Comparative Analysis of Environmental payback time

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STUDENT REPORT

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Synopsis:

The thesis explores the method of environmental payback time (EPBT) for two existing buildings: A Row house and an Office. Four different renovation scenarios are investigated for the two buildings. The scenarios are the following: demolish+build, new build with photovoltaic (PV) panels and heat pumps (HP), a refurbishment scenario using reusable brick and concrete, and a retrofit renovation. The study aims to evaluate the renovation scenario with the shortest EPBT, which contributes to the best sustainable practice.
The results show the Row house, the EPBT for 18.4 years for new construction, 22.8 years for new construction with HP and PV, 7.5 years for new construction with reused materials, and 13.8 years for retrofit. For the office building, EPBT is 30.4 years for new construction, 26.4 years for new construction with HP and PV, 16.0 years for new construction with reused materials, and 17.0 years for retrofit. Based on these results, the most favorable renovation scenario is new construction using reused materials.

Resume

Dette speciale handler om, at brugen af metoden "klimamæssig tilbagebetalingstid", for to eksisterende bygninger fra 1960'erne, der skal renoveres. Fire forskellige renovering scenarier undersøges som følgende: standard nybyggeri, nybyggeri med varmepumpe og solceller, nybyggeri med genbrugs materialer, og sidst et scenarie for udskiftning af dele af klimaskærmen.

Først er der bestemt energiforbrug med Be18 af de to eksisterende bygning og dernæst de fire nævnte renoveringsscenarier. I anden omgang er der udført LCA for miljøpåvirkninger beskrevet i BR18 til bestemmelse af indlejret miljøpåvirkninger fra nye materialer og driften.

Miljøpåvirkningen fra driftbesparelsen blev beregnet ved differensen af drift påvirkningen fra de eksisterende bygninger og renoveringer. Metoden "klimamæssig tilbagebetalingstid" identificerer balancepunktet mellem de indlejrede miljøpåvirkninger fra de nye materialer og besparelsen i driftspåvirkningen. Resultaterne viser, at for rækkehuset var den klimamæssige tilbagebetalingstid 18.4 år for nybyggeri, 22.8 år for nybyggeri med varmepumpe og solceller, 7.5 år for nybyggeri med genbrugsmaterialer og 13.8 år for udskiftning af dele af bygningen. For kontorbygningen var den klimamæssige tilbagebetalingstid 30.4 år for nybyggeri, 26.4 år for nybyggeri med varmepumpe og solceller, 16,0 år for nybyggeri med genbrugsmaterialer og 17,0 år for udskiftning af dele af bygningen. Baseret på disse resultater er det mest fordelagtige renoveringsscenario nybyggeri med genbrugsmaterialer.

Preface

This study is conducted in Aalborg University according to the education indoor environmental and energy engineering 4th. semester 2023. The report is structured with an abstract written in Danish. Furthermore, a nomenclature with abbreviations helps the reader in the process. A literature review to highlight the inspiration for the research. A problem description with research questions. Additionally, the report is structured with a methodology description, description of case studies, scenario analysis, and result.

Lastly, the thesis article can be written on page 50-61 and afterwards comes to bibliography and appendix.

The appendix of the results from the Be18 and LCA is found seperately from the report.

The project period was attended from September 2022 - June 2023.

Reading Guide
Source references are made using the Harvard method. Thereby, sources are referenced as [Surname, Year] in the text and the associated bibliography.

The abbreviation appears in the text after the word has been introduced. So the first time the reader reads heat pump (HP), the next lines with heat pump are described with the abbreviation.

Also the description of the building cases are noted as Row House and Office. The big letter should identify the case study investigated in this study.

Additionally, the renovation scenario has changed name from "demolish+build new" to "build new". This occurs after the chapter scenario analysis due to negleting demolition processes in the renovation new build scenarios.

Figures and tables are numbered with reference to chapter and chronological order. The 1^{st} figure in chapter 7 is hereby mentioned as "figure 7.1", the 2^{nd} as "figure 7.2", and so on. Appendices are numbered A to C but follows this the same principles as in the main report.

Nomenclature

EPBT	Environmental payback time
HP	Heat pump
PV	Photovoltaic
DHW	Domestic Hot Water
BR18	Danish Building Regulations from 2018
BR61	Danish Building Regulations from 1961
EPD	Environmental product declaration
EPS	Expanded polystyrene
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCAbyg	Tool to calculate LCA
GHG	Greenhouse gases

Contents

1 Introduction

The building sector consumes around 40% of the total energy demand globally and regarding the environmental effects it contributes around 36% greenhouse gas emissions. The European Parliament has promoted various directives for energy efficiency in the building sector in order to address climate change issues. Regulations include building energy certification and incentives to reduce operational energy use in buildings through the implementation of minimum energy requirements for new buildings and the promotion of energy retrofitting of existing ones. [European Comission, 2010]

Before 2001, more than 220 million building units were constructed in the EU, accounting for 85% of the EU's building stock. Additionally, it is forecasted that in 2050, 85-95% of the structures that exist today will still be standing. The majority of those existing structures are inefficient in terms of energy use. A significant part of the heating and cooling systems of the buildings in Europe still rely on fossil fuels with the usage of outdated technologies and inefficient appliances [EU, 2020b].

EU sets a decisive framework for the climate goals in Denmark, it was stated that the aim was to reduce the CO2 emissions with 70 % in relation to 1990. Furthermore, the building sector should reduce the amount of global warming potential by 39 % in 2030 in relation to 2005, where the final aim in 2050 Denmark should become climate neutral. Additionally, it was insisted that, a minimum of 27 % should be achieved for the supply of renewable energy resources.

Additionally, to investigate the potential of increasing material efficiency and reducing climate impact, the EU Commission has launched a new comprehensive strategy in 2020 for a sustainably built environment. The promotion of circularity principles throughout the building life cycle is a major factor to reduce further the GHG-emissions and reach the goal of a climate neutrality world in 2050. The circularity principles that are introduced are addressing the potential of recycling materials, promoting measures to enhance the durability and adaptability of product materials, setting a scheme for recovery of materials from demolition waste, and according to the renovation wave that focuses mainly on energy improvement, circular principle tends to become in the same line of measures. [EU, 2020a]

2 Literature review

A literature review is conducted in this master thesis to investigate the existing research for renovations in Denmark and overall the method for EPBT. In this project, the focus with be on different building typologies and typical renovation methods. The chapter for the literature review with be divided into subchapters to highlight different focuses of renovation that will be used to research environmental payback time.

2.1 Environmental effectiveness of Retrofitting vs. demolish and build new

BUILD investigated the environmental impact of different cases, with three building typologies a residential house, a multi-story building, and an office. It was found that there may be a temporal balance point where a renovation loses out to demolition and build new, because of a high operational energy emission. This was mainly the case for residential houses, where the environmental payback time was shorter due to the operating energy emission share of the new build being significantly lower than the renovated scenario. Overall, it was found that, if the difference between the operating energy consumption before and after renovation was small, there would not be a great climatic advantage of the renovation. For multi-story housing construction and office buildings, renovation results in being climate-wise better than demolition/new construction. Generally, it was found that the operating energy contributes relatively much to the climate impact (30-66%) for renovation, while for demolition/new construction, it is primarily material-related and a smaller part of the climate accounting (19-24%). Regarding the environmental impact of the demolition, it accounts for 6-20% of the total climate impact if existing buildings had been demolished to build new, rather than renovate. Additionally, kitchen and bath replacement for single-family housing constitutes 8% and 18% of the total climate impact of all renovation measures, when calculated with a lifespan of 33 and 11 years respectively. [Mai et al., 2021]

2.2 GWP and LCC measures of different renovations

An investigation was performed by Rambøll in 2020, where 16 cases were introduced. Five of the cases were single-family houses, and the rest were offices, apartments, and institutions. For each building, an analysis of four scenarios has been carried out. The four scenarios consisted of:

- Renovation of roof (T)
- Renovation of roof and exterior wall (TY)
- Renovation of roof, exterior wall and installations (TYI)
- The existing building is demolished and replaced by a new building (N)

For the cases of the single-family houses that were built in the 1960s, it was shown that the accumulated global warming potential was lowest for the demolition and build new (N) with the 50-years reference study period. However, the pricing net present was generally cheaper for all the retrofit measures compared to the new building (N). For the office building scenarios, the worst scenario regarding the lowest environmental impacts was the demolition and rebuild with also the largest economic investment [Rambøll, 2020].

2.3 Waste and potential circular economy in the building sector

The amount of waste from the building sector depends on the building activities, which in turn depends on the economic cycle. According to the recent data for waste management construction waste makes up 40% of the total waste in Denmark. Around 33% of the of demolition materials from buildings is recycled. The remainder is repurposed by being broken down and used as noise barriers or road surfaces before being disposed or incinerated [Kiilerich, 2020].

The building sector has one of the greatest potentials for recycling materials, however, according to BR18, there is not yet enough data to develop any generic standard values for given materials. Additionally, BR18 introduces a guiding report that consists of reusable materials developed from the BUILD report.

The build report consists of data for reusable materials throughout an investigation of GWP impacts from the international database Ecovient. The data includes the GWP impact from different countries, where with respect to develop a scenario of reusable material, including the processes for disassembly, cleaning, and repairing materials from existing buildings. After extracting the existing building material, there will be a small amount of waste generated, with the waste percentage determined based on standard values provided by "Energistyrelsen" [Ernst Andersen et al., 2019] [BR18, 2018].

2.4 Barriers when reusing and recycling building materials

When a building's lifetime is met and the materials are demolished, the end-of-life stages for the materials can either be reused, recycled, or used for other purposes. However, certain barriers can prevent these scenarios, which will be described in some materials in this section according to the BUILD-report [Mortensen et al., 2015].

The company Novopan produces wood materials for the building industry experiences that some local municipalities are dependent on wood for incineration. Thereby, mostly all their demolished wood materials are transported to the incineration sites to secure optimal operation. Furthermore, using wood for recycling can be a problem, due to its very high content of hydrocarbons, which means that the wood waste can be classified as hazardous waste.

The company "Gamle Mursten" has a patented cleaning process, which removes the mortar from the old bricks so they are ready for reuse. The bricks are mechanically cleaned so that no harmful chemicals are introduced, According to the company, 2000 washed bricks save the environment one ton of CO2, and 65 % of old bricks can directly be reused for new buildings. The barriers for brick, it is quite hard to obtain due to the limited number of demolitions of cases with brick materials. Additionally, it is also a requirement that the product is CE-marked which means the product meets the EU's requirements for safety, health, and environmental protection. Furthermore, it can be difficult to obtain old bricks that have the same static properties as new bricks [Gamle Mursten Svendborg, 2023].

2.5 Research of buildings with application of circular economy

One of the newest research for the circular economy has been examined in the report for 65 unique real-world examples of new construction, renovation, and demolition projects. Case studies were examined in terms of the circular economy solution used, the level of application in buildings, and the reported decarbonization potential. The circular economy strategy has been presented into four categories of principles which are [Nußholz et al., 2023]:

- Closing resource loops (i.e., recycling materials)
- Narrowing resource loops (i.e., using fewer resources per product)
- Slowing resource loops (i.e., keeping products in use as long as possible)

- Regenerating resource loops (i.e., using renewable resources and regenerating the natural environment)

The focus of this study was to explore the implementation of circular building strategies and provide a critical discussion on the challenges of using life cycle assessment (LCA) for assessing circular economy in buildings. The results from this report indicated that for future research, the aim should be to identify circular strategies with high decarbonization potential that can be implemented beyond individual projects, such as the reuse of bricks and steel beams. One way to address the limitations of this study is by increasing the sample size, potentially by incorporating LCAs from databases maintained by practitioners.

2.6 Renewable sources for energy effiency in buildings

The European Council approved a resolution in March 2007 that reiterated the Union's commitment to the growth of renewable energy across the Union. In 2020, energy coming from renewable sources must be a minimum of 20% by 2020.[European Comission, 2010]. In the long term, by increasing energy efficiency and with increasing use of renewable energy sources, the building sector will also be able to contribute significantly to the 2050 goals of a 100% fossil-free society. Furthermore, in 2016 the energy performance building directive (EPBD) introduced Nearly Zero Energy Buildings, which aim was that all new buildings constructed by 2020 should have very low heating consumption.

In Denmark, it is classified as the building class 2020 in BR18, where the energy demand is significantly lower and the building is contributed with energy-producing systems on-site. By using different types of energy sources for heating and electricity, primary energy factors are used to weigh each source with respect to environmental impacts. The Energy demand multiplies the factor, which can vary depending on the source of energy and reduce further the environmental impacts. Primary energy factors in Denmark change in the future due to the development of green energy production, where "energistyrelsen" have future cast factors for 2030, 2035, and 2040.

2.7 EPBT method - state of the art

A literature review of cases using the method "environmental payback time" is performed to find, the latest updates. One article from BUILD will be described in section 2.7.1, whereas the others are found in science articles developed in other countries than Denmark.

2.7.1 EPBT - Climate effective renovation

In this report, it is to demonstrate, when energy renovations can achieve net savings in climate impact and how such calculations can be carried out with the available data. The report includes analyses of three types of renovation measures: insulation, window replacement, and installation of solar panels. These analyses are based on publicly available environmental data, where both generic data were used from ÖKOBAUDAT and EPDs.

The insulation study has investigated the climate efficiency of insulating roofs, exterior walls, and ground floors. The analysis explores various parameters, including existing and new insulation levels, types of insulation, and insulation products. Typically, the reduction in climate impact resulting from insulation is significantly greater than the environmental impact associated with the insulation materials alone. When considering any additional cladding materials that may be required, most insulation measures remain environmentally beneficial, although with extended payback periods in some cases. The overall profitability depends on the balance between energy savings and material burdens. Higher profitability is achieved when the existing insulation level is low, the material burden from insulation and cladding is minimal, and the new insulation level is high. Solutions with longer payback periods are more sensitive to initial parameters, such as insulation design, including quantity, type, and product, as well as calculation assumptions like indoor temperature.

In the window analysis, the installation of new double-glazed windows throughout the facade was compared with a combination of new triple-glazed windows on the north side and double-glazed windows on the remaining sides for three types of residential buildings. The combined solution has proven to be the most environmentally profitable. The exception is the renovated multi-story building, where no significant difference is observed. Additionally, the smaller buildings experience issues with overheating when using double-glazed solutions without sun shading. If the issue is addressed with sun-shading glass, it simultaneously reduces passive solar heating in winter and increases the climate impact. To achieve both good climate efficiency and indoor climate, the sun shading should be adaptable to summer and winter conditions.

The solar panel analysis has investigated whether the climate benefits of electricity production outweigh the climate impact of solar modules. Half of the examined modules are environmentally profitable. Generic data from ÖKOBAUDAT indicate a slightly less profitable level. Thin-film cells have shorter payback periods compared to crystalline cells. The high climate impact of crystalline cells is primarily attributed to the production of the substrate, known as the wafer. Thin wafers and those produced using renewable energy show significantly reduced payback periods. Assessing the profitability of solar panels in construction projects involves relatively high uncertainty. This is due to the lack of Environmental Product Declarations (EPDs) for solar panels available in Denmark and a less robust basis for comparison among EPDs due to methodological differences.

2.7.2 EPBT - Old school from 1960

A literature in 2020 [Asdrubali et al., 2021] uses the method for "EPBT" for an old school located on Ostia near Rome Italy built in 1960 with very low energy performance. Four different retrofit intervention was performed to evaluate the energy payback time and carbon payback time. The analysis of the energy of the building was performed with a dynamic hourly regime simulation tool "TRNSYS", where the following inputs were defined such as location, weather-climatic conditions, the plant components, the indoor temperature set point, and the characteristics of the building envelope. Furthermore, to calibrate their building model, physical measurement was performed. First, a heat flow meter to measure the thermal transmittance of the wall, secondly temperature probes measured the air temperature of the building, and lastly, a thermal imaging camera was used to analyze the heat losses of the building envelope. Then after the physical measurements, the energy model was calibrated, which was then used to simulate the retrofit strategies, which improved the building performance and reduced the energy consumption. Then the result of the simulated retrofit energy models was used as input in LCA, where the stages included were A1-A4 and C2-C4. The objective of the analysis was to assess the economic and environmental efficacy of four proposed retrofit interventions, specifically related to the replacement of fixtures and the application of an insulating coat on the windows. The results indicate that the replacement of windows emerges as the most advantageous intervention compared to insulating the envelope with regard to energy.

2.7.3 EPBT - NZEB scenario vs retrofit and cost-optimal scenario

This article focuses on the evaluation of energy and carbon payback times for different retrofit scenarios applied to a school building in Turin, located in Northern Italy. Three retrofit options were considered: an optimal cost retrofit and two NZEB retrofits, involving variations in envelope insulation, heat generation, and lighting systems, as well as shading and control devices. Initially, the building's energy consumption was simulated and the results were calibrated using actual energy bills data. The calibrated model was then used to assess the building's energy demand after implementing the proposed retrofit interventions. Additionally, a Life-Cycle Analysis (LCA) was conducted to calculate the environmental payback times. The findings revealed that the NZEB retrofit options resulted in energy and environmental payback times that were shorter than the building's life cycle. These results suggest that such solutions hold promise in addressing the challenges posed by global warming and energy supply in the foreseeable future.

2.7.4 EPBT - prefabricated envelope-cladding system (reuse material)

A study was conducted to develop a material-efficient prefabricated concrete element system that utilizes construction and demolition waste to renovate residential buildings by over-cladding their walls. The aim of the study was to assess the life cycle performance of the prefabricated concrete element system and compare it with more traditional wall construction in terms of energy conservation, carbon mitigation, and cost reduction in three European countries: Spain, the Netherlands, and Sweden.

Life cycle assessment and life cycle costing were carried out using the payback approach. The results showed that the energy payback periods for Spain, the Netherlands, and Sweden were 20.45 years, 17.60 years, and 19.95 years respectively. The results showed that the carbon payback periods were 23.33 years, 16.78 years, and 8.58 years, respectively. However, it was found that the financial payback periods were unlikely to be achieved within the building's lifetime. Only the Swedish case achieved a payback period specifically 83.59 years, which last over the building's lifetime.

Circularity solutions were explored to reduce the Prefabricated concrete element payback periods. The use of secondary material only had a minor effect on reducing the payback period. However, reusing the Prefabricated concrete element significantly decreased the energy and carbon payback periods to less than 6 years and 11 years, respectively, in all three cases. In terms of cost, reusing the prefabricated concrete element shortened the payback period to 29.30 years in Sweden, while the Dutch and Spanish cases achieved investment payback at 42.97 years and 85.68 years. [Zhang et al., 2021]

3 Problem description

As society becomes more concerned about climate change, there is an urgent need for effective methods that can address the environmental impacts on buildings. According to the building regulation in Denmark, a renovation emphasizes the reduction of energy consumption by improving the insulation of the building's envelope, more energy-efficient windows and doors, optimizing heating and ventilation systems, and implementing renewable energy in 2022. The first environmental requirements for buildings entered into force in 2023. All new buildings now have to be performed by a life cycle assessment (LCA), and new buildings above 1000 m^2 should not exceed the threshold of 12 $kgCO_2eq/m^2/year$. However, the Danish building regulation has no standard acquired for circular economy strategies, which could have reduced carbon emissions and waste from buildings.

In order to support the building sector to reduce its environmental impacts on global warming potential (GWP), there is a way to look at building materials, and for that, the method "Environmental payback time" (EPBT) comes into effect. EPBT determines if investments in new materials for renovation will bring environmental benefits. The information from EPBT can thus support a sustainable business practice by assisting stakeholders and investors regarding whether a renovation project is advantageous or not.

This study focuses on the implementation of EPBT on two case studies, row house and office building, to investigate the potential of this EPBT method in the Danish context.

3.1 Research questions

In this study, the research questions will be as follows:

- What is the potential EPBT for a more conventional new build for the building typology of Row house and Office?
- How will the use of renewable sources, such as photovoltaic panels and heat pump, impact the EPBT of an Office and a Row house?
- What are the potential environmental benefits for the EPBT when adopting reusable building materials?
- How much will the EPBT for a comprehensive retrofit renovation differ from demolition and building new?

