Energy renovation packages for decarbonisation of Swedish multi-family homes

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Master thesis in Energy-efficient and Environmental Buildings

Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö and Helsingborg. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Most of the existing European buildings are not energy efficient while 85-95% of them will still be in use by 2050. To reach our energy and climate goals the existing building stock needs to be upgraded. Currently in Sweden there is a large building stock, multi-family homes included, that were built between 1960 and 1975. A large part of this stock faces the challenge of needing to be renovated in a sustainable way. With the European Green Deal in 2019 aiming for Europe to be the first climate-neutral continent by 2050, Sweden aiming for 2045, with some major Swedish cities targeting 2030, there is increased need for suitable renovation measures. This study investigates a multitude of renovation packages for Swedish multi-family homes with a principle focus on decarbonisation in a cost-effective manner.

A representative archetype for one of these multi-family buildings was used in this study for a detailed parametric analysis. Roughly 11 300 simulations were carried out covering a multitude of renovation scenarios including passive measures such as additional insulation or window improvements, and active measures such as heat pumps and ventilation systems, all paired with introducing various levels of photovoltaics. The outputs from the parametric analysis considered global warming potential, costs and operational energy use. To carry out such substantial number of simulations, the Grasshopper plug-in in the Rhino 3D modelling program was used to curate an all-encompassing script which generated energy, global warming potential, and costing results. Data from Wikells database (costs), Oneclick LCA (global warming potential), and System Advisor Model (photovoltaics) were input into the script. A sensitivity analysis was carried out aiming at identifying which critical assumptions influence results the most.

The renovation scenarios resulting from the parametric analysis were organised into different “goal categories”: decarbonisation, profitability, and limited investment. Results show that, according to the considered definition of carbon neutrality, there are several renovation scenarios that reach carbon neutrality in a cost-effective manner. Some level of envelope renovation paired with significant levels of PV were enough to achieve a level of decarbonisation within 1 $kgCO_2e/(m^2.A_{temp})$ of carbon neutrality by 2050, while incorporating additional active measures were enough to surpass carbon neutrality. The sensitivity analysis shows that the definition of climate neutrality that was used in this study plays a big role on the outcome of the renovation packages which significantly favours large PV installations.

The parametric input variations and corresponding results of all packages considered in the study can be viewed on the interactive web-based tool ‘Design Explorer’ using the following link:

https://tt-acm.github.io/DesignExplorer/?ID=BL_3FJoZRK

Preface

This study is the conclusion of our two-year studies in the master program in Energy-efficient and Environmental Building Design at Lund University, based at campus Helsingborg in Sweden. The study worked collectively under the umbrella of a Doctoral thesis that is ongoing and had close links to two other master thesis projects that were conducted concurrently.

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I would like to thank my parents, fiancé, family and friends for constant support and faith in me achieving my master's degree and succeeding with this thesis as a culmination of two years of studies. I would like to convey my utmost appreciation for the opportunity granted to me by the Swedish Institute (SI) to undertake these studies through a fully funded scholarship. Finally, I would like to thank my thesis partner for his dedication throughout the thesis and relentlessness for achieving the best possible outcome.

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Terminology and Abbreviations

A_{temp}: Heated floor area
A_{om}: Area of enclosing building parts against heated indoor air
AHU: Air Handling Unit
BBR: Boverket's Building Regulations
BOS: Balance of System
CAV: Constant Air Volume
CF: Cellulose Fibre
CG: Cellular Glass
CO_2: Carbon Dioxide
COP: Conference of the Parties
CS: Climate Studio
DH: District Heating
DHW: Domestic Hot Water
EAHP: Exhaust Air Heat Pump
EC: European Commission
EPD: Environmental Product Declaration
EU: European Union
EC: European Commission
EPS: Expanded Polystyrene
FTX System: Exhaust and supply air ventilation with heat recovery
GH: Grasshopper
GHG: Greenhouse Gas
GWP: Global Warming Potential
GW: Glass Wool
HB: Honeybee
HF: Hemp Fibre
HR: Heat recovery
HVAC: Heating Ventilation and Air-Conditioning system
$kgCO_2e$: Kilogram of Carbon Dioxide equivalent
kWh: Kilowatt hour
kW_{peak}: Kilowatt peak
LB: Ladybug
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCP: Life Cycle Profit
$m^2\ A_{temp}$: Meter squared heated floor area
m^2_{GA}: Meter squared glazing area
m_{GP}: Meter glazing perimeter
MHP: Million Home Programme
MSEK: Million Swedish Krona
NPV: Net Present Value
Q1: Quarter One
ROI: Return on Investment
RSP: Reference Study Period
SAM: System Advisor Model
SGBC: Swedish Green Building Council
SHGC: Solar Heat Gain Coefficient
SCOP: Seasonal Coefficeint of Performance
TWh: Terawatt hour
UN: United Nations
UNFCCC: United Nations Framework Convention of Climate Change
Wikells: Wikells Sektionsfakta cost books
WF: Wood Fibre

Terms and definitions

Building life cycle stages as defined by EN 15978 and EN 15804 standards:

- A1: Raw material extraction and processing, A2: Transport to the manufacturer, A3: Manufacturing, A4: Transport to the building site and A5: Installation into the building.
- B1: Use or application of the installed product, B2: Maintenance, B3: Repair, B4: Replacement, B5: Refurbishment, B6: Operational energy use and B7: Operational water use
- C1: De-construction, or demolition, C2: Transport to waste processing, C3: Waste processing for reuse, recovery and/or recycling and C4: Disposal
- D: Reuse, recovery and/or recycling potentials, expressed as net impacts and benefits

Decarbonisation:

For the purposes of this study, all considerations of climate neutrality are only considered in terms of Global Warming Potential, and carbon reduction only.

Packages:

The renovation packages were made up of envelope improvements in terms of various façade insulation types and thicknesses, roof insulation types and thickness along with a potential window alteration, this is coupled with some level of PV coverage in percentage and potentially the inclusion of an active measure. Any combination of the aforementioned is considered a package and resulted in 11 292 package iterations across the study.

1 Introduction

Large parts of Sweden have residential areas containing multi-family buildings built in what is commonly known as the “record years” of 1961–1975, which accounts for roughly 20% of the countries building stock. Having past a 50-year lifespan, or fast approaching such, these buildings are in urgent need of extensive renovation (Olsson et al., 2015; Nordstrand & Landelius, 2021). 90% of the existing building stock in Europe was built before 1990 and 50% before 1970, a time where building codes were not focused on energy performance. This means that a large share of the current EU building stock was built without any energy performance requirement, while 85-95% of them will still be in use by 2050 (European Commission, 2020). This further supports the substantial need to renovate the existing stock to alleviate the energy demand from the building sector (Filippidou & Jiménez Navarro, 2019).

In recent years, more studies have showed the correlation between renovations that aim for high energy-efficiency having negative consequences for impacts on environmental, economic, and social sustainability (Mjörnell et al., 2019;.Francart et al., 2018). One fifth of Sweden’s GHG emissions comes from the construction and real estate sector, while it also impacts emissions in other countries through imports of construction products (Boverket, 2019b). Extensive energy renovation can be contra-productive as there are high embodied emissions linked to the materials used which dwarf benefits from reduced operational energy use, especially in a future scenario of a carbon neutral energy mix (Francart et al., 2018). While energy reduction is typically a factor in renovation, and reductions in CO_2 emissions are considered, the most prominent decision tool tends to be the economic one (Sesana et al., 2020). This highlights the need for a change of focus in renovation methodology that is driven by considering options of optimising energy reduction, environmental impact, and cost effectiveness holistically.

1.1.1 Background

As established in the European Green Deal in 2019, Europe aims to be the first climate-neutral continent by 2050 (European Commission, 2019a). This goal was bound by the European Climate Law legislation that was initiated in 2021, which instilled the commitment of climate neutrality by 2050, as well as a minimum 55% net reduction of greenhouse gas (GHG) emissions by 2030 compared to 1990 levels. It also ensures that all European Union (EU) policies and sectors contribute to the objectives of carbon neutrality (European Parliament, 2021). Sweden has set a target to have zero net GHG emissions by 2045 into the atmosphere and looks to attain negative emissions in the subsequent years (Regeringskansliet, 2018).

The Swedish government has a further goal to become the world's first fossil-free welfare state. A 29% decrease in GHG emissions was recorded from 1990 - 2019, this means, to reach the 2045 goal, GHG emissions must reduce by an average of 6 –10% annually. The Swedish Climate Policy Council in 2017 further indicated that the countries challenge was that current measures and policies were not sufficient to achieve Sweden's long-term climate goals (Regeringskansliet, 2021).

Buildings have a considerable influence on these objectives as it accounts for 40% of primary energy use worldwide and 37% of global energy-related CO_2 emissions in 2020 (United Nations Environment Programme, 2021). The GHG emissions stem from direct, indirect, and operational uses such as on-site use of fossil-fuels as a direct use, while indirect and operational use can be considered as electricity, district heating (DH), cooling systems and embodied energy in construction materials (Marzouk et al., 2017). With urbanisation expected to continue an upward trajectory, Sweden will require continued housing construction in years to come (Statista, 2022e). This requirement for more housing provides a platform for embracing more vibrant and climate-smart communities. This needs to also be administered to the existing building stock, such as homes constructed during the 1960s-1970s, in the public housing programme known as ‘The Million Programme’, considered to be where the greatest energy savings potential of the Swedish building stock lies (Regeringskansliet, 2019).

Many European countries, Sweden included, have a large post war building stock that requires renovation (Mjörnell et al., 2019b). It has been suggested that a key factor to influencing GHG emissions in 2050 is to build less, so to rather renovate older buildings, using processes that promote circular flows and utilise less carbon-intensive construction materials (Francart et al., 2018) This was echoed through Sweden’s 2016 Energy Agreement view that increased energy efficiency of existing building stock will alleviate future challenges of the county's electricity system, noting potential demographic growth, increased industrial production and a growing economy as future challenges (Sweden Energy Deal, 2016).

Recent EU wide statistics show the rate of energy reducing renovation of current building stock being below 1% (European Commission, 2020d). Suggestions of a requirement of around a 5.6% rate of renovation is required together with a linear decrease to net zero operational and embodied environment by 2050 (Weber et al., 2021) to achieve the global emission scenario and carbon budget based on shared socioeconomic pathways (SSP) that has a probability to reach the UN-Climate goals (Riahi et al., 2017). As larger property portfolio owners come to the stage where their portfolio's require renovation, or simply are challenged to renovate so that a more energy efficient and GHG emission conscious building stock is realised, they will need appropriate control methods and guidelines to realise such. These methodologies would need to ensure that a multitude of aspects, such as environmental, economic, and social, are covered rather than having singled out one or two specific criteria only (Häkkinen et al., 2012).

1.1.2 Objectives

The thesis will look to explore various renovations options that are available in the Swedish market, and through carefully designed filter criteria will aim to provide a set of economically and environmentally viable solutions for an archetype of a Swedish multi-family building from the Million Programme. The goal of the study is to accumulate a series of renovation packages, of which the purpose of achieving carbon neutrality is a driving factor.

The study also investigates innovative renovation measures that are based on environmentally conscious materials compared to the more typical renovation measures that are generally being employed in industry currently. The results of the study will support a larger ongoing research project focusing on energy renovation towards climate neutral neighbourhoods in Sweden.

The study aims at investigating the following:

- sets of renovation solutions for highest profitability;
- requirements for reaching carbon neutral renovation solutions at lowest possible costs;
- feasibility of using innovative materials and renovation solutions; and
- insights of main driving factors for profitability and carbon impact during renovation for a specific definition of carbon neutral buildings

1.1.3 Delimitations

The below mentioned aspects are the main delimitations and have been neglected throughout the study. Where any consideration of these aspects has been considered prior to neglecting, such is detailed within the methodology section. These aspects and their impacts have not been considered in terms of the results and solutions provided by this study.

- Other climate impact categories other than global warming potential (GWP);
- Moisture analysis;
- Daylight analysis;
- Thermal comfort;
- Future climate analysis; and
- Social sustainability.

2 Literature review

To further understand what affected the goals of the study and how they could be achieved, a literature review was first conducted on research topics related to the report.

2.1 Policies and framework of a climate neutral future

There have been framework policies, long-term and short-term goals and roadmaps established from the macro level of the globe to the micro levels of local municipalities, all with a common goal of reducing the carbon emissions of our planet.

On a global scale, the first major step came from the United Nations Framework Convention of Climate Change (UNFCCC), a UN entity tasked with supporting the global response to the threat of climate change. Established in 1992, the convention has a widespread enrolment of 197 parties (UNFCCC.int). This stemmed the first Conference of the Parties (COP) in Berlin in 1995 which continues annually. The most notable COP in 2015 resulted in The Paris Agreement: a legally binding international treaty on climate change, which was adopted by 196 parties. The goal of the agreement is to limit global warming to preferably 1.5°C above pre-industrial levels, which was already recorded as a global average of 1.1°C above those levels in 2019 (European Commission, 2020b).

From a continental standpoint, the European Union is strongly aligned to The Paris Agreement. The European Commission (EC) has established policies (European Commission, 2019b) and proposed frameworks for all sectors, with the construction playing a vital role (European Commission, 2018). According to the European Environment Agency (EEA), the 2020 key targets, adopted in 2007, of 20% cut in GHG emissions from 1990 levels; 20% of EU energy from renewables; and to cut energy consumption by 20% of projected levels by improvement in energy efficiency (European Commission, 2012) were all reached. The most successful target accomplishment was a 34% reduction in net GHG emissions, with projections of a 41% reduction by 2030. However, these achievements, notably the latter two, may have to be more carefully considered, as strong indications attribute achievement to the effects of the Covid 19 pandemic (EEA, 2021). Notably in Figure 2.1, leading up to 2019 Europe was not on track to reaching the 20% reduction in energy consumption, only dropping below by roughly 8.5% for both primary and final energy consumptions after the pandemic began.

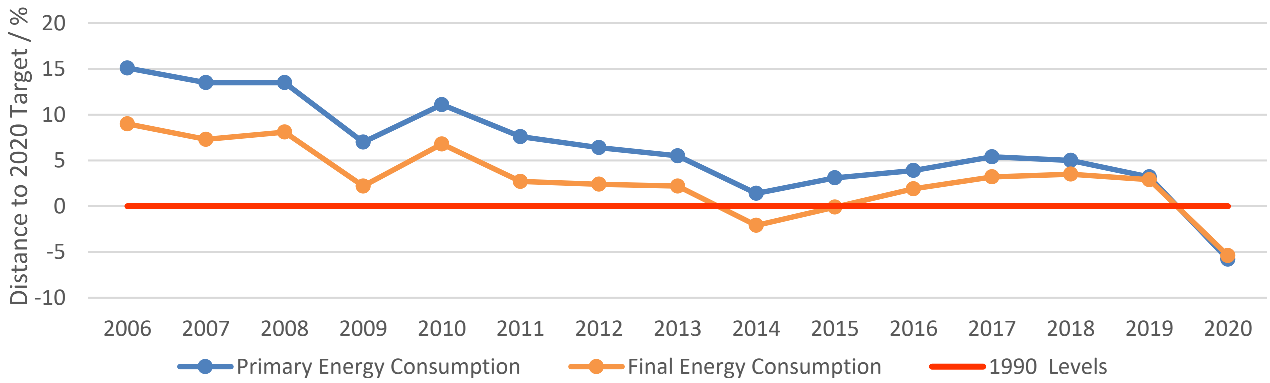


Figure 2.1: Primary and final energy consumption trends for Europe towards attaining a 20% reduction from 1990 levels based on Eurostat data (Eurostat, 2021)

Although it is promising that all 2020 targets were achieved, there is a significant amount of work to be done over the next decade to reach Europe's 2030 goals. The original 2030 targets were: a minimum 40% reduction in GHG emissions, at least a 32% share of renewable energy; and at least a 32.5% improvement in energy efficiency; all compared to their respective 1990 levels (European Commission, 2020a). However, in 2021 the EC revised the plan to be more stringent, setting a new goal of 55% reduction in GHG emissions, a 40% share of renewable energy, and 36-39% improvement of the final and primary energy uses respectively by 2030 (European Commission, 2020e).

From the building and construction sector, there is focus on both new and existing buildings, such as the Build Up Initiative or frameworks like Level(s) established by the EC as a means of building sustainability assessment in conjunction with the EU Green Deal objectives (European Commission, 2021). However, there is a consensus that building renovation plays a key role in Europe's path toward being a climate-neutral continent (European Commission, 2020e).

As previously mentioned, Sweden has a target of climate neutrality for 2045, with some of the larger Swedish cities having even more ambitious targets for climate neutrality. The capital Stockholm has a strategy to reach this goal by 2040 (City Executive Office, 2016), with the city also having signed the Viable Cities Climate City Contract with cities like Malmo, Gothenburg, Lund among others with targets for 2030. The Stockholm's contract sets out targets for aiming to reduce GHG emissions drastically by 2030, with the city aiming to be a fossil free organisation by 2030 and reducing the GHG emissions from city related activities to below maximum 105,000 tonnes of CO_2 (Viable Cities, 2021), equivalent to the emissions from approximately 515 return flights from Stockholm to New York (Turgut et al., 2019).

In order to drive the renovation sector towards a more environmental methodology, municipal policy is required as guidance. Municipal policy has shown to contribute effectively to sustainability for new residential buildings, however for the renovation of existing residential buildings the current municipal policies does not have a high efficacy rate. There has however been an indication that introducing voluntary agreements for existing residential buildings, results in stakeholders, such as social housing agencies, to consider sustainable building practices as part of their renovation projects. Furthermore, there could be a further drive where even private individuals could be encouraged to renovate their homes towards a more environmentally conscious state if there is some financial support from municipalities (Häkkinen, 2012).

2.2 Environmental impacts of construction

Earlier building techniques involved using local materials with low energy costs and low environmental impact. However, in recent times, the use of materials such as cement, aluminium, concrete, and PVC are common, at times procured large distances from the site where it is to be utilised. This results in an increased amount of energy use and a higher environmental impact (Zabalza Bribián et al., 2009). Construction thus plays a part in the environmental impact that stems from sectors such as industrial, energy and even transport considering the various elements that make up a building construction. A study which conducted LCAs of five apartment building construction types in Sweden found the construction stage (A1-A5) accounted for over 50% of the carbon impact, followed by the operational energy stage (B6) with around 40%, the study also indicated that construction types with a lot of concrete generally have a higher climate impact in the product phase (A1 - A3) (Malmqvist et al., 2018).

The Swedish National Board of Housing, Building and Planning reports on several environmental indicators for the housing sector (Regeringskansliet, 2020). These indicators allow for an understanding on climate and environmental impacts, as well as provides a platform for monitoring such impacts from a life cycle perspective. Through this reporting and increased life cycle analysis of construction impact, it is understood that the product and construction production stages (A1 – A5) in a building life cycle account for a significant proportion of the climate impact. The trend of construction, especially in the Nordic region has an increased focus on reducing the carbon footprint of buildings through reducing heat loss to lower operational energy. Increasing the insulation, ensuring airtightness and eliminating thermal bridges are ways of reducing operational energy. The materials used often required more intense manufacturing processes or increased raw materials resulting in an overall increase of lifetime emissions (Totland et al., 2019). This is increasingly significant for energy efficient buildings, as extensive energy-efficient renovations require much greater quantities of material which results in very high embodied carbon. It is important to find the balance between the two, by using biogenic and low-carbon materials, by sourcing locally where possible to minimise transport impacts, and by optimising construction process to renovate buildings and decrease the existing high energy demand of the current building stock (Zabalza Bribián et al., 2009).

Reduction of construction material related embodied carbon emissions must occur and supports the wide scale need to use innovative materials, in an industry that tends to shy away from new technology or change of conventional practices (Giesekam et al., 2015).

Environmentally conscious renovation

The deteriorating state of aging multifamily homes, and management thereof are an issue in Sweden today, increasing the need of renovation. The issue comes where these renovations are expected to be profitable, in the sense that they can carry the costs of the renovation and not be a burden on the company that owns the building. Many of these owners are public housing companies, so apart from having the business mentality of being profitable, they also required to provide affordable housing, so a balance between social responsibility and business-like goals needs to be achieved (Jonsson et al., 2017). Renovation with a focus on sustainability and improved energy-efficiency bring about reduced operational cost and climate impact, while also providing a better housing situation for tenants, promoting a better living standard. These improvements however come at a cost, in some cases meaning the displacement of original tenants as they are unable to afford the increased rentals of their post renovation previous homes (Mjörnell et al., 2019a).

Realising more environmentally conscious renovations solutions means that the use of more innovative materials, more common for new construction, are now starting to be used in renovation projects as well. The first instance of renovation that has a profound impact of energy reduction is that of insulation. The production of insulation materials differs immensely, and this has a direct impact on the environmental impact. A study of the effects of different insulation materials on primary energy and CO_2 emissions of a Swedish multifamily home looked at commonly used insulation materials and their environmental impact. The materials studied included rock wool (RW), glass wool (GW), cellulose fibre (CF), expanded polystyrene (EPS) and cellular glass (CG) insulations and were designed to achieve the same functional equivalent. Considering two data sets, the study broadly concluded that cellulose fibre gives the lowest primary energy in production stage followed by rock wool and glass wool, this was attributed to CO_2 emissions based on the production energy requirement. EPS generally required the lowest thickness compared to the other insulation materials, but the primary energy required for its production along with glass foam were the two highest (Tettey et al., 2014).

A German study has also investigated the environmental and economic performance of biobased, and non-renewable insulation materials. The study concluded that from 18 environmental categories considered, the two biobased materials of wood fibre (WF) and miscanthus insulation performed far better in almost all categories in comparison to hemp fibre and flax insulation denoting them as the most environmentally friendly solutions of these four considered materials. The non-renewable materials of EPS and stone wool both performed poorly over most categories and were the worst in the Global Warming impact category (Schulte et al., 2021).

Innovative materials such as super insulation plaster (SIP) are an alternative to the conventional insulation methods. A Chalmers study based on numerical simulations concluded that there is a large potential for reducing building energy use along with carbon emissions if SIP were to be used on the facades of just 10% of Sweden's multifamily homes. The study further concluded, through industry professionals interviewed that for an uptake of such innovative materials there is a need for the properties of the material to be clearly documented and that the producer supply more product information for larger scale implementation (Karim et al., 2020).

Windows are another essential building component, the characteristics of which has a direct impact on the energy performance and consumption of the building. In colder climates such as Sweden, windows are crucial in limiting heat flows through leaky or high transmittance windows. Therefore, it is common for multi-glazed windows to be used in Sweden as they reduce heat losses through the window component. Energy consumed and carbon emitted during window production has an impact on its suitability for building use. An American study over a multitude of cities investigated decades performance data of double hung windows. It considered energy, carbon and cost savings and concluded that improving existing windows by installing an additional layer can lead to energy savings across climate zones, with a reduced environmental impact compared to replacing windows (Frey et al., 2012). Apart from window performance, material selection also plays a role in environmental impacts of material sourcing, manufacturing, and delivery. The consideration of window selection based on its life cycle assessment (LCA) and material selection has an impact on the life span of a window and its treatment at the end of its service life. Material impacts in the case of windows are also exaggerated due to their higher value and greater level of engineering and manufacturing versus other building materials leading to disproportionate impacts relative to weigh and area (Salazar, 2014). Emphasising the need to choose a window of suitable performance with minimal climate impact.

2.3 Energy Use

The production and use of energy accounts for more than 75% of the EU's GHG emissions, with the residential and services sector being a major consumer. Buildings alone account for 37.5% of the total final energy consumption, with 80% of that total energy being attributed to space and water heating (IEA, 2020b) An inefficient building stock leads to higher energy use as demand for housing increases. 97.5% of the EU building stock is below the Energy Performance Certificate label A (BPIE, 2017).

The European Commission's energy roadmap to 2050 suggests that there will be a significant increase in the contribution that electricity will give to the percentage of Europe's final energy demand, predicted to be 36-39%. Renovating the existing inefficient building stock of Europe will help to mitigate this transition towards an increased dependence on electricity as a source of energy, by reducing the electricity needs regarding the buildings' current electricity demand and future dependency on electricity related to the buildings' heating and cooling needs.(European Commission, 2011) If the assumption is that there will be a decarbonised energy mix in the future (Wachsmuth et al., 2022) extensive energy-efficient renovations will reduce operational energy use, deterring the pressure on the grid.

Sweden's energy use

Roughly 40% of the final energy use in Sweden in 2019 was attributed to the residential and service sector, of which 50% was electrical energy. 30% of the energy use in residential and service sector stemmed from DH, however, in apartment buildings DH is the most common energy source (Energimyndigheten, 2021). Being a global and European front runner in terms of low-carbon electricity generation, Sweden has a well-established grid to supply the national demand, predominantly from hydro and nuclear means.

With a target of 100% renewable energy by 2040, the 2016 Energy Agreement noted that Sweden has a high dependence on nuclear power, abolishing the nuclear capacity tax and endorsing the existing regulation, further mentioning the 2040 goal as not being a cut-off date for banning nuclear power (Regeringskansliet, 2016). Six of Sweden's eights nuclear power plants have planned operational timelines that run into the early 2040s, meaning Sweden would need almost 60TWh of additional renewable electricity generation to meet current levels (IEA, 2019). This reiterates the need to renovate existing buildings to lower this future energy need, regardless of how clean the electricity will be. With such a poor performing existing building stock, it would not be enough to solely depend on new buildings having low energy usage. A low-carbon energy mix in the future correlates to building electricity and heat being a relatively small part of total emissions in 2050, making carbon neutrality targets achievable with only moderate energy performance reduction upgrades for existing buildings. This avoids extensive energy-efficiency renovation that requires high initial investment and has high embodied emissions (Francart et al., 2018). A prominent method of reducing energy use has been by incorporating the use of heat pumps for air or water heating systems, with the larger exhaust air heat pump becoming more common in Sweden for multifamily homes, either as new builds or renovation (Lindahl et al., 2014).

Coal and the Nordic Energy Pool

Despite the shift towards renewable and low-carbon energy production, notably in Scandinavia, Europe remains the fourth-largest coal consumer in the world, providing roughly 21% of the European electricity supply and DH. Of note, 843 million tonnes of carbon dioxide equivalent emissions were associated with building heating alone in Europe in 2017 (IEA, 2020a). Equivalent to the emissions from over 4 million return flights from Stockholm to New York (Turgut et al., 2019). Reducing the energy demands of the existing building stock is crucial to mitigate the EU's dependence on coal within their energy mixes.

However, from a national perspective, Sweden's electricity production is 92% low carbon and 63% renewable in 2021, supplied predominantly by nuclear and hydro sources (electricityMap, 2022). Sweden overproduces and exports it's green energy to the Nordic pool, exporting roughly 30 TWh per annum, compared to an import rate of roughly half of that (Statista, 2022f). Sweden exports to both Poland and Germany, both with predominantly coal-based electricity sources (electricityMap, 2022).

Onsite Energy Production

To reduce the impact of energy demand on the grid, numerous end users have opted for their own onsite energy production, which is generally also a clean means of energy production. For larger commercial and industrial end users this could mean using sources such as wind and hydro, whereas with the residential sector it is far more common to utilise solar energy. While solar energy accounts for less than 1% of Sweden's electricity generation (Energimyndigheten, 2021), it has seen a sharp increase in a very short period. It has increased almost ten-fold over the last five years, from an installed capacity of 125MW in 2015 to 1226MW in 2020, and way up from the 2010 installed capacity of 11MW (IEA, 2021b).

The EU's installed photovoltaic (PV) capacity was greater than 138 GW by the end of 2020, where just below 55% was rooftop installation in residential and commercial settings. The installation of PV in the EU market was on the decline for six years prior to 2018 when the trend reversed. Since then, Sweden has installed 957 MW, accounting for 78% of its overall installed PV capacity (IEA, 2021b). The Swedish Energy Agency is optimistic that installed PV capacity will continue to increase further supporting the countries target of being 100% renewable, with an estimate that solar energy will account for 5-10% of Sweden's electricity production in 2040, corresponding to roughly 14TWh (Energimyndigheten, 2016). A reason for the current fractional use of solar energy on site in Sweden could be cause of the competitively low electricity prices in Sweden (Statista, 2022h) or the substantial differences in production throughout the year due to seasonal variations of irradiation. To encourage solar energy use, the Swedish government currently has a 0.6 SEK/kWh tax reduction on energy sold back to the grid and a previous subsidy on installation. This incentive to invest in solar energy proved dividend, as the electricity production from PV increased more than 20-fold in the last 10 years. The government subsidy for PV installation costs have been decreasing over time in Sweden, which started at 60% in 2009 (Ordinance: 2009:689), dropped to 20% in 2019 (Ordinance: 2019:192), and was discontinued at the end of 2020. From 2021 this subsidy is replaced by a 15% tax deduction on labour and material costs for installation of green technology (IEA, 2021b). This reduction brings into question the financial viability of the tax reduction that is currently in place for selling back to the grid and installation costs.

2.4 Carbon neutral definitions

Contributing approximately a fifth of Sweden's GHG emissions, the real estate sector and the construction of buildings has a considerable influence on Sweden's ability to achieve its climate target of zero net GHG emissions by 2045. As such, the sector requires a method that will increase the move towards the low emissions that it is required to achieve carbon neutrality. The Swedish government introduced the need for a climate declaration on all new buildings constructed after 1 January 2022. This requirement brings into focus how the various choices that need to be made in the construction process plays a role in the climate and carbon impact of the entire construction process. The current proposal is to include this end-of-life stage in climate declarations from 2027 (Boverket, 2019b). Although these measures are necessary to start the transition of a decarbonised industry, definitions, and guidelines to on how to achieve carbon neutrality for a specific building are also paramount.

An examination of different carbon neutral definitions found that while there were similarities in what was considered necessary to attain carbon neutrality, there was a clear level of contrasting opinions on how such aspects were calculated (Hedberg, 2021). Moreover, there are little-to-no definitions that are applicable to a renovation project, which is a critical area that needs greater consideration. Below is an overview of some of the different carbon neutral definitions that are from around Sweden, Scandinavia, and Europe.

Noll CO_2

The Swedish Green Building Council (SGBC) created NollCO_2 as a method for certifying new buildings that are targeting a net zero climate impact. NollCO_2 defines “climate neutral” as a net zero impact in terms of GHG when the building’s construction, operation and end-of-life aspects are weighed against any climate actions, or offsets, that allow the total climate impact to be balanced to zero (SGBC, 2020b). Figure 2.2 gives an overview of what the definition considers in its carbon balance calculations.

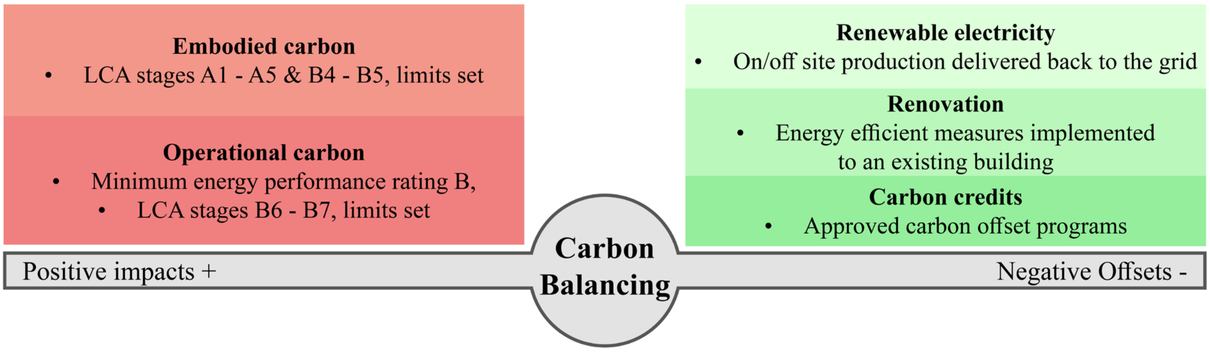


Figure 2.2: NollCO$_2$ carbon balance considerations

NollCO_2 is designed for the certification of new buildings and not for renovation projects, and as such limit values have been determined by SGBC do not resonate to appropriate values for renovations. (SGBC, 2021). In terms of offsetting, NollCO_2 considers overproduction of renewable electricity sold back to the grid at any hour offsets coal somewhere in the Nordic Pool electricity network. It also accepts energy-efficient renovations of an existing building as a means of offsetting the new build, but it is unclear how it calculates the impact of the renovation itself. Finally, it accepts the purchasing of carbon credits as a means of offsetting the buildings impacts. The SGBC is currently looking into having climate certification for buildings that undergo major renovation or for just the use stage, however at present certification is only for new building, or new additions to an existing building (SGBC, 2020b).

