts for a student housing at the Otto Wagner Areal in Vienna under the aspects of sustainability, energy efficiency and heritage protection
2. Evaluating the impact of indoor insulation on historic buildings: A multilevel approach involving heat and moisture simulations
3. Integration of energy-efficient ventilation systems in historic buildings—review and proposal of a systematic intervention approach
4. Energy in cultural heritage: The case study of Monasterio de Santa maria de Montero in Galicia
5. Energy retrofitting of dwellings from the 40's in Borgata Trullo -Rome
6. The protection of the Baserri as an energy efficient building: The optimized insulation strategy
7. A new decision guidance tool for the adoption of energy retrofit solutions in historic buildings.

   Evaluating the impact of indoor insulation on historic buildings: A multilevel approach involving heat and moisture simulations
8. Historic building energy audit and retrofit simulation with hemp-lime plaster-A case study.
9. Refurbishment of historic buildings at a district scale: Enhancement of cultural value and emissions reduction potential

   Thermal retrofitting, refurbishment, and re-use of traditional and historic building stock in Malta: A cost-sensitive, value-added approach
10. Thermal insulation alternatives of historic brick buildings in Baltic Sea Region
11. Visual documentation process of historic building refurbishment "Improving energy efficiency by insulating wall cavity".
12. The use of natural stone as an authentic building material for the restoration of historic buildings in order to test sustainable refurbishment: Case study.
13. On an innovative integrated technique for energy refurbishment of historical buildings: Thermal-energy, economic and environmental analysis of a case study
14. Optimal and sustainable plant refurbishment in historical buildings: A study of an ancient monastery converted into a showroom in Florence.
15. Energetic refurbishment of the historic windows of the listed heritage building Alte Schafflerei and its influence on the overall energy balance
16. Simulation aided optimization of a historic window's refurbishment.
17. Refurbishment of the concrete-glass windows of Aachen City Hall

    Refurbishment of Timber Floors with Screwed CLT Panels: Tests on Floor Elements and Connections

    Refurbishment of a historical building-design issues
18. Development of an aerogel-based thermal coating for the energy retrofit and the prevention of condensation risk in existing buildings.
19. Evaluation of natural-based internal insulation systems in historic buildings through a holistic approach.
20. Conservation and Innovation – The Challenge of 'Eco' Renovation in Heritage Buildings.
21. From the dynamic simulations assessment of the hygrothermal behaviour of internal insulation systems for historic buildings towards the hello project.

    Historic building energy audit and retrofit simulation with hemp-lime plaster-A case study.
22. Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: A cultural properties case study.
23. Applied Research of the hygrothermal behaviour of an internally insulated historic wall without vapour barrier: In situ measurements and dynamic simulations.
24. Towards Resilience and Sustainability for Historic Buildings: A Review of Envelope Retrofit Possibilities and a Discussion on Hygric Compatibility of Thermal Insulations.

    Eco-efficiency in early design decisions: A multimethodology approach
25. Climate resilience of internally insulated historic masonry assemblies: Comparison of moisture risk under current and future climate scenarios.

    Examining the attitude-behaviour gap in residential energy use: Empirical evidence from a large-scale survey in Beijing, China
26. The evaluation of historic building energy retrofit projects through the life cycle assessment.
27. Optimizing energy efficiency and thermal comfort in building green retrofit.
28. Enhancing the sustainability and energy conservation in heritage buildings: The case of Nottingham Playhouse.
29. Interstitial hygrothermal analysis for retrofitting exterior concrete wall of modern heritage building in Korea.
30. Hygrothermal performance of an internally insulated masonry wall: Experimentations without a vapour barrier in a historic Italian Palazzo.