4 Methodology

This study investigates the EPBT for four different renovation scenarios for two buildings: an Office, and a Row house. The purpose of the renovation scenarios is to find which renovation has the shortest EPBT. For this approach, the methodology for these scenarios can be illustrated by a flowchart in figure 4.1:

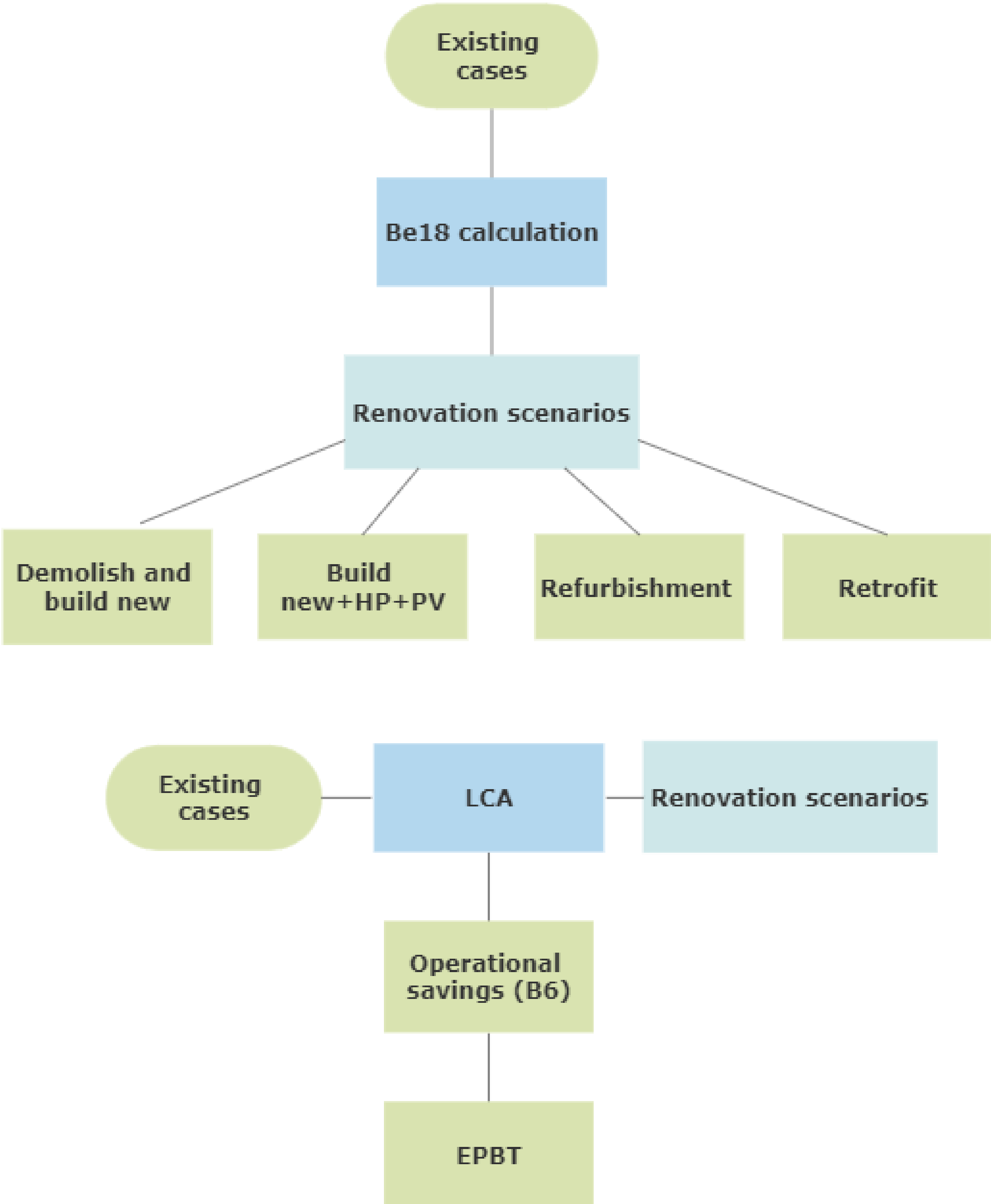

Figure 4.1. Flowchart for the EPBT-method

The methodology in this study includes the evaluation of the existing cases. The existing models were analyzed from documents that were shared by AAU. The first step was to study the envelope by counting the m^2 of the different materials and thicknesses for both existing cases. The evaluation of heat losses from the installation and the pumps was not clearly described in the documents. This led to the assumption of no insulation for the pipe network and standard size of pumps for installations. After analyzing the envelope, Be18 was used to perform the energy calculation for the existing cases. The purpose of the Be18 calculation was to act as the baseline for the two cases. Then after reviewing the literature, the final proposal of renovation typologies led to the four renovation scenarios: Demolition and build new, build new+HP+PV, refurbishment, and retrofit. The aim for the renovation scenarios is to find the most sustainable renovation resulting in the shortest EPBT. Thereby, a comparative analysis with more conventional renovation in Denmark would lead to more attention to the benefits regarding sustainability.

Next, an LCA was conducted for the existing cases and renovation scenarios following the Danish regulation for conducting an LCA [EN15978, 2011]. The operational saving for renovation scenarios compared to existing ones was determined and evaluated. The largest operational saving could potentially be the most beneficial, and lastly, the EPBT was calculated for all renovation scenarios.

4.1 Energy framework Be18

The energy demand for buildings in Denmark is based on the standard calculation with Be18. Be18 calculates the energy and electricity usage for space heating, domestic hot water (DHW), ventilation, and pumps. All heat losses and internal heat gains are calculated with standard assumptions depending on different building typologies, for people load, usage time, lightning, and devices.

Be18 also uses DRY 2013, which is a standard weather file, that has the option to change to other weather files, where the calculation for all the parameters depending on the temperature difference is based on monthly average outdoor temperatures [SBI, 2013].

The results from Be18 create an energy framework, which has the function of a benchmark to describe buildings' energy efficiency. Be18 is generally a theoretical calculation of a building's energy performance, and therefore the result is not expected to be the same for its actual energy consumption.

The theoretical calculations of residential houses and actual measured energy consumption were analyzed. It was shown according to the energy labels, that residential buildings with low energy efficiency have lower energy consumption than the theoretical calculation from Be18.

Additionally, energy-efficient residential buildings have a slightly larger actual energy consumption than the theoretical calculation. This occurs due to user behavior and indoor temperature, where the more energy-efficient building adapted to a higher indoor temperature for experiencing comfort. This gives an uncertainty of the operational impact, which creates an uncertainty in the results for the operational impact calculation [Gram-Hanssen og Anders Rhiger Hansen, 2016].

4.2 Energy labels - Buildings

Energy labels are used to describe a building's energy consumption in the form of product declaration. The product declaration visualizes an overview of energy-related improvements, that are beneficial to implement. Today, it is a requirement that all new residential, commercial, and public buildings have been energy labeled before selling or renting out [Energistyrelsen, 2023].

The scale of an energy label is ranged from A2020 to G, where A is the best label. The energy labels are based on standard energy consumption. This means that they do not provide the actual energy consumption, but they are indicators of showing how well a building is performing based on its energy qualitative. Table 4.1 shows the limit values for any given energy label:

Table 4.1. Labels indicator with respect to energy demand

Energy labels	**Energy demand** [$\mathbf{kWh/m^2year}$]
A2020	≤ 27
A2015	≤ 30.0 + 1000 / A
A2010	≤ 52.5 + 1650 / A
B	≤ 70.0 + 2200 / A
C	≤ 110 + 3200 / A
D	≤ 150 + 4200 / A
E	≤ 190 + 5200 / A
F	≤ 240 + 6500 / A
G	> 240 + 6500 / A

4.3 LCA for buildings

EN15978 is used for evaluating environmental impacts, which are applicable to new buildings, existing buildings, refurbishment projects, and retrofit projects. In terms of analyzing the LCA more accurately on a product level, EPDs are included for the scenarios, which follow the standard EN15804. The stages in the LCA will be described in this section [EN15978, 2011].

4.3.1 Product stage A1-A3

The product stage (A1-A3) refers to the processes leading to the manufacturing of a product. It involves the environmental impacts from extracting raw materials, to transporting them to the factory, and the process of manufacturing the product itself.

4.3.2 Construction stage A4-A5

When the product leaves the factory, it enters the construction stage (A4-A5). It includes the transportation of products to the construction site and the construction processes for the building. During the A4-A5, the emission of greenhouse gases occurs due to groundwork, on-site transportation, the transformation of products, and the generation of waste materials.

It is important to note that the waste of construction materials not only involves disposal but also additional production of materials and the end-of-life impact of the wasted materials.

4.3.3 Use stage B1-B7

Once the construction work is finished, the use of it commences and continues until the building is no longer usable (B1-B7). The B1-B7 stage emphasizes activities such as maintenance, repairs, replacements, and renovations. Replacements and renovations involve elements from the product stage, construction process stage, and end-of-life stage. Furthermore, the operational impacts from energy usage and water usage are defined as B6 and B7.

4.3.4 End of life stage C1-C4

end-of-life-stage (C1-C4) occurs, when when the building reaches its lifetime. This stage involves assessing the environmental impact associated with the deconstruction process, transportation to disposal sites, waste processing, and disposal of materials. As materials and products disassemble from a building, some of the materials will be discarded while other materials can be reused, recycled, or recovered.

4.3.5 Beyond system loads D

Items that have the potential for reuse, recycling, or recovery are considered resources that extend beyond the system boundary. This means that these materials are valuable and can be used to benefit the environment with CO2 reduction and eliminating energy waste. Beyond system loads (D) is typically evaluated independently from the other stages, as it explores the potential benefits and impacts beyond the system boundary rather than specifically within the system under consideration.

4.3.6 System boundaries for LCA scenarios

In this study, the LCA for a building is determined by standard modules that follow EN15978. These standard modules are A1-A3, B4, B6, C3 and C4, which are shown in figure 4.2:

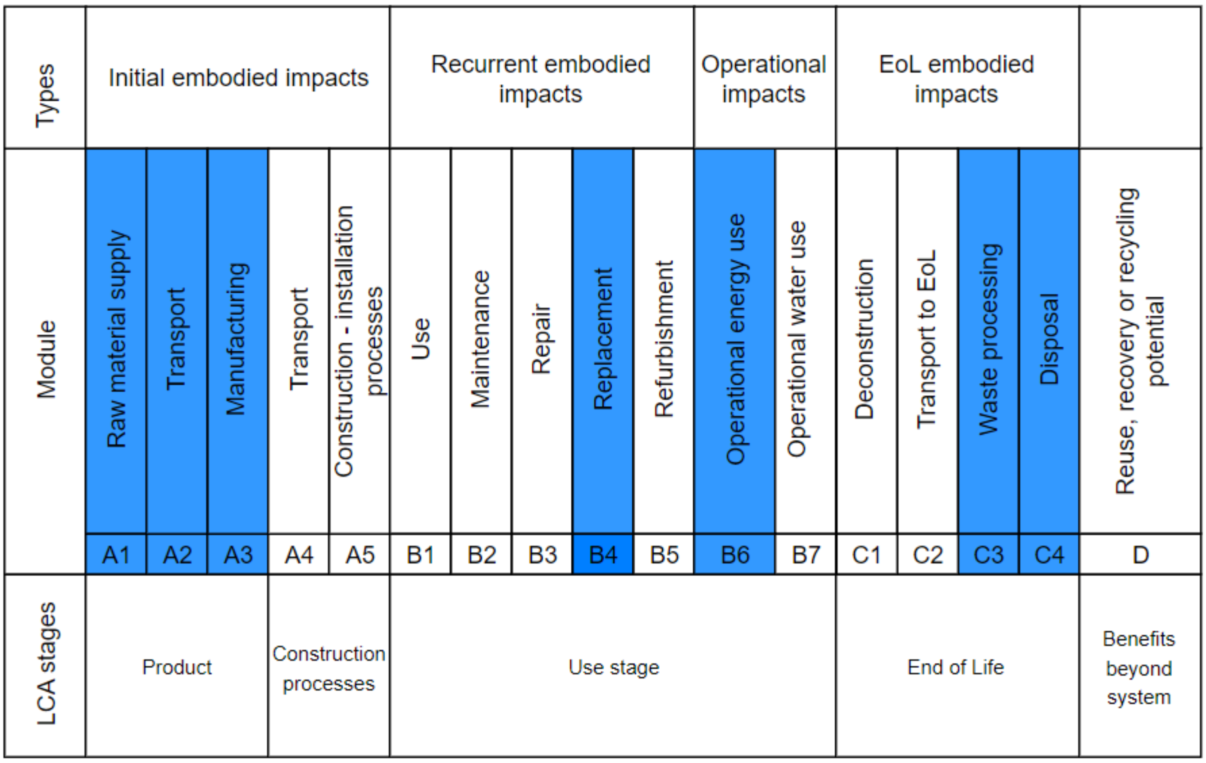

Figure 4.2. Description of each module in LCA (blue marked for included in this thesis) [EN15978, 2011].

For the system boundary, that determines the processes of the assessment In this study, in table 4.2 the modules included in all renovation scenarios are illustrated:

Table 4.2. Moduls included in all renovation scenarios marked with "x", and "xx" for retrofit with EoL from existing

Scenarios	**Existing**		**New build**		
Modules	B6	C3, C4	A1-A3	B6	C3, C4
Existing	x	x			
Demolish+build new			x	x	x
New build+HP+PV			x	x	x
Refurbishment			x	x	x
Retrofit		xx	x	x	x

A short introduction to the renovation scenario is described in this section. A more detailed description of the renovation presumption is found in appendix B.

Existing
The existing scenario includes the modules of operational impact (B6) and the end-of-life stage (EoL). As the energy efficiency of the existing cases is poor, the operational impact plays a significant role in the environmental impacts. The EoL is included to compare the environmental impact of demolishing, which is contributed to the other renovations.

Demolition+build new
The demolition+build new scenario includes solely new materials. The demolition of the existing is described as the EoL but is not considered in this scenario. This is chosen, due to study a comparative analysis of the renovation scenario. The demolition could be added to the renovation scenarios and result in a longer EPBT. The environmental impacts are considered from the use stage with B4 and B6. Lastly, the EoL is included.

Build new+HP+PV
The build new+HP+PV scenario is identical to the demolition+build new stage but with integrated HP and PV panels. Renewable resources lead to a larger operational saving and potentially a shorter EPBT. The renovation scenario includes the same stages described previously.

Refurbishment
The refurbishment scenario is identical to the demolition+build new stage, but with the use of reusable materials extracted from the demolition project. Reusable materials has a lower initial impact (A1-A3), which potentially results in a shorter EPBT. The renovation scenario includes the same stages described previously.

Retrofit

The retrofit scenario is different from the other scenarios. The existing building's interior layer of the envelope is retained. The exterior layer of the envelope is replaced with an identical new layer and with an increase in insulation. This results in improved energy efficiency and a lower burden in initial embodied impacts. This renovation type could potentially result in a shorter EPBT. The renovation scenario includes the EoL of the layers that are replaced from the existing and the new build stages from the new materials.

The construction materials that are included in the LCA will be listed:

- Foundation
- Interior - walls and doors
- Beams/columns
- Balcony
- Roof and ceiling
- Floor and deck
- Exterior wall
- Windows and door
- Installation: DHW, Heating, ventilation
- PV and HP

4.3.7 LCA calculation with LCAbyg

LCAbyg, a Danish-developed tool, is utilized as a means to calculate the life cycle assessment for buildings. By inputting data regarding various construction components and operational energy, the tool can perform the necessary calculations for the stages typically considered in Denmark. LCAbyg primarily relies on generic data sourced from the German ÖKOBAUDAT database to assess environmental impacts. Nevertheless, it is also possible to incorporate data from Environmental Product Declarations (EPDs) [BUILD, 2023].

In this study, LCAbyg is used to evaluate the GWP impact from the building cases. The dataset used is solely generic data from ÖKOBAUDAT and "EPD Denmark" for wood and concrete materials.

4.4 Reference year and lifetime of components

The reference year is set at 50-years as a frame for investigating if the scenarios are profitable in relation to the environmental payback time of the new materials and the operational saving. For the replacements of building materials (B4) are included in the calculation if the lifetime is less than 50-years. The lifetime of the different materials is based on the new updated lifetime table given from [Haugbølle, 2021].

The remaining lifetime from the existing building for the retrofit scenario is not included in the assessment, because the existing building parts are materials with a long lifespan e.g. brick, concrete, and insulation, which is expected to hold over the building lifespan. therefore, the remaining lifetime of the building parts is preserved as the initial lifetime of the given materials.

4.5 Environmental impact for district heating and electricity

The environmental impacts from the building's operational energy usage (B6) are calculated using emission factors in the LCA. These emission factors are based on dynamical calculation, due to the development of the Danish energy supply, where in the future, a transition from coal-fire at central plants to more use of biomass, and continued expansion with onshore wind, offshore wind, and solar cells will reduce the emission further. These data from the Danish Energy Agency (Energistyrelsen) had been provided to COWI in a report. COWI analyzed these emission factors by forecasting electricity and district heating for 2025, 2030, 2035, and 2040 [COWI, 2020].

In figure 4.3, the GWP impact of 1 kWh of electricity and district heating is illustrated:

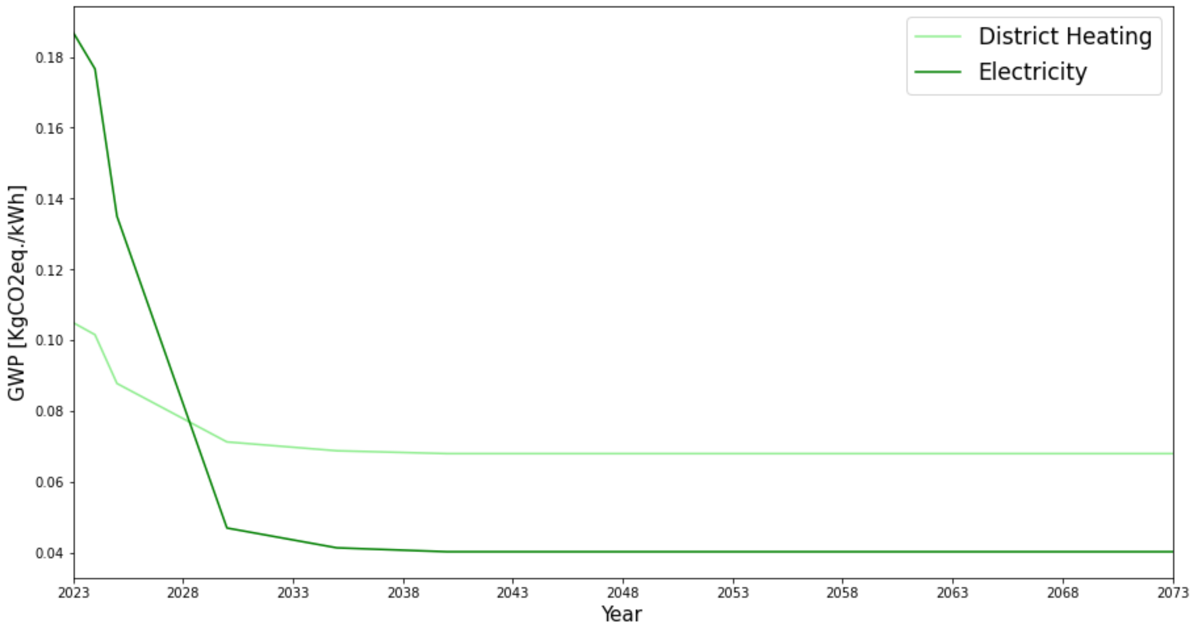

Figure 4.3. Forecast of 1 kWh of in GWP impact for district heating and electricity

Between the years 2023, 2025, 2030, 2035, and 2040 a linear interpolation is calculated. From 2040-2070 the GWP's impact is assumed to be constant because a forecast is based on existing technology and current efficiency, and therefore it is uncertain to conduct a forecast for these years.

4.6 Environmental payback time (EPBT)

In this section, a simple step-by-step is made to illustrate, how the EPBT-method works. The first step is to calculate the energy consumption in Be18 for the existing buildings, furthermore the energy consumption for the renovation scenarios.

The second step is to calculate the cumulative operational impact over the 50-year reference period.

The third step includes the calculation of the energy saving as the difference between energy consumption from the existing and renovation.

This step-by-step description is illustrated in figure 4.4.

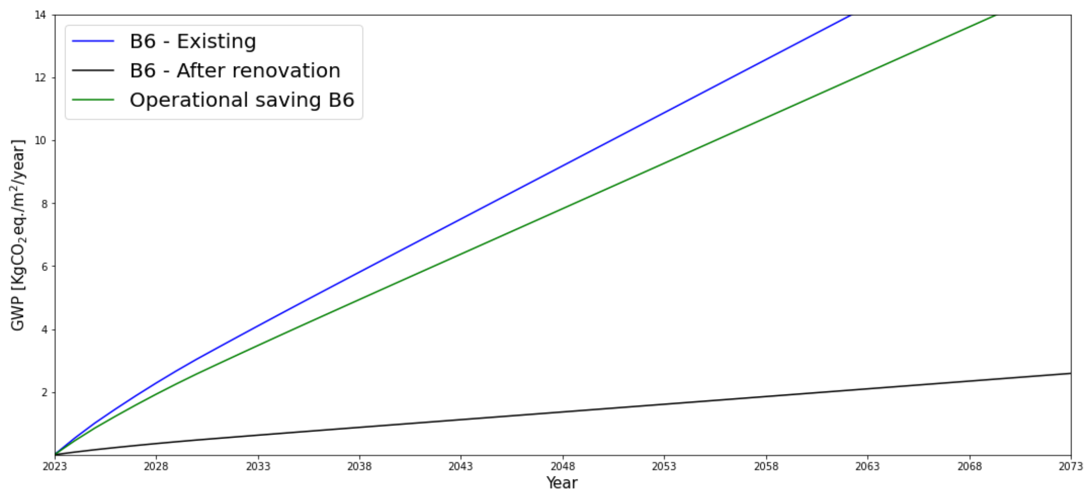

Figure 4.4. B6 impact from reference, renovation and the saving in B6

The fourth step is determining the environmental impact of the new material for the renovation scenarios, where the modules that are included in the embodied impacts are shown in figure 4.5. The EPBT can now be calculated as the balance point for where the embodied impacts reach the operational impact savings after renovation. This is illustrated in figure 4.6, where the red dot is marked as the balance point between the operational saving and investment of new materials also known as the EPBT.