ZEB

Created by the Norwegian Research Centre on Zero Emission Buildings, the Zero Emission Buildings (ZEB) was developed based on the Energy Performance Building Directive’s (EPBD) definition of net zero energy buildings (Fufa et al., 2016). It also considers generated renewable energy as a means of offsetting the positive impact and has different ambition levels for carbon neutrality. The life cycle stages considered in each ambition level is shown in Table 2.1. ZEB also considers the offset of biogenic carbon, but only for the COME or COMPLETE ambition levels.

Table 2.1: Reconstruction of the ZEB description of ambition levels table (Fufa et al., 2016)

ZEB ambition levels	**NS-EN15978: 2011 System Boundaries**																
	A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
O/EQ											*						
O																	
OM									**								
COM									***								
COME																	
COMPLETE																	

** does not include operational energy of electricity equipment*
*** does not include A4, A5 or C1-C4 of the replaced materials*
**** does not include C1-C4 of the replaced materials*

White Arkitekter

Some larger companies have their own definitions and methodologies for calculating carbon neutrality, such as White Arkitekter (white, 2020). It is a simplified calculation process in comparison to the previous definitions discussed and only considers the embodied impact of the initial construction, not the replacements of materials throughout the building's life cycle. Their definition rewards the use of organic materials more by including the offset benefits of biogenic carbon. It also considers the offset of renewable electricity, but only the net surplus on an annual basis rather than the hourly rate of overproduction. The breakdown of their carbon balance consideration is in Figure 2.3.

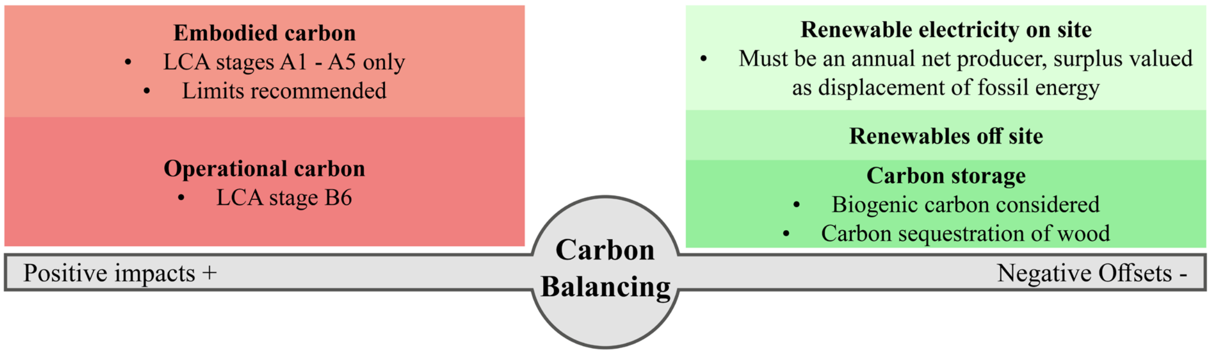


Figure 2.3: White Arkitekter's carbon balance considerations

CIBSE-LETI

The 'London Energy Transformation Initiative' (LETI), a voluntary organisation focused on making the UK carbon neutral, curated their own definition of climate neutrality for buildings (LETI, 2021). Like the previous definitions, it encourages the use of on-site renewable electricity, however it does not reward any negative offset value for such measures. It only considers the benefit of avoiding the 'upstream' emissions of the national mixes. The only means of offset considered are:

- Compensation: where carbon emission savings are achieved elsewhere, such as an energy efficient retrofit of an old building or through carbon capture/storage in the industrial process. This reduces emissions but doesn't reduce actual atmospheric carbon levels.
- Neutralisation: where carbon is removed from the atmosphere, achieved through means such as reforestation and ecosystem restoration (LETI, 2021).

The definition also sets energy targets that must be achieved in order to meet the criteria of the definition, as in Table 2.2

Table 2.2: CIBSE-LETI Energy requirement criteria

Local Energy Demands		Energy Use Intensity Demands / [kWh/(m^2.yr)]		
All energy used should be fossil fuel free	Space heating demand should be below 15 kWh/(m^2.yr)	Homes	Offices	Schools
		35	70	65

Carbon neutrality definition for this study

From the review of different carbon neutral definitions, it is clear that the result of a carbon neutral calculation will be very dependent on what definition is considered. With such uncertainty, it could be useful if a more general consensus was agreed upon within the EU to aid its shift towards carbon neutrality. NollCO_2 was chosen as the definition used in this study as it was developed by the SGBC and is likely to be the staple of carbon neutral certification in Sweden in the future. However, the definition was adapted where appropriate to suit a renovation project. Also, on-site renewable electricity was considered as the only means of offsetting, as the purpose of the study was to assess how decarbonisation could be achieved from a renovation aspect only. For the purposes of this study, only carbon related impacts are considered for "climate neutral", thereby referred to as carbon neutrality hereafter.

2.5 The million-home programme

As previously mentioned, here was an increase of domestic construction in Sweden during a period known as the 'record years' between 1961–1975. Within this period, the Swedish government implemented a state-subsidised program with the goal of constructing one million new homes, known as the million-home programme (MHP). Numerous studies have looked at the extent of this building stock which notably still has many buildings that require renovation, with 2019 estimates at around 125,000 dwellings that still require renovation (Mjörnell et al., 2019a). Apartments that form part of the MHP were built all over Sweden, more than a third of which are concentrated around the three largest cities: Stockholm, Gothenburg and Malmo or their surrounding regions (Hall & Vidén, 2005). Previous studies have highlighted how this building stock is amongst what can be considered the most common multi-residential building type in Sweden. The studies also point out that these buildings are prime for renovation due to age or neglected maintenance. These replacement and refurbishment requirements include, but are not limited to, plumbing, ventilation systems, windows, electrical installations, and facades (Hadzimuratovic & Swedmark, 2016) (Jäger, 2021). The main point that all these studies agree on is that many of these buildings are at a suitable point to undergo major renovation, and in doing so, provide a perfect opportunity to combine environmental and energy sensitive measures as an investment for the anyway renovation is inevitable.

Although there is a lot of homogeneity amongst the building stock, an in-depth review of the Swedish post-war construction noted that it was difficult to attain a single archetype to encapsulate the majority of buildings (Berggren & Wall, 2019). The report assessed the most common characteristics of certain building elements, summarised in Table 2.3. Not included in the report was the fact that roughly on third of the roofs of multifamily buildings were flat roof (Björk, 1992) and over 70% used a mechanical exhaust ventilation system (Reppen & Vidén, 2006).

Table 2.3: High-level overview of the most common to least common typologies based on findings from (Berggren & Wall, 2019)

Typology	**Most common (left) to least common (right)**			
Dwelling type	Slab block	Point block	Balcony access	Other
Number of stories	3-4	5-8	1-2	≥9
Structure	Transverse load bearing	Longitudinal load bearing	Pillar construction	Other
Façade material	Clay Brick	Render*	Concrete	Other**

**Usually applied to on lightweight concrete or concrete*
***Lesser common façade materials not shown*

As the MHP buildings are fundamental to the Swedish aging building stock, they are often used as case studies or in reports regarding renovations. Thus, some archetypes have been previously developed to try best represent a common MHP building. The most comprehensive analysis of the Swedish building stock was the BETSI project, conducted in the mid-2000s by Boverket. The project surveyed the energy use, technical characteristics, and indoor environment of buildings around Sweden, with a particular focus on cases of damage or lack on maintenance. The information collected from the project was used to curate two general archetypes (Boverket, 2011b).

The information collected was used again to further develop ten archetypes for a report that assessed optimal cost renovations for energy efficiency (Boverket, 2013). The report created archetypes for different build types, such as offices or apartments, from different periods. Two archetypes were linked to the MHP era, but they were identical except for the space heating source.

The Intelligent Energy Europe (IEE) program funded the TABULA project to generate typical building typologies for 13 European countries (TABULA, 2012). Four generic archetypes were developed for Sweden, two that could be linked to the 'record years' era, with typical construction elements, building characteristics and system data. However, the archetypes are quite basic with limited information on what was considered for the archetype data. The project also suggested possible energy-saving renovation measures that could be implemented but gave little information about the economic feasibility of such measures.

Most other studies that analyse buildings from the MHP era use specific case studies, which can be more beneficial in terms of calculations and specific details but are not always representative of the common characteristics of buildings from the era.

2.6 Previous studies

Table 2.4 gives an overview of other similar studies that were reviewed that assessed the impacts of renovations from a climate or economic standpoint or included both.

Table 2.4: Summary of studies related to renovations considering carbon neutrality

Study	Summary	Outcomes
(Francart et al., 2018)	Extensive renovation for energy efficiency means a trade-off between increased embodied emissions and decreased operational emissions.	Modelled a quantitative estimation of GHG emissions and operational energy use for the built environment to fulfil GHG emission targets for 2050
(Mjörnell et al., 2019a)	Dealing with renovation levels, rent increases and related social problems.	Extensive renovation of MHP not affordable for occupants, sustainability and social responsibility becoming a crucial driver in renovation strategies.
(Venkatraj & Dixit, 2021)	Different life cycle inventory techniques to calculate embodied energy causes massive variations in embodied energy factors	Understanding of interdependencies between different life cycle energy components in renovations based on embodied energy and operational energy.
(Liu et al., 2014)	Energy retrofit investigation for eleven multi-family buildings in Sweden with CO_2 emission analysis	Different energy efficiency measure packages, profitability analysis, CO_2 emissions reduction analysis. Shows possibility of multifamily buildings in Gävleborg region with potential to reduce CO_2 emissions by 48%
(Mata et al., 2019)	Decarbonisation linked energy demand renovation and impacts thereon of future climate.	Energy renovation measures focused only on energy need for space heating, such as increased insulation, are more robust than electricity usage reduction for lowering CO2 emissions.
(Santamouris & Vasilakopoulou, 2021)	Assessment of building energy technological developments for their potential regarding future energy, environmental and economic aspects	Discusses energy and environmental situation for the building sector and analyses routes to attaining decarbonisation in the future.
(Höfler et al., 2017)	IEA multi-national project, developed a methodology for cost effective energy and carbon emissions optimisation renovations	Guidelines and calculation tools for cost effective renovation solutions and finding the balance between energy efficiency and emissions for exemplary case studies from the participating countries
(Pombo et al., 2016)	Multi-criteria approach of LCC and LCA for retrofitting of a residential building	Compared the LCA and LCC of various cases against a ‘business as usual’ renovation. Found that the extra investment costs generated LCA and LCC savings of 43% and 45% respectively for the optimal case
(Bouzarovski et al., 2018)	Review of the potential socio-economic that may arise with energy efficient or sustainable renovations	Gives evidence of gentrification cases around Europe and America linked to an ‘eco-social paradox’ of expensive energy retrofits. Coins the term ‘energy-efficient renoviction’.
(Ekström et al., 2018)	Cost-effective Passive House renovation of a Million home programme single-family home	Concluded there were cost-effective passive house renovation solutions but was heavily dependent on what measures were taken. Installing an exhaust air heat pump was the most cost-effective individual measure, whereas installing new windows was the least.

3 Methodology

The methodology approach of this study focused on the desire of finding a balance between decarbonisation potential and profitability, when undertaking an energy renovation. As it was unclear how exactly that balance could be achieved, a collection of renovation measure iterations were parametrically analysed to limit the possibility of neglecting any potential combination that could provide a suitable solution across the spheres of decarbonisation, profitability, and energy reduction. This avoided establishing a chronological order of how different renovation iterations were analysed, rather it assessed each potential iteration across the spectrum: from having no other renovation measure considered, to being part of an extensive renovation.

The Grasshopper plug-in (GH) in the Rhino 3D modelling program was used to curate an all-encompassing script which generated the desired results within one program. This allowed for an optimisation process with reasonable time allocation per iteration. Moreover, it minimised the risk of human error regarding data handling and processing compared to using multiple different programs. Certain aspects of the script flow, as well as post processing of results, were formatted based on similar script layout used in an ongoing research project (E2B2, 2022). A diagrammatic workflow of the methodology and GH script can be seen below in Figure 3.1, followed by a high-level overview of each string.

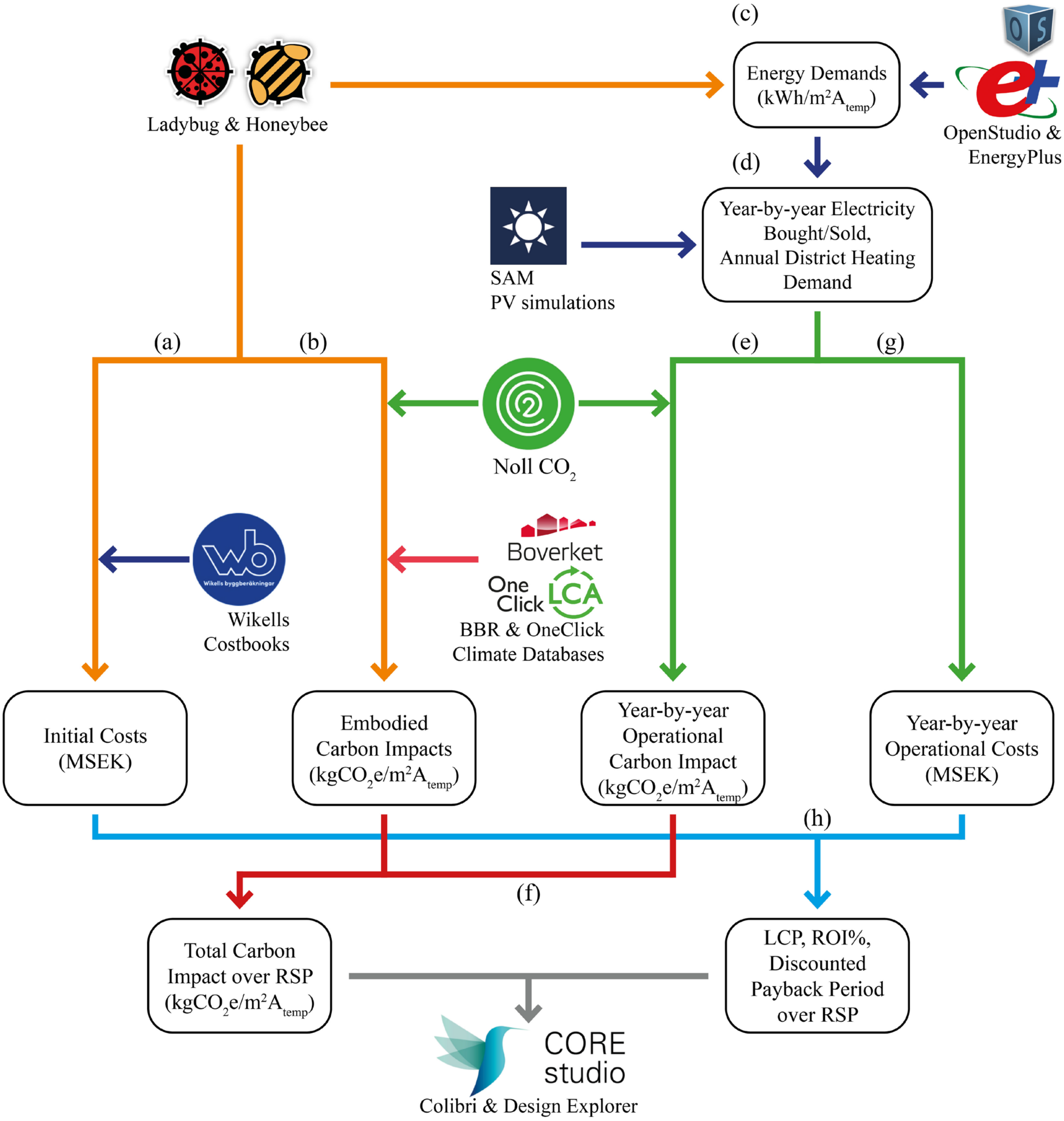


Figure 3.1: Diagrammatic workflow of the methodology of the study and grasshopper script

The Ladybug and Honeybee (LB&HB) tools in GH were used to construct the building model, allocate the material properties of the construction elements, specify the internal loads of the building zones, and assign the weather data.

String (a): The type of material, its thickness, and the total area it covers were extracted from the LB&HB components for each iteration and used to quantify how much is needed per m^2 of their respective elements (i.e. façade, roof, or glazing area). Wikell's cost books (Wikells Sektionsfakta, 2022) were used to get costs for each iteration in SEK/m^2 of their respective elements. Where applicable, the costing in SEK/unit was used instead. The costs were input into the script, calculated for each element, and summed to establish the cost of each iteration in millions of SEK (MSEK). Further details are contained in section 3.5.

String (b): Regarding the embodied carbon impact, predominantly generic data was then taken from both the BBR (Boverket, 2019a) and OneClick (OneClick, 2022) climate databases in units such as $kgCO_2e$ per m, m^2, m^3 or kg. Once again, the material properties, measurement and density information were extracted from the LB&HB components in order to match the required unit of the A1-A3 impact for each iteration. $NollCO_2$ values (SGBC, 2020a) were also used as an input into the script and paired with the LB&HB information to calculate the respective A4, A5 and C4 climate impacts. Further details are contained in section 3.4.

String (c): The OpenStudio software was then used to convert the LB&HB inputs into an EnergyPlus script, which was then run through the EnergyPlus processor. The results were interpreted as annual energy demands of kWh/(m^2.A_{temp}) for heating and DHW, cooling, and property electrical demands for equipment and lighting.

String (d): The System Advisory Model (SAM) program was used to simulate the total PV production in kW/m^2 of PV area, for each hour of the year in the first year of production, as further detailed in section 3.4.7. This data was transferred to the GH script and components within GH were then used to calculate the annual production on a year-by-year basis, accounting for the degradation of the PV system efficiency. The result was then multiplied by the area of PV to attain the kW of each hour for each PV system size considered. In turn, the electricity production in kW for each hour of the year was extracted from the simulated annual energy demand. The two were them combined, with the results categorised into the total amount of electricity produced, bought, sold, and self-consumed for the PV system iteration in question.

String (e): The year-by-year bought and sold electricity and DH demand were then used in conjunction with the $NollCO_2$ values of carbon impacts/offsets in $kgCO_2e$/kWh to determine the total operational carbon impact from the DH, and the bought and sold electricity over the specified reference study period (RSP) of 28 years in the unit of $kgCO_2e$/(m^2.A_{temp}) . This was then added to the total embodied impact to get the total carbon impact of an iteration over the RSP, as illustrated with string (f).

String (g): The year-by-year bought and sold electricity, along with the annual DH demand, were also used to calculate the operational costs of the building on a year-by-year basis to allow for the changing of the RSP if desired. Moreover, when combined with the initial costs, it allowed for the further processing of results to quantify various economic outputs listed in string (h).

All iterations were dictated by the GH components of Colibri, which are part of the TT toolbox collection. Colibri is a tool that cycles through all iterations of GH sliders connected to the component and records the results of the inputs and outputs attached in an Excel csv file. The outputs that were recorded are listed in the six circles at the bottom of Figure 3.1. The full list of iteration inputs/outputs in the Excel file were then uploaded to the online data visualisation tool "Design Explorer" by CORE Studios (Thornton Tomasetti, 2019). Design explorer is an interactive data visualisation tool that conveys all the iteration inputs and outputs in a parallel coordinates graph and allows for the filtering of results as further detailed in section 3.7. The tool was a practical means of assessing both the overall results and specific cases and helped to identify any outliers within the results that may have been caused by errors within the GH script.

Due to the high number of iterations that would ultimately result from this methodology approach, it was decided to have a decision gate at a midpoint of the study, which would assess all the envelope renovation iterations. If there were any iterations that were performing the worst outright from a combined environmental and economical perspective, they were neglected before introducing additional active measure iterations knowing they would never be viable options for the investigation objectives of the study.

3.1 Description of archetype studied

As discussed in the literature review, although there is a level of homogeneity in the building stock from the period, it is difficult to use an archetype that holistically represents the spectrum of MHP apartment buildings. The archetype chosen to be assessed for this study was based on a reference building from a BBR report published in January 2013 that looked at the optimal costs for energy efficiency renovations across a range of building typologies from different periods and different locations around Sweden (Boverket, 2013). Although the reference buildings from the report had their limitations, the construction details, apparent circulation typology and location of the 'Existing apartment building from 1970 with DH, climate zone III' reference building was deemed to be a suitable enough archetype for what this study wanted to assess. This study needed an archetype that was representative of a generic but difficult renovation case in order for the results of packages assessed to either be proportionate, if not better, when applied to other multi-family apartment buildings from the MHP.

Although a building that was 9 stories or greater was uncommon for the MHP (Berggren & Wall, 2019), a high-rise lamella was still desirable for this study as the building would have a poor ratio of roof area to heated-floor area, in turn limiting the potential for on-site PV production. Using the SGBC's NollCO2 climate neutral definition, the overproduction and delivering of on-site renewable energy played a key role in offsetting the building's carbon impact. The larger the heated floor area of the archetype, the higher the electricity demand that would need to be met, in turn deterring the amount of electricity that could be delivered back to the grid as a means of carbon offset. As multi-family apartment buildings were typically constructed in groups of at least four or more buildings (Hall & Vidén, 2005) and had suburban areas develop around them (Dalenbäck et al., 2012) it was assumed that only the roof or façade of the archetype were viable options for PV installations and that extra PV systems could not be installed around the building's periphery. The location of the archetype was Stockholm, the coldest and darkest city out of the three major metropolitan regions that make up over a third of the MHP apartment locations (Hall & Vidén, 2005) which would increase the potential heating demand and decrease the number of hours for potential PV production.

The north and south facades were identical and were the main orientations of the building, containing the majority of the window distribution. The east and west facades were also identical, but only had a single, centrally located window per floor. There were no balconies and only six entrance doors, insinuating it may be a slab block building, which was the most common type from the MHP era (Berggren & Wall, 2019). The façade was a lightweight concrete construction with a small amount of mineral wool insulation. The ground floor, intermediate floors and roof were all concrete constructions, whether they were prefabricated or cast in-situ was unclear. The roof had a layer of lightweight insulating concrete, and the ground floor had no insulation at all, containing just a concrete slab and gravel base. Most of the internal loads and ventilation rate conformed to typical values from BETSI findings (Boverket, 2021), SVEBY recommendations (SVEBY, 2012) and Swedish building code (Boverket, 2019a).

A synopsis of the archetype information attained from the BBR report can be found in Table 3.1 and a perspective image of the building can be seen later in the report in Figure 3.2.

Table 3.1: BBR archetype information

Description	**Value**
General information	
Location	Stockholm
Number of apartments	108
Number of people	194
Ventilation (l/(s.m^2)	0.35
Required flow rate (l/s)	2477
Ventilation system	Mechanical exhaust (F)
SFP (kW/(m^3/s))	1.5
Heating setpoint (°C)	22
Heating system	District heating
System losses of heating energy (%)	5

Table 3.1: BBR archetype information (continued)

Description	Value
Construction	
Length / m	60.5
Width / m	13
No. of floors	9
A_{temp} / m^2	7078
Wall thickness / m	0.188
Wall U-value / W/(m^2.K)	0.481
Wall area / m^2	2586
Roof thickness / m	0.510
Roof U-value / W/(m^2.K)	0.493
Roof area / m^2	786
Ground floor thickness / m	0.350
Ground floor U-value, including or excluding soil (W/(m^2.K))	0.438 or 3.088
Ground floor area / m^2	786.5
Window U-value / W/(m^2.K)	2.8
Window area / m^2	697
Door U-value / W/(m^2.K)	2
Door area / m^2	24
Thermal bridge factor / %	20
U_{mean} of the climate screen, including thermal bridges / W/(m^2.K)	1.023
Energy demands provided in the BBR report	
Household electricity / (kWh/m^2)	30
Property energy / (kWh/m^2)	15
Domestic hot water (DHW) / (kWh/m^2)	25
Heating demand, including 5% system losses / (kWh/m^2)	105
Total building energy use / (kWh/m^2)	145

3.1.1 Anyway renovation

All buildings from the MHP are approaching 60 years since construction. Therefore, they are in need of refurbishment, regardless of any desire to lower the buildings' energy use. A report from SABO which gives an overview of the need for renovation of the MHP buildings, notes that damage to the façade, leaky roofs and window damages are common renovation needs that occur in varying levels of severity (SABO, 2017). The report also speaks to the typical issues within the apartments such as plumbing, outdated electrical installations and potential bathroom mould. However, as this study is only focused on energy renovations, coupled with the fact that renovations within the apartments are on a more detailed case-by-case basis and would need to be addressed whether the building envelope was renovated or not, renovation needs within the apartments have been neglected from this study.

For this study, two anyway renovation measures were considered: maintenance and repair of firstly the facades and secondly the roof. The costs of the anyway renovation and its resultant operational costs over the RSP were considered as the base case and any further energy renovation measures were compared against these costs to indicate total costs, profitability and payback period. This meant the results from this study considered scenarios where the need of renovation was used as an opportunity to carry out extra energy-saving renovation measures.

For the facade repair, an anyway renovation of applying a 10mm layer of lime plaster to the exterior was considered from an energy, costing and environmental impact perspective. For the roof repair, an anyway renovation of applying a layer of waterproofing was considered over the entire roof. A method of investigation and patch work may be the approach for an actual case which would result in less area needing repair. However, no consideration was made for any other preparation on the roof regarding renovation, thus it was assumed the extra preparation costs would be offset by the areas that would not need to be renovated or would be an additional cost that would need to be further accounted for in a more detailed costing. The renovation packages that were considered were based on the building archetype as described in section 3.1.

3.2 Energy Renovations

Common energy reduction strategies in a building renovation include reducing envelope losses by increasing the building U_{mean}, minimizing thermal bridges, reducing infiltration and ventilation losses through improved envelope airtightness and means of heat recovery from the exhausted air, and decreasing the overall electricity demand of the building. As there was limited information of the breakdown of property energy of the studied archetype regarding lighting systems, equipment or pumps, the focus of the study was predominantly on measures to reduce the high heating demand that is typical of buildings from the MHP period. Reduction of property electricity was addressed through means of assessing varying on-site PV system sizes across all iterations considered.

Figure 3.2 shows a 3D perspective of the archetype and gives an overview of all iterations considered within the study, which will be further discussed later in the chapter. Although the ground floor construction had no thermal insulation and could benefit from a renovation measure, the lack of a basement meant there would be no simple way of adding insulation without affecting the floor-to-ceiling height and existing doors. The detailing of LCA and LCC for such a measure would be very difficult to quantify with such high-level information of a generic archetype and would potentially have substantial variation on a case-by-case basis regarding real renovation projects, which deviated from the purpose of this study and was therefore excluded.

The materials selected for the various iterations were largely based on finding the more environmentally friendly options that are available in the market, while also considering the more common renovation materials. To an extent a large emphasis had been placed on finding the most innovative materials available, however in many instances no sufficient environmental impact data or environmental product declarations (EPDs) are available for these materials. Moreover, the more unique and innovative the material, the less it is commonly available for construction cases across the country, in turn affecting the transport and costs. As the goal of the study was to analyse renovation packages that could be applied to MHP multifamily buildings across Sweden, innovative materials that had generic data from either local or regional LCA databases, as well as a somewhat available average material cost, were selected.

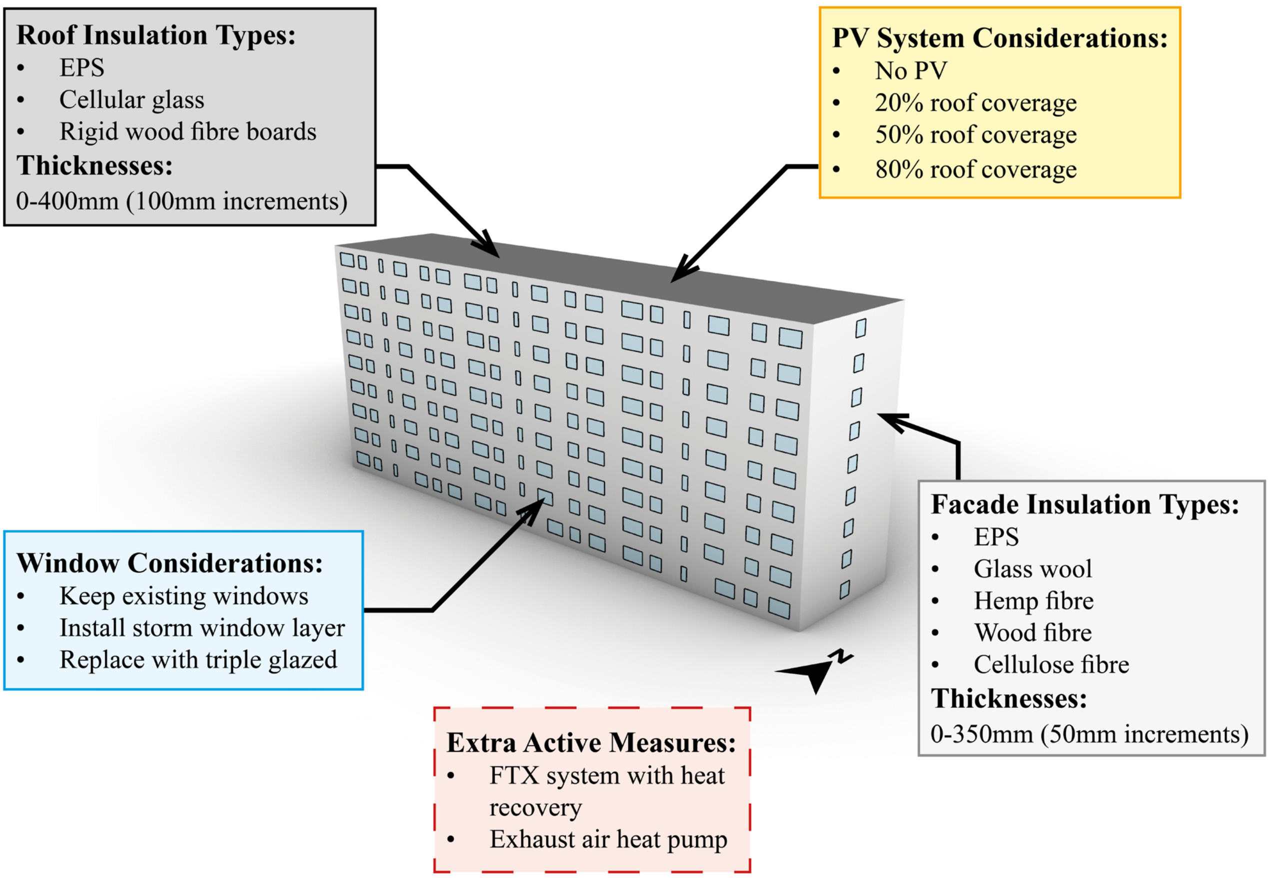


Figure 3.2: An overview of all renovation package iterations considered

3.2.1 Facade and roof renovations

The insulation improvements were applied in a manner that would increase the building façade thickness towards the exterior, thereby having no impact on the interior floor area of the building and allowing for renovations to be carried out with minimal tenant disruption. Based on this method, it is assumed that for the reference archetype building, the footprint does not occupy its maximum allowed area, thereby allowing for expansion towards the exterior.

Five variations of insulation types were considered for the facade: EPS, glass wool (GW) batts, hemp fibre (HF) batts, wood fibre (WF) batts and blown-in loose cellulose fibre (CF). A mix of organic and inorganic materials were chosen on the premise that depending on the LCA boundaries, biogenic carbon from organic materials would reduce the embodied carbon of the construction and may even act as an offset. However, in $NollCO_2$, biogenic carbon is not considered. The facade insulation thicknesses studied increased in increments of 50 mm, from 0 mm to 350 mm. When the façade insulation thickness was 0 mm, the anyway renovation measure of a new layer of cement-lime plaster on the existing façade would be considered.