31. Potential retrofits in office buildings located in harsh Northern climate for better energy efficiency, cost effectiveness, and environmental impact.
32. Overheating Risks and Adaptation Strategies of Energy Retrofitted Historic Buildings under the Impact of Climate Change: Case Studies in Alpine Region.
    Protective energy-saving retrofits of rammed earth heritage buildings using multi-objective optimization.
33. An energy retrofit roadmap to net-zero energy and carbon footprint for single-family houses in Canada.
34. Retrofit Proposals for Energy Efficiency and Thermal Comfort in Historic Public Buildings: The Case of the Engineering Faculty's Seat of Sapienza University
35. Hygrothermal Performance Evaluation of Internally Insulated Historic Stone Building in a Cold Climate
36. Energetic refurbishment of historic brick buildings: Problems and opportunities
37. Efficiency and comfort through deep energy retrofits: Balancing energy and moisture management.
38. The thermal retrofitting of walls, windows, and ceilings in traditional Scottish buildings.
39. Energy upgrade to Passive House standard for historic public housing in New Zealand.
40. Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process.
41. Environmental impact trade-offs in building envelope retrofit strategies.
42. Adaptive reuse of buildings: Eco-efficiency assessment of retrofit strategies for alternative uses of an historic building.
43. Thermal performance of internally insulated historic brick building in cold climate: A long term case study.
44. Influence of envelope properties on interior insulation solutions for masonry walls.
45. Influence of human behaviour on cool roof effect for summer cooling.
46. Thermal-energy analysis of roof cool clay tiles for application in historic buildings and cities.
47. Green roofs to improve the energy renovation resilience of historic buildings.
48. Green systems integrated to the building envelope: Strategies and technical solution for the Italian case.
49. Historical building renovation and PV optimisation towards NetZEB in Sweden.
50. Integrated retrofit solutions for improving the energy performance of historic buildings through energy technology suitability analyses: Retrofit plan of wooden truss and masonry composite structure in Korea in the 1920s.
51. Historic building energy conservation with wooden attic using vacuum insulation panel retrofit technology.
    Balanced design for blast-mitigating window retrofits for historic structures
52. Heating, ventilating and cooling impacts of double windows on historic buildings in Mediterranean area.
53. Energy retrofit interventions in historic buildings: Exploring guidance and attitudes of conservation professionals to slim double glazing in the UK.
    Wooden windows in the historic alpine architecture: Balancing energy and conservation needs
54. A method for sustainable lighting, preventive conservation, energy design and technology-Lighting a historical church converted into a university library.
55. Internal wall insulation with a new aerogel panel: SLENTITE® for energetic retrofit in historic buildings.
56. Conservation-compatible retrofit solutions in historic buildings: An integrated approach.
57. Comprehensive energy renovation of two Danish heritage buildings within IEA SHC task 59.
58. Balancing Trade-offs between Deep Energy Retrofits and Heritage Conservation: A Methodology and Case Study.
59. A Review on Technical Challenges and Possibilities on Energy Efficient Retrofit Measures in Heritage Buildings.
60. A transdisciplinary approach on the energy efficient retrofitting of a historic building in the Aegean Region of Turkey.
61. Modelling and calibration of a high-mass historic building for reducing the prebound effect in energy assessment.
62. Innovative technologies for energy retrofit of historic buildings: An experimental validation.
63. Assessing the needs and gaps of building information technologies for energy retrofit of historic buildings in the Korean context.
64. Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building.
65. Development and evaluation of an automatic steam radiator control system for retrofitting legacy heating systems in existing buildings.
66. Potential of GSHP coupled with PV systems for retrofitting urban areas in different European climates based on archetypes definition.
67. Hotel Adapted to the Requirements of an nZEB Building—Thermal Energy Performance and Assessment of Energy Retrofit Plan.
    Historical building acoustical retrofit: An experimental examination of traditional wooden floors
68. Reconciling energy and heritage: Retrofit of heritage buildings in contexts of energy vulnerability.
69. On an innovative approach for microclimate enhancement and retrofit of historic buildings and artworks preservation by means of innovative thin envelope materials.
    A method for sustainable lighting, preventive conservation, energy design and technology-Lighting a historical church converted into a university library.
70. Historical buildings' energy conservation potentialities: A methodology focused on building operation.