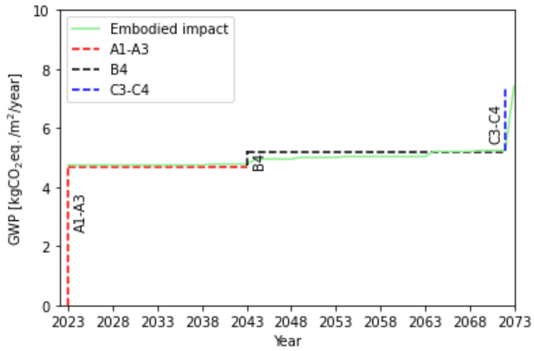

Figure 4.5. The embodied impacts included of modules

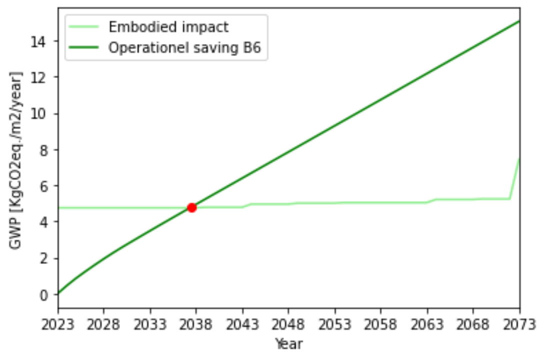

Figure 4.6. Payback time of operational saving and embodied impact for renovation

5 Case studies

To investigate the environmental impacts of the four renovation scenarios, two real cases are given for a residential house and an office from 1963 and 1958. The scenarios investigated in this thesis will focus on the potential reduction in environmental impacts of the renovation measures, neglecting the economic factor. In order to form a more representative comparison with the scenarios, environmental impacts based on generic data will be examined. In appendix A a detailed illustration of the envelope is sketched in 2D and compared to U-values given from BR61.

5.1 Row House - Torpedammen

The building is located in Brøndby, which is part of a row house block that consists of ten houses. It was built in 1963, where the total heated floor area is 640 m^2 of one block and consists of an unheated storage room of total 64 m^2. The building and 2D sketch of two houses are illustrated on figure 5.1 and 5.2

Figure 5.1. Torpedammen - North face [Google maps]

Figure 5.2. Torpedammen - From above [Google maps]

The exterior wall is constructed as cavity walls with brick on the front and back and stone wool in between. The building has no cellar and the construction of the floor are wood beams on joists, concrete, and a layer of gravel. Additionally, the roof has a slope of 11°, constructed with brick roofing, wood joists, stone wool, and plasterboard. Lastly, the windows are assumed to be of 2-layer glass with a tree-aluminum frame. The U-values have been determined with regards to design values of thermal properties given from [Dansk Standard, 2011]. A more detailed description of the building and U-values are found in appendix A.

5.2 Office - Knud Hoejgaard hus

The building Knud Højgaard hus is an office building, which was built in 1957-1958 and located in the center of Copenhagen. The building consists of a heated basement, ground floor, and up to 5. floor. The overall heated floor area of the commercial building is 11 240 m^2, and the functionality of the building consists of grocery stores, shops, and restaurants on the ground floor and for the 1. to the 5. the floor is open space with a few office rooms and meeting rooms. The cellar consists of bicycle parking spaces, storage rooms for the shops and restaurants, and technical room for installations.

Figure 5.3. Knud Højgaard hus - West face [Google, 2023]

Figure 5.4. Knud Hoejgaard hus - From above [Google maps]

The whole building is mainly of heavy materials, where the basement walls are made of concrete and with aerated concrete on the inner layer. The cellar deck consists of gravel and concrete which has been constructed on-site. The exterior walls of the building are constructed with cavity walls, with concrete on the front and back and air in between. On the ground floor, a concrete footing is placed around the glass facades. Additionally, the roof is built with concrete and with a top layer of roof paper. Lastly, the windows are of 2-layer glass with a tree-aluminum frame. A more detailed description and calculation of U-values are found in appendix A

In this thesis, a baseline model for both cases is developed according to the existing building. For the renovation scenarios, clear changes to the building envelope will be demonstrated with also new energy demand calculation, which will be illustrated with regard to energy labels. In table 5.1 the U-values and building materials for the envelope is listed for the existing buildings of both cases.

Table 5.1. Existing model of the envelope with U-values and energy label with respect to the energy consumption

Cases	Envelope	Material	Thickness[m]	U-value [W/m^{2}K]	Energy class
Row house	Wall	108mm Brick	0.108	0.55	F
		Stonewool	0.050		
		Brick	0.108		
	Roof	Brick roofing	0.002	0.53	
		Wood beams	0.039		
		Roof truss	0.025		
		Stonewool	0.050		
		Plasterboard	0.020		
	Floor	wood boards	0.022	0.30	
		Wood beams	0.022		
		Stonewool	0.050		
		Concrete	0.100		
		Gravel	0.250		
	Windows	2-layer glazing	0.024	2.80	
		Tree-aluminium frame	[-]		
		SHGC=0.75			
Office	Wall	Concrete	0.240	2.70	F
	Basement wall	Concrete	0.300	0.42	
		Aerated concrete	0.050		
	Basement deck	On-site concrete	0.250	0.54	
		Gravel	0.150		
	Roof	Concrete	0.240	1.66	
		Asphalt roofing	0.002		
	Windows	2-layer glazing	0.024	2.80	
		Tree-aluminium frame	[-]		
		SHGC=0.75			
	Columns	Concrete 4x4	0.040	[-]	

All the concrete materials are with a standard amount of reinforcement of steel for both cases, given by the LCAbyg library. From the existing building model, the CO_2 emissions from heating and electric use are needed to calculate the operational impact savings. The heating source is from district heating (DH) for all scenarios except the scenario with new build+HP+PV. This given, the energy usage for heating and electricity will be listed in table 5.2

Table 5.2. Energy usage for heating and electricity according to the reference cases

Case	Source	Energy usage [kWh/m^{2}year]
Row house	Heating (DH)	227.4
	Electricity	3.3
Office	Heating (DH)	167.9
	Electricity	45.4

6 Scenario analysis

In the following chapter, the results of the different scenarios will be presented in the sections below. First, the environmental impacts from the reference scenario will be presented. For the renovation scenarios there will be an introduction of the changes made, then the calculation of the operational impact and embodied impact for the scenarios, and lastly the payback time.

6.1 Existing building

The consideration of End-of-Life (EoL) impacts in the analysis is limited to the demolition phase of the existing building. As the construction of the building is already completed, the only embodied impact that would arise comes from the dismantling and disposal of the structure. For the two case studies, the results will be shown for the LCA modules described in the table 4.2. The fact, that both cases are built around the 1960s, the building energy efficiency is slightly poor due to the building regulation in BR61 being less strict. On appendix A a more detailed description of the building regulation for the case studies is enlightening. Furthermore, an illustration of the materials is shown in appendix A.

the embodied impact of construction parts for the Row house, as well as the six major contributors to the embodied impact for the office building are shown in figure 6.1.

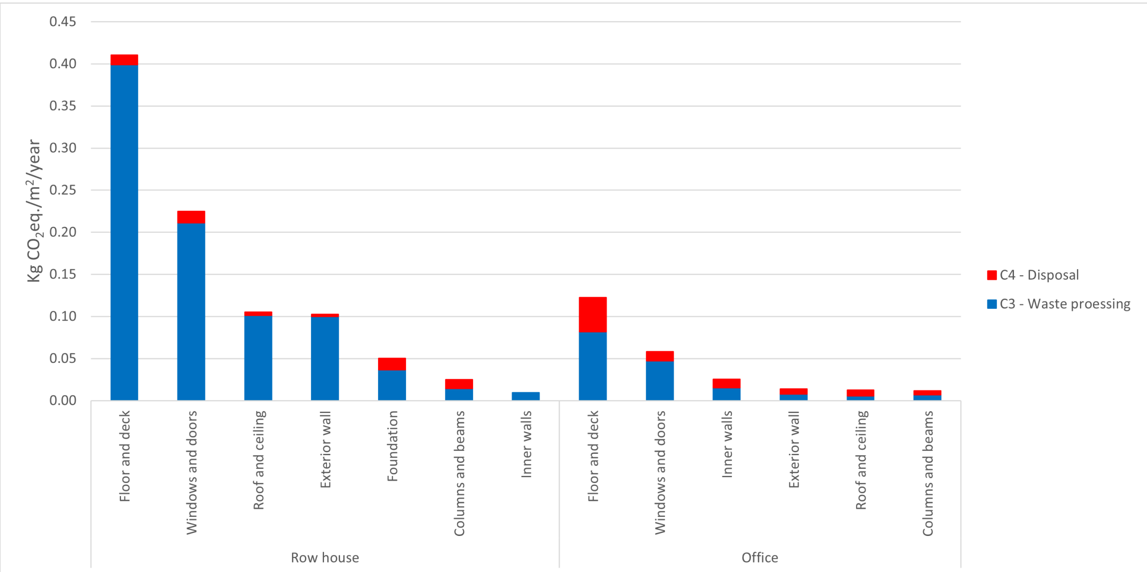

Figure 6.1. C3 and C4 stages from construction parts of case studies

It is shown in figure 6.1. that waste processing has the largest contribution to the GWP. The reason the floor and deck in both cases have the largest C3 is because of the wood material being incinerated and releasing CO_2 in the atmosphere. This indicates that proper waste management and recycling initiatives associated with wood waste would potentially be beneficial for the reduction of the total environmental impacts.

In general, the row house EoL impacts are significantly higher than the office. This occurs, due to the relationship between the total area of a building and the functional unit of GWP. The larger amount of m^2 the building has, the lower the environmental impact GWP.

Additionally by including the operational impact compared with the EoL impacts, the total embodied impacts are shown in figure 6.2.

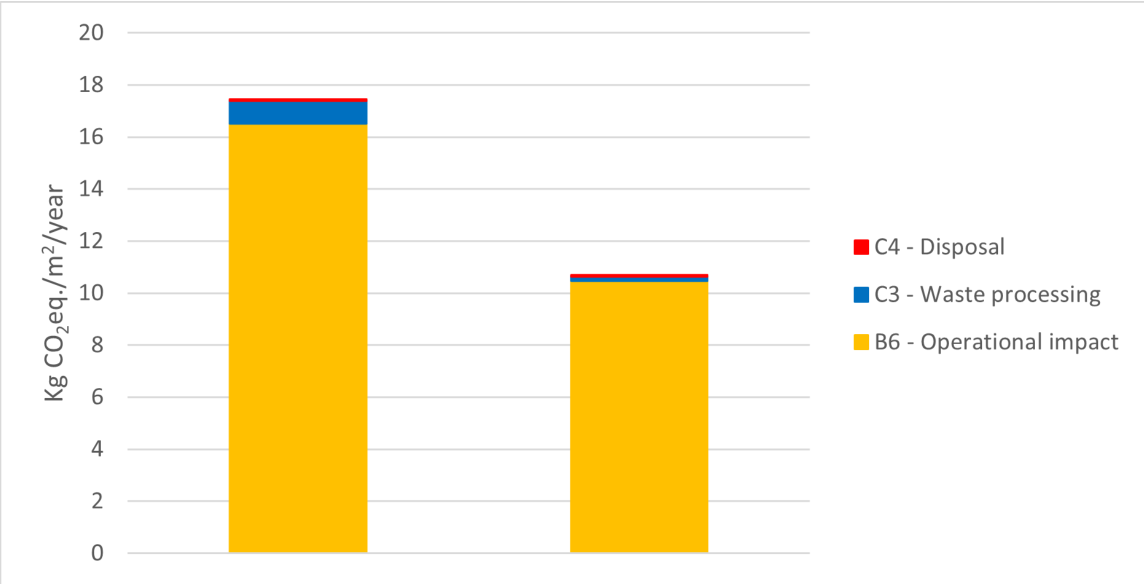

Figure 6.2. Total operational and embodied impact of the existing cases

Table 6.1. GWP of the LCA modules for the reference scenario

Case	B6	C3	C4	Total
	[$kgCO_2/m^2/year$]			
Row house	16.52	0.87	0.06	17.45
Office	10.46	0.16	0.08	10.70

The significant operational impact indicates that efforts to reduce the GWP should primarily focus on optimizing energy efficiency and minimizing energy consumption during the building's operational phase.

6.2 Demolish+build new

For the demolish+build new scenario, the existing building is demolished and not considered in the LCA. The demolish+build new scenario includes conventional materials for the envelope according to Row houses and Office. The aim is to fulfill the requirement of energy demand given from BR18 [BR18, 2018]. Furthermore, a more detailed description of presumption are described in appendix B. The Be18 inputs can be seen in the appendix "Be18 - data".

6.2.1 Case study - Row house

For the terraced house building, the materials used for the envelope have been chosen on the basis of five real new builds of residential houses. in appendix C a description and illustration of the five real cases material and U-values are to be found.

A new decentral mechanical ventilation system is installed with a standard constant ventilation rate for $0.3\,\mathrm{l/sm^2}$ for winter and summer. Additionally, the installations located in the unheated area have been insulated with 50 mm PUR insulation, where the existing case was non-insulated.

In table 6.2 are the materials for the envelope. U-values and new energy label is illustrated for Row house:

Table 6.2. demolish+build new envelope construction for Row house, FH*=floor heat

Construction	Material	Thickness [m]	U value [W/m^{2}K]	Energy label
Exterior wall	Brick Stonewool class 34 Aerated concrete	0.108 0.190 0.100	0.14	A2010
Ceiling and roof	Troldtekt Gypsum plasterboard 22x95 wood joists Stonewool class 34 Granules 34 28x45 wood beams Asphalt paper	0.025 0.013 0.022 0.450 0.028 0.002	0.06	
Deck and floor	Floor tiles Concrete C25 FH* EPS insulation	0.008 0.120 0.400	0.07	
Windows	3-layer glazing SHGC=0.31 Tree-alu frame	0.036 - -	0.83	

6.2.2 Case study - Office

For the Office case, it is assumed that the strength of the concrete element is between C30-C37, due to the higher impacts of loads from outdoor conditions, from materials, people, and equipment. For evaluating the indoor environment, MTH Hoejgaard has conducted an indoor environment simulation for thermal and atmospheric comfort with BSim for the real renovation of the office. The real renovation is very comprehensive and has very similar U-values for the envelope and the same interior design of inner walls, floor decks, and rooms. It is assumed that their results for minimum ventilation rate are representative of this renovation scenario.

In table 6.3, the materials for the envelope. U-values and new energy label is illustrated for Office.

Table 6.3. demolish+build new envelope construction for Office

Construction	Material	Thickness [m]	U value [W/m^{2}K]	Energy label
Exterior wall	Brick Stonewool C34 Concrete C37	0.070 0.190 0.150	0.17	B
Basement deck	Concrete C37 EPS insulation Gravel	0.200 0.300 0.200	0.08	
ground-4. floor deck	linoleum Concrete C37 Stonewool C34	0.0025 0.120 0.100	[-]	
Roof and ceiling	Stonewool C34 Concrete C37 Asphalt paper	0.400 0.120 0.002	0.08	
Basement wall	Concrete C37 Stone wool class 34 Aerated concrete	0.300 0.180 0.050	0.14	
Windows	3-layer glazing SHGC=0.31 Tree-alu frame	0.036 - -	0.83	
Columns/beams	Concrete C37	0.4x0.4		

6.2.3 Total embodied and operational impact

The embodied impact from both case studies has been evaluated using both generic data and branches EPDs given from the LCAbyg library. The branches EPDs are used for the different concrete strengths and for construction wood, which is more representative of the Danish marked compared to ÖKOBAUDAT data. The included modules are for demolish+build new scenario, A1-A3, B4, B6, and C3-C4, where in figure 6.3, the A1-A3, B4, C3-C4 stages for the construction parts are illustrated and top five highest contributors on table 6.4:

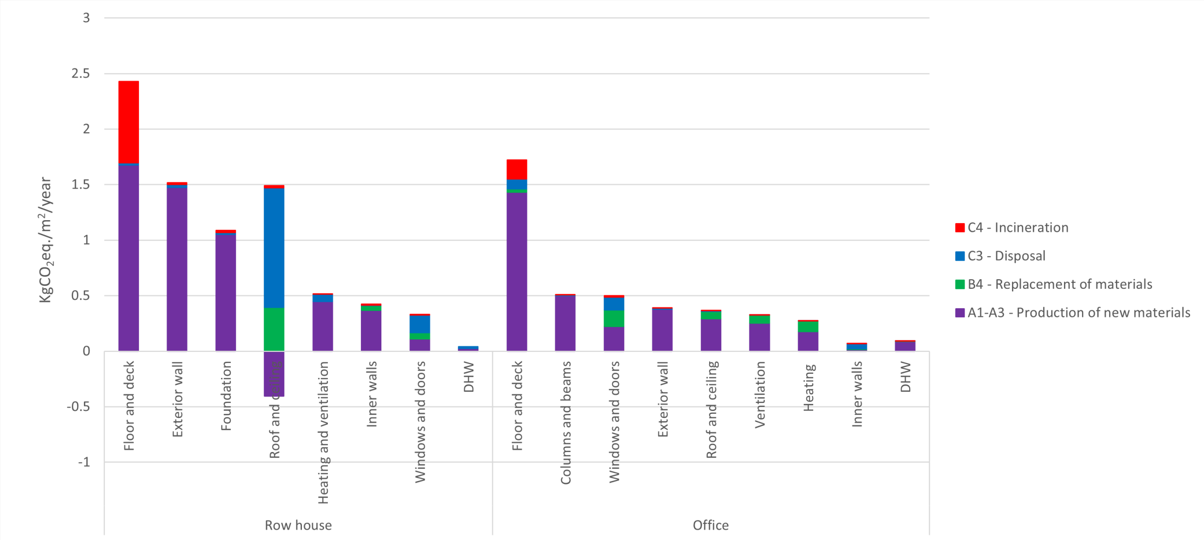

Figure 6.3. A1-A3, B4, C3-C4 stages for demolish+build new scenario for construction parts

Table 6.4. Top five highest contributor from figure 6.3

		A1-A3	B4	C3	C4
		[$kgCO_2/m^2/year$]			
Row house	Floor and deck	1.68	0.00	0.02	0.73
	Exterior wall	1.48	0.00	0.03	0.02
	Foundation	1.05	0.00	0.02	0.02
	Roof and ceiling	-0.41	0.39	1.08	0.02
	Heating and ventilation	0.45	0.00	0.06	0.00
Office	Floor and deck	1.43	0.03	0.09	0.17
	Columns and beams	0.50	0.00	0.01	0.01
	Windows and doors	0.22	0.15	0.12	0.01
	Exterior wall	0.38	0.00	0.01	0.00
	Roof and ceiling	0.29	0.07	0.00	0.01

It is seen in figure 6.3 that the floor and deck have the highest contribution for both cases. This occurs due to the deck is constructed with a high amount of concrete. The row house uses C20-C25 concrete and Office C30-C37, which has a higher GWP. For the office, the exterior wall is a conventional sandwich element facade, where the back wall of concrete is used as the structural element and the brick as the cladding. The inner walls are standard light walls with two-layer gypsum plasterboard on each side and 45 mm gypsum in between steel profiles given by MTH-hoejgaard. However, the office has generally a lower embodied impact due to the relationship between GWP and m^2 heated floor. Additionally, comparing the accumulated operational impact with the embodied impact is shown in figure 6.4 with the values given from table 6.5:

