Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Zohaib Ali

Whole building life cycle Assessment (WBLCA) of an adaptive reuse of a heritage building: A case study of an Industrial building

Master's thesis in Industrial Ecology Program
Supervisor: Edgar Hertwich
Co-supervisor: Sahin Akin
July 2023

NTNU
Norwegian University of
Science and Technology

Zohaib Ali

Whole building life cycle Assessment (WBLCA) of an adaptive reuse of a heritage building: A case study of an Industrial building

Master's thesis in Industrial Ecology Program
Supervisor: Edgar Hertwich
Co-supervisor: Sahin Akin
July 2023

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

NTNU
Kunnskap for en bedre verden

DEPARTMENT OF ENERGY AND PROCESS ENGINEERING

MASTER THESIS

Whole building life cycle Assessment(WBLCA) of an adaptive reuse of a heritage building: A case study of an Industrial building

---

Author:

Zohaib Ali

Date:07/11/2023

Table of Contents

List of Figures

List of Tables

1 Acknowledegment

This thesis has been submitted to Norwegian University of Science and Technology, Trondheim, Norway, in line with the requirements of completing Masters degree Program in Industrial Ecology. The thesis has been completed at the department of Energy and process engineering with Professor Edgar Hertwich, and co-supervisor Sahin Akin. The work is part of the project ARV.

I would like to extend my gratitude to all for providing necessary guidance. Starting from, Professor Edgar Hertwich, Post doc candidate Jan Sandstad Næess, PhD scholar Sahin Akin, Eirik from KONTUR arkitekter (Architectural firm) and Eirik Resch from Reduzer. I would also like to thank a dear friend and ex-colleague Mohammad Ali Abu Shariah for all whatsapp voice notes and remote discussions. And Hany Mina for all the support.

Additionally, my colleague, Chibuikem has always been there to discuss and tackle the challenges encountered.

And most importantly, I'm grateful for having a wonderful and supportive wife who managed her own Masters degree and taking major responsibilities when it comes to kids.

With the help of this thesis, i have been able to improve my understanding about the whole building life cycle assessment including the embodied and operational emissions associated with the built environment. This would potentially fill the gap related to my previous work experience and moving forward it will allow me to technically and critically review the aspects associated with the built environment.

The Journey has been challenging from the day 1 of Industrial ecology Masters program, but it is worth the knowledge, skills and tools gathered during the program in general and thesis in particular.

Leaving a comfort zone is challenging and endearing.

2 Abstract

Building refurbishment and adaptive reuse is known to have less environmental impacts when compared with the demolition of the existing building and constructing a new building. However, refurbishment and adaptive reuse processes of the building can potentially increase the upfront embodied emissions which are offset due to better operational energy performance. This study explores benefits associated with the reuse of materials (avoided emissions due to in-situ materials) and comparing renovation and new construction . Additionally, for holistic analysis, Operational energy phase (B6) has been considered and assessment has been expanded to see the changes when buildings are upgraded to TEK 17 minimum or more advanced energy efficiency levels . It is achieved through conducting a whole building life cycle assessment (WBLCA). In order to understand and visualize this further, a case study building was selected in Oslo. The building was originally built in 1922, and went through the changes for adaptive reuse (function of the building changed and refurbishment process took place). The results were compared with a hypothetical new construction (Material inventory without reuse) and further scenarios were developed to understand the influence of materials and energy trade off. Additionally, the potential of renewable energy was considered as part of the assessment. The case study showed that with regards to refurbishment process the product phase (A1-A3) and operational phase (B6) are dominating in spite of demolition phases. Overall emission reduction ranges from 7-9 % when compared with New construction. And it would approximately 20 years for the minimum renovated building to offset a newly construction energy efficient building.

To estimate the amount of CO_2-eq emissions associated with the selected building elements and there components, the inventory was gathered from BIM model of the project. Operational energy requirements were determined through the use of IDA ICE and total emissions were determined through the use of Reduzer (LCA software).

The findings confirmed that it was more environmentally friendly to refurbish and adaptively reuse old historic and redundant buildings.

3 Introduction

Buildings historically are known for extensive energy consumption. The energy can be in the form of embodied or operational. The consumption of energy leads to production of green House gas emission (GHG) leading to a subsequent increase in the Global warming potential (GWP) associated with the construction industry. Building renovation has gained considerable spike after the introduction of European green deal and renovation drive.

This research is part of the ARV (Norwegian word for “heritage” or “legacy”) project under H2020 commenced in January 2022. The project comprises of 3 conceptual pillars, 6 demonstration projects, and 9 thematic focus areas. It focuses on the development of climate positive circular communities and promotes the refurbishment of heritage buildings to a high energy standard. ARV project has 6 different demonstration communities namely Czech Republic, Denmark, Italy, The Netherlands, Norway, and Spain. Voldsløkka School and Cultural area in Uelands gate 85, 0462 Oslo, Norway is the **demonstration project in Norway**.

4 Structure of thesis

In order to maintain the continuity of the thought and coherence, the thesis has been split it following chapters:

- Module -01

  This module simply reflects on the recent updates of Climate Change (CC), Green house gas (GHG) emissions and trends of refurbishment at local, regional and global level. It is attempted to identify additional aspects when assessing the adaptive reuse of the buildings. Based on the same, the problem statement is is formulated and research questions are established.

- Module- 02

  The module provides precise information about the jargon associated with different terminologies when it comes to adaptive reuse, renovation, retrofitting etc. And then develops the link among them. Additionally, the debate about the adaptive reuse and demolition will be assessed in this section and recent trends, external and internal factors are explored contributing to the adaptive reuse of the old historical buildings in general and for the industrial buildings in particular. Moreover, different approaches of estimating the benefits associated with adaptive reuse are analysed.

- Module -03

  Module will provide in-depth understanding of methodology and research design. The chapter represents the case study, followed by the approach for determining the embodied and operational emissions associated with the building. Data collection sources and benchmarking are discussed in this module.

- Module -04

  Results for embodied and operational emissions are presented followed by comparative assessment . The results are presented across different elements and life cycle stages for onward comparison among different scenarios. The analysis also include the emissions payback time period and the benefits beyond the payback. The benefits will also explain if the targets for 2050 can be met in the context of adaptive reuse of the building .

- Module-05

  Discussions will provide further context and understanding of the results as obtained in Module 04. And in the light of the findings the research questions will be evaluated. In this chapter the shortcomings and benefits of similar research are further divulged and importance of such analysis are discussed.

- Module-06

  Conclusions and way forward are presented here along with recommendation to avoid similar challenges while exploring the benefits of such buildings.

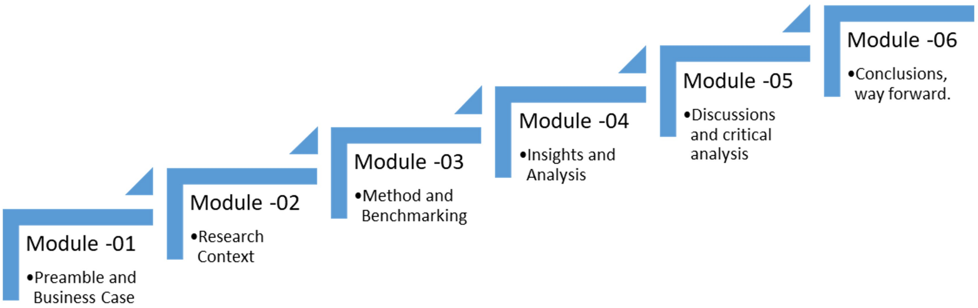


Figure 1: Progressive development

5 Module 01-Business Case

Buildings are responsible for consumption of considerable natural resources and inducing negative environmental impacts[1]. Throughout the lifespan of the building, energy is required to keep it habitable. The energy is either used in the manufacturing of materials and products for the construction and maintenance or it is continuously used for thermal comfort of the inhabitants [2]. Sourcing and utilization of energy required for the buildings have its environmental impacts during the life cycle.Around 30–40 % of global CO_2 emissions are attributed to building stock [3]. While the environmental impacts from operational energy use are mitigated through through the introduction of energy efficiency measures on the demand and supply side, the emissions attributed to production of materials (namely embodied emissions) are also gaining importance. Therefore , in order to reduce the embodied emissions, building refurbishment together with adaptive reuse are considered to have been mostly suggested by the scientists and designers[4]. In line with Paris agreement, Norway aims for up to 55 % reduction in Green house gas(GHG)emissions by 2030 when compared with 1990 levels with an aim to be low emission society by 2050. 85-90 % of the current building stock in EU is likely to be in use by 2050, and options like refurbishment and adaptive reuse of buildings can potentially contribute in achieving targets with regards to emissions[5]. Additionally, Owing to accelerating de-industrialization in Norway since 1980's, considerable large number of industrial buildings are awaiting new use or demolition[6]. Adaptive reuse of such buildings will also contribute to the overall aim of becoming a low emission society.

Building sector and its significant contributions towards energy consumption and associated emissions continue to rise despite global efforts, approximately 40 % of energy consumption and 36% of EU's GHG's are attributed to buildings[7]. EU has been at the forefront in tackling climate change impacts and developing policies and guiding principles in mitigating the climate risks. Owing to recent changes in climate targets from 40 % to 55 % in GHG emission cut, EU through EU green deal has set the road map for achieving the revised targets. The environmental impacts associated with the materials termed as embodied impacts have gained considerable traction. The focus has shifted from operational energy use in terms of buildings to curtailing the impacts arising from extraction and production of materials. In order to achieve revised EU targets and embodied emissions, the EU has set embarked on renovation wave, with a target to double the renovation rate for public and private buildings. During the process, the energy efficiency measures will be introduced, and refurbishment will be encouraged over new construction leading to less strenuous natural resource scarcity [8]. Additionally, owing to recent pandemic the construction sector has seen contraction and this may further slow down the energy efficiency measures which will further lead to divergence from the target in reducing the GHG emissions associated with the buildings. Potential of harnessing renewable energy has also been investigated to reach the Net zero emissions building -O for old historic buildings in recent times[9].

Considering the above, the evaluation of environmental performance through LCA for existing buildings and renovated buildings while utilizing a transparent and harmonized methods, will enable avoiding problem shifting. And it can also provide insights in following up the emission reduction ambitions. The current study will provide an understanding about the net environmental benefits and cost implications associated with the renovation of the building for adaptive reuse.

With the formulation and promulgation of the European green deal, the construction industry is currently experiencing an impetus as all future development in the building sector needs to be energy and resource efficient. In order to facilitate such transition and that too on extensive scale, EU is collaborating with other stakeholders for promoting Research and innovation. H2020 is one such funded project which lasted for 6 years and then it was succeeded by Horizon Europe, and it will continue until 2027.

ARV(Norwegian word for “heritage” or “legacy”) project under H2020 commenced in January 2022. The project comprises of 3 conceptual pillars, 6 demonstration projects, and 9 thematic focus areas. It focuses on the development of climate positive circular communities and promotes the refurbishment of heritage buildings to a high energy standard. ARV project has 6 different demonstration communities namely Czech Republic, Denmark, Italy, The Netherlands, Norway, and Spain. Voldsløkka School and Cultural area in Uelands gate 85, 0462 Oslo, Norway is the **demonstration project in Norway**. The project includes the construction of new building and refurbishment of an old existing building. The project key stakholders are mentioned below in the table.

Table 1: Project Stakeholders

	Details
Owner	Undervisningsbygg Oslo KF
Contractor/ Builder	Veidekke Entreprenør AS
Project Design Consultant	Norconsult AS
Architect	KONTUR arkitekter AS
Roof Manufacturer and supplier	Lett-Tak Systemer AS

6 Module 02- Background

Although, environmental benefits associated with renovation have long been investigated, but there is no clear approach for investigating refurbishment and/or adaptive reuse. The level of granularity varies in each study. A thorough assessment of an existing building can be a challenging task and could potentially include considerable time and multiple stakeholders. Therefore, the assessment carried as part of the thesis will likely yield interesting outcomes that can be useful for the Industrial heritage building as well as for the built environment.

The case study was chosen to understand the environmental benefits and trade off associated with adaptive reuse. Since the building transformation was already in process, therefore the literature review was done retrospectively to understand the available current practices for investigating environmental benefits of such case study.

The most relevant parts for such kind of investigations like key definitions, adaptive reuse, retrofitting, material inventory, assessment methodology and service life of the building after renovation were considered during the literature review.

Environmental evaluations carried out for heritage buildings are further represented in this section with the focus to address the key considerations while transforming an industrial heritage building. The study is likely to bring forth the limitation, challenges and benefits associated with the intervention of an existing building.

As part of the literature review, the scopus(science direct database), google scholar were considered for further shortlisting of the relevant and appropriate selection of the research articles.

Primary key words considered for onward investigation included ”adaptive reuse of industrial buildings”, ”life cycle assessment in historical buildings”, ”heritage building”, ”circular economy in historical buildings”, ”Renewable energy and adaptive reuse” were considered.