Allowance for wood studs within the construction was allocated by calculating the façade studwork, assuming 45 mm wide studs with a 600 mm centre spacing, in line with a typical stud wall. The calculations are shown in Appendix A and resulted in the studwork covering 12% of the total facade area, excluding windows. The calculations were consistent with general rules of thumb from insulation providers (Isover, n.d.). Wood studs were not used in any EPS iterations as EPS was rigid and could be fixed directly to the existing wall using adhesive and plugs. It was used for all other insulations studied as they were either batts or loose insulation. As shown in Figure 3.3 for all improvement with studwork, a wind-resistant exterior gypsum plasterboard was fixed to the stud, followed by a ventilated air gap with vertical battens and a final timber cladding layer. For the EPS improvements, a cement-lime plaster render with a mesh reinforcement was applied as an exterior finish.

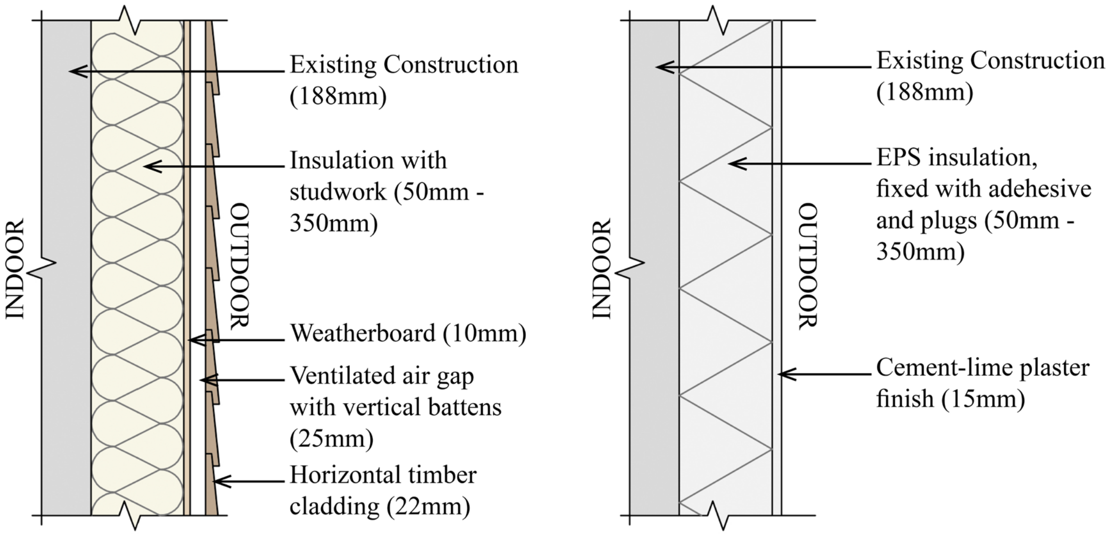


Figure 3.3:Facade construction details, where insulations with studwork are on the left, and EPS with no studwork is on the right

The studwork could not be included in the constructions assigned to the energy model, but they were considered when calculating the LCA and LCC of each iteration. The ventilated air gap and battens were also neglected from the construction in the energy simulations, but the battens were included in the LCA and LCC.

The roof insulations considered were suitable for a flat roof that would need to potentially support a PV system or mechanical plant, as well as any maintenance activity that would take place on the roof. Therefore, only rigid insulation options where chosen, namely EPS, cellular glass (CG) and a more rigid wood fibre (WF) board. The roof insulation thicknesses studied increased in increments of 100 mm, from 0 mm to 400 mm. Both the anyway renovation and any insulation improvement had the same exterior finish of a bitumen waterproofing layer that was selected based on its ability to be fixed onto various substrates. The bitumen felt was neglected from the energy simulations but was included in the LCA and LCC calculations.

3.2.2 Window renovations

For this variable there were three main options: first was to leave the windows unchanged; the second to add an additional glazing layer onto the existing windows (storm window installation); and the third was to remove the existing windows and replace them with new, better performing, tripled glazed windows. Considering that the door area only accounted for 0.5% of the total A_{om}, the changing of doors was neglected to keep the number of iterations down as the window change was sufficient. However, if a building in need of renovation had balconies and the number of external doors was increased, they could have a more considerable effect.

The addition of a storm window layer of glazing followed the methodology used by a Swedish company (Grundels, n.d.-b) that involves installing a window spacer frame fixed with a sealant along the cleaned existing glass, a low emissivity glass is then added and finished with a wooden trim as shown in Figure 3.4. The company further details a reduction in U-value from 2.8-3.0 to 1.2-1.3 by installing this storm window, whereas a 2010 study showed a 20-30% decrease in U-value (Boverket, 2011a). Based on these factors, along with the thermal bridge considerations discussed later in Section 3.3.4, a midrange U-value of 1.7 was assumed for this renovation method. The main materials were considered in the LCA calculations, verified by (Schåman, 2021), and the LCC calculations, verified by pricing received from Grundels

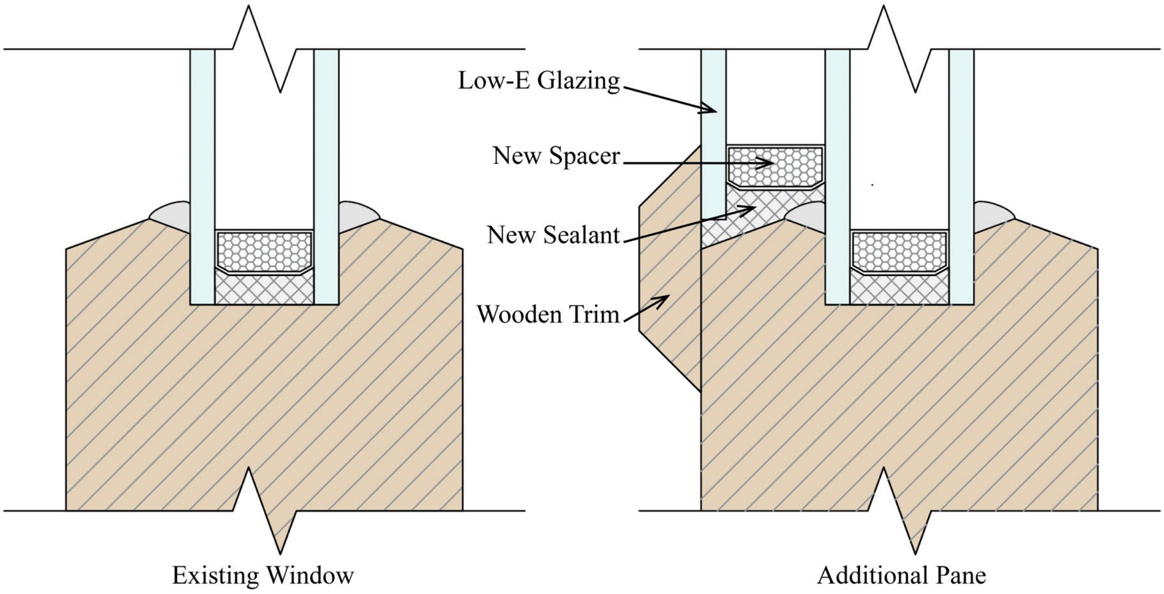


Figure 3.4: Diagrammatic representation of a before (left) and after (right) installation of a storm window, based on images from Grundels (Grundels, n.d.-a)

The selection of the triple-glazed window replacement was guided by the generic data of the available EPD from the databases used, alongside the costs in the Wikell's cost books. Both sources specified a U-value of 1.2 W/(m^2.K) for a wood-framed, operable window. As replacement would allow the new window to be aligned with the new insulation, the thermal bridges were considered to be much less than those assumed later in Section 3.3.4. The window properties of the improvements are detailed in Table 3.2:

Table 3.2: Window properties of the renovation measures

Description	Script input	Source or method of calculating
Additional storm window layer		
U-value / (W/(m²K))	1.7	Midrange value between 20-30% reduction (Boverket, 2011a) and the Grundels' value (Grundels, n.d.-b)
SHGC	0.65	Rounded midpoint value between existing and new triple glazed window, supported by values from SVEBY (SVEBY, 2012)
New triple glazed window		
U-value / (W/(m²K))	1.2	OneClick generic database, Wikell's cost books
SHGC	0.55	Typical value from Pilkingtion triple glazed windows (Pilkington, n.d.)

3.2.3 FTX system

This measure assessed the feasibility of converting the existing exhaust system (FX) into a balanced mechanical ventilation system with heat recovery by means of utilising the existing exhaust ductwork and incorporating a new supply air duct system into the external façade renovation. This concept derived from the smartTES research project, which studied innovative means of renovating building envelopes with timber constructions (Tulamo et al., 2014). Notably, it had a case study of a Finnish concrete multifamily building with an existing mechanical exhaust system. They used the existing exhaust ductwork and subsequently incorporated a supply duct system into the external envelope renovation. The concept was also realised in a previous Master's thesis that assessed the feasibility of prefabricated multi-active façade renovations on a multifamily building of a similar scale from the MHP in Sweden (Hadzimuratovic & Swedmark, 2016). In both studies, the supply air ductwork along the façade was wholly situated within the envelope renovation to the exterior of the existing wall to minimise the installation work and disturbance of the occupants. The façade-integrated ductwork consisted of individual duct lines to each apartment.

Due to the lack of details regarding the archetypes floor plans, existing exhaust duct system or hydronic system, as well as to maintain the focus of the study, only a high-level supply air duct work layout and AHU sizing were designed. Any more of an in-depth design of a HVAC system would get increasingly complex which would add to the simulation time per iteration. Moreover, the system would become very case-specific, rather than represent a generic level of performance, which would be outside the scope of the study. The system was designed to a sufficient enough level that would provide the necessary information for subsequent LCA and LCC calculations. The FTX system considered was a CAV system originating from a single AHU located centrally on the roof.

The archetype description noted there were 108 apartments within the building but had no detailed floor plan illustrating the size or distribution of the apartments. Therefore, it was assumed that all apartments were equally sized and evenly distributed across the A_{temp}. A breakdown of the areas and respective flow rates are in Table 3.3.

Table 3.3: Breakdown of values used in determining the design of the FTX system

Total A_{temp} / m^2	**Required flow rate / [l/(s.m²)]**	**Design flow rate / (l/s)**	**No. of apartments**	**Area per apartment / m^2**	**Flow rate per apartment / m^2**
7078.5	0.35	2478	108	65.5	23

The sizing of the ducts adhered to the equal friction method and were sized to maintain roughly 1 Pa/m, which is a typical rate of pressure loss that would result in low air velocities, in turn minimising the risk of noise pollution from the ducts (ASHRAE, 2017). A rectangular duct system was designed to allow for a smaller duct height, thus accommodating smaller levels of insulation thicknesses to be used for this renovation measure. A minimum of 100 mm insulation to the exterior of the duct was deemed adequate to mitigate the heat loss within the supply air in the ducts, based on the transmission losses tests carried out by (Hadzimuratovic & Swedmark, 2016). Figure 3.5 depicts a typical façade duct design considered.

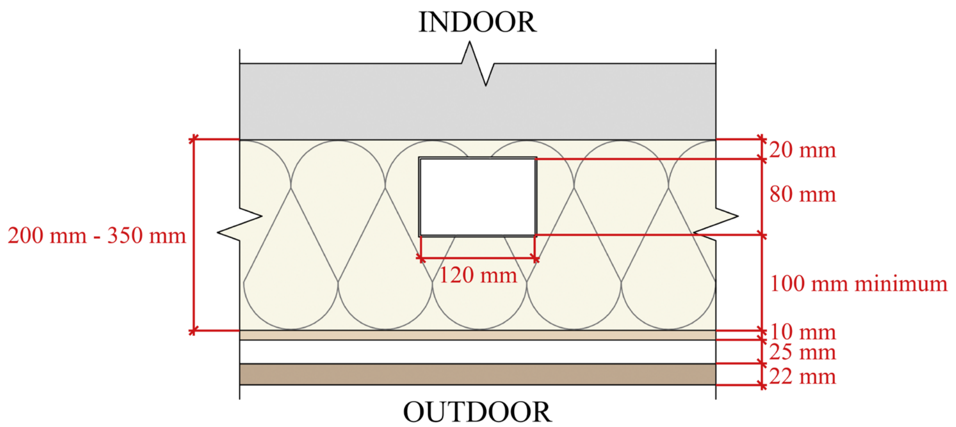


Figure 3.5: Plan detail of a typical 120mm x 80mm facade duct layout

The centrally located AHU on the roof allowed for a uniform subdivision of the duct paths. A series of wye and tee junctions were used to filter the paths on the roof into eight groups of branches on the facade: four on the north façade and four on the south, as per Figure 3.6. The location of the vertical ducts of the branches corresponded to the available space between windows. At the closest point between the window and ductwork (the central branches on the ninth floor), a tolerance gap of 165 mm was left between the window and the outermost duct to allow for studwork and insulation between the two. This gap increased by 120 mm per floor.

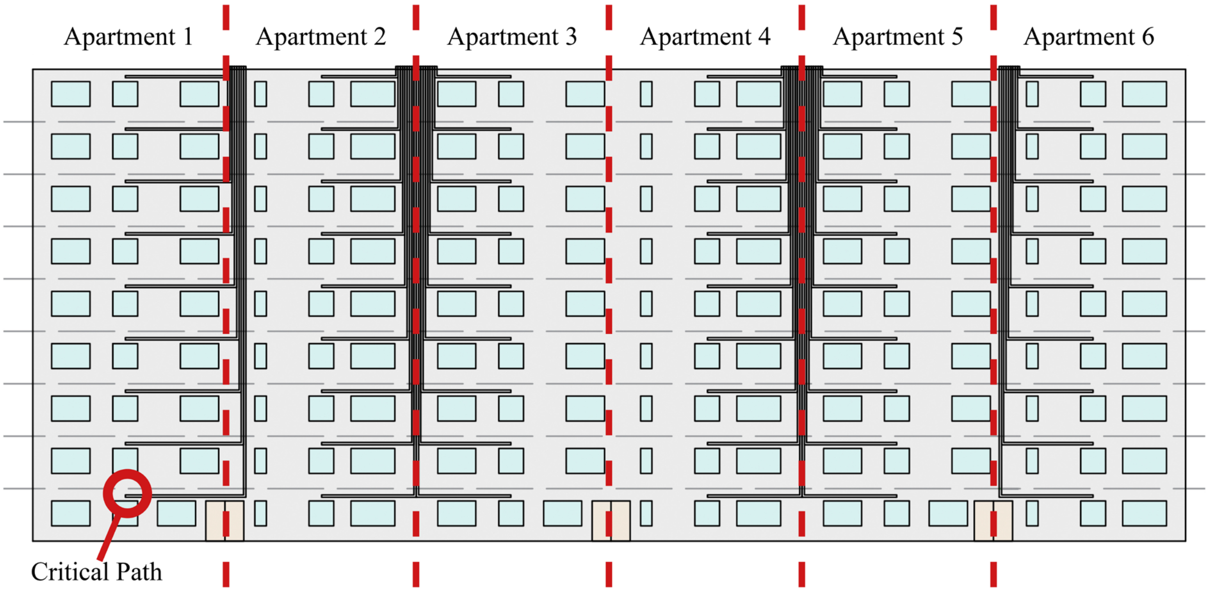


Figure 3.6: Distribution of apartments and duct layouts on the north/south facades, with the system critical path highlighted within the red circle

The horizontal ducts led to the individual apartments and ran above the windows. Two supply air diffusers were allocated to each apartment on the assumption that the windows were situated in the bedroom and living space of each apartment, with an equal supply of 11.5 l/s to each diffuser.

The duct sizing and pressure losses of the junctions were calculated using the VariTrane Duct Designer program (TRANE, 2020). The pressure losses of all the paths that led to terminal units were calculated in Excel to determine the system's critical path, highlighted in Figure 3.6. The total pressure losses of the critical path were 84.2 Pa, a similar result to the previous study of the same system on a MHP multifamily building (Hadzimuratovic & Swedmark, 2016) The calculations of the critical path can be found in Table 0.3 of Appendix A.

The specific fan power (SFP) specified in the archetype was 1.5, however details of how this SFP was attained, such as the number of fans, the system efficiency or the pressure drops of the system, were not specified. With the low pressure drops of the new supply air ductwork, it was assumed that the SFP of the new FTX system would remain at 1.5. This assumption was supported by a previous report, also from BBR, that formulated the technical characteristics and calculations for energy in Swedish buildings based on the results of the BETSI project (Boverket, 2011b). The building characteristics detailed the report were the foundation on which the archetype used in this study was based. The report noted that when replacing a system with a new FTX system, an SFP of 1.5 was used for their calculations, regardless of the original value. Moreover, if only a fan replacement of an F system would be carried out, the new SFP used in the calculations of the BBR report was 0.75, irrespective of the existing SFP, reiterating the improvement in system efficiency between existing and new builds.

The system design regarding duct sizing and length, number of dampers and diffusers, AHU size, and construction process were all used in the respective LCA and LCC calculations later in the study. Details of which can be found in Appendix C and Appendix D.

3.2.4 EAHP

As a simplification, the renovation measure to install an EAHP was considered to only cover the domestic hot water (DHW) need, with no impact on reducing the space heating demand. The details surrounding the sizing of the EAHP are contained in Table 3.4. Various studies have investigated the efficiency of EAHPs, with seasonal coefficients of performance (SCOP) ranging from 3, to values greater than 5, a conservative SCOP value of 3 was assumed for this study. The capacity of DHW accumulator tanks, which are primarily intended for connection to heat pumps to attain greater storage, were calculated based on data showing average hot water consumption daily (Energimyndigheten, 2012) and peak daily usage based on a previous study looking into the daily simultaneous DHW use in apartment buildings (Lundh et al., 2008). The EAHP and accumulator tanks chosen where both from the manufacturer NIBE, and were supported by costing data available in Wikells for the same manufacturer.

Table 3.4: Details considered for sizing of EAHP and associated components.

DHW need / (kWh / (m^2·y))	Total A_{temp} / m^2	Power required / kW	SCOP	Additional electricity required / (kWh / (m^2·y))	Average daily DHW consumption per person / m^3	Building occupants	Number of apartments	Building daily DHW requirement / liters
25	7078.5	20.20	3	8.33	18	194	108	9 500

Contact with the manufacture confirmed details used in sizing the system and the choice of EAHP and storage tanks, details of which can be found in Appendix C and Appendix D, with associated carbon impact and costing data. The details around piping can be found in these appendices as well and are based on an assumed DH to DHW connection at the ground level, with the new EAHP and tanks at roof level piped to this supply point. An online calculator for pipe by velocity of water (TLV, 2022) and the manufacturer installation guides (NIBE, 2022b) were used to determine the pipe diameters required in line with the Swedish standard, SS-EN 806-3:2006 (SIS, 2006), of specifications for installations conveying water for human consumption, as detailed in Table 3.5.

Table 3.5: Details for pipe sizing based on SS-EN 806-3:2006 and take off from high level CAD design.

Draw-off flow rate for sinks and showers) / (l/s)	Maximum flow velocities for pipework / (m/s)	Length of pipe to main connection point / m	Pipe diameter for main / mm	Length of connection pipework /m	Pipe diameter for connection pipework / mm
0.2	2	26	40	68	22

3.3 Simulation model

This chapter begins with a synopsis of the main simulation model inputs used in the GH script in Table 3.6, followed by a brief explanation of the key factors that influenced the simulation model.

Table 3.6: GH input data for the base base simulation model

Description	GH script value	Source / Method of calculating
Heated floor area A_{temp} / m^2	7078.5	GH model
Envelope area A_{om} / m^2	5211	GH model
Heating setpoint / ºC	22	As per BBR archetype data
Building air tightness / [l/(s/m²) at q50]	1.2	See 3.3.3
Exhaust ventilation air flow / l/(s·m²), heated floor area	0.35	As per BBR archetype data
Domestic hot water (DHW) use / (kWh/(m²·y))	25	As per BBR archetype data, assigned a constant schedule
Household electricity / (kWh/(m²·y))	30	As per BBR archetype data, assigned consumption profiles aligning to (SBUF, 2020) & loads aligning to SVEBY (Energimyndigheten, 2007)
Property electricity / (kWh/(m²·y))	15	As per BBR archetype data, aligned to SVEBY
Radiance faction from electricity / %	70	As per SVEBY
People load / (people/$m^2 A_{temp}$)	0.027	As per BBR archetype, schedule and load per person aligned to SVEBY
Losses of heating energy / %	5	As per BBR archetype data, added to annual heating demand result
External roof *U*-value / (W/(m².K))	0.616	See thermal bridge section 3.3.4
External wall *U*-value / (W/(m².K))	0.688	See thermal bridge section 3.3.4
Ground *U*-value / (W/(m².K))	3.088	See thermal bridge section 3.3.4
Window *U*-value / (W/(m².K))	3.5	See thermal bridge section 3.3.4
Door *U*-value / (W/(m².K))	2.5	See thermal bridge section 3.3.4
U_{meam} / (W/(m².K))	1.02	Calculated from areas and U-values above
Weather file	Stockholm, Arlanda	Based on building location being Stockholm, sourced from EPWmap

Zones within the model were sized on floor-to-floor heights, rather than the internal floor-to-ceiling as per BBR report. The extra 2.25 m of façade height resulted in a new façade area of 2916.4 m^2, which was truer to the external façade area that the renovations would have to cover. This revised façade area was connected to all LCA and LCC calculations through the GH script. The extra area at the corner junctions were neglected to maintain the correct A_{temp} in the model for the simulations.

3.3.1 Control Method

To ensure the simulation model had minimal risk of error, a series control method tests were conducted. The testing of the GH script model was done on a simple shoebox geometry with steady state conditions and then slowly scaled up to a form and complexity that was more representative of the studied archetype. The control method followed a step-by-step process where adjustments to GH script model were carried out simultaneously alongside an excel spreadsheet for hand calculations. For an extra level of comparison, an identical shoebox model was constructed in a separate Rhino 3D model and was simulated using the Climate Studio plug-in: another energy simulation tool that also uses EnergyPlus as the parent simulation processor, but with a more simplistic interface compared to HB in GH. Including simulations from Climate Studio in the control method was a way to ensure that the GH script was considering the same input parameters for EnergyPlus and there were no errors within the flow of the GH script as the model got increasingly more complex. At each step of the control method process, the same change was implemented to the GH script, the Climate Studio model and the Excel hand calculations, and the results recorded and compared to measure the margin of error. A breakdown of the steps taken, along with their results, are found in Appendix A. As mentioned, the GH script also extracted material information from the model and used general GH components to calculate the respective LCA and LCC results. Hand calculations made outside of the script to verify the script was calculating them properly.

3.3.2 Simulation complexity vs. run time

EnergyPlus is a multi-layered processing program that can become increasingly complex as more inputs are altered from the default settings. Adding more and more detail to a simulation model can help to attain results that are very representative of how the building would function in reality, however going to such levels can impede the run time of the EnergyPlus script.

As the goal of this study was to assess thousands of iterations, maintaining a reasonable simulation run time, while retaining a high level of simulation accuracy, was crucial. A series of tests were conducted to try to find a balance between the two, by comparing the simulation run time and margin of error of various true-to-form vs simplified aspects. The most significant tests conducted assessed the number of zones, number of windows and influence of shading, the details and results of which can be found in Table 0.2 Appendix B. The final simplified model used for the study consisted of a single zone per floor, with windows grouped together based on the WWR ratio per façade on a floor-by-floor basis. It had a simulation runtime of roughly 1 minute and 25 seconds.

The cooling results from all tests ranged from 1 to 3 kWh/(m^2.A_{temp}). Therefore, introducing natural ventilation to the simulation was ignored to keep the runtime low. As indoor comfort was not the core focus of the study, it was assumed that opening of windows would help mitigate the overheating hours. If the cooling demand increased in conjunction to any improvement measures, they would be addressed in more detail.

The final major simplification of the GH script model related to the ventilation. Different HVAC system templates were available within HB, but there were no means of simulating a mechanical exhaust ventilation system with hydronic heating. Moreover, any designed HVAC system did not give a heating and cooling demand output in kWh, but rather the amount of electricity and fuel the HVAC system would consume. As the goal of the study was to use general heating demands to calculate the DH need and its associated LCA and LCC results thereafter, the 'HB ideal air' component was used. This component gave a result of the heating demand in kWh that would need to be covered to meet the setpoint temperature if no other system losses occurred. This limitation meant a ventilation or HVAC system was not specified, but the simulation result would mimic the scenario of outdoor air entering the zone and the subsequent heating demand that would need to be met.

3.3.3 Building air tightness

The BBR building information was simplified and assumed the infiltration rate was included in the provided natural ventilation rates. However, it was felt that air leakage could be a fundamental aspect of heat loss in a building and was an important means of reducing the building energy demand. Therefore, infiltration losses were considered in this study, supported by the fact that a high infiltration rate of 1.2 l/(s.m^2) at 50 Pascal had been measured in a previous report that studied a building of a very similar typology from the MHP. (Hadzimuratovic & Swedmark, 2016). Therefore, 1.2 l/(s.m^2) infiltration rate was also assumed in this study and was verified using Zou's (Zou, 2010) prediction model for airtightness of buildings in Sweden. The prediction model used a weighted average system based on varying typologies including decade of construction, number of floors, ventilation type and construction type to name a few.

The 50 Pa pressure was converted to an operational building pressure in accordance to the Swedish building code SS 24300-1:2020 (SIS, 2020), which uses equation 1

$$q_{operational} = \frac{q_{50}}{k_l} \tag{1}$$

Where:

$q_{operational}$	*is the air tightness of the building*
q_{50}	*is the measured air tightness at 50 Pa*
k	*is the conversion factor, either 20 for a natural or balanced ventilation system, or 30 for a mechanical exhaust system*

As it would be difficult to quantify the level of infiltration improvement for each iteration, a limitation was set to simplify the means of calculating the infiltration rate improvement. The limitation was based on the premise a very deep renovation would yield a maximum 40% level of improvement in infiltration loses, as indicated in a previous study (Younes et al., 2011). It was assumed that the greatest reduction of infiltration losses for this study would correspond to the greatest reduction of the U_{mean} assessed, i.e. 350 mm of insulation on the facades, 400 mm of insulation on the roof and the replacement of the existing windows with triple glazed units.

The U_{mean} of the base case and the deepest renovation mentioned above were calculated, and the difference between the U_{mean} of the respective cases was used to represent 100% of the possible infiltration rate improvement being achieved, i.e. a reduction of from 1.2 l/(s.m^2) to 0.72 l/(s.m^2), or 40%. A linear infiltration rate improvement that coincided with the U_{mean} improvement was assumed. The GH script was set up to calculate the U_{mean} of each iteration and determine where is fell on the spectrum between the base case and maximum possible improvement as stated above. Whatever percentage improvement it was corresponded to the percentage improvement of the infiltration rate.

3.3.4 Thermal bridges

As the 20% thermal bridge factor indicated in the archetype would have significant effects on the transmission losses, they were included in the simulation model. The allocation of thermal bridge factors and resulting U-values for the simulation input are mentioned in Table 3.7.

Table 3.7: Breakdown of the thermal bridge allocations and resulting U-values

	Walls	**Floor**	**Roof**	**Windows**	**Door**	**U_{mean}**
No thermal bridge U-value / [W/(m^2.K)]	0.481	3.088	0.493	2.8	2.0	0.815
Thermal bridge factor / %	30	0	20	20	20	20
With thermal bridge U-value / [W/(m^2.K)]	0.687	3.088	0.616	3.5	2.5	1.020

No thermal bridge factor was allocated to the ground as there was no insulation in the construction and any factor allocated was cancelled out by the soil temperature and conductivity. 30% was therefore allocated to the walls to recoup and meet the overall 20% thermal bridge factor, and to account for the extra levels of thermal bridges from corner-to-corner and intermediate floor-to-wall junctions.

Thermal bridges could not be factored in the simulation model, therefore conductivity of the existing construction elements was increased to correspond to the respective thermal bridge factors aforementioned. However, as the material properties of the improvement layers would be linked to various parameters throughout the script, and the study relied on an accurate comparison of different material options from an embodied and operational carbon impact perspective, the thermal properties of the improved layers were not altered to account for thermal bridges. Instead, tests were performed to assess what level of thermal bridge factor would remain from the existing construction as the improved insulation thicknesses increased. The results showed an adequate reduction in the thermal bridge factor as the insulation thicknesses increased, compared to accounting for no thermal bridges, thus was deemed acceptable for the study. An example of one of the thermal bridge tests conducted can be found in Figure 0.1 of Appendix B.

As mentioned in section 3.2.3, a minimum of 100 mm thickness requirement to the exterior of the façade ductwork for the FTX system was assumed to mitigate the heat losses from the supply air within the duct. As the supply air in the duct would always be close to the setpoint temperature of the room, it was assumed that the transmission losses between the indoor environment and the duct would be negligible, supported by assessment from (Hadzimuratovic & Swedmark, 2016). Therefore, no additional thermal bridge factor was accounted for in this regard.

3.4 Life cycle assessment

When conducting an LCA study, there are numerous ways in which it can be carried out, and to what extent various aspects are included in the study. It was therefore vital to clearly define the boundaries of the LCA study and indicate what was included or excluded.

3.4.1 Goal and scope

The purpose of this study's LCA was to holistically assess the carbon impact of all improvement iterations considered regarding their global warming potential (GWP). The main RSP of the LCA was the EU climate neutral goal of 2050, as anything after 2050 would no longer have any offset potential from on-site renewable energy sources. The study aimed to help inform people from the construction sector on means of potentially limiting their embodied GWP and mitigating or decreasing their operational GWP.

The functional unit used in the study was $kgCO_2e/(m^2.A_{temp})$.The functional unit of the respective EPDs and energy use results throughout the study were all converted to $kgCO_2e/(m^2.A_{temp})$.

3.4.2 System boundaries

The system boundaries considered in this LCA mostly adhered to the $NollCO_2$ system boundaries, with a few exceptions. The SS-EN 15978: 2011 life cycle stages considered for the renovations of the study are highlighted in red in Figure 3.7

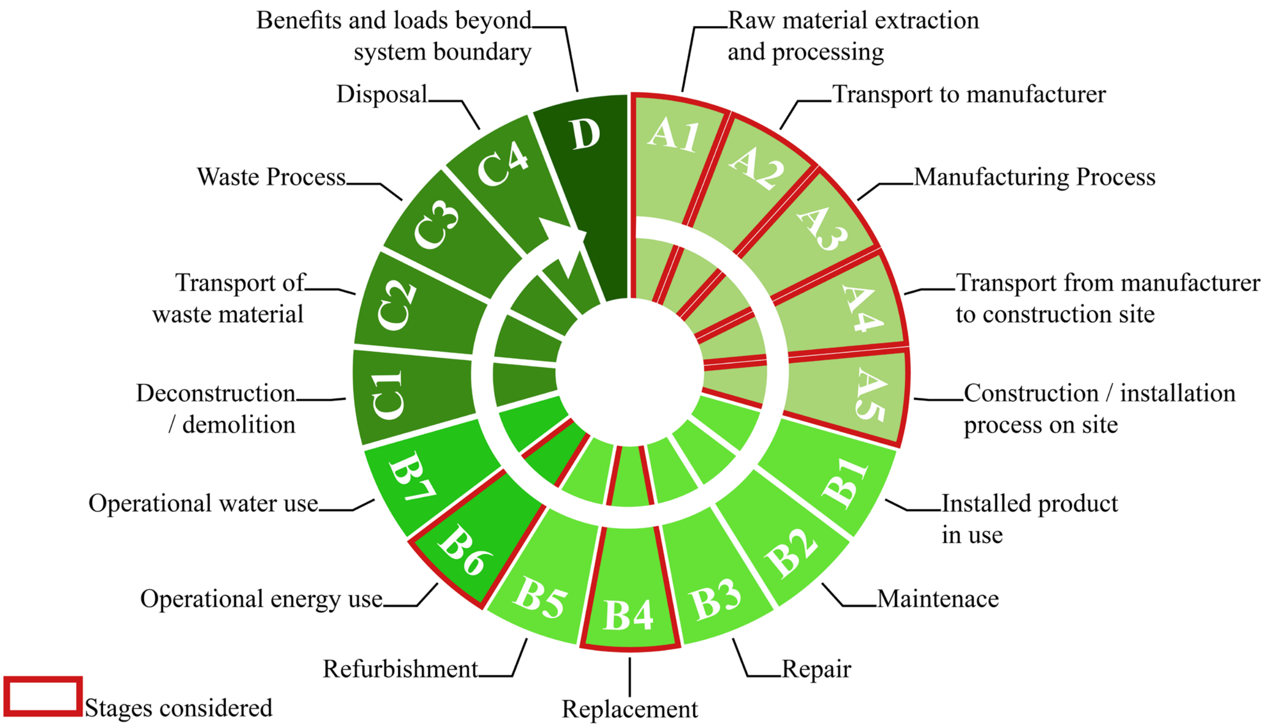


Figure 3.7: SS-EN 15978: 2011 life cycle stages, with the stages considered in the study highlighted in red

$NollCO_2$ neglects the end-of-life stages (C1 – D) on the premise that a construction should have a life span of at least 50 years, thus its end-of-life stage should be no sooner than 2070. Therefore, it assumes that any impact of demolition, removal, transport or disposal at the building end of life should have no climate impact on the premise that the EU is supposed to be climate neutral by 2050. The definition neglects stages B1 – B3 as they are difficult to forecast and are expected to have marginal impact on the overall LCA. B5 is excluded in this study as the renovations of the study are considered as refurbishment.