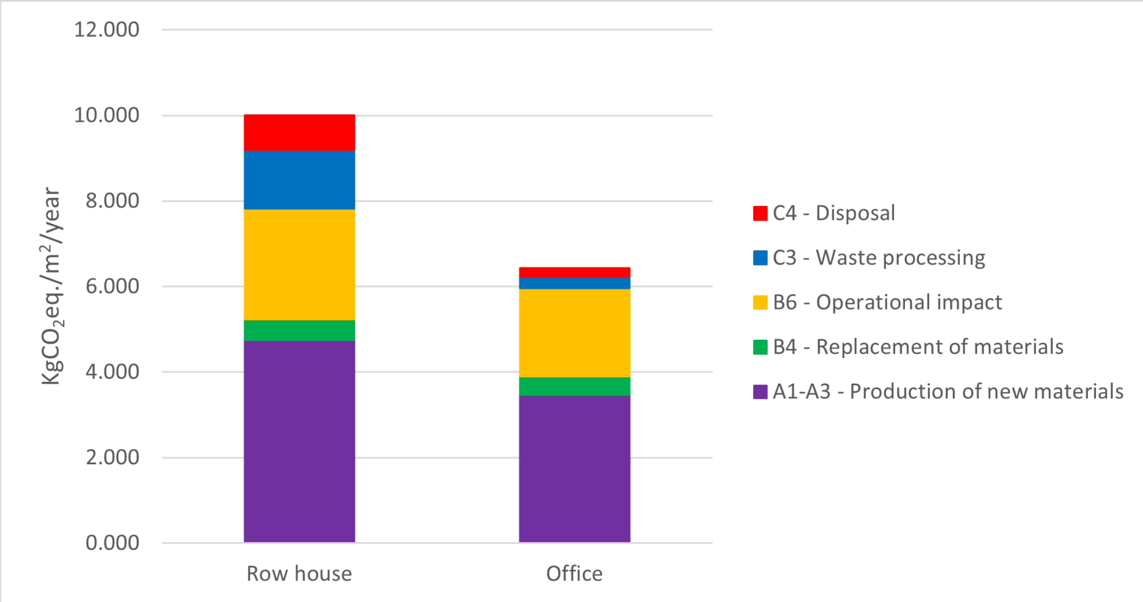

Figure 6.4. Total operational and embodied impact of the demolish+build new

Table 6.5. GWP of the LCA modules for the demolish+build new scenario

Case	A1-A3	B4	B6	C3	C4	Total
			[$kgCO_2/m^2/year$]			
Row house	4.75	0.49	2.58	1.39	0.80	10.04
Office	3.47	0.43	2.07	0.27	0.20	6.44

The demolish+build new scenarios have a large improvement in the energy quality, which leads to a low operational impact B6. On table 6.6 the reduction compared to the reference scenario in energy usage for heating and electricity is illustrated:

Table 6.6. Energy usage for heating (DH) and electricity for demolish+build new scenario

Case	Heating (DH)	Electricity
	[kWh/m^2year]	
Row house	36.0	3.1
Office	12.2	23.1

The operational savings from the LCA stage B6 are calculated cumulative for a reference study period of 50-years. The difference between the B6 from reference and demolish+build new. Hence, the EPBT can be calculated for both cases and shown in the figures 6.5 and 6.6:

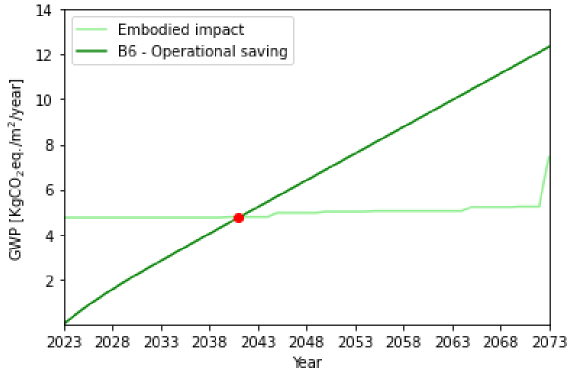

Figure 6.5. EPBT for the demolish+build new scenario of Row house

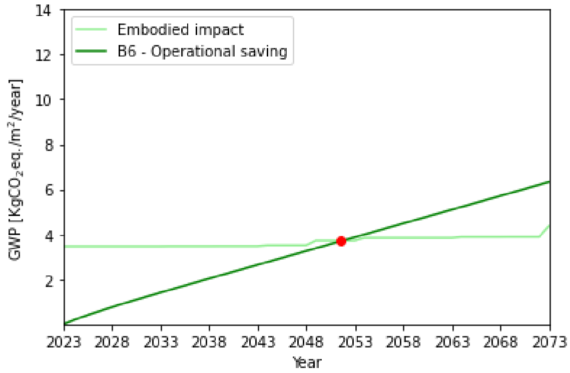

Figure 6.6. EPBT for the demolish+build new scenario of Office

6.3 New build+HP+PV

For the new build+HP+PV scenario, all the materials determined from the scenario new build are retained. Conventional PV and HP are selected to analyze the impact on the EPBT when the building has a supply from renewable sources. The conventional supply from DH is replaced with renewable sources that consist of a combination of PV and an air-water HP. In these case studies a 50 m^2 standard monocrystalline PV panels has been chosen for the terrace house with a slope of 11° on the south orientation, and a 100 m^2 with a slope of 45° on south for the Office. A more detailed description of the scenario is found in appendix B and Be18 inputs from the "Be18 - data".

6.3.1 Case study - Row house

For the be18 input of Row house a specific product for HP is selected, which is the Metroair F6, The Metroair F6 has a standard P_{nom} of 5.1 kW/6 kW for space heating/DHW according to EN14511. Furthermore, a COP value of 4.84/4,72 according to test temperatures 2 °C outside and supply temperature of 35 °C. The HP is a split function, where it is placed outside and heating all the heat floor pipes and water tank [Metrotherm, 2023]. Additionally, the PV system is a standard monocrystalline panel with connection to a standard inverter and wires [Vivaenergi, 2023], For the be18 input, the peak demand power is given as 0.197 $kW_p/4m^2$ for a two panel, with a system efficiency of 85 %,

6.3.2 Case study - Office

For the be18 input of Office, a conventional HP for large Offices is selected with the product Aerotop M24 [GASTECH ENERGI, 2023]. It has a size of 21 kW, which is a bit oversized compared to the minimum size, but to ensure that it can supply sufficient heat and provide good thermal comfort, this is assumed to be representative. The Aerotop M24 has a P_{nom} of 15.6 kW/7.2 kW and a COP of 4.3/3.7 for space heating and DHW according to EN14511. The PV system is the same type described for the Row house but with 100 m^2 module area.

6.3.3 Total embodied and operational impact

For the embodied and operational impacts calculation, generic data for HP and PV are used from the LCAbyg library. The quantities in the library are scaled, so that they match with the selected products described previously for both cases. The focus is to estimate the influence on the EPBT by the added embodied and reduction of operational impact by comparing it to the new build scenario. The embodied impact contribution from the PV and HP is shown in the table 6.7:

Table 6.7. Embodied impact from the PV and HP for both cases

Case		A1-A3	B4	C3	C4	Total
		[$kgCO_2/m^2/year$]				
Row house	PV	0.277	0.288	0.000	0.011	0.58
	HP	0.009	0.009	0.001	0.000	0.02
Office	PV	0.029	0.031	0.000	0.001	0.06
	HP	0.003	0.003	0.000	0.000	0.01

The HP and PV contribution to the embodied and initial impact is low for Office, whereas Row house receives a higher contribution. Comparing the HP and PV with the other construction parts, they have a small contribution to the embodied impacts. The cumulative operational impact with the embodied impact is shown in figure 6.7 with values from table 6.8:

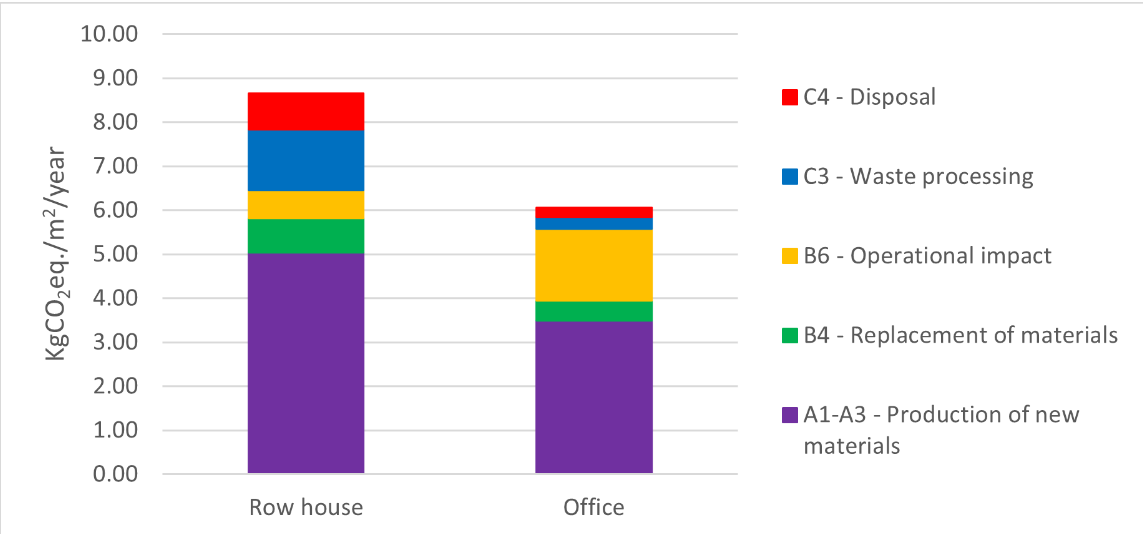

Figure 6.7. Total operational and embodied impact of the new build+HP+PV scenarios

Table 6.8. Total embodied impact and operational impact of new build+HP+PV

	A1-A3	B4	B6	C3	C4	Total
			[$kgCO_2/m^2/year$]			
Row house	5.03	0.79	0.64	1.39	0.81	8.66
Office	3.50	0.45	1.63	0.27	0.20	6.05

The operational impact is lower compared to the new build scenario, which potentially could result in a shorter or longer payback time, due to the increase in the initial embodied impact. In the table, 6.9 energy usage for heating and electricity and the new energy label is illustrated:

Table 6.9. Energy usage for heating (DH) and electricity for new build+HP+PV scenario

Cases	**Heating (DH)**	**Electricity**	**Energy label**
	[**kWh/m^{2}year**]		
Row house	-	3.1	A2020
Office	-	23.1	B

The new energy calculation results in the energy quality becoming in class A2020, which symbols the low-energy class according to BR18 [BR18, 2018].

This means, the building has reached the best energy quality and thereby this scenario obtains the largest operational saving compared to the other renovation scenarios. The EPBT is calculated cumulative and the results in figure 6.8 and 6.9:

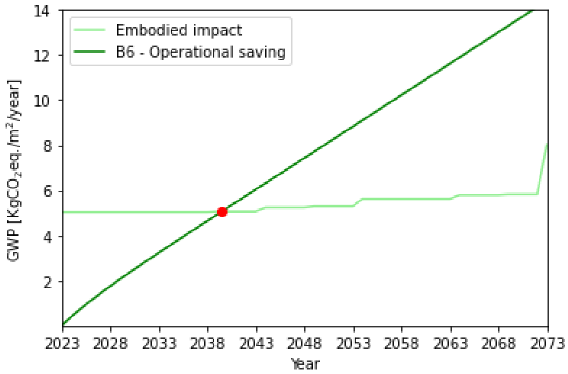

Figure 6.8. EPBT for the new build+HP+PV scenario of Row house

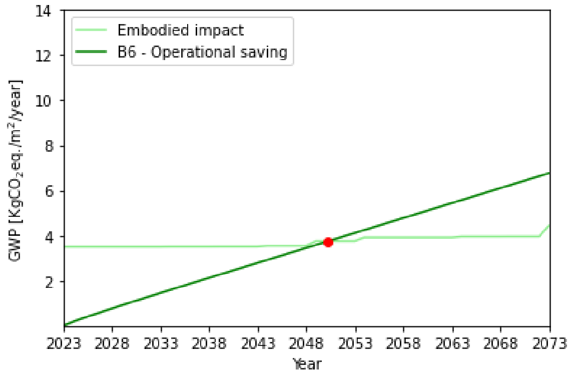

Figure 6.9. EPBT for the new build+HP+PV scenario of Office

6.4 Refurbishment - Reuseable materials

For the refurbishment scenario, the aim is to see the potential reduction in the EPBT, by using one of the strategies based on circular economy. If the building is built new with reusable materials, it can help reduce the demand for new resources (A1-A3) and minimize waste (C3-C4). By repurposing existing materials from demolition projects, it can contribute to sustainable practices, conserve energy, and decrease environmental impacts.

Generic data for reusable materials are not yet developed thoroughly to represent standard calculation. However, to highlight the potential reduction in GWP compared to conventional materials, the data given from BUILD with a presumption of reusable materials are added in this scenario [Ernst Andersen et al., 2019]. A further description of the scenario is described in appendix B and the Be18 calculated is the same as the demolish and build new scenario.

6.4.1 Case study - Row house

The first step is to identify the building materials that have the greatest impact on CO2 emissions. Then, it can be determined where the greatest reduction in GWP can be achieved through the use of reusable materials. On the figure 6.10, the largest contribution to the GWP of the Row house is shown.

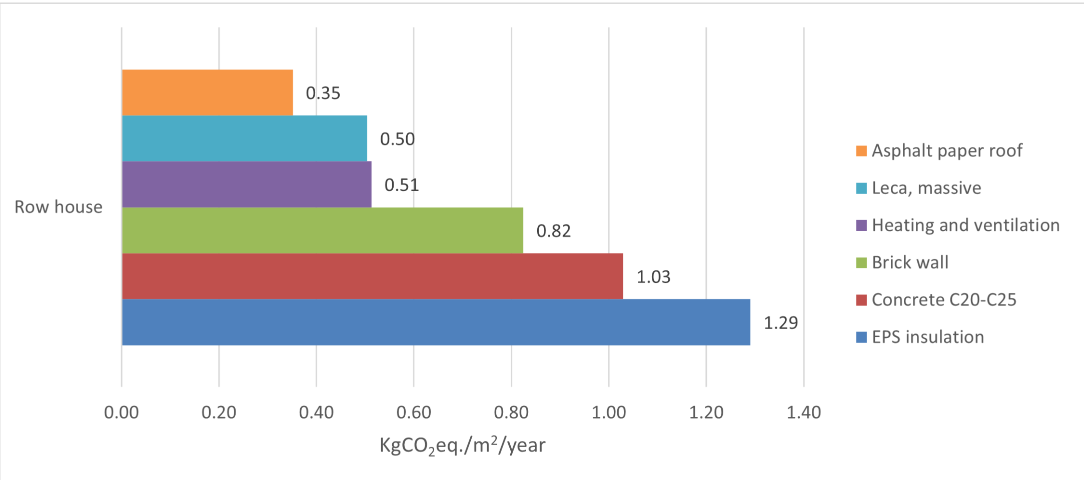

Figure 6.10. Top six highest contributor for total embodied impact A1-A3, B4, C3-C4

It is seen in figure 6.10 that mostly, the EPS insulation and the structural element have the highest contributor to the GWP. No data are given for reusable insulation materials, then the EPS insulation is kept as new material. Hence, using structural reusable materials should achieve the largest reduction in the GWP, which will be for the materials brick and concrete listed under:

- Brick wall - Reusable brick wall
- Concrete C20-C25 - Reusable concrete

6.4.2 Case study - Office

The same process is conducted for the office. The impacts from the highest contributor of GWP are illustrated from the new build scenario 6.11.

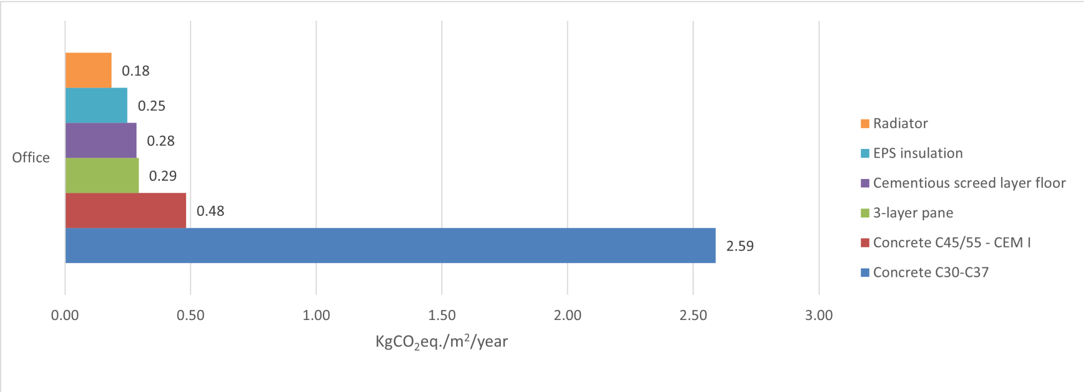

Figure 6.11. Top six highest contributor for total embodied impact A1-A3, B4, C3-C4

Also for the Office, the structural materials have the highest contribution to the GWP. Additionally, the window area is very large for the Office, which is why it also contributes as the third highest. However, the data available for the window are only from 2-layer glazing windows, but would not differ significantly if it was 3-layer glazing. It is chosen not to incorporate reusable windows due to, the structural elements having a significantly high GWP impact and thereby the largest reduction when replaced with reusable materials. The materials investigated are listed under:

- Concrete C30-C37 - Reusable concrete elements
- Concrete C45/55-CEM I - Reusable concrete elements

6.4.3 Presumption for reusable materials

The data for reusable materials that will be investigated for the cases are reusable- brick and concrete. The presumption given of reusable brick and concrete will be described:

Reusable bricks are given from existing bricks that are cleaned of old mortar before reuse in a new life cycle, where a new production of calcium mortar is produced, where a relatively large amount of waste is assumed of the production of mortar with 35 %,

Reusable concrete data is given for a C25 strength, where existing concrete elements from facades, floor, roof, and column/beams are cut off directly on site and reused. Then it is assumed that 10 % waste is achieved after the process. In the Office, the construction element demands a strength of C30 and higher. It is assumed that the embodied impact of reusable concrete higher than C30 is the same as that of C25.

Additionally, it is assumed that the thermal performance of the reusable material is the same as new materials. Overall, the thermal performance of the structural elements does not play a key role. It is the insulation material that has the highest thermal conductivity to prevent cold air from entering the warm building.

In table 6.11 the data for embodied impacts from A1-A3, C3-C4 are shown for the reuse materials, and in table, the generic and EPD used for the new build scenarios are shown to see the difference in table 6.10.

Table 6.10. Data used for conventional new build scenario for 1 m^3 concrete element

Data	quantity	Material	A1-A3	C3	C4	Total
EPD Danmark		Concrete C25	230.00	6.70	4.95	241.65
EPD Danmark	kgCO2eq /m^3	Concrete C37	282.00	6.72	4.79	293.51
Okobaut		Brick	528.50	13.21	0.00	541.71

Table 6.11. A1-A3 and C3-C4 for reusable C25 concrete and brick, 1 m^2 reuse brick, 1 m^3 of concrete element [Ernst Andersen et al., 2019]

Material	quantity	process	A1-A3	C3-C4	Total
Reusable brick	kgCO2eq /m^2	Cleaning	0.71	1.07	15.46
		lime mortar	11.6		
		Transport	1.75		
		Waste	0.33		
Reusable concrete	kgCO2eq /m^3	Cut-off	0.01	12.2	13.43
		Waste	1.22		

The reuseable materials for brick and concrete are reduced by almost 94-97% compared to the conventional data given from table 6.10

6.4.4 Embodied and operational impact

By inputting the data of reusable concrete element and brick from table 6.11 into the new build scenario and fixating the operational impacts, the total embodied and operational impacts are calculated in table 6.12 and shown on figure 6.12:

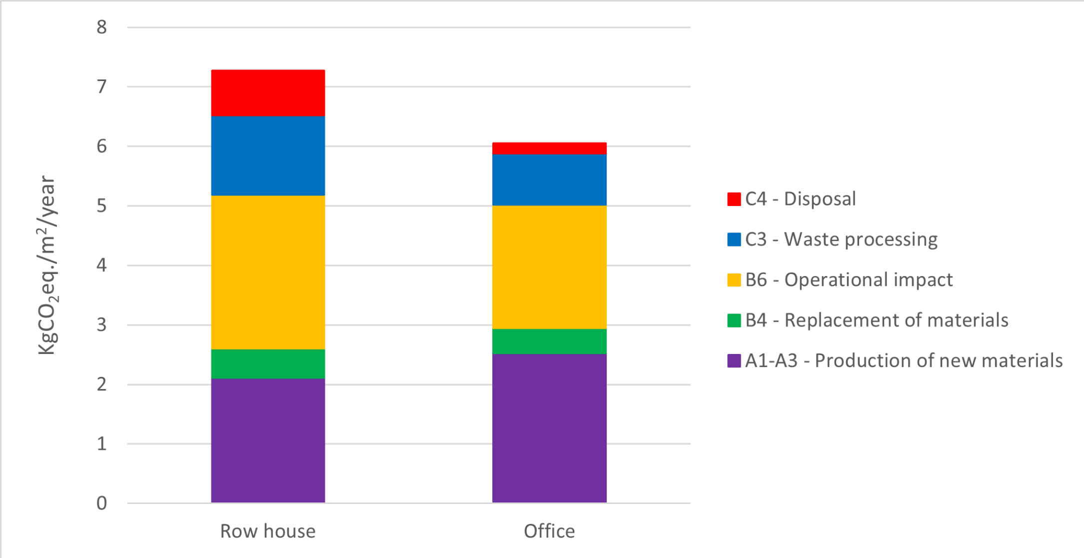

Figure 6.12. Total embodied and operational impact of the refurbishment scenario

Table 6.12. Total embodied and operational impact from the refurbishment scenario

	A1-A3	**B4**	**B6**	**C3**	**C4**	**Total**
			[$\mathbf{kgCO_2/m^2/year}$]			
Row house	2.11	0.49	2.58	1.33	0.76	7.49
Office	2.52	0.42	2.07	0.87	0.18	6.06

The EPBT is calculated for both cases accumulative and the result will be shown in figure 6.13 and 6.14:

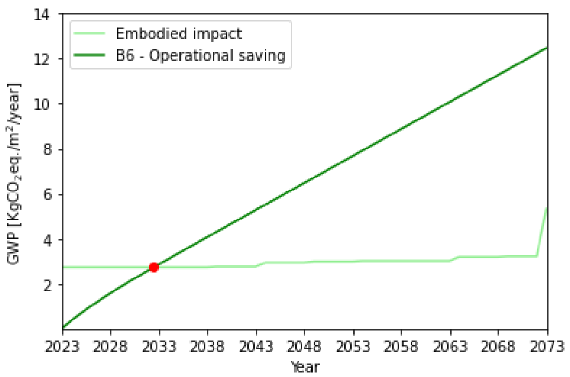

Figure 6.13. EPBT for the refurbishment scenario of Row house

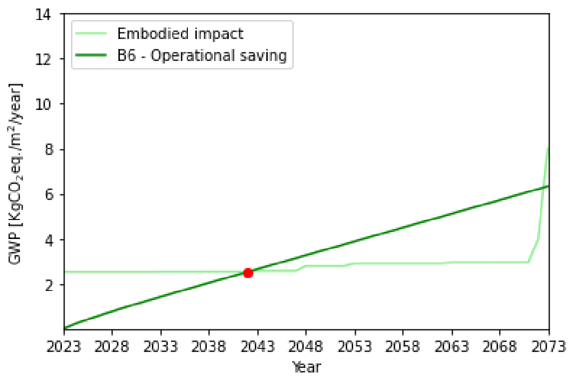

Figure 6.14. EPBT for the refurbishment scenario of Office

6.5 Retrofit

The idea for the retrofit scenario investigated in this thesis is about replacing some of the existing construction and adding more insulation. There are several advantages to replacing building components compared to demolishing and building new ones. Some key factors are, it can preserve historical or architectural value, minimal disruption for the replacements, and can contribute to sustainability and waste reduction. The aim is to evaluate if the retrofit scenario is potentially more beneficial for EPBT compared to other scenarios. A further description of retrofit requirements given from BR18 are in appendix B. Be18 file is found in "Be18 - total".