In line with the research aim and objective, the articles were selected for onward scrutiny. Approximately 50 plus articles were extracted through science direct and snow balling.And approximately 30 were selected for onward review and understanding of the adaptive reuse of the buildings.These include only core topics.Additional information about the terminologies, applicable and local international standards were additional to these studied research articles.

Research articles above and beyond year 2000 were considered while shortlisting the articles for onward review.

There can be multiple jargon and challenges in understanding the terminologies that have been considered when conducting the Life cycle assessment which includes existing building.

For simplification purpose. The terminologies are addressed initially, followed by the more details about the literature and background about has been investigated.

6.1 Defining key terminologies relevant to adaptation in buildings

Existing building undergoing modification encompasses different variety of jargon which may include the terms, reuse, retrofit, renovation, refurbishment that are used interchangeably.[10] represented basic terminologies revolving around building adaptation in two main categories

6.1.1 Refurbishment

The process of enhancing the existing building prevailing conditions through repair, maintenance and replacement of existing systems and incorporating energy conservation measures so that building can fulfil the prevalent building standards while ensuring the **same use** (i.e. the original function remains the same). For instance, adding more insulation, replacing windows and changes in HVAC system along with other passive measures like changing window to wall ratio fall. Refurbishment is further categorized into the following:

- Retrofitting
  Retrofitting comprises of adding materials, products and components that were not existing in the building for the implementation of energy conservation in the existing building that will reduce the energy use or improve the energy efficiency.
- Renovation
  Building renovation of an existing building focuses on the **aesthetic aspects** and can include structural or non-structural improvements.Therefore, a window replacement or fixing and changes in the interior layout of an existing building can be considered renovation.
- Rehabilitation
  Rehabilitation mostly addresses the structural integrity of the building and repairing or changing structure, envelope and HVAC systems.

6.1.2 Adaptive reuse

Adaptive reuse is the process of reusing an obsolete, redundant, old, abandoned building by completely changing its original function for which the building was originally built. During the process, building materials, products and components are either reused on site or they are used for different purposes. Adaptive reuse is further categorized into below:

- Conversion
  Building conversion comprises of considerable changes to those buildings which are not used anymore or which do not meet the demands of their users. As part of conversion, either refurbishment (retrofitting, renovation, rehabilitation) takes place.
- Material reuse
  Material reuse process includes partial repair or refurbishment of recovered materials to be used more than once for different purpose or reuse of the materials in the same building.

Additionally, Building **renovation, conversion and material reuse,** can involve both structural and non-structural elements.

In light of above, onward mention of the term refurbishment would capture rehabilitation, retrofitting, renovation. Whereas, the adaptive reuse would reflect the conversion and material reuse.

Additionally, it is also imperative to understand the different life cycle stages occurring during the renovation process. The author believes that due to multiple layers (existing, during renovation, post-renovation) along with different life cycle stages of building LCA, the simplication is required. Therefore the below table provides more insights.

Table 2: Life cycle stage relevant to adaptive reuse

	Details
Existing Building Product and construction Stage-A	A1- A5 (initial product and construction for the building considered for renovation
Existing building Use Stage	Module B of the existing building before renovation
Existing building End of life(EOL)	C1- C4 stage of the building before renovation, it can be partial or complete.
Existing Building D Stage	Reuse, recycle and recovery before renovation
Reused use stage(Module B)	This includes B1, B2, B3, B4 of in-situ or materials reused
Reused EOL stage	C1-C4 for items that were in-situ or reused.
Reused D Stage	Reuse, recycle and recovery of materials for in-situ materials.
New Products Product and Construction Stage	A1-A5 of new materials added during renovation.
New Use stage(Module B)	B1, B2, B3, B4 after renovation has taken place.
New EOL stage	Includes C1-C4 of the newly added materials.
New D stage	Reuse, recycle and recovery newly added materials.

This is also further illustrated in the image below which demonstrates the life cycle stages that been considered for this Master thesis and explaining more about the selected literature.

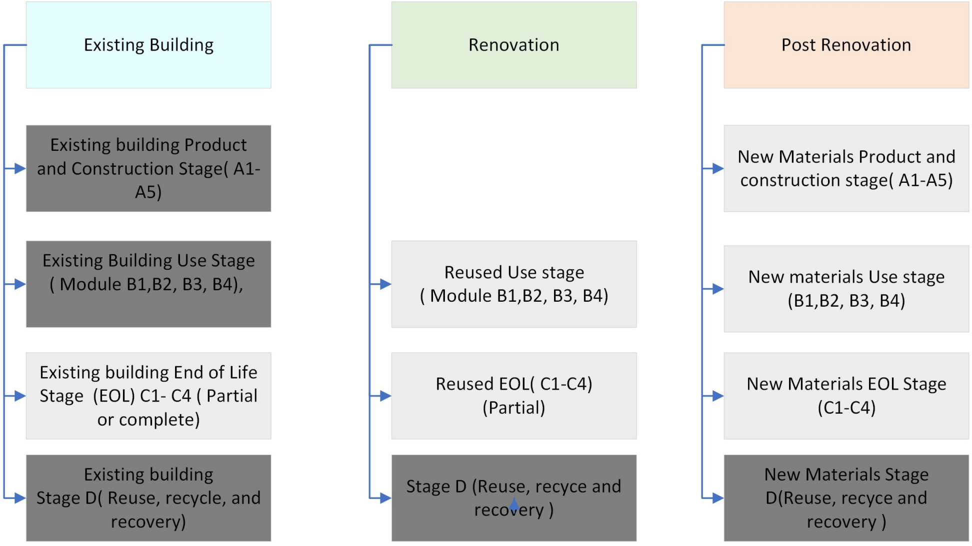


Figure 2: Life cycle stages during adaptive reuse (Source: Adopted from[11])

6.2 New construction Vs Demolition

[11] noted that many studies have been conducted with the focus on the refurbishment and assuming that all other components do not change barring the intervention that has been carried out to improve the energy performance of the existing building.This can be introduced on supply or demand side through active and passive measures (e.g. additional insulation, HVAC system etc.) In other words, A1-A5, B1-B4 along with B6 due to newly added materials are compared with B6 from the existing building. These are generally refurbishment projects where the building function remains the same. Due to introduction of new materials and available information about the energy use of existing building, the energy or emissions pay back can be computed. One of the key assumption in such studies include that other building components remain the same before and after the refurbishment.

[4]concluded in a review paper that during the refurbishment of a project, Existing building Stage A, B and **D** are generally excluded. Reused use stage(Module B) for materials that have reused. And all life cycle stages for new materials are considered. Additionally, it is optional to use EOL for existing building and Reused EOL.

Examining more seminal studies focusing on renovation when compared to new construction, different system boundaries selection have been noted.[**empty citation**] fey et.al conducted the LCA of seven building types across four locations based while comparing renovation (EOL of existing building-partial) along with newly added materials all life cycle stages) and new construction (EOL of existing building - complete along with newly added materials with all life cycle stage. **Embodied and operational** emissions were considered, However, **stage D was excluded**. The operational energy use was streamlined by having a base case (minimum energy efficiency measures) and advanced case (more intense energy conservation measures).

Similarly, [12]concluded that it is better to demolish the old and existing building(Norwegian Bank headquarters,) due to considerable cost associated with operation and maintenance required.Renovation scenario included (EOL of existing building- Partial demolition and Reused Use stage(Module B2,B3, B4) whereas the New construction included (EOL of existing building- complete demolition and Newly added materials product and Use stage). **Embodied and Operational emissions were considered**. Whereas, EOL stage C(New and reused) and **Stage D** was excluded.

Another study,[**empty citation**] considered only renovation scenario (Existing EOL and Only New product and construction stage(A1-A5) compared to new construction scenario (Existing building EOL- complete and New product and construction Stage (A1-A5)).All other stages were excluded.

Only two studies were found which considered the stage D while comparing renovation and new construction. Two studies which included the Stage are further elaborated. [1] introduced a methodology to compare renovation and construction with respect to Primary energy demand, GWP and cost. Renovation included (EOL of Existing building- Partial and Newly added materials) compared with the new construction (EOL of Existing Building- Complete demolition and New added materials will all life cycle stages).The emissions from the in-situ materials were calculated and then subtracted from the total. The emissions associated with the in-situ materials were considered at %100.

Similarly,

[11] used a hypothetical construction (which is a combination of existing building and newly added materials)for comparative assessment. However, only embodied emissions were considered and A5, B1, B6, B7 and D were excluded. The elements of the building assessed included only structural and non-structural components and no systems. Renovation scenario included only newly added materials and reused use stage(B2, B3, B4) of the building elements. Whereas the new construction included existing building along with the newly added materials and all life cycle stages.

[13]used one click carbon designer tool for new construction comparative assessment. Emissions from existing building were **not** considered. As such, Renovation(Newly added materials all life

cycle stages) were compared with the New construction(carbon designer tool).In all scenarios, the environmental impacts from additional materials and components were considered,whilst existing materials have been considered as carbon neutral.

In order to determine the environmental impacts, ([11]) combined the existing building along with the new materials/products and defined it as a new construction scenario, whereas for the renovation scenario, new materials/products and use stage of the reused components was considered. Six impact categories were assessed using BIM and TRACI with the focus on environment as compared health. The results indicated considerable reduction. By applying this approach to a case study, the result indicated 53 to 75 % reduction across the selected impact categories and a maximum of 75% reduction in GWP.

[14]introduced a new tool for determining the GHG emission payback for LEED projects and expanded the system boundary to include the MEP systems as well. The project followed refurbishment approach and considered the embodied emissions of the materials that will be added on top of the baseline building.

This master thesis is considering similar hypothetical scenario for comparative assessment, however, reuse of materials (in-situ) and B6 has been considered to develop more understanding about the whole building life cycle assessment comparing new advanced buildings with the renovated building with minimum energy level. Additionally, renewable energy potential has also been considered.

Review articles have concluded that there is a varying degree in developing the scenarios and system boundaries when it comes to renovation vs replacement. And most of the studies are utilizing the concept of energy retrofits to determine the emissions payback time. This includes GHG emissions attributed to the renovation plus the operational energy efficiency post renovation when compared with the no renovation scenario. And in such scenarios it is assumed that non-retrofit materials will remain unchanged and as such will have identical impacts [4],[15],[5].

EN 16883 [11] states the importance of evaluating the environmental performance of heritage buildings from a life cycle perspective when making a decision on energy performance improvement measures.

[16] determined the life cycle emissions during while including the renovation stage only. And estimated that carbon reduction due to the refurbishment are over overestimated by 5.54% (from 29.59% to 35.13%) when embodied carbon is disregarded. In other words, when refurbishment is carried for a project, there are potential changes (partial demolition, addition of materials etc.)

which needs to be accounted for.

6.3 Refurbishment

Based on the literature review, the reused use stage of the building mostly includes energy retrofitting where the operational use (B6) phase of the building is considered after the renovation has occurred. For all other phases in the use stage, there is no clear indication about the emissions that are considered when in-situ materials have been considered. The refurbishment stage includes either B2, B3, B4 for existing/in-situ component or it is A1-A5 for new components. In other words, the emissions associated repair, maintenance and replacement have not been considered.

Cultural and historical buildings have been under discussion since long due to their inherent valuable characteristics and maintaining them while ensuring sustainability. Since, these buildings are old, the interventions need to be carefully implemented, translating to considerable time and cost for the developers. As such it is not of much interest to resources and as such it becomes less

This section provides insights about renovation of buildings in general and for adaptive use in particular, the emissions associated with the life cycle of the building stage and use of LCA framework for developing comprehensive understanding about the followed by formulation of research questions that will be addressed as part of the study.

Owing to climate change mitigation and adaptation, sustainability in built environment can be achieved through efficient use of earth's natural resources[17].In order to achieve the 55% emission reduction target by 2030, GHG emissions in the buildings needs to be reduced by 60%, whereas final energy and energy associated with heating and cooling by 14% and 18 % respectively[8].

Since buildings have been attributed to considerable emissions across its lifespan, there has been a spike in interest in improving a building's performance over their life cycle stages namely **production, construction, operation, and End-of-Life (EoL)**.

Studies have identified that through adaptive reuse, sustainability and circular economy can be achieved and it provides a suitable alternative to completely new building[15].

While some studies have focused on the environmental and economic benefits associated with the adaptive reuse[18]. Others have opted for developing criteria and framework in assessing the suitability for renovation of projects[4]. On other occasions, it has also been investigated to utilize the existing assets for achieving sustainability in urban settlements. While reusing the building has its advantages, there can be potential barriers and challenges in harnessing the benefits associated with reuse and due to the poor performance of buildings, these can be replaced with new [12]

Despite the above, there is still a lack of studies which provide a comprehensive life cycle analysis including the emissions that have been avoided due to the reuse of the materials. Lack of expertise, technical complexities and methodological intricacies makes it more challenging.

