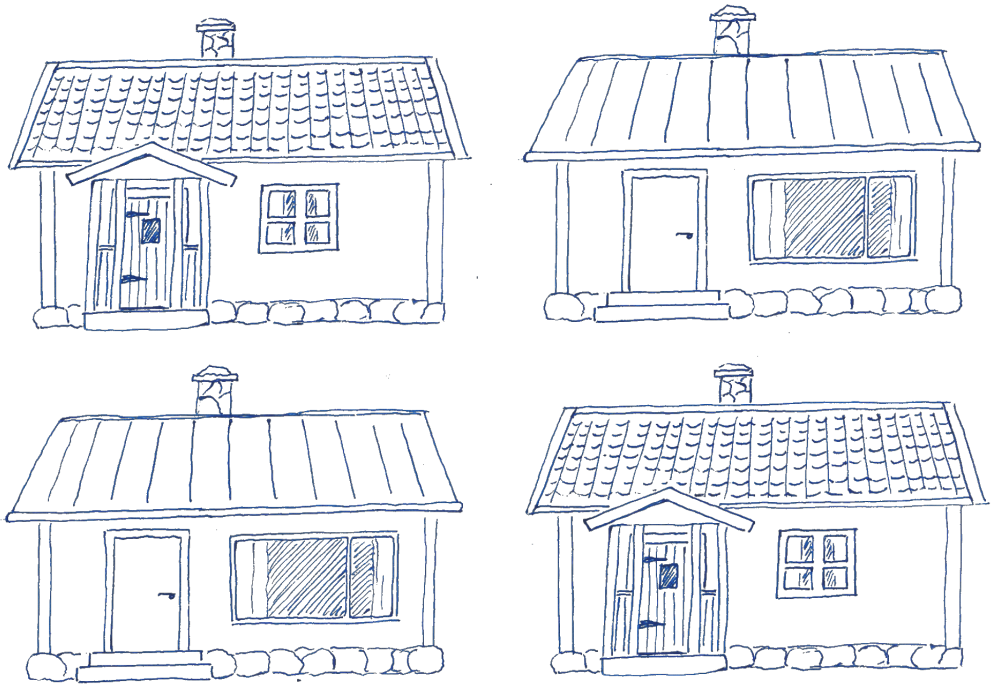


Environmental impact of retrofitting second homes

A case-study of the net global warming potential of different retrofit measures in a Swedish context

Master's thesis in Industrial Ecology

JULIA GUTKE

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

Environmental impact of retrofitting second homes

A case-study of the net global warming potential of different retrofit measures in a Swedish context

JULIA GUTKE

Department of Architecture and Civil Engineering
Division of Building Technology
Sustainable Building
Chalmers University of Technology
Gothenburg, Sweden 2023

Environmental impact of retrofitting second homes
A case-study of the net global warming potential of different retrofit measures in a Swedish context

Supervisor: Kristina Mjörnell, RISE Research Institutes of Sweden
Examiner: Holger Wallbaum, Department of Architecture and Civil Engineering

Master's Thesis 2023
Department of Architecture and Civil Engineering
Division of Building Technology
Sustainable Building
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Sketch of a Swedish cottage before and after a hypothetical renovation, however unrelated to the objects studied in this thesis.

Gothenburg, Sweden 2023

Abstract

The building and construction sector is responsible for a fifth of the greenhouse gases released by human activities, and retrofits are promoted by the IPCC as an effective way to reduce the energy consumption and hence environmental impact of buildings. Retrofits initially implies an increased environmental footprint associated to the addition of materials and activities that are then successively compensated by the expected savings in operational energy. For permanent housing this trade-off normally implies a decreased life cycle environmental impact, however this study focuses on second homes. What separates second homes from permanent housing is that they are used intermittently, typically during weekends or vacations, hence suggesting that the compensation for a footprint caused by a retrofit takes longer. This thesis compares the added environmental impact of three common retrofit measures to the reduced impact from the lower operational energy following each retrofit respectively. The analysis is performed on three different case houses in southern Sweden, and the studied measures are changing windows, addition of roof-insulation and installation of an air-sourced heat pump. The difference between the impact embodied in a retrofit measure and the reduced impact from operational savings is referred to as the net environmental impact. The findings suggest that it is not environmentally preferable to retrofit second homes, but rather to keep a low indoor temperature while not using the house if it can can be assured that this does not cause any risks or damages to the house.

Keywords: Life Cycle Assessment, Environmental impact, Energy use, Retrofit, Energy renovation, Second homes

Acknowledgements

I appreciate that the acknowledgements allows me to be a little bit more personal, and write more freely, than what is custom in the rest of this thesis. I really enjoy writing, however I don't like it when it's restricted and subject to rules as is the case with scientific writing. Hence I am very lucky to have had a supervisor who has guided me very well through this work, allowing a high level of self-responsibility while still not allowing me to not lose focus and instead stay on track. I would also like to thank my mother for her continuous and indefatigable reading and commenting of this and other texts and reports I have written throughout my education about subjects that are not always understandable or interesting for someone with a non-technical background. Another person subject to my gratitude is Isak Brundin who also read and provided important feedback and comments. Finally I want to thank the three house owners who allowed me to use their second homes as case houses in this thesis. Unfortunately I haven't had the opportunity to see the houses in real, however they all seem to be wonderful places to spend weekends or long and lazy summer days in.

Julia Gutke, Gothenburg, April 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ASHP	Air-sourced heat pump
BIM	Building Information Modelling
CF	Characterization Factor
EOL	End-of-Life
EPC	Energy Performance Certificate
EPD	Environmental Product Declaration
FU	Functional Unit
GHG	Green House Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
RSL	Reference Service Life
SIS	Swedish Standards Institute

Glossary

Below is a list with descriptions of commonly used terms and words listed in alphabetical order.

Embodied impact	The sum of all life cycle environmental impacts of a product or service.
Permanent housing	What is normally considered as a home, or the home were most time is spent. This is the home were inhabitants are registered.
Refurbishment	The process of repairing *or* improving a building, including both for energy efficiency purposes and other, such as aesthetics.
Renovation	Same as refurbishment but the two are used in different regions.
Repair	Bringing back the function of an element, but not necessary the original state of it.
Restoration	Bringing back the original state of an element or building.
Retrofit	The addition of new materials or elements previously not present to improve the energy efficiency of a building.
Second home	Houses used as occasional residences, typically during weekends or vacations.

Contents

List of Figures

List of Tables

1
Introduction

1.1 Background

Climate change and other environmental impacts are for good reasons widely discussed and researched today, and the interest for this topic has been increasing during the last decades. Despite all this attention, greenhouse gas (GHG) emissions from human activities have continued to rise (Pörtner et al., 2022). Buildings are responsible for 21% of all GHG emissions globally, and this share is composed of 57% electricity and heat generation, 24% on-site direct emissions and 18% embodied in the major building materials (Pathak et al., 2022). In Europe, buildings are responsible for 40% of the energy consumption and 36% of energy related GHG emissions and the single largest consumer of energy in the union (European Commission, 2018). Both the Intergovernmental Panel on Climate Change (IPCC) and the European Commission identifies retrofitting as a major measure to make the existing building stock more energy efficient, especially in developed countries (European Commission, 2019; Pathak et al., 2022).

Some recent efforts that address the performance of buildings include the European Commission's strategy Renovation Wave wich has the overall aim to reach a fully decarbonised building stock in 2050, and a new regulation in Sweden that require climate declaration of new buildings that aims to decrease the environmental footprint of buildings (Boverket, 2021; European Commission, 2018). Energy renovations, or retrofits, are also recommended by the Swedish Energy Agency to those who wish to decrease the energy consumption of their houses (Swedish Energy Agency, 2022). However, IPCC projects that the sector's GHG emissions will continue to increase globally as a result of population growth, increased floor area per capita, inefficiency of new buildings in the developing countries, and the still low renovation rates and ambition level in developed countries (Pathak et al., 2022). Retrofits come with an environmental footprint and hence implies a trade-off between the expected savings in operational energy use and the impact embodied in the measure (Ramírez-Villegas et al., 2019; Shirazi and Ashuri, 2020; Beccali et al., 2013).

Second homes are houses used as occasional residences, typically during vacations or weekends, and their presence and use is a popular and common phenomenon in the Nordic countries; more than half of the Swedish population is believed to have access to a second home (Back and Marjavaara, 2017; Hiltunen, 2007). The total energy consumption and environmental impact of second homes is without doubt minor to that of the overall residential sector, however they represent a category with potentially increasing relative importance as other types of housing receive more attention in terms of energy efficiency. Second homes are different from permanent housing in that they are used intermittently, which creates other energy requirements. This intermittent use is assumed to affect the operational energy use and hence how retrofits pay off environmentally. Hypothetically, the embodied environmental impact of retrofits would take longer to compensate for a second home and might not even pay off at all.

1.2 Theoretical framework

Below there will be a description of the performed literature review (1.2.1), what a retrofit is and what retrofit measures that are recommended by Swedish authorities (1.2.2), and an overview of the standard for how to perform LCAs of building refurbishments (1.2.3). This is followed by a summary of earlier research from the literature review (1.3).

1.2.1 Literature review

A literature review was performed with the general aim to generate a better understanding of the field and in a structured way get an idea of recent developments, without performing a full and systematic literature review. This review rather followed the steps of a structured literature review, a smaller and hence less time-consuming method more suitable for a master's thesis (Karolinska Institutet, 2022). Literature in both Swedish and English were included and searched for through Google scholar and Chalmers library. The identified concepts and keywords are displayed in table 1.1.

Literature is initially selected based on titles, year of publication (in favour of more recent studies: the oldest one is from 2007, three are older than from 2010) and scientific level. Master's theses were included while lower-level works were excluded. The main reason to include some other master's theses was that there were some examples of similar studies within this category. Further refinement of the selection was done by reading abstracts and judging the relevance of the literature. The keywords and searches were also continuously adapted to generate a more relevant result. Literature that was considered especially relevant were used for snowballing, i.e. drafting further literature from their lists of references. All articles were then read through and potentially irrelevant literature sorted out. In total, the final sample amounted to 28 articles, student's theses and reviews. These form the background and are the basis for the theoretical framework of this study.

Vilches et al., 2017 highlights the confusion regarding terminology in their review, and the varied usage of words with different meanings to describe similar things. The terms *retrofit*, *refurbishment*, *renovation*, *repair* and *restoration* are often used interchangeably, however they refer to different things.

Table 1.1: Concepts and associated keywords used when searching literature.

Concept	**Keywords and search blocks**
LCA of retrofits	English: energy AND (renovation OR refurbishment OR retrofit OR restoration OR repair) AND (building OR single-family houses OR residential) AND ("life cycle assessment" OR "environmental footprint" OR "environmental impact") Swedish: (energieffektivisering OR renovering) AND (bostäder OR villa OR hus) AND (livscykelanalys OR miljöpåverkan)
Second homes	English: ("summer house" OR "second home") AND ("energy efficiency" OR "energy consumption" OR "energy use" OR "electricity consumption") Swedish: (sommarstuga OR fritidshus OR fjällstuga OR sommarhus OR torp) AND (energiförbrukning OR elförbrukning OR energianvändning OR elanvändning OR energieffektivisering)

- **Retrofit** refers to the addition of new materials or elements previously not present to improve the energy efficiency of a building.
- **Refurbishment** and **renovation** are used in different regions but means essentially the same. These two include retrofit measures but could also cover other e.g. aesthetic improvements.
- Both **repair** and **restoration** refer to the giving back of a function. Restoration means to bring something back to its original state, whereas repair could imply bringing back a function without returning the element or building to it's original state.

All terms were included in the literature search because of the mentioned confusion, however the term "retrofit" will be used in the rest of this study when not citing or referring to earlier literature using other terms. Similarly, there are various words used to describe different types of houses not used for permanent housing, e.g. summer house, second home, cottage or cabin. Many of them were included in the search for literature but for the sake of consistency "second home" will be used in this text.

1.2.2 Retrofits

As described, retrofits are measures where materials or elements are added to a building in order to improve its energy efficiency. What measures exactly that are suitable depends on the characteristics already present in a certain building. Following the current relatively high energy prices, the Swedish Energy Agency presented a guide directed towards owners of single-family houses or second homes who wish to improve their energy efficiency (Energiföretagen, 2022; Swedish Energy Agency, 2022). The guide consist of 5 sections:

- Introduce energy efficient habits.
- Identify current state and improvement possibilities.
- Reduce the need for heating.
- Examine the heating system.
- Optimization, “take your house to the next level” .

The first step introduces habits that decreases your consumption of energy, such as lower temperature, decreased use of hot water and reduced or more efficient use of electric appliances. The second step recommend that the owner should make an inventory of the house to identify what measures that could have the highest impact, what the present energy consumption is and if the house has an energy declaration. The third step involves retrofit measures such as adding insulation, changing doors and windows, and maintenance or change of ventilation systems. The fourth step consists of measures related to the heating system and comes after the third step because it is inefficient to upgrade the heating system for a house that cannot keep the heat. This step presents advice for optimizing the already present heat system or changing system. The fifth step introduces measures such as measuring and automatically controlling your energy consumption, and production of electricity through e.g. solar panels.

1.2.3 Life cycle assessment of building refurbishment

Life Cycle Assessment (LCA) is a method for analysing the environmental impacts of products or services (henceforth simply referred to as ‘products’). In short, it aims to evaluate the impacts associated to all stages of a product’s life cycle, from the extraction of raw materials to the disposal. An LCA consist of three major phases: goal and scope definition, inventory analysis (LCI) and impact assessment (LCIA), and a continuous interpretation phase (Baumann and Tillman, 2004).

LCA is recognized as one of the most complete methods for assessing the environmental performance of buildings (Soust-Verdaguer et al., 2016). The Swedish standard SS-EN 15978 outlines a method for LCA of buildings where different life cycle stages are separated in ‘modules’ that describe the different stages of a building’s life cycle, see Figure 1.1. Earlier studies have recognized that LCAs are more commonly performed on new buildings or buildings built with the purpose of having a lower environmental impact, whereas studies on building refurbishment or the existing building stock are lacking (Vilches et al., 2017; Cabeza et al., 2014; Moschetti and Brattebø, 2017). However, it is also recognized that new buildings in advanced economies are most often already operationally energy efficient, whereas upgrading the existing building stock implies a big energy saving potential (Famuyibo et al., 2013). Ekström and Blomsterberg, 2016, claims that the energy use in older single-family houses in Sweden could be reduced by as much as 75% if appropriately retrofitted. “Refurbishment” is described in a separate module, B5, (see figure 1.1) within the use-phase and has the following system boundaries:

- Production of the new building components
- Transportation of the new building components (including production of any materials lost during transportation)
- Construction as part of the refurbishment process; (including production of any material lost during refurbishment)
- Waste management of the refurbishment process
- The end of life stage of replaced building components

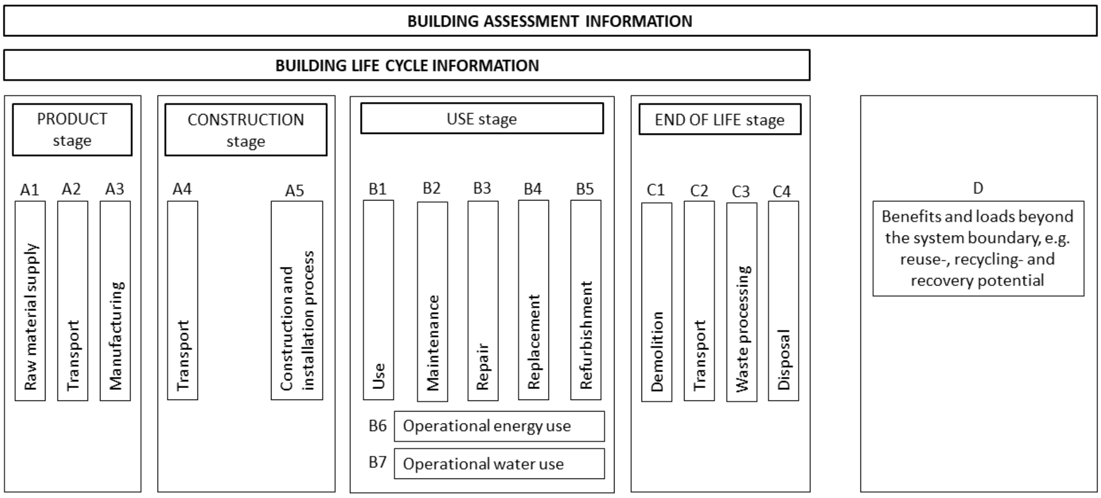


Figure 1.1: Modules describing life cycle stages of a building, (Swedish Standards Institute, 2011).

Assessing the environmental impacts of retrofits is a relatively recent phenomenon (Moschetti and Brattebø, 2017), and there is a lack of consensus regarding how the standard should be interpreted (Vilches et al., 2017; Hasik et al., 2019; Nydahl et al., 2019). Even among studies not consulting the standard there is an identified absence of consensus for how to perform the LCA (Obrecht et al., 2020). In general, LCA is recognised for being highly dependent on the choices made by the specific practitioner, which makes interpretation by non-experts and comparison of different results difficult (Soust-Verdaguer et al., 2016; Seleborg, 2019; Vilches et al., 2017).

1.3 Former research

In a review, Vilches et al., 2017, summarizes contributions related to the assessment of environmental performance of building refurbishment or renovation using LCA methodology and identifies some main causes of the current variation in methodological choices regarding system boundary interpretation of the standard, choice of functional unit (FU), life cycle inventory-method, operational stage and end of life (EOL) stage definition. The interpretation of the system boundaries made in the review by Vilches et al., 2017, is that all life cycle stages of the new materials should be included, with the potential extension to include the end of life of substituted and remaining original materials. The FU is commonly defined as area, heated area or the entire building. Among the papers studied by Vilches et al., 2017, the LCI method used is almost exclusively process analysis, with one exception that uses a hybrid analysis (Famuyibo et al., 2013). Input-Output analysis (IOA) is not used in any identified study, neither by Vilches et al., 2017, nor in other found review or article. Hasik et al., 2019, also identified this lack of consensus regarding system boundaries and highlights a certain disagreement regarding waste management and EOL, e.g. whether to include waste management both from the process of installing new components or also from the process of demolishing old products, and if the end of life-stage concerns both newly added and old replaced components. Another critical system boundary-related choice is that of the temporal scope, for how long impacts are accounted, called the reference service life (RSL). Typically, this varies between 50 and 150 years in studies on building retrofits (Vilches et al., 2017; Obrecht et al., 2020).