$NollCO_2$ also excludes the climate impact of infrastructure for water supply around the periphery of a new build, but includes the B7 stage of operational water use. However, as the climate impact of DHW was included in the B6 operational energy use stage of this LCA, coupled with the lack of available information on the other water usage of the archetype, B7 was neglected from this LCA.

The physical system boundary of the study was limited to the actual renovation measures undertaken and excluded any other potential construction or landscaping work around the periphery of the building. The level of climate impact inclusion regarding material used in the building elements, such as external walls or the roof, coincided with NollCO_2's boundaries. This included the likes of studwork, climate screens, cladding, window sealing strips, etc., but excluded the impact of smaller elements like nails, screws or staples. The expected service life of the respective building elements and construction products also aligned with NollCO_2, namely 30 years for façade and roof screens elements and 20 years for AHUs and hot water systems.

3.4.3 LCA limitations

As the study was focused on parametric design an optimisation, there were elements of the LCA aspect where simplifications or limitations occurred. The main limitations of the LCA study are detailed below:

- There is current a lack of detail across all climate databases regarding the LCA of HVAC elements. OneClick LCA has some generic values for some HVAC elements or rough estimations of system climate impacts per ($m^2.A_{temp}$), but it is difficult to attribute these to specific designs, such as the façade-integrated ductwork of this study. Moreover, it was difficult to attain what influences these 'typical' values per m^2. Therefore, due the high-level design of the study's FTX system and limitation of detailed HVAC LCA data, some aspects considered in the LCA may be oversimplified and could have more hidden embodied carbon that was not considered.
- As regional generic data was predominantly used and there was no specified construction site, the OneClick 'Nordic' default distance of 130 km was used for all transport. A 30% tolerance either side of the distance had a negligible effect on the overall embodied impact of the iterations.
- Due to lack of credible sources for A5 construction energy assumptions of a renovation project, it was assumed that there would be 20% of the electricity and 10% of fuel use compared to the OneClick generic energy use for a new construction. A 30% tolerance either side of the values had minimal impact on the overall LCA.

3.4.4 Stages A1-A5

The stages A1 – A5 of an LCA represent the embodied carbon impact. The aim was to limit the climate impact associated with the manufacture of building elements, construction products and building service systems used for the construction of the building. For stages A1 – A3, the Oneclick LCA (OneClick, 2022) and Boverket embodied GWP (Boverket, 2022) climate databases were used for material selection for the study, with the hierarchy of the data selection process illustrated in Figure 3.8. A breakdown of the values considered can be found in Appendix C. As mentioned in the methodology overview, the GH script extracted relevant information of each material (e.g., volume, bulk density, area, length, etc.) from the building model and calculated their respective carbon impacts.

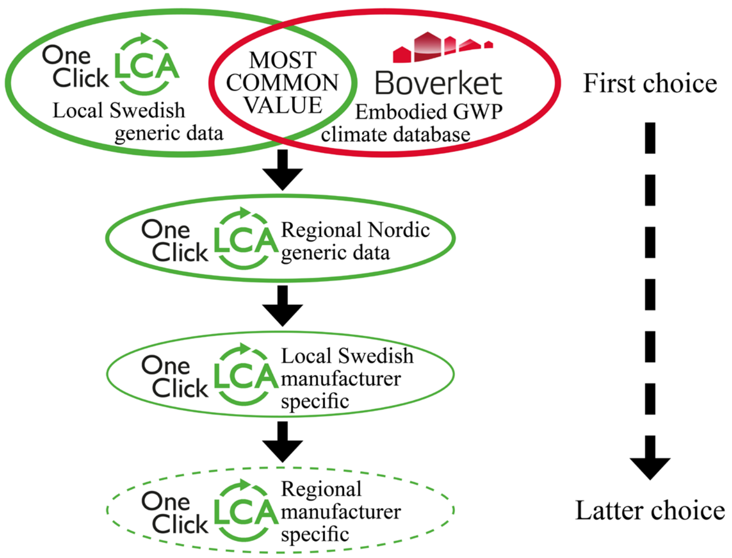


Figure 3.8: Hierarchy of decision process for material specific carbon impact data selection

The A4 stage used the $NollCO_2$ values stated in Table 3.8. The GH script grouped common materials that would be from the same supplier and calculated their accumulated weight per iteration. The total weight of the groups were then filtered and allocated to the appropriate $NollCO_2$ value to be multiplied by the fixed distance of 130km. The sum of the groups was divided by the building A_{temp} to give the total A4 impact per iteration in $kgCO_2e/(m^2.A_{temp})$.

Table 3.8: $NollCO_2$ values for A4 (transport) stage impact of materials from manufacturer to site based on weight

Weight category	< 12 tonnes	Between 12 and 26 tonnes	Between 26 and 40 tonnes	< 40 tonnes
kg CO_2e / tkm	0.23	0.13	0.071	0.064

The A5 stage is based on energy used on site along with the impact of wastage. Material wastage is calculated for each material class based on the $NollCO_2$ values in Table 3.9 Again, the GH script delegated the materials of each iteration to the appropriate wastage category, and the sum of the categories gave the total A5 wastage for each iteration.

Table 3.9: $NollCO_2$ values for A5 construction process wastage

Site wastage category	Individual, preassembled products (e.g., windows)	Products used in large quantities (e.g., timber, insulation, etc)	Other wastage
% of wastage	2	10	5

The energy usage is based on electricity use and biodiesel use on the construction site. The values assumed for envelope renovations were percentages of the OneClick generic construction energy values for a Swedish new build, as per Table 3.10. It was assumed the extra electricity consumption for core drilling diffuser holes, and increased fuel consumption of the crane for installing the AHU would increase the A5 climate impact for the FTX case proportionally by and extra 5%.

Table 3.10: Assumed A5 construction energy impact

New build Electricity use / [kWh/(m^2.GFA)]	**Assumed 20% electricity of new build / [kWh/(m^2.GFA)]**	**Carbon impact / ($kgCO_2e/kWh$)**	**New build fuel use / [l/(m^2.GFA)]**	**Assumed 10% fuel of new build / [kWh/(m^2.GFA)]**	**Carbon impact / ($kgCO_2e/l$)**
43	8.6	0.02	6	0.6	0.95

3.4.5 PV system impact

Noll CO_2 uses a set value of 41 gCO_2e/kWh to account for the entire life cycle of installed PV, which corresponds to an old value provided by the IPCC (IPCC 2014). However, $NollCO_2$ mentions values more than 5 years old should be avoided in a LCA calculations. Moreover, calculating carbon impact based on the actual production of the system would mean that there would be different results based on orientation, tilt or external shading. Therefore, this study considered the embodied energy based the kW peak of the installed system, as per Table 3.11.

Table 3.11: Considered carbon impact values of PV systems in $kgCO_2e/kW_{peak}$

Module carbon impact	**BOS carbon impact**	**Total PV system impact**
797 $kgCO_2e/kW_{peak}$	240 $kgCO_2e/kW_{peak}$	1037 $kgCO_2e/kW_{peak}$

The value above was for a PV module manufactured in China and used in Europe (Müller et al., 2021). This was chosen as China manufactured roughly 70% of the worldwide module production in 2020, with another 22% of manufacturing attributed to other Asian countries. Europe as a continent only attributed to 1.8% of the worldwide production (Statista, 2022c). The balance of system (BOS) value, which included such aspects as mounting, wiring and installation, was assumed to be manufactured in Europe and was based on a study that included a BOS carbon impact from a European energy mix (Friedrich et al., 2021)

3.4.6 Stage B4

Most products or materials of the iterations had life spans that were longer than the RSP and therefore did not need to be considered in the B4 stage of replacement, except for the AHU and EAHP. The removal, transport, and processing of the waste material were calculated along with the embodied impact of the replacement. As $NollCO_2$ assumed the end-of-life impacts linearly interpolated to 0 $kgCO_2e$ by 2050, Equation 2 below was used to calculate the carbon impact of the products for the year they would be replaced. Both products had a lifespan of 20 years.

3.4.7 Stage B6

The NollCO$_2$ 2019 operational impact and offset values are illustrated in Figure 3.9. The definition assumes that any on-site renewable energy delivered back to the grid will offset the production of coal somewhere in the Nordic Pool electricity market, on the premise that renewable electricity always has a lower trading price than fossil electricity and that electricity that has not been traded 24 hours before start of production is not produced (SGBC, 2020a).

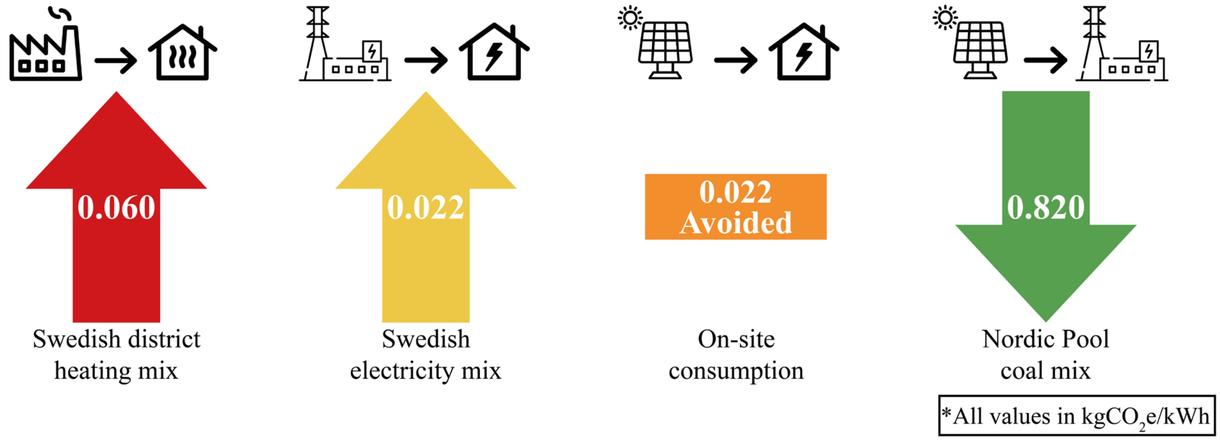


Figure 3.9: NollCO$_2$ 2019 carbon impact and offset values in kgCO$_2$e/kWh, where upward arrows are positive impacts and downward is negative offset

NollCO$_2$ considered a linear interpolation from these values to the future values of zero, depending on the source. For carbon offset of coal in the Nordic Pool, the value interpolated to 0 by 2050, when Europe and the Nordic Pool intend to be carbon neutral. However, for the respective Swedish mixes, the carbon impacts were interpolated to 0 by 2045, when Sweden has envisaged to be carbon neutral. The values in Figure 3.9 are 2019 values from the NollCO$_2$ manual (SGBC, 2020b). As the RSP of this report began in 2022, equation 2 was used to linearly interpolate them to their respective 2022 values, as well as the yearly values thereafter.

$$a_n = a_1 + (n - 1)d \tag{2}$$

Where

a_n is the nth term in the sequence
a_1 is the first term in the sequence
d is the common difference between terms

Figure 3.10 graphically depicts the linear interpolations. Even when the Swedish mixes are neutral in 2045, the carbon offset value is still greater than the two positive impact 2019 values combined.

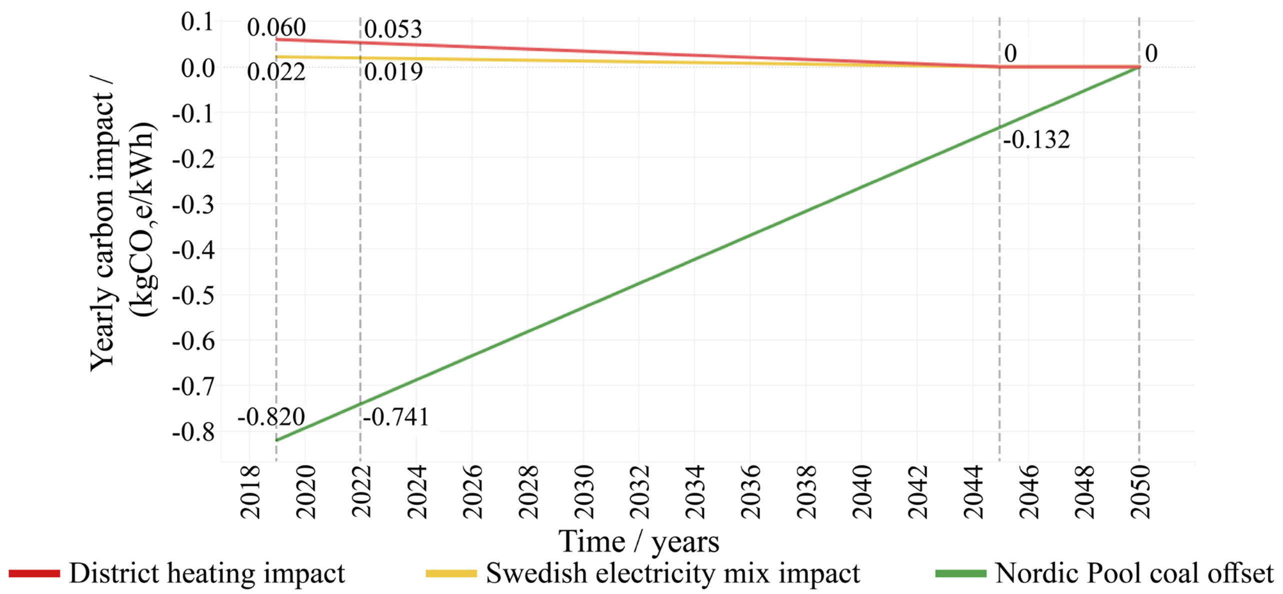


Figure 3.10: NollCO2 impact values linearly interpolated to 0 kgCO2e/kWh

PV systems were investigated to reduce the property electricity demand and potentially act as a carbon impact offset. The studied systems were applied to all iterations from both the independent envelope renovations and additional active measures implemented, as the iterations studied in each package, bar the EAHP, had no impact on property electricity demand.

The annual PV production was calculated in the System Advisor Model (SAM) software, using Stockholm as the location. Monocrystalline panels were mounted flat in order to maximise the amount of potential production, rather than optimizing the azimuth and tilt of the panels. This design was more attuned to achieving the best climate offset rather than to be the most economically feasible PV system. Moreover, as the study was based on an archetype that is supposed to represent apartment buildings from the MHP, it was preferable to analyse a PV system that would resonate to other buildings regardless of their orientation on the assumption that shading from surrounding context would be minimal. The System Advisor Model (SAM) simulation information and PV system sizes considered in the study are listed in Table 3.12.

Table 3.12: PV system considerations for SAM and details for GH script inputs

SAM PV System simulation							
Tilt / °	Module area / m^2	Nominal efficiency / %	Number of modules	System area / m^2	Inverter AC to DC ratio	System kW_{peak}	**System kW_{peak}/m^2**
0	1.65	19.32	15	24.75	1.23	4.73	**0.191**

GH Script simulation inputs				
PV System considered	**0% of roof area**	**20% of roof area**	**50% of roof area**	**80% of roof area**
Size / m^2	0	155	393	630
Size / kW_{peak}	0	30	75	120

The SAM hourly breakdown of production in kW/m^2 was transferred to the GH script and multiplied by the respective PV systems. The property electricity demand of 15 $kWh/(m^2.A_{temp})$ was assumed to be dispersed equally throughout all hours of the year, resulting in a hourly electricity demand of 12.12 kW/h. The hourly production of the respective PV systems were subtracted from the hourly consumption of property electricity to determine the amount of electricity overproduced by the PV system on an annual basis that could be delivered back to the Swedish grid. The hourly electricity produced by the PV system, the amount of electricity to be bought or sold to the grid, and the amount of self-consumption all summarised into their respective annual values to be used for the LCA and LCC calculations elsewhere in the GH script.

As the offset potential of delivering electricity back to the grid was so substantial, degradation of the PV system production over its lifespan could have a significant impact on the total carbon offset over the RSP. Studies and guidelines indicated that there would be roughly 20% degradation by the end of a PV system's life span (Skoczek et al., 2009;IEA, 2016;Jordan & Kurtz, 2012), with varying means of how to consider it over a system's lifespan. Different considerations for degradation can be seen in Table 3.13. For each option, the degradation rate was only assigned to the hourly production, but the system losses remained constant. The annual 0.5% degradation rate method was used for the further calculations in the study as it was deemed most accurate.

Table 3.13:Impact of total carbon offset based on details for accounting for PV degradation

Degradation tests on 80% PV	No degradation considered	10% fixed on average reduction	Accumulating 0.5% degradation rate per year
Total carbon offset over RSP to 2050 / [$kgCO_2e/(m^2.A_{temp})$]	63.98	51.77	58.64

3.5 Life cycle costing

To understand the economic impact and cost-effectiveness of the various renovation packages, an LCC analysis was performed. The analysis included the initial investment cost of the renovation package, the operation cost once the renovation package is implemented and any replacement costs that are required. No maintenance costs were considered. Initial costs for most materials were sourced from Wikells Sektionsfakta (Wikells) cost books dated 2022-03-05 (Wikells Sektionsfakta, 2022) or obtained from specific manufactures where not available from Wikells, as detailed in Appendix . Additional hidden costs that would be apparent on a conditional assessment of an existing building are not accounted for in anyway. For example, the potential additional costs of an increased parapet to accommodate greater insulation thicknesses were not considered.

Costs that occurred at either the start of the project, throughout the lifetime, or at specific years in the future, are detailed in Appendix D. The net-present value (NPV) method was used to calculate the discounted price for future replacement costs, using equation 3. Equation 3 was also used for calculating operational costs using the initial electricity price or price of DH (A_0) for each year over the RSP using the input values in Table 3.14. The costs for electricity bought and sold over the RSP was set to be a fixed price per hour throughout the year and did not account for any seasonal fluctuations in pricing that would normally be the case. A dataset of the future trend expected for the price of electricity to 2050 was used to determine the growth rate (Statista, 2022a). The data showed an average increase of 0.5% with a maximum increase of 2.85%. Based in this a mid-point value was attained of roughly 1.5% and was used as the growth rate for electricity. The price for electricity bought from and sold to the Swedish electricity mix is based on the Nord Pool Spot price (IEA, 2021a). The selling price includes the 0.60 SEK/kWh tax reduction that is offered by the Swedish government currently. DH price was based on a mean price for multi-family buildings from a study that investigated DH pricing all over Sweden across service providers (Egüez, 2021).

$$NPV = \left[(A_0(1+i)^{-1}) \left(1 - \frac{(1+g)^n (1+i)^{-n}}{(i-g)} \right) \right] \quad (3)$$

Where:

A_0 *is the electricity or DH price for n = 0*
g *is the growth rate*
i *is the interest rate*
n *is the number of years (Reference study period)*

The energy prices per year were multiplied by the annual amount of electricity bought and sold over the RSP, adjusted in line with the PV degradation (section 3.4.5) within the GH script. The same was done for DH within the same section of the GH script. The total DH and electricity bought minus electricity sold resulted in the total energy purchased, giving an output of the total value of operational costs over the RSP.

Table 3.14: Input data for the LCC calculations

Description	Script input	Source or Method of calculating
PV production sold back to grid / (SEK / kWh)	1.24	National survey report 2020
PV production self-consumed / (SEK / kWh)	1.24	National survey report 2020
Swedish electricity mix purchased. / (SEK / kWh)	1.58	National survey report 2020
District heating / (SEK / kWh)	0.85	DH network ownership and prices study (Egüez, 2021)
Interest rate / %	2	Riksbank
Growth rate electricity price / %	1.5	Midpoint of average and maximum of future predictions
Reference study period / years	28	Based on European target for climate neutrality

There were numerous inputs into the GH script to calculate the initial cost based on all the various materials that were used for the passive and active measures to attain the *Initial cost*. The NPV of the accumulative annual operation cost from the RSP for that specific iteration, calculated using equation 3, was then added to the initial cost for that iteration to give the case specific total NPV cost calculated using equation 4. This was done for each single iteration through the GH script as shown in Figure 3.1.

$$Total\ NPV\ cost = Initial\ cost + NPV\ running\ costs \quad (4)$$

3.5.1 LCP, discounted payback period and ROI

The life cycle profit (LCP) was used to denote the profitability of each case by comparing the total NPV cost of the anyway renovation versus the total NPV cost of each of the various package iterations, using equation 5. Results of zero denoted the total NPV cost of the anyway renovation, a positive LCP result indicated the profitability of the iteration over the RSP, while a negative value indicated the loss over the RSP.

$$LCP = Total\ NPV\ cost\ of\ anyway\ renovation - Total\ NPV\ cost\ of\ improvement \qquad (5)$$

To calculate the discounted payback period for the various scenarios, the GH script was set up to calculate the annual discounted cumulative total operational cost of the anyway renovation and of each of the improvement cases for each year. The improvement was subtracted from the anyway renovation cost to get the operational cost difference for the two cases, representative of the discounted annual cumulative savings resulting from introducing the improvement. The discounted cumulative annual total savings for each year was then tested for when it was larger than the value of the difference of the initial cost of the improvement to the initial cost of the anyway renovation. The first year for when this is true is then extracted and recorded as the payback period.

The return on investment for each iteration is calculated using the same inputs that are used in the calculation of the discounted payback period using equation 6. This ROI is for the whole RSP of 28 years, with an annual representative value obtained from dividing by the number of years in the study period.

$$ROI = \frac{Current\ Value\ of\ Investment - Cost\ of\ Investment}{Cost\ of\ Investment} \text{ x } 100 \qquad (6)$$

Where:

$Current\ Value\ of\ Investment$	*Anyway renovation cumulative operational costs minus Improvement cumulative operational costs*
$Cost\ of\ Investment$	*Improvement initial investment costs minus anyway renovation initial investment costs*

3.5.2 Facade and roof renovation costing

The costing for facade and roof renovations was based on Wikells for the full addition to the wall construction including all layers as shown in Figure 3.3, including costing for scaffolding required for access during installation and a material lift to facilitate logistics. The breakdown of prices are shown in Table 0.1 and Table 0.2 of Appendix D . The costs of materials that are only used in a single thickness are shown in Table 0.1, while those with various thickness options are shown in Table 0.2. Unlike all other insulation types with a breakdown of installation based on time and wage cost, the cost for EPS was drawn from Wikells as a total construction cost considering a different installation and finishing method inclusive of labour cost. Scaffolding and material lift time and costs were based on time required for the respective trades of studwork, insulation installation, boarding and battens and final cladding.

3.5.3 PV system costing

The costing for the PV system was based on the same National Survey Report from where the electricity prices were sourced. The report provides average prices for turnkey grid-connected residential PV systems for various residential applications. For Multi-family houses with a 50–100 kW_{peak}, a turnkey price of 11.65 SEK/W_{peak} was indicated, this price was used to cost each PV system size as detailed in Table 0.3 of Appendix D The current 15% PV installations for private individuals is replaced by a tax deduction for installation of green technology. Through this incentive a 15% deduction for labour and material costs can be applied, based on the trajectory of the decreasing PV subsidies from the Swedish government, this incentive of the investment cost of PV is neglected in this study.

3.5.4 Window renovation costing

The first option for window renovation is to retain the existing windows, in this case there are no initial costs or future maintenance costs. The windows were treated as being in a satisfactory condition to last until the end of the maximum RSP of 28 years. Option two were storm windows, where an additional glazing panel is added to the current windows. These were priced in terms of their individual components as detailed in Figure 3.4. Option three was to install new triple glazed windows, removal cost of the old windows and transporting it away from the site was also accounted for. All detailed cost data can be found in Table 0.4 in Appendix D. The total cost for each of these window renovations were the only values used as inputs in the GH script.

3.5.5 Active measures costing

Two options were considered for the active measures, the first being the incorporation of an FTX system through façade integrated supply ducting, and the second being that of installing an EAHP for the heating of DHW. The costing data for both measures in terms of material and labour were sourced from Wikells and local Swedish manufacturers. Future costs associated with replacement, removal and disposal were discounted to NPV terms, with the future values assumed to remain in line with current prices in nominal terms. Further details are contained in Table 0.5 Appendix D.

3.6 Sensitivity analysis

The various sensitivity analysis options that were considers are based on the categories of how the results are presented, and as such the sensitivity analysis methodology is presented in the same breakdown withing each of the associated results and discussion sub-sections.

3.6.1 Decarbonisation

As the decarbonisation rate was highly influenced NollCO_2's definition, a sensitivity analysis of NollCO_2's offsetting considerations was necessary. The huge offsetting potential of on-site renewable energy being delivered back to the grid could play a more vital role in the decarbonisation of a renovation than many innovative material or circular design. Although NollCO_2 have conducted their own research to support their assumption that delivering renewable energy to the grid will prevent the use of coal for energy somewhere within the Nordic Pool (SGBC, 2020a), it cannot be taken as a guarantee. The sensitivity analysis looked at two extreme scenarios on either end of the spectrum with the idea that any other variation on the NollCO_2 offset values would fall somewhere in between.

The first scenario, an optimistic one, argued that if delivering renewable energy back to the grid meant offsetting coal in Nordic Pool on the premise that renewable electricity is cheaper than coal electricity, then why would self-consumed renewable electricity not carry the same merit. Sweden's electricity mix was 63% renewable, 88% of its production being low carbon (electricityMap, 2022) at the time of writing, and Sweden is typically an annual net exporter of their electricity, having a net export of 25 TWh in 2020 to countries within the Nordic Pool (Energimyndigheten, 2021). If grid-delivered energy from renewable, low carbon resources on site would offset coal use somewhere in the Nordic Pool, then why would renewable, low carbon electricity produced by the Swedish grid itself not have the same effect? In turn, by avoiding consumption of the Swedish energy mix due to self-consumption of on-site produced electricity, that renewable energy produced by the Swedish mix could be used elsewhere in the Nordic Pool, thus could offset coal. Therefore, the 'optimistic' sensitivity analysis of this study considered that self-consumption of on-site electricity would mean that coal would be offset by the Swedish electricity mix. This consideration was calculated using equation 7.

$$O_{self-consumption}{}^{n} = O_{coal}{}^{n} - I_{electricity}{}^{n} \tag{7}$$

Where:

$O_{self-consumption}$	*is the offset value considered for the self-consumption of electricity produced on-site*
O_{coal}	*is the NollCO_2 carbon offset value for coal, with an annual linear decrease to zero*
$I_{electricity}$	*is the NollCO_2 carbon impact value for electricity from the Swedish mix, with an annual linear decrease to zero*
n	*is the year considered*

While some coal offsetting by delivering renewable electricity is probable, it can be difficult to definitively say it will happen. The other scenario assessed in the sensitivity analysis considered that selling electricity produced on-site back to the grid would only offset the impact of the Swedish mix itself, which would be quite a pessimistic scenario. The means of calculating this value are specified in equation 8.

$$O_{delivered}{}^{n} = I_{electricity}{}^{n} \qquad (8)$$

Where:

$O_{delivered}$ *is the carbon offset value considered for the electricity produced on-site being delivered back to the grid*

$I_{electricity}$ *is the NollCO$_2$ carbon impact value for electricity from the Swedish mix, with an annual linear decrease to zero*

n *is the year considered*

3.6.2 Economic sensitivity

Changes in the economic climate could impact the viability of a solution, as such a sensitivity analysis was carried out on some of the economic factors that are could greatly impact the results. Values lower and higher than the base case values were used in the sensitivity analysis as detailed in Table 3.15.

The cost of borrowing money would need to be considered for a large initial investment as a direct financial cost, or if the money was available, this could have been invested in an alternative investment, which is an opportunity cost. The interest rate reflects the costs to borrow money, or the reward of money invested, along with associated risks. Interest rates are largely governed by the repo rate, the rate at which a country's central bank lends to commercial banks. In early 2022, the central bank of Sweden (Riksbank) had an optimistic view and looked to leave the repo rate unchanged, however Q1 of 2022 seen an unexpected rise, contrary to earlier forecasts (Trading Economics, 2022). Sensitivity is carried out using a value in line with the highest recorded values of interest over the last 25 years, with a lower value just above zero as shown in Table 3.15.

Electricity price growth rate variations were determined through analysis of two historic price trend datasets dating from 2010 to 2021 (Statista, 2022g), and 2008 to 2021 (Statista, 2022h). A third dataset of the expected future trend to 2050 was also (Statista, 2022b). The historic data, adjusted for inflation (Statista, 2022d), showed a large variation in price increases or decreases over the years. The future predictions gave a view of an average increase of 0.5% with a maximum increase of 2.85% and a minimum of -2.11%. Based on averages of values from the three datasets a lower growth rate value was determined, while the higher growth rate value was based on the maximum of the future predictions as shown in Table 3.15.

DH prices are multifaceted and not regulated by the Swedish state. Numerous factors, such as DH owner business decisions, municipal decisions, network size, local conditions, market share and local consumption, among others impact the DH price. Taxes, such as CO_2 tax and other financial instruments also can impact DH pricing. The base DH price assumed that in real terms, i.e. accounting for inflation, there was no growth on the price. Considering that DH prices are difficult to predict based on variations between systems, and evolving price models to better reflect variations between systems (Sköldberg & Rydén, 2014), a simplification was made for equally impactful values on either side of the current value as shown in Table 3.15.

Table 3.15: Higher and lower values of interest rate, electricity and DH growth rate for sensitivity analysis

	Lower value	Current value (Base case)	Higher value
Interest rate / %	0.5	2	4
Electricity growth rate / %	-0.8	1.5	2.85
DH growth rate / %	-1.5	0	1.5

The economic sensitivity was undertaken for the best performing envelope renovation case in terms of LCP that at a minimum incorporated at least every aspect of the passive iterations together with 80% PV.
27 economic permutations were undertaken, and there after 5 scenarios across the spectrum were chosen to be carried out for the same best case, with 0% PV to see the impact of buying and selling electricity. The five scenarios included the current values, as shown in Table 3.15, as a base case, together with the best and worst performing cases in terms of NPV over the RSP. The final two cases were a midpoint scenario between the best case and the base case, as well as a midpoint between the worst case and the base case.

3.7 Data handling

As a result of the parametric simulation approach, large amounts of data were obtained as results, approximately 11 300 individual iterations. The input and output parameters are summarised in Table 3.16. All input and output variables were connected to the Colibri components in GH, which recorded and exported all results to an Excel file. The guidance for which stemmed from the ongoing research of our co-supervisor.