Additionally, there are not many studies which holistically conducted a complete LCA including all aspects when it comes to renovation vs replacement. As part of the study, embodied and operational emissions have been considered to provide more insights about the research aim.

[3]Demonstrated LCA comprising of both embodied and operational GHG emissions for an office building in Norway through the use of IDA ICE and One Click LCA. As part of energy conservation measures, All air system with Demand control ventilation(DCV) was compared with with radiator space heating and constant air volume (CAV). In all air system, the heating and cooling is controlled through air only. There is no liquid or hydronic side of the HVAC system. Through retrofitting scenarios, the net total emissions could be reduced up to 52% from 1336–637 kg carbon dioxide equivalent (CO2-eq)/m2. Embodied emissions were highest in product stage, followed by transportation and end of life stage. Building technical and envelope characteristics were modelled in IDA ICA and results were further assessed in One Click LCA along with other life cycle stages of building (A1- A5,B4-B5, C1-C4). Reference building (baseline) material inventory was calculated per building gross floor area through carbon designer tool and operational emissions were determined based on the TEK87 technical and envelope requirements. After establishing the embodied and operational emissions for the baseline building, the emissions attributed to the retrofitting scenarios are evaluated afterwards to note and record the changes due to retrofitting.It is to be noted here that reuse, recover and recycle potential is not considered in the system boundary. In other words the GHG emissions due to renovation phase and GHG emissions avoided due to reuse of the building materials on site are not considered.

6.4 Circularity

[1]concluded that adaptive reuse of the building is a superior alternative when compared with demolition and construction of new buildings. The aim was to analyze the net environmental benefits and cost performance for and adaptive reuse case for structural systems only, several studies indicate that structural systems substantial negative environmental load due to concrete and steel. GHG emissions and Primary Energy demand were evaluated under environmental impacts. The life cycle stages included A1-A5, C3-C4 and D. The focus of the study was on structural systems, as a result it did not focus on the operational energy us of the building. Two scenarios were compared. Baseline scenario included LCA of demolition and new construction. For the second

scenario, partial demolition and renovation works for adaptive reuse. At the both were compared to determine the environmental and cost benefits associated with the adaptive reuse. Module D with regards to this study included recycling of materials through avoided burden approach in which the burden of primary material production is allocated to the subsequent life cycle based on the quantity of recovered secondary material.

6.5 Life cycle emissions in buildings

Emissions in buildings are characterized by life cycle stages. Considerably significant energy use and associated emissions are attributed to the buildings. These emissions are spread over the life span of the building. Energy consumption associated with the buildings can be split into embodied energy and operational energy. And accordingly there will be embodied carbon operational carbon. the embodied carbon can also include carbon affecting by sequestration and chemical reactions. Owing to the consumption of energy in the production of materials, construction, operation and EOL, Embodied emissions occur at the initial stage of the building , they recur during the life span and are also found during the EOL of the building. While the operational emissions occur during the operational phase of the building due to energy consumption (e.g electricity, heat)[2]. As such, energy consumption excluding the operational stage is termed as embodied energy[19]. Most of the focus in the past 3 decades has been towards achieving operational energy efficiency, as 70-90 % of the energy in the building is attributed to operational phase. Owing to considerable advancements in technology, energy use reduction of 75% or higher can be achieved in an energy efficient building. Additionally, deep energy retrofit in 50-90 %. As such, the focus now has been shifted to embodied emissions associated with production, construction and EOL stage. This has led to the debate about trade-off between operational and non-operational embodied energy[20]. And it means that a building can potentially obtain high operational energy efficiency at the cost of increasing embodied energy due to more production of materials, construction, transportation and EOL treatment. Owing to the slow turnover rate of the building sector[21], the new energy efficient buildings would take several years to have a cumulative and considerable positive environmental impact. Therefore, there has been an impetus in the retrofitting, renovation and refurbishment of existing buildings.EN 16883[22] suggests the life cycle perspective in assessing the environmental performances when making a decision on energy performance of a heritage building.

6.6 Research Objections

The objectives of the study are:

1. To analyse the net environmental impacts because of adaptive reuse of the existing building associated with different renovation scenarios and new buildings.
2. To determine how many years it would take for a new building to have the same cumulative environmental impacts compared to renovated building scenarios.
3. To identify building elements and life cycle stages that have the most significant impact during the renovation of the building compared with the new building. Investigate how different refurbishment strategies affect the life cycle environmental impact with respect to materials and operational energy use.
4. Identify and discuss how the different life cycle stages contribute to the total environmental impact for these renovation strategies.

7 Module 3: Methods and Tools

In order to achieve the research objectives,Whole building life cycle assessment(WBLCA) was conducted to determine the environmental impacts in terms of Green house gas (GHG) emissions owing to renovation and/or hypothetical new construction of a building built in 1922. NS-3720, a customized Norwegian standard which is based on EN 15978 for determining the (GHG) emissions attributed to buildings was the basis for selecting the system boundary.

As per kyoto protocol, GHG emissions is a basket of namely 6 gases (Carbon Dioxide- Co2, Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbdons(HFCs), perflurocarbons(PCFs) and SF6). These are weighted as per their Global warming potential (GWP 100) and then aggregated to give a single unit CO2-eq[23].

Technical and construction details attributed to scenarios was developed and updated in IDA ICE for onward simulation and analysis. The resultant delivered energy (kWh/m2) for every scenario was further used in Reduzer (LCA Software) to determine the emissions.

Upon completion of this step, WBLCA was conducted to determine the over all GHG emissions (Embodied and Operational) for all selected life cycle stages and system boundary of the building as per the ambit of NS 3720.

Project information (Drawings, reports etc.) pertinent to the case study was sourced from different stakeholders engaged in design and development. Original drawings since inception were also available. However, most recent drawings were used for estimating the the material inventory of existing building. Additionally, estimation of material inventory (existing and new building) was determined through the use of BIM Architectural and structural models. Project renovation drawings were also reviewed to develop the building geometry and other technical details for onward simulation in IDA ICE.

Since the case study is part of ARV project, other participants and PhD candidates were also coordinated for seeking the information about the project. More specific details about the methodology is presented in the below sections

7.1 Case Study

Further to initial description about the case study in the introduction, the below provides more comprehensive understanding about the project and summarizes all the necessary information about the case study.

The building was originally built in 1922. However, changes have occurred since then. As per the drawings received, some modifications were carried out on facade in 1935 when compared with the original. It could be noted that additional openings were added to the building. But no changes were recorded on the internal layout of the building.

Figure 3: Google map Image (Source: Google map)

Heidenreich building Built in 1922 is located at 59.94 latitude, 10.75 longitude. It mainly comprised of 2 floors and small storage area in the basement.The building was constructed with focus on the application of load bearing structures(includes columns, beams, floor slabs) in the building for the first time in Norway. Primary **function** of the building was industrial use for the production of precast for various infrastructure projects.

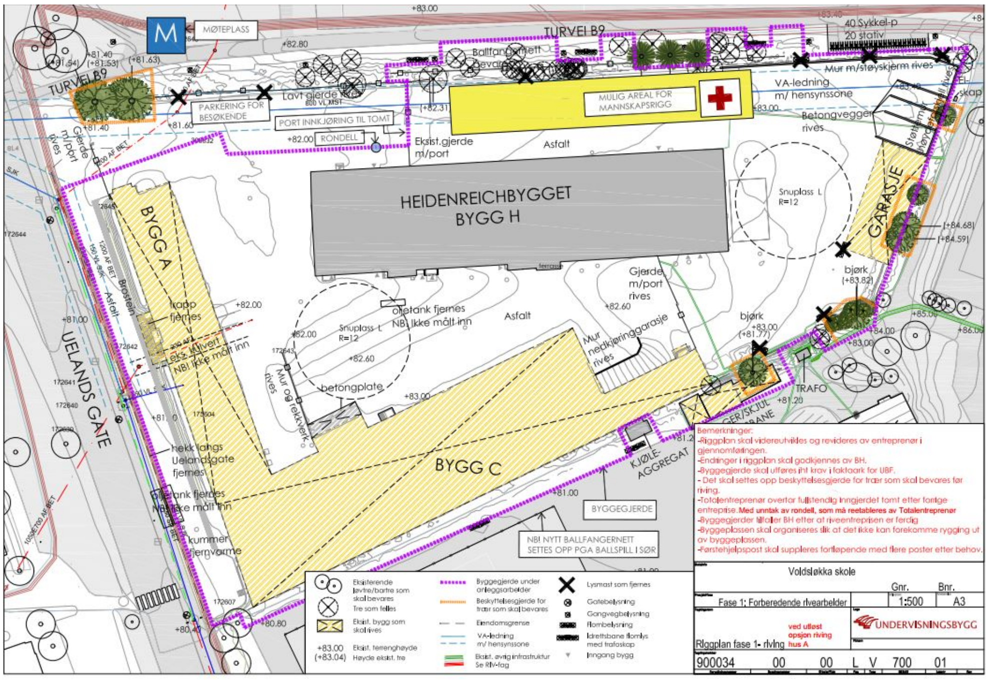
First floor of the building mainly comprised a large central storage or production area along with some offices. Whereas, the upper floor comprised of mostly offices mostly and m2 for storage as well. A small area of approximately is also dedicated for storage. More details about the building can be found in the Annex...

In 1935 pipe wholesaler Heidenreich took over and operated for over 70 years. Owing to its unique formation the buildings holds a historical and architectural value and as such listed in yellow list.As per the Oslo kommune the the cultural monuments are colour-coded based on their cultural and historical importance. They are further classified into

As noted above, the building underwent changes on the facade. However, since 1935, there were no changes recorded. A report about the structural integrity in October 2020, concluded that due to insufficient information about reinforcement used within the load bearing system and considering the recent required loads, the existing building cannot withstand the load. As a result it was notified that building would not be safe based on the proposed changes to meet the required function and regulatory requirements. Therefore, all internal spaces, partitions, load bearing structures (columns, beams, upper floor slab, ground floor slab) were demolished. Only facade of the building along with the foundations(Footings and ground beam) supporting the facade have been reused as part of the renovation. The structural load has been rearrange and shifted to wooden columns, beams and steel **transoms**.

The industrial land parcel has been transformed to the school and cultural building And the school building is built in place other demolished buildings. A and C have been demolished to make way for new building while H-building has been intact as explained above and as reflected in the below image.....

All other buildings have been demolished, barring H building owing to its unique formation.



Bemerkninger:
-Riggplan skal videreutvikles og revideres av entreprenør i gjennomføringen.
-Endringer i riggplan skal godkjennes av BH.
-Byggegjerde skal utføres iht krav i faktaark for UBF.
- Det skal settes opp beskyttelsesgjerde for trær som skal bevares før riving.
-Totalentreprenør overtar fullstendig inngjerdet tomt etter forrige entreprise. **Med unntak av rondell, som må reetableres av Totalentreprenør**
-Byggegjerder tilfaller BH etter at riveentreprisen er ferdig
-Byggeplassen skal organiseres slik at det ikke kan forekomme rygging ut av byggeplassen.
-Førstehjelpspost skal suppleres fortløpende med flere poster etter behov.

Figure 4: Demolition plan

Design and development phase of the project includes the following details.

1. Building 1- Comprises of Kultusal (Culture hall) and Ungdomsskole(Secondary school)
2. Building 2- H (Heidenreich) Building

3. Connection bridge between building 1 and 2
4. Landscape, infrastructure and other utility works.

The image below reflects the overview site outlook and perspective image for the proposed development with new and adaptive reuse.

Figure 5: Render Image of project (Source: Project team)

In the light of findings and to meet the latest building regulatory requirements, the following changes were recorded in the H-Building.

- Façade: No major changes.
- Roof : Replaced with new roof meeting TEK 17 requirements.
- 4 Skylights added.
- Demolition for most of the building as explained above.
- All windows have been replaced with new windows with similar outlook

As mentioned above, the facade did not undergo changes apart from the replacement of windows. Building roof was replaced and skylights were added to increase the daylight factor. Additionally, the windows were replaced with new to reduce the heat loss. One of the key changes recorded during the adaptive reuse was that building is not concreted framed anymore.

As part of the new development, the building is not concrete framed anymore. The structural elements are mostly based on the wood. The external columns of the existing facade have been affixed to the wooden columns. These wooden columns are holding the roof structure together with other wooden and steel beams along with

In order to capture the keep the heritage aspect alive, few traces of the existing building have been kept on the 2nd floor for the visitor and user to experience the heritage value of the building.

Below table provides more details about the changes that have occurred with regards to envelope and gross floor area (GFA).