6.5.1 Case study - Row house

For Row house, the exterior brick wall will be replaced with a new brick wall and 90 mm insulation of stone wool is added. Furthermore, the deck and floor will be dug full up, due to ensure that the new insulation does not create moisture problems and that the vapor barrier is properly placed and intact.

On table 6.13 the materials added are shown for Row house 6.13

Table 6.13. Material with the retrofit scenario for Row house,FH*=floor heat

Construction	Material	Thickness[m]	U-value [W/m^2K]	Energy label
Exterior wall	Brick Stonewool C34	0.108 0.090	0.18	C
Ceiling and roof	Plasterboard 22x95 wood joists granulate C34	0.013 0.022 0.220	0.12	
Deck and floor	Wood boards Concrete C25 FH* EPS insulation	0.022 0.100 0.260	0.10	
Windows	3-layer glazing SHGC=0.31 Tree-alu frame	0.036 [-] [-]	0.83	

6.5.2 Case study - Office

For Office, a real retrofit renovation started in 2021, where the data given from MTH-hoejgaard will be used. Standard retrofit renovation by replacing elements from Offices can vary differently compared to residential buildings. For instance, most contractors want a transparent design with lots of glass facades that has an aesthetic appeal. Glass facades can create a modern and visual appearance and can give a sense of openness, transparency, and allow more natural light to enter the building.

In the real renovation case, the exterior wall is as a cassette with 209 mm insulation with an internal timber frame of 95 mm insulation in between. All the floor decks from the ground to 4. floors and the ceiling have between 200-300 mm added Kingspan insulation. Windows are of 3-layer glazing with an SHGC value of 0.31 and constructed together with an Aluminium profile. The new glazing facades are from Eiler Thomson named ETA50, which are connected together with a new steel skeleton construction. The basement constructions are kept the same as the reference scenario. On table 6.14 the added materials are illustrated:

Table 6.14. Materials added for the retrofit scenario of Office

Construction	**Material**	**Thickness**[m]	**U-value**[W/m^2K]	**Energy label**
Exterior wall	Cladding Stonewool C34 Wood profiles 38x73	0.026 0.209 0.038	0.17	C
Roof and ceiling	Roof paper Kingspan C34 Concrete C37	0.002 0.200 0.12	0.11	
ETA 50	3-layer glass SHGC=0.31 Tree-alu frame	0.036	1.00	
Ground - 4. floor deck	Linoleum Kingspan C34	0.002 0.300		

The ETA 50 is an EPD that is given by Eiler Thomson, which consists of 3-layer glazing that is connected with aluminum profiles. An illustration of it is shown in figure 6.15:

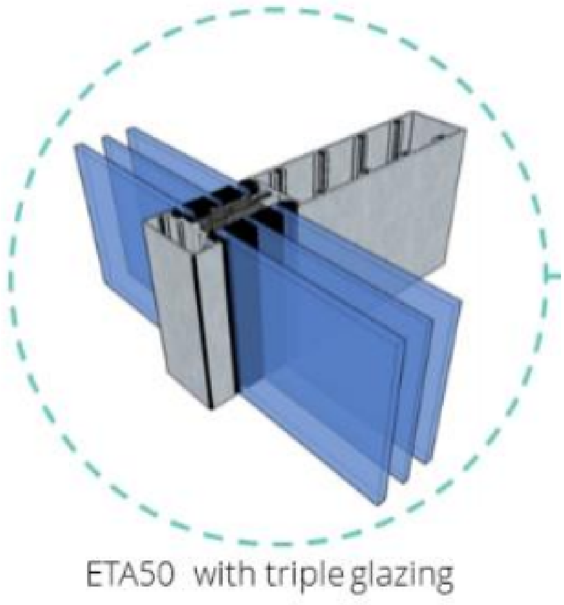

Figure 6.15. Illustration of the ETA50 from Eiler Thomson EPD [Eiler Thomson, 2023]

6.5.3 Embodied and operational impact

The total embodied and operational impact will be shown for the stages A1-A3, B4, B6 and C3-C4 over the reference year of 50 years. On figure 6.16 and table 6.15 the results are illustrated:

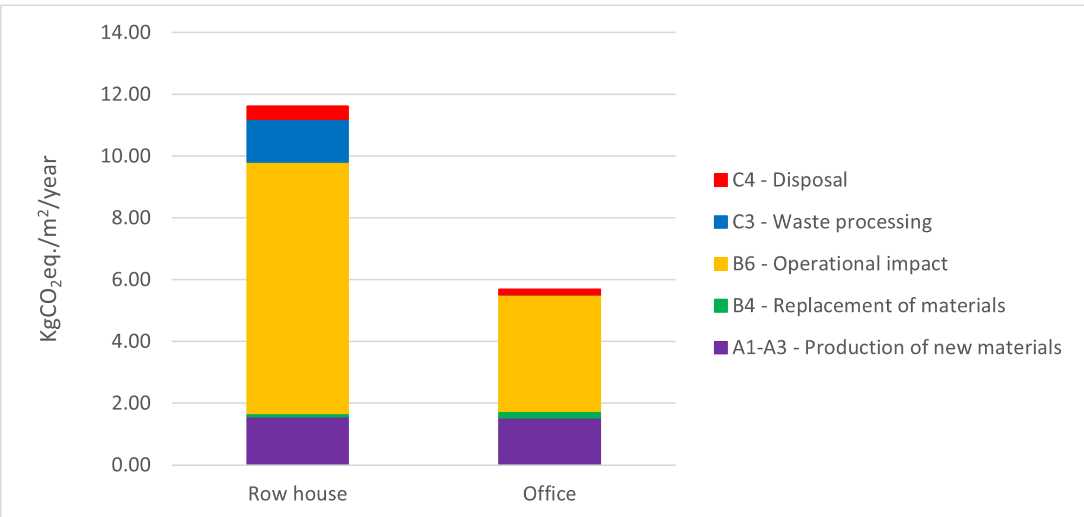

Figure 6.16. Total embodied and operational impact of the retrofit scenario

Table 6.15. Total embodied and operational impact from the retrofit scenario

	A1-A3	B4	B6	C3	C4	Total
	[$kgCO_2/m^2$/year]					
Row house	1.57	0.10	8.13	1.39	0.42	11.52
Office	1.53	0.21	3.77	0.01	0.18	5.58

It is seen, that the initial embodied impact of A1-A3 is lower, where the operational impact is less reduced compared to the new build scenario.

In table 6.16 energy usage for heating and electricity is shown:

Table 6.16. Energy usage for heating (DH) and electricity for demolish+build new scenario

	Heating (DH)	Electricity
	[kWh/m^2year]	
Row house	101.6	1.5
Office	40.9	29.2

Lastly, the EPBT for both cases is calculated and illustrated in figure 6.17 and 6.18:

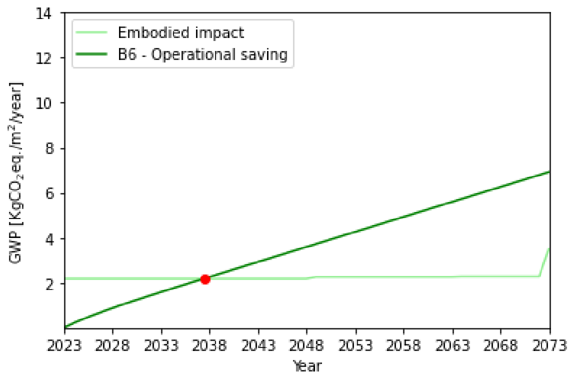

Figure 6.17. EPBT for the retrofit scenario of Row house

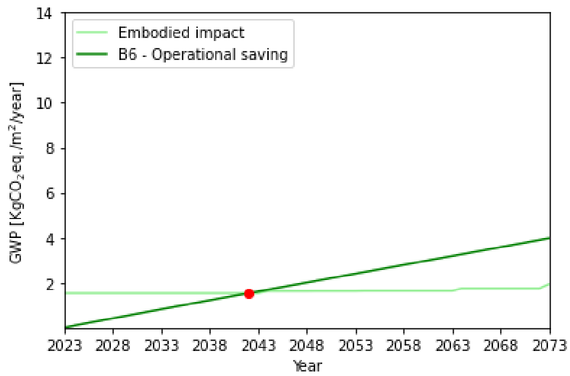

Figure 6.18. EPBT for the retrofit scenario of Office

7 Results

In this chapter, the results from the scenario analysis of the renovation will be compared with the given calculation of the EPBT of GWP for both case studies.

7.1 Operational impacts after renovation scenarios

For the operational impacts, which include the carbon emission from the electricity and heating are calculated in the chapter 6. Thereby, a calculation of the operational saving is conducted to see the difference between the operational impact from the existing building and after the renovation scenarios. In figure 7.1 and 7.2 the amount of operational impact savings are calculated with respect to the new energy usage from the after-renovation scenarios.

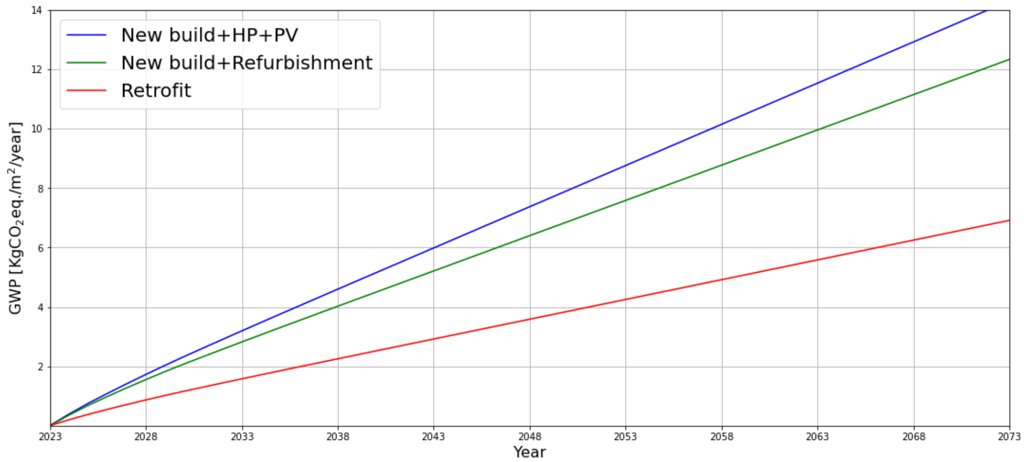

Figure 7.1. Operational saving between reference and renovation scenarios for Row house

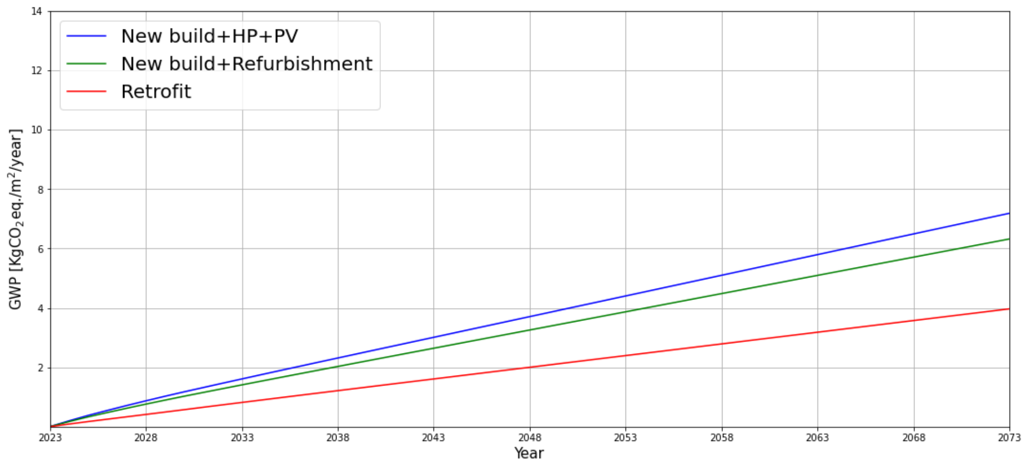

Figure 7.2. Operational saving between reference and renovation scenarios for Office

For the renovation scenario, the greatest savings are achieved through the use of an HP and PV panels for both cases. Hence, the use of renewable sources achieves the greatest operational savings, due to the building only operating with electricity which has lower emissions factors compared to district heating (DH). An even greater reduction could be obtained if the m^2 of PV panels were increased, but on the other hand, it would increase the initial embodied impact. This would affect the EPBT and would potentially not shorten the payback period necessarily. Additionally, the Row house case obtain in general the highest amount of operational savings compared to the Office case. This is due to the calculation for GWP unit, which is given $kgCO_2eq/m^2/year$ and the m^2 of the office heated area is significantly higher than the Row house.

The reduction of the operational usage for heating and electricity for all scenarios with the percentage of reduction in the operational usage for all scenarios is listed with the energy label in 7.1.

Table 7.1. Reduction of energy usage from DH and electricity compared to existing building, DH=District heating, EL=Electricity

Scenario	Cases	DH	EL	DH	EL	Energy label
		[kWh/m²year]		[%]		[-]
Reference	Row house	227.4	3.3	[-]	[-]	F
	Office	167.9	45.4	[-]	[-]	F
New build	Row house	34.2	3.1	-85.0	-6.1	A2015
	Office	12.8	23.1	-92.4	-49.1	B
New build+HP+PV	Row house	[-]	3.1	[-]	-6.1	A2020
	Office	[-]	23.1	[-]	-49.1	B
Refurbish	Row house	34.2	3.1	-85.0	-6.1	A2015
	Office	12.8	23.1	-92.4	-49.1	B
Retrofit	Row house	101.6	3.1	-6.1	-54.5	C
	Office	40.9	29.2	-75.6	-35.7	C

The electricity usage is only calculated according to the pumps for DHW and space heating pipes, which is fixated on 3.1 kWh/m^2year for Row house and 23.1 kWh/m2year for Office. The pumps are kept as the same products as the existing buildings. It is chosen not to change it, due to the fact that it has a very small influence on the electricity demand when selecting a new and better pump. For the retrofit scenario of the Office, the electricity demand is higher than in the other renovation scenarios. This occurs due to MTH-hoejgaard having set a higher luminous flux for the offices with 500 lux, whereas the other scenarios have the standard minimum of 300 lux for offices.

7.2 Total embodied and operational impact

The total embodied impact from the renovation scenarios is investigated to see the difference between the LCA modules of A1-A3, B4, B6, and C3-C4. This is due to the fact that each scenario uses different materials, which are based on fundamentally conventional materials, which provide a more representative picture of the GWP impact associated with traditional construction. However, the scenario with refurbishment, which is based on using reusable materials for the construction elements is more nontraditional and it is not a requirement to implement according to BR18. This given the refurbishment scenario provides an insight into the potential reduction of GWP impact, which visualizes a step further into a more sustainable building.

The calculation of the total embodied and operational impact over the reference year of 50 years is shown in figure 7.3 and with the values determined in table 7.2.

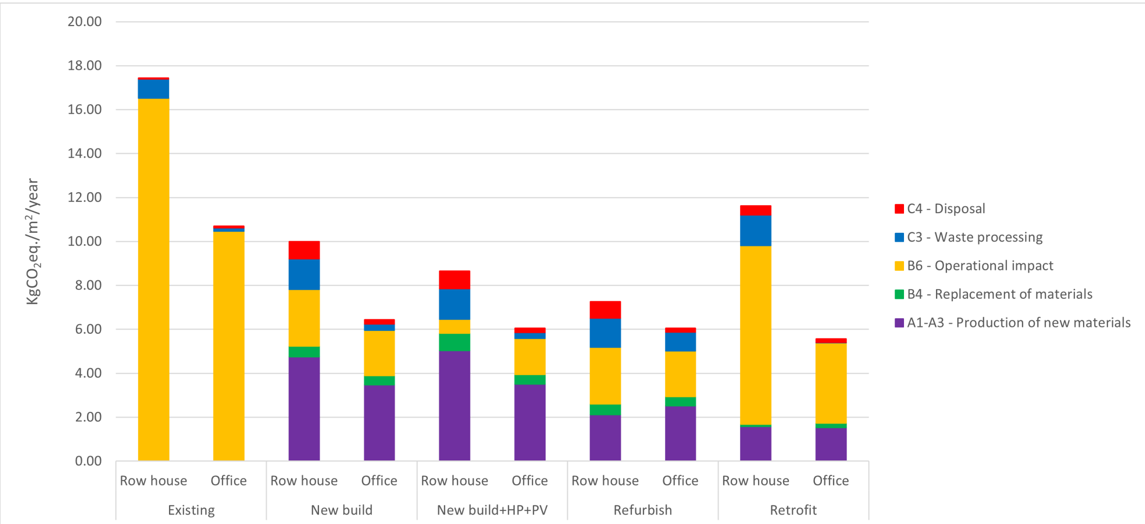

Figure 7.3. Total embodied and operational impact of all scenarios for Row house and Office

Table 7.2. Embodied and operational impact from all scenarios of both cases

		A1-A3	B4	B6	C3	C4	total
				[$kgCO_2/m^2/year$]			
Existing	Row house	[-]	[-]	16.52	0.87	0.06	17.45
	Office	[-]	[-]	10.46	0.16	0.08	10.70
New build	Row house	4.75	0.49	2.58	1.39	0.80	10.00
	Office	3.47	0.42	2.07	0.27	0.20	6.44
New build+HP+PV	Row house	5.03	0.79	0.64	1.39	0.81	8.66
	Office	3.50	0.45	1.63	0.27	0.20	6.05
Refurbish	Row house	2.11	0.49	2.58	1.33	0.76	7.27
	Office	2.52	0.42	2.07	0.87	0.18	6.06
Retrofit	Row house	1.57	0.10	8.13	1.39	0.42	11.62
	Office	1.53	0.21	3.65	0.01	0.18	5.58

From the results, the initial embodied impact is the largest for the scenario of new build+HP+PV, due to the embodied impact from PV and HP. However, a larger saving from the B6 is achieved which results in total a lower GWP impact. For the retrofit scenario of the Office case, it is not comparable with the other scenarios in regards to the dataset used. The retrofit scenario includes mainly EPDs with low embodied impacts, which was investigated from MTH-Højgaard from a variant analysis of the building envelope. Overall, the refurbishment scenario has the lowest total GWP impact, which means this scenario is more sustainable to implement.

7.3 EPBT after renovation

To determine the EPBT, the calculation of the embodied impact from the investment of new materials for the renovations is conducted to find the balance point between the embodied impact after renovation and operational savings. From the scenario analysis, the EPBT occurred from the initial embodied impact from the new materials, which included modules A1-A3. For the renovation scenarios of new build and new build+HP+PV for Office, the EPBT was calculated from the A1-A3 and B4. A linear regression has been carried out for the operational savings shown in figures 7.1 and 7.2 and used to calculate the EPBT time shown in figure 7.4 and 7.5 with values in table 7.3:

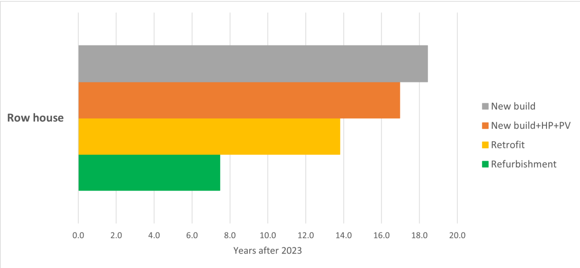

Figure 7.4. EPBT for case 1 with all scenarios

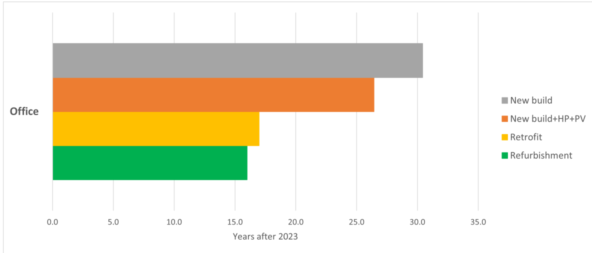

Figure 7.5. EPBT for case 2 with all scenarios

Table 7.3. EPBT for both cases with respect to the renovation scenario, IEC=initial embodied impact (A1-A3, B4*)

Scenario	**Case**	**IEC** [$kgCO_2/m^2/year$]	**Carbon saving** [$kgCO_2/m^2/year$]	**EPBT** [Year]
build new	Row house	4.79	0.24	18.4
	Office	3.90*	0.12	30.4
New build+HP+PV	Row house	5.03	0.28	22.8
	Office	3.95*	0.14	26.4
Refurbish	Row house	2.11	0.24	7.5
	Office	2.52	0.12	16,0
Retrofit	Row house	2.17	0.14	13.8
	Office	1.53	0.10	17.0

The shortest EPBT occurs for the refurbishment scenario with the use of reusable materials for the structural elements. This mean, that implementing strategies that rely on a circular economy has a significant impact on a more sustainable building. This means stakeholders should consider reusable materials with regards to the lower GWP, but it should also benefit cost-savings, compared to buying new materials. For the new build and retrofit, it is more cost-benefit to retrofit compared to building new, and a more sustainable approach for the building sector is to focus more on renovating existing buildings than demolishing and building new ones. But for some buildings that are older and in bad condition due to mold issues or damage to the structural elements, it is potentially better to demolish and build new ones.

7.4 Conclusion

In conclusion, this research aimed to investigate the potential EPBT for different building typologies, specifically row houses and office buildings. Four scenarios were investigated for the Row house and Office, which included a demolition+build new and with integration of HP and PV, adopting circular economy principles, and lastly a comprehensive retrofit scenario.

It was found that the new build scenario had a EPBT of 18.4 and 30.4 years for the Row house and Office. For both cases compared to the other renovation scenarios, the new build scenario had the longest EPBT, resulting in a comparatively higher environmental burden associated with this approach. On the other hand, the integration of renewable energy sources, such as PV panels and HP, was found to have a positive influence which resulted in a shorter EPBT for the Office, but for the Row house, the EPBT was increased to 22.8 years compared to the new build. The PV panels had the largest contribution to the embodied impact compared to the HP and, the lifetime of PV panels is standard 20 years. This means the PV panels would be replaced two times over the building lifetime, which increases the embodied impacts and results in a less sustainable approach, For the office the integration of HP and PV had significant benefits to the EPBT, The Office has in general a larger electricity demand carried out from lightning, HVAC, and occupants, which results in the PV panels contributes to a significant portion of the office building's electricity demand. The operational saving is thereby greater leading to a shorter EPBT. Furthermore, the embodied impact for the office is very low compared to the office due to a large amount of m^2, which the calculation of GWP [$kgCO_2eq/m^2/year$] becomes low. This resulted in the initial embodied impact almost being the same as the conventional new build without renewable sources and lead to a shorter EPBT.

Based on the scenario for refurbishment for the EPBT, the scenario involving the implementation of circular economy principles and the use of reusable materials, particularly for the structural elements in construction, appears to be the most favorable option. Using reusable concrete and brick for both cases achieves the shortest EPBT of 7.5 years and 16 years for the Row house and Office, thereby enhancing the environmental sustainability of a building renovation. The use of reusable materials eliminates the demand for new material, which results in the initial embodied impact being less of a burden compared to the new build scenario.

it can be concluded that the retrofit scenario resulted in a shorter environmental payback time (EPBT) compared to building new for both the Row house and Office. This highlights the potential environmental benefits of adopting retrofit approaches in the context of sustainable building practices. By renovating and improving the energy performance of the row house and office building, the need for new material production A1-A3 are significantly reduced. The operational saving is lower compared to the new build scenario, but it would be very different if the building's energy quality were better. A further investigation could be to try implement these scenario for a building in 1990, which has a better energy quality compared to these case studies.

7.5 Discussion

From the investigation of the two case studies, both buildings were built around 1960, where the U-values of the building envelope differ significantly compared to the U-value requirement today. This leads to a large operational saving when calculating the EPBT compared to the renovation scenarios. In contrast, buildings constructed in 1985 benefitted from more energy-efficient design and the implementation of stricter building regulations. As a result, the EPBT calculation for renovation of buildings constructed in 1990 may be comparatively longer due to the reduced energy consumption and lower environmental impact associated with improved U-values and energy-efficient systems.

Throughout the literature review, science articles investigation the EPBT for different renovations uses a dynamically software, which provides more accurate model of the actual energy consumption. Additionally, physical measurements are used to calibrate the model to more precise. Due to the fact that the occupancy behavior is an uncertainty parameter, physical measurement would potentially generate a robust estimation of the energy usage. In Denmark the dynamical simulation tool BSim, which mainly is used to analyze the indoor environment can also be used to determine the energy consumption accurately compared to be18. This occurs because BSim calculates all the indoor parameters such as heat loss based on an hourly-average temperature difference between indoor temperature and outdoor, whereas be18 relies on a monthly-average temperature difference. The usage with BSim approach in this thesis would enable a more precise calculation of the operational impact, leading to a more robust and reliable estimation of the EPBT.

In regard of the indoor environment, there has not been conducted an active evaluation of indoor comfort with respect to thermal-, atmospheric-, acoustic- or visual comfort. This involves mainly the office case study, whereas the Row house should consider summer comfort criteria, which is fulfilled. The requirement states that the room temperature in the cooling season should not exceed more than 100 h of 27 °C and 25 h of 28 °C for the Row house. The office on the other hand has strict rules according to the BR18, where for thermal comfort the room temperature over the year should not exceed 100 h of 26 °C and 25 h of 27 °C. Furthermore, with respect to atmospheric comfort, the office also has a strict rule according to

BR18 that the CO_2 level should not exceed more than 1000 ppm over the year. The method to consider thermal and atmospheric comfort criteria would first be to evaluate the critical room and conduct an indoor environment simulation with BSim. BSim can consider all the factors that impact the room such as orientation, envelope U-values, interior construction, people load, lighting, and heating. Furthermore, with the dynamical simulation for an hourly average of the outdoor condition, a more accurate estimation of the ventilation rate and interior materials construction could be determined, Additionally, such as investigation discomfort criteria would also contribute to a limitation of the material and ventilation rate. However, in this thesis the values determined for new build renovation scenarios, the ventilation rate are used from MTH-højgaards simulation, which is assumed to be representative due to the indoor materials and U-values being almost the same compared to their final proposal of renovation.

Some challenges with the EPBT investigation for the renovation scenarios occur for the large set of LCA data, which can be obtained from EPD's all over the world and Ecoveint. A more accurate estimation would amplify the use of other dataset, and compare the results due to the material impacts can differ significantly. This means, that the investigation in this thesis is narrowing only towards generic data, which results in a more or less theoretical and rough estimation of the embodied impacts. For future research, other datasets would improve the robustness of the results for calculating the EPBT.

If a material study were to be conducted, to mainly find materials with low embodied impact, Biogen materials offer significant advantages. They have the ability to absorb carbon dioxide emissions, which results in a negative impact on the A1-A3 life cycle phases and can lead to either a negative or a very short EPBT. However, in this thesis, the scenarios that are investigated are based on conventional materials, but for the office building, there are further possibilities in investigating other cladding materials for the exterior wall. In this thesis, brick is used as the cladding material, which has a large GWP impact, whereas if the wood were chosen, the GWP would be lower. Thereby, a further investigation in a material study for more nontraditional construction of the walls, roof and floor could be conducted with a sensitivity analysis to find solutions that are more promising for the total environmental impacts.

For renewable sources, uncertainty relies on the fact that the HP and PV-panel degrade over time, which leads to less effective energy production. Additionally, the electricity production of the PV panels is dependent of solar radiation which is different with respect to the geographical location. In this thesis the parameters for the PV panels and HP in this case are found by selecting real products from the Danish market, A more accurate estimation of the energy production from renewable resources would include a dynamic tool, which could consider the solar radiation from the geographical location, shading, efficiency, orientation, tilt angle, based on an hourly average. For the heat pump, several other types of HP exist such as ground-source Heat Pump which has a larger COP value compared to air-water. The reason the ground-source HP is more efficient is due to the fact that it used the heat from the ground which has a higher temperature in the winter compared to the air temperature. This would affect better energy production and thereby a larger operational saving. However, a larger embodied impact would be obtained due to the size of pipes that would be dug under the ground.

8 Thesis Article

Comparative Analysis of Conventional New Build, Renewable Energy Integration, Reusable Materials, and Retrofit Renovation for Row Houses and Office Buildings

Abstract

This thesis is about the use of a new method to assess whether different renovation scenarios can be considered sustainable using the "environmental payback period" (EPBT) method. In this thesis, four renovation scenarios are considered for a row house block and an office building. The four renovation scenarios are demolish+build new, integration with heat pump(HP)+photovoltaic panels(PV), refurbishment, and finally a retrofit scenario for the replacement of parts of the building envelope. The renovation scenarios, excluding retrofitting, includes the utilization of standard construction materials for walls, ceilings, floors, and windows in accordance with the building typology of new Row houses and offices in Denmark. The refurbishment scenario includes the same construction materials but with reusable concrete and brick for the structural elements. The EPBT for the Row house renovation scenarios is 18.4 years, 22.8 years, 7.5 years, and 13.8 years for the new construction, new construction, refurbishment, and replacement of parts of the building respectively. For the office building, the EPBT is 30.4 years, 26.4 years, 16.0 years, and 17.0 years. The most favorable renovation scenario for both cases is thereby refurbishment scenario.

Intro

The building sector consumes around 40% of the total energy demand globally and regarding the environmental effects it contributes around 36% green house gas emissions. The European Parliament has promoted various directives for energy efficiency in the building sector in order to address climate change issues. Regulations include building energy certification and incentives to reduce operational energy use in buildings through the implementation of minimum energy requirements for new buildings and the promotion of energy retrofitting of existing ones [European Comission, 2010].

Before 2001, more than 220 million building units were constructed, accounting for 85% of the EU's building stock. Additionally, it is forecasted that in 2050, 85-95% of the structures that exist today will still be standing. The majority of those existing structures are inefficient in terms of energy use. Many people rely on fossil fuels for heating and cooling, and they use outdated technologies and inefficient appliances. Buildings account for roughly 40% of overall energy consumption in the EU. [EU, 2020b]

EU sets a decisive framework to the climate goals in Denmark, it was stated that the aim was to reduce the CO_2 emissions with 70 % in relation to 1990. Furthermore, the building sector should reduce the amount of global warming potential by 39 % in 2030 in relation to 2005, where the final aim is in 2050 Denmark should become climate neutral. Additionally, it was insisted that, a minimum of 27 % should be achieved for supply of energy-producing systems.

Additionally, to investigate the potential of increasing material efficiency and reducing climate impact, the EU commission has launched a new comprehensive strategy in 2020 for a sustainably built environment. The promotion of circularity principles throughout the building life cycle is a major factor to reduce further the GHG-emissions and reach the goal of a climate neutrality world in 2050. The circularity principles that are introduced are addressing the potential of recycling materials, promoting measures to enhance the durability and adaptability of product materials, setting a scheme for recovery of materials from demolition waste, and according to the renovation wave that focuses mainly on energy improvement, circular principle tends to become in the same line of measures. [EU, 2020a]

Methodology

The methodology in this study is following the standard calculation methods that are used by practitioners in Denmark, in order to demonstrate the method of environmental payback time (EPBT) in a simple way. Two Danish case buildings are investigated in this study which are a Row house and an office, The renovation scenarios that are investigated are as listed:

- Existing building
- Demolish+build new
- Demolish+build new+HP+PV
- Refurbishment - reusable materials
- Retrofit

The existing row house and office buildings were constructed in 1963 and 1958, respectively. These buildings have poor energy efficiency characteristics attributed to the low energy requirements in the 1960s. The study analysis aims to compare the renovation scenario, specifically focusing on a conventional new build in Denmark, in order to assess the advantages associated with improved energy efficiency and potentially shorter payback time, compared to retrofitting. Furthermore, an additional scenario incorporating renewable sources such as HP and PV is incorporated to examine the potential benefits of transitioning from district heating to renewable sources on the EPBT. The refurbishment scenario emphasize one specific principle within the strategies of the circular economy, where the primary objective is to highlight the potential reduction in embodied impacts through old reusable structural materials. The reusable materials specifically brick and concrete will be going through a repairing and cleaning process that is assumed to meet the standard static requirements equivalent to that of new materials. Lastly, the retrofit scenario aims to fulfill the requirement of the minimum U-values for wall, floor, and roof with §279 and for window §258 in the Danish building regulation [BR18, 2018]. In this scenario, the actions utilize, the dismantling of the current exterior construction, followed by the addition of more insulation and a new identical exterior material. These measures aim to preserve the aesthetic design and also enhance the energy efficiency of the building.

The energy calculation is conducted with the Danish software be18, which calculates the energy and electricity used for space heating, domestic hot water, ventilation, and pumps. All the heat losses and internal heat gains are calculated with standard assumptions depending on building typologies, for people load, usage time, lightning, and devices. The energy calculation for all the parameters is based on monthly average outdoor temperatures [SBI, 2013]. The provided calculation methodology is used to assess the energy demand in both the existing scenario and the renovation scenario, which afterward the energy savings can be calculated as the difference between the energy demand from existing building and the renovations scenarios.

Energy labels are used to describe the building's energy consumption in the form of product declaration, where it visualizes an overview of energy-related improvements, that are beneficial to implement. The energy label scale is ranged from A2020 to G, where A is best label. The calculation of the energy labels are based on standard energy consumption, On the table 8.1 the energy labels can be determined with respect to the energy demand:

Table 8.1. Labels indicator provided with respect to the energy demand

Energy Labels	**Energy demand** [$\mathbf{kWh/m^2year}$]
A2020	≤ 27
A2015	≤ 30.0 + 1000 / A
A2010	≤ 52.5 + 1650 / A
B	≤ 70.0 + 2200 / A
C	≤ 110 + 3200 / A
D	≤ 150 + 4200 / A
E	≤ 190 + 5200 / A
F	≤ 240 + 6500 / A
G	> 240 + 6500 / A

After the energy calculation, the environmental impact is determined with the Life Cycle Assessment (LCA) method, which is widely acknowledged as a comprehensive approach to assessing the environmental impact of buildings. LCA considers every life cycle stage of construction products. It takes into account various factors such as energy use, ozone depletion, acidification of land and water, eutrophication, land use, water depletion, and human toxicity. In this study, the stages included in the LCA are A1-A3 (production stage), B4 (replacements), B6 (operational) and C3-C4 (end-of-life stage), which are standard according to the Danish regulation. The software LCAbyg, a Danish-developed tool, is utilized in this study to calculate the life cycle assessment for the case buildings. By inputting data regarding various construction components and operational energy, the tool can perform the necessary calculations for the environmental impact. Only the Global Warming Potential are analysed with the functional unit [$kgCO_2eq/m^2/year$]. The system boundaries for the LCA of the scenarios are shown on table 8.2:

Table 8.2. LCA moduls included in all renovation scenarios marked with "x", and "xx" for retrofit with EoL from existing

Scenarios	**Existing**		**New build**		
Modules	B6	C3, C4	A1-A3	B6	C3, C4
Existing	x	x			
New build			x	x	x
New build+HP+PV			x	x	x
Refurbishment			x	x	x
Retrofit		xx	x	x	x

The reference year is set for 50 years, which also is standard in Denmark, where the cumulative operational impact is determined. The environmental impacts on the building's operational energy usage (B6) are calculated using emission factors developed in Denmark. These emission factors are based on dynamical calculation, due to the development of the Danish energy supply, where in the future, a transition from coal-fire at central plants to more use of biomass, and continued expansion with onshore wind, offshore wind, and PV-panels will reduce the emission factor further [COWI, 2020].

The dataset in this study utilizes the most recent and updated generic data sourced from ÖKOBAUDAT for all materials, excluding wood and concrete. For these specific materials, Danish Environmental Product Declarations (EPDs) were utilized.

Environmental payback time (EPBT)

A simple illustration of how the EPBT method is performed is defined step by step. The first step is calculating the cumulative operational impact over the 50-year reference given from the energy consumption in be18 for the existing buildings, and furthermore the energy consumption for the renovation scenarios. Thereby, the operational impact saving is calculated as the difference between energy consumption from existing and renovation, which is shown in figure 8.1.

The next step is determining the embodied impact (A1-A3, B4,C3,C4) from the new material for the renovation scenarios, where the modules that are included in the embodied impacts are shown in figure 8.2. For the B4 (replacement) only the windows are replaced after 25 years. The EPBT is thereby calculated as the balance point for where the embodied impacts after the renovation reaches the amount of operational impacts saving. This is illustrated in figure 8.3, where the red dot is marked as the balance point between the operational saving and investment of new materials.

This given, all the EPBT for the four renovation scenarios for both the Row House and the Office are investigated and the most beneficial scenario with regards to the shortest EPBT is defined as the best sustainable renovation type.

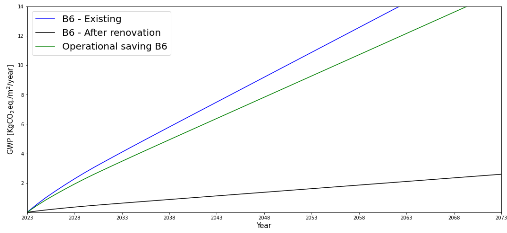

Figure 8.1. The embodied impacts included of modules

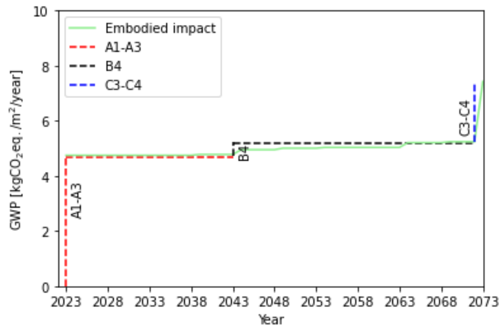

Figure 8.2. The embodied impacts included of modules

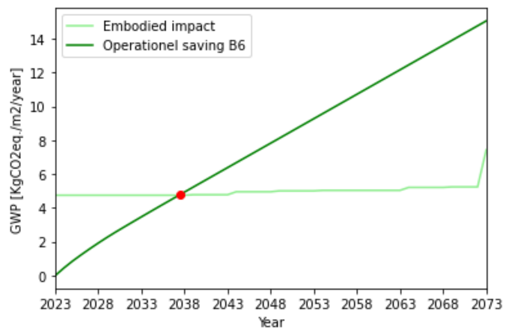

Figure 8.3. Payback time of operational saving and embodied impact for renovation

Description of cases

For the existing buildings, the Row house has 640 m^2 heated floor for one block which consists of ten houses and with an unheated storage room of total 64 m^2. The office building consists of a heated basement, ground floor, and up to 5. floor, with a total of 11 240 m^2. The materials included are shown on table 8.3:

Demolish+build new

In the context of new build Row houses in Denmark, the conventional U-values determined for various building components are as follows: 0.17 W/m^2K for wall, 0.06 W/m^2K for roof and ceiling, 0.07 W/m^2K for deck and floor and 0.83 W/m^2K for wall, ceiling+roof, deck+floor and windows. The energy label is improved from the energy label "F" to "A2010", which is the standard energy demand required for new build according to the Danish regulation.

Demolish+build new+HP+PV

For the new build+HP+PV scenario, all the materials determined from the scenario new build are retained. The Photovoltaic panel and heat pump products are selected in the scenario from the Danish market. In these case studies a 50 m^2 standard monocrystalline PV panels has been chosen for the terrace house with a slope of 11° on the south orientation, and a 100 m^2 with a slope of 45° on south for the Office. In the case of the heat pump selection, a standard air-water heat pump is with a coefficient of performance (COP) of 4.84/4.71 and 4.3/3.2 for space heating and domestic hot water, respectively, in relation to the Row house and office building. The building energy label is improved to "A2020", which is the low-emission building class in Denmark.

Refurbishment

Standard generic data for reusable materials are not yet developed in Denmark to represent an estimation of the GWP from reusable materials. From the case building, the heavy construction contributes the largest embodied impact, which achieves the largest GWP reduction, if replaced with reusable materials. Thereby, from the new build scenario, all the heavy construction materials of concrete and brick are replaced with reusable- brick and concrete elements that are cut-off demolition project. The data for the reuse of materials are derived from the report by [Ernst Andersen et al., 2019], which takes into account empirical GWP impact from actual dismantling and demolition practices in Danish buildings. The energy demand is assume to be the same as the demolish+new build scenario.