Table 3.16: Breakdown of all input and output parameters considered in the study

Input parameters							Output values		
Façade Insulation Thickness	Façade Insulation Type	Roof Insulation Thickness	Roof Insulation Type	Window Type	Active Measure	PV System Size	Energy Demands	Carbon impacts	LCC
0mm 50mm 100mm 150mm 200mm 250mm 300mm 350mm	EPS GW (Glass wool) HF (Hemp fibre) WF (Wood fibre) CF (Cellulose fibre)	0mm 100mm 200mm 300mm 400mm	EPS CG (cellular glass) WF (Wood fibre)	Existing Storm Triple	None FTX EAHP	0% 20% 50% 80%	kwh/ $(m^2.A_{temp})$	$kgCO_2e$/ $(m^2.A_{temp})$	MSEK or % or years
							Heating & DHW Cooling	Embodied Operational Total	Initial Operational LCP ROI Payback period

The large amounts of data collected through the numerous simulations were then viewed on Design Explorer, an online data visualisation tool that used interactive parallel coordinates graphs. The tool had threads that could be followed for each iteration regarding its inputs and results. Ranges and filters could also be set to allowed for more focused assessment of specific cases. A diagrammatic representation of the Design Explorer overall input-to-output threads, as well as its interactive filtering abilities, can be seen in Figure 3.11.

As Design Explorer provided the level of control as described above, it allowed for singling out of a specific case, or a group of cases that should follow a certain trend. It was also used to verify the results by looking for outliers that did not conform to the overall trends. Where any discrepancies were found, these were investigated in the GH script to find the source of the error. Corrections or alterations were made and then re-simulated and further analysed. This process was repeated until no outliers were found and the overall trends aligned to the expected results.

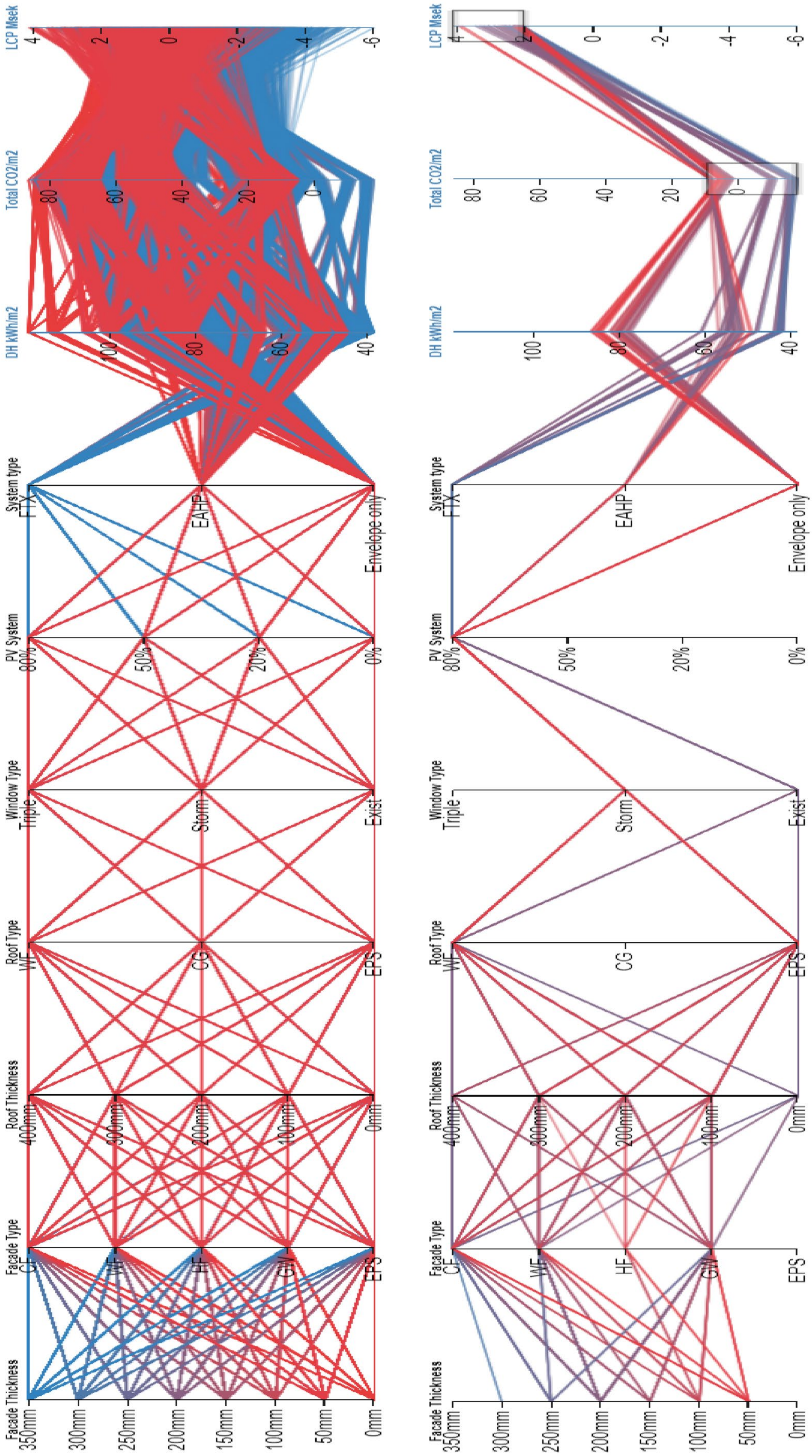


Figure 3.11: Screenshot of Design Explorer interface showing all renovation iterations as parallel coordinates for the seven input parameters and an example of three output values (left) and specific results based on the interactive filtering tools (right)

4 Results

The results of this study follow the chronological order of the progression through the study: the base case simulations and comparison to the archetype were first analysed and verified; an overall review of all iteration results was conducted to see how the spectrum of results related to the anyway renovation and to assess what were the key factors that influenced the trends; a more in-depth assessment of the better performing iterations was then undertaken in relation to their LCA and LCC aspects; and a sensitivity analysis was performed to determine the influence of the study parameters.

4.1 Base case verification

Table 4.1 compares the base case simulation annual results to the BBR archetype values and includes the margin of error between the heating demands.

Table 4.1: Comparison of base case GH simulation and BBR archetype annual energy demands

	Household electricity demand / kWh	**Property electricity demand / kWh**	**DHW demand / kWh**	**Cooling demand / kWh**	**Heating energy demand / kWh**	**Margin of error in heating / %**
BBR archetype	30	15	25	N/A	105	N/A
GH simulation	30	15	25	3	97	7.6

4.2 Overview of iteration results

This section contains the high-level overall results obtained through the 11 292 package iterations. The volume of results makes it challenging to interpret the individual characteristics of each result, therefore the purpose of the scatterplots herein is to rather offer a method of understanding the overall trends of the entire datasets. The section also breaks down the building electricity consumption vs. PV production for the PV systems studied and assess each sizes' decarbonisation potential.

The overall results obtained are broken down into two main datasets: the first assessing the envelope renovation packages independent of additional active measures to understand the weight and influence of each iteration variable. The second adds the active measures of EAHP and FTX system showing how these influenced the overall results. In Figure 4.1, a scatterplot diagram illustrates the relationship between the total carbon impact and the LCP of each envelope renovation for the RSP to 2050.

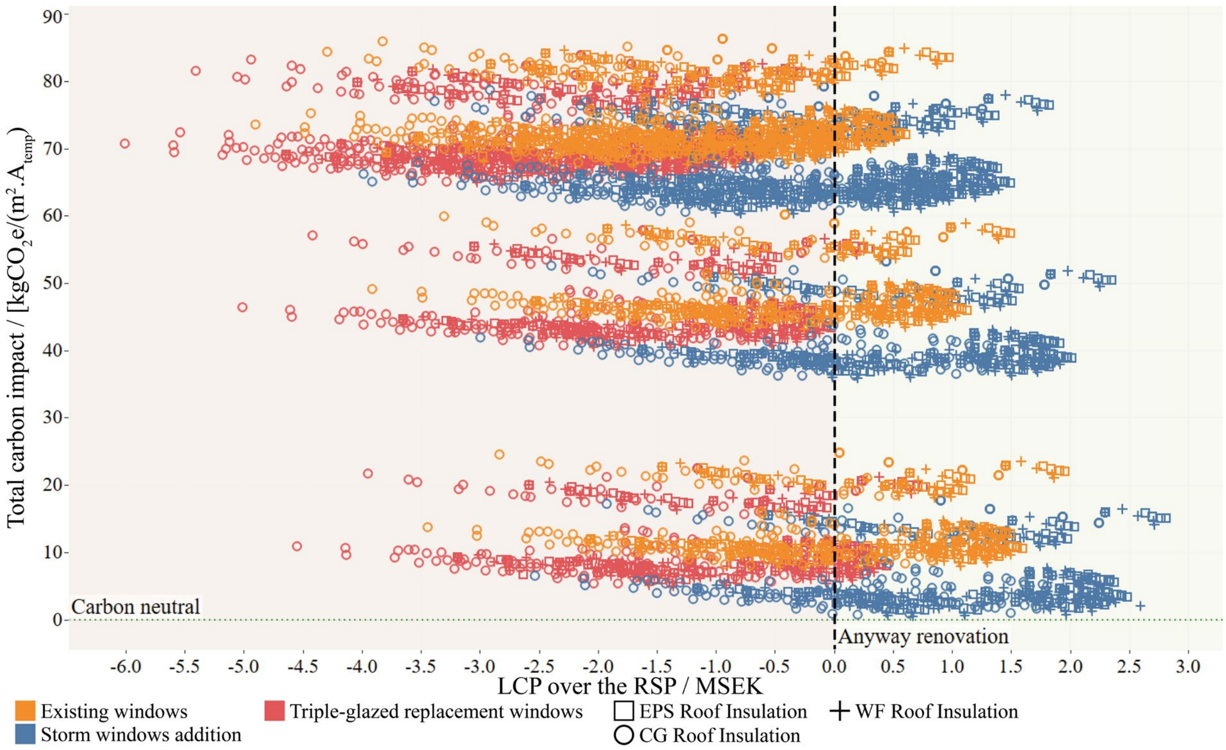


Figure 4.1: Scatterplot depicting the window types and roof insulation types of all the envelope renovation iteration results in terms of total carbon impact in kgCO$_2$e/(m^{2}A$_{temp}$) vs. LCP over the RSP in MSEK

The results of Figure 4.1 are separated by the cost of the anyway renovation, depicted as 0 LCP, with results to the left accounting for roughly 65% of iterations that are not profitable over the RSP, while those to the right represent the 35% of possible iterations that are profitable. Approximately 6% of all iterations were profitable and within 10 $kgCO_2e/(m^2.A_{temp})$ over the RSP of being carbon neutral. The three clusters of results are actually four clusters that represent the level of PV coverage installed, the top two clusters that overlap are those of 0% PV and 20%. The next cluster shows 50% PV coverage, with results largely in the range of 35 to 60 $kgCO_2e/(m^2.A_{temp})$ and -5 to +2.5 MSEK. The greatest decarbonisation rates are renovation packages paired with 80% PV coverage.

Figure 4.2 illustrates the overall trend in the results that after a certain point, it was typically neither environmentally nor economically feasible to undertake deeper levels of renovation. The trend is depicted by the increasing façade insulation thicknesses on the x-axis, but the data represented on the y-axis on the left is the overall average carbon impact of all iterations from Figure 4.1. The sum of the embodied and the operational impact for each bar equates to the average total impact. The circles relate to the secondary y-axis and represent the average LCP of each iteration. There were come iterations with higher thicknesses that were low-carbon and profitable, but they were for specific combinations of the iterations.

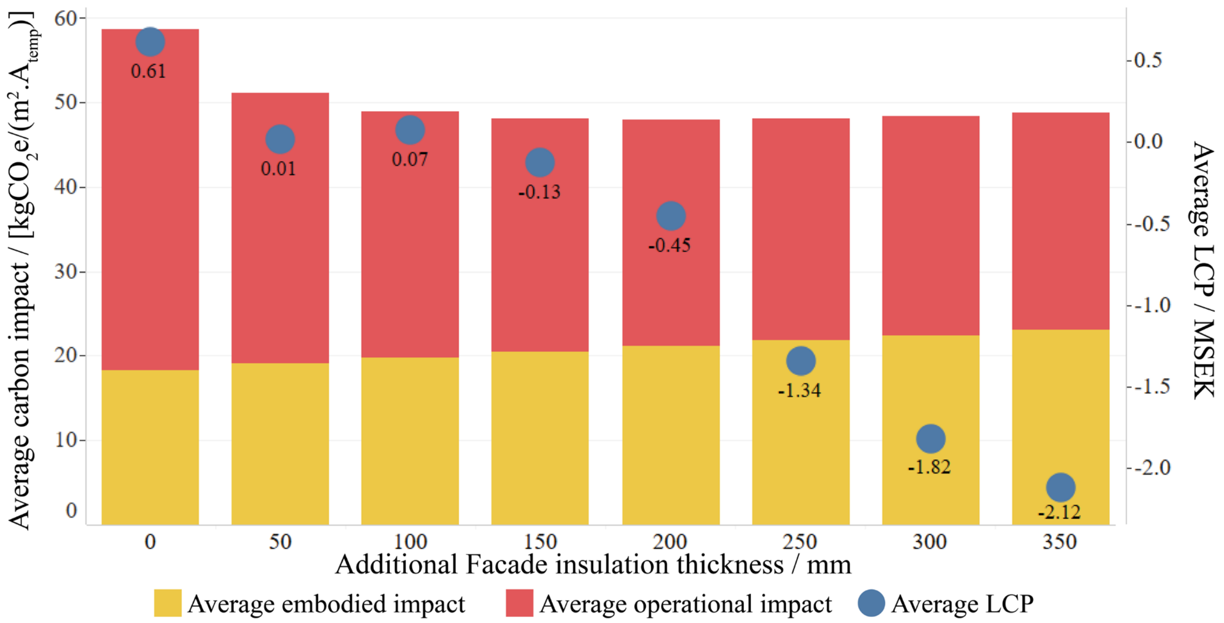


Figure 4.2: Combined stacked bar and scatterplot graph depicting the average carbon impact (left y-axis) and LCP (right y-axis) of all iterations with respect to increasing facade insulation thickness

The LCA of the additional active measures to the envelope iterations are presented in Figure 4.3, using the same scatterplot presentation technique as the Figure 4.1. The results showed that the FTX system outperformed the EAHP iterations in terms of total carbon impact, with only FTX system options reaching carbon neutrality. The best performing FTX system reached a carbon impact of -17.9 $kgCO_2e/(m^2.A_{temp})$, while the EAHP has a best-case carbon impact of 7.1 $kgCO_2e/(m^2.A_{temp})$, denoting an improvement of over 350%. There were 233 packages involving the FTX system that reached carbon neutrality and had a positive LCP, all of which were coupled with having 80% PV coverage on the roof. However, in terms of LCP, the packages with the EAHP showed the most profitability reaching a best value of around 4.123 MSEK, 18.5% higher than the best case of the FTX system of 3.48 MSEK.

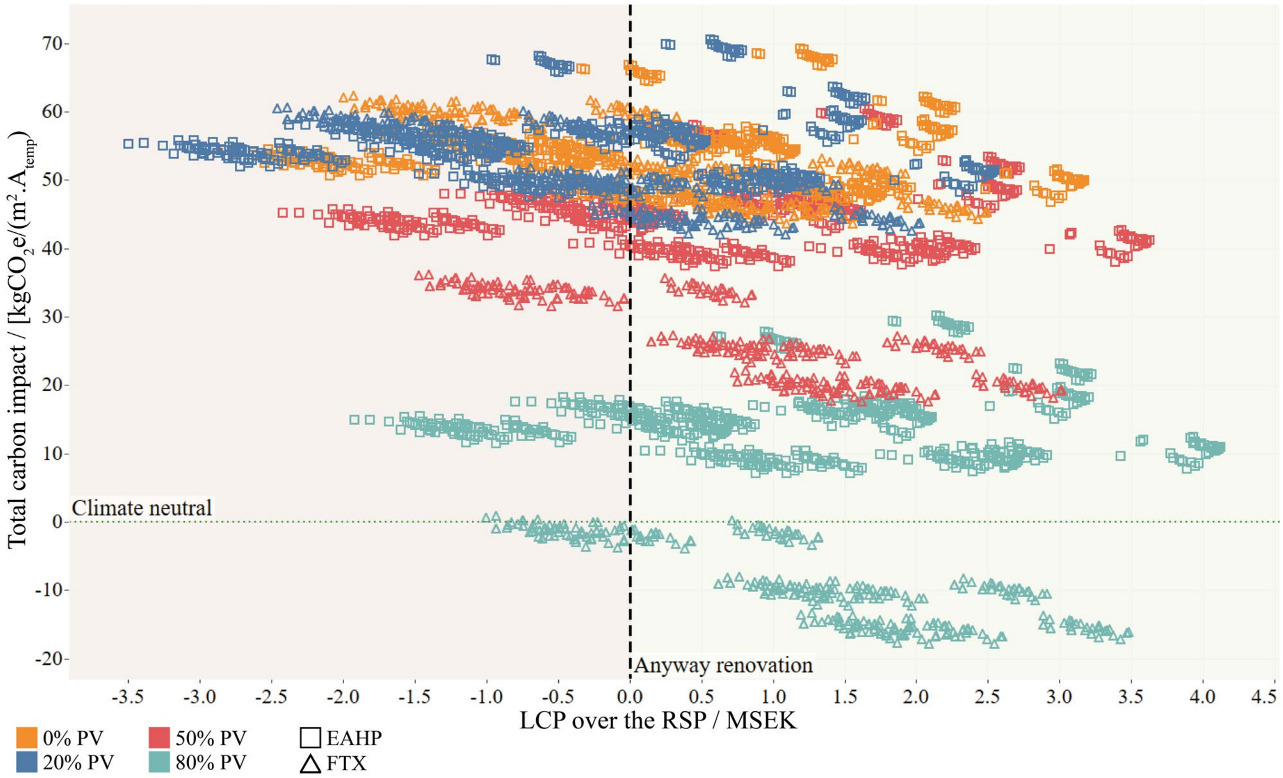


Figure 4.3: Scatterplot depicting the active system type and PV system size of the active package iterations in terms of total environmental impact in kgCO$_2$e/(m^{2}A$_{temp}$) vs LCP over the RSP in MSEK

4.2.1 Electricity consumption vs PV production

This section analyses the influence each PV system had on the total carbon impact. The results shown are irrespective of any heating demands and focus purely on the production vs consumption of electricity, as that was the only means of offsetting the carbon impact. All iterations that focus on reducing the heating demand can only ever reduce the positive carbon impact, never offset it. The only variation in electricity consumption in the study came from the EAHP, which increased the hourly demand, thus the two consumption profiles reviewed in the subsection represent the potential carbon offset values of all iterations considered in the study.

Figure 4.4, depicting the hourly production profile of each PV system over the course of the year, illustrates the increased levels of electricity production proportional to the PV system size.

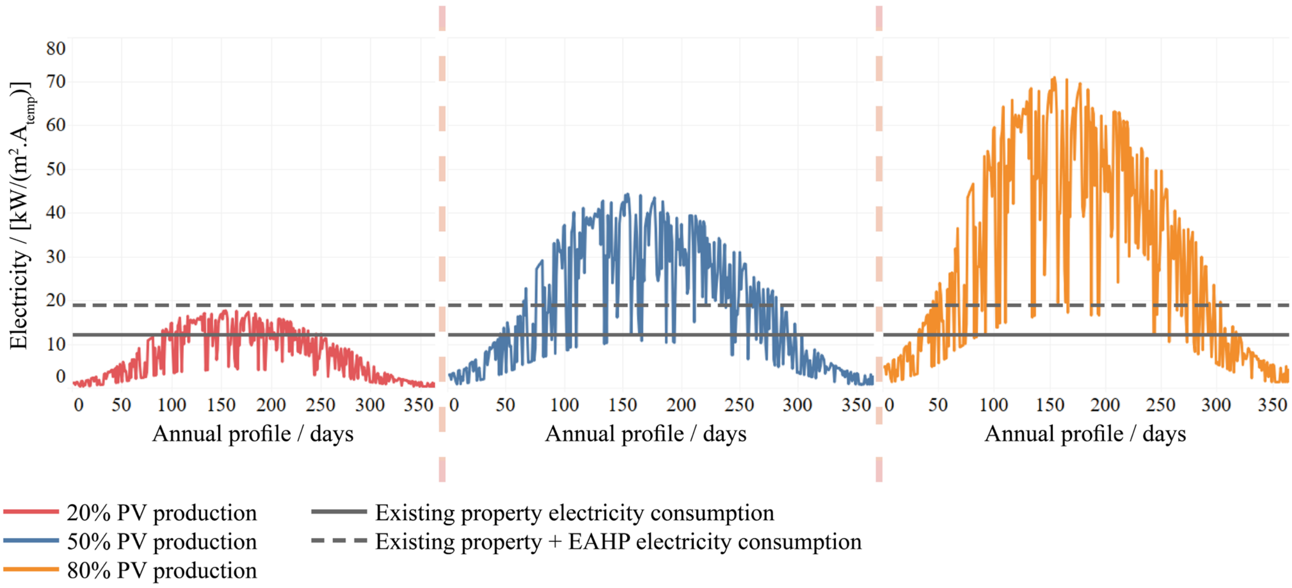


Figure 4.4: The annual electricity consumption profiles of the property energy scenarios of the study, vs the annual PV production profiles of the 20% (left), 50% (middle) and 80% (right) PV system sizes

Self-consumption of PV production relates to the inner area where the PV production profile is below the line of property electricity consumption in Figure 4.4. There was a more notable difference in the amount available to sell back to the grid, depicted by the PV production curve being above the line of property electrical consumption. The dashed horizontal line illustrates the increased consumption of the EAHP, in turn effecting the amount of overproduction. The overproduction of each PV system correlated to its carbon offset potential for the building.

Figure 4.5 depicts the annual accumulating carbon impacts for the six possible electricity demand options used across all iterations. These options were the only means of carbon offset potential considered in the study, therefore played a significant role in each iteration's decarbonisation potential. The y-axis conveys the positive carbon impact or negative carbon offset value in the LCA functional unit of $kgCO_2e/(m^2.A_{temp})$. The initial positive values represent the embodied carbon of each PV system. The x-axis is the accumulating carbon impact on a year-to-year basis over the RSP, from construction in 2022 to European climate neutrality in 2050, after which there would be no more coal offset potential. The four cases that have an overall negative impact have offset themselves by 2030. The extra electricity demand of the EAHP had a significant impact on the 80% and 50% PV system offset potential and eradicated any offset potential for the 20% PV.

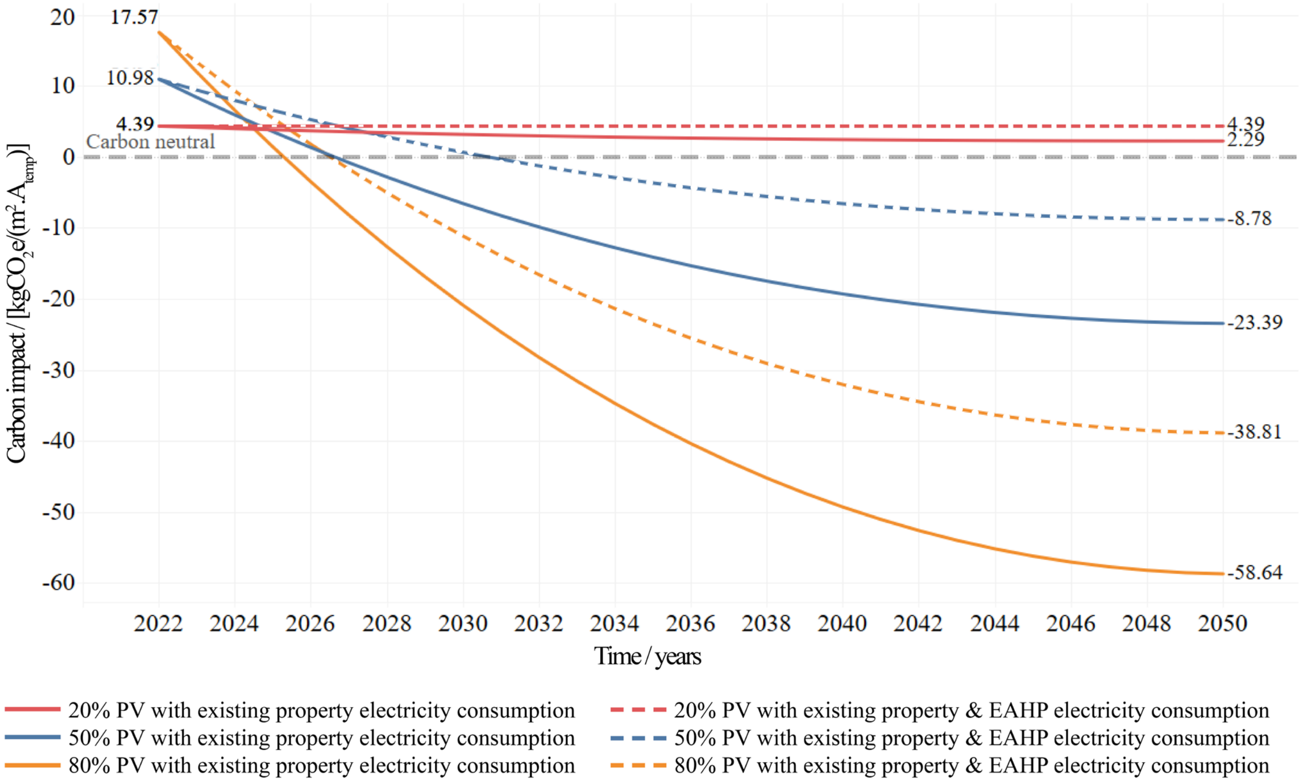


Figure 4.5: Annual accumulating carbon impact of each PV system size over the RSP used across all iterations, for both property electricity consumption profiles of including or excluding an EAHP

4.3 Decarbonisation

As seen in the overview of results above, some of the envelope measures alone were enough to be on the brink of carbon neutrality by 2050, when paired with and 80% PV system size. Furthermore, if the extra measures of the FTX system installation were applied, some cases were well below climate neutrality by 2050. This section assesses the renovation iterations that came closest to climate neautrality for the envelope renovations and EAHP iterations, and those that reach climate neautrality for the FTX.

Figure 4.6 is a parallel coordinates graph that shows a simplified number of cases over the spectrum of the 50 best performing envelope renovations regarding their decarbonisation potential. The top 50 cases all had some level of at least 150 mm of façade insulation, as well as storm windows and 80% of the roof area used for a PV system. In the figure, the colour of the lines corresponds to the thickness level of the façade insulation as it had the most variables. The main consideration for the results of this graph was the 'Total carbon $/kgCO_2e/m^2$)', which is situated at the end of the graph. Other outputs inculded alongside the total carbon impact were the annual DH demand, a breakdown of the embodied and operational CO_2, and a high-level LCC analysis.

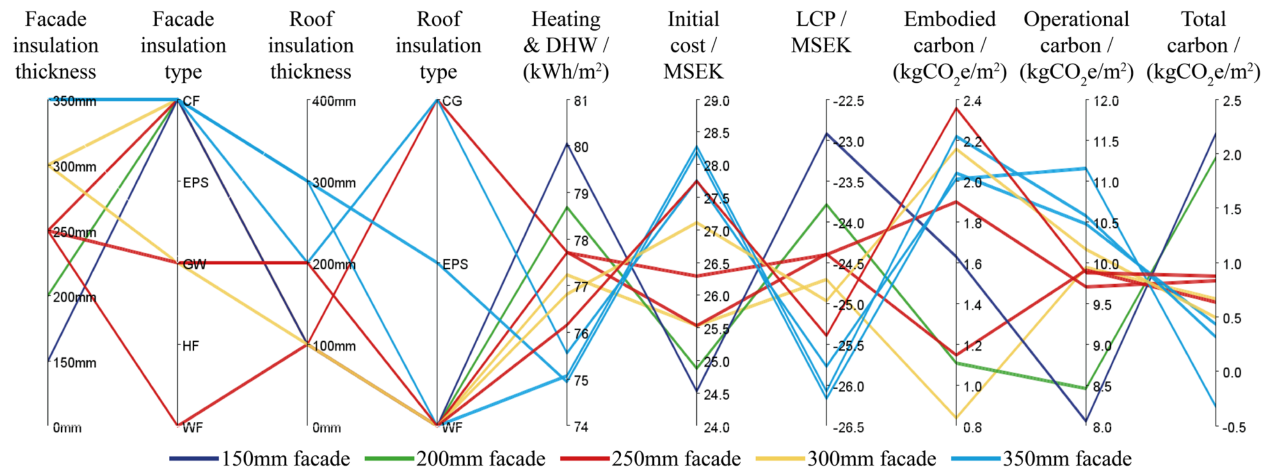


Figure 4.6: Parallel coordinates graph of a simplified number of cases representing the spectrum of the 50 envelope renovation cases with the highest decarbonisation rate over the RSP to 2050

Neither EPS or hemp fibre façade insulation were among the best performing decarbonisation cases, with lower thicknesses of hemp fibre falling just short of the cut. Some level of roof insulation was needed, but the higher thicknesses had a greater influence of increasing embodied carbon rather than decreasing operational. As mentioned storm windows and 80% PV were both necessary for all the best decarbonisation potential cases. 300 mm of cellulose fibre facade insulation with 100 mm of wood fibre roof insulation had the greatest decarbonisation potential with only 0.84 $kgCO_2eq/(m^2.A_{temp})$, however it was among the lower profitability outcomes with respect to the other best cases. By decreasing to 150 mm cellulose fibre insulation, the total carbon impact rose slightly to 1.63 $kgCO_2eq/(m^2.A_{temp})$, however the 3 MSEK saved in the initial costs meant it was roughly 1.6 MSEK more profitable by 2050.

The trends among the best 50 EAHP and FTX cases was similar to those shown in Figure 4.6, thus the comparision was not repeated. A comparison between decarbonisation potential of the anyway renovation and one of the best performing cases that resonated throughout the envelope only, the EAHP and the HVAC iterations was performed instead to illustrate the influence of the additional active measure options. The best performing case common amongst the envelope renovations alone, the EAHP and the FTX iterations in Table 4.2:

Table 4.2: Case with the highest decarbonisation potential common across envelope renovations only, and with an additional EAHP or FTX system

Façade insulation type	**Façade insulation thickness**	**Roof insulation type**	**Roof insulation thickness**	**Window type**	**PV system size**
Cellulose fibre	250mm	Rigid wood fibre	100mm	Storm window	80% of roof area

The comparison of the cases was twofold: firstly, a detailed assessment of the embodied carbon was broken down into the main elements that affected the A1-A3 and B4 stages, as per Figure 4.7; then Figure 4.8 depicts an overall carbon balance of each case by 2050.

The breakdown of the main elements in Figure 4.7 are noted in the figure legend. With all envelope iteration parameters the same, the difference between the improved renovation results was the affect of the respective active measure's additional embodied carbon and the impact of replacing the EAHP or AHU after their 20 year lifespan. As mentioned in the methodology, an equidistance of 130 km was assumed for all transport distances. The FTX also considered slightly higher construction energy use, to account for the core drilling for diffusers on the wall and extra crane use for the AHU instalation. The impact of the PV system life cycle for the improved cases was not shown in order to maintain a readable scale, as the carbon impact from the 80% PV system was 17.6 $kgCO_2e/(m^2.A_{temp})$.