Table 3: Voldsløkka skole- Heindrich Building

	Existing Building Component	New Building Component
Year of Construction	1922	2022
Type of Building	Concrete Framed	Wood Framed
Building Length(m)	85.5	85.5
Building width(m)	20.8	20.8
Building height(approximately)(m)	7	7
Gross Floor Area(GFA) [m^2]	3,672	2,300
Gross Volume-as per IDA ICE model [m^3]	12712	12712
Building Footprint [m^2]	1,778	1,778
Use able Floor Area[m^2]	3,304(90% of GFA)	2,290
Heated Floor Area [m^2]	information is not available	2,270
Number of Floors(levels)	3	2
Ground Floor Area	1907	1539
Upper Floor Area	1726	668
Basement Floor Area	40	-
Roof Area [m^2]	1,721	1,721
External wall area[m^2] approximately	1249	1249
External window area [m^2]	250	326
External door area [m^2]	51	51
Window to wall ratio [%]	17	22

Due to the unique geometry of the building, minor simplifications were made while developing the building geometry in IDA ICE. As such, the total volume envelope area may slightly differ.

7.2 Organization of Study In terms of LCA Method

The method used for the analysis is further presented below in line with the ISO 14044 requirements.

7.2.1 Goal

This study was aimed at investigating the net environmental impacts while comparing renovation and hypothetical new construction in terms of embodied as well operational emissions , additional benefits(D)/circularity and renewable energy source (PV)through conducting whole building life cycle assessment. The objectives are further listed below.

1. To analyse the net environmental impacts because of adaptive reuse of the existing building associated with different renovation scenarios and new buildings.
2. To determine how many years it would take for a new building to have the same cumulative environmental impacts compared to renovated building scenarios.
3. To identify building elements and life cycle stages that have the most significant impact during the renovation of the building compared with the new building.

The application of the above was observed through an adaptive reuse case study, where an old industrial and historical building was converted to a cultural building. The method adopted may serve as an example for similar variants in built environment.

7.2.2 Scope

The scope of the analysis include:

- Renovation (RE) and hypothetical New Construction (NC) assessment cuts across all life cycle stages as available in the software for all selected building elements.
- In terms of RE, new additional materials, partial demolition and benefits of in-situ materials is considered.
- With regards to NC, it includes complete demolition and hypothetical new construction. The hypothetical NC means combining the emission from newly added materials with the emission attributed to the quantities of material that have been retained. In other words, the retained materials benefits are not considered in this scenario.
- Embodied as well operational emissions have been included for reference study period of 60 years.
- The potential for offsetting the energy use after the renovation was explored. Site specific and realistic data was chosen to determine the PV potential.

7.2.3 Functional Unit

The functional units of study are ton-CO_2 e/m2 or ton-CO_2 e.

7.2.4 System Boundary

Defining a system boundary holds utmost significance. It not only provides basis for comparative assessment, but also allows benchmarking of the results. The setting up of system boundary in LCA of building would affect results. It needs to be selected in a way that addresses the goal and research objectives of the study. The availability of the data, effort required, time limitations and continuous development in building LCA can make it more challenging.

The system boundary for the building includes two parts.

1. Selection of Building Elements and systems. Selection of the building Elements and systems are key while conducting an LCA. It can follow the green building schemes, regulatory requirements and other international standards. Building elements and systems selection will also highly depend upon the availability of data for the products, components and materials that constitute a building element or a technical system.
2. Select of the life cycle stages. The inclusion of the Life cycle stages will also depend upon the scope of the study, green building scheme, ISO standards, local and other regulatory requirements.

Table 4: Case Study Assessment Summary

	Summary
Building name	Heidenreich-bygget
Building location	Uelands gate 85, 0462 Oslo
Bill of materials compiled by	Author.
Year of assessment	2023.
Assessment timing	Building Completion and post occupancy
Assessment Method	Reduzer LCA Tool
Scope of Model	Foundation, columns and beams, floors and roof, external walls, Internal walls and partitions
Reference study period	60 years
Data source	Generic NEPD as per the software, product specific EPD were not available
System Boundary	Cradle-to-grave, more details presented below

Owing to structural uncertainty, the existing building went through deep renovation. As part of renovation, priority was given to energy efficiency by reducing the thermal losses, reducing the energy use, introducing energy efficient equipment and lighting along with a ventilation system to cater for the thermal comfort of the occupants.Thus, based on the research objective and the intervention executed, the study is based on the investigating the life cycle impacts attributed existing building, demolition and new construction.

Table 5: Life Cycle Stage included in the Study

Life Cycel Stage	**Code**
Production and Construction Stage	-
Raw Materials	A1
Transport	A2
Production	A3
Transport to construction site	A4
On-site	A5
Operational Phase	-
Use Phase	B1
Maintenance	B2
Repair	B3
Replacement	B4
Operational Energy	B6
End of Life Stage	-
Transport to Waste processing facility	C2
Waste Processing	C3
Excluded	-
C1, C4, D	

NS 3720:2018, B1 has been considered. As part of refurbishment B5, it is either B2, B3, B4 or A1-A5, therefore B2- B5 have been considered. However, in LCA tool, B2, B3, is not computed.

The system boundary considered for the project is illustrated below. All life cycle stages as available in the Reduzer software were selected. And for operational energy use, results from IDA ICE were used in reduzer to estimate the life cycle GHG emissions for the selected scenario. Substitution impacts of module D have been considered in the study. In line with the study, avoided emissions were subtracted during the adaptive reuse due to the materials that have been retained/ in-situ. The emission from the in-situ materials(retained materials) were 20% emission. In other words 80% reduction considered to ensure circularity as per the LCA software. These reductions are recorded in the product and construction stage (i.e.A1-A5).

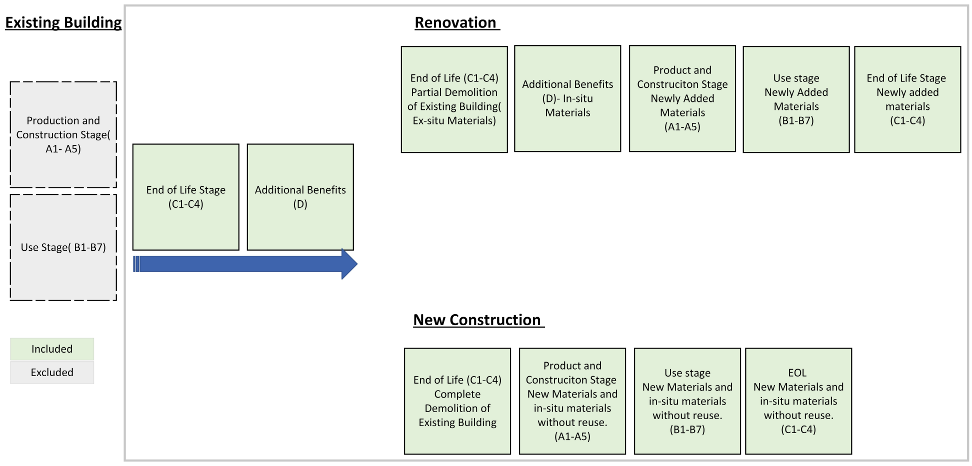


Figure 6: System boundary

Based on the selected scenario and energy optimization, changes were made in the building envelope. These changes resulted in the inventory of the materials and corresponding variations were updated in the reduzer for embodied emissions. Similarly, the energy use intensity was obtained from IDA ICE and whole building simulation was achieved through Reduzer. The below image provides further information about the work flow.

With regards to renewable energy source, PV panels as available in the IDA ICE and Reduzer were selected to further explore the potential of material and energy trade off attributed to PV panels. More details about the PV Panel can be found in the section below.

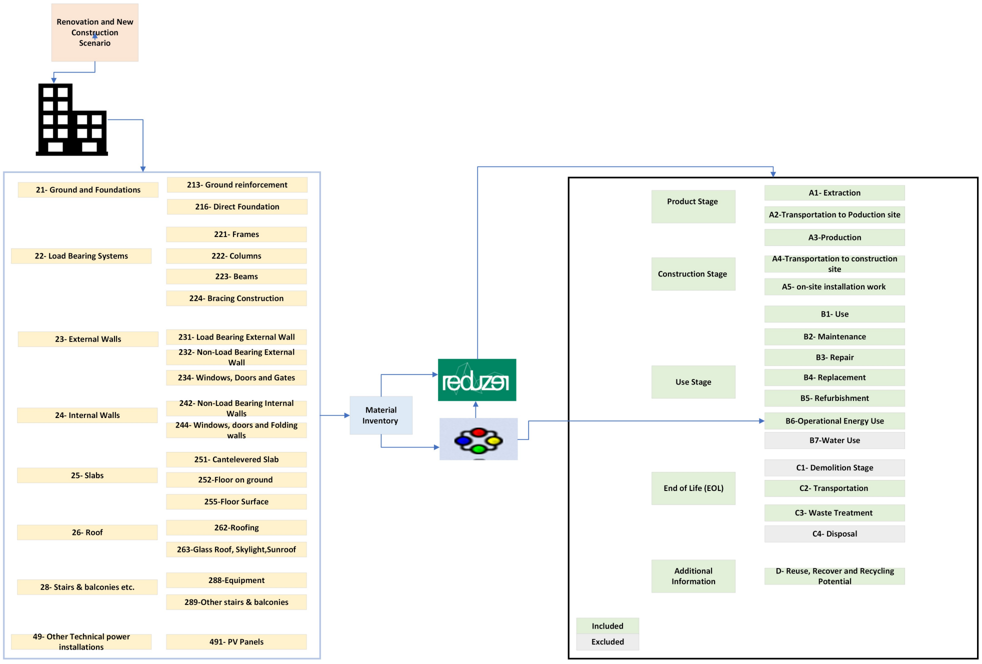


Figure 7: Work Flow

7.2.5 Scenario development

While performing LCA, scenario development is quite important for comparative assessment[24].As part the scenario development, it was spread into following 7 classifications. Since the intervention has already been completed for the case study and modifications have been implemented on-site, thus As-built scenario was also considered in addition to 6 other possible scenarios.

- D0- It is the base case which includes renovation of the building up to TEK17 minimum requirements. Building envelope and other technical details are modified to meet the standard requirements.This is generally the case for old and historic buildings to meet the minimum energy requirements. The emissions from newly added components, partial demolition from existing building and corresponding emissions from in-situ materials are considered.Emissions from the materials retained or reused(in-situ) are at 20% only.
- D1: In this case, new construction and complete demolition of an existing building has been considered. BOQ for the new construction includes materials that have been added newly and those which were retained. But in this, the emissions from retained materials are considered 100 %.
- D2:- As part of this scenario, D0 was further improved through Energy efficiency measures for a non-residential building as mentioned in Passive House standard NS-3701 to reach Passive house level.
- D3: In this scenario, D1 was further enhanced to reach Passive house level as per NS-3701.
- As Built: In this scenario, all technical and building details are as per the current status. And emissions from partial demolition as well and in-situ materials have been considered. As-built information is further represented for comparative assessment
- hypothetical new construction: In this scenario, ”reuse of” material is not considered (in other words, emissions from retained materials is 100 %. Complete demolition of existing building and And all other details are similar to As- Built.

  The above are further explored with respect renewable energy production at source and assessing the emission payback time for reaching Net zero emission building - O for each case.

Table 6: Scenario Development

	Scenario development
D0	Newly added materials to reach TEK 17 Minimum requirements+ Partial Demolition+ Emissions from retained materials
D1	Complete demolition of existing building and New construction.
D2	Same as D0 with more energy efficiency measures.
D3	Same as D1 and with more energy efficiency measures.
As-Built	New added materials, better U-values for roof and ground as compared to TEK 17 minimum requirements, Partial demolition and in-situ materials.
Hypothetical New Construction	Same as As-built , but without the reuse.

Through the selection of these scenarios, the environmental impact of renovation and new construction can be compared among and between the level of renovation and new construction. Net environmental benefits can be evaluated with regards to selection of materials and their contribution to embodied and operational emissions. This is further illustrated in the image below.