1.3.1 Life cycle assessments of building refurbishments

The inconsistency of methodological choices is problematic both because it makes comparison of results difficult and probably also is a reason why LCA is prejudiced or experienced as complicated and time consuming. Soust-Verdaguer et al., 2016, highlights that even though the interest to investigate the environmental impact of buildings, this negative experience or idea hinders application. The solution proposed is to provide guidelines on how to simplify the application of LCA, i.e. further development of common criteria for process definitions (what modules to include and what is included in each module), continuous development of Environmental Product Declarations (EPDs), integration of Building Information Modeling (BIM) with LCA to easier estimate type and amount of materials and common criteria for communication in order to increase comparability of results. Regarding the integration of BIM with LCA, Obrecht et al., 2020, reviews recent efforts and concludes that there are still many technical obstacles before such an integration is adaptable. In general, many authors seems to call for more well-defined guidelines, however the openness of the guidelines leaves space for the heterogeneity present among buildings and retrofit measures. One interesting aspect identified by both Van de Moortel et al., 2022, and Österbring et al., 2019, is that most studies are static LCAs, modeling different scenarios as a step-change, namely a direct change from one static state to another. In reality though, many parameters such as energy mixes and also the uptake of renovation measures in a building or housing stock is dynamic. Van de Moortel et al., 2022, compared static and dynamic application and concluded that the dynamic approach resulted in lower environmental impact, whereas Österbring et al., 2019, applied a dynamic uptake when assessing renovation measures to a housing stock in Gothenburg using two different types of logic (either that renovation was performed at component's EOL or when it was cost efficient to perform the measure). Considering buildings with cultural or historic value in particular, which is not unusual in the case for second homes, Serrano et al., 2022, investigate whether it implies a higher environmental load to restore the original aesthetics of buildings (as in a restoration) than to renovate with the use of modern techniques, and concluded that the methods had similar environmental performance. Angrisano et al., 2021, on the other claimed that the use of traditional methods such as hemp insulation can have much lower environmental impact than if modern materials are used. The studies are however very different and include both different measures, impact categories, software and databases and are hence not considered comparable. Arvidsson and Farsäter, 2011, studied what energy renovation measures that could be sustainable for older (built 1880-1945) small houses in Sweden. No LCA was performed by Arvidsson and Farsäter, 2011, however a list of proposed sustainable energy efficiency measures is presented which contains insulation of the roof and renovation of windows (i.e. not exchanging the windows completely, but renovating the present ones). Many of the found articles makes no economic assessment, although that aspect is probably of high importance for the choice of retrofit measure and whether to perform measures at all. Moschetti and Brattebø, 2017, assessed the interaction of environmental and economic performance of different renovation scenarios and found a close to negative linear relationship but with higher variation for the environmental side, i.e. while the difference in cost showed small variations between the most and least expensive scenario, the environmental impact was very different.

1.3.2 Trade-off between operational energy and embodied impacts

When performing retrofits, the life cycle environmental impact could either increase or decrease, depending on if the added environmental impact embodied in the measure is greater or smaller than the reduced impact associated with the energy savings. In earlier studies investigating this trade-off between operational energy savings and embodied energy it is almost exclusively concluded that retrofits decrease the life cycle environmental impact. Beccali et al., 2013, studied the net environmental savings of different retrofit action performed in a single-family house in the Mediterranean. Shirazi and Ashuri, 2020, conducted a trade-off analysis of different retrofit actions performed to houses of different construction years in Atlanta, US, to find the most efficient in terms of energy and environmental impacts. Ramírez-Villegas et al., 2019, conducted an LCA on a multi-family house in Sweden. Rabani et al., 2021, used the software OneClick LCA and IDA-ICE (IDA Indoor Climate and Energy) to evaluate the net environmental impact of different retrofit scenarios for a typical office building in Norway. Nydahl et al., 2019, performed this kind of trade off analysis using traditional economic performance tools (Return on Investment and Annual Yield). The measures that were studied in the articles from the literature review were in general considered to pay off environmentally, one exception is found in the study by Nydahl et al., 2019 were changing windows for a certain building at a certain location was not environmentally favourable. Nydahl et al., 2019, studied the net impact of 6 different measures, listed below:

- Energy recovery ventilation.
- 3-glass windows.
- Roof insulation of 50 cm loose glass wool.
- Additional wall insulation.
- 70 m^2 of CIGS Photovoltaics.
- 55 m^2 Multi-Si Photovoltaics.

Measures were tested for a specific case building but in three different locations, and the results of the study concluded that all measures pay off environmentally except from the installation of new windows in one of the chosen locations, Lund in Sweden. Shirazi and Ashuri, 2020, also investigated windows, as well as a set of many other measures including insulating different building elements, changing ventilation or heating systems and exterior shadings. Installing a heat pump was not investigated, and the measure with the highest GWP was to install new windows. The studies are different in many ways, but both give the result that adding insulation is more favourable than changing windows in terms of GHG emissions. Overall, retrofits are recommended as an effective way to reduce the environmental impact of buildings.

1.3.3 Second homes

There are currently more than 600 000 second homes in Sweden owned by Swedish people and to a minor extent by people of other nationalities, mainly Norwegian, Danish or German people (Statistics Sweden, 2022). They are distributed almost all over Sweden except for in the north western part, however the concentration is higher in southern Sweden and along coast (Back and Marjavaara, 2017; Energimyndigheten, 2012). Although great internal heterogeneity some general distribution characteristics can be identified (Back and Marjavaara, 2017). One such characteristic is that the houses in southern Sweden are more frequently visited, whereas the northern second homes to a greater extent are used more seldom but for longer periods. Another observation is that there exist certain clusters of "purpose-built" second homes in especially attractive areas, whereas converted houses (originally built for another purpose) is more common elsewhere. According to statistics compiled by Energimyndigheten, 2012, the total energy consumption of second homes that year amounted to approximately 3.5 TWh, or 6 MWh per house, and the most common source for heating was electricity and biofuel. Opposed to other types of houses, there is no requirement to make an energy performance declaration of second homes which could result in poor interest in making the houses more energy efficient (Boverket, 2022; Vestlund, 2009). However, energy retrofits of second homes could become more attractive as energy prices are rising.

In comparison to permanent residences or non-residential buildings (which have been discussed in 1.2.3 and 1.3.2) very few studies discussing environmental impacts of second homes, retrofitting second homes, or a combination, were found. An ongoing study by Mjörnell et al., 2023, compiles available information on and investigates use patterns, energy source for heating and retrofit measures carried out in second homes. This study claims that the houses are most commonly used for longer periods during summer, and shorter periods for the rest of the year; the most common energy source is direct electricity or heat pumps, and the most common retrofit measures were to change heating system, windows, or insulate the roof or attic. Of the energy performance certificates available for compilation, Mjörnell et al., 2023, found that most second homes belonged to energy class E, F or G, i.e. have a poor energy performance. It is also found that electricity consumption of second homes have decreased in Sweden, from 3.5 TWh in 2012 to 2.83 TWh in 2020. Andersen et al., 2008, showed that the electricity consumption in second homes in Denmark had increased considerably more than in first homes in the period 1990-2007, and that the main reason was the increased number of second homes, their increased use and intensified use of electric appliances. Kofoed et al., 2010, also concludes that the electricity consumption in second homes in Denmark has increased, and that the potential energy saving within this category is considerable. Sundin, 2014, examined how to renovate a summer house in Sweden to make it more energy efficient and hence suitable for use also in winter, but only examines two scenarios representing different thickness of added insulation. Hiltunen, 2007, reviews trends and conduct a survey on environmental impacts of second home tourism in Finland and highlights housing, land use and transportation of occupants as key aspects. According to Hiltunen, 2007, impacts are also expected to grow. No previous study on the operational energy savings and embodied environmental impacts of retrofits trade-off in second homes has been found.

1.4 Aim and research question

The aim of this study is to investigate whether improvements of the energy efficiency of second homes by performing retrofit measures pay off. Because of the intermittent use and overall lower use intensity of second homes, the operational energy saving is presumably lower than for permanent housing. From an environmental point of view, the embodied energy associated with the up-and downstream activities of a retrofit could even be greater than the savings in the operational phase, which would imply an overall higher environmental impact. The research question is: What is the net environmental impact of common retrofit measures in second homes?

2 Methods

To investigate the net environmental impact of retrofitting second homes, the life cycle impact of three different retrofit measures was estimated and compared to the reduced impact associated to the energy savings. Initially, a literature review described in section 1.2 was conducted to gain insights about the field and state-of-the-art methodological choices. Second, information about 3 case houses was collected and then used to model the energy savings for each retrofit scenarios. Third, these energy savings were translated to environmental impact and compared to the embodied impacts of each retrofit measure respectively to attain a net impact. The following chapter describes what retrofit measures that will be investigated (2.1), the LCA performed to attain the net environmental impact of each retrofit scenario (2.2), values changed in the sensitivity analyses (3.4) and the collection of information about case houses (2.3).

2.1 Retrofit measures

Choice of retrofit measures was based on what had actually been performed in the case houses and what was discussed as energy efficient measures in the literature. All measures are recommended in the guide "Husguiden" provided by the Swedish Energy Agency to house-and second home owners who wish to improve their energy efficiency (Swedish Energy Agency, 2022). The number of measures to test was restricted to three to also be able to test for combination and still keep the number of simulations at a reasonable size, and the measures also had to be implementable in BIM Energy. Chosen measures are also reported as the three most common ones performed (Mjörnell et al., 2023). The measures are:

A Change all windows to new ones with an U-value of 1.1.
B Insulate the roof or attic, depending on whether there is a cold or warm attic.
C Install an air-sourced heat pump (ASHP).

2.2 Life cycle assessment

LCA was used to calculate the added environmental impact resulting from the life cycle of that measure. The waste management of the entire process is included, as well as the end-of-life of the added components, whereas the end-of-life of the replaced components is excluded. This choice was done because the replaced components were regarded as belonging to the original house, and in need of waste

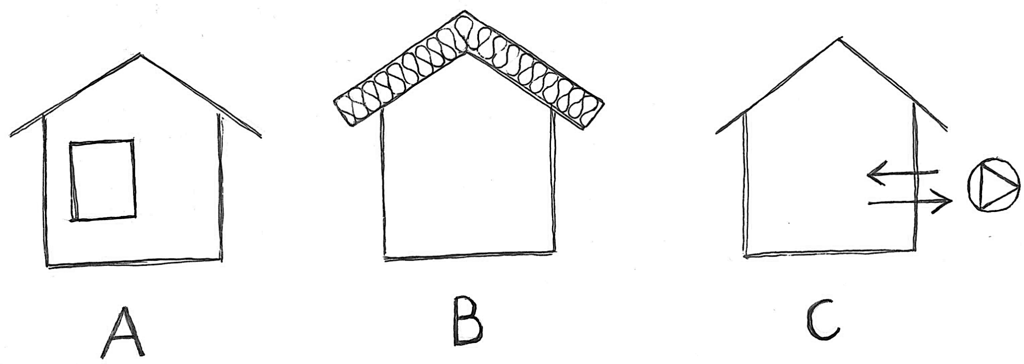


Figure 2.1: Visualisation of the three chosen retrofit measures.

treatment even without the retrofit, whereas the added components represent an added impact resulting from the retrofit.

Included modules are presented in figure 2.2 and aims to cover additional impacts caused by the retrofit, i.e. from the new components. Excluded modules in the use-phase are assumed to remain unchanged by the retrofit measure. The temporal scope considered is 50 years and the functional unit is one heated m^2, both common choices in earlier articles investigating environmental impacts of retrofitting buildings (Vilches et al., 2017; Soust-Verdaguer et al., 2016).

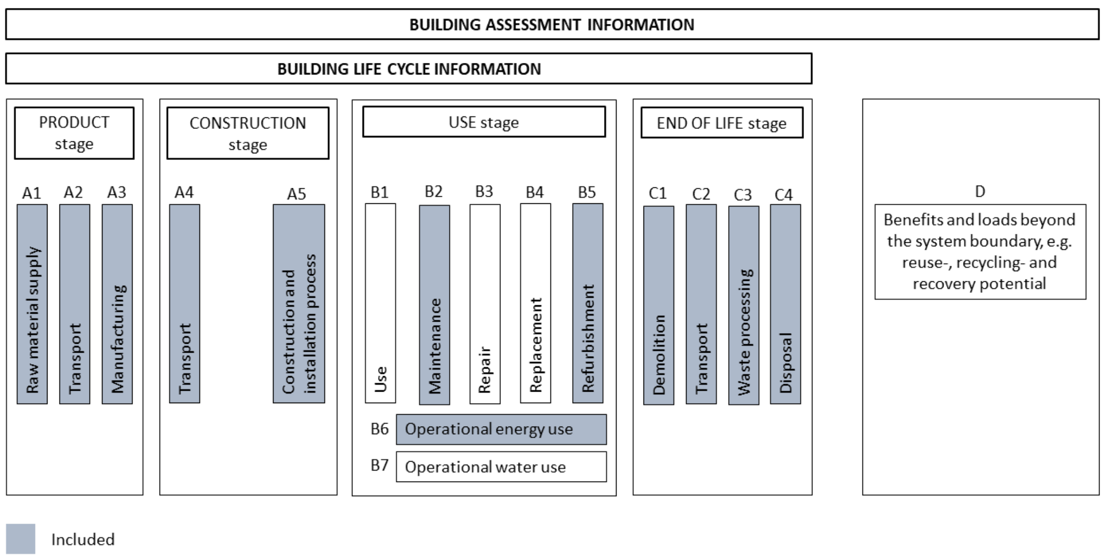


Figure 2.2: Modules included in the LCA.

The geographical boundary was global, however data was collected for products representative for Sweden to as high extent as possible. Data was primarily collected from environmental product declarations (EPDs). If there was no EPD available, or if the EPD did not cover a sufficient scope, the impact was modelled in openLCA version 1.11, a free and open source LCA-modelling software (GreenDelta, 2022). The data in the chosen EPDs is specific for the respective production sites, and the generic data comes from the GaBi database (2021) or Ecoinvent 3.8. Average data is used. EPDs where available for windows and insulation, however not for the heat pump, hence the impact of scenario C was modelled in openLCA. For scenario C (ASHP), data was sourced from scientific literature and background data from Ecoinvent 3.8. All input values for scenario A, B and C are displayed in appendix E, as well as the values used when calculating the renovation actually performed in the case-houses.

The impact category considered is climate change and the indicator is global warming potential over 100 years (GWP100). Including only one category makes the assessment incomplete, but that decision was made to limit the work load. One limitation of this is the risk of causing burden shifting between categories, which is undesirable. Retrofit measures that appear as a good choice might have a big environmental impact for other, unconsidered, categories. The impact for each measure is calculated as shown in equation 2.1.

$$IS_j = \sum_i Q_i \times CF_{i,j} \tag{2.1}$$

where
IS_j = Impact score for category j.
Q_i = Quantity of i.
$CF_{i,j}$ = Characterization factor for i to category j.

The energy consumption of the houses was estimated using the software BIM Energy, a dynamic building energy analysis software (StruSoft AB, 2022). Information provided by house-owners were used to model the houses as accurately as possible and the model was calibrated using the reported electricity consumption of the house. Once calibrated, the model was used to simulate different retrofit options and different indoor temperatures when the house was not used. The indoor temperature when used was set to 22°C, and the indoor temperature when not used was 15°C, 10°C or 5°C. Note that the choice of indoor temperature, both when in use and the three choices for when not in use, and use patterns are not related to how the case houses are actually used. All houses were simulated for a base case (no renovation), a today-case (as actually renovated), and seven other cases (the three retrofit measures A, B and C and combinations of them), see table 2.1. The operational energy use was defined as the energy provided in terms of heat and electricity.

All the cases were also simulated for different use-patterns representing a low, medium and high usage of the house to evaluate how this might impact the results. The use patterns are displayed in figure 2.3. Second homes could be used both more, less, and in other ways than this. However the patterns allows comparison to understand how different use patterns could impact the results. In the

Table 2.1: Schedule for different retrofit and operation scenarios.

Scenario	NR	R	A	B	C	AB	AC	BC	ABC
low 15	-	-	-	-	-	-	-	-	-
low 10	-	-	-	-	-	-	-	-	-
low 5	-	-	-	-	-	-	-	-	-
medium 15	-	-	-	-	-	-	-	-	-
medium 10	-	-	-	-	-	-	-	-	-
medium 5	-	-	-	-	-	-	-	-	-
high 15	-	-	-	-	-	-	-	-	-
high 10	-	-	-	-	-	-	-	-	-
high 5	-	-	-	-	-	-	-	-	-

NR: Not Renovated, R: Renovated, A: Change windows, B: Attic or roof insulation, C: Air-sourced heat pump (ASHP). AB, AC, BC and ABC indicates combinations of measures.

figure 2.3, darker dots indicates one full week of use, whereas lighter dots represent a weekend visit. The circle represents the year. For example, in the case of the medium use, the four dark dots represent that the house is used week 27, 28, 29 and 30.

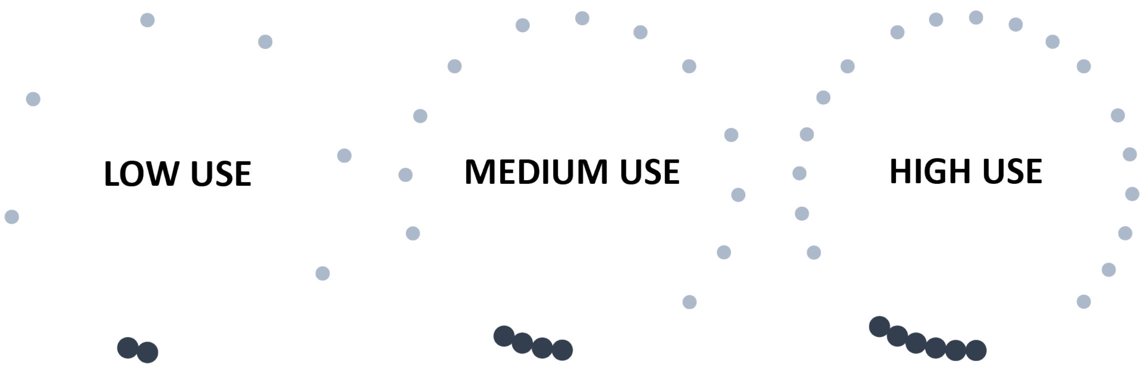


Figure 2.3: Low, medium and high use. Light dot = one weekend, dark dot = one week.