Retrofit

The retrofit scenario investigated in this study is about keeping the existing building and replacing some of the existing constructions. In the scenario, the exterior layer for wall and roof are removed and replaced with a new identical exterior layer. Furthermore, more insulation is added to increase the energy efficiency. The U-values that must be required in this scenario for the construction parts are as follows: 0.18 W/m^2K for wall, 0.12 W/m^2K for roof and ceiling, 0.10 W/m^2K for deck and floor. Furthermore, the inclusion of a new window with a U-value of 0.83 W/m^2K is deemed necessary as windows offer significant benefits for enhancing the energy effiency.

Results

For the operational impacts, which include

Table 8.3. The materials included for the existing buildings with U-value and energy label

Cases	Envelope	Material	Thickness[m]	U-value [W/m^{2}K]	Energy class
Row house	Wall	Brick Stonewool Brick	0.108 0.050 0.108	0.55	F
	Roof	Brick roofing Wood beams Roof truss Stonewool Plasterboard	0.002 0.039 0.025 0.050 0.020	0.53	
	Floor	wood boards Wood beams Stonewool Concrete Gravel	0.022 0.022 0.050 0.100 0.250	0.30	
	Windows	2-layer glazing Tree-aluminium frame SHGC=0.75	0.024 [-]	2.80	
Office	Wall	Concrete	0.240	2.70	F
	Basement wall	Concrete Aerated concrete	0.300 0.050	0.42	
	Basement deck	On-site concrete Gravel	0.250 0.150	0.54	
	Roof	Concrete Asphalt roofing	0.240 0.002	1.66	
	Windows	2-layer glazing Tree-aluminium frame SHGC=0.75	0.024 [-]	2.80	
	Columns	Concrete 4x4	0.040	[-]	

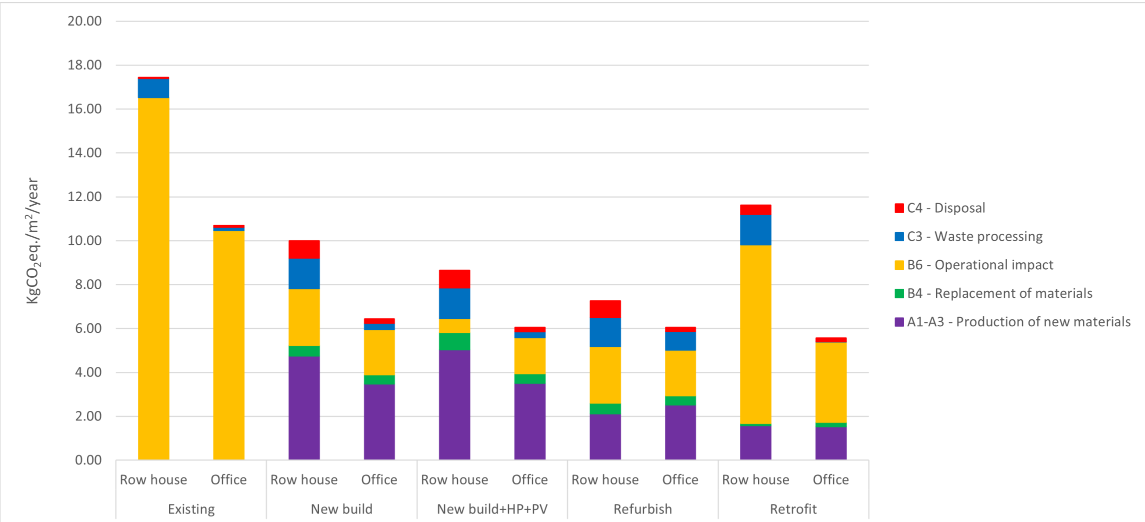

Figure 8.4. Total embodied and operational impact of all scenarios for Row house and Office

the carbon emission from the electricity and heating, the calculation of the operational saving is conducted to see the difference between the operational impact from the existing buildings and after the renovation scenarios. In figure 8.5 and 8.6 the amount of operational impact savings are calculated with respect to the new energy effiency from the after-renovation scenarios.

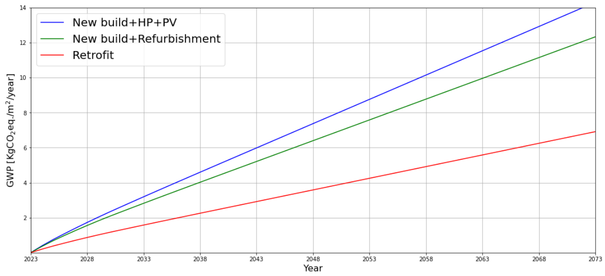

Figure 8.5. Operational saving between reference and renovation scenarios for Row house

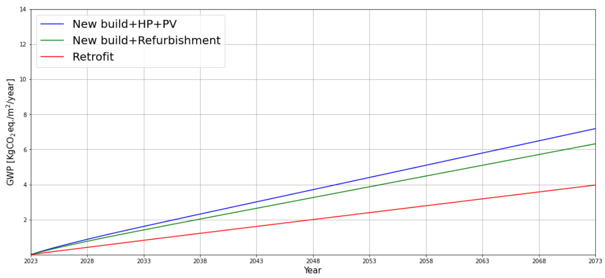

Figure 8.6. Operational saving between reference and renovation scenarios for Office

For the renovation scenario, the greatest savings are achieved through the use of an HP and PV system for both cases. Hence, the use of renewable sources achieves the greatest operational savings, due to the building only operating with electricity which has lower emissions factors compared to district heating (DH). An even greater reduction could be obtained if the m^2 of PV panels were increased, but on the other hand, it would increase the initial embodied impact. This would affect the EPBT and would potentially not shorten the payback period necessarily. Additionally, the Row house case obtain in general the highest amount of operational savings compared to the Office case. This is due to the calculation for GWP unit, which is given $kgCO_2eq/m^2/year$ and the m^2 of the office heated area is significantly higher than the Row house.

The total embodied impact from the renovation scenarios are investigated to see the difference between the LCA modules of A1-A3, B4, B6, and C3-C4. The calculation of the total embodied and operational impact over the reference year of 50 years is shown in figure 8.4.

For the existing building scenario by analyzing only the operational impact B6 and end-of-life stages C3-C4 of the existing building allows the evaluation of the potential benefits and drawbacks of demolition versus maintaining the existing building in terms of operational energy consumption. If the existing building were to be retained, the existing building would results in the less sustainable scenario due to the very high operational impact. If the renovation scenarios were to be performed , theEoL stages would be evaluated which has a very low contribution to the GWP. Hence, the notable operational impact highlights the need for renovation to reduce the GWP.

For the renovation scenario, the greatest savings are achieved through the use of renewable sources with HP and PV-system for both cases. Hence, the use of renewable sources achieves the greatest operational savings, due to the building only operating with electricity which has lower emissions factors in the future compared to district heating (DH). An even greater reduction could be obtained if the m^2 of PV panels were increased, but on the other hand, it would increase the initial embodied impact. This would affect the EPBT and would potentially not shorten the payback period necessarily. Additionally, the Row house case obtain in general the highest amount of operational savings compared to the Office case. This is due to the calculation for GWP unit, which is given $kgCO_2eq/m^2/year$ and the m^2 of the office heated area is significantly higher than the Row house.

The retrofit scenario of the Office case, it is not comparable with the other scenarios in regards to the dataset used. The retrofit scenario includes mainly EPDs with low embodied impacts, which was investigated from MTH-Højgaard from a variant analysis of the building envelope. Overall, the refurbishment scenario has the lowest total GWP impact, which means this scenario is more sustainable to implement.

To determine the EPBT, the calculation of the balance point between the embodied impact after renovation and operational savings. From the scenario analysis the EPBT occurred from the initial embodied impact from the new materials, which included the modules A1-A3. However, for the renovation scenarios of new build and new build+HP+PV for Office, the EPBT was calculated from the A1-A3 and B4. A linear regression has been carried out for the operational savings shown in figures 8.5 and 8.6 and used to calculate the EPBT time shown in the figure 8.7 and 8.8 with the values on the table 8.4:

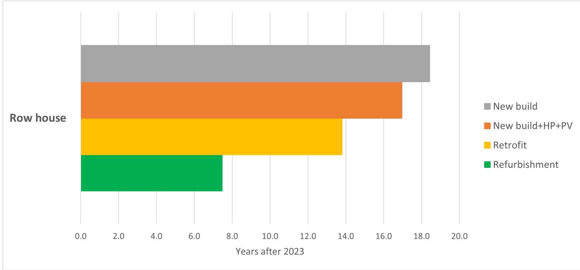

Figure 8.7. EPBT for case 1 with all scenarios

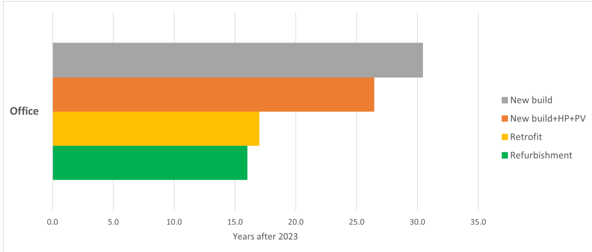

Figure 8.8. EPBT for case 2 with all scenarios

Conclusion

In conclusion, this research aimed to investigate the potential EPBT for different building typologies, specifically row houses and office buildings. Four scenarios were investigated for the Row house and Office, which included a demolition+build new and with integration of HP and PV, adopting circular economy principles, and lastly a comprehensive retrofit scenario.

It was found that the new build scenario had a EPBT of 18.4 and 30.4 years for the Row house and Office. For both cases compared to the other renovation scenarios, the new build scenario had the longest EPBT, resulting in a comparatively higher environmental burden associated with this approach. On the other hand, the integration of renewable energy sources, such as PV panels and HP, was found to have a positive influence which resulted in a shorter EPBT for the Office, but for the Row house,

Table 8.4. EPBT for both cases with respect to the renovation scenario, IEC=initial embodied impact (A1-A3,B4*)

Scenario	Case	IEC [$kgCO_2/m^2/year$]	Carbon saving [$kgCO_2/m^2/year$]	EPBT [Year]
New build	Row house	4.79	0.24	18.4
	Office	3.90*	0.12	30.4
New build+HP+PV	Row house	5.03	0.28	22.8
	Office	3.95*	0.14	26.4
Refurbish	Row house	2.11	0.24	7.5
	Office	2.52	0.12	16,0
Retrofit	Row house	2.17	0.14	13.8
	Office	1.53	0.10	17.0

the EPBT was increased to 22.8 years compared to the new build. The PV panels had the largest contribution to the embodied impact compared to the HP and, the lifetime of PV panels is standard 20 years. This means the PV panels would be replaced two times over the building lifetime, which increases the embodied impacts and results in a less sustainable approach, For the office the integration of HP and PV had significant benefits to the EPBT, The Office has in general a larger electricity demand carried out from lightning, HVAC, and occupants, which results in the PV panels contributes to a significant portion of the office building's electricity demand. The operational saving is thereby greater leading to a shorter EPBT. Furthermore, the embodied impact for the office is very low compared to the office due to a large amount of m^2, which the calculation of GWP [$kgCO_2eq/m^2/year$] becomes low. This resulted in the initial embodied impact almost being the same as the conventional new build without renewable sources and lead to a shorter EPBT.

Based on the scenario for refurbishment for the EPBT, the scenario involving the implementation of circular economy principles and the use of reusable materials, particularly for the structural elements in construction, appears to be the most favorable option. Using reusable concrete and brick for both cases achieves the shortest EPBT of 7.5 years and 16 years for the Row house and Office, thereby enhancing the environmental sustainability of a building renovation. The use of reusable materials eliminates the demand for new material, which results in the initial embodied impact being less of a burden compared to the new build scenario.

it can be concluded that the retrofit scenario resulted in a shorter environmental payback time (EPBT) compared to building new for both the Row house and Office. This highlights the potential environmental benefits of adopting retrofit approaches in the context of sustainable building practices. By renovating and improving the energy performance of the row house and office building, the need for new material production A1-A3 are significantly reduced. The operational saving is lower compared to the new build scenario, but it would be very different if the building's energy quality were better. A further investigation could be to try implement these scenario for a building in 1990, which has a better energy quality compared to these case studies.

Future research

From the investigation of the two case studies, both buildings were built around 1960, where the U-values of the building envelope differ significantly compared to the U-value requirement today. This leads to a large operational saving when calculating the EPBT compared to the renovation scenarios. In contrast, buildings constructed in 1985 benefitted from more energy-efficient design and the implementation of stricter building regulations. As a result, the EPBT calculation for renovation of buildings constructed in 1990 may be comparatively longer due to the reduced energy consumption and lower environmental impact associated with improved U-values and energy-efficient systems.

Throughout the literature review, science articles investigation the EPBT for different renovations uses a dynamically software, which provides more accurate model of the actual energy consumption. Additionally, physical measurements are used to calibrate the model to more precise. Due to the fact that the occupancy behavior is an uncertainty parameter, physical measurement would potentially generate a robust estimation of the energy usage. In Denmark the dynamical simulation tool BSim, which mainly is used to analyze the indoor environment can also be used to determine the energy consumption accurately compared to be18. This occurs because BSim calculates all the indoor parameters such as heat loss based on an hourly-average temperature difference between indoor temperature and outdoor, whereas be18 relies on a monthly-average temperature difference. The usage with BSim approach in this thesis would enable a more precise calculation of the operational impact, leading to a more robust and reliable estimation of the EPBT.

In regard of the indoor environment, there has not been conducted an active evaluation of indoor comfort with respect to thermal-, atmospheric-, acoustic- or visual comfort. This involves mainly the office case study, whereas the Row house should consider summer comfort criteria, which is fulfilled. The requirement states that the room temperature in the cooling season should not exceed more than 100 h of 27 °C and 25 h of 28 °C for the Row house. The office on the other hand has strict rules according to the BR18, where for thermal comfort the room temperature over the year should not exceed 100 h of 26 °C and 25 h of 27 °C. Furthermore, with respect to atmospheric comfort, the office also has a strict rule according to BR18 that the CO_2 level should not exceed more than 1000 ppm over the year. The method to consider thermal and atmospheric comfort criteria would first be to evaluate the critical room and conduct an indoor environment simulation with BSim. BSim can consider all the factors that impact the room such as orientation, envelope U-values, interior construction, people load, lighting, and heating. Furthermore, with the dynamical simulation for an hourly average of the outdoor condition, a more accurate estimation of the ventilation rate and interior materials construction could be determined, Additionally, such as investigation discomfort criteria would also contribute to a limitation of the material and ventilation rate. However, in this thesis the values determined for new build renovation scenarios, the ventilation rate are used from MTH-højgaards simulation, which is assumed to be representative due to the indoor materials and U-values being almost the same compared to their final proposal of renovation.

Some challenges with the EPBT investigation for the renovation scenarios occur for the large set of LCA data, which can be obtained from EPD's all over the world and Ecoveint. A more accurate estimation would amplify the use of other dataset, and compare the results due to the material impacts can differ significantly. This means, that the investigation in this thesis is narrowing only towards generic data, which results in a more or less theoretical and rough estimation of the embodied impacts. For future research, other datasets would improve the robustness of the results for calculating the EPBT.

If a material study were to be conducted, to mainly find materials with low embodied impact, Biogen materials offer significant advantages. They have the ability to absorb carbon dioxide emissions, which results in a negative impact on the A1-A3 life cycle phases and can lead to either a negative or a very short EPBT. However, in this thesis, the scenarios that are investigated are based on conventional materials, but for the office building, there are further possibilities in investigating other cladding materials for the exterior wall. In this thesis, brick is used as the cladding material, which has a large GWP impact, whereas if the wood were chosen, the GWP would be lower. Thereby, a further investigation in a material study for more nontraditional construction of the walls, roof and floor could be conducted with a sensitivity analysis to find solutions that are more promising for the total environmental impacts.

For renewable sources, uncertainty relies on the fact that the HP and PV-panel degrade over time, which leads to less effective energy production. Additionally, the electricity production of the PV panels are dependent of solar radiation which is different with respect to the geographical location. The presumptions given from the products from the danish market is not necessarily correct. A more accurate estimation of the energy production from renewable resources would include a dynamic tool, which could consider the solar radiation from the geographical location, shading, efficiency, orientation, tilt angle, based on an hourly average. For the heat pump, several other types of HP exist such as ground-source Heat Pump which has a larger COP value compared to air-water. The reason the ground-source HP is more efficient is due to the fact that it used the heat from the ground which has a higher temperature in the winter compared to the air temperature. This would affect better energy production and thereby a larger operational saving. However, a larger embodied impact would be obtainted due to size of pipes that would been digged under the ground.

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A Building description of case studies

In this section a description of the building envelope of both cases will be presented to clearly see the materials and U-value.

A.1 Torpedammen

Torpedammen is a terrace house, where in this thesis only one block has been evaluated, which consist of ten houses.The building was constructed in 1963, where the current Building Regulation was BR61. U-values of the constructions are listed in table A.1 along with the requirements from BR61 and BR18. As this project considers a retrofit renovation focusing on replacing, the listed BR18 requirements are those applicable to renovated construction from paragraph 279. The materials used for each construction element are described in the following sections.

Table A.1. Overview of U-values for the standard construction elements and requirements to the U-value from BR61 and BR18.

Construction	**U-value [$\frac{W}{m^2K}$]**		
	Existing building	**BR61**	**BR18 §279**
Exterior walls	0.55	0.85	0.18
Roof	0.44	0.40	0.12
Ground deck	0.30	0.40	0.10
Windows	2,80	2,80	1,40

A.1.1 Exterior wall

The exterior wall are construction as a hollowed wall, with 108 mm brick on front and back and 50 mm insulation in between. It is assumed that the insulation material is stone wool with a higher thermal conductivity on $\lambda = 0.05\,\mathrm{W/mK}$ to compensate for the material thermal properties has deteriorated over the years. An illustration is shown on figure A.1

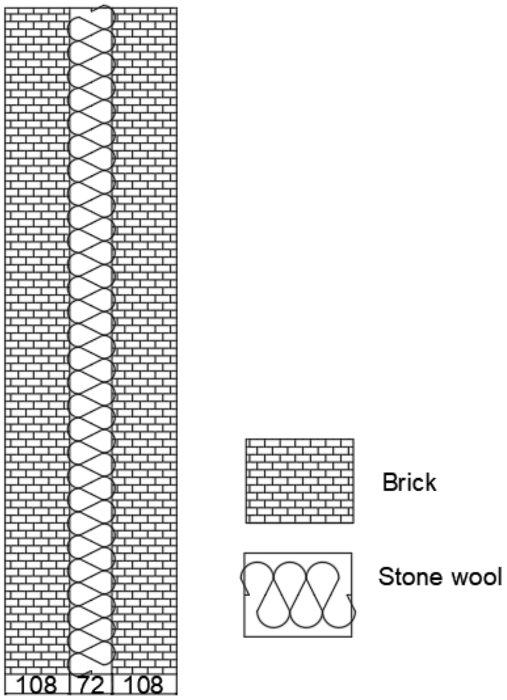

Figure A.1. 2D sketch of the existing exterior wall of Torpedammen

A.1.2 Roof

The roof construction is tilted with 11° and consist of roof bricking as the toplayer, 39x54 wood joints with 450 c/c, and 50 mm insulation and lastly 20 m cladding with plasterboard. An illustration is shown on figure

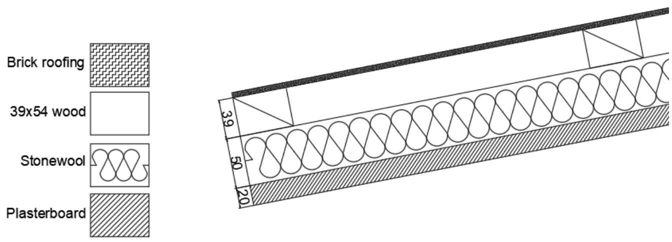

Figure A.2. 2D sketch of the existing roof of Torpedammen

A.1.3 Floor

The floor is made with wood floor and 50 mm insulation, 100 mm reinforced concrete and lastly 250 mm sand as the capillary layer. Wood beams are in 22 mm as the inner layer and with wood joints in 20x20 with 300 c/c. The insulation material is either glass wool or stonewool, but it is assumed that it is stone wool. An illustration is shown on figure A.3

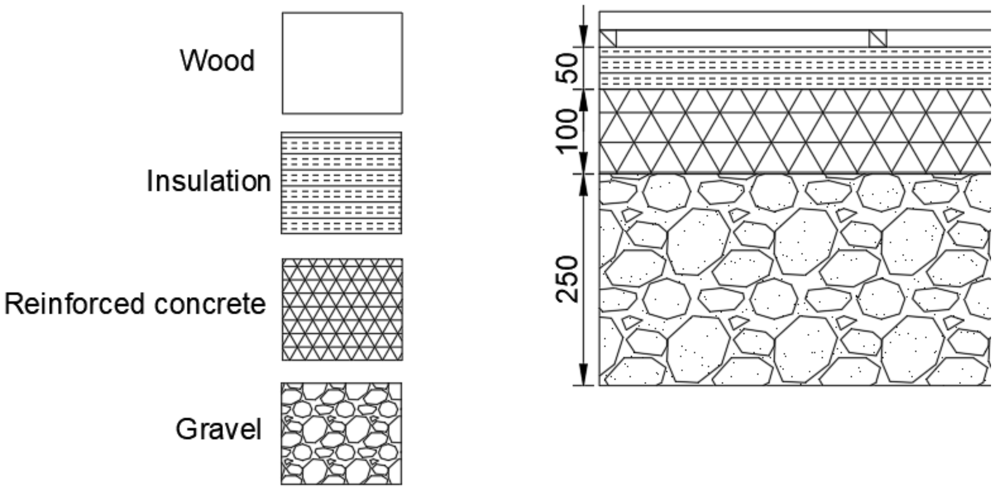

Figure A.3. 2D sketch of the existing floor of Torpedammen

A.1.4 Windows

For the windows, it is assumed that the windows are of 2-layer glass, which was common for a long time, and thereby set on 2.8 W/m^2K with a g-value on 0.75 The details of the windows is shown on table, where the orientation is given as S for south and etc, size is given in meter for height and length with both glass and frame, and lastly amount for total for one block A.2.