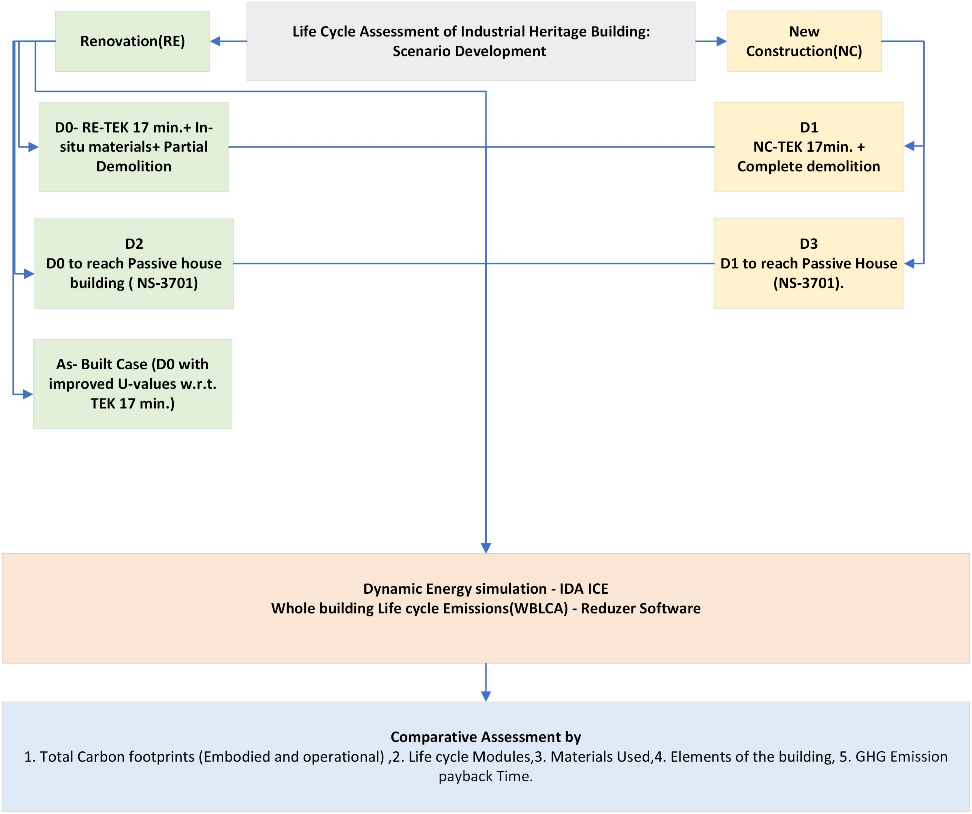


Figure 8: Scenario Development

With regards to As-built case, the building in question underwent considerable changes due to non-availability of precise information about the load bearing structures. A survey was conducted about the structure integrity was conducted by Dr.techn. Olav Olsen AS, Rev-02, issued on 02.10.2022. And as an outcome, only facade wall, concrete columns and foundations (footing, tie-beams, neck columns) were kept intact. All floors were demolished along with roof. Windows and doors have also been replaced. Thus, substantial demolition was carried out as part of the project.

In line with the project, stakeholder and regulatory requirements, H-building has been developed to meet the Energy budget as mentioned in TEK 17. The building has been designed to meet net energy requirements of 130 kWh/m^2 as defined in Chapter 14. Energy of TEK 17 requirements. This translates to energy grade B as per NS 3031 energy grade classification.

7.3 Life Cycle Inventory

7.3.1 Materials- Embodied Energy Emissions

Material inventory for the study is based on information available in the Building information model (BIM) for structural and architectural and associated Design drawings(Architectural, Structural, Mechanical, electrical and plumbing). Due to time constraints, type of contractual agreements and lack of communication with Design team, data sourcing attributed to the material inventory was carried out by author. Other researchers and PhD candidates were instrumental in providing the necessary guidance and information about the project. All Drawing (existing building before any intervention and new), BIM Model and other reports (structural integrity, lighting, building performance simulation) were provided.

NS 3451 -2022- Table of building elements, was considered as the starting point. The building elements were given a reference code as per the standard in the BIM Models. On the basis of the code, corresponding project data(quantities of material) was extracted from the BIM model. Once the inventory was extracted, the information was attributed to existing and new phase Only. BIM Models did not include information about the building elements that have been demolished. In order to estimate the demolition part, latest revision(1935) of the existing building and blue print version(1922) was referred. Whereas for the **materials retained (in-situ)** and **newly added materials**, BIM Models and Design drawings were used.

After extraction of the data, it was firstly sorted into existing, demolished and new, followed by the location of its use in the building.

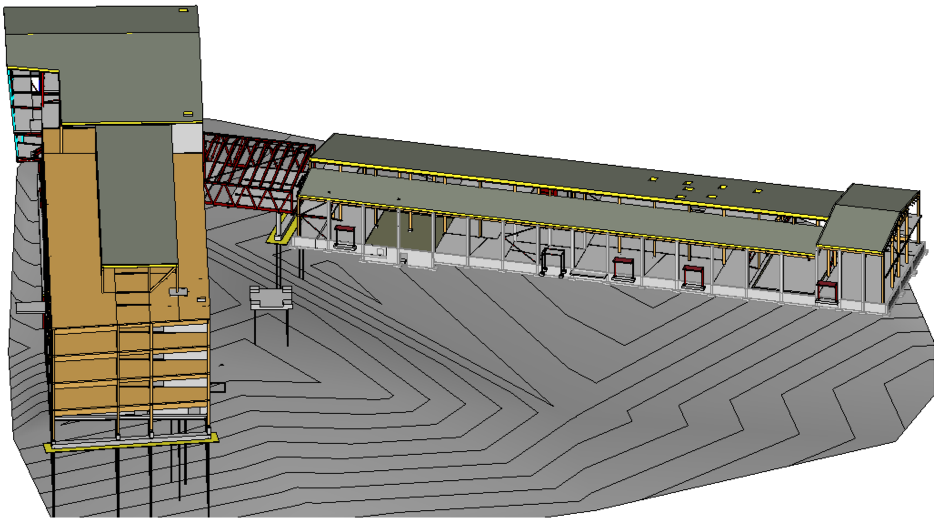


Figure 9: BIM Model- Structural

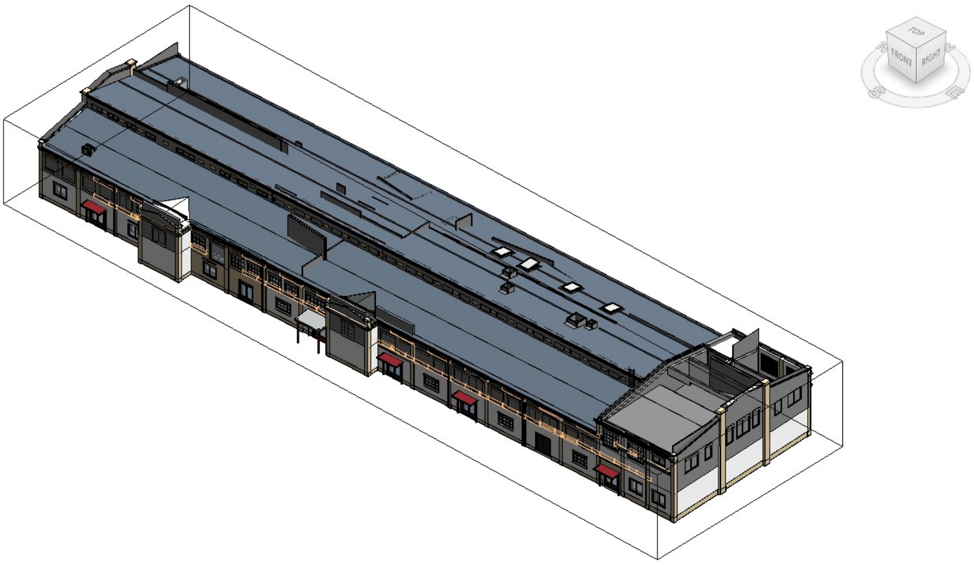


Figure 10: BIM Model- Architectural

Upon finalizing the material inventory, a further discussion was held with architect about the validation of the same.

The data was organized in terms of the material/products and as per the assembly or component for the further use in the LCA software. Details about the data can be found in the appendix.

Although the material inventory, BOQ or tender documentation was not provided, yet the information from the Drawings(layouts, sections and elevations) were used to ensure that Environmental data points adopted are mostly product specific. Where information was not available, EPD norge was referred to as per the information available in the software. All EPDs are either based on cradle-to-grave or cradle-to-gate, developed according to EN 15804 and EN 15978 standards. For transportation purposes standard distance of 500km was used. And all available life cycle stage in the software as per NS 3720 was used for onward computation.

7.3.2 Energy- Operational Energy Emissions

In order to estimate the operational energy need as per the selected scenario, building performance simulation was carried out through the use of tool IDA ICE student version 4.8 SP2. This provided more insights about the influence of the materials selected for the passive measures to reduce the demand and their corresponding affect on the embodied emissions as well as operational emissions.

As project was already executed, the design and development team conducted energy simulation through a software called Simien and considering the building as one thermal zone. The final report was available with all necessary information reflecting building details, envelope design inputs and other technical details. As the working/ original file was not available, thus, in order to meet the research the goal and objectives, more detailed geometry with several thermal zones as per the architectural drawings was developed in IDA ICE for onward simulation and recording the changes as per the selected scenarios.

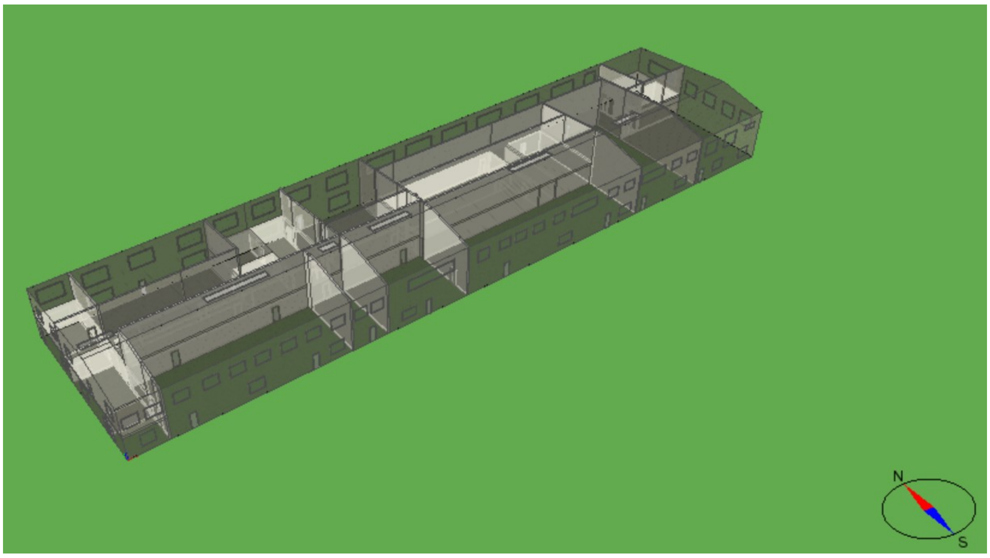


Figure 11: IDA ICE- 3D Model X Ray

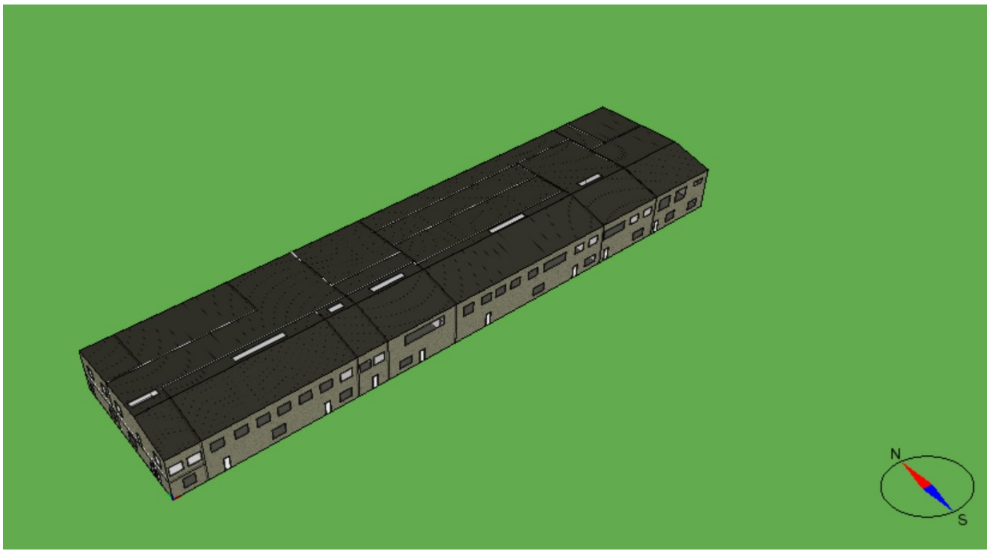


Figure 12: IDA ICE-3D Model

Since the existing building product, construction and use stage is excluded, the emissions attributed to Operational Phase of the building is not determined. Additionally, the different functional uses throughout the history of the building makes it challenging to determine the operational emissions. Moreover, the building had been redundant for quite a while. As a result operational net energy need of the existing building was not determined. In order to reuse the existing and redundant building, the building needs to meet the basic and minimum requirements set forth by the regulatory local and international building guidelines. The energy efficiency measures are not always implemented during the renovation of older buildings. The below table provides input parameters for the minimum and low energy requirements.

In order to simplify the process, Thickness of the insulation material in the building envelope was changed to meet the required U-value for all scenarios, while other components of wall had been kept constant. Similarly, with regards to Fenestration/glazing TEK 17 and low energy requirements were used. As mentioned earlier, that the case study has already been executed and energy efficiency measures are already in place, As-built information is also reflected in the below table for reference and onward comparison among the different scenarios.