71. Investigating the potential impact of energy-efficient measures for retrofitting existing UK hotels to reach the nearly zero energy building (nZEB) standard.
72. An integrated energy and environmental audit process for historic buildings.
73. Energy and Seismic Retrofit of Historic Buildings in New Zealand: Reflections on Current Policies and Practice.
    Heritage retrofit and cultural empathy; a discussion of challenges regarding the energy performance of historic UK timber-framed dwellings.
74. Retrofit strategies for energy efficiency of historic urban fabric in Mediterranean climate.
75. An AHP-based methodology for the evaluation and choice of integrated interventions on historic buildings.
76. Deep renovation of historic buildings: The IEA-SHC Task 59 path towards the lowest possible energy demand and CO2 emissions.
77. Methodological approach for performance assessment of historical buildings based on seismic, energy and cost performance: A Mediterranean case.
78. Planning energy retrofit on historic building stocks: A score-driven decision support system.
79. Impact of climate change in cultural heritage: from energy consumption to artefacts' conservation and building rehabilitation.
80. Facility energy management application of HBIM for historical low-carbon communities: Design, modelling and operation control of geothermal energy retrofit in a real Italian case study.
    Energy retrofit infill panels for historic timber-framed buildings in the UK: physical test panel monitoring versus hygrothermal simulation.
81. Making good decisions: avoiding alignment problems and maladaptation in retrofit and construction.
    Performance assessment of hygrothermal modelling for diagnostics and conservation in an Italian historical church.
82. Risk-benefit assessment scheme for renewable solar solutions in traditional and historic buildings.
    Performance of passive retrofit measures for historic buildings that house artefacts viable for future conditions.
83. Beyond cultural and historic values, sustainability as a new kind of value for historic buildings.
84. The smart evolution of historical cities: Integrated innovative solutions supporting the energy transition while respecting cultural heritage.
85. Indoor environmental quality evaluation strategy as an upgrade (Renovation) measure in a historic building located in the Mediterranean zone (Athens, Greece).
86. Exploring the relationship between environmental and economic payback times, and heritage values in an energy renovation of a multi-residential pre-war building.
87. Applying international guidelines on historic building's retrofit in New Zealand: A critical context view.
88. Methodology for energy retrofitting of Modern Architecture. The case study of the Olivetti office building in the UNESCO site of Ivrea.
89. Integrated computational approaches for energy retrofit of historical buildings in extreme climate environments.
90. Integration between photovoltaic systems and cultural heritage: A socio-technical comparison of international policies, design criteria, applications, and innovation developments.
91. Measurement and Diagnosis of Comfort in a Historic Building.
92. Developing a database of energy use for historic dwellings in Bath, UK.
93. The use of Passive House Planning Package to reduce energy use and CO 2 emissions in historic dwellings.
94. Building with history: Exploring the relationship between heritage and energy in institutionally managed buildings.
95. A method to assess the potential for and consequences of energy retrofits in Swedish historic buildings.
96. EFFESUS methodology for assessing the impacts of energy-related retrofit measures on heritage significance.
97. Energy study of a non-residential and historic building in transient conditions.
98. Energy retrofit of historic and existing buildings. the legislative and regulatory point of view.
    Lessons learned: ASHRAE's approach in the refurbishment of historic and existing buildings.
99. Dynamic simulation and on-site measurements for energy retrofit of complex historic buildings: Villa Mondragone case study.
100. The experience of international sustainability protocols for retrofitting historical buildings in Italy.
101. Thermal and Economic Analysis of Renovation Strategies for a Historic Building in Mediterranean Area.
    Energy retrofit interventions in historic buildings: Exploring guidance and attitudes of conservation professionals to slim double glazing in the UK.
102. The future of historic buildings: Retrofitting to improve the thermal performance of New Zealand architectural heritage.
103. CO2 based ventilation control in energy retrofit: An experimental assessment.
    Assessing the needs and gaps of building information technologies for energy retrofit of historic buildings in the Korean context.
    Performance optimization of a demand-controlled ventilation system by long term monitoring.
104. Daylight performance of classrooms in a Mediterranean school heritage building.

105. Performance of hydrophobized historic solid masonry – Experimental approach.
106. Retrofit Room in Roof insulation: Guide to best practice.
107. From "16 to 1"– Retrofitting airtightness of roofs in existing buildings from the inside.
108. Aligning historic preservation and energy efficiency: legal reforms to support the greenest buildings.
109. Projektbeschreibung und Fotodokumentation - Fassadensanierung Bauernhof Trins.
110. Aerogel materials for heritage buildings: Materials, properties, and case studies.
111. A material characterization and embodied energy study of novel clay-alginate composite aerogels.
112. Developing of an Internal Insulation System made of wood-fibre boards for energy-efficient retrofitting of heritage buildings in Vienna.
113. Energy Efficiency and Historic Buildings: Insulating Solid Ground Floors
114. Responsible Retrofit Guidance Wheel
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