Table A.2. Window type in total for Torpedammen,

Window type	Orientation	Size [m]	amount [no.]
V1	S	3.73x2.27	10
V2	N	1.19x1.25	10
V3	N	1.31x1.25	10
V4	S	1.39x1.265	20
D1	N	1.39x1.265	20

A.2 Installations and ventilation

In this section the installations for pipe for DW and heating will be described with regards to heatlosses, which is going to be input for the energy calculation. It is assumed, that the pipes are with no insulation, and that the pipes are both in the heated and unheated area. The pipenetwork are located in the storage room, and then transferred into the building under the floor. On table A.3 the heatlosses is shown:

Table A.3. Heatloss from no insulation of pipes in storage room

Type	Length [m]	Heatloss [W/mK]
Heating pipes in storage room	120	1,03
DW pipes	80	1,03

Then, it is assumed that the terrace house block has one hot water tank of 150 L, which is a rough estimate, but was mainly conventional to have back in the 1960 in Denmark. It is assumed that the tank has no insulation and thereby a heatloss is given on 14.8 W/K, which is estimated from the report [Klima, 2019]. The details of the hot water tank are given on table A.4:

Table A.4. Details of the hot water tank

Type	Amount	Size [L]	Heatloss [W/K]
Hot water tank	1	150	4

Lastly, the pumps are also an assumption due to no specific documentation of the pumps are given. It was tested for different nominal power in be18, and in conlusion, it did not had any high impact on the key numbers for the electricity demand. Thereby, its assumed there are ten pumps with a nominal power of 30 W that are used constantly over the year and with a reduction factor of 0.8, which is due to manual adjustment of pressure.

Additionally, the ventilation is only based on natural ventilation, which is inputted as a ventilation rate on $0.3\,\mathrm{L/sm^2}$ in winter period and $2.4\,\mathrm{L/sm^2}$ in summer over the whole heating area.

A.3 Knud Hoejgaard hus

In this section a description of the building case Knud Hoejgaard hus will be presented, The office building was constructed back in 1958, where no national building regulations were required to fulfill. Thereby, the building construction were more focused on the static condition and less about improving the energy effiency. The building has a total of 11 240 m2 heated floor area and consist of a heated cellar and a ground floor up to 5. floor. The area pr. m2 floor is shown on table A.5:

Table A.5. Distribution of heated area on all floors

Floor	Heated floor area [m^2]
Heated cellar	2475
Mezzanine	841
Ground	2141
1.	1809
2.	1809
3.	1809
4.	1550
5.	1182
Roof house	99
Sum	11240

The U-values of the constructions are listed in table A.6 along with the requirements BR18 and BR61. As this project considers a retrofit renovation focusing on replacing, the listed BR18 requirements are those applicable to renovated construction from paragraph 279. The materials used for each construction element are described in the following sections.

Table A.6. Overview of U-values for the standard construction elements and requirements to the U-value from BR61 and BR18.

Construction	**U-value [$\frac{W}{m^2K}$]**		
	Existing building	**BR61**	**BR18 §279**
Exterior walls	1.96	0.85	0.18
Cellar wall	0.42	0.85	0.18
Roof and ceiling	1.66	0.40	0.12
cellar deck	0.54	0.40	0.10
Windows	2.80	2.80	1.40

A.3.1 Exterior wall and concrete footing

On the ground level a concrete footing is place just beneath the window facades. The thickness is 300 mm, and the U-value is 0.55 W/m^2K

The exterior wall is construction as a hollowed wall with 150 mm concrete on front and back and with 50 mm air in between. This type of wall is constructed on 1. to 4. floor, where the U-value is calculated to 1.96 W/m^2K. On figure A.4 an illustration in 2D is shown.

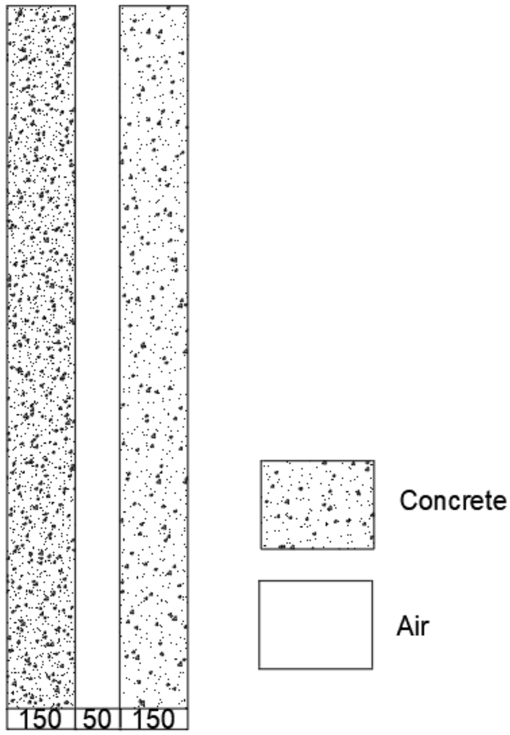

Figure A.4. 2D sketch of the existing exterior wall of Knud Hoejgaard hus from Mezzanine to 5. floor

A.4 Cellar wall

For the cellar wall, it constructed as 300 mm reinforced concrete with 50 mm in the inner layer. This gives an U-value on 0.42 W/m^2K, where it is illustrated on figure A.5

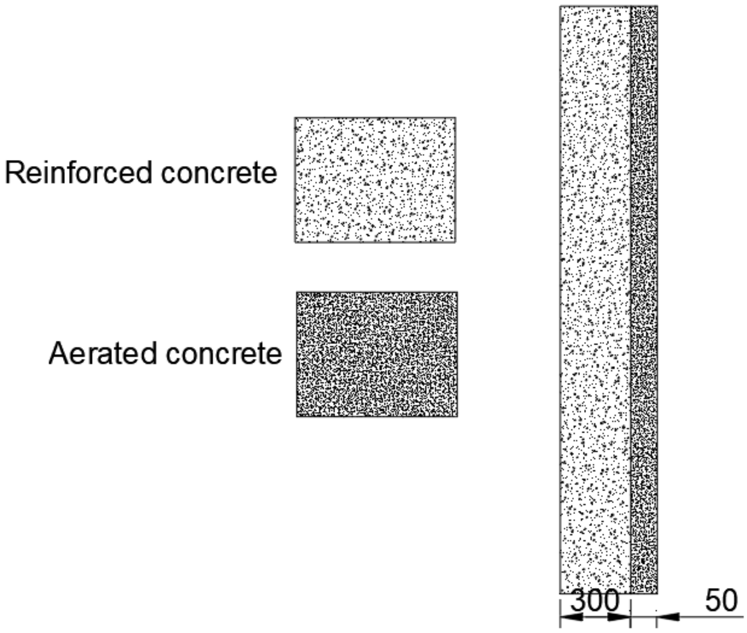

Figure A.5. 2D sketch of the existing cellar wall of Knud Hoejgaard hus

A.4.1 Cellar deck

For the cellar deck, it is a simple heavy construction of 250 mm concrete and 150 mm gravel. This gives an U-value on 0.54 W/m^2K. An illustration is shown on figure A.6

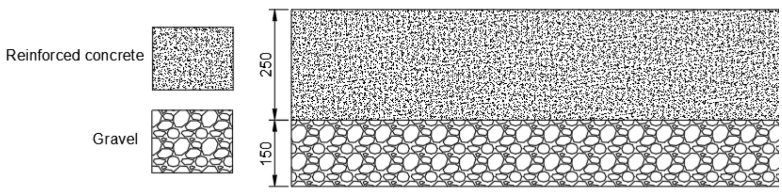

Figure A.6. 2D sketch of the existing cellar deck of Knud Hoejgaard hus

A.4.2 Roof, floor decks and ceiling

The roof is flat with only a heavy construction of 240 mm concrete, where the top layer is a thin roof paper. This also occurs for the floor decks from the ground up to 5. floor, where the floor layer is 22 mm linoleum with a thin layer wearing course. An illustration is shown on figure A.7

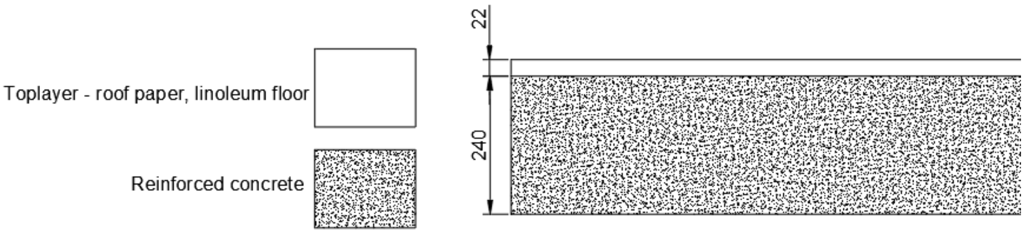

Figure A.7. 2D sketch of the existing floor decks and roof of Knud Hoejgaard hus

A.4.3 Windows

For the windows, it is also assumed that the glass is of 2 layers, with a typical U-value on 2.8 W/m^{2}K and with a g-value of 0.75. The details of the windows are shown on the table, where the orientation is given as S for south and etc, size is given in meters for height and length with both glass and frame and lastly amount. A.7.

Table A.7. Window type in total for Knud Hoejgaard,

Window type	Orientation	Size [m]	amount [no.]
V1 ground	S,E,W,N	2.27x3.46	71
V2 1.-4	S,E,W,N	2.55x0.94	129
V3 1.-5	S,E,W,N	1.94x0.94	489
D1 ground	S,E,N	2.04x1.87	4
D2 ground	S,N	2.16x0.9	2
D3 ground	W	1.07x2.64	2
D4 ground	W	1.39x1.265	2
D5 5.	N,E,S,W	1.7x0.85	4

A.4.4 Installations

For the installations for heating and DW, it is also assumed that the pipes are with no insulation, and the length for the pipes going to the technical room, and ventilation aggregate are already evaluated from MTH-hoejgaard company. THereby, the inputs for the installations of heating and DW are given on table A.8

Table A.8. Heatloss from no insulation of pipes in storage room

Type	Length [m]	Heatloss [W/mK]
Heating pipes in cellar	190	1,03
DW pipes	8	1,03

Furthermore, the pumps for DW and heating are also given from MTH-Hoejgaard, which are dimensioned according to the demanding requirement. This is then also used as an input in this model.

A.4.5 Ventilation - natural and mechanical

To determine the minimum ventilation rate to secure a sufficient atmospheric indoor environment for all the rooms, it should be dimensioned for the critical room. The existing building rooms are constructed as large spaces, where the renovation aims to also change the interior design of the rooms. This gives free possibilities for developing different room types and sizes, For Example, the building could consist of small offices, big offices, meeting rooms and shops.

According to MTH Hoejgaard the ground level consists of grocery shops, restaurants, and shops. Furthermore, 80 % of the heated room area from 1. floor to 5. floor will be offices, and 20 % will be meeting rooms. Additionally, the minimum ventilation rate of the rooms is found for the rooms types from MTH Hoejgaard with simulation in BSim. This distribution of rooms types will also be used in this thesis and also the ventilation rates, which is listed on table A.9:

Table A.9. Distribution of area for room types and the minimum ventilation rate

Types	Heated room area [m^2]	q_{min} [l/sm^2]
Offices	6527	2.78
Grocery store, resturants and shops	2141	2.78
Meeting rooms	1632	5.56
Cellar	2475	1.39

On table A.9, it is seen that the q_{min} for the meeting rooms is the double ventilation rate with $5.56\,l/sm^2$ of the office rooms. Lastly the cellar consists of mainly technical rooms, storage rooms, and bicycle parking has half of the ventilation rate of the office with $1.39\,l/sm^2$

B Description of renovation scenarios

B.1 demolish and build new scenario

The scenario for the demolish and build new, aims is to fulfill the energy framework according to §259 in BR18. It states that for residential building's total energy supply for heating, ventilation, cooling and DHW must not exceed more than 30.0 kWh/m² per year plus 1,000 kWh per year divided by the heated floor area. Here a more common construction build of the exterior wall, floor, roof, and ceiling will be chosen that emphasizes the more conventional new build today. The conventional new build materials are chosen from five real new build cases, which is found in appendix C

To fulfill the requirement of summer comfort for the critical room with max 100 h with 27°C and 25 h with 28°C room temperature, an iteration of the minimum natural ventilation rate were conducted. The critical room is the living room, due to the window being located on the south and having the most glass area. This given, a minimum natural ventilation rate of $5.2\,\mathrm{l/s \cdot m^2}$ is used to fulfill the requirement of summer comfort in the most critical room.

B.2 Build new+HP+PV

In this scenario, the influence of electricity as an energy source on the EPBT will be investigated. This is important due to the transition in the future for more energy-producing systems, which is a huge stepping stone to becoming climate neutral in 2050. In the building sector, primary energy factors are used to weigh the produced heating or electricity, where if you produce 1 kWh electricity for heating, it is weighed as 1.9 kWh heating [BR18, 2018]. This means, the energy consumption should be potentially lower using electricity as source compared to district heating. However, using energy-producing systems increases the initial embodied impact, so the aim is to study how much influence, it has on the EPBT.

The amount of $\mathrm{m^2}$ for PV is chosen to mainly receive a rough estimation and to see the impact in the initial embodied- and operational. Additionally, the HP evaluated is an air-water type which is a conventional type for heating of both space and DHW. The minimum size is calculated in table B.1:

Table B.1. Minimum sizing of HP to cover demand of DHW and heating

Cases	**DHW** [$\mathbf{kWh/m^2}$]	**heating** [$\mathbf{kWh/m^2}$]	**Operation** **[h]**	**Area** [$\mathbf{m^2}$]	$\mathbf{HP_{min}}$ **[kW]**
Case 1	13.1	19.3	8765	640	2.4
Case 2	5.3	6.7	8765	11240	15.4

B.3 Refurbishment - Circular economy

Additionally, a refurbishment scenario with focus on circular economy will be investigated to see the potential reduction in the embodied impacts by reusing old materials. The reusable materials will be going through a repairing and cleaning process that should achieve the standard requirement for new materials. However, It is not a requirement to implement circular economy for new build or renovation according to BR18, nor any form of reward are given if considered. The benefit of building with reusable materials is that they prevent the amount of waste from demolishing projects, and avoid the production of some new materials. To investigate the potential environmental impact, the data given from [Ernst Andersen et al., 2019] for reusable concrete, and brick will be calculated assuming that the static and thermal properties are the same as for new materials.

B.4 Retrofit scenario

The retrofit scenario aim is to fulfill the requirement of the minimum U-values for wall, floor, and roof with §279 and for window §258 which are based on new build according to BR18. In the residential building case, the actions in this scenario include tearing down the existing exterior construction, where extra insulation and a new identical exterior material will be added to both preserve the aesthetic design and increase the energy effiency. Furthermore. all the layers of the floor will be demolished to ensure that there is no risk of mold, which is commonly done if the house insulation thickness is less than 100 mm. The minimum U-values that is included in this scenario are listed on table B.2 and the requirement for new build for windows on table B.3

Table B.2. Minimum U-values for construction part according to §279 [BR18, 2018]

Construction part	U-value [W/m^{2}K]
Exterior wall	0.18
Floor	0.10
Roof and ceiling	0.12

Table B.3. Energy balance for windows according to §258 [BR18, 2018]

Construction part	$E_{ref} > 0\,\text{kWh/m}^2$	$E_{ref} > 10\,\text{kWh/m}^2$
Windows and glassfacade	$196.4 \cdot g_w - 90.36 \cdot U_w$	
Skylight windows		$345 \cdot g_w - 90.36$

C New build cases from 2020-2022

Table C.1. Real residentual buildings from 2020-2022

cases	**construction**	**thickness [m]**	**Material**	**U value [W/m2K]**
billeskoven 4		0.108	brick	
9230 svenstrup	exterior wall	0.19	stonewool class 34	0.14
34.9 kWh/m2year - 2021		0.1	Porebeton	
		0.022	gypsum plasterboard	
		0.0002	vapor barrier	
		0.038	38x72 forskalling	
	Roof and ceiling "cold ventilated"	0.095	stonewool class 34	0.07
		0.46	granulat	
		0.018	Plywood	
		0.25	Roof paper	
	windows and doors	A-class - energy glass	3x glass, tree frame	0.86, 0.89, 0.83
		0.022	floor tiles	
	floor with floor heat	0.12	C20 MPa concrete	0.07
		0.36	insulation - expandet polystyren 31	
	heavy Internal wall	0.1	porebeton	
Klarup have		0.11	brick	
9270 Klarup	Exterior wall	0.19	Isover wallbatts class 32	0.17
182.3m2 residentual house		0.1	Porebeton	
32.8 kWh/m2 year - 2022		5stk/m2	stainless steel binder	
		0.022	wood	
	floor with floor heat	0.12	concrete C20 Mpa	0.08
		0.37	polystyren	
		0.022	gypsum plasterboard	
		0.0002	vapor barrier	
		0.025	trolltex	
	Roof and ceiling "cold ventilated"	0.12	stonewool class 34	0.09
		0.304	granulat	
		0.018	plywood	
		0.015	Brick roofing	
	windows and doors	A-class - energy glass	3x glass, tree frame	0.92, 0.85, 0.83
	heavy Internal wall	0.1	Porebeton	
Kildebækhøj 70		0.108	brick	
9280 Storvorde	Exterior wall	0.19	stonewool class 32	0.16
217 m2		0.1	Porebeton	
34.6 kWh/m2 year		8stk/m2	stainless steel binder	
-2021		0.022	floor tiles	
	floor with floor heat	0.12	concrete C20 Mpa armed	0.07
		0.4	polystyren class 31	
		0.013	gypsum	
		38x73mm	wood beams with insulaton inbetween	
		0.0002	vapor barrier	
	Roof and ceiling "cold ventilated"	0.1	stonewool 34	0.06
		0.5	cellular insulation 37	
		0.018	plywood	
		0.25	Roof paper	
	Windows and doors	A-class - energy glass	3x glass, tree frame	0.83, 0.85, 0.93
	heavy Internal wall	0.125	porebeton	

Table C.2. Real residentual buildings from 2020-2022

cases	construction	thickness [m]	Material	U value [W/m2K]
Ingefærbakken 8		0.108	brick	
8930Randers Nø	Exterior wall	0.19	stonewool class 34	0.17
167m2-2022		0.125	Porebeton	
35.6kWh/m2 year	floor with floor heat	0.1	concrete	0.09
		0.12	polystyren class 31	
		0.022	gypsum plasterboard	
		25x78	wood beams with insulaton inbetween	
	Roof and ceiling "cold ventilated"	0.0002	vapor barrier	0.07
		0.5	cellular insulation 37	
		0.018	plywood	
		0.015	Brick roofing	
	windows and doors	A-class - energy glass	3x glass, tree frame	0.8-0.9
		0.012	gypsum plasterboard	
	light Internal wall	0.095	C18 c/c 600mm	
		0.095	stonewool	
		0.012	gypsum plasterboard	
Cirkelbuen 44		0.108	brick	
, 3400 Hillerød,	Exterior wall	0.19	stonewool class 34	0.17
171 m2 ,		0.1	light concrete	
16 kWh/m2 year		0.022	floor tiles	
-2021	floor with floor heat	0.12	concrete C20	0.09
		0.4	polystyren class 31	
		0.022	gypsum plasterboard	
		0.0002	vapor barrier	
		38x73mm	wood beams, 300 cc	
	Roof and ceiling "cold ventilated"	0.095	Insulation batts 37	0.07
		0.45	cellular insulation 37	
		0.022	Plywood	
		0.25	Roof paper	
	windows and doors	A-class - energy glass	3x glass, tree frame	0.8-0.9
		0.012	gypsum plasterboard	
	light Internal wall	0.095	C18 c/c 600mm	
		0.095	stonewool	
		0.012	gypsum plasterboard	
	PV cells	4.0 kWp, 26.8m2, 16 modules	monocrystalline	