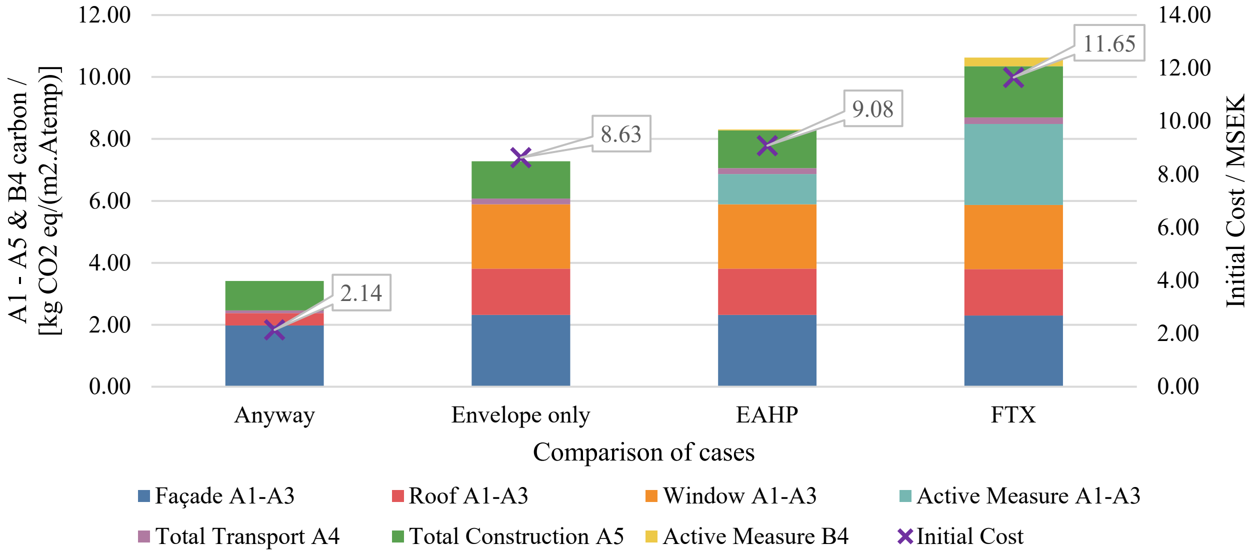


Figure 4.7: Breakdown of the A1 - A5 & B4 impacts for the anyway renovation and the common case with the lowest accumulated emissions between the envelope only, EAHP and FTX iterations, also including the initial costs on the secondary axis and in the callout tabs

Figure 4.8 assessed the total carbon impact of the above cases of an RSP to 2050. The embodied carbon shown is a sum of the breakdown of each iteration assessed in Figure 4.7, along with the A1-A5 and B4 impacts of the 80% PV system. The operational CO_2e is broken down into the positive impacts of the DH and electricity consumption, and the offset from PV production delivered back to the grid. A sum of the total positive impact or offset values are noted at the ends of each stacked column.

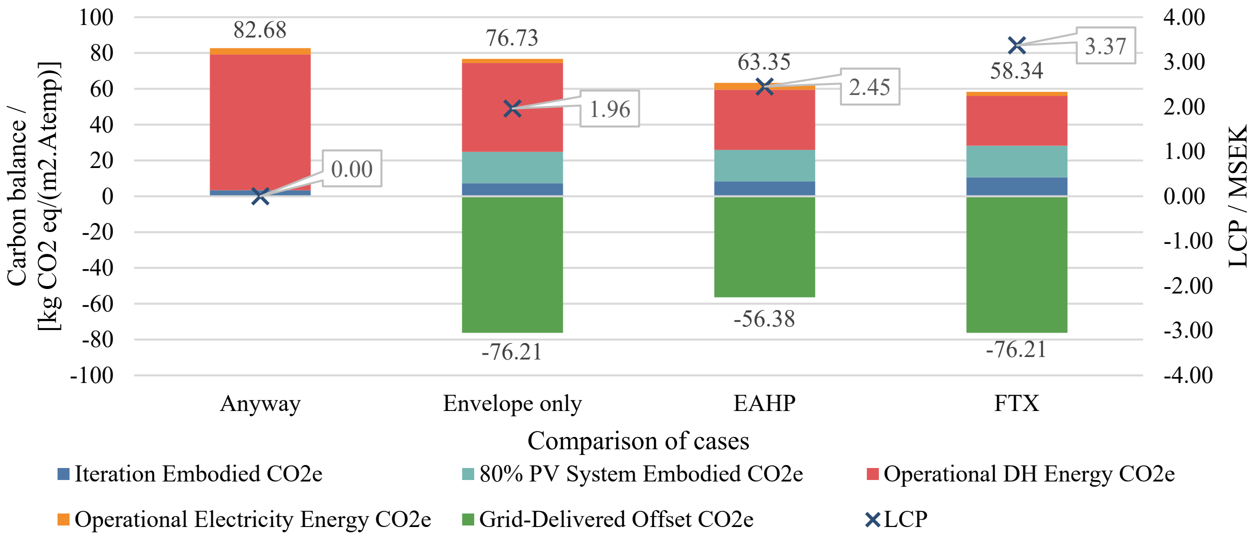


Figure 4.8: Carbon balance of the cases over an RSP to 2050, including the LCP on the secondary axis and in the callout tabs

The anyway renovation only consisted of maintenance of the building and had no means of offset. The sum of the iterations' embodied impact was less than half of the embodied carbon of the 80% PV system. However, the operational offsetting of the PV was greater than any reduction in the heating impact. The addition of an FTX system would decrease the overall positive carbon value to roughly 58 $kgCO_2e/(m^2.A_{temp})$, making it the only case in the comparison to reach carbon neutrality. Table 4.3 gives an indication of how the cases performed without PV, as the iterations had some of the highest decarbonisation potential of their iteraion variables when exluding the impact of PV also.

Table 4.3: Total carbon impact of the cases above including and excluding the impact of the 80% PV system

	Envelope only	**Envelope & EAHP**	**Envelope & FTX**
With 80% PV system	0.52	6.97	-17.87
With no PV	59.16	45.78	40.77

4.4 Profitability

This section considered the main criteria of LCP over the RSP to ascertain the most profitable solutions for all package iterations. With the best cases across the board incorporating the 200mm EPS roof insulation, storm window and 80% PV.

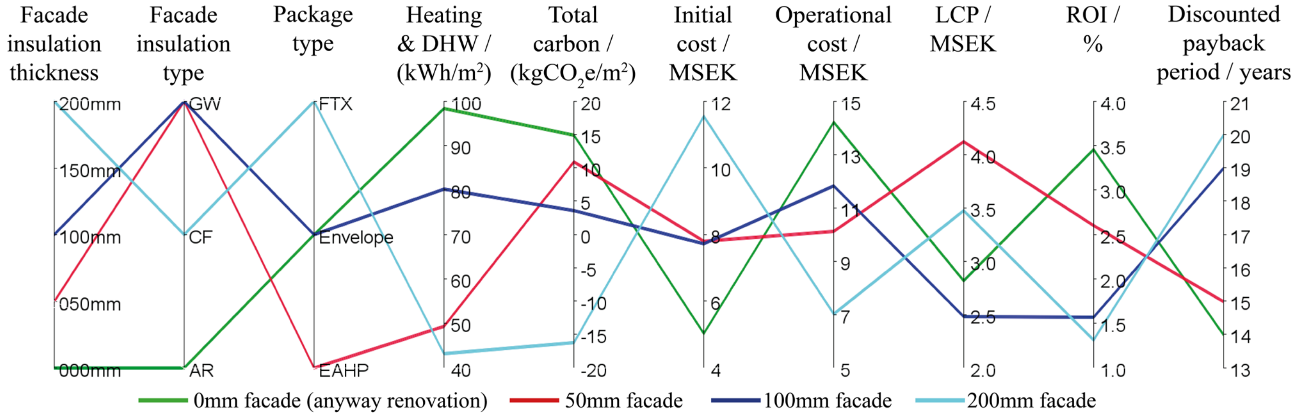


Figure 4.9: Parallel coordinates graph showing non common input parameters of best profitable cases over the various package iterations

Figure 4.9 shows the best cases in a parallel coordinates graph, with insulation thickness as a colour indicator to track the results through the various input parameters and output results. The anyway renovation (AR) applies when no wall insulation is added. The best case of EAHP, was the only case with 50 mm facade insulation, and the highest LCP of 4.123 MSEK, followed by the best case of FTX system with 3.480 MSEK, the third most profitable is the passive option without any facade insulation at 2.815 MSEK, the least profitable of these options is the passive improvement with some level of insulation. The most profitable option has the second lowest payback period of 15 years, while the second most profitable option of FTX system has the longest payback period of 20 years followed closely by the passive improvement with facade insulation at 19 years, the lowest payback period is for the passive improvement with no facade insulation at 14 years. The results further show the option with the shortest payback time has the highest carbon impact, while the option with the longest payback period has the lowest carbon impact of -16.11 $kgCO_2e/(m^2.A_{temp})$ over the RSP. Below the best results are shown for the independent envelope measures, and EAHP or FTX.

4.4.1 Envelope renovations

The envelope only renovations showed that the most profitable cases were those that had no insulation on the facade, with eight out of the top ten cases being a combination of improvements that only included the AR. Figure 4.10 shows this trend through a parallel coordinate graph where the insulation type on the facade in used as the colour indicator, with blue as WF, red as glass wool and green as the AR. The eight iterations with no facade insulation had an LCP that ranged from around 2.82 to 2.58 MSEK and a carbon impact of around 15 $kgCO_2e/(m^2.A_{temp})$. Whereas the best performing iteration with facade insulation in terms of LCP, dropped the total carbon impact by roughly 73% to 3.92 $kgCO_2e/(m^2.A_{temp})$, with only a 0.35 MSEK difference in LCP.

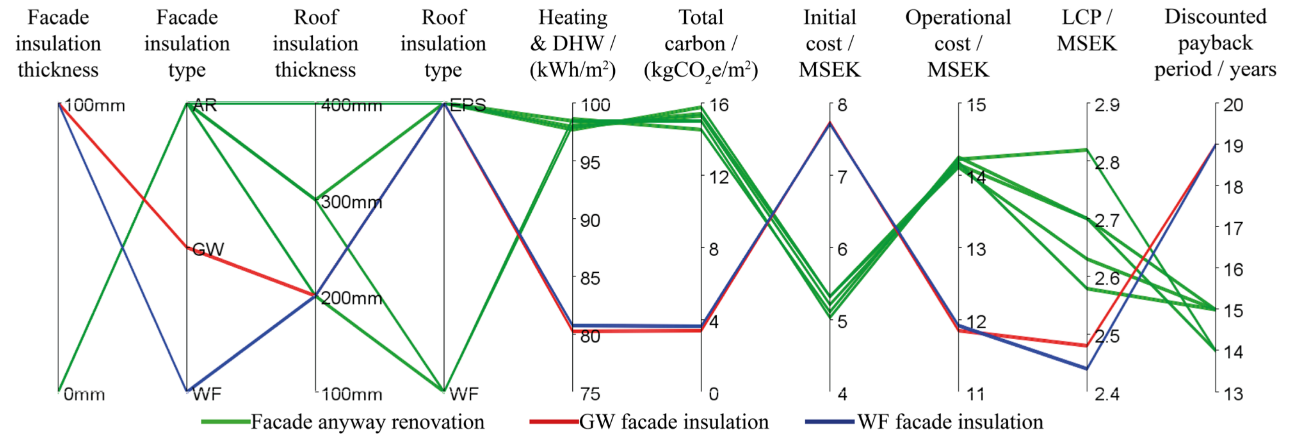


Figure 4.10: Parallel coordinates graph showing non common input parameters of top 10 most profitable cases over the various passive package iterations

4.4.2 FTX system

For the FTX, only the top five cases that were the most profitable were looked at, as these were also the cases with the lowest environmental impact over the spectrum. The cases were all with only 200 mm CF facade insulation and various thicknesses of roof insulation from 200 mm to 300 mm of either EPS or rigid WF. All cases had the same window treatment of a storm window, with 80% PV coverage. As shown in Figure 4.11, the LCP of all five cases ranged from around 3.48 to 3.35 MSEK with payback periods of 20 years, and one case of 19 years for the second most profitable option.

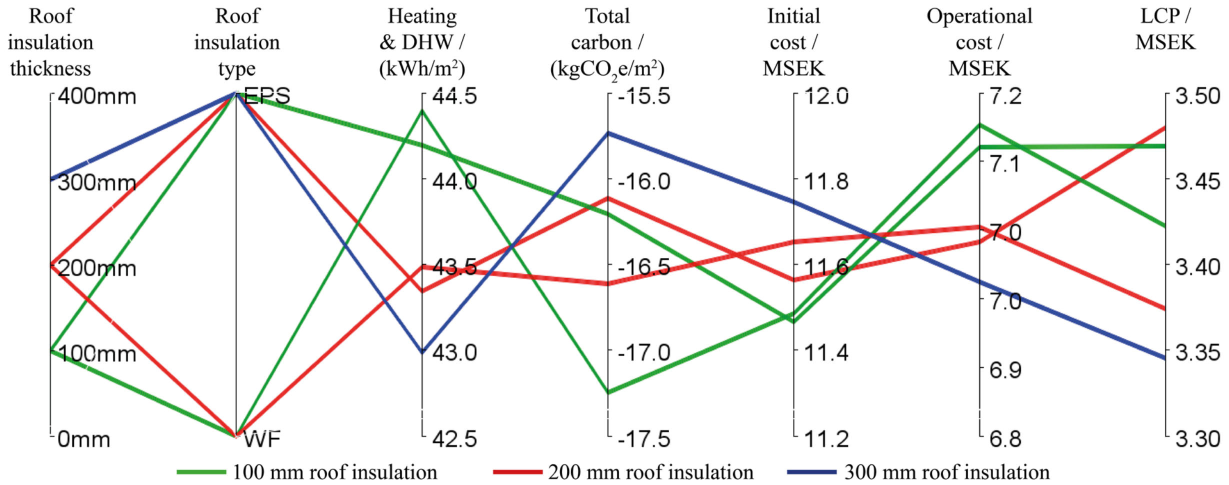


Figure 4.11:Parallel coordinates graph showing non common input parameters of top 5 more profitable FTX system cases over the various active package iterations

4.4.3 EAHP

The top 10 results were again considered, as was the case with the passive measures to ascertain the trend of the top performing cases in terms of profitability. Figure 4.12 shows that with the EAHP, all the cases were a variation of EPS or wood fibre of roof insulation in the range of 100 mm to 300 mm thickness, the thickness level was used for the colour range of the lines within the parallel coordinates graph. The cases also had only 50 mm of facade insulation of either glass wool, wood fibre or cellulose fibre. All these cases were those that had a storm window introduced and 80% PV coverage, all the top 10 cases also had a payback period of 15 years. The best performing case provided an LCP of 4.12 MSEK and was the case of having 50 mm glass wool insulation on the facades, with 200 mm EPS insulation on the roof and the introduction of the storm and 80% PV. These last two variations of storm window and 80% was noted as a commonality among the top 25 best cases with an EAHP. The parallel coordinates graph in Figure 4.12 excludes all common aspects among the cases being 50 mm of facade insulation, storm windows, 80% PV and a payback period of 15 years.

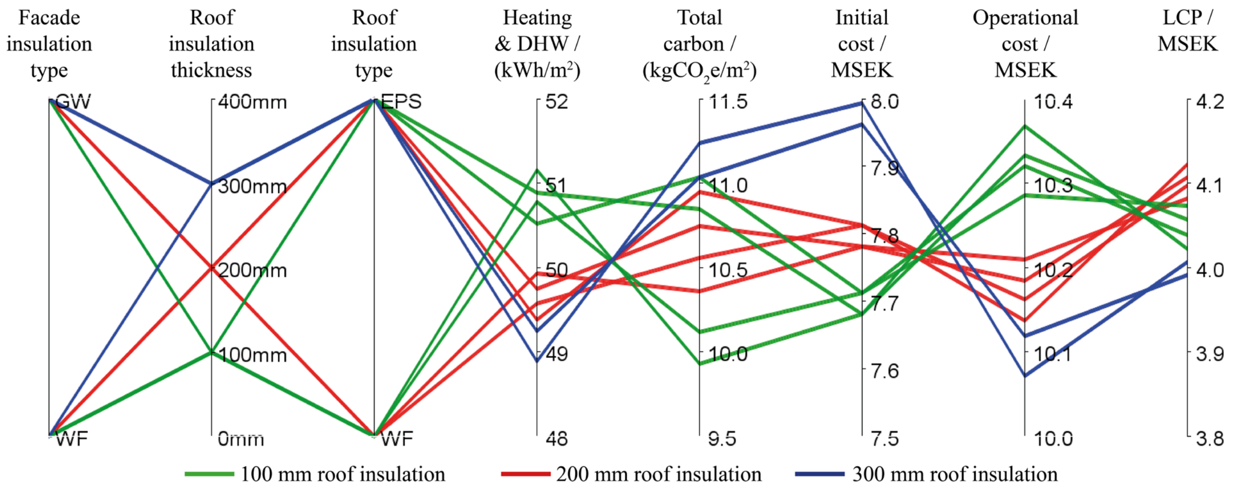


Figure 4.12: Parallel coordinates graph showing non common input parameters of top 10 more profitable EAHP cases over the various active package iterations with either glass wool (GW) or wood fibre (WF) façade insulation and EPS or wood fibre (WF) on the roof

4.5 Budget limitations

The results for this section were based on what level of initial investment a building owner would be willing to put into the project, and from there determine what options are most profitable as well as best from a carbon impact perspective. The initial costs for the anyway renovation was calculated to be slightly lower than 2.140 MSEK, being the minimum investment required. The most expensive renovation that still had a positive LCP was that of 250 mm wood fibre insulation on the facades, 300 mm EPS on the roof, introduction of triple glazed windows and 80% PV with installing the FTX system, costing 15.543 MSEK. Based on this, four increments of investment above the anyway renovation costs and below this most expensive option were explored. The first budget limitation was 3 MSEK, the second was 7 MSEK, the third was 11 MSEK and the fourth was 15 MSEK, which meant the most expensive solution was not a possibility. These ranges are simply an indication and are not formed based on any specific logic. The best case for carbon impact (LCA) and LCP were evaluated in each case and are presented in Table 4.4.

Table 4.4: Breakdown of best options in terms of carbon impact and LCP for the various initial investment budget limits

Budget limit	Best in terms of	Façade Thickness	Façade Type	Roof Thickness	Roof Type	Window Type	PV System coverage	Package type	Total CO2 / (m^2.A_{temp})	Initial Cost / MSEK	LCP / MSEK	Payback Period / years
3 MSEK	LCP	0mm	-	200mm	EPS	Exist	20%	Passive	83.49	2.81	0.970	11
	LCA	0mm	-	100mm	WF	Exist	0%	EAHP	68.05	2.856	0.711	10
7 MSEK	LCP	0mm	-	200mm	EPS	Storm	80%	EAHP	21.52	5.572	3.221	13
	LCA	50mm	CF	100mm	WF	Exist	80%	EAHP	15.08	6.771	2.960	16
11 MSEK	LCP	50mm	GW	200mm	EPS	Storm	80%	EAHP	10.95	7.813	4.123	15
	LCA	200mm	CF	100mm	WF	Exist	80%	FTX	-11.52	10.448	2.833	20
15 MSEK	LCP	50mm	GW	200mm	EPS	Storm	80%	EAHP	10.95	7.812	4.123	15
	LCA	250mm	CF	100mm	WF	Storm	80%	FTX	-17.87	12.457	2.545	22

As shown in Figure 4.13, for the first budget limit had 87 possible variations of the passive package only with none having a carbon impact below 5 or 10 $kgCO_2e/(m^2.A_{temp})$. For the second limit, there were 1878 possible variations that included passive packages as well as 604 EAHP options, again none of these provided a carbon impact below 5 or 10 $kgCO_2e/(m^2.A_{temp})$. The third budget limit had 4385 possible variations, of which 1623 were EAHP options and 251 options with the FTX system. At this point the amount of options that affected the carbon impact rose to having 592 cases where the total carbon impact was below 10 $kgCO_2e/(m^2.A_{temp})$ and 283 options below 5 $kgCO_2e/(m^2.A_{temp})$. The final budget limit increased the potential options to 5160, with 1711 EAHP options and 935 FTX system options. The carbon friendly options rose further to 532 cases where the total carbon impact was below 10 $kgCO_2e/(m^2.A_{temp})$ and 864 options below 5 $kgCO_2e/(m^2.A_{temp})$.

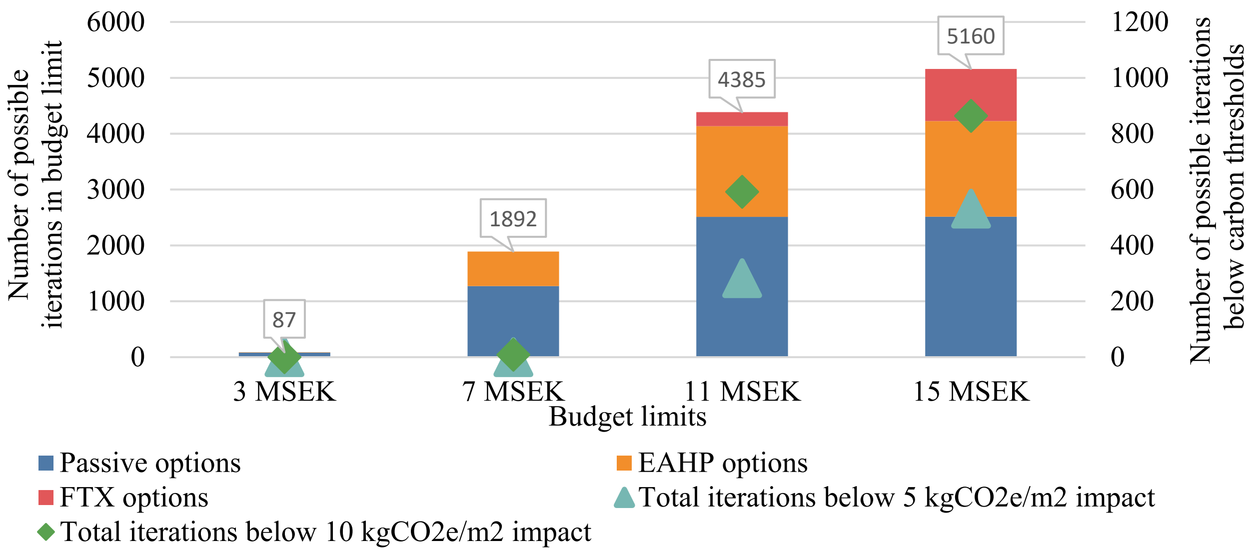


Figure 4.13: Breakdown of number of possible options across package types for the various budget limits on initial investment and cases below 5 or 10 $kgCO_2e/(m^2\ A_{temp})$.

4.6 Sensitivity analysis

This section reviews the different outcomes of both the LCA and LCC analysis, subdivided into their respective assessments.

4.6.1 Decarbonisation

The sensitivity analysis of the decarbonisation potential compared the accumulating carbon impact until 2050 for each PV size on the best decarbonisation case aforementioned in Table 4.2. This case was chosen as it was less than 1 $kgCO_2e/(m^2.A_{temp})$ above carbon neutrality by 2050 with 80% PV, thus the scale of any sensitivity analysis would be easily comprehendible. The other PV system sizes for the same case were also included to observe if there would be any change in the best size for decarbonisation potential. Finally, the anyway renovation with the different PV sizes were also included to see how close the more 'optimistic' sensitivity analysis option could bring them to climate neutrality with no other measures taken. Moreover, their inclusion helped to estimate how the other iterations not shown would be affected, as most fell somewhere on the spectrum between the anyway renovation and best case, for each PV system size. The two 0% PV cases acted as controls for each test, as any alteration to the electricity offset value would not affect them.

Figure 4.14 depicts the total carbon impact for the current NollCO_2 definition. The y-axis representing the carbon value in $kgCO_2e/(m^2.A_{temp})$ and the x-axis containing the yearly value up to 2050. The characterisation of each line can be observed in the figure legend. The initial 2022 values are the embodied impact of each case with the trajectory to 2050 dependent the carbon balance of each year.

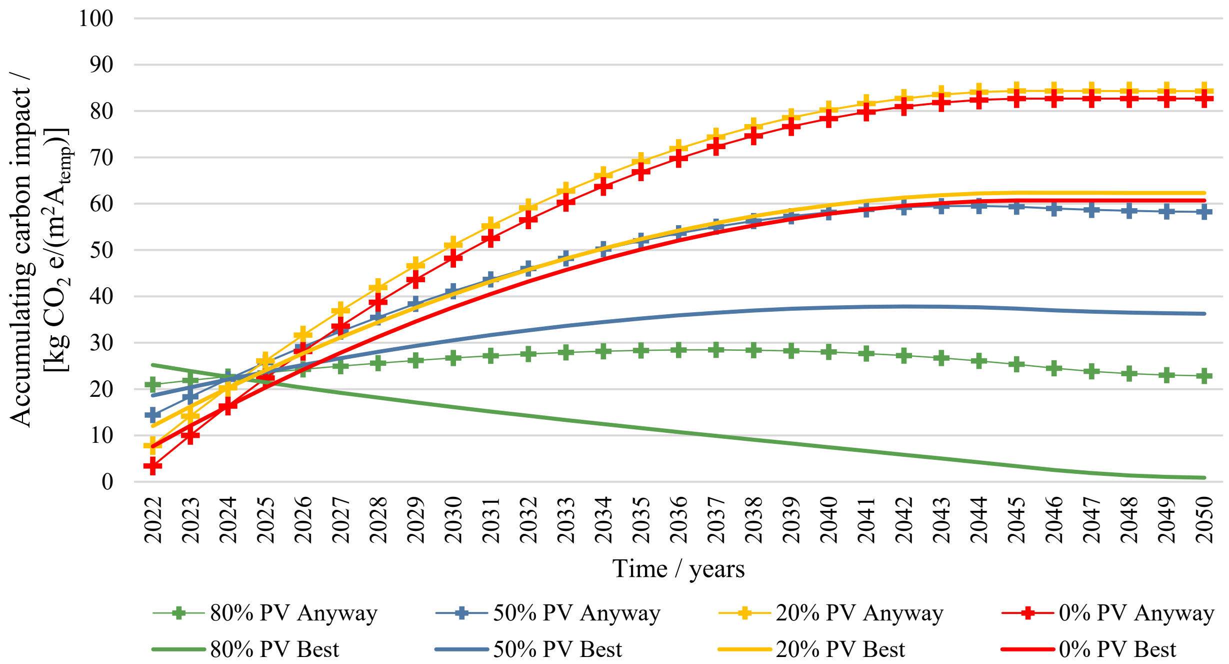


Figure 4.14: Accumulating impact of the current NollCO_2 offset potential consideration over an RSP to 2050

The best case with 80% PV had the highest embodied carbon, but the reduction in heating demand and high level of PV overproduction meant it was on a constant negative trajectory. The notable change in trajectory at year 2045 depicts when the positive impacts from DH and electricity consumption from the respective Swedish mixes are neutral, but the offsetting of coal continued until 2050. 50% PV with the anyway renovation had better decarbonisation potential than implementing the envelope improvements with little or no PV installed. Most cases overlapped with each other within the first five years, reiterating the huge offset potential of on-site renewable energy under the current NollCo$_2$ considerations. 20% PV had a higher total carbon impact than not installing a PV system.

Figure 4.15 conveys the 'pessimistic' or neutral sensitivity consideration of overproduction delivered to the grid only offsetting within Sweden instead of the Nordic Pool. The trajectory of the PV system sizes inverted, with 80% PV on the anyway renovation almost reaching 100 $kgCO_2e/(m^2.A_{temp})$ by 2045, which was much higher than considering the anyway renovation by itself. The offset potential of PV is rendered negligible, no

PV system ever offset enough to even cover its own embodied impact. There was much less overlap between cases as there was little-to-no means of negative carbon impact by offsetting the low-carbon Swedish mix.

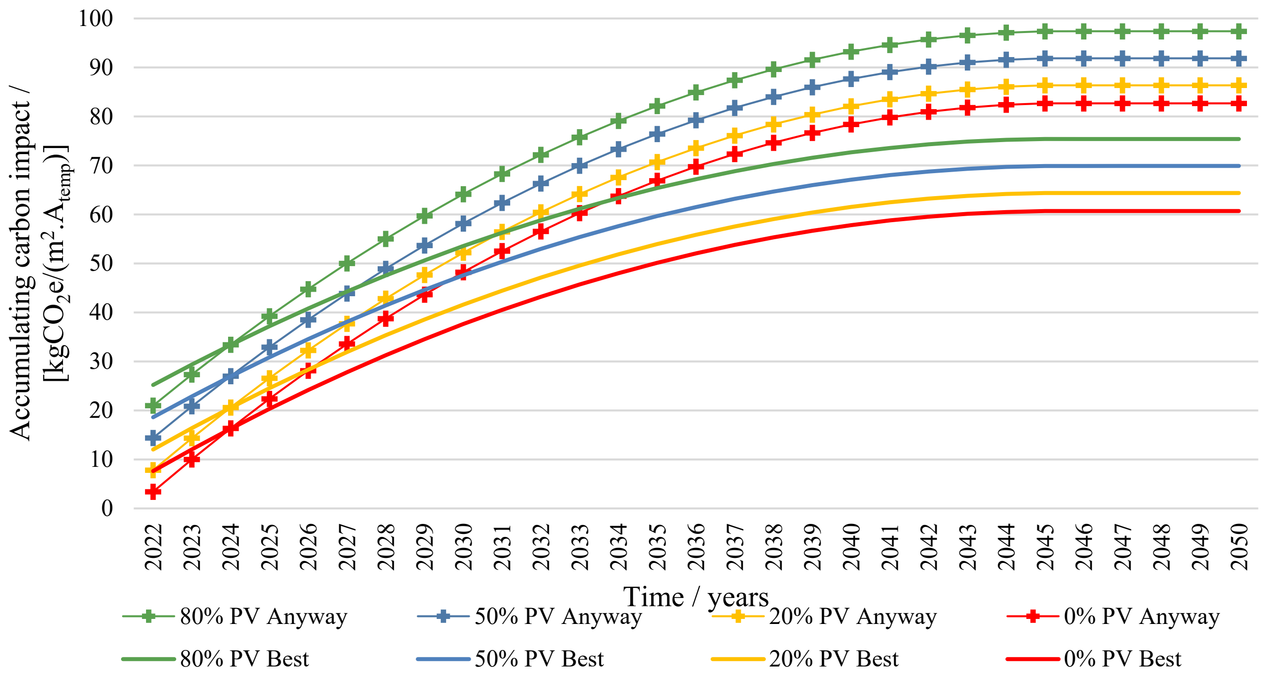


Figure 4.15: Accumulating impact of the 'Pessimistic' offset potential consideration over an RSP to 2050

Figure 4.16 portrays the ‘optimistic’ sensitivity consideration of self-consumption of a PV system having almost the same offset potential as delivering back to the grid, minus the positive impact from the Swedish energy mix itself. With this consideration the anyway renovation with 50% PV had a total carbon impact of roughly 10 kgCO$_2$e/(m^2.A$_{temp}$), which was half the value of the anyway renovation with 80% PV under the current NollCO$_2$ values. A 20% PV system was now a viable option for offsetting as it was mostly self-consumption. With this consideration, 20% PV with the anyway renovation had a higher decarbonisation potential than the best case with no PV. Three cases were now below carbon neutrality, with the best case 80% PV becoming carbon neutral by 2028 and having a total carbon impact of roughly -55 kgCO$_2$e/(m^2.A$_{temp}$) by 2050, which was three times lower than the outright best case from the study.