Table 7: Input Parameters as per TEK 17 and NS-3701

	TEK 17 Minimum Parameters	Passive house NS-3071	As-Built
U-Value- Wall [W/m^{2}k]	0.22	0.10–0.12	0.21
U-Value- Roof [W/m^{2}k]	0.18	0.08–0.09	0.13
U-value- Floor [W/m^{2}k]	0.18	0.08	0.13
U-Value- Window [W/m^{2}k]	1.2	$\leq$0.8	0.88
U-Value- Door [W/m^{2}k]	1.2	$\leq$0.8	1.2
g-Value- Glass	0.8	0.6	0.35
Thermal Bridge [W/m^{2}k]	0.1	$\leq$0.03	0.05
Heat exchange Efficiency [%]	0.5	$\geq$0.80	$\geq$ 0.85
SFP Ventilation [kWh/m^{3}s](supply and return)	1.67	$\leq$1.5	1
Air leakage 50 Pa Air change /h fixed infiltration	1.5	$\leq$0.6	1

Table 8: Design Set point and thermal comfort levels

Design set point°C	**Value**
Minimum Ventilation-NS3031 [m^3/h.m^2](Operational)	21°C
Minimum Ventilation-NS3031 [m^3/h.m^2](Non-operational)	19°C
Supply Air temp(Winter)	19°C
Supply Air temp(Summer)	17°C
District heating efficiency	0.9
Air to water heat pump Efficiency	3
Cooling	AHU
Cooling Efficiency	2.4
Lighting [W/m^2]	6.4
District heating efficiency	0.9
DHW [kWh/m^2]	6.4
Equipment[kWh/m^2]	3.2
Personnel[kWh/m^2]	2.1
MET	0.2

Air to water heat pump was installed for domestic water heating. All space heating was attributed to District heating network. Cooling set point is achieved through AHU only. There are no room cooling units considered for the zones. For space heating, AHU and water radiators have been considered. Ventilation rates have been selected for each model according to NS 3031. VAV with temperature control had been considered for all scenarios.

IDA ICE was calibrated to reach the same Energy use intensity 112 kWh/m^2 before onward analysis.

As per ASHRAE 90.1 the unmet hours for baseline or proposed building needs to be below 300 and the difference between both should not exceed 50. The unmet hours and thermal comfort are well within the range of AHSRAE . The unmet hours provide information about the number of hours during the simulation during which the design set point temperatures for cooling and/or heating have not been met. Whereas, the thermal comfort is based on the NS-EN 16798-1:2019 and CEN/TR 16798-2:2019 (E).

CEN/TR 16798-2:2019 (E) provides a reference for thermal comfort. Annex D ”Long term evaluation of the general thermal comfort conditions” and E ”Recommended criteria for acceptable deviations” Indoor Environmental Quality Category. Method A was selected which is based on the Percentage outside the range ”Calculate the number or % of occupied hours (those during which the building is occupied) when the PMV or the operative temperature is outside a specified range.” A reference of 3 to 6% which translates to 259 and 518 hours respectively out of 8640 hours.

NS-EN 16798-1:2019 provides default indoor temperature range for energy calculation. ”Table B.5 — Temperature ranges for hourly calculation of cooling and heating energy in four categories of indoor environment” have been considered for operative temperature. Type of building or space ”Auditoria” and category of IEQII (medium level of expectation) was considered, which requires 20°to 26°indoor temperatures to main the minimum indoor requirements.

The above have been considered as benchmark for determining the accuracy of the model developed for the baseline and proposed cases for scenario development. In addition the reference values as mentioned in Table A.10 (Tabell A.10 – Energi per år i en normert beregning) were considered for bench marking the simulation. The said table illustrated the information about the consumption of different loads (DHW, lighting, equipment, and person).

indoor operative temperature in winter and summer for buildings with mechanical cooling systems are based on the schedule as per the NS NS 3031: 2021(Tabell A.9 – Normerte settpunkttemperaturer), the minimum temperature for out of use and use are 19 and 21°C during winters and maximum temperature of 24°C for cooling.

Table 9: Design Set point and thermal comfort levels

Design set point°C	**Value**
Heating set point(Operational)	21°C
Heating set point(Non-operational)	19°C
Cooling set point	24 °C
Operative Temperature heating	20°C
Operative Temperature cooling	26°C

7.3.3 Emission factor(KgCO_2 eq. emissions due to operational energy use)

GHG emissions for the operational phase of the building were calculated based on net delivered energy. The emission factor estimating GHG emissions associated with the operational stage are based on NS3720. EU28+NO(production mix approach in the electricity supply) has been considered for electricity. As such, 136gCO2/ kWh or or 0.136kg Co2/kWh were taken as a reference. EU28 mix is a global power producer with an aim to reduce GHG among partnering countries. With regards to emission factor associated with district heating, 0.0138 kg CO2-eq/kWh, which was based on the public data from Norwegian District Heating Fellowship.

7.4 Life Cycle Impact Assessment

The impact category that will be addressed as part of the project is Global warming potential(GWP) and the indicator is KgCO_2-eq.

7.5 Assumptions

1. Additional Benefits (D) are considered at 80% reduction as per the software selected.
2. Material inventory for new construction is based on newly added materials and materials that been retained. If the building was completely demolished, the use of materials can potentially vary due to the design.
3. Bill of quantities for the building elements that were demolished were estimated based on the available drawings.
4. PV panel efficiency and type of the material is based on the available information in the reduzer and IDA ICE software.

7.6 Exclusions

1. The case study building had been abandoned for quite some time. In addition, during the past 100 years, it went through certain changes as per the need and function of the building. Therefor, accounting for the emissions of existing building is excluded from this study, however, the EOL and additional benefits (D) have been included.
2. Furniture,Fixtures,and Equipment.
3. Mechanical, electrical and Plumbing systems.
4. temporary work and excavations.

7.7 Functional Equivalent

Functional equivalent is a description that includes the building's design characteristics, functions, required service life, and in-use conditions. The purpose of defining the functional equivalent is to enable future comparisons with results for buildings that are functionally similar enough to make for a fair comparison.

Table 10: Functional Equivalent

	Details
Building type	Multi-purpose Cultural facility -Low-rise free-standing building
Gross floor area(GFA)	2271 square meters).
Technical requirements	TEK 17 minimum, NS 3031.
Functional requirements	Provides space for Music and cultural activities (Events and practice).
Pattern of use	Auditorium, rehearsal for 780 Pupil (for the whole project , which also includes another school building)
Required service life(RSL)	60 years.

7.8 Solar Potential

As illustrated in the literature, the potential of PV panels to reduce the energy use of the building was also further explored. Total estimated energy production is determined through the PVGIS with the help of coordinates. And total area required was determined through by using the following equation.

Due to limited options available in the reduzer, mono crystalline PV panel was considered. And Emissions per square meter of the panel were extracted from the

The addition of on-site PV panels would offset the purchased/imported energy for the project.Due to the location and availability of the Peak sun hours, energy production varies across the year. During winter, there is less energy produced than required, and vice versa in summer. As such, it is assumed that surplus energy is sold to the grid during summer. And during winters the same energy is imported.

The potential for harnessing solar energy generally depends upon the available area, orientation, efficiency, effective output(system output), and peak sun hours. In addition, the type of PV systems like on-grid, off-grid, and hybrid can potentially provide more realistic estimates about the renewable energy generated on-site[25].

The following was used to calculate total solar energy required
Solar Energy Generated = Area of the PV Panel (m2) $*$ Annual Energy Kwh/m2 $*$ efficiency

7.9 GHG Emission Payback Time

One of the important indicator when it comes to comparing the results from renovation and new construction, the emission payback time is critical. It provides the time required to offset the emissions associated with the no renovation scenario or the time to off set the emissions associated with the materials by the high energy efficient buildings when compared with the renovation. In other words its a ratio between the total change in the embodied emissions and emissions savings/avoided. If the emission payback time period is shorter then demolition and new construction has been preferred and vice versa.

The effort and energy associated with the intervention in the building will introduce upfront embodied emissions. These will be off set due to the benefits that will be yielded across the service life of the building due to energy efficiency measures that are selected as part of intervention. As such, the break even and benefits beyond the break-even point can be seen through the GHG emission pay back time (GPBT). Upon reaching the GPBT, any additional savings from there onward will be avoided GHG emissions that can potentially contribute to reaching climate goals.

This metric is mostly considered in refurbishment projects (without changing the function of the building) where it is assumed that all other material inventory in the building remains same. It is generally computed with the help of following equation.

$$\text{Payback period} = \frac{\text{Emissions due to Intervention} - \text{Emissions of baseline building}}{\text{Operational energy emissions Baseline} - \text{Operational energy emissions post intervention}}$$

Similarly, like any other material or product, this concept is also applicable to the energy generation system on source. The production of Photovoltaic system (PV) will constitute embodied emissions, whereas the production of renewable energy by PV will offset the emissions attributed to the production of PV. In this study, renewable energy generation system has been added together with the scenarios due to the recent trends and potential of Norway to produce solar energy.

KgCO_2e

The term GHG payback time (GPBT) is defined as the number of years it takes for an energy generation system to “pay back” its embodied emissions through renewable energy generation (Reich-Weiser et al., 2008). It is calculated according to Eq. (2), whereby (CO2 eqavoided(year)) (kg CO2 eq) are the emissions avoided per year due to the production of electricity from the installation. CO2 eqavoided(year) is calculated by multiplying the annual production with the average emissions per kW h per year from the local grid. GPBT CO2 eqembodied CO2 eq.avoidedyear

8 Module -04: Results

In this section, the results and key findings are presented with regards to the As- Built case and other developed scenarios. The finding suggest that building reuse yield environmental benefits despite considerable demolition. Energy efficient adaptive scenarios present more insights and trade off between energy and materials.

Firstly, the results are presented with respect to reuse of the materials for adaptive reuse. And followed by that the comparative assessment is presented further to illustrate the influence of both **reuse of materials**, refurbishment (retrofit, renovation and rehabilitation) and Net Zero Emission-Operational Stage. The below also further summarizes the arrangement.

- Adaptive Reuse Vs New Construction.
- Cumulative Impacts.
- Comparison among all scenarios.
- Contribution of All life cycle stages with respect to all scenarios.
- Comparison among all scenarios with regards to building elements.
- Comparison among all scenarios with regards to All sub elements.
- Comparison among all Scenarios with respect to Elements and life cycle stages.
- Achieving Net Zero Emission Building -O and contributions of PV.

A total of 82 materials/products have been used in the LCA tool. In the reuse case, some of them have been reused. But the number of materials would remain the same.

As part of the analysis, LCA was conducted to determine the emissions associated with the original building, partial demolition, renovation (which includes reuse of the materials) and new building (where the reuse is unchecked). This step was important to assign the emissions with each phase of the development and use relevant life cycle stages for onward assessment.

Case study building has already been transformed to a cultural building and below image provides current situation.

Figure 13: As-Built H-Building (Source: LinkedIn)

Figure 14: As-Built H-Building Upper floor (Source: LinkedIn)

The above Figure 14 some traces (old beams and columns) to reflect that fraction of the building has been reused.

8.1 Reuse of Materials

Adaptive reuse when considered with new construction, the reduction is recorded at -8.20, -7.8 and -8.07% for D0, D2 and As-built. In case the building is adopting a TEK minimum standard, the emissions due material use and demolition will currently outperform that adaptive re-use targeting Passive House. Similarly, the As-Built scenario is more material intensive.

Total Emissions for D0(REN-TEK-17 min) were 909 Tons CO_2 eq. and 990 for D1 (NC-TEK-17 Min), D2(REN- Passive house) 950, D3(NC- Passive house) 1031. Similarly, for As built , 925 and NC Hypothetical are 1006 respectively over 60 years period.

These also include emissions due to partial demolition and complete demolition which are part of "REN" and "NC".

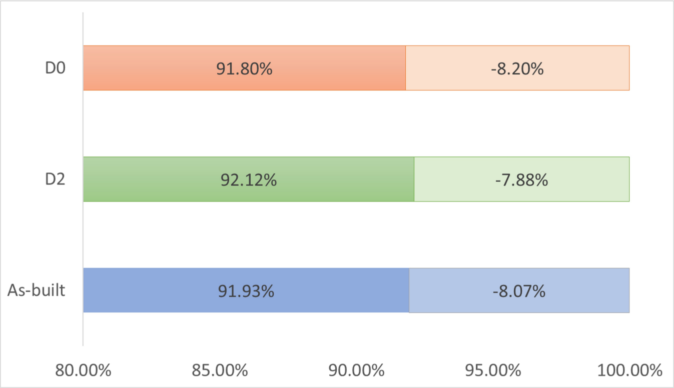


Figure 15: Adaptive reuse Impacts Vs New Construction

8.2 Refurbishment

While comparing different cumulative impacts across the life cycle, It can be seen that it takes around 20 years approximately for the new energy efficient building to meet the TEK 17 miniumm renovated building. The little difference is due to the fact that when emissions for the demolition are considered, a minor difference of (76 and 81 Tons) is recorded between partial demolition and complete demolition. The calculations included C2 and C3 life cycle phase of the materials only. Building Facade was in tact where as all other building materials have been newly installed. Therefore the difference between the renovation and New construction is less as reflected in the figure 16.

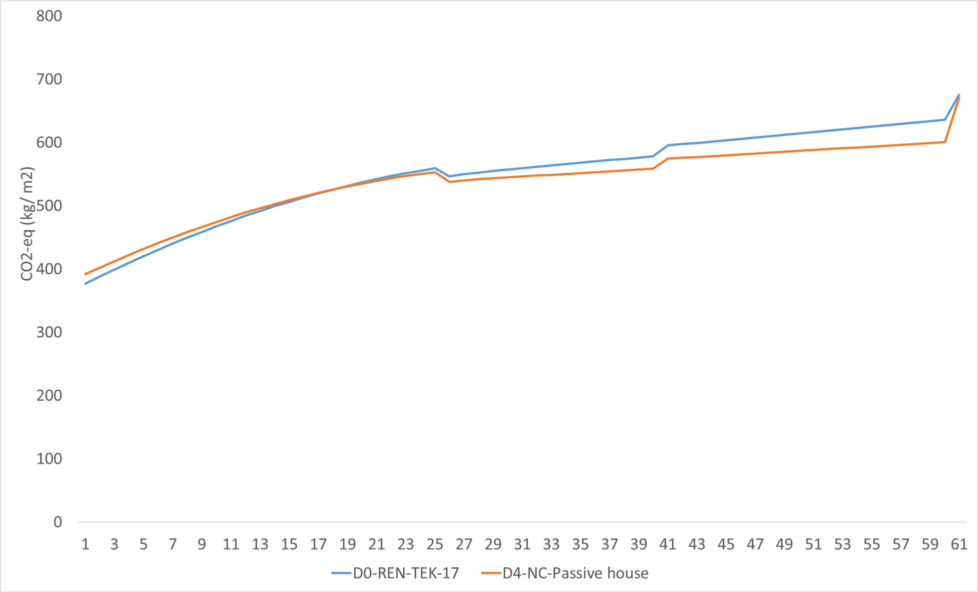


Figure 16: Minimum renovation level Vs New Highly Energy Efficient Building

With respect to the overall impacts (embodied and operational) As Built is observed as the lowest, because of the optimum level of building envelope materials and other technical considerations. 620 kg of Co2 eq/ m2 is noted for As built. Minimum level(D0) refurbishment and enhanced level (D2) will yield more emissions due to operational phase emissions. Similarly trends are noted for new construction (D1 and D3). As explained for the figure above, due to the difference among D0(665 kg CO_2 eq/m^2) and D3 (671 kg CO_2 eq/m^2). It will take considerable time for the New energy efficient building to reach the same level D0.

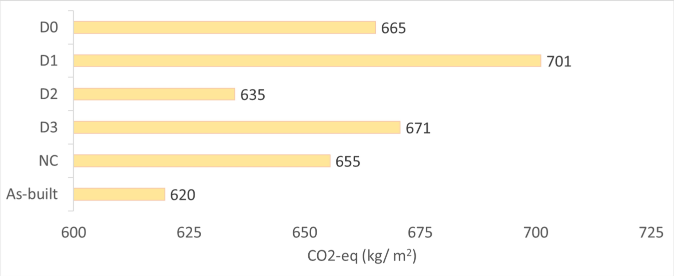


Figure 17: Comparison among All scenarios in terms of Total GWP per m^2

Major contributions are recorded in product phase(A1-A3) in all scenarios. Similarly, the operational phase (B6) also contributes. The emissions owning to partial and complete demolition can be seen in C2 and C3. The proportion of comparatively less when compared with A1-A3 and B6.

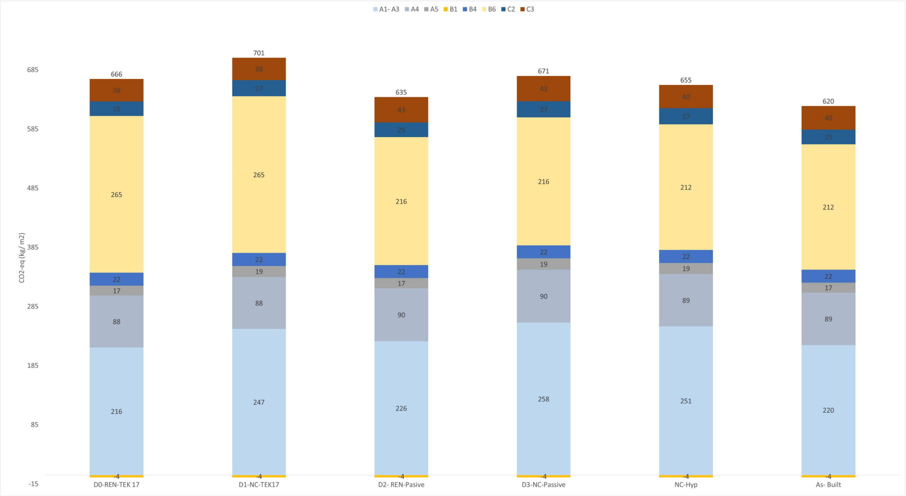


Figure 18: Life cycle stages contribution

With regards to emissions from building elements changes are mostly recorded in ground and foundations (21),external wall (23), and Roof (26). This is due to the additional insulation materials owing to the variations among minimum and advanced energy efficiency level. Similarly, the reuse of the materials is recorded in building element 21 and 23.

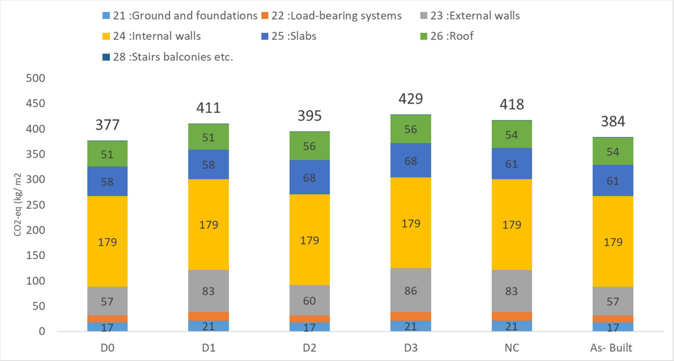


Figure 19: Building Elements comparison m^2

Further breakdown of the building illustrates the reuse of materials in all renovation scenarios (D0, D2, and As-built). Direct foundations (216), Columns (222)load bearing external wall(231)non load bearing external walls(232). Similarly, the emissions attributed to addition of materials can be seen in roofing(262), Floor on ground (252), and non-bearing external wall(232). Building element 232 has emissions attributed to the reuse of materials as well as due to the changes in the insulation thickness that installed on the internal side of the external wall.

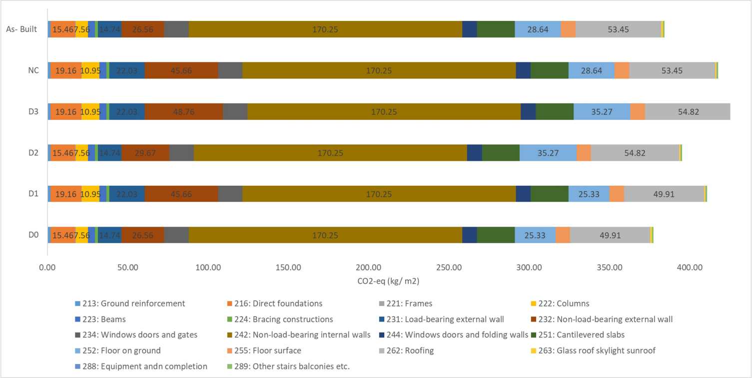


Figure 20: Changes due to reuse and insulation thickness

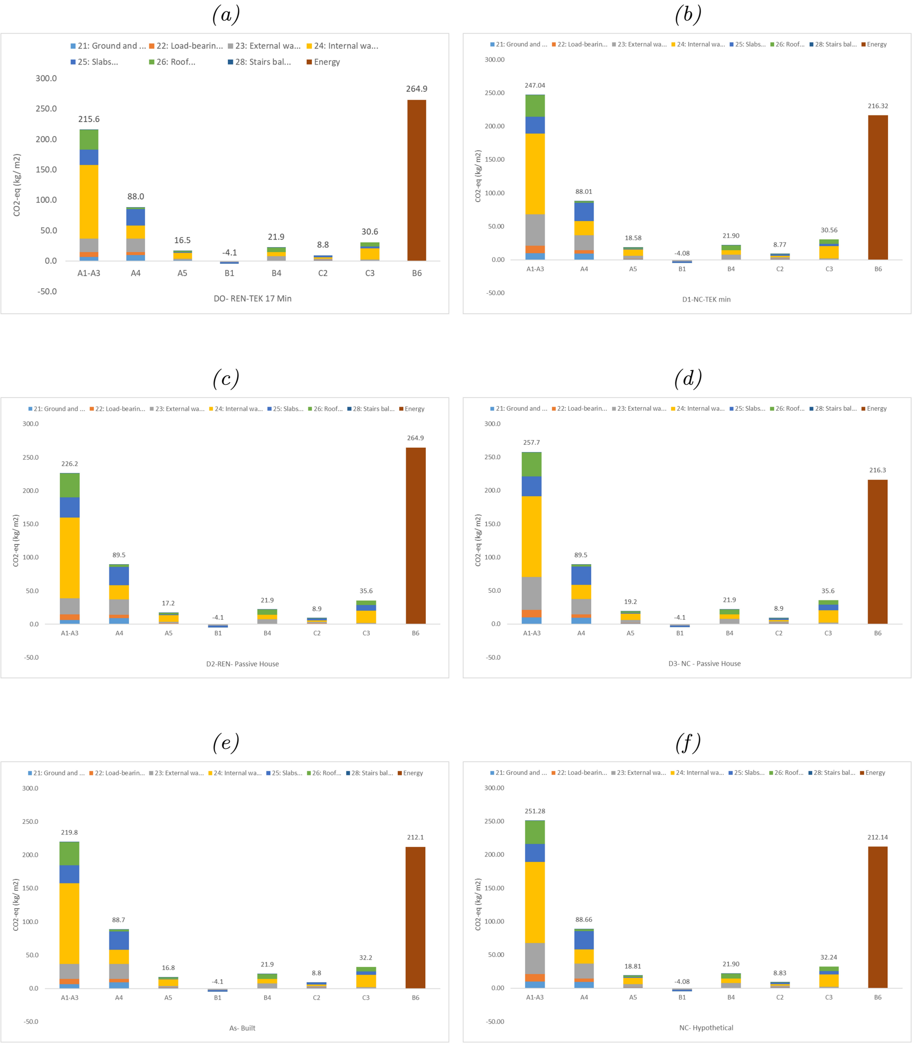

(a) *(b)* *(c)* *(d)* *(e)* *(f)*

Figure 21: Relative contribution of building element towards life cycle stages

With regards to below image,the base case, D0 with minimum renovation and reuse of the materials produce approximately 265 Kg(CO_2/m^2). And the product stage (A1-A3) contributes approximately 216 Kg(CO_2/m^2). Major Changes are reported in the B6, A1-A3 and A5. This is primarily due to the reuse of materials. Additionally, the changes are also recorded in the building elements. Similarly, for the As- built case, 220 Kg(CO_2/m^2) for product stage was calculated. And the operational stage emissions were 212 Kg(CO_2/m^2). The change is due to the addition of more insulation, technical improvements between both scenarios resulting in 20% reduction.

8.3 Net Zero Emissions Building- O

Net Zero Emission building-(O) for the building can be achieved through implementation of renewable energy on site. As part of energy simulation, the delivered energy was considered to estimate the energy required to off set the emissions the associated with the delivered energy.

Net impacts change within the range of 19% to 23 %. Most reduction was observed was observed in D2 (Renovation with Passive house standard) and least NC. Operational energy requirements are less in Passive house, as such less area is required for the PV. Consequently, lower embodied emissions are recorded with regards to PV. The efficiency of the selected PV panel was 0.17. This was to align with the available EPD of PV Panels in the LCA tool. These result can slightly improve with more efficient PV panels. please refer to Fig 23.