Operational energy savings were translated into global warming potential by multiplication with the carbon intensity of electricity production. Direct electricity was assumed to be the source of energy in all case houses. The carbon intensity of the Swedish electricity mix of 9 gCO_2eq/kWh was used (European Environment Agency, 2022). Other intensities were tested in the sensitivity analysis as well, as this value can differ widely between different places and energy sources. The final net GWP was calculated as the difference between operational savings and the embodied environmental impact as shown in equation 2.2.

$$GWP_{net} = I_s - OS_s \times CI \times RSL \quad (2.2)$$

where
GWP_{net} = net Global Warming Potential [kgCO_2eq]
I_s = Impact of scenario S [kgCO_2eq]
OS_s = Operational Savings of scenario S [kWh/year]
CI = Carbon Intensity of electricity production [kgCO_2eq/kWh]
RSL = Reference Service Life of the measure [years].

2.3 Case houses

Case houses were used as a framework for the investigation, with the aim of simulating the effect of the retrofit measures for different types of houses. Since houses differs widely in style and energy efficiency, and since users probably have different patterns of use, the cases provided some real examples. Information about the houses were requested using a form (see appendix A), and assumptions were made where the information was lacking or not sufficient. The initial aim was to model case houses of different types, located in different geographical regions and used for different purposes (e.g. during different seasons), however this was limited by for which houses information was received.

2.3.1 Kuba

Case house 1 (Kuba, figure 2.4) is located in the southern part of Sweden, in Halland. Kuba consists of two different parts, one older two-storyed part connected to a newer one-storyed part. Renovation has been performed in different stages however the one studied as the retrofit scenario and compared to the base-case here is the changing of windows and doors in the one-storyed part, i.e. in half of the house. The older windows had an assumed U-value of 1.5 W/m^{2}K whereas the new windows have an assumed U-value of 1.04 - 1.12 W/m^{2}K. All input values for the energy calculation performed in BIM Energy, i.e. building parts and materials, can be found in appendix B.

2.3.2 Örnahusen

Case house 2 (Örnahusen, figure 2.5) is located in the south-eastern part of Skåne, Sweden. Originally the house consists of one brick-building with a furnished attic and a non-insulated barn connected to the house. During the retrofit the walls in both parts were insulated, as well as the floor and attic in the barn to make it a liveable part of the house. The retrofit hence resulted in a larger heated floorspace. The walls were insulated from the inside of the house, and were then covered in gypsum, wallpaper and finally paint. An ASHP has also been installed after the other retrofit measures were performed. All input values for the energy calculation performed in BIM Energy, i.e. building parts and materials, can be found in appendix C.

2.3.3 Dovers

Case house 3 (Dovers, figure 2.6) is located on an island on the west coast, in Bohuslän, Sweden. It was originally constructed as a one-floored house in 1880 and have since then gone through several phases of renovation. It is a wooden house, with walls of massive timber. A second floor and extension was added in 1936. The current owners have not performed any specific retrofit, and hence that scenario is left out for this house. There is an ASHP installed in the house today, but to allow for comparison with scenario C this one is removed for the "Not Renovated" case and replaced with direct electricity to create an artificial base case. All input values for the energy calculation performed in BIM Energy, i.e. building parts and materials, can be found in appendix D.

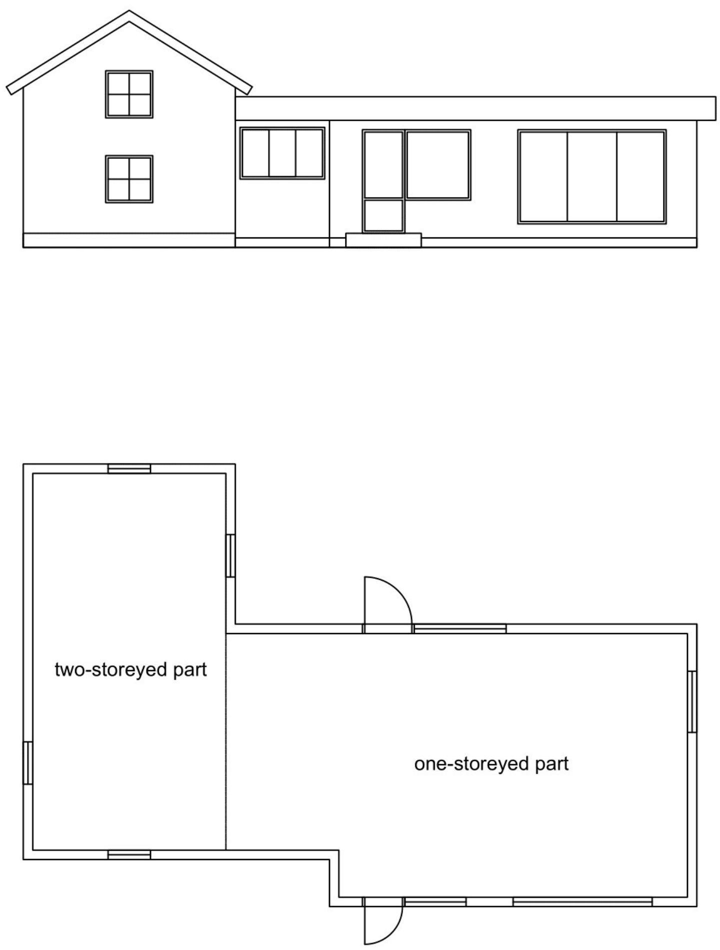


Figure 2.4: Kuba plane and façade.

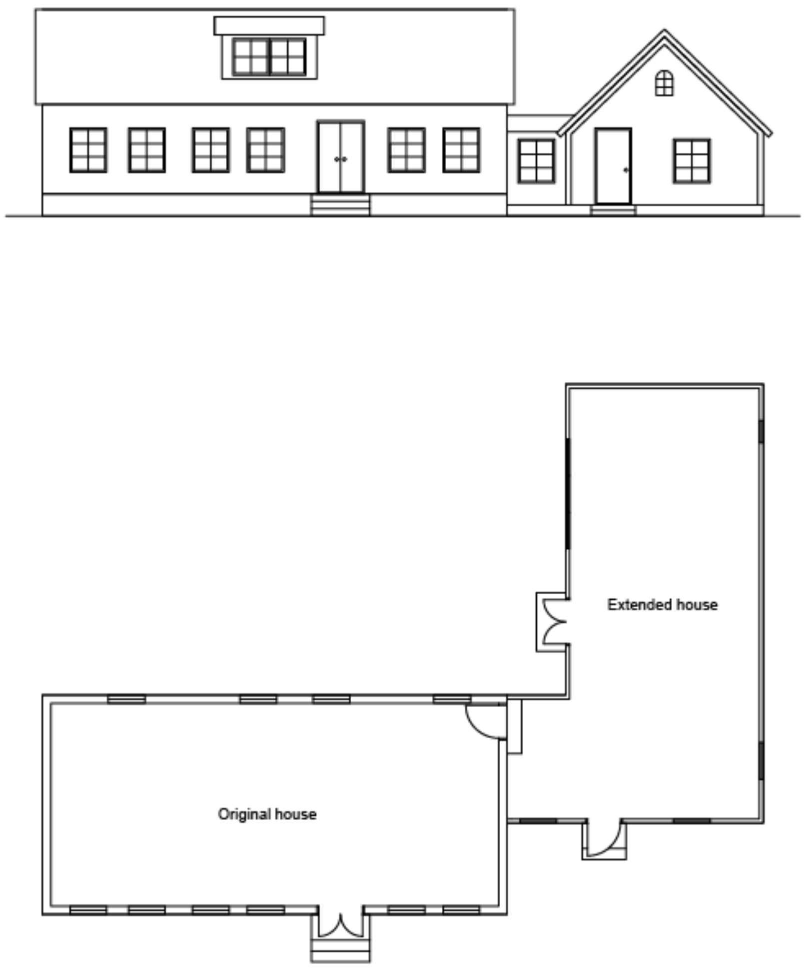


Figure 2.5: Örnahusen plane and façade.

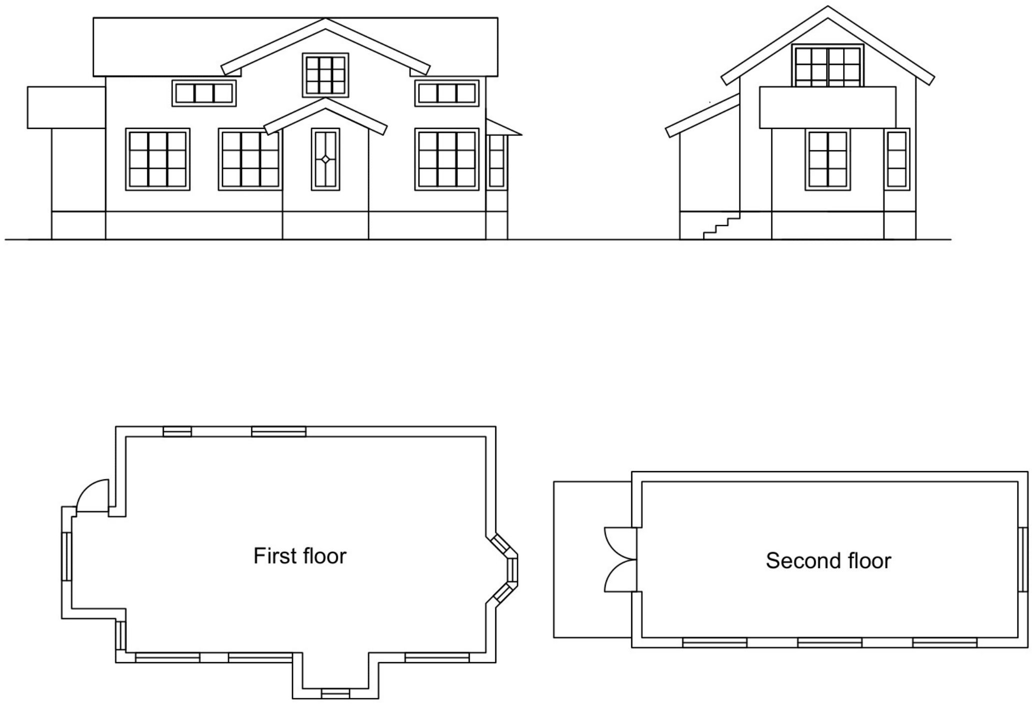


Figure 2.6: Dovers floor planes and façade.

3
Results

This chapter presents the results for each case-house respectively. Energy savings associated with each scenario are shown, followed by the net environmental impact in terms of GWP. The first chart for each house displays how the energy use varies with different use patterns. Since the variation is considered rather small, the energy saving and net GWP is only shown for medium use as it could be hard to see the difference between different use patterns. Energy savings and net GWP for all use patterns can be seen in appendix F. What can be seen in the results is that all measures generates energy savings to different extents, but that it could save more energy to lower the indoor temperature than to perform retrofits.

3.1 Kuba

The first figure (3.1) show the energy consumption for low, medium and high use when Kuba is not renovated. As mentioned in the introduction of this chapter, there is a difference but this difference is considered small, hence the energy savings (figure 3.3) and net GWP (figure 3.4) are shown here for the medium use only. Figure 3.2 shows the GWP of the different scenarios for Kuba, where B (adding insulation) has the lowest impact, and C (installing a heat-pump) the highest of the three A, B and C. In figure 3.3 one can see that changing indoor temperature from 15°C to 10°C when not using the house saves more energy than both scenario R (performed retrofit), A (changing windows), B (insulating the roof) and AB if the indoor temperature is kept at 15°C. Another observation is that if a heat pump is installed, the indoor temperature is of very little importance for the amount of saved energy, which can be seen in scenario C (installing an air-sourced heat pump), AC, BC and ABC. The highest saving comes from installing an ASHP and decrease the indoor temperature from 15°C to 10°C.

When looking at the net GWP, the most favourable options are to only decrease the indoor temperature to 5°C or to do so in combination with with insulating the roof as in scenario B. All scenarios that involve an ASHP has a increased net GWP, with the highest impact from the scenarios that involve both installing an ASHP and changing windows. It is not surprising that lower temperature is a favourable option as this measure has no impact of its own but only contribute to a decreased GWP.

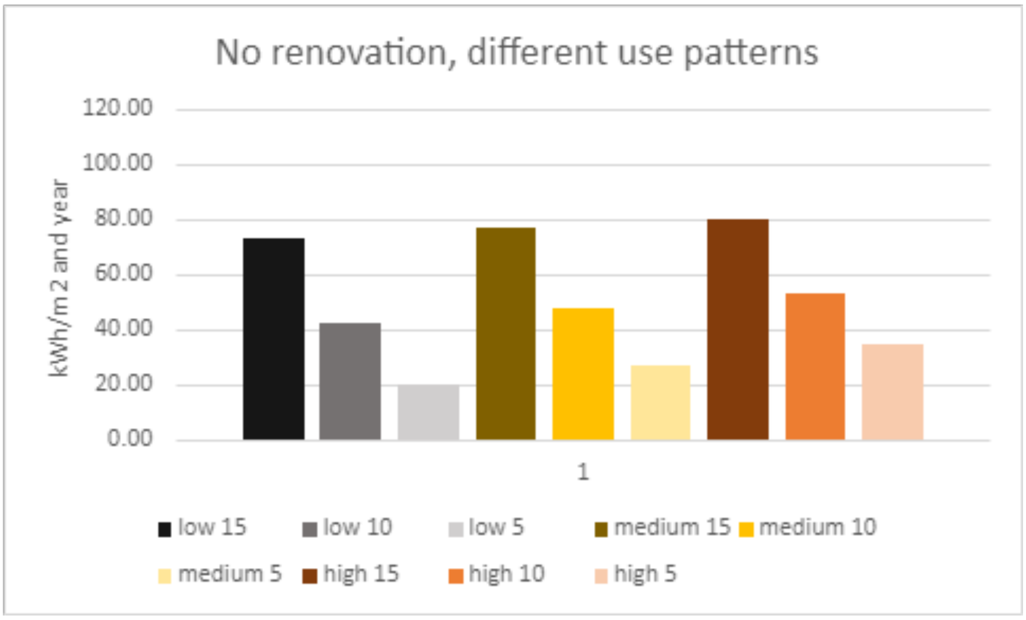


Figure 3.1: Energy use for the different use patterns, Kuba.

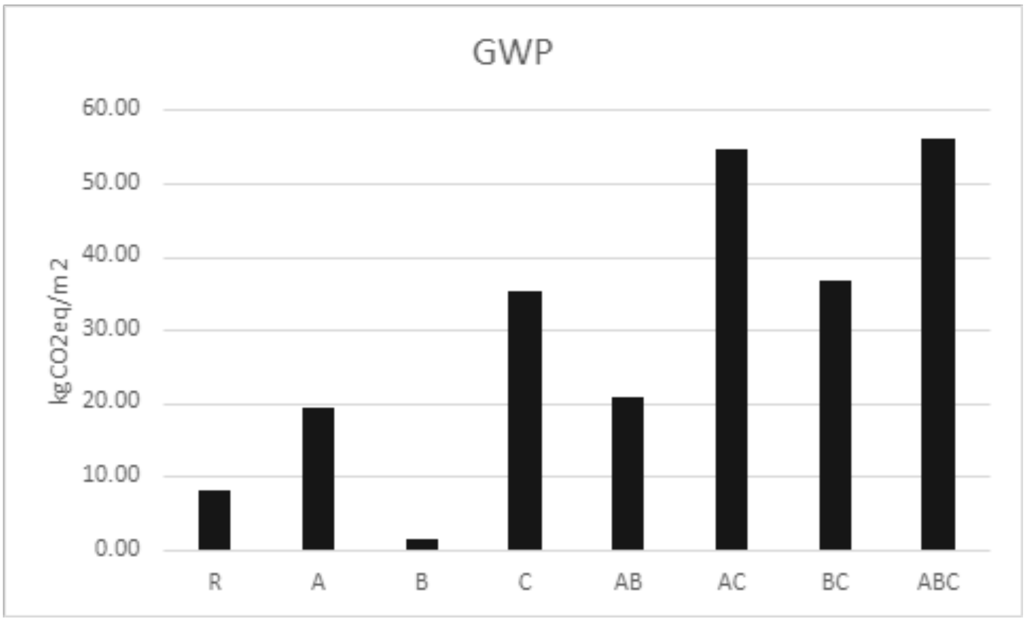


Figure 3.2: Global warming potential of the different scenarios, Kuba. R: Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

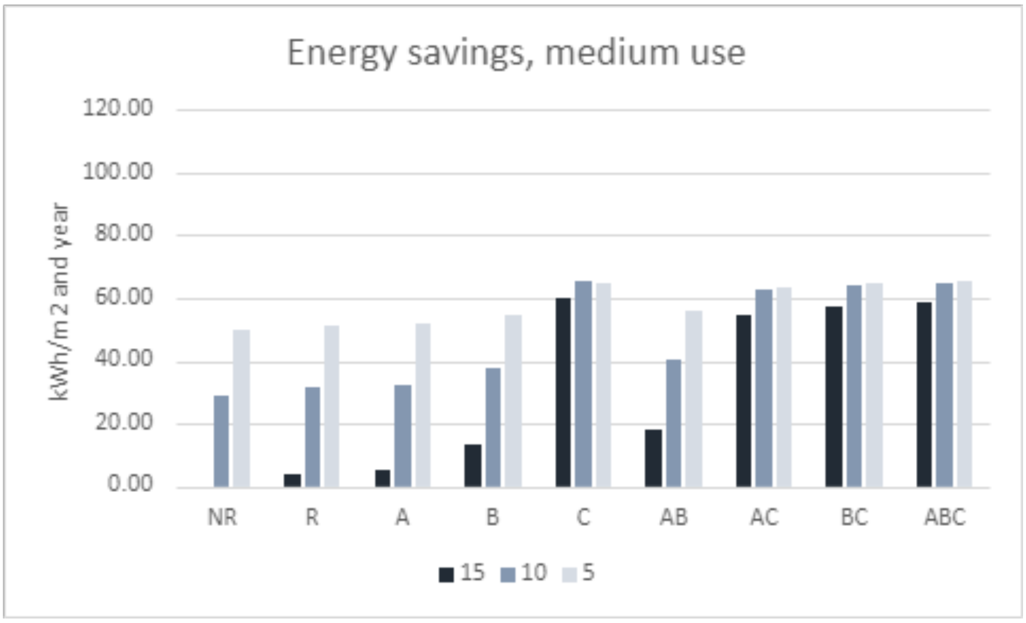


Figure 3.3: Kuba energy savings, medium use, compared to a base case of no renovation and 15°C indoors when not used. NR: Not Renovated, R: Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