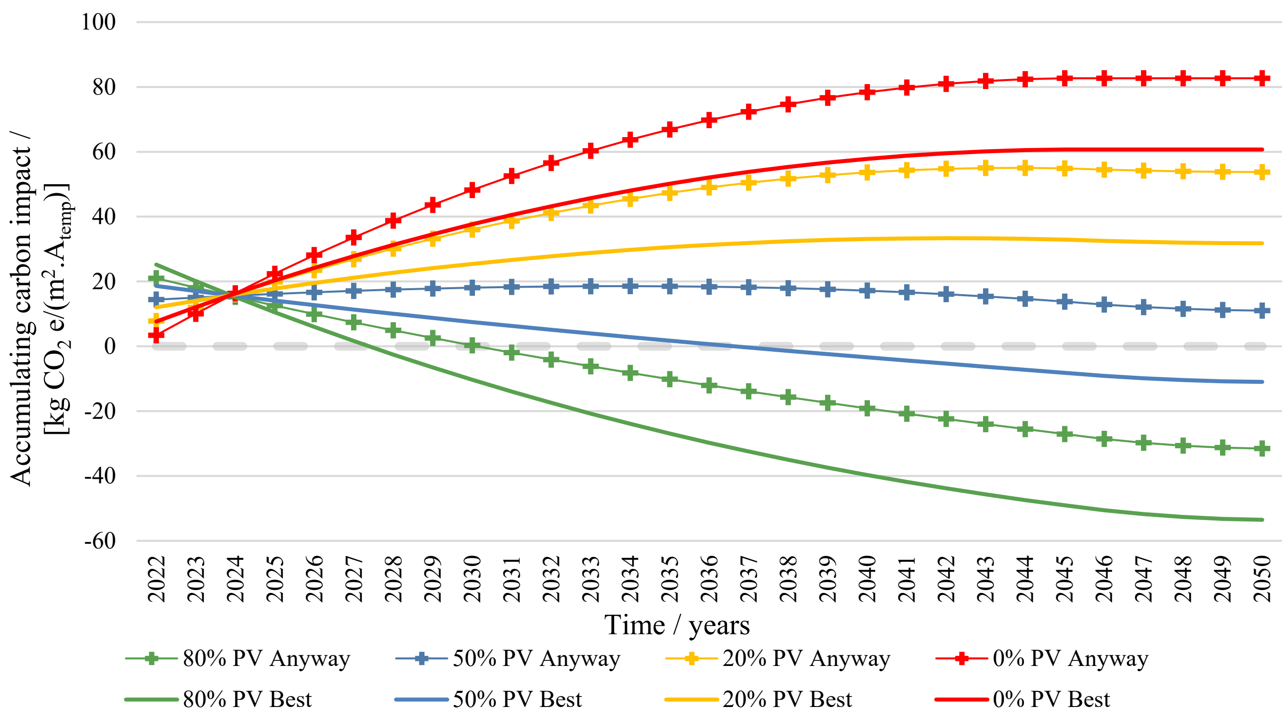
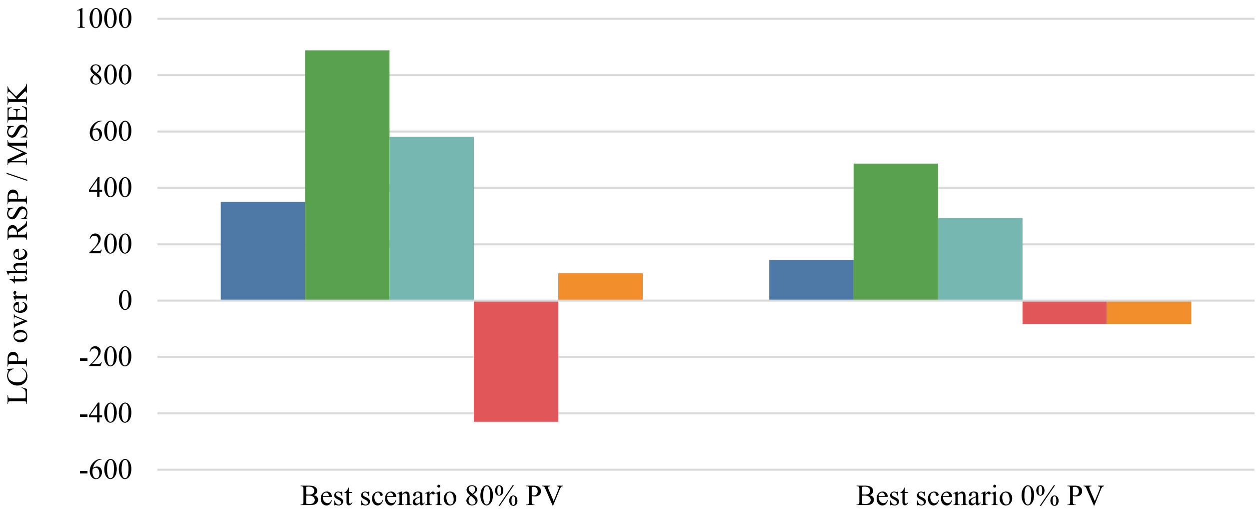


Figure 4.16: Accumulating impact of the 'Optimistic' offset potential consideration over an RSP to 2050

4.6.2 Economic sensitivity

The economic sensitivity was undertaken for the passive scenario with the highest LCP that still incorporated some level of insulation on the facade to account for a reasonable carbon offset, as the best performing LCPs were scenarios with no facade insulation. The scenario that was used was that of 100 mm glass wool on the facades, 200 mm EPS on the roof, introduction of storm windows and 80% PV. The results of the full 27 economic variations of the sensitivity analysis can be seen in Appendix E. Based on those results 5 variations were selected, from best to worst across the spectrum of the 27 variations, as shown in Figure 4.17. The 5 variations were tested on two scenarios, the above-mentioned best scenario with 80% PV, and also the same scenario with no PV.



	Interest rate / %	Electricity growth rate / %	DH growth rate / %
Base case	2	1.5	0
Best	0.5	2.85	1.5
Midpoint base to best	2	2.85	1.5
Worst	4	-0.8	-1.5
Midpoint base to worst	4	2.85	-1.5

Figure 4.17: Impact on LCP in MSEK of economic condition, such as interest rate (IR), variations for best performing case with 80% PV and no PV

For the best and midpoint base to best cases the LCP for the best scenario with 80% PV increased by more than 153% and 65% respectively, while for the worst and midpoint base to worst cases the LCP decreased by more than 222% and 72% respectively. A similar trend is noted for the scenario with 0% PV where the best and midpoint base to best cases increased by more than 235% and 102% respectively, and the worst and midpoint base to worst cases both decreased by more than 157%.

5 Discussion

In terms of the base case, there was a 7.6% margin of error between the BBR archetype and the simulation model. However, the relationship between hand calculations and dynamic simulations is not coplanar, especially for a building of this scale. Several considerations could slightly alter this margin of error for better or worse, but the purpose of the study was not to exactly match the hand calculations of the archetype as the archetype itself was a fictional building with simplifications of its own. Therefore, the margin of error was deemed acceptable moving forward in the study. This section further analyses the results of this study and discusses the key indicators that influenced the outcomes.

5.1 Overview of iteration results

The process of parametric simulations yielded many iterations that demonstrated how the ability to achieve high levels of decarbonisation and a profitable solution can change drastically based on variations of factors related to the various renovation packages. The consideration for finding solutions that provide a suitable energy reduction coupled with targeting carbon neutrality and profitability are multifaceted, however some clear trends, as noted below were apparent from the overall results. With large volumes of results a clear process of verification is vital to align outcomes of all results.

The storm window replacements were clearly notable as the best performing in terms of both the economic and environmental perspective due to low initial costs and embodied carbon while providing a significant decrease in heating energy demand and associated operational energy carbon impacts. Leaving the existing windows unchanged was generally a more profitable option over the reference study period (RSP) then installing new triple glazed windows, which offered better total operational carbon reduction over the RSP despite its large initial embodied carbon impact. The EPS façade insulation was predominantly in the higher spectrum of total carbon, whereas the organic insulations tended to be in the lower spectrum, it can further be noted that cellulose fibre tended to perform the best in terms of carbon neutrality for the facade insulation, while EPS and wood fibre both outperformed cellular glass as best roof insulation.

The results further indicated that as the level of renovation increased, especially with additional facade insulation thicknesses, generally around 150 mm to 250 mm of façade insulation the impact on energy savings between thickness steps becomes minimal, leading to lower operational savings and carbon offsets. However, as the thickness increases the larger volume of insulation means there was still an increased amount of embodied carbon impacts and greater initial costs. This shows that intensive renovation with just energy savings in mind may not be beneficial from a carbon neutrality and cost perspective and the level of improvement should be determined based on the ideal balance between these factors.

The influence of greater levels of PV coverage in achieving carbon neutrality was clearly demonstrated in the results of the various passive and active package iterations, this was strongly driven by the carbon offset considered by the NollCO_2 definition. Considering the high level of self-consumption for this particular case means avoidance of purchasing from the Swedish energy mix was beneficial in terms of both avoidance of costs and the carbon impact for purchased electricity. While overproduction provides a large carbon offset based on replacing coal in the Nordic pool along with the economic benefit, which is currently supported by the 0.6 SEK/kWh tax reduction, driving increased profitability by reducing operational costs.

80% PV coverage was a key factor in coming close to achieving carbon neutrality for the studied archetype where the purchased electricity was still greater than the electricity sold back by roughly 20% and there was a high level of self-consumption. However, if the balance were reduced and the building overproduces more than it consumes, this additional electricity sold back would not be eligible for the tax reduction of 0.6 SEK/kWh, decreasing profitability. Furthermore, a large PV system with low self-consumption would still be beneficial in terms of the carbon offset based on the NollCO_2 definition, but the economic side would be less viable as selling back to the grid would be less beneficial than self-consumption. This could be the case if the property energy were to be reduced, as no such energy renovations were considered in this study, or if the roof area to heated floor area ratio was greater. Such as in the case of a lower building with maximum 4 floors, representative of approximately 65% the MHP building stock. (Berggren & Wall, 2019).

5.2 Decarbonisation

The addition of the mechanical balanced ventilation with heat recovery (FTX) system were the only iterations that surpassed carbon neutral by 2050. The use of the existing exhaust ductwork helped to mitigate the embodied carbon of the whole ventilation system which may typically be higher for a full new system. Almost all FTX cases were below carbon neutral when paired with 80% PV, with the best performing cases having the minimum 200 mm façade insulation required for the façade-integrated ductwork. The controlled ventilation system would also achieve greater levels of indoor comfort, which was not assessed in depth in this study, but is often a co-benefit that motivates such a renovation choice. Although these FTX iterations have the greatest decarbonisation potential, the overall initial cost of these measures were 35% greater than having only the associated envelope renovation that comes within 0.5 $kgCO_2e/(m^2.A_{temp})$ of achieving carbon neutrality.

In general, for the façade iterations, the lower carbon insulations like cellulose fibre or wood fibre attained greater levels of decarbonisation. However, the difference in total carbon impact between façade insulation materials alone was minor once impacts of associated elements, such as studwork, weatherboard, cladding, and the A4 – A5 processes were added. The difference was lessened further when assessing on a whole building level,when much greater embodied impacts from window renovations or PV systems were included. Thus in principle, for façade renovations, low-carbon insulations paired with other less carbon-intensive materials such as timber are necessary to achieve a higher level of decarbonisation, however the difference between the low-carbon insulations is neglible on the building scale if paired with other renovation measures. Therefore elements such as initial cost could probably dictate the insulation material selection.

The high embodied carbon of cement-lime plaster meant that the embodied carbon of the anyway façade renovation was almost on par with the low-carbon façade improvements that consisted of insulation with timber studwork and cladding. Cement-lime plaster was considered as it was a commonly accessible render. However if one was to use a less common render with a lower impact, such as hemp-lime, the reduction in the anyway renovation would be reduced. EPS had slightly lower operational impacts than other façade iterations due to its better thermal properties of the insulation, however the reduction was never enough to offset the combined embodied impacts of the cement-lime render and adhesive compared to the insulations with timber cladding and studwork, thus EPS was never a viable option regarding decarbonisation potential.

There was a more notable difference between the embodied carbon of anyway renovation and improvement iterations of the roof as they used the same bitumen layer finish. Although lower levels of roof insulation were necessary for the cases with the highest decarbonisation rate, the larger thicknesses of any type had minimal effect on the reducing the operational GWP. If the roof area was greater, the improvements assessed could have had a greater influence on the overall results.

As depicted in the overview of results, reduction in window transmission losses was necessary to achieve greater levels of decarbonisation, however finding the balance between reducing the operational GWP and minimising the embodied GWP was critical. Figure 4.7 illustrates that even when considering the addition of a storm window only, the embodied carbon of a window improvement was greater than the wall improvement, despite only covering a quarter of the area. Replacing the windows with new triple glazed units in the same case would have increased the embodied GWP by 7 $kgCO_2e/(m^2.A_{temp})$, but the extra reduction in transmission losses would have only reduced the operational GWP by roughly 4.5 $kgCO_2e/(m^2.A_{temp})$ for envelope renovations only.

In Figure 4.7, the increased number of trucks and higher weight for the active measure iterations resulted in slight differences in stage A4. Attaining more accurate information regarding travel distances and modes of transport for a real project could increase the A4 impact, but on the holistic scale of the LCA the difference would be negligable. As the Swedish mixes for energy and transport are low carbon, particularly in comparison to some other European countries, a renovation project should try to source local products and materials to mitigate the A1 – A4 impacts. The B4 climate impact of replacing the heat pump or AHU was not significant due to the $NollCO_2$ linear depreciation of impacts to zero by 2050.

The EAHP had the lowest A1 – A3 impact of all elements assesses in Figure 4.7. If analysing the reduction of the positive impact alone, as in Table 4.3, the EAHP total carbon impact was only 12.5% greater than the FTX total impact, while being a much cheaper initial investment. However as illustrated in Figure 4.5, NollCO$_2$'s offset consideration of the PV overproduction meant that the slight increase in electricity demand had a much greater impact than the reduction in heating demand in any EAHP iteration. As a result, the EAHP iterations performed worse than iterations without additional active measures. If the heat pump had a higher SCOP of 4, which would be attainable (Lindahl et al., 2014), the reduced amount of electricity consumption could be enough to help the better performing EAHP cases reach carbon neutrality. Alternatively, if one was to consider a carbon neutrality definition that wasn't so dependent on delivering back to the grid, the EAHP iterations may also perform a lot better.

The offset potential of the larger PV systems had a much greater impact on the total carbon balance than any other measure conducted due to NollCO$_2$'s definition. Figure 4.5 illustrated the importance of the PV overproduction, as merely avoiding the consumption of the Swedish mix with a 20% PV system did not even offset embodied carbon of the PV itself. Comparing the accumulating carbon impact in Figure 4.14, installing the 50% PV system with the anyway renovation had a lower total carbon impact than implementing the best envelope improvements with little or no PV. The trajectories were similar for the earlier years, but after 2045, when the positive impacts of the Swedish mixes are neutral, but the offsetting of coal continued, the 50% PV with the anyway renovation began to have a negative trajectory.

As noted in Figure 4.8, the embodied impact of the 80% PV system, consisting of Chinese modules and a BOS from the European energy mix, was twice as high as all other embodied impacts combined. This is due to the higher GWP of the Chinese energy mixes used in A1 – A3 of the module, as well as the increased travel distance from Asia. Although the PV production market is predominantly from Asian countries, sourcing modules from European manufacturers could help mitigate this high level of embodied carbon.

If the NollCO$_2$ offset considerations remain the same, measures to reduce the electricity demand paired with a PV system sized for high levels of overproduction would have greater decarbonisation potential than other iterations within this study. One could argue this level of decarbonisation from PV overproduction disincentivises implementing any renovation measures to tackle the high energy demand of the MHP. Moreover, relying on PV from a renovation standpoint deters focus from other aspects such as increased thermal comfort, which can be a prominent issue in MHP buildings. Thermal comfort could only be resolved through the other energy renovation iterations simulated in this study. The sensitivity analysis of the NollCO$_2$ offset values further iterated that the definition may be overly dependent on the offsetting of coal, which would mostly occur outside of Sweden.

5.3 Profitability

Considering the most profitable options that are shown by the results of the iterations for all passive and active packages the introduction of an EAHP provided the highest profitability. This was driven by the low initial investment that would be required for the EAHP as it connected to the existing exhaust duct system, required only four storage tanks and limited pipework. Combined with the lowest thickness of glass wool insulation on the facade, one of the most cost-effective options with the second lowest cost among the organic facade insulation types, and lowest thermal conductivity. Installing the lowest thickness of glass wool insulation on the facade still had an immediate impact on the overall energy performance of the building and provides a significant decrease in operational costs over the RSP which was further reduced by the EAHP providing DHW.

The clear trend among all the most profitable cases was also that of including a storm window as the initial cost of doing so was 71% lower than installing a new triple glazed window, while providing a decrease of 40% on the U-value of the original windows compared to a 57% decrease when installing triple glazing. This solution was also better from an environmental perspective as it has less embodied carbon, while still providing a great saving in terms of reduced heat losses through the window elements. This leads to less operational emissions as well as lower operational cost over the RSP further boosting the profitability of these solutions. Together with storm windows, all the most profitable cases share the commonality of having 80% PV coverage, due to the roof to heated floor area ratio of the studied archetype, the 80% PV coverage provides a good level of self-consumption while still over producing to a sufficient level for selling back to the grid making its initial investment worthwhile. A building with the same roof area but less heated floor area would not benefit as much as the overproduction could surpass maximum allowable to be sold back to the grid making the initial investment less profitable.

Although the FTX system offers a great LCP, the high payback period was driven by the fact that there was a large initial investment compared to the other cases as there was a requirement to have a minimum of 200 mm insulation on the facade to provide sufficient space for the supply duct work to be accommodated within the façade. This was further exacerbated by the high initial cost of the actual HVAC system itself considering all the ductwork required plus the AHU and diffuser costs along with associated labour and plant hire costs. It was also notable that as the initial costs increase when a FTX system was installed, the operational costs are reduced, which would have a larger impact on the profitability based on variations to the interest rate, electricity prices and DH prices. From an LCP perspective this case performs better than the passive counterparts and considering the great environmental impact and reaching carbon neutrality, was a favourable choice over the EAHP which does not reach carbon neutrality in any scenario. Although not analysed in this study, the FTX system would have the added benefit of improved thermal comfort making it a more attractive option for building owners and occupants. However, it has a large initial investment and the worst ROI on an annual basis over the RSP of the most profitable cases at 1.32%, in contrast to the EAHP option with a 2.60% ROI with an initial investment that was 32% lower.

5.3.1 Economic sensitivity

The trend of the data for the 27 variations shows that irrespective of interest rate, if the prices of DH and electricity are to decrease, this has a negative impact on profitability as the value of the savings on electricity and DH are reduced, and the large initial costs of PV do not get paid back over time. This can be seen in Figure 4.17 where for the 80% PV scenario, the decreasing electricity and DH prices over time with an increased interest rate have a detrimental impact on the profitability of the scenario resulting in a loss over the RSP. However, in the same case of decreasing DH price and higher interest rate, if there was an increase in electricity price, as seen in the midpoint base to worst case, than the case can still be profitable, but just less so than the base case. This was driven by the impact of receiving higher compensation when selling electricity back to the grid when there was over production, reducing the impact of less savings from a lower DH price. When the same two economic cases are applied to the scenario with no PV it becomes unprofitable in both instances as there was no selling of electricity to offset the negative impact of a lower DH price. However, the LCP values are the same for both cases in this instance as the difference of the anyway renovation and the improvement balance out.

Holistically, if there is to be a substantial PV installation, then the profitability of the project is strongly dependant on higher electricity prices, so any reduction in electricity price will reduce the value of savings that are to be realised.

5.4 Budget limitations

On the lower spectrum of the budget limitations, the 3 MSEK limit clearly shows that the introduction of any window improvement was not possible as this would require a utilisation of almost 35% of the budget, where the anyway renovation already utilises 66% of this budget limit. The most profitable option for this budget limit also does not include any level of facade insulation, as the introduction of facade insulation starts at a cost of 1.5 MSEK greater than the budget limit. Based on these limits, from an LCA perspective, it was sensible that only an EAHP would be installed with minimal roof insulation as this provides a sizable reduction to the DH energy requirement and associated carbon impact which was higher than the carbon impact of the Swedish electricity mix which was only increased by a third of what the DH was decreased based on the SCOP of 3. The EAHP option remains a top performing solution for the next budget limit of 7 MSEK in terms of both LCA and LCP, and thereafter for the 11 MSEK and 15 MSEK limits was the better performing in terms of LCP, but the FTX system becomes the better option in terms of LCA as it is the only renovation among all iterations that reach climate neutrality. The FTX system only really becomes affordable at these levels of initial investment due to its high initial cost of roughly 2 MSEK plus the requirement for a minimum of 200 mm insulation on the facade to fit the duct work costing a minimum of 2.27 MSEK. At these levels, and from the 7 MSEK limit the introduction of 80% PV coverage becomes highly influential on the carbon impact front linked back to the offset potential noted in Figure 4.5, and the LCP front based on the ability to sell back to the grid and having reduced DH costs.

5.5 Review of the NollCO_2 carbon neutrality definition

NollCO_2 considerations had significant impacts on the overall decarbonisation potential of the iterations. This section assesses the definition as a whole, and discusses possible ways to adjust it for renovation projects.

The definition was formulated by the SGBC and is aligned with the Swedish building code. As the construction industry steadily shifts towards a greater consideration of the environmental impacts of buildings, indicated by the introduction of climate declarations to all new builds from 2022 (Nair et al., 2021), having a definition that is attune to the common building codes and practices of the country could make it more user-friendly for those within the industry.

It could be argued that there is an over-reliance on renewable energy delivered back to the grid. As depicted in the linear interpolation of the NollCO_2 values: in 2045, when Europe is 5 years from being a climate neutral, the offset potential of coal was still greater than the 2019 positive impacts from the Swedish electricity and DH mixes combined. As the interpolation was so influential to the overall carbon impact of the iterations, a revised method could yield more realistic results. This could be achieved by assessing the roadmaps to climate neutrality of the individual countries within the electricity pool.

Although having some simplified methods of calculating impacts and offsets, such as neglecting maintenance or the end-of-life stages of the life cycle stages, help make the calculation process easier, some aspects were too simplified. Calculating the impact of PV in $kgCO_2e/kWh$ would mean the impact of the system would change on an annual basis and be dependent on the positioning of the design itself. Moreover, the impact of the PV degradation had a considerable impact on the overall offset potential, but was not necessary to calculate as part of the definition. The accumulation of such simplifications could yield significant differences of the overall result of decarbonisation and could be calculated more accurately. The climate impact of a PV system could use the functional unit $kgCO_2e/kW_{peak}$ as it is a more consistent value that would not be influenced by the production of the system itself. Also, the annual 0.5% system degradation should be calculated using an arithmetic series equation for the RSP of the study.

Though the reasoning behind the assumption that there would be little to no impact from the end-of-life stages as the constructions should still be in use by 2050 seems logical, by completely neglecting any benefit that could be attained at these stages, the definition almost disincentivises designing from a circular aspect. From both a renovation and a new build perspective, designing for reuse could help to maintain carbon neutrality in the future. Although the GWP impact from the disposal of certain materials may be much less in the future, certain materials will probably still not be recyclable and end up in landfill, which on a holistic environmental aspect should be avoided where possible. There could be a credit system similar to Miljöbyggnad (SGBC, 2022), which is also from the SGBC, that would award certain practices such as circular design that do not directly affect the decarbonisation but are environmentally beneficial overall.

The definition only adheres to new constructions and is not directly applicable to renovations. The use of impact limits for the embodied and operational GWP is very beneficial for narrowing the scope of how achieving carbon neutrality is possible, but the current value limits are oversized for renovations as they account for the additional impacts of a new build elements like foundations or structure. Revised limit values should be introduced for renovations as well. Although having fixed values may be difficult to adhere to as the scale of renovations can differ on a case-by-case basis and can be dictated by design boundaries of the building. A solution would be to have reference buildings to which different impact levels are based, similar to the current system used by the definition for calculating the impact limits of the new constructions. These limits should be achievable across most renovation types without needing to buy carbon credits as a means of offset. A priority hierarchy could be introduced for how impacts should be offset for renovation projects: starting with implementing renewable energy on the building scale; if there’s limited ability to do so, then offsets could be achieved by facilitating renewable energy on a neighbourhood scale; finally, if neither of the previous options are enough, then carbon credits could be purchased to offset the remainder.

Finally, NollCO_2 requires an energy class B or better in the current definition. Again, although this is more suitable for new constructions, it could be difficult for renovations to achieve and could be heavily dictated by the limitations of a renovation project itself. As seen from the results of this study, attaining the lowest energy use did not coincide with the cases that achieved the greatest levels of decarbonisation.

6 Conclusion

Considering that there is a large building stock that requires an anyway renovation, it is opportune to incorporate some level of energy renovation that is cognisant of both carbon impact and life cycle costing (LCC). Any additional initial investment aligns to a need to decarbonise this existing building stock and has the potential to be offset by life cycle savings. Parametric modelling of solutions in the early planning stage creates the platform for considering key performance indicators across the spheres of energy demand, decarbonisation, and LCC. This brings a new dimension to business as usual where commonly only one or two of these factors are prioritised and the remaining considerations are adapted at a later stage to align with any business or regulatory objectives that may need to be achieved. The results clearly conclude that aiming for energy reduction alone may not translate into the best economic or decarbonisation solution.

Onsite energy generation is a key factor for decarbonisation on a project level, where key consideration for optimal economic benefit should guide the case specific design optimisation. On a macro level it provides a decrease of overall dependence on the energy grid to aid in a transition to a more renewable and carbon neutral energy mix, which further supports trade of clean electricity to the Nord pool to offset coal production. The NollCO_2 definition's consideration for carbon offset clearly influenced how greater levels of PV coverage were crucial for achieving carbon neutrality, even where the 2045 offset value for coal is greater than the 2019 impact of the Swedish electricity and district heating mixes combined.

When renovating, the focus should be on cost optimal renovations that provide a high level of energy savings with low embodied carbon, rather than specifically targeting energy efficiency as an independent target. Investigations of the various components that require renovation allow for insight into where the most benefit can be deprived, as achieved for the studied archetype by introducing the storm window replacements where a modest initial investment had a substantial impact on energy demand and carbon offset, driving profitability across all iterations. The results further indicated increased levels of renovation such as additional facade insulation above 200 mm had a marginal impact on additional energy savings, leading to lower operational savings and carbon offsets in proportion to higher initial investment and embodied carbon. Demonstrating that intensive renovation focused on just energy savings may not be beneficial from a carbon neutrality and cost perspective, and the level of improvement should be determined based on a balance between these factors.

To achieve carbon neutrality, the addition of the mechanical balanced ventilation system with heat recovery (FTX) provided the only iterations that surpassed carbon neutrality by 2050, with profitability of this supported by 80% PV, storm windows, 200 mm cellulose fibre façade insulation and 200 mm EPS roof insulation. Almost all iterations with the FTX system reached carbon neutrality, with most proving to be profitable as well. The 35% greater initial investment compared to an envelope only renovation that comes within 0.5 $kgCO_2e/(m^2.A_{temp})$ of achieving carbon neutrality becomes a factor is investment level versus level of carbon neutrality to be achieved. However, when aiming for highest profitability, introducing an exhaust air heat pump with a minimal amount of façade insulation was the most suitable, driven by its low initial investment and high energy savings, the exhaust air heat pump also provides the best solution when limited budget is available for initial investment.

A renovation specific definition for attaining carbon neutrality, with appropriate carbon limits for each building stage linked to a renovation, is necessary to guide renovation projects to be aligned with Europe and Sweden achieving their carbon neutrality targets. Such a certification system could also boost the desirability for property owners to renovate towards carbon neutrality. Accounting for factors such as degradation, project specific suppliers and detailed design considerations impact life cycle assessment (LCA) calculations and majorly influences the result, notably with NollCO_2's offset values. The results of this study can be a good indicator for decarbonisation potential of different renovation measures at an initial design stage.

New innovative, low embodied carbon, materials are increasingly entering the market, although not deeply investigated in this study due limited generic data. However, these innovative materials are constantly evolving and locally sourced innovative materials on a project specific basis can provide better solutions than the generic material data used in this study as a guide of potential outcomes. If investigated early enough they can be incorporated into a renovation for better performance across energy reduction, LCA and LCC. Furthermore, the option of using prefabricated facades exist as a more cost effective and carbon friendly alternative renovation compared to the more conventional methods used in this study.

7 Future Studies

This section gives an overview of the potential future studies that could further develop the findings of this report.

This study focused purely finding optimal solutions to reduce the GWP of a renovation, but did not assess any other climate impact categories and neglected stage B7 for water use. Although decarbonisation is at the forefront of the global, European and Swedish goals over the next three decades, other climate impact categories should not be neglected in the design process. A future study could conduct a more holistic LCA for the best performing cases to see how they affect the other key climate indicators within Sweden.

Use of prefabricated construction elements were neglected from the study as they would be more dependent on availability of manufacturers within the vicinity of an actual construction site and are less generic solutions. However, prefabricated construction elements are becoming increasingly popular within the renovation field and have many benefits such as ease of assembly, reduction in construction time and minimal interference with tenants. From a decarbonisation standpoint, using prefabricated elements would mean a lower A5 impact by quicker assembly and less wastage, and possibly lower A4 impact if all the materials were transported together. However, not having control of the material sources for the actual construction elements could limit the amount of embodied impact that you could reduce. One could work with the manufacturers to address this. A further study could assess the availability of manufacturers within the Swedish market, particularly ones with the potential to implement the façade integrated ductwork, and to conduct a more detailed LCA of the components themselves.

As mentioned in the LCA limtiations, there may have been some extra embodied carbon that was not considered due to the high-level design of the system, coupled with the lack of detailed climate data of HVAC elements. Some Nordic companies related to HVAC systems such as Lindab, Swegon and Solenco have begun to release EPD related to specific HVAC products, however there is still lack of resources available in climate databases for more detailed design. Furthermore, the simulation for the FTX system may have been too simplified by using the 'HB ideal air' component, it was unclear what it considered in its calculations regarding such aspects as system losses when a heat recovery factor was introduced. It only considered the HVAC system as a single entity, presumably an all-air system, as opposed to a direct outdoor air system with heating recovery combined with an existing hydronic system. Such a system could be designed in other simulation programmes such as IDA ICE, or in standalone OpenStudio program, but it would require a lot more detail about the system itself and would probably increase the simulation time. Also, it is unclear how it could be incorporated back into the GH script for parametric design if an outside program had been used. A more detailed study of such a system using the best performing cases from this report could be beneficial to attain a more accurate decarbonisation potential of such innovative measures.

The focus of the study was purely on attaining a balance between energy reduction, decarbonisation and profitability, thus some key performance indicators, such as the indoor climate, were not assessed. The level that the renovations measures would affect the hours of overheating was assumed to be minimal and the additional benefits of a controlled ventilation system were not considered. As the global temperature continues to rise, a detailed study of how the different renovation measures would affect the indoor climate using current weather files and possible future climate scenarios could be beneficial to the decision making process.

A moisture safety analysis was not conducted on the envelope iterations. There may be a possible risk of mould growth at section between the existing wall and external improvements for organic materials. E2B2 discusses the importance of having a small air gap at this junction to limit this risk (Shankar, 2020). The extra air gap would mean extra bracing material and an extra board to contain the non-rigid insulations, which would affect the LCA and costing of the improvements. As there would be many contributing factors, such as location, microclimate, orientation, WDR and surrounding context, a moisture risk analysis should be carried out on a case-by-case basis, but conducting such analysis would be beneficial on a more detailed case study.

8 Summary

With the goals of Sweden and Europe aimed at being carbon neutral by 2045 and 2050 respectively, upgrading the existing building stock has been identified as having great potential in assisting to realise these goals. Half of Europe's building stock was built before energy performance was a focus resulting in a large share of the current building stock being energy inefficient while 85-95% of them will still be in use by 2050. In Sweden, the building sector accounts for one fifth of greenhouse gas emissions, while 20% of Sweden's building stock, multi-family buildings constructed in the 1960s and 1970s in what is commonly known as the "The Million Homes Programme", is in an urgent need for extensive renovation. This period is also known as the "post-war" housing boom in Europe. Renovation provides an opportunity to reduce greenhouse gas emissions by reducing the typically high energy demands of the existing building stock. Renovation also aids in avoiding building new buildings where possible, which would have much higher embodied carbon impacts.

The aim of this study was to accumulate a series of cost-effective renovation packages for buildings in the Million Homes Programme, for which the purpose of achieving carbon neutrality was a key driving factor. The study investigated more environmentally conscious and innovative renovation options through carefully designed filter criteria along with the more typical renovation measures that are currently used in the Swedish market. Furthermore, parametric analysis was used to ensure that every combination of the 30 inputs parameters were considered, resulting in thousands of possible solutions. The NollCO_2 definition was adapted to suit a renovation project for the purpose of this study. The improvements considered ranged from various insulation types on either the façade or roof in various thicknesses, there were further improvements to the windows, along with consideration for various levels of photovoltaics to be installed on the roof and finally active measures of either a balanced ventilation system with heat recovery or introduction of an exhaust air heat pump. Resulting in a total of 11 292 packages that were assessed.

The holistic overview of the results was broken into two main categories as guiding aspects of discussion. The first was profitability against the base case of undertaking the required maintenance that these buildings would require due to age and potential neglect. The second criteria, which is the key focus of the study is what packages achieve a good level of decarbonisation or achieved carbon neutrality. Only 8% of results proved to be both profitable and below a threshold value considered to be suitable for decarbonisation.