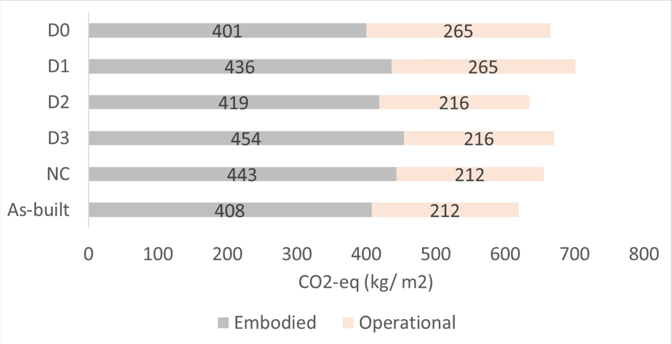


Figure 22: Embodied and Operational Emissions per m^2

The embodied emissions owing to PV panels are based on mono crystalline solar panel available in the LCA tool. The ability to harness the renewable energy will potentially vary due to the selection of the PV panels available, proximity to the site of use and efficiency of the panel.

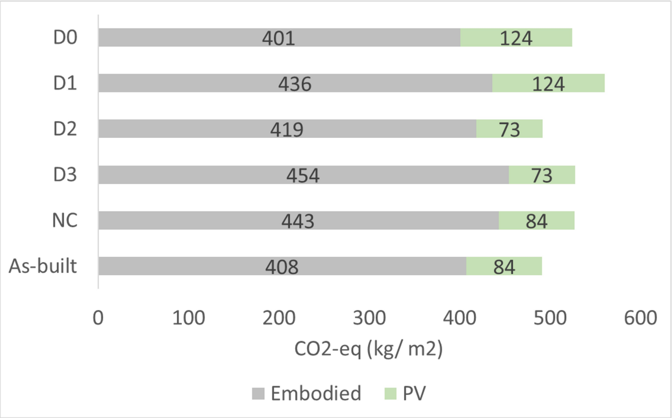


Figure 23: Embodied Emissions Building materials and PV(Kg CO_2 eq/m^2)

9 Module 05- Discussion

Climate crisis have been at forefront.There is a great need to assiduously address the impending fallout of climate change. Green house gas (GHG) emissions and their global warming potential (GWP) has been causing damage to the climate. Intergovernmental Panel on Climate Change (IPCC),shows that 1°C since the industrial era and it is also likely to increase if the situation does not change. Built environment significantly contributes to wide spread propagation of GHG emissions across different life cycle stages in the construction industry

This debate of demolition and constructing new building has been on-going for quite some time. plethora of academic literature is available to reflect the same. Varying approaches, framework and methodologies have been introduced, However, there is still no single reference with regards to precise selection of system boundary, service life and building elements. This is often due to lack of technical expertise, data availability, prior experience of the researcher and interoperability issues concerning different software used.

As there is no effort, there are no emissions, and the building remains redundant. However, such spaces cannot be overlooked, while having a flourishing neighborhood besides it. Therefore, the development in the proximity also requires to integrate such redundant spaces. Besides the cultural heritage and values, the building is a symbol of national wealth and allows the natives to cherish the past. So, hinging on to traces of past and simultaneously embracing the recent regulatory requirements requires considerable deliberations.

Integrating such buildings with bare minimum is not a plausible option for inhabitants and environment due to unknown construction integrity, construction techniques used and local expertise

Historically, the criteria and regulations didn't require thermal comfort, well being and environmental damage. So utilizing such old historic building will increase the energy and environmental burden along with inadequate thermal comfort for the visitors and /or dwellers.

And this introduces the dilemma of whether to reuse the building or demolish the building.

Owing to the increasing awareness and education, users and visitors of such buildings also tend to be inquisitive about the operational energy use and thermal comfort.

Due to recent developments in the energy efficiency measures, the operational energy use of the buildings are able to be controlled and management. However, the focus has shifted to embodied energy and emissions. Embodied emissions are outpacing the operational energy emissions.

The primary objective of this study was to understand environmental benefits linked to the reuse of materials, refurbishment and achieving Net Zero emission building -O in the context of an old, redundant and historic building. And see how it contributes to the transition towards a achieving climate goals. The results of the Life cycle assessment and findings from IDA ICE suggest that construction materials and products have the primary role in refurbishment process or in new construction when it comes to total emission across the life cycle of the building. Product stage (A1-A3) and operational phase (B6) are considerably important despite of demolition phases from the previous life cycle of the existing building. The addition of PV panels to off set the delivered energy has also be explored. Through the use of modelling tools and available data it was noted that an area of 1550 square meter would be sufficient to offset all the operational energy needs.However, the net change in the overall emissions range from 22- 24% .This can further improve due to selection of more efficient PV panels.

Results have been bench marked in line with IEA, review paper and other similar studies. The adaptive reuse of this building is special, because the building requirements were one-off. As such, due to the functional use of the building, the acoustic requirements needed to adhered to. This led to additional use of insulation materials in space partitions. The results found when compared with other literature follow similar trends. However, there are some key differences due to the unique use of this building which requires more materials for internal partition to meet the acoustic requirements. Additionally, the building underwent considerable demolition due to uncertainty in the structural integrity. As a result the material reuse (in-situ) was only available for the facade wall and associated foundation structure.[26] 2.1 Kg(CO_2/m^2/year) for refurbished buildings (3.8 when including replacements). The case study it was found to be 3.6 Kg(CO_2/m^2)/year for the As- Built case(which includes both reuse and refurbishment).

With regards to adaptive reuse and new construction,[27]recorded approximately 52 years for the new energy efficient building to reach the same level of emissions as a refurbished building. Similarly,[28] while comparing the renovation with new construction reported approximately 50 years for the new building to reach the same level of emissions as embodied. However, as per the Norwegian reference case study[12], 15 years were also recorded. But, as part of this study Operational and maintenance emissions were also considered. Regardless, the refurbishment process yields more environmental benefits as compared to the demolition and new construction.

Finding a functional equivalent for these kinds of buildings is not readily available as the research is still limited. Thus, a hypothetical construction scenario was developed to see the difference when it comes to reuse of materials as well as the impact of energy efficient renovation and New construction.

A high material intensive building (passivhouse) can potentially increase the cooling loads in summer, leading to more electricity use and increasing the demand load.

Although Technical requirements and other building envelope characteristics can be improved, yet, the energy need of the building can only be reduced to a certain extent due to the limitations linked to the building geometry(size, shape and orientation). And as per passive standard, the renewable primary demand must not exceed 60 kWh per square of the energy demand attributed to the space heating and domestic hot water. There Passive house certifications for these kind of buildings are less likely to be achieved.

Due to the goal and scope of the study, it was more focused on the reuse potential and less towards the historic value. Simultaneous assessment has been carried out which includes reuse and energy savings potential. However, Additional evaluations in terms of cost and heritage value can be further explored. Moreover, reuse of materials that will continue into the next life cycle stage may potentially require maintenance that needs to taken into account. Therefore, a clear tagging of the building elements in BIM models can potentially provide more opportunities for further estimating the materials that will be demolished. The tagging could potentially be based on the project phases like existing,demolition and New Construction.

10 Module 06: Conclusion

The main findings brought forward by this study is that emissions related to the use of building materials in adaptive reuse is quite critical when it comes to the net climate benefits. We can also see that level of demolition and emissions from reuse of the materials contribution are less when compared with the new materials. Due to lesser differences with regards to demolition emissions The building with high energy efficiency level will take approximately 20 years to recover its upfront embodied emissions. The study, however is line with the previous studies which have also indicated, that the refurbishment(retrofitting, renovation and rehabilitation) process of historic buildings enables them to perform better with regards to GHG emissions. This reflects that the redundant and old historic buildings should be rejuvenated through refurbishment process in contributing towards the climate change objectives of the nations while keeping the historic value in tact.

Bibliography

[1] Benjamin Sanchez, Mansour Esnaashary Esfahani and Carl Haas. 'A methodology to analyze the net environmental impacts and building's cost performance of an adaptive reuse project: a case study of the Waterloo County Courthouse renovations'. In: *Environment Systems and Decisions* 39.4 (2019), pp. 419–438.

[2] Taofeeq Ibn-Mohammed et al. 'Operational vs. embodied emissions in buildings—A review of current trends'. In: *Energy and Buildings* 66 (2013), pp. 232–245.

[3] Mehrdad Rabani et al. 'Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building'. In: *Building and Environment* 204 (2021), p. 108159.

[4] Alberto Vilches, Antonio Garcia-Martinez and Benito Sanchez-Montanes. 'Life cycle assessment (LCA) of building refurbishment: A literature review'. In: *Energy and Buildings* 135 (2017), pp. 286–301.

[5] Selamawit Mamo Fufa, Cecilie Flyen and Anne-Cathrine Flyen. 'How Can Existing Buildings with Historic Values Contribute to Achieving Emission Reduction Ambitions?' In: *Applied Sciences* 11.13 (2021), p. 5978.

[6] Grete Swensen and Sveinung K Berg. 'Use of redundant industrial buildings as injections into the cultural sector in Norway'. In: *Planning Practice & Research* 33.3 (2018), pp. 344–358.

[7] UNEP. *Global status report for building and construction.* https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf. Oct. 2020.

[8] European Commission. *A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives.* https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662. Oct. 2020.

[9] Jonas Manuel Gremmelspacher et al. 'Historical building renovation and PV optimisation towards NetZEB in Sweden'. In: *Solar Energy* 223 (2021), pp. 248–260.

[10] Sheida Shahi et al. 'A definition framework for building adaptation projects'. In: *Sustainable cities and society* 63 (2020), p. 102345.

[11] Vaclav Hasik et al. 'Comparative whole-building life cycle assessment of renovation and new construction'. In: *Building and Environment* 161 (2019), p. 106218.

[12] Anne Rønning, Mie Vold and Guro Nereng. 'Refurbishment or Replacement of Buildings–What is Best for the Climate'. In: *Proceedings of the Conference Join Action on Climate Change Economics, Aalborg, Denmark.* 2009, pp. 8–10.

[13] KS Kyaw, SM Fufa and D Kraniotis. ‘Adaptive reuse of industrial heritage building–comparative life cycle assessment using a case study in Norway’. In: *IOP Conference Series: Earth and Environmental Science*. Vol. 1196. 1. IOP Publishing. 2023, p. 012107.

[14] Hao Cai et al. ‘Whole-building life-cycle analysis with a new GREET® tool: Embodied greenhouse gas emissions and payback period of a LEED-Certified library’. In: *Building and Environment* 209 (2022), p. 108664.

[15] Rayman Mohamed et al. ‘Adaptive reuse: a review and analysis of its relationship to the 3 Es of sustainability’. In: *Facilities* (2017).

[16] Xiaoyu Luo et al. ‘Life cycle assessment for carbon emission impact analysis for the renovation of old residential areas’. In: *Journal of Cleaner Production* 367 (2022), p. 132930.

[17] UNEP. *Sustainable buildings*. https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/sustainable-buildings. Oct. 2016.

[18] Peter A Bullen and Peter ED Love. ‘The rhetoric of adaptive reuse or reality of demolition: Views from the field’. In: *Cities* 27.4 (2010), pp. 215–224.

[19] Bin Liu et al. ‘Embodied energy consumption of the construction industry and its international trade using multi-regional input–output analysis’. In: *Energy and Buildings* 173 (2018), pp. 489–501.

[20] Marco Beccali et al. ‘Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits’. In: *Renewable and Sustainable Energy Reviews* 27 (2013), pp. 283–293.

[21] Gustav Sandin, Greg M Peters and Magdalena Svanström. ‘Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling’. In: *The International Journal of Life Cycle Assessment* 19.4 (2014), pp. 723–731.

[22] CEN. *Conservation of cultural heritage - Guidelines for improving the energy performance of historic buildings*. https://www.standard.no/nettbutikk/sokeresultater/?search=EN+16883&subscr=1. Feb. 2017.

[23] Laurence A Wright, Simon Kemp and Ian Williams. ‘‘Carbon footprinting’: towards a universally accepted definition’. In: *Carbon management* 2.1 (2011), pp. 61–72.

[24] Haibo Feng et al. ‘BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia’. In: *Journal of Cleaner Production* 250 (2020), p. 119543.

[25] Torhildur Fjola Kristjansdottir et al. ‘Embodied greenhouse gas emissions from PV systems in Norwegian residential Zero Emission Pilot Buildings’. In: *Solar Energy* 133 (2016), pp. 155–171.

[26] MK Wiik et al. ‘GHG emission requirements and benchmark values for Norwegian buildings’. In: *IOP Conference Series: Earth and Environmental Science*. Vol. 588. 2. IOP Publishing. 2020, p. 022005.

[27] Fredrik Berg and Mie Fuglseth. ‘Life cycle assessment and historic buildings: energy-efficiency refurbishment versus new construction in Norway’. In: *Journal of Architectural Conservation* 24.2 (2018), pp. 152–167.

[28] Preservation green lab. *The Greenest Building: Quantifying the Environmental Value of Building Reuseguidelines*. Vol. 0. Preservation green lab, 2009.

Appendix

A Bill of Quantity- Material Inventory

These have been provided in the supplementary material for all the scenarios as extracted from LCA Software.

B Operational Energy considerations

All operational energy outputs are also provided in the supplementary materials.

NTNU

Norwegian University of
Science and Technology