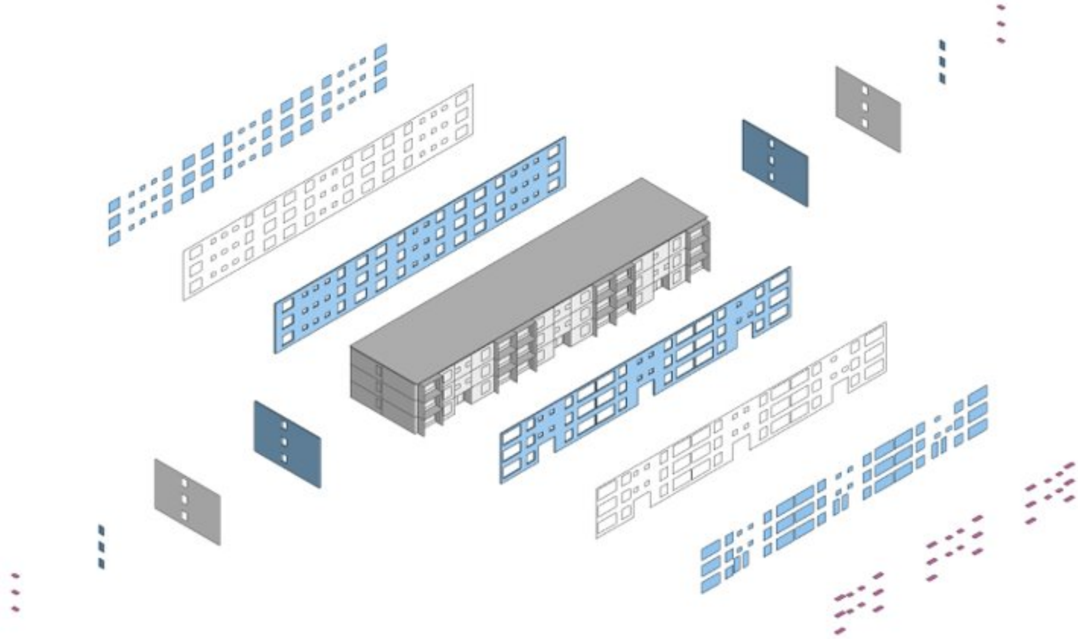


Evaluating the Environmental Efficiency of Passive Climate Change Adaptation Measures in the Built Environment

Master's thesis in Industrial Ecology

HEDDA EGERLID

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF ARCHITECTURAL THEORY AND METHODS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

MASTER'S THESIS ACEX30

Evaluating the Environmental Efficiency of Passive Climate Change Adaptation Measures in the Built Environment

Exploring synergies between cooling energy reduction and environmental impact of passive climate adaptation retrofit measures in Gothenburg

Master's Thesis in the Master's Programme Industrial Ecology

HEDDA EGERLID

Department of Architecture and Civil Engineering
Division of Architectural Theory and Methods
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2022

Evaluating the Environmental Efficiency of Passive Climate Change Adaptation Measures in the Built Environment
Exploring synergies between cooling energy reduction and environmental impact of passive climate adaptation retrofit measures in Gothenburg

Master's Thesis in the Master's Programme Industrial Ecology

HEDDA EGERLID

Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2022

Department of Architecture and Civil Engineering
Division of Architectural Theory and Methods
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Visualisation of the selection of passive measures, described further in chapter 3.5.
Department of Architecture and Civil Engineering
Göteborg, Sweden, 2022

Evaluating the Environmental Efficiency of Passive Climate Change Adaptation Measures in the Built Environment

Exploring synergies between cooling energy reduction and environmental impact of passive climate adaptation retrofit measures in Gothenburg

Master's thesis in the Master's Programme Industrial Ecology

HEDDA EGERLID

Department of Architecture and Civil Engineering
Division of Architectural Theory and Method
Chalmers University of Technology

ABSTRACT

In an increasingly warming climate with higher frequencies of heat waves and extreme heat, literature indicates that cooling will have increased relevance even in the Nordic climate. To ensure thermal comfort during summers and limit the use of electricity for air conditioning, climate adaptation in the form of passive cooling measures can be implemented. This study aims at evaluating the environmental efficiency of passive cooling measures that could be implemented in future renovations of the Swedish building stock, to illustrate how interdisciplinary assessments could aid in greenhouse gas emission reductions when considering climate change adaptation. A multi-family residential building built in the 1970s is used as a case study and the assessed measures include added insulation, improved glazing, added solar shading, improved solar reflectivity of façade material, and natural ventilation. The measures were assessed on their ability to reduce peak cooling demand, annual cooling demand, overheating hours and maximum temperature during peak conditions using an hourly energy simulation model, and the environmental impact of the measures was calculated based on material use.

The study concludes that using natural ventilation is the most environmentally efficient passive cooling measure due to the devoid of environmental impact. However, to sustain thermal comfort in a future climate it could be beneficial to include complementary passive measures. Changing to triple glazing is the second most efficient in all aspects of thermal performance and has a similar environmental impact to the other assessed measures, and the option is consequently the next recommended measure, followed by the less environmentally efficient solar shading option. A combination of all measures is associated with the greatest cooling reduction potential; however, it poses a large trade-off in terms of environmental impact. The study illustrates that the inclusion of environmental impact when assessing climate adaptation measures is useful to provide guidance on GHG reduction when implementing climate change adaptation measures.

Key words: climate change adaptation, passive cooling, passive design, retrofitting, renovation, overheating, building energy performance

Contents

Preface

This study is a master's thesis of 30 ECTS within the Industrial Ecology master's programme at Chalmers University of Technology, carried out from January to June in the year of 2022. The study explores the potential synergies and trade-offs between cooling energy demand reduction and environmental impact, by evaluating the environmental efficiency of a selection of passive measures applied to a case study in the Gothenburg region.

The work was conducted at the Department of Architecture and Civil Engineering, Division of Architectural Theory and Method under the main supervision of Xinyue Wang. Additional supervision was given by Alexander Hollberg and Daniela Maiullari. The examiner of the project was Liane Thuvander, Professor at the Department of Architecture and Civil Engineering. Thank you all for the support, guidance and feedback you have provided by sharing knowledge and experience.

Additional thanks to Andreas Skälegård at Uddevallahem for the generous provision of data and information regarding the case study building. Finally, I want to express my gratitude to my opponents and friends, Jonna Ljunge and Helena Nerhed Silverhjelm, for valuable discussions and conversations.

Gothenburg June 2022

Hedda Egerlid

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAT	Best available technology
CO_2e	Carbon dioxide equivalents
℃	Degrees Celsius
CIBSE	Chartered Institution of Building Services Engineers
EPD	Environmental product declaration
EPW	EnergyPlus Weather file
EU	European Union
FEBY	Forum för energieffektivt byggande (Eng: Forum for Energy Efficient Construction)
GCM	Global climate model
GHG	Greenhouse gas emission
GWP	Global Warming Potential
LCA	Life-cycle assessment
RCM	Regional climate model
RCP	Representative concentration pathway
UHI	Urban heat island
SETAC	Society of Environmental Toxicology and Chemistry
SMHI	Sveriges meteorologiska och hydrologiska institut (Eng: Swedish Meteorological and Hydrological Institute)
SNBHW	Swedish National Board of Health and Welfare
TMY	Typical Meteorological Year
TMM	Typical Meteorological Month
TRY	Typical Reference Year
WYEC	Weather Year for Energy Calculations

1 Introduction

This section introduces the background, aim and delimitations of the thesis, followed by the research questions of the thesis. Lastly, an outline of the thesis structure is presented.

1.1 Background

Global warming changes the climate for the coming centuries, both by an increase of the average temperature but also in the occurrences of extreme weather such as heat waves (IPCC, 2014a). Global warming thus has the potential of substantially affecting the cooling energy demand for the building stock (Santamouris, 2019; Yassaghi & Hoque, 2019). According to the IEA (2018), one fifth of the energy used in buildings globally is due to cooling using fans and air conditioners, and they predict that the number of homes with air conditioning in the EU will triple by 2050. In addition, IEA (2018) reports that in many cases small, non-efficient air conditioners are used, further increasing electricity demand. Wu & Pett (2006) writes that air conditioners are often bought during periods of excessive heat, such as heat waves, and are continued to be used not only during periods of heat stress but to keep lower, comfortable temperatures throughout the cooling period. In a future scenario when other sectors increase their dependence and demand on electricity and the building sector strives towards increased energy efficiency (Energimyndigheten, 2019), the limiting of increase in cooling energy demand from the building stock and the avoidance of installing cooling systems or the use of air conditioners would be beneficial. This emphasises the need for passive solutions, i.e., solutions that does not require active energy use, when considering adaptation measures.

EU has forecasted that 80% of the existing homes will be renovated by 2050 (EU, 2021a), meaning passive design strategies will have the opportunity to be implemented in the existing building stock within the next few decades. This study aims to evaluate the efficiency of different passive cooling measures possible to include in future renovations, by measuring the reduced cooling demand and comparing it to the associated environmental impact of the measure. By including environmental impact in the assessment, the study suggests a broader perspective when considering climate change adaptation measures and demonstrates how the limitation of environmental impact can be incorporated in design for adaptation by an interdisciplinary assessment method.

1.2 Aim

The aim of the thesis is to evaluate the environmental efficiency of passive cooling measures that could be implemented in the renovations of the current residential buildings to reduce peak cooling energy demand in future climate scenarios. This will be done by combining an energy model with an environmental impact assessment model and compare the reduction in cooling energy demand with the environmental impact for a set of potential passive climate adaptation measures. The assessment uses a multi-family residential building built in 1970 as a case study. Additionally, the impact on annual energy demand will be assessed for each measure. The study is aimed at architects, property developers, contractors and other interested parties, to provide an interdisciplinary perspective on the importance of climate change adaptation as well as the environmental impact consequences of design choices and climate adaptation measures.

1.3 Delimitations

The assessment only considers reducing the energy demand and excludes the supply side, i.e., any temporal differences in available supply energy and the possible reduced environmental impact from energy savings. The results are only valid for a building type similar to the assessed case study building and is not recommended to be extrapolated to other building types or functions, nor should it be viewed as representative for the urban area of Gothenburg in general. The assessment focuses on passive climate adaptation measures, excluding active climate change adaptation measures and coping mechanisms. The assessment includes measures that are relevant to retrofitting objects, i.e., measures that need to be incorporated in the design stage of the building are excluded. Additionally, any measures that are only effective when incorporated on a district scale has been excluded. The energy model and climate data does not include microclimatic effects such as the urban heat island effect. The environmental impact is assessed by global warming potential, whilst other environmental impact categories such as acidification, eutrophication, resource depletion or biodiversity loss are excluded. Furthermore, the assessment does not include any economic aspects relating to the implementation of passive climate adaptation measures.

1.4 Research questions

Conducive to the aim, four main research questions form the basis of the thesis and are presented below.

> *How does the peak and annual energy demand due to cooling increase for an existing multi-family residential building in 2050?*
>
> *What common passive cooling measures can be implemented in the renovation of an existing building? How efficient are the measures in limiting peak and annual cooling energy demand?*
>
> *What is the associated environmental impact of the measures?*
>
> *How do the measures affect the total annual energy demand of the building?*

1.5 Thesis outline

The thesis is presented in six main parts, the introduction, background, method, results, discussion, and conclusion. The introduction section introduces the subject of passive climate adaptation and its relevance, the background provides relevant theories and previous research, the method chapter presents key input data and describes the different methodologies applied, the results section presents the obtained results, and the discussion provides a critical analysis of the results and suggests further research. Finally, the conclusions section summarizes key points from the results and discussion sections.

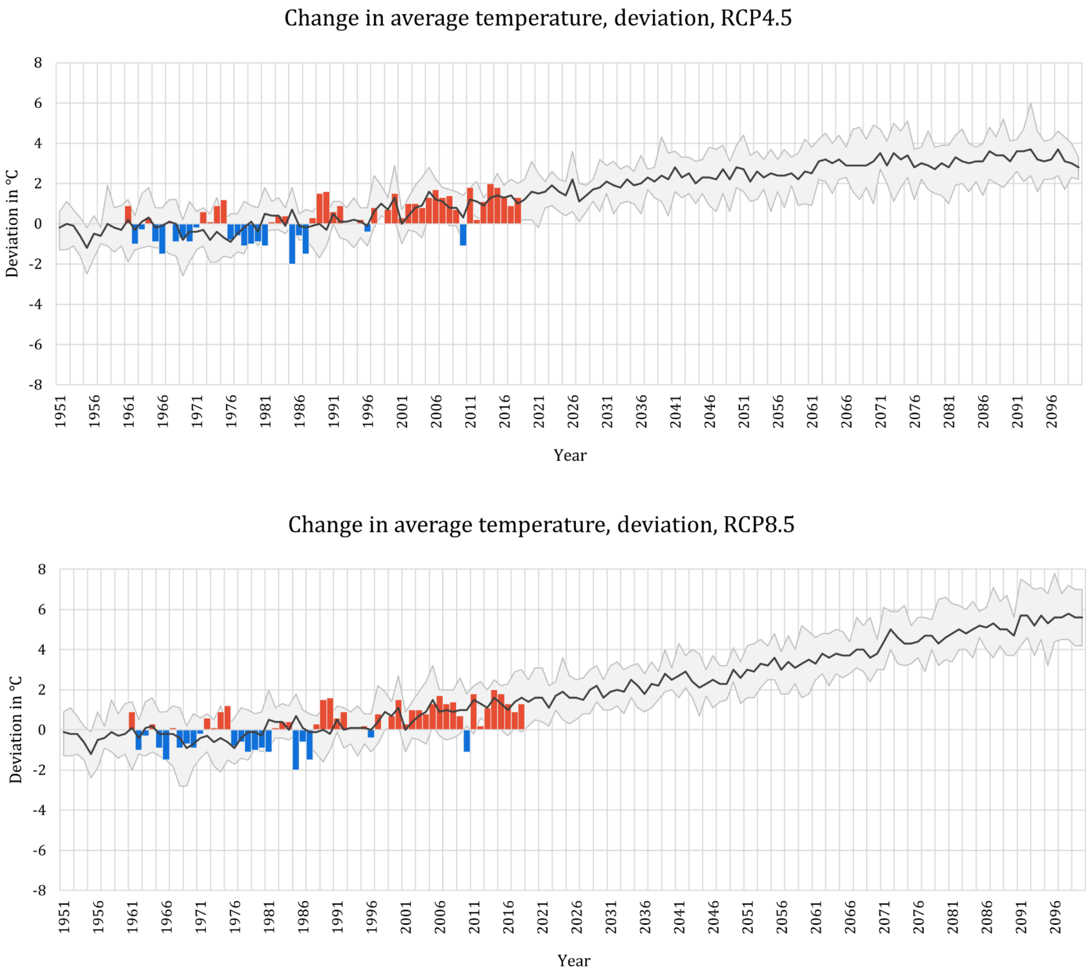
2 Theory and conceptual frameworks

This section places the aim of the thesis into the context of previous research and presents theories and concepts relevant to the study.

2.1 Climate change adaptation

IPCC (2014a) projects that global warming due to greenhouse gas emissions (GHGs) will cause an increase in global average temperature as well as an increase in the intensity and frequency of heat waves. IPCC (2014b) has condensed the possible future accumulation of GHG into four different Representative Concentration Pathways (RCPs). The RCP2.6 scenario, limiting radiative forcing to 2.6 W/m^2 by 2100, implies heavy implementations of mitigation measures and corresponds to a scenario where global warming is likely to stay below 2°C compared to pre-industrial temperatures, in line with the Paris agreement. This scenario is deemed as increasingly unlikely due to the continued increase in GHG emissions (Dodoo & Gustavsson, 2016; Roux et al, 2016). RCP4.5 and RCP6.0, corresponding to a radiative forcing of 4.5 and 6.0 W/m^2 respectively by 2100, are described as two intermediate scenarios and the RCP8.5 scenario, considering a radiative forcing of 8.5 W/m^2 by 2100, is described as a high emission scenario. According to the latest climate report by IPCC (2021:67) the likelihood of the RCP8.5 scenario is debated due to recent developments in the energy sector, but since there are possible carbon-cycle feedback loops there is a possibility that even with adequate GHG mitigation, RCP8.5 remains a feasible scenario.

Global warming in combination with the urban heat island effect (UHI), i.e., the local heating effect in urban areas due to heat being retained and stored in hard surfaces of buildings and roads, risk a substantial increase in thermal discomfort and cooling energy use during the cooling season (UN-Habitat, 2011). For the region of Västra Götaland, increased average temperatures for all seasons have already been recorded and the increase in average temperature is projected to continue during the coming century, see Figure 2.1.


Change in average temperature, deviation, RCP4.5

Change in average temperature, deviation, RCP8.5

Figure 2.1 *Observed and predicted change in average temperature measured as the deviation from the pre-industrial mean temperature for the Gothenburg region, 1951-2100, for the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios. Adapted from SMHI (n.d.a.).*

In addition to increased temperatures, the Swedish Meteorological Institute (SMHI) (n.d.b) reports that the length of warm periods, defined as how many days in a row the temperature exceeds 25°C at some point during a 24-hour period, will increase with 300% in 2071-2100 compared to the reference period of 1971-2000 in a RCP4.5 scenario. SMHI (n.