Considering that the NollCO_2 definition was adapted for this study, its reliance on offsetting coal from overproduction meant that careful consideration needed to be taken for the various inputs of the photovoltaic system in order to not have over exaggerated results. Through this the results for decarbonisation clearly showed that the most favorable results were those that incorporated high levels of photovoltaics. This also rang true of the profitability scale where further incorporation of storm windows was also very favorable and generally not having too high levels of insulation achieved a good balance for decarbonisation, profitability, and energy reduction.

The study concluded that it was possible to renovate the existing building stock and achieve carbon neutrality in a cost-effective manner. However, NollCO_2's definitions possible overreliance on renewable electricity meant that even well performing measures that reduced the ability to sell back electricity appeared less favourable even if it performed well for energy reduction and from a cost perspective. Assessing the current state of a building and addressing the weakest points regarding heat loss is crucial for achieving a high decarbonisation rate withing fair costs. Furthermore, intensive renovation that focuses on energy reduction alone may not be beneficial from a carbon neutrality and cost perspective. Rather conscious renovations that assess the tri factor of cost, carbon and energy are paramount in order to achieve a high level of decarbonisation.

Certain co-benefits such as increased thermal comfort was not considered in this study, but could influence decision making. If budget limitations were a factor, many of the envelope only renovations came close to achieving carbon neutrality, and on a project specific level could be altered to achieve such. Finally, a renovation specific definition for attaining carbon neutrality will be necessary to guide renovation projects to align with European and Swedish carbon neutrality targets. Such a certification system could also boost the desirability for property owners to renovate towards carbon neutrality.

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Appendix A

Table 0.1: Determination of allowance for stud studs to insulation proportion in wall construction

Location	Insulation and Wood stud percentage of wall construction	Percentage of overall wall construction	Weighted allowance.
Typical East/West wall unit	89.73% 10.35%	18.01%	1.86%
Ground North/South wall unit	86.72% 13.28%	9.11%	1.21%
Typical North/South wall unit	87.93% 12.07%	72.88%	8.80%
Total allowance for wood studs in construction			**11.87%**

Table 0.2 - Breakdown of insulation material properties used in energy simulations

Material	Thickness / m	Conductivity / W/(m.K)	Specific Heat / J/(kg.K)	Bulk Density / kg/m^3
Façade materials				
EPS	0.050 – 0.350	0.033	1690	16.0
Glass Wool	0.050 – 0.350	0.035	1030	18.7
Hemp Fibre	0.050 – 0.350	0.040	1600	36.0
Wood Fibre	0.050 – 0.350	0.038	2100	50.0
Cellulose Fibre	0.050 – 0.350	0.039	2020	47.0
Gypsum Plasterboard	0.010	0.220	936	760
Timber Cladding	0.022	0.160	2736	525
Cement-Lime Plaster	0.015	0.110	800	2000
Roof materials				
EPS	0.1 – 0.4	0.033	1690	16
Cellular Glass	0.1 – 0.4	0.036	1000	100
Rigid Wood	0.1 – 0.4	0.038	2100	160

Table 0.3: Calculations of the FTX system critical path

AHU to apartment 1 on the 1st floor									
Section	**Volume Flow Rate**	**Velocity**	**Width**	**Height**	**Pf/L**	**Length**	**Duct Loss**	**Fitting Type**	**Fitting Loss**
	m3/s	**m/s**	**mm**	**mm**	**Pa/m**	**m**	**Pa**	**-**	**Pa**
AHU-R1	2.48	4.1	1200	500	0.3	1	0.3		
R1-R2	1.24	6.9	600	300	1	9	9	Dovetail	3.16
R2-R3	0.415	5.5	300	250	1.2	8.75	10.5	Double Wye+Transition	6.97
R3-R4	0.208	4.3	300	160	1	1.93	1.93	Double Wye	4.5
R4-F1	0.023	2.4	120	80	0.95	5.36	5.092	Wye	8.88
F1-1A	0.023	2.4	120	80	0.95	22.45	21.3275	Elbow	0.84
1A-1B	0.023	2.4	120	80	0.95	3.57	3.3915	Elbow	0.84
1B-1C	0.0115	1.2	120	80	0.28	2.7	0.756	Tee	0.59
1C-Diff	0.0115	1.2	120	80	0.28	0.2	0.056	Elbow	1.1
Diffuser								Diffuser	5
AHU-1C							**52.353**		**31.88**
Total Friction losses / Pa							**84.233**		

Appendix B

Table 0.1: Simulation control method step-by-step process with excel, grasshopper (GH) and Climate Studio (CS) results

Assessment	Description	Excel result (kWh/m^2)	GH result (kWh/m^2)	GH margin of error (%)	CS result (kWh/m^2)	CS margin of error (%)	GH vs CS margin of error (%)
Transmission losses	Shoebox with no windows, U-value of 0.2 W/(m^2.K) assigned all surfaces. No infiltration, ventilation or internal gains. Steady state, 20°C indoor and 0°C outdoor	133.00	134.38	1.02	134.36	1.01	0.01
Infiltration losses	Previous description with introduction of 0.3 l/(s.m^2) at q50 infiltration losses	145.00	147.40	1.63	147.34	1.59	0.04
Ventilation losses	Previous description with introduction of 0.35 l/(s.m^2) ventilation rate	218.41	221.81	1.53	221.76	1.51	0.02
Heat recovery	Previous description with introduction of 75% heat recovery efficiency	163.22	165.99	1.67	165.94	1.64	0.03
Window losses	Previous description with introduction of 0.25 WWR glazing on south façade, with U-value of 1.21 W/(m^2.K) and 0.31 SHGC. Still no irradiation, just a test of window transmission	176.49	176.21	0.16	173.58	1.65	1.49
Internal load gains	Previous description with introduction of 3 W/m^2 internal load, set to 'Always on' schedule	149.00	149.93	0.62	147.78	0.82	1.44
Real outdoor conditions	All previous steps included. Real Copenhagen weather file used in simulations. Assumed effective indoor temperature of 17°C and annual outdoor of 9°C in Excel.	69.00	53.59	22.33	53.18	22.93	0.77
Revision of real outdoor conditions	Previous description with a change in assumption of effective indoor temperature to 15°C	51.75	53.59	3.44	53.18	2.69	0.77

The increased margin of error once the real weather file could be attributed to the dynamic calculations of the simulation models vs. the somewhat still steady state calculations of the Excel. As the simulation models become increasing more complex by adding more zones, different internal loads and varying schedules, more windows with different orientations, more floors with adjacencies, etc., the margin of error between the hand calculations and simulation results began to increase, with no single variable responsible for the difference. Therefore, as the GH script grew in complexity, the major changes were also made to the climate studio model and the results were compared to ensure that the inputs that were being sent to EnergyPlus were still correct.

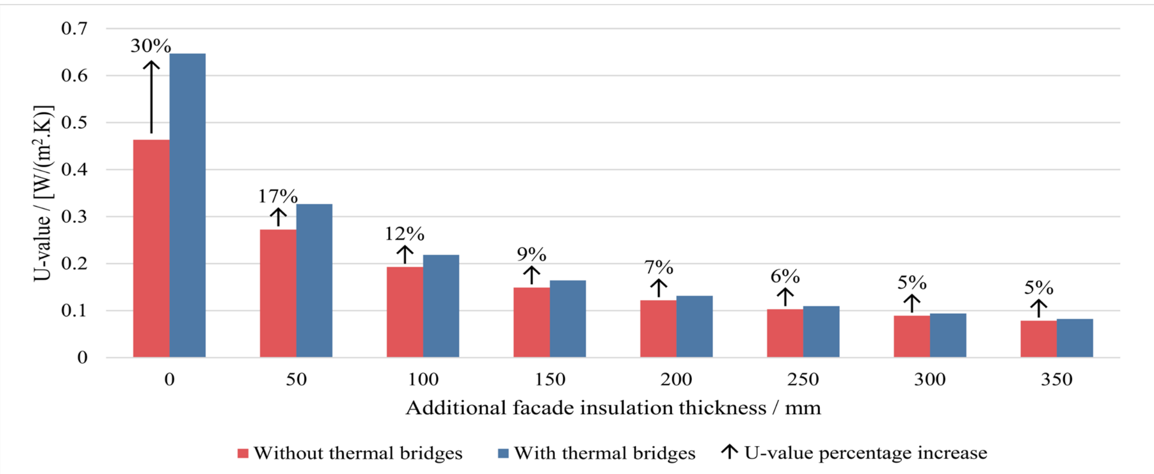
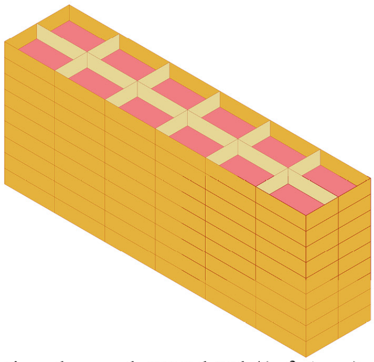
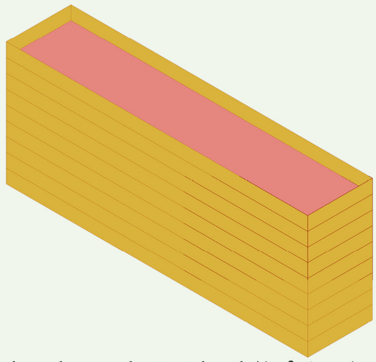
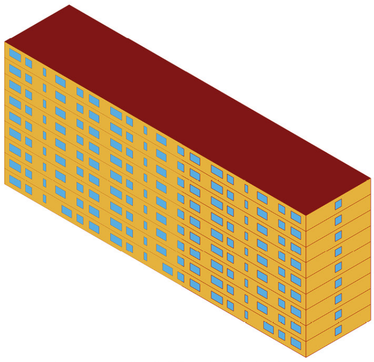
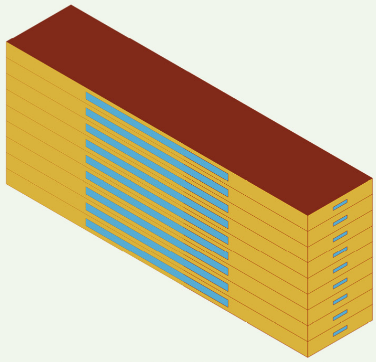
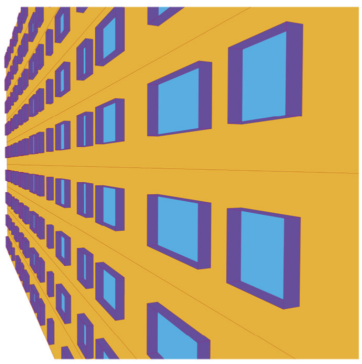
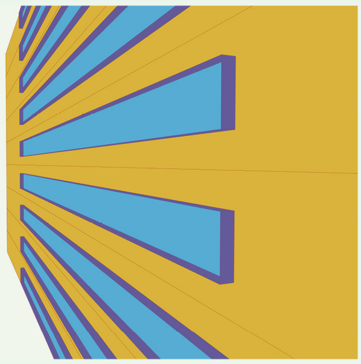


Figure 0.1: U-value percentage increase for each additional facade insulation thickness as a result of including thermal bridge factors

Table 0.2: Breakdown of the main simulation complexity vs runtime tests, where the one highlighted in green was taken to the next test in the table

Number of zones		
Simplified model: Grouping each apartment into one zone per floor **Reasoning:** EnergyPlus simulates each zone individually. The internal walls of adjacent zones will be considered adiabatic anyway so there should not be much change from zone to zone.	 Heating demand: 87.9 kWh/(m^2.A_{temp}) Simulation time: 3 minutes 15 seconds 5,000 simulations runtime ≈ 270 hours	 Heating demand: 87.5 kWh/(m^2.A_{temp}) Simulation time: 27 seconds 5,000 simulations runtime ≈ 38 hours
Number of windows		
Simplified model: Grouping the individual windows on each facade per floor, excluding shading **Reasoning:** EnergyPlus does Raytracing simulations for each individual window in the model at each timestep, vastly increasing the simulation complexity and run time	 Heating demand: 118.4 kWh/(m^2.A_{temp}) Simulation time: 1 minute 30 seconds 5,000 simulations runtime ≈ 125 hours	 Heating demand: 118.5 kWh/(m^2.A_{temp}) Simulation time: 22 seconds 5,000 simulations runtime ≈ 31 hours
External reveal shading on windows		
Test: Addition of external shading from the wall depth to the previous test **Reasoning:** Could drastically increase raytracing complexity, especially for individual windows, but the additional shading neglected by grouping windows may increase the margin or error by too much.	 Heating demand: 123.5 kWh/(m^2.A_{temp}) Simulation time: 50 minutes 5,000 simulations runtime ≈ 174 days	 Heating demand: 121.8 kWh/(m^2.A_{temp}) Simulation time: 1 minute 5 seconds 5,000 simulations runtime ≈ 90 hours

Appendix C

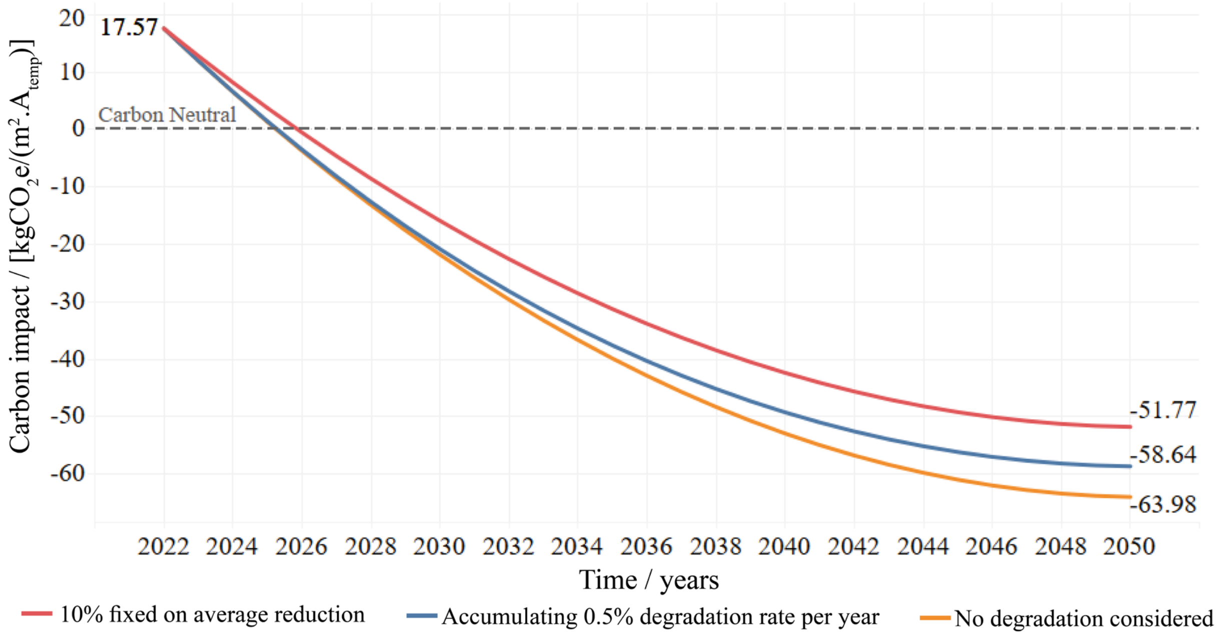


Figure 0.1: Effect of degradation considerations on the 80% PV system over an RSP to 2050, where the initial value is the embodied carbon and the final value is the accumulated offset potential

Table 0.1: Breakdown of weights for the window iterations

Material	**Density**	**Unit (Varies)**	**Weight / kg**
Addition of storm windows			
New glass	15 kg/m^2	698 m^2 window area	10471.10
Window spacer 25mm x 0.4mm perimeter (Hot-dip galvanized steel sheets)	0.079 kg/m	1962 m window perimeter	154.02
12mm wooden trim	0.092 kg/m	1962 m window perimeter	181.29
Acrylic sealant	0.060 kg/m	1962 m window perimeter	117.72
New triple glazed windows			
New windows	35.6 kg/m^2	698 m^2 window area	24851.43
Old windows	37 kg/m^2	698 m^2 window area	25828.73

Table 0.2: Breakdown of weights for the active measure systems

Material	**Density**	**Unit (varies)**	**Weight / kg**
FTX System			
Sum of all ductwork	Varying kg/m	2267 m total	3569
AHU	850 kg/unit	1 unit	850
Diffusers	0.5 kg/unit	216 units	108
Roof duct insulation wrap	37.58 kg/m^3	27.5 m^3	1033
EAHP System			
EAHP	2.16 kg/unit	1 unit	691.2
1000l Storage tanks	7.79 kg/unit	4 units	6232
22mm insulated pipework	0.627 kg/m	68 m	42.64
40mm insulated pipework	1.088 kg/m	26 m	28.29

Table 0.3: Input data for environmental impacts of all iterations considered in the LCA

Environmental impact of:	**LCA Stage/s**	**Script input**	**Source or method of calculating**
Facade renovations (bulk densities found in Appendix A Table 0.2)			
EPS / ($kgCO_2e/kg$)	A1-A3	3.200	Most representative data across databases
Glass Wool / ($kgCO_2e/kg$)	A1-A3	1.113	Most representative data across databases
Hemp Fibre / ($kgCO_2e$ / kg)	A1-A3	0.644	Most representative data across databases
Wood Fibre / ($kgCO_2e/kg$)	A1-A3	0.371	Most representative data across databases
Cellulose Fibre / ($kgCO_2e/kg$)	A1-A3	0.160	Most representative data across databases
Lime cement plaster / ($kgCO_2e/kg$)	A1-A3	0.240	Most representative data across databases
Gypsum Plasterboard / ($kgCO_2e/kg$)	A1-A3	0.266	Most representative data across databases
Timber Cladding / ($kgCO_2e/kg$)	A1-A3	0.110	Most representative data across databases
Wood studs and battens / ($kgCO_2e/kg$)	A1-A3	0.120	Most representative data across databases
EPS Adhesive / ($kgCO_2e/m^2$)	A1-A3	13.5	Sto EPD (Sto Corp., 2019)
Roof renovations (bulk densities found in Appendix A Table 0.2)			
Bitumen membrane / ($kgCO_2e/kg$)	A1-A3	0.650	Most representative data across databases
EPS / ($kgCO_2e/kg$)	A1-A3	3.200	Most representative data across databases
Cellular Glass / ($kgCO_2e/kg$)	A1-A3	1.260	Most representative data across databases
Rigid Wood Fibre / ($kgCO_2e/kg$)	A1-A3	0.619	Most representative data across databases
Additional storm window layer (weights found in Appendix C Table 0.1)			
New glass / ($kgCO_2e/kg$)	A1-A3	1.250	OneClick LCA database – float glass with low emissivity layer
Hot-dip galvanized steel sheets / ($kgCO_2e/kg$)	A1-A3	2.780	OneClick LCA database – Hot-dip galvanized steel sheets
12mm wooden trim / ($kgCO_2e/kg$)	A1-A3	0.560	OneClick LCA database – Painted pine lining
Acrylic sealant / ($kgCO_2e/kg$)	A1-A3	8.960	OneClick LCA database – Acrylic mastics joinery sealants
New triple glazed window (weights found in Appendix C Table 0.1)			
Tripled glazed windows / ($kgCO_2e/kg$)	A1-A3	2.125	Boverket database – Window, wood, inward, 3-glass
Transport of old windows / ($kgCO_2e/km$)	C2	3.357	Noll CO_2 transport values
Disposal of old windows / ($kgCO_2e/kg$)	C4	0.42	Nordvestvinduet EPD sourced from OneClick database
FTX system (weights found in Appendix C Table 0.2)			
AHU / ($kgCO_2e/kg$)	A1-A3	8.11	OneClick database local generic data
Ductwork / ($kgCO_2e/kg$)	A1-A3	2.71	OneClick database local generic data
Insulation around exposed ductwork / ($kgCO_2e/kg$)	A1-A3	1.59	OneClick database – Alu foil
Diffusers / ($kgCO_2e/kg$)	A1-A3	2.85	Swegon EPD (Swegon, 2021)
AHU replacement / [$kgCO_2e/(m^2.A_{temp})$]	B4	0.28	AHU replacement impact at year 2042 based on 2020 impact interpolated to zero by 2050
EAHP (weights found in Appendix C Table 0.2)			
Heat pump / ($kgCO_2e/kg$)	A1-A3	2.16	OneClick database - Electric heat pump (air-water), 14 kW
Storage tanks / ($kgCO_2e/kg$)	A1-A3	7.79	OneClick database - Heated water storage tank, for collective use, 932.5L (Uniclima)
Pipe work plus insulation / ($kgCO_2e/kg$)	A1-A3	0.03	OneClick database – Domestic PE foam clad copper pipe
EAHP and storage tank replacement / [$kgCO_2e/(m^2.A_{temp})$]	B4	0.03	EAHP and storage tanks replacement impact at year 2042 based on 2020 impact interpolated to zero by 2050

Appendix D

In the case of 0mm for either facade or roof insulation, the cost of the anyway renovation of lime cement plaster or bitumen waterproofing is applied respectively.

Table 0.1: Cost data inputs for roof and facade renovation measures in SEK /m^2 A_{temp} with associated source for material pricing and labour costs based on installation time

Description	Cost	Material source	Labour source
Scaffolding for anyway renovation	168.92	Wikells	Wikells
Scaffolding for improvements	Varies by thickness	Wikells	Wikells
Material lift for improvements	Varies by thickness	Wikells	Wikells
Lime cement plaster	661.83	Wikells	Wikells
Façade timber cladding	503.35	Wikells	Wikells
Gypsum board	138.11	Wikells	Wikells
Battens	68.22	Wikells	Wikells
Bitumen waterproofing**	264.00	Wikells	Wikells
EPS facade insulation	Varies by thickness	Wikells	Material cost all inclusive
Glass wool facade insulation	Varies by thickness	Wikells	Wikells
Hemp fibre facade insulation	Varies by thickness	(Optimera, 2022a)*	Wikells
Wood fibre facade insulation (Batts)	Varies by thickness	(Optimera, 2022b)*	Wikells
Cellulose fibre facade insulation	Varies by thickness	Wikells	Wikells
Wood studs for insulation (excluding EPS)	Varies by thickness	Wikells	Wikells
EPS roof insulation	Varies by thickness	Wikells	Wikells
cellular glass roof insulation	Varies by thickness	Wikells	Wikells
Wood fibre roof insulation (Rigid board)	Varies by thickness	Adjusted to 2022 pricing (GUTEX, 2013)	Wikells

**These sources were crossed checked with Wikells data with materials such as EPS and Glass wool, and marginal price differences were noted which justified the use of these sources as suitable for the wood fibre and hemp fibre pricing*
*** Chosen based on a product suitable to have either concrete, EPS, cellular glass or wood fibre as a substate.*

Table 0.2: Cost data inputs for roof and facade renovation measures with various thickness options as noted above, in SEK /m^2 A_{temp}

	Facade EPS	Facade glass wool	Facade hemp fibre	Facade wood fibre	Facade cellulose fibre	Wood studs	Equip-ment*	Roof EPS	Roof Cellular glass	Roof wood fibre
50 mm	1369.07	1247.37	1274.53	1236.62	1280.47	226.97	351.64	-	-	-
100 mm	1562.92	1374.79	1439.56	1366.98	1400.78	303.28	383.13	390.50	1131.90	520.59
150 mm	1660.77	1495.11	1623.00	1509.40	1466.10	379.60	430.36	-	-	-
200 mm	1789.77	1640.22	1808.07	1643.82	1571.01	455.91	461.85	517.00	1714.56	732.96
250 mm	1935.62	1852.57	2035.64	1853.52	1756.75	607.55	608.80	-	-	-
300 mm	2071.62	1963.29	2219.09	1991.89	1888.06	683.86	656.04	643.50	2582.46	981.18
350 mm	2207.62	2075.19	2379.05	2093.09	1978.86	735.06	656.04	-	-	-
400 mm	-	-	-	-	-	-		770.00	3165.11	1201.92

** Scaffolding and material lift*

Table 0.3: Cost data inputs for PV system based on size including discounted price for inverter replacement at year 15

PV System size based on percent of roof area covered	kW_{peak}	Turnkey price of PV system/ SEK	Inverter replacement / SEK
20%	30	349 300	60 800
50%	75	873 200	152 000
80%	120	1 397 100	243 100

Table 0.4: Cost data inputs for elements of storm window installation and new triple glazed windows

Description	**Script input**	**Source or method of calculating**
Storm window*		
Addition glazing layer / (SEK / m^2_{GA})	609.19	Wikells Addition low emission glass
Channel for spacer / (SEK / m_{GP})	133.16	Wikells ER 70 steel channel
Acrylic sealant / (SEK / m_{GP})	100.23	Wikells Acrylic sealant with bottom strip
Wooden trim painted white / (SEK / m_{GP})	79.66	Wikells Lining, 12x43 painted white
Total cost of adding additional layer to all window types / SEK	1 038 806.22	Sum of above breakdown
New triple glazed window**		
New triple glazed window type 1 / SEK	656 140.50	Wikells - Wooden window 3-glass painted U-value 1.2
New triple glazed window type 2 / SEK	1 046 172.96	Wikells - Wooden window 3-glass painted U-value 1.2
New triple glazed window type 3 / SEK	252 358.20	Wikells - Wooden window 3-glass painted U-value 1.2
New triple glazed window type 4 / SEK	1 254 841.20	Wikells - Wooden window 3-glass painted U-value 1.2
Removal of existing windows / SEK	192 684.10	Wikells – Demolition of small and large windows
Transport away from site of existing windows / SEK	180 174.50	Wikells – Transport of demolition materials
Total cost of replacing all windows, removal and transport away from site / SEK	3 582 371.46	Sum of above breakdown

* *Priced in terms of individual components accounting for installation costs based on time, the cost of desiccant within the window spacer was neglected due to insufficient costing data.*

Table 0.5: Cost data inputs for elements of active measures of EAHP and FTX systems including replacement after 20 years for AHU and EAHP

Description	**Script input**	**Source or method of calculating**
FTX system		
AHU initial cost including installation cost / (SEK /m^2 A_{temp})	44.21	Wikells IVP Env Flex TC HP 240 rot vvx AHU SEK
Ductwork and duct installation initial cost / (SEK /m^2 A_{temp})	215.02	Wikells – various duct sizes and duct insulation
Diffusers initial cost including installation cost / (SEK /m^2 A_{temp})	24.53	216 Swegon DOMO diffusers (Luftbutiken, 2022)
Crane hire and operator costs / (SEK /m^2 A_{temp})	1.69	Wikells – crane driver plus crane truck 34 tons
AHU replacement cost / (SEK /m^2 A_{temp})	26.95	Discounted future value in line with current price in nominal terms
AHU removal cost / (SEK /m^2 A_{temp})	0.10	Wikells - HVAC and air appliances are demolished (Discounted future value)
AHU disposal cost / (SEK /m^2 A_{temp})	0.07	Wikells - Transport of demolition materials (Discounted future value)
Replacement and removal crane hire and operator costs / (SEK /m^2 A_{temp})	0.34	Wikells – crane driver plus crane truck 34 tons (Discounted future value)
EAHP		
EAHP initial cost including installation cost / (SEK /m^2 A_{temp})	28.98	1000 NIBE F1345-60 heat pump (NIBE, 2022a)Wikells labour costs and time for heat pump installation
DHW storage tanks initial costs including installation cost / (SEK /m^2 A_{temp})	14.73	4 x 1000 NIBE UKV 20-1000 accumulator tanks (NIBE, 2022c)Wikells labour costs and time for water heat installation
All pipework, including insulation and installation costs / (SEK /m^2 A_{temp})	20.79	Wikells - Pipe in boiler and appliance room insulation with plastic sheet heat press
Crane hire and operator costs / (SEK /m^2 A_{temp})	1.69	Wikells – crane driver plus crane truck 34 tons
EAHP replacement cost / (SEK /m^2 A_{temp})	9.65	Discounted future value in line with current price in nominal terms
EAHP removal cost / (SEK /m^2 A_{temp})	0.07	Wikells - HVAC and air appliances are demolished (Discounted future value)
EAHP disposal cost / (SEK /m^2 A_{temp})	0.02	Wikells - Transport of demolition materials (Discounted future value)

Appendix E

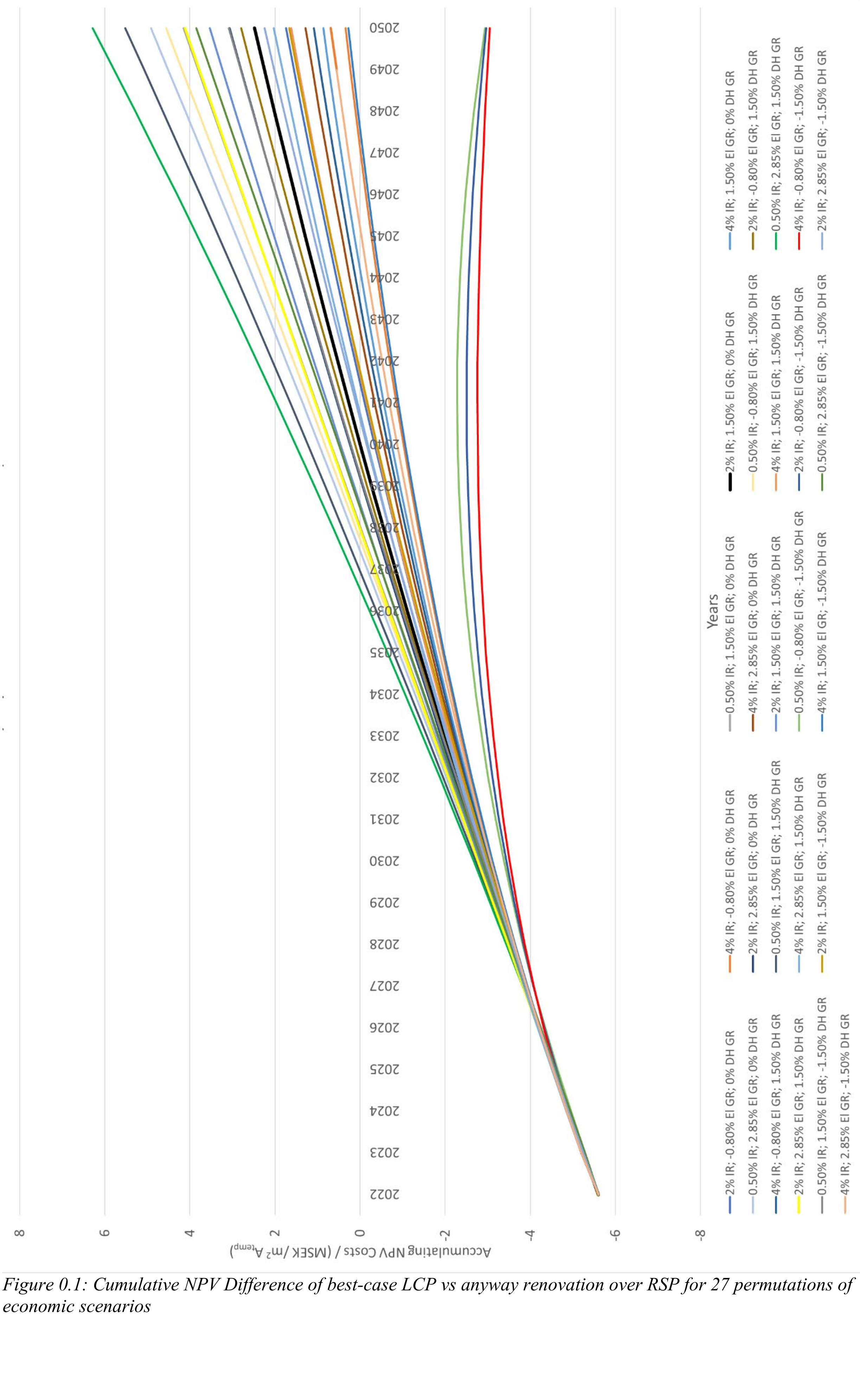


Figure 0.1: Cumulative NPV Difference of best-case LCP vs anyway renovation over RSP for 27 permutations of economic scenarios

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