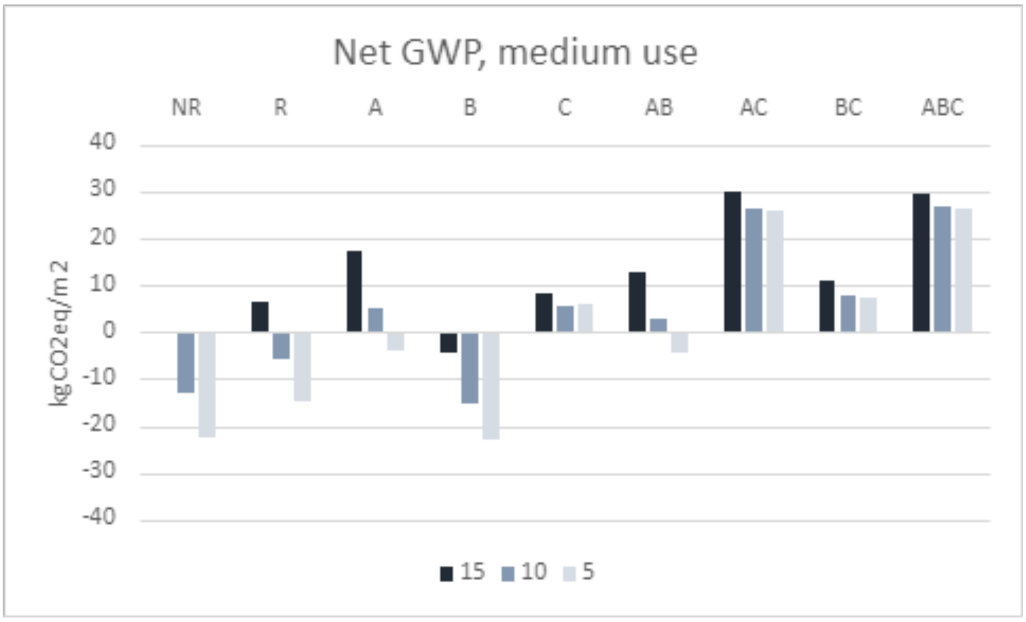


Figure 3.4: Kuba net global warming potential, medium use. NR: Not Renovated, R: Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

3.2 Örnahusen

The first figure (3.5) show the energy consumption for low, medium and high use when Kuba is not renovated. As mentioned in the introduction of this chapter, there is a difference but this difference is considered small, hence the energy savings (figure 3.7) and net GWP (figure 3.8) are shown here for the medium use only. The GWP of the different scenarios follow the same pattern for Örnahusen as for Kuba, i.e. that B (insulation) is lowest, A (windows) second lowest and C (ASHP) is highest considering the three A, B and C cases. For Örnahusen, as well as the other houses, there is a high energy saving in all scenarios involving the installation of an ASHP. The other measures could reach the same levels of savings but only if the indoor temperature is 5°C when the house is not used.

Regarding the net GWP, the highest reduction in GWP comes from decreasing the temperature in all scenarios that does not involve an ASHP, noticeably NR and B, which was also the case for Kuba (see figure 3.4). Örnahusen is different from Kuba and Dovers in that sense that the impact from the ASHP-scenarios (C, AC, BC and ABC) performs better environmentally. This is affected by that the savings are higher for Örnahusen compared to Kuba and that the impact is lower compared to Dovers (see figure 3.10) which itself is caused by the different areas of the houses.

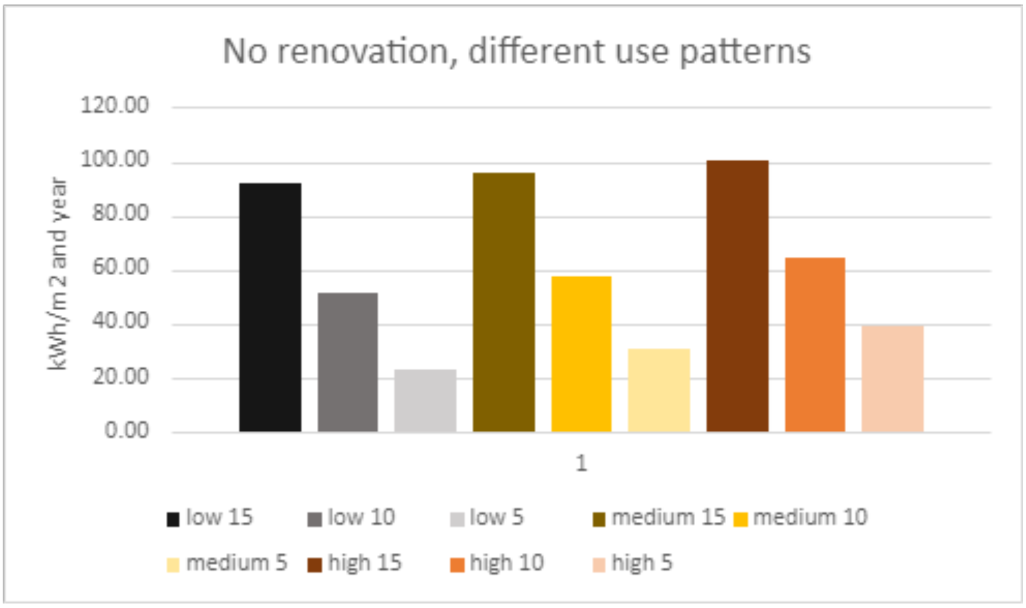


Figure 3.5: Energy use for the different use patterns, Örnahusen.

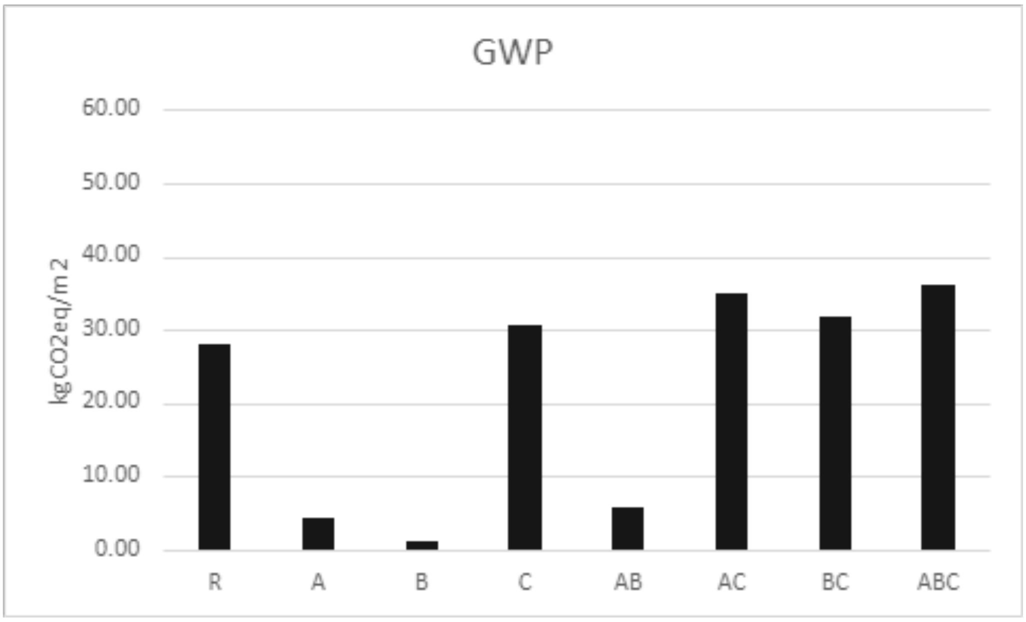


Figure 3.6: Global warming potential of the different scenarios, Örnahusen. R: Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

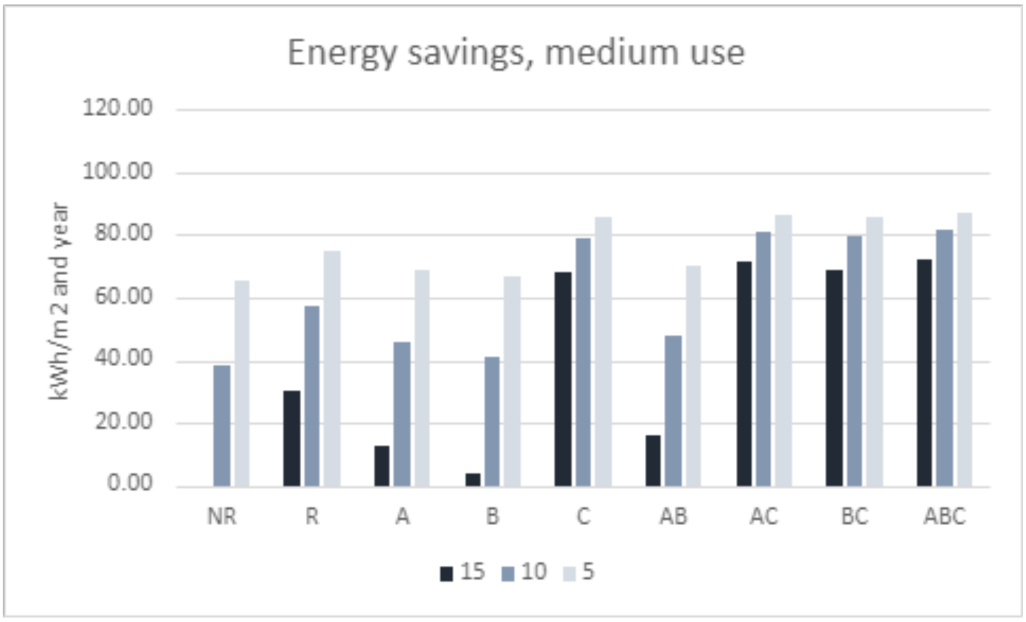


Figure 3.7: Örnahusen energy savings, medium use, compared to a base case of no renovation and 15°C indoors when not used. NR: Not Renovated, R: Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

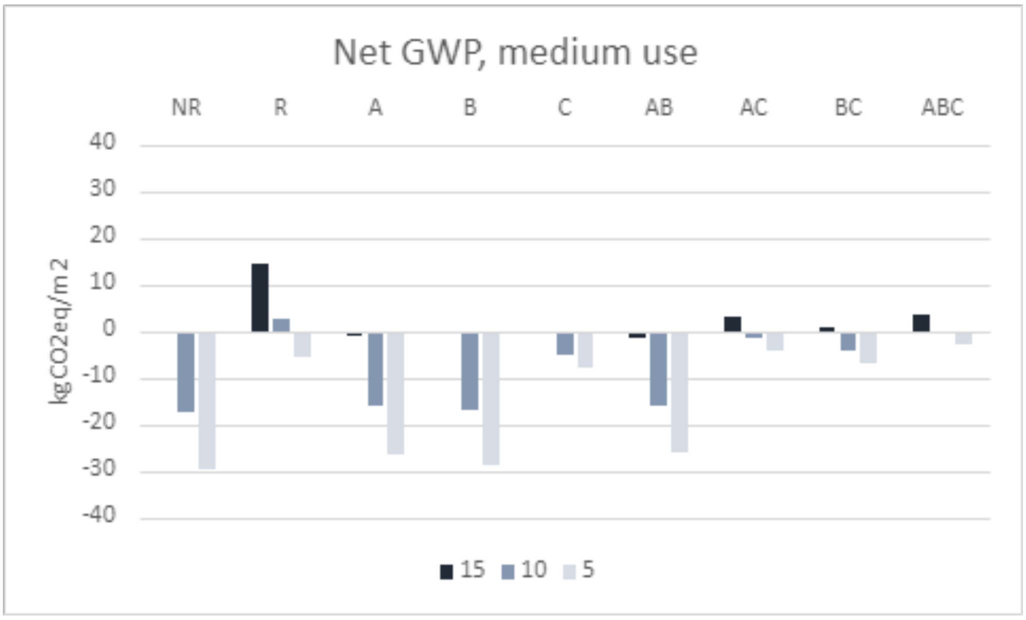


Figure 3.8: Örnahusen net global warming potential, medium use. NR: Not Renovated, R: Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

3.3 Dovers

As for Kuba and Örnahusen, the energy consumption of different use patterns (shown in figure 3.9) vary but to a minor extent, hence further results are shown for medium use only. In figure 3.10 the GWP of the different scenarios are shown, and the pattern is similar to the ones of Kuba and Örnahusen, where installing a heat pump (C) have higher impact than both adding insulation (B) and changing windows (A). The energy savings for Dovers are shown in figure 3.11 and is, as for the other case houses, highest for the scenarios involving an ASHP. Decreasing the indoor temperature by 10°C is comparable to installing an ASHP and keeping the indoor temperature at 15°C. The global warming potential of installing an ASHP is slightly higher than for the other cases, however this comes from that Dovers has a smaller area than Kuba and Örnahusen. The impact of one ASHP is given per unit, and is hence in total the same for all houses, but varies as the results are presented per area.

The net GWP (figure 3.12) also show a similar pattern as for Kuba and Örnahusen, i.e. that the ASHP implies a high GWP that are not compensated by the high energy savings. The best option from an environmental point of view are scenario NR and B combined with decreasing the indoor temperature by 10°C. Kuba and Dover show more similar results than Örnahusen, especially for the ASHP-scenarios.

Note that there is no R (renovated) scenario for Dovers since there was no particular retrofit performed to the house that was studied.

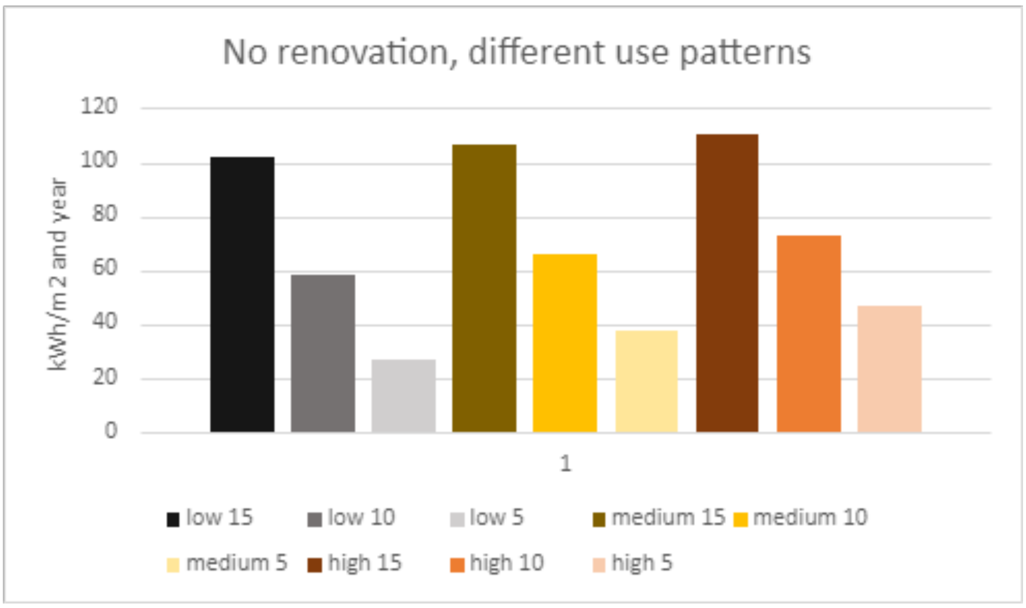


Figure 3.9: Energy use for the different use patterns, Dovers.

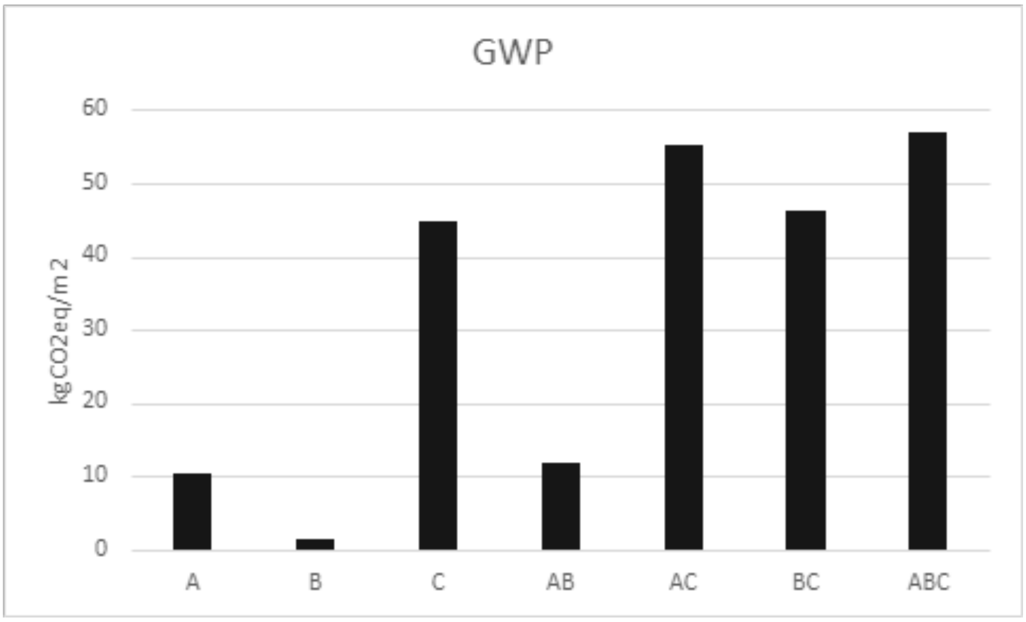


Figure 3.10: Global warming potential of the different scenarios, Dovers. A: Changing windows, B: insulating the roof, C: install an ASHP.

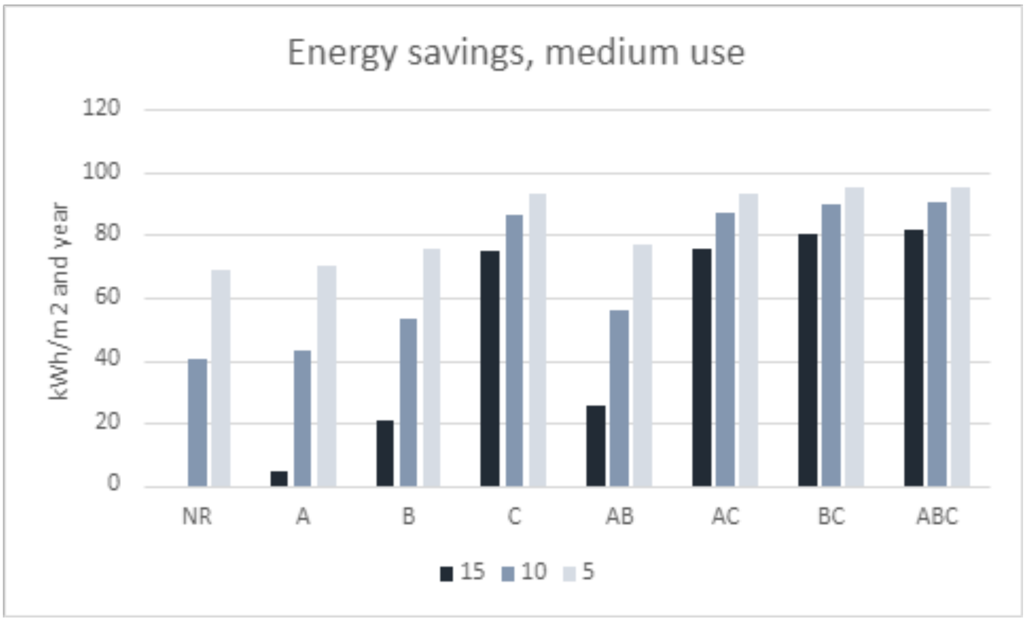


Figure 3.11: Dovers energy savings, medium use, compared to a base case of no renovation and 15°C indoors when not used. NR: Not Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

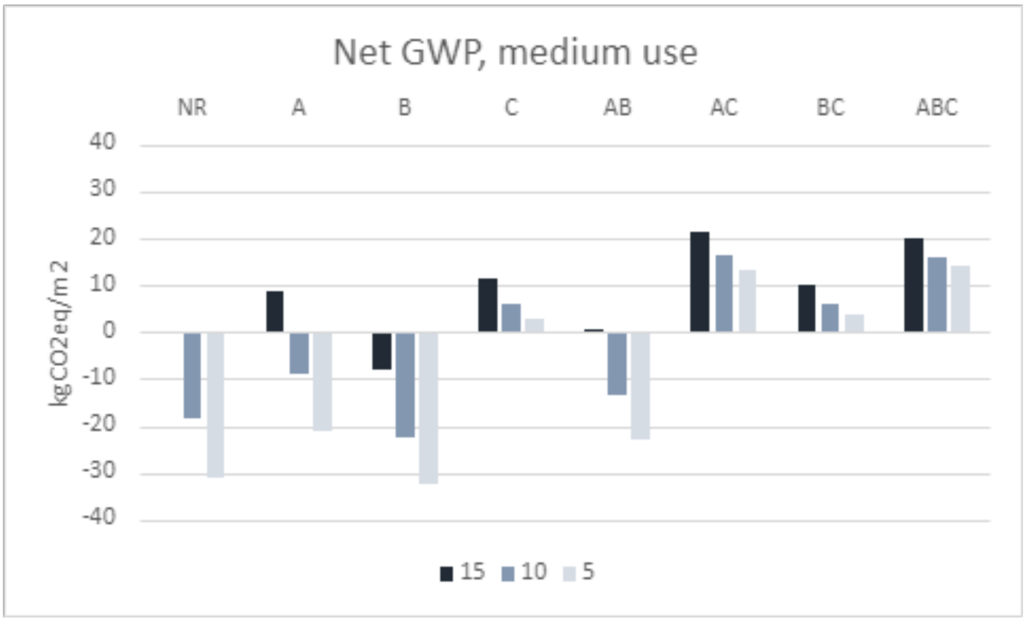


Figure 3.12: Dovers net global warming potential, medium use. NR: Not Renovated, A: Changing windows, B: insulating the roof, C: install an ASHP.

3.4 Sensitivity analyses

To get an idea of how the results might vary with different input values, some of the assumed or chosen values were changed for other potential ones, shown in table 3.1. The first value is the one used in the original scenario, whereas the following ones are alternatives. The results of the alternative input values can be found in appendix G.

Table 3.1: Values changed in sensitivity analysis

Factor	Value	Unit	Source
Carbon intensity	9	gCO_2/kWh	Swedish average (EEA)
Carbon Intensity alt. 1	102		Göteborg energi
Carbon Intensity alt. 2	4.5		Assumed scenario[1]
ASHP	4655	$kgCO_2/unit$	Assumed scenario[2]
ASHP alt. 1	9433		Assumed scenario[3]
ASHP alt. 2	1470		Assumed scenario[4]
Windows	64.68	$kgCO_2eq/m^2$	Elitfönster, 2021
Windows alt.	35.74		Elitfönster, 2022
Insulation	0.66	$kgCO_2eq/kg$	ROCKWOOL Nordics, 2022
Insulation alt.	1.14		Paroc Group, 2020

Comments on table 3.1:

1. If the intensity of the Swedish average was halved in line with reaching net zero.
2. In the original scenario, it is assumed that 80% of the refrigerant is reused.
3. If 50% of the refrigerant is reused. This value is chosen to represent the worse case and is also the default value in the attributional model used in Ecoinvent.
4. If 100% of the refrigerant is reused. This scenario is chosen as the best case.
All values correspond to a RSL of 50 years to be comparable.

4 Discussion

The results show similar patterns for all houses. An initial observation is that there is a difference between the energy consumption of the different use patterns, however this difference is not very big. If use patterns of greater internal variation had been used this would probably have resulted in more visible differences. In all cases, the scenarios involving an ASHP gave the highest energy saving, and also reduced the effect of changing indoor temperature. However, reducing the indoor temperature to 5°C either without any other measures at all or combined with changed windows, added insulation or both, gave similar results as the installation of an ASHP with kept indoor temperature. The GWP for each measure is highest for C (installing an air-sourced heat pump), followed by A (changing windows) and finally B (adding roof insulation). The scenarios involving an ASHP (C, AC, BC and ABC) hence get a high environmental impact that is not compensated by the high savings. The GWP of these scenarios are positive (i.e. produces a net increased GWP) in all cases for both Kuba and Dovers, whereas the GWP could be negative if combined with lower indoor temperatures in Örnahusen. From an environmental point of view, the best option was to simply reduce the indoor temperature, potentially in combination with adding insulation as in scenario B. If indoor temperature should be kept at 15 degrees, the best option for Kuba and Dovers is to add insulation, whereas for Örnahusen the best scenario is to change windows.

When looking at the sensitivity results (see appendix G), it is obvious that the results could show considerable variations given other representative input values. The impact of changing the carbon intensity is very direct, since it is multiplied by the energy savings. The lower the carbon intensity, the less the gain from performing retrofits becomes. Sweden has a relatively low carbon intensity compared to other European countries (European Environment Agency, 2022), and also aim to make it even lower (Naturvårdsverket, 2022), which would imply that the net environmental gain of performing retrofits would become lower. This also makes scenarios with high savings, those involving an ASHP, more sensitive to variations in carbon intensity. The choice of carbon intensities 102 gCO_2/kWh and 4.5 gCO_2/kWh were made to show two relevant alternatives. 102 gCO_2/kWh is the average intensity reported from the Gothenburg municipal energy company Göteborg Energi and 4.5 gCO_2/kWh is half of the current average Swedish intensity, which would be in line with the aims to reach net zero emissions. For the higher intensity, all scenarios resulted in a net GWP reduction, whereas the low intensity gave the result that fewer scenarios pay off.

Next sensitivity consisted of changing how much of the refrigerant that is reused when reaching it's EOL. This was done as the waste management of the refrigerant turned out to have the highest impact on GWP over the life of an ASHP, 68% for the original case where 80% was reused. The refrigerant used, tertafluoroethane (R-134a), is a potent GHG and one important notion is that venting of this refrigerant is prohibited in some countries, e.g. the U.S. and Sweden (Stocker et al., 2013; Wernet et al., 2016), and strictly regulated in the EU. Despite this, venting is still used when applying a global average in Ecoinvent. 50% reuse is chosen as a worst case scenario, as it is the value used in Ecoinvent if an attributional model and a global market is applied. 100% reuse was tested as a best case, and also a case more probable in a Swedish context. In ecoinvent, 90% reuse rate is used when using the consequential model (Naumann et al., 2022), and the decision to use 80% for the original case was to go somewhere in between the better and worse scenarios, but still lean towards the better to be more representative for an European case. In the scenario where 100% of the refrigerant was reused the impact of one ASHP was considerably lower (588 $kgCO_2$ instead of 1862 $kgCO_2$), with the result that the ASHP-scenarios had a negative GWP in almost all cases, except for the AC and ABC scenarios for Kuba. If instead only 50% of the refrigerant was reused, the GWP increased for all ASHP scenarios from being positive in almost all to all scenarios (the exception was C, AC10-5, BC10-5 and ABC10-5 for Örnahusen, see figure G.5a).

The main novelty this study contributes with is that it shows that retrofitting second homes does not always pay off in terms of GWP. This type of trade-off analysis has not, at least not to our knowledge, been performed before on second homes and hence it adds to the existing knowledge of environmental impacts of energy renovations. Earlier research on permanent housing and recommendations from e.g. IPCC, the European Commission and the Swedish Energy Agency all support retrofits as a means to improve the environmental performance of buildings, whereas this thesis diversify the consensus surrounding the topic.

As mentioned in section 1.2.3, comparison of studies is complicated both because of the low number of existing studies on similar topics found, and because of the internal variation of methodological choices. One such variation that prohibit comparison is that studies include different modules, i.e. have different scopes (Vilches et al., 2017). Another factor that would complicate comparison is that, as seen in the sensitivity analysis, results are highly dependent on choices related to input values. Even though the results are similar for the different houses, whether they imply a positive or negative impact could switch simply by the local carbon intensity. Since there are no found earlier studies of environmental trade-offs when retrofitting second homes, there are also no earlier studies with which results can be compared. This means that there is no other study available to which the chosen method for second homes specifically can be compared. However, the only way the houses in this study differ from permanent housing are the use patterns. What can be compared however is what modules that have been included in different studies, choice of functional unit or data sources. Even though the results cannot be directly compared, the internal relationship between investigated scenarios in different studies should be comparable. For example, the results of these studies show that installing an ASHP in general saves a lot of energy, but also implies a high GWP, whereas changing windows or adding insulation have lower GWP but also less effect on energy consumption. Changing windows had a higher impact than adding insulation, given the specific choice of products. Both Nydahl et al., 2019, and Shirazi and Ashuri, 2020, also studied windows and insulation and found (among other findings) that windows in general have a higher environmental impact than insulation. Even though the exact environmental impact is not reported by Arvidsson and Farsäter, 2011, changing windows completely is not recommended as a sustainable option, whereas insulation is. In the case of windows, Arvidsson and Farsäter, 2011, rather recommend renovation of windows.

If comparing to the studies investigated in the review by Vilches et al., 2017, this study includes in general more modules than many other studies, uses the most commonly used FU and RSL and also the most used LCI method. Among the 13 reviewed studies, all studies included A1-3, 9 included A4 and A5 however it varied whether this included construction and installation of only new materials or also the process of deconstructing the old materials. B6 is included in all studies, whereas B1-5 is included to a varying extent in 5 studies. C1-4 is accounted for in 6 cases, and only one study accounts for D. Four studies uses m^2 over 50 years as the FU, and it is the single most common FU. All studies except one use process analysis, the one exception uses hybrid process analysis (Famuyibo et al., 2013). In conclusion, some generalities can be seen between the studies, however comparison is overall deemed difficult and should be done with caution.

The GWP of the different scenarios (A, B and C) considered in this study have been calculated in different ways, which could affect their representativeness. Data for scenario A (changing windows) and B (insulating the roof) is provided through EPDs of products representative for Sweden. Since there was no EPD found for any air-sourced heat pump – which in itself is considered noticeable – and the background data taken from Ecoinvent represented a global average, the GWP of the heat pump becomes representative for a different geographical region. Sweden has a relatively low carbon intensity of the energy production, and also relatively strict environmental rules for e.g. waste management, hence there is a risk that the global average gives a much higher impact than a Swedish heat pump would do. This would then imply that the net GWP of the scenarios that involve an ASHP (C, AC, BC, ABC) could be lower than what is now the result. This problem is one of data availability, and to increase the reliability of the results the data acquisition should be of more similar character.

What is evident from the sensitivity analysis is that the choice of product can affect the results. When choosing which EPD to use in the original case, the choice was made randomly among products representative for a Swedish context. There were many different EPDs available for a variety of building product (however, as discussed, not for heat pumps), and the sensitivity results shown two similar products with other impacts. The impact of the alternative windows is lower, whereas the impact of the alternative insulation is higher. In retrospective, it could have been better to model all scenarios in openLCA with global average data to make the scenarios more comparable, however they would then have made little sense in a Swedish perspective. The choice to model the scenarios with as representative data as possible made the result more applicable in Sweden, yet with the result that the impact of the heat pump might not be very representative.

One major limitation of this study is that it only includes one impact category – GWP – and hence miss other potentially severe impacts. This could result in burden shifting, which means that measures that are good from one perspective get promoted even though they imply unknown or unconsidered other negative effects. Another limitation is that there are only houses in southern Sweden represented, and that the different climate in northern Sweden would give different results. One aspect of this is that houses in other parts of the country probably are constructed in a different way. Regarding representation, it would also have been interesting to look at houses that were used as winter residences, and not mainly during summer.

Related to the choice of houses is that many second homes have a cultural or cultural historic value and are not suitable for any type of retrofits. Changing windows from older traditional windows to energy efficient ones as considered here could harm the aesthetic appearance of the house. There are earlier studies discussing what retrofit measure that could be suitable in historic buildings or buildings with cultural historic value specifically (Vestlund, 2009; Arvidsson and Farsäter, 2011; Serrano et al., 2022; Angrisano et al., 2021), however the measures discussed here were chosen because they are recommended or common rather than necessarily suitable for any type of house.

This study has considered only the environmental impact and there has not been any economic assessment nor study of the effect of the measure on risk related to indoor humidity due to lower temperatures. Neither has any social impacts been investigated. Presumably, lower overall costs are an important factor when private house owners choose renovation measure. Retrofits are promoted as a way to reduce the energy costs faced by house-owners, not only to reduce the environmental impact of the residential sector. In future studies, it would be interesting to also look at the economic performance of different measures, and potentially also investigate which measures that gives the highest environmental saving at the lowest possible cost or find an optimum considering both factors. As found by Moschetti and Brattebø, 2017, environmental and economic factors showed an almost linear negative relationship where higher investments implied better environmental performance. However, the environmental impacts varied to a higher extent, i.e., a small increase in costs implied a relatively larger reduced environmental impact. Regarding moisture, no assessment was made on how the lower indoor temperature affected the risk for e.g., mold or other moisture related damages. To assure that houses does not get damaged by lower temperatures, these risks should be studied before giving any recommendations.

A final limitation is that heat pumps are not necessarily able to be used if the indoor temperature is too low, as there has to be a sufficient indoor temperature to allow for defrosting of the outer part. In these cases the necessary energy to keep the temperature in these cases will not be supplied by the heat pump but by the original type of energy, which in all these cases have been direct electricity. The heat pump used in the simulation is a default heat pump provided by the software, and not a specific brand or type, and hence it is unknown how this problem is handled by the program. Heat pumps of different brands can operate for different indoor temperatures, and there are certain ones designed to provide "maintenance" heat for e.g. second homes or garages between 5 and 13 degrees (Polarpumpen, n.d.).

As a continuation, it would be interesting to examine a greater variety of house-types and with better geographical coverage. A broader selection of different products should be tested to gain insight about how much the product's impacts vary, and the same method for data gathering should be used. A recommendation would be to produce EPDs for heat pumps to facilitate future studies of this kind. To avoid burden shifting, a full set of impact categories should be included. Finally, it would be interesting and necessary to assess the economic factors and potential problems related to changed relative humidity.

5 Conclusion

The main conclusion of this work is that it does not necessarily pay off to retrofit second homes in terms of environmental impact. If it doesn't imply any moisture related damage to the building, which is necessary to investigate, it could rather be a good option to simply apply a lower indoor temperature when not using the house. This would also be an economic gain if energy prices does not change or increase. If lower temperature would damage the building, this could imply a potentially higher environmental impact from reparations or rebuilding or damaged parts. From an environmental point of view, the best option found in this study was reduced indoor temperature, potentially in combination with adding insulation as in scenario B. An additional conclusion is related to the method, and the prevailing inconsistency among performed studies. Comparison is already complicated due to the high level of varying factors and assumptions (such as type of house, geographical location, choice of studied products), but if some methodological choices (e.g. scope, or covered modules, functional unit, reference service life) were more consistent this would make it easier to compare different options. One main limitations of this study is that the data to calculate the environmental impact was collected from different sources, hence their relevance for a Swedish context is different. The result would be more trustworthy if EPDs for heat pumps would have been available and used. A second major limitation is related to what is mentioned above, i.e. that it is not investigated how the measures and lower indoor temperatures affect the house's climate and whether it poses any risks. Two final limitations is that only one impact category is included, GWP, which might cause burden shifting, and that no economic assessment has been performed as economic performance normally is an important factor when choosing what measures to perform.

References

Andersen, F. M., Christensen, M. S., Jensen, O. M., Kofoed, N. U., & Morthorst, P. E. (2008). Second-home electricity consumption. *Energy Policy*, *36*(1), 280–289. https://doi.org/10.1016/j.enpol.2007.09.013

Angrisano, M., Fabbrocino, F., Iodice, P., & Girard, L. F. (2021). The evaluation of historic building energy retrofit projects through the life cycle assessment. *Applied Sciences (Switzerland)*, *11*(15). https://doi.org/10.3390/app11157145

Arvidsson, E., & Farsäter, K. (2011). miljöanpassning av befintlig bebyggelse.

Back, A., & Marjavaara, R. (2017). Mapping an invisible population: the uneven geography of second-home tourism. *Tourism Geographies*, *19*(4), 595–611. https://doi.org/10.1080/14616688.2017.1331260

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA*. Studentlitteratur.

Beccali, M., Cellura, M., Fontana, M., Longo, S., & Mistretta, M. (2013). Energy retrofit of a single-family house: Life cycle net energy saving and environmental benefits. https://doi.org/10.1016/j.rser.2013.05.040

Boverket. (2021). Klimatdeklaration av byggnader. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/klimatdeklaration/

Boverket. (2022). Ska din byggnad ha en energideklaration? https://www.boverket.se/sv/energideklaration/energideklaration/

Boverket. (2023). Boverkets Klimatdatabas Plastfolie, ångspärr.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. https://doi.org/10.1016/j.rser.2013.08.037

Ekström, T., & Blomsterberg, Å. (2016). Renovation of Swedish Single-family Houses to Passive House Standard - Analyses of Energy Savings Potential. *Energy Procedia*, *96*, 134–145. https://doi.org/10.1016/j.egypro.2016.09.115

Elitfönster. (2021). *Environmental Product Declaration AFK* (tech. rep.). https://api.environdec.com/api/v1/EPDLibrary/Files/f16646b3-c906-4548-1517-08da85915ae2/Data

Elitfönster. (2022). *Environmental Product Declaration - EFS* (tech. rep.). https://api.environdec.com/api/v1/EPDLibrary/Files/21cf8515-58ca-4164-1b7e-08da2ccce1bd/Data

Energiföretagen. (2022). Energiföretagen förklarar: Därför ser vi nu högre elpriser. https://www.energiforetagen.se/pressrum/nyheter/2022/juli/energiforetagen-forklarar-darfor-ser-vi-hogre-elpriser/

Energimyndigheten. (2012). *Energistatistik i Fritidshus - Energy statistics for dwellings with no registered permanent resident (holiday homes) 2011* (tech. rep.). www.energimyndigheten.se

European Commission. (2018). *DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance)* (tech. rep.). European Commission. Brussels.

European Commission. (2019). Communication from the Commission to the European Parliament, the European Council, the council, the European economic and social committee and the committee of the regions on The European Green Deal.

European Environment Agency. (2022). Greenhouse gas emission intensity of electricity generation in Europe. https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1

Famuyibo, A. A., Duffy, A., & Strachan, P. (2013). Achieving a holistic view of the life cycle performance of existing dwellings. *Building and Environment*, *70*, 90–101. https://doi.org/10.1016/j.buildenv.2013.08.016

GreenDelta. (2022). openLCA. https://www.openlca.org

Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., & Bilec, M. M. (2019). Comparative whole-building life cycle assessment of renovation and new construction. *Building and Environment*, *161*. https://doi.org/10.1016/j.buildenv.2019.106218

Hiltunen, M. J. (2007). Environmental Impacts of Rural Second Home Tourism – Case Lake District in Finland. *Scandinavian Journal of Hospitality and Tourism*, *7*(3), 243–265. https://doi.org/10.1080/15022250701312335

Karolinska Institutet. (2022). Structured literature reviews – A guide for students. https://kib.ki.se/en/search-evaluate/systematic-reviews/structured-literature-reviews-guide-students

Kofoed, N., Road Rasmussen, E., Weldingh, P., Worm, J., Adams Rasmussen, L., Reuss, M., Ellehauge, K., Kjaergaard, C., & Jensen, O. (2010). *Skabelon til udgivelser fra SBi* (tech. rep.).

Mjörnell, K., Johansson, D., Femenias, P., Eriksson, P., Donarelli, A., & Johansson, T. (2023). Energy use patterns in Swedish second homes [Unpublished manuscript].

Moschetti, R., & Brattebø, H. (2017). Combining life cycle environmental and economic assessments in building energy renovation projects. *Energies*, *10*(11). https://doi.org/10.3390/en10111851

Naturvårdsverket. (2022). Sveriges Miljömål. https://www.sverigesmiljomal.se/etappmalen/utslapp-av-vaxthusgaser-till-ar-2045/

Naumann, G., Schropp, E., & Gaderer, M. (2022). Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach. *Procedia CIRP*, *105*, 351–356. https://doi.org/10.1016/j.procir.2022.02.058

NIBE ENERGY SYSTEMS. (2018). NIBE Heat pumps. https://www.nibe.eu/download/18.57b7da7016794bba1a0119/1545039269498/KBR%20UK%20Heat%20pumps%20M12272-3XB.pdf

Nydahl, H., Andersson, S., Åstrand, A. P., & Olofsson, T. (2019). Environmental performance measures to assess building refurbishment from a life cycle perspective. https://doi.org/10.3390/en12020299

Obrecht, T. P., Röck, M., Hoxha, E., & Passer, A. (2020). BIM and LCA integration: A systematic literature review. https://doi.org/10.3390/su12145534

Österbring, M., Mata, É., Thuvander, L., & Wallbaum, H. (2019). Explorative life-cycle assessment of renovating existing urban housing-stocks. *Building and Environment*, *165*. https://doi.org/10.1016/j.buildenv.2019.106391

Paroc Group. (2020). *Environmental Product Declaration PAROC Stone Wool Thermal Insulation (eXtra)* (tech. rep.).

Pathak, M., Slade, R., Shukla, P., Skea, J., Pichs-Madruga, R., & Ürge-Vorsatz, D. (2022). *Technical Summary* (tech. rep.). IPCC. Cambridge, UK, New York, NY, USA. https://doi.org/10.1017/9781009157926.002

Polarpumpen. (n.d.). Underhållsvärme med luft-luftvärmepump. https://www.polarpumpen.se/kunskapsbanken/varmepump-kunskapsbank/luftvarmepump-kunskapsbank/valja-luftvarmepump/funktioner/underhallsvarme-med-luft-luftvarmepump/

Pörtner, H.-O., Roberts, D., Poloczanska, E., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., & Okem, A. (2022). *Summary for Policymakers* (tech. rep.). IPCC. Cambrige, UK, New York, USA. https://doi.org/10.1017/9781009325844.001

Prieto, C. (2021). Environmental Product Declaration Tikkurila Group.

Rabani, M., Madessa, H. B., Ljungström, M., Aamodt, L., Løvvold, S., & Nord, N. (2021). Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building. *Building and Environment*, *204*. https://doi.org/10.1016/j.buildenv.2021.108159

Ramírez-Villegas, R., Eriksson, O., & Olofsson, T. (2019). Life cycle assessment of building renovation measures–trade-off between building materials and energy. *Energies*, *12*(3). https://doi.org/10.3390/en12030344

ROCKWOOL Nordics. (2022). *Environmental Product Declaration General Building Insulation products for the Swedish market* (tech. rep.).

Saint-Gobain Sweden AB, G. (2020). Environmental product Declaration Gyproc Normal Standard Plasterboard.

Seleborg, M. (2019). *Analys av klimatpåverkan av byggnader i svenska LCA-studier Kartläggning av utsläppskällor och kunskapsluckor* (tech. rep.).

Serrano, T., Kampmann, T., & Ryberg, M. W. (2022). Comparative Life-Cycle Assessment of restoration and renovation of a traditional Danish farmer house. *Building and Environment*, *219*. https://doi.org/10.1016/j.buildenv.2022.109174

Shirazi, A., & Ashuri, B. (2020). Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta. *Building and Environment*, *171*. https://doi.org/10.1016/j.buildenv.2020.106644

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2016). Simplification in life cycle assessment of single-family houses: A review of recent developments. https://doi.org/10.1016/j.buildenv.2016.04.014

Statistics Sweden. (2022). Antal svensk- och utlandsägda fritidshus efter land och år. https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BO__BO0104__BO0104H/BO0104T11/table/tableViewLayout1/

Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., Nauels, A., Via, Y., Bex, V., & Midgley, P. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group l to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (tech. rep.). Cambridge, UK, New York, USA.

StruSoft AB. (2022). BIM Energy. https://bimenergy.com/sv/

Sundin, H. (2014). *Förändring av klimatskal* (tech. rep.).

Svenskt Trä. (2021). Environmental product Declaration Swedish sawn dried timber of spruce or pine.

Swedish Energy Agency. (2022). Husguiden – för dig som vill energieffektivisera ditt hus. https://www.energimyndigheten.se/energieffektivisering/husguiden---for-dig-som-vill-energieffektivisera-ditt/

Swedish Standards Institute. (2011). *Svensk Standard SS-EN 15968:2011* (tech. rep.). www.sis.se

Van de Moortel, E., Allacker, K., De Troyer, F., Schoofs, E., & Stijnen, L. (2022). Dynamic Versus Static Life Cycle Assessment of Energy Renovation for Residential Buildings. *Sustainability (Switzerland)*, *14*(11). https://doi.org/10.3390/su14116838

Verband der Deutschen Tapetenindustrie e.V. (2017). Environmental Product Declaration Paper wallpaper.

Vestlund, J. (2009). *Energieffektivisering i byggnadsminnen* (Doctoral dissertation). Högskolan på Gotland. Visby. http://eprints.sparaochbevara.se/578/1/Vestlund%2C_Jenny.pdf

Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. https://doi.org/10.1016/j.enbuild.2016.11.042

Wernet, G., Bauer, C., Steubing, B., & Reinhard, J. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. http://link.springer.com/10.1007/s11367-016-1087-8%3E

A

Requested information about case-houses

The form is originally in Swedish.

Geografi, arkitektur och allmänt
(Geography, architecture and general information)

- Byggnadens geografiska läge.
  (Geographic location).
- Ritningar på byggnaden, helst med mått utsatta.
  (Blueprints).
- Finns det bilder på huset som du/ni vill dela? Det hjälper mig få en förståelse för hur huset ser ut.
  (Do you have pictures of the that you would like to share? It helps me to get a better idea of the characteristics of the house).

Byggnadsteknisk information
(Technical information)

Uppbyggnad (vilka material som ingår) och om möjligt även U-värde för:
(What materials composing and if possible also U-value for:)

- Golv/grund (Floor/Foundation)
- Väggar (Walls)
- Bjälklag (Joist)
- Tak (Roof)
- Fönster/Dörrar (Windows/Doors)

Energiförbrukning
(Energy consumption)

- Hur värms huset upp?
  (How is the house heated?)
- Hur mycket energi förbrukas över ett åt, med fördel dokumenterat per månad?
  (How much energy is used in a year, preferably documented per month?)
- Hur ventileras huset?
  (What type of ventilation is there?)

Exempel på olika sätt att värma huset är direktverkande el, ved, värmepump eller fjärrvärme.

Exempel på olika ventilationssystem: Självdrag, Frånluftsventilation, Från- och tilluftsventilation, med-eller utan värmeåtervinning.
(Examples of different types of heating systems are direct electricity, wood, heat pump or district heating.)
Examples of different ventilation systems: natural ventilation, exhaust air ventilation, supply-and exhaust air ventilation with our without recycling of heat.)

Solpaneler
(Solar panels)

- Finns det solpaneler installerade? (Om nej kan 2-4 hoppas över).
  (Are there any solar panels? (If no: skip question 2-4))
- Hur mycket el produceras av dem?
  (How much electricity do they produce?)
- Produceras all el för eget bruk eller exporteras el även till nätet?
  (Is all electricity produced for private use or is electricity also sold/exported to the grid?)
- Finns batterier installerade för att lagra el för senare användning?
  (Have you installed any batteries to store electricity for later use?)

Användning
(Use)

- Hur mycket används huset under vår, sommar, höst och vinter?
  (How much is the house used during spring, summer, autumn and winter respectively?)
- Vilken innetemperatur hålls när huset används?
  (What indoor temperature is kept when the house is used?)
- Vilken innetemperatur hålls när huset inte används?
  (What indoor temperature is there when the house is not used?)
- Finns dokumentation på hur mycket varmvatten som förbrukas?
  (Is there any documentation of consumption of hot water?)

Renovering
(Renovation)

- Vad ändrades vid renovering?
  (What renovation has been performed?)
- Om en byggnadsdel ändrades: finns information om byggnadsdelens utformning före renovering?
  (If a building element has been changed: is there information about how it looked before?)
- Om system för värme eller ventilation ändrades: finns information om vad som användes före renoveringen?
  (If heating-or ventilation systems has been changed: is there any information about what was used before?)

- Har användningen av huset förändrats i och med renoveringen?
  (Has the use of the house changed as a result of the renovation?)

B
Information about Kuba

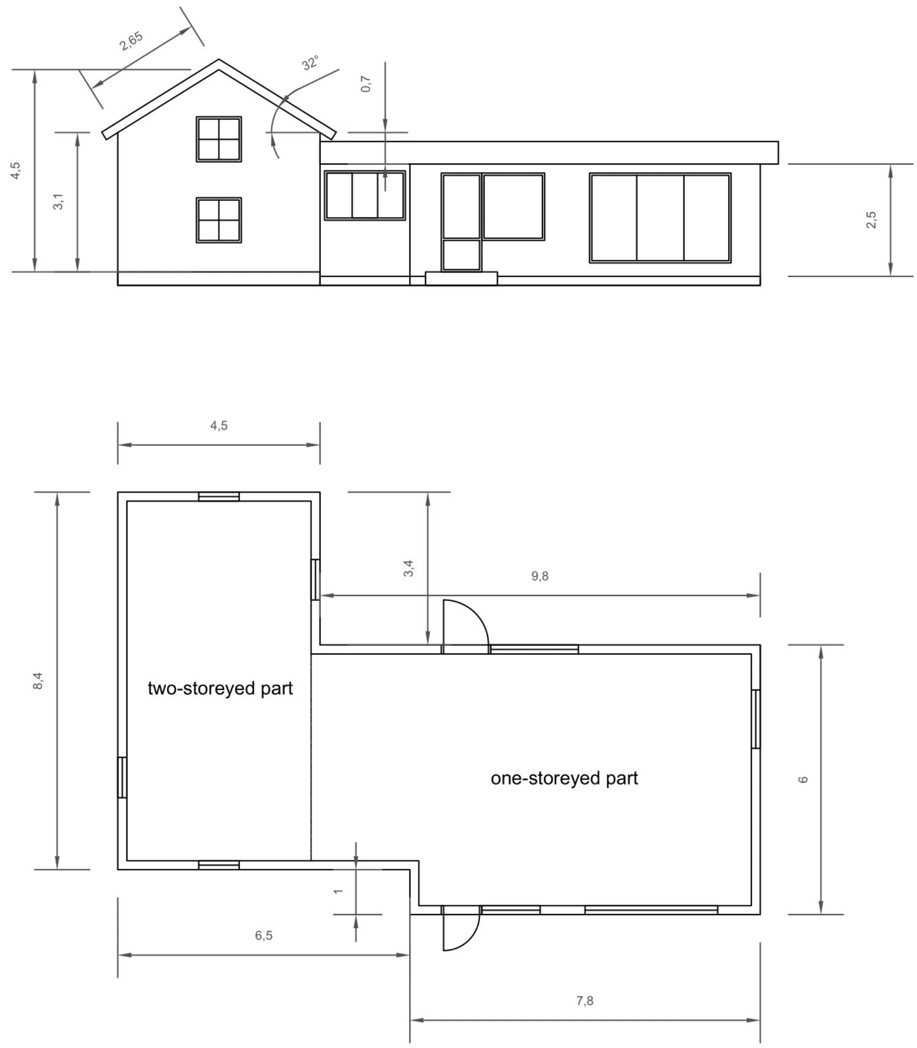


Figure B.1: Kuba plane and façade with dimensions.

Location for sourced climate: Båstad 1991-2020
Total heated floor area: 132.40 m^2
Total wall area: 104.59 m^2
Total window area: 20.75 m^2
Ventilation: natural

Table B.1: Information about building elements used in simulations, Kuba.

Part	**Materials (ext-int)**	**d [m]**	**U-Value [W/m^{2}K]**
Floor[1]	Macadam	0.15*	0.31
	Mineral wool 36	0.1	
	Concrete	0.1	
	Timber	0.022	
Joists*	Timber	0.028	0.46
	Mineral wool 36	0.07	
	Timber	0.028	
Roof 1[2]	Exterior roof	0.02*	0.24
	Timber	0.019	
	Beams cc600 and mineral wool 36	0.15	
	Timber	0.019	
	Gypsum	0.013	
Roof 2	Exterior roof	0.02*	0.71
	Timber	0.017*	
	Mineral wool 36	0.0254	
	Timber	0.022*	
Wall 1	Timber	0.022*	0.33
	Asfaboard	0.025*	
	Beams cc600 and mineral wool 36	0.095	
	Timber	0.017	
	Gypsum	0.013	
Wall 2	Timber	0.202	0.39
	Mineral wool 36	0.0254	
	Tretex	0.013	
Windows BR			1.5
Windows AR			1.04
Doors			1

Comments on table B.1: *1. In the actual case, the two parts of the house have different foundations, however the software only allows for one. Therefore the entire house is modelled with the foundation of the one-storied part, a concrete slab. In the real case, the other part of the house has a crawl-space. This assumption might make the transmission slightly higher than what is actually the case. The flooring in the model is of wood, whereas in the real case it is plastic. There was no plastic flooring available in the software, and no reliable values of plastic flooring's thermal resistance could be found.*
2. In the description of the roof, it is said that there is maybe an extra sheet of mineral wool, however this is excluded because of the uncertainty.
* *Assumed value.*
BR: Before Renovation.
AR: After Renovation.
1 and 2 represent one-storied and two-storied part.

C
Information about Örnahusen

Figure C.1: Örnahusen plane and façade with dimensions.

Location for sourced climate: Simrishamn 1991-2020
Total heated floor area with extended part: 222.80 m^2
Total heated floor area without extended part: 152.40 m^2
Total wall area with extended part: 148.30 m^2
Total wall area without extended part: 96.54 m^2
Total window with extended part area: 25.18 m^2
Total window without extended part area: 15.2 m^2
Ventilation: natural

Note: Since the renovation of case-house 2 resulted in a changed floor area, i.e. part

2 was turned into a liveable space, there is no "Wall 2 BR", as that part never was used in any simulations. Also note even though the house was rebuilt to consist of the two bodies, all scenarios are performed on the original body only, without the extension.

Table C.1: Information about building elements used in simulations, Örnahusen.

Part	**Materials (ext-int)**	**d [m]**	**U-Value [W/m²K]**
Floor[1]	Gravel Concrete Timber beams Wood flooring	0.1 0.1 0.12 0.022	0.31
Joists*	Timber Mineral wool 36 Timber	0.028 0.07 0.028	0.46
Wall 1 BR	Brick Tretex	0.25 0.02*	1.03
Wall 1 AR[2]	Brick Mineral wool 36 Beams cc600 and mineral wool 36 Gypsum	0.25 0.05 0.1 0.013	0.23
Wall 2 AR[2]	Brick Mineral wool 36 Beams cc600 and mineral wool 36 Gypsum	0.12 0.05 0.1 0.013	0.24
Roof 1	Exterior roof Asfaboard Chipboard Mineral wool 36 Gypsum	0.02* 0.025* 0.02* 0.1 0.013*	0.26
Roof 2[3]	Exterior roof Timber Mineral wool 36 Timber	0.02 0.02 0.2 0.02	0.16
Windows			3
Doors			1.5

Comments on table C.1: *1. This house consists of two bodies with different foundations. The main part of the house, 1, has a crawlspace. To make the modelling easier, this was approximated as a concrete foundation which will make the transmission loss higher than what is actually the case.*
2. In both these cases there was also wallpaper and paint on the walls however these were deemed negligible.
3. In reality this roof consist of a cold attic insulated downwards, which is modeled as if the roof was the floor of the attic. Hence the exterior rood comes directly after the attic insulation.
* *Assumed value.*
BR: Before Renovation.
AR: After Renovation.

D
Information about Dovers

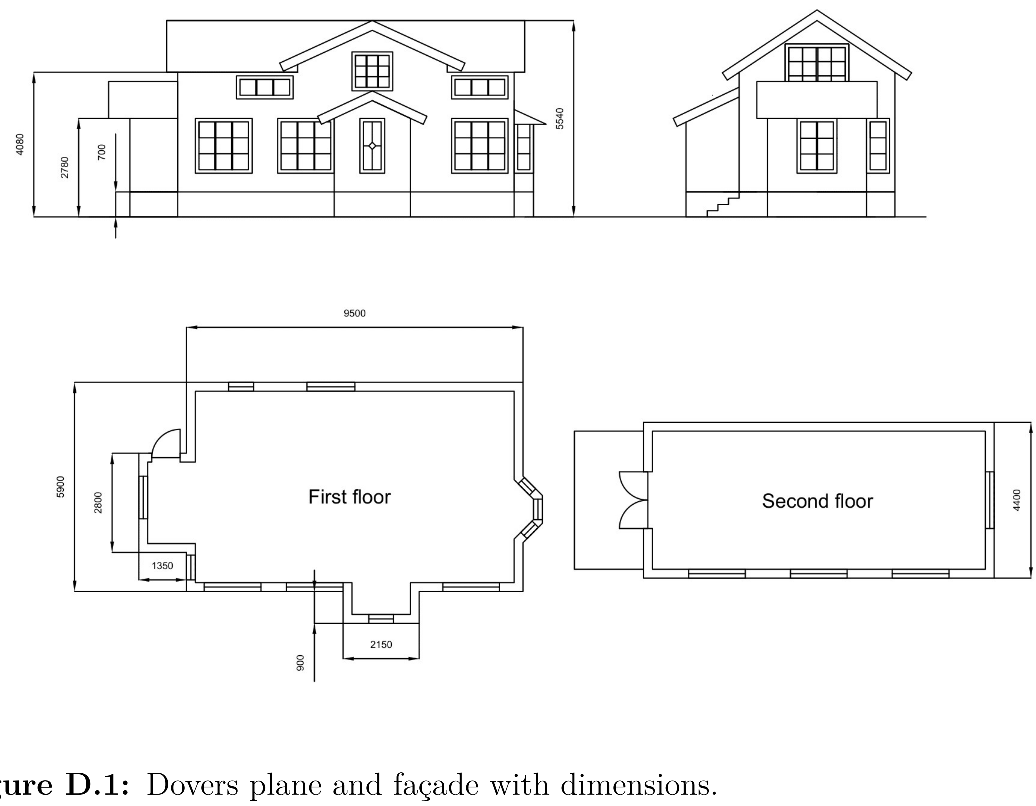


Figure D.1: Dovers plane and façade with dimensions.

Location for sourced climate: Skärhamn 1991-2020
Total heated floor area: 103.75 m^2
Total wall area: 107.70 m^2
Total window area: 16.79 m^2
Ventilation: natural

Table D.1: Information about building elements used in simulations, Dovers.

Part	Materials (ext-int)	d [m]	U-Value [W/m²K]
	Macadam	0.1*	
Floor[1]	Concrete	0.1	2.19
	Timber	0.022	
Joists[x]	Timber	0.19	0.66
	Exterior roof	0.02*	
	Timber	0.017	0.71
Roof[2]	Mineral wool 36	0.0254	
	Timber	0.022	
	Timber panel	0.022*	
Walls	Timber	0.28	0.42
	Gypsum*	0.013	
Windows BR			1.5
Doors			1

Comments on table D.1: *1. As in the other houses, the foundation is modelled as a slab even though there is originally a crawl space due to that the modelling of a slab is easier in BIM Energy. The result is that the energy loss increases.*
2. There was no information about the composition of the roof and hence the same composition as in Kuba was used.

E
Impacts of retrofit scenarios

The GWP of the different measures as sourced from EPDs or modelled in openLCA can be seen in table E.1. Values are adjusted for a RSL of 50 years and only account for the included modules.

E.1 Scenario A

The characterization factor ($CF_{i,j}$) for windows are given as kgCO_2eq/m^2. The total impact for each case house was calculated by multiplying the characterization factor by the exchanged amount of window area (Q_i).

E.2 Scenario B

The characterization factor ($CF_{i,j}$) for insulation are given as kgCO_2eq/kg. The total impact for each case house was calculated by multiplying the characterization factor by the total weight of adding 10 cm insulation to the area of the roof or attic (Q_i). The FU of the EPDs are given as 1 m^2 with the thermal resistance of 1 m^{2}K/W, which corresponds to 37 mm for the original and 95 mm for the alternative scenario. The alternative insulation also had a density of 29.5 kg/m^3 compared to the original ones of 29 kg/m^3. Because of this, the amount of insulation material was multiplied by a factor of $\frac{95}{37}$ for the effect (purpose) of the insulation to be the same. installation was assumed to be done manually hence having no impact.

Table E.1: Input values for impacts.

Scenario	Unit	Impact	Sources
A	[kgCO_2eq/m^2]	64.68	EPD: Elitfönster Fixed frame Alu - AFK (Elitfönster, 2021)
B	[kgCO2eq/kg]	0.66	EPD ROCKWOOL General Building Insulation products for the Swedish market (ROCKWOOL Nordics, 2022)
C	[kgCO2/unit]	1862 (RSL=20) 4655 (RSL=50)	Naumann et al., 2022 Wernet et al., 2016

Table E.2: Inventory of ASHP production (Naumann et al., 2022)

Material	Unit	Amount
Copper	kg	36.6
Elastomer	kg	16
HDPE	kg	0.5
Low-alloyed steel	kg	32
Lubricating oil	kg	27
Medium-voltage electricity	MJ	36.6
Natural gas	MJ	1400
PVC	kg	1.6
R134a	kg	4.9
Reinforcing steel	kg	120

E.3 Scenario C

The inventory of one ASHP was sourced from Naumann et al., 2022, and is displayed in table E.2. The weight of one (1) unit is assumed to be 100 kg based on (NIBE ENERGY SYSTEMS, 2018) and the transport distance was assumed to be 50 km for both module A4 and C2 respectively. The system was modelled in openLCA 1.11 with background data from ecoinvent 3.8. The original scenario was modelled with the assumption that 80% of the refrigerant is reused. This rate was used since 50% reuse rate is the default value in the attributional model in ecoinvent, and 90% reuse rate is used in the consequential model. 80% was chosen since the waste management in Sweden was assumed to be better than the global average but not optimal. The results were also calculated for 50% as a worst case scenario and 100% as a best case scenario. No data on packaging of the ASHP was found and also assumed to have a minor impact, hence left out. All inputs were provided by market activities, and as local as available in the database. The characterization factor ($CF_{i,j}$) is given in kgCO$_2$eq/unit.

E.4 Kuba

The retrofit of Kuba investigated in this study consisted of changing the windows in the one-storyed part, and was calculated using the values of Scenario A, i.e. the same EPD was used. Impacts for the three scenarios can be seen in table E.3.

E.5 Örnahusen

Örnahusen provided a special case since the energy renovation resulted in an extended living area. The retrofit consisted of insulating the walls of the original part and making the extended part to a livable space by insulating walls, attic and floor. All this was included in the R scenario, however the extended part was excluded for the remaining scenarios which were calculated on the original part only. Wallpaper, plastic film and paint was excluded in the energy calculations as their contribution

Table E.3: Impacts for Kuba.

Scenario	CF [unit]	Quantity	Impact	Sources
A	64.68 [$kgCO_2eq/m^2$]	39.64 m^2	2563.72	EPD: Elitfönster Fixed frame Alu - AFK (Elitfönster, 2021)
B	0.66 [kgCO2eq/kg]	293.83 kg	192.99 (RSL=50)	EPD: ROCKWOOL General Building Insulation products for the Swedish market (ROCKWOOL Nordics, 2022)
C	1862 [kgCO2/unit]	1 unit	1862 (RSL=20) 4655 (RSL=50)	Naumann et al., 2022 Wernet et al., 2016
R	64.68 [$kgCO_2eq/m^2$]	16.78 m^2	1085.39	EPD: Elitfönster Fixed frame Alu - AFK (Elitfönster, 2021)

was deemed minor, however they are included in the environmental impact as they are necessary parts of the retrofit to provide a desirable result regarding aesthetics and indoor climate.
The walls were insulated with 10 cm insulation between beams, and 5 cm additional insulation only. To estimate the amount of wood, it was assumed that there was a beam of standard dimensions 45x100 [mm] every 600 cm (cc600) plus one beam following top and bottom of the walls, windows were disregarded.

Table E.4: Impacts for Örnahusen.

Beginning of Table E.4				
Scenario	**CF [unit]**	**Quantity**	**Impact**	**Sources**
A	64.68 [$kgCO_2eq/m^2$]	10.6 m^2	685.64	EPD: Elitfönster Fixed frame Alu - AFK (Elitfönster, 2021)
B	0.66 [$kgCO^2eq/kg$]	286.93 kg	188.46	EPD: ROCKWOOL General Building Insulation products for the Swedish market (ROCKWOOL Nordics, 2022)

Continuation of Table E.4				
C	1862 [kgCO2/unit]	1 unit	1862 (RSL=20) 4655 (RSL=50)	Naumann et al., 2022 Wernet et al., 2016
R	**CF [unit]**	**Q**	**I**	**Sources**
Timber beams	36.92 [$kgCO_2eq/m^3$]	1.73 m^3	64.82	EPD: Svenskt Trä Swedish sawn dried timber of spruce or pine (Svenskt Trä, 2021)
Insulation walls	0.66 [$kgCO^2eq/kg$]	594.10 kg	390.22 (RSL=50)	EPD: ROCKWOOL General Building Insulation products for the Swedish market (ROCKWOOL Nordics, 2022)
Plastic film[1]	7.70 [$kgCO_2eq/kg$]	26.70	205.61	Boverkets Klimatdatabas 02.04.000 (Boverket, 2023) and Ecoinvent 3.8. Wernet et al., 2016. Modelled in openLCA 1.11.
Gypsum[2]	2.60 [$kgCO_2eq/m^2$]	148.28 m^2	384.93	EPD: Gyproc Normal Standard Plasterboard (Saint-Gobain Sweden AB, 2020)
Wallpaper	0.57 [$kgCO_2eq/m^2$]	148.28 m^2	83.83 (RSL=25) 167.67 (RSL=50)	EPD: Paper wallpaper (Verband der Deutschen Tapetenindustrie e.V., 2017)
Paint	2 [$kgCO_2eq/L$]	42.37 m^2	84.77	EPD: Beckers, Alcro and Tikkurila. (Prieto, 2021)
Insulation attic	1.42 [$kgCO_2eq/kg$]	267.26 kg	379.18 (RSL=60) 315.98 (RSL=50)	EPD: ROCKWOOL General Building Insulation products for the Swedish market (ROCKWOOL Nordics, 2022)
End of Table E.4				

Comments on table E.4: *1. Regarding the plastic film, it was assumed to consist of*

75% LDPE and 25% HDPE. No background data on UV-stabilizers was found and hence left out. The film has a thickness of 0.2 mm and a density of 900 kg/m^3.
2. The reference product here is 12.5 mm thick, whereas the energy calculation was done for a thickness of 13 mm. This difference was disregarded, however this would imply that the impact is slightly higher than what is shown here.

E.6 Dovers

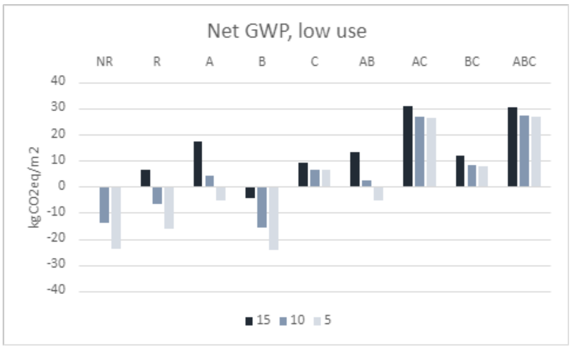
As there was no specific energy renovation performed to Dovers during the ownership of the current owners, the "R - Renovated" scenario was excluded. The imapcts for scenario A-C are displayed in table E.5.

Table E.5: Impacts for Dovers.

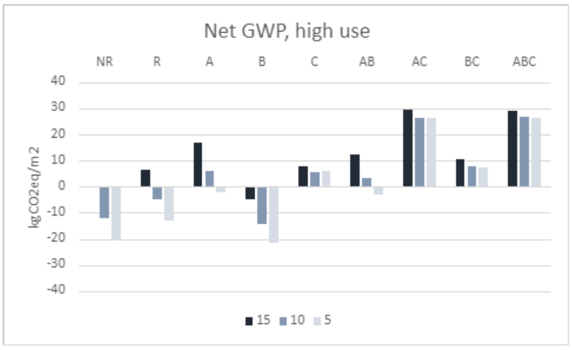
Scenario	CF [unit]	Quantity	Impact	Sources
A	64.68 [kgCO_2eq/m^2]	16.79 m^2	1086.03	EPD: Elitfönster Fixed frame Alu - AFK (Elitfönster, 2021)
B	0.66 [kgCO2eq/kg]	241.83 kg	158.84	EPD: ROCKWOOL General Building Insulation products for the Swedish market (ROCKWOOL Nordics, 2022)
C	1862 [kgCO2/unit]	1 unit	1862 (RSL=20) 4655 (RSL=50)	Naumann et al., 2022 Wernet et al., 2016

F
Total results

F.1 Kuba

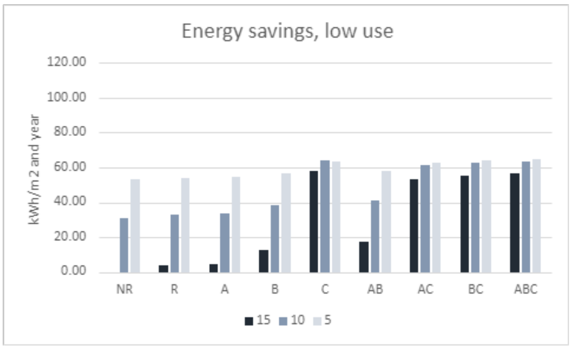


(a) Kuba net global warming potential, low use

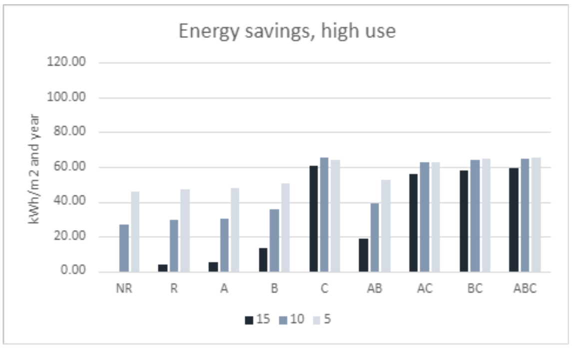


(b) Kuba net global warming potential, high use

Figure F.1: Full net global warming potential results for Kuba.



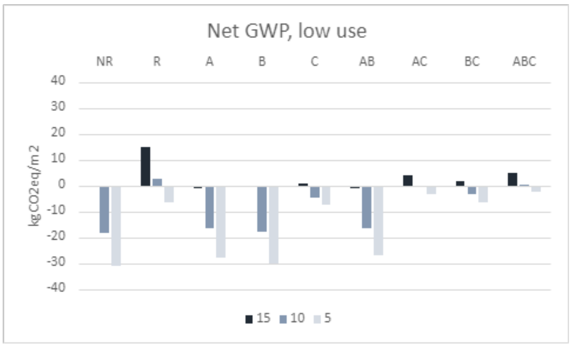
(a) Kuba energy savings, low use.



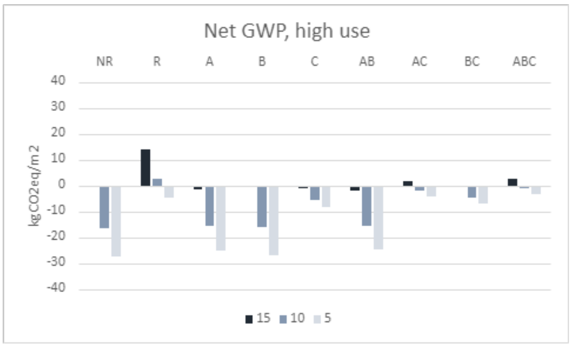
(b) Kuba energy savings, high use.

Figure F.2: Full energy savings results for Kuba.

F.2 Örnahusen

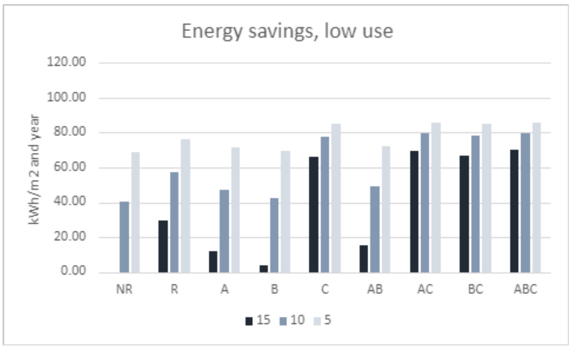


(a) Örnahusen net global warming potential, low use

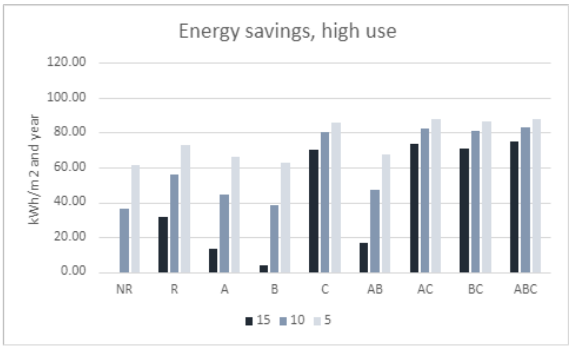


(b) Örnahusen net global warming potential, high use

Figure F.3: Full net global warming potential results for Örnahusen.



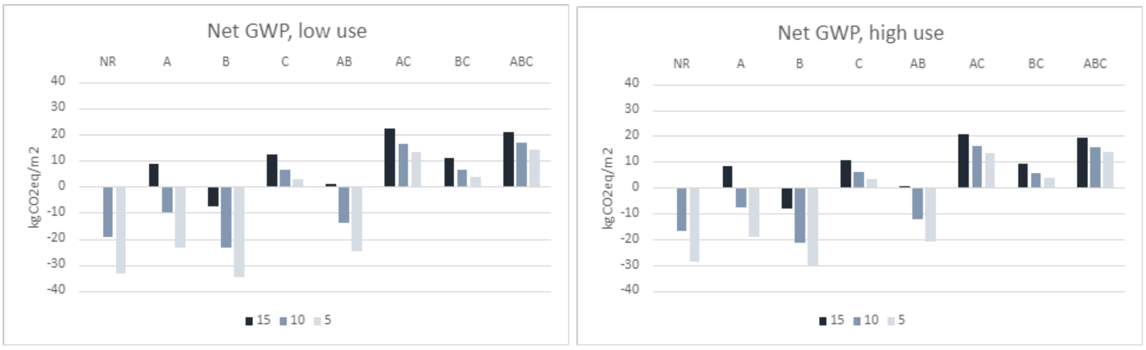
(a) Örnahusen energy savings, low use.



(b) Örnahusen energy savings, high use.

Figure F.4: Full energy savings results for Örnahusen.

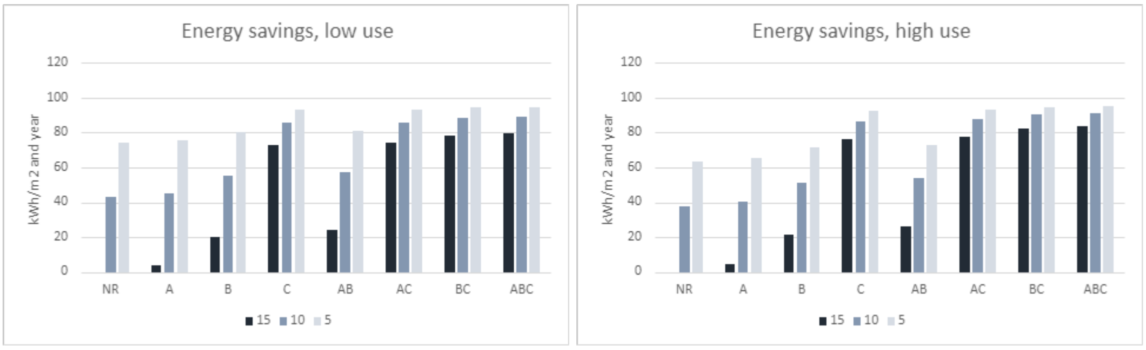
F.3 Dovers



(a) Dovers net global warming potential, low use

(b) Dovers net global warming potential, high use

Figure F.5: Full net global warming potential results for Dovers.



(a) Dovers energy savings, low use.

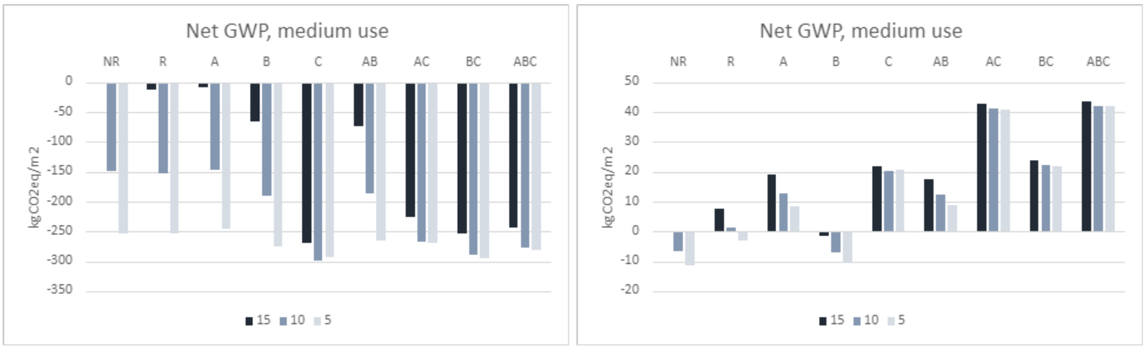
(b) Dovers energy savings, high use.

Figure F.6: Full energy savings results for Dovers.

G
Sensitivity analyses

The sensitivity results are only shown for medium use, both because the different use patterns did not result in very different impacts but also to not make the amount of figures overwhelming.
When performing the calculation with a different provider of insulation material, the reference product of the EPD was used, called "PAROC Stone Wool Thermal Insulation eXtra", from a product group of "flexible slabs and mats". It would have been more appropriate to use a product specifically for roofs, which was discovered afterwards. The reference product has a relatively low environmental impact compared to the other products, hence the impact would potentially have been higher if a more suitable product had been used. The products within the category "Roofs" have a scaling factor of 1.63-7.22 of the reference product. In the original case, values of the reference product (FLEXIBATTS ⩾70mm) were scaled to be valid for a product adapted for attic use "ROCKWOOL Vindsull".

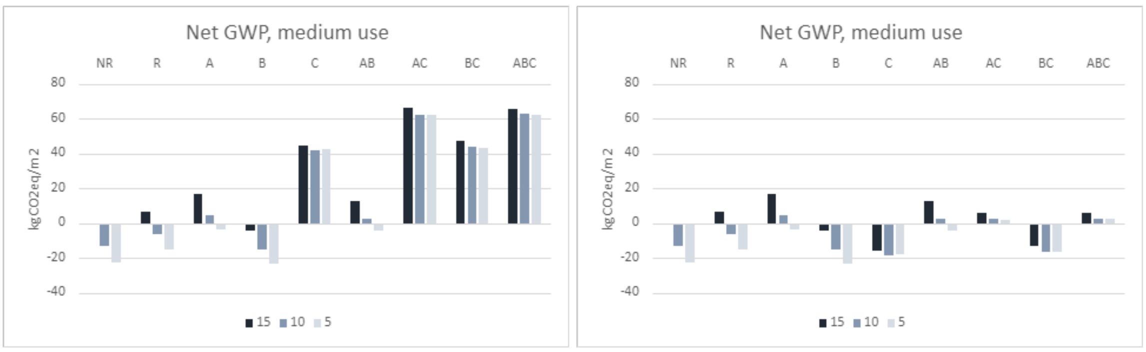
G.1 Kuba



(a) Kuba net global warming potential when the carbon intensity is 102 gCO_2/kWh.

(b) Kuba net global warming potential when the carbon intensity is 4.5 gCO_2/kWh.

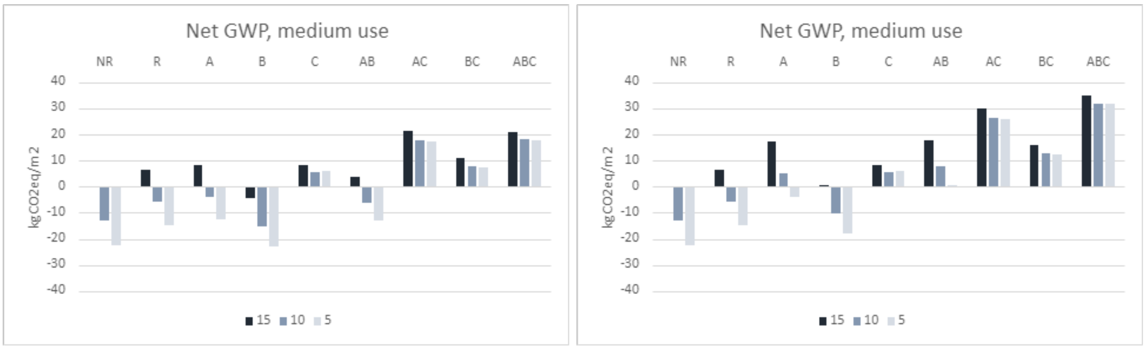
Figure G.1: Different carbon sensitivities for Kuba. Note that axes have different scales due to the high variation in values.



(a) Kuba net global warming potential when the reuse rate of the refrigerant is 50%.

(b) Kuba net global warming potential when the reuse rate of the refrigerant is 100%.

Figure G.2: Different reuse rates of the ASHP refrigerant, Kuba.

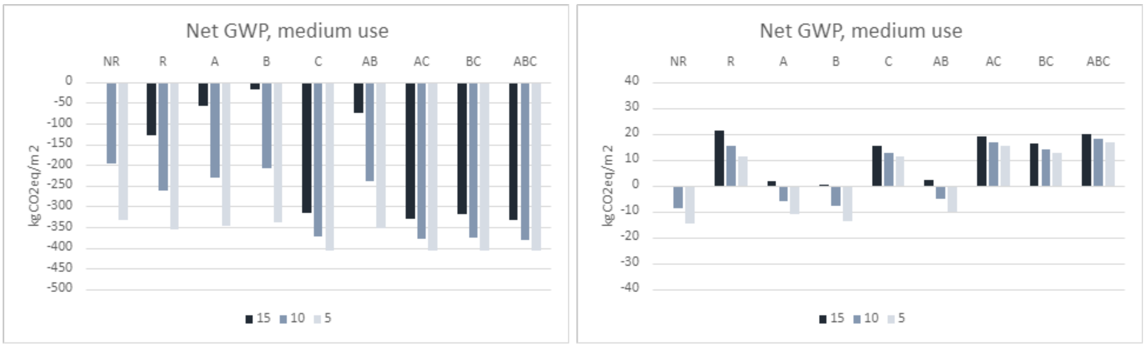


(a) Kuba net global warming potential with another impact from the windows.

(b) Kuba net global warming potential with another impact from the insulation.

Figure G.3: Different EPDs for windows and insulation, Kuba.

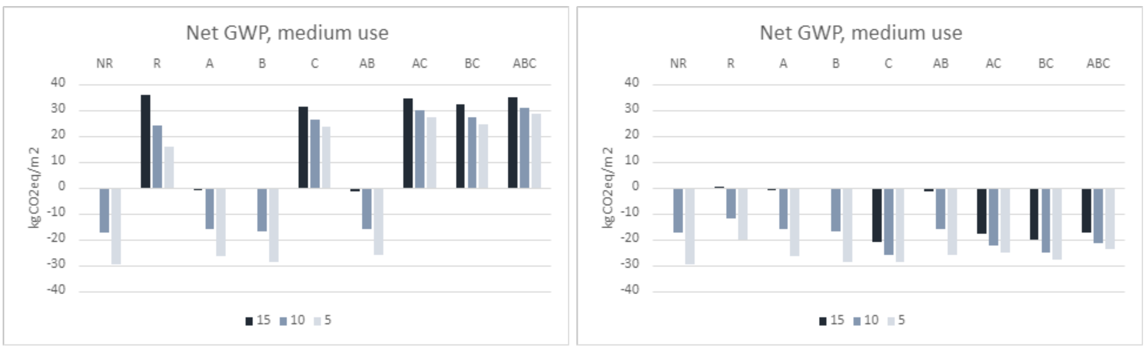
G.2 Örnahusen



(a) Örnahusen net global warming potential when the carbon intensity is 102 gCO_2/kWh

(b) Örnahusen net global warming potential when the carbon intensity is 4.5 gCO_2/kWh

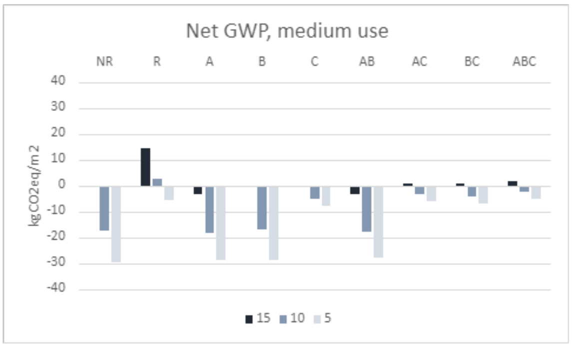
Figure G.4: Different carbon sensitivities for Örnahusen. Note that axes have different scales due to the high variation in values.



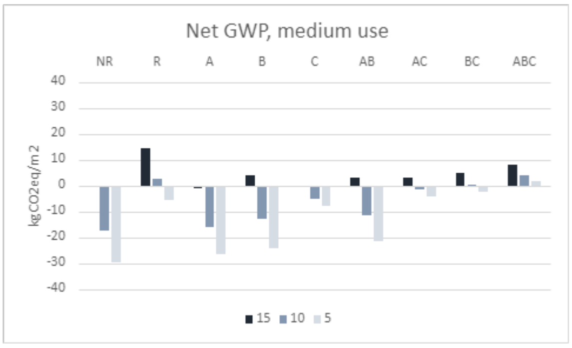
(a) Örnahusen net global warming potential when the reuse rate of the refrigerant is 50%

(b) Örnahusen net global warming potential when the reuse rate of the refrigerant is 100%

Figure G.5: Different reuse rates of the ASHP refrigerant, Örnahusen



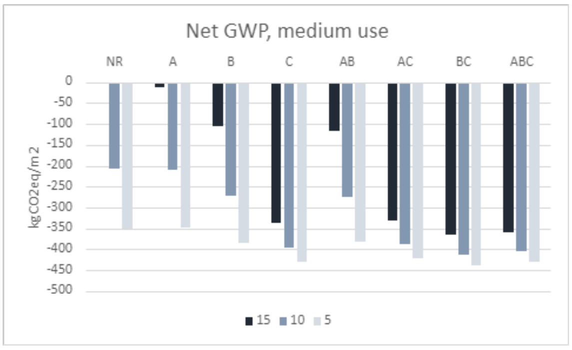
(a) Örnahusen net global warming potential with another impact from the new windows



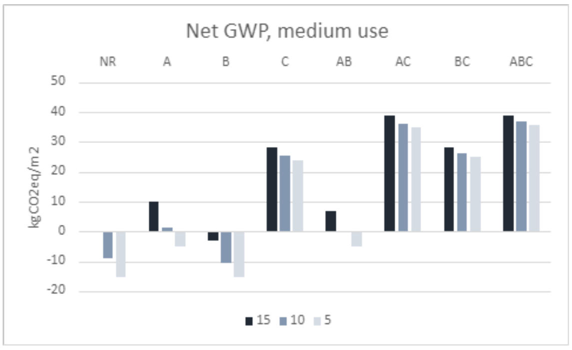
(b) Örnahusen net global warming potential with another impact from new insulation

Figure G.6: Different EPDs for windows and insulation, Örnahusen

G.3 Dovers

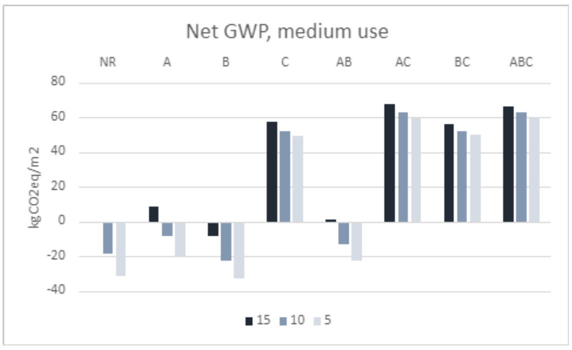


(a) Dovers net global warming potential when the carbon intensity is 102 gCO_2/kWh

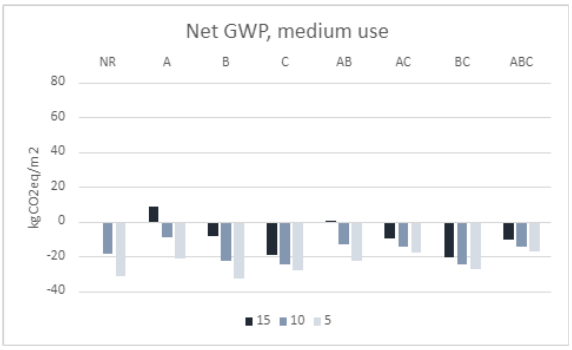


(b) Dovers net global warming potential when the carbon intensity is 4.5 gCO_2/kWh

Figure G.7: Different carbon sensitivities for Dovers. Note that axes have different scales due to the high variation in values.

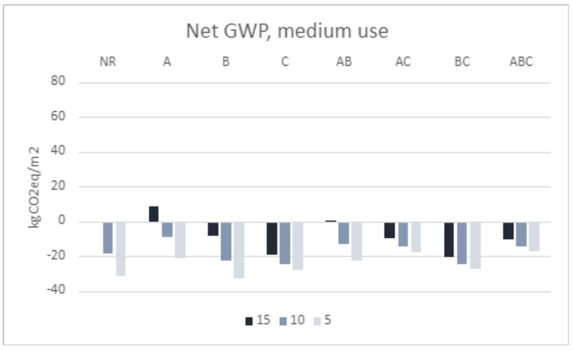


(a) Dovers net global warming potential when the reuse rate of the refrigerant is 50%

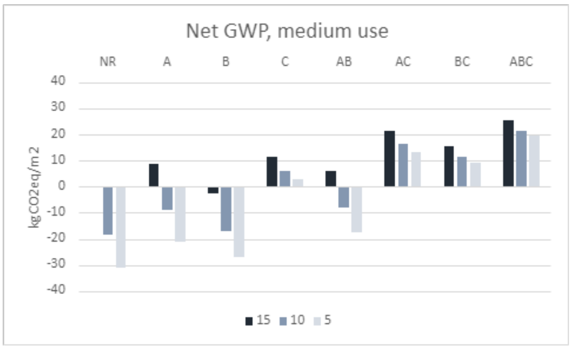


(b) Dovers net global warming potential when the reuse rate of the refrigerant is 100%

Figure G.8: Different reuse rates of the ASHP refrigerant, Dovers.



(a) Dovers net global warming potential with another impact from the windows



(b) Dovers net global warming potential with another impact from the insulation

Figure G.9: Different EPDs for windows and insulation, Dovers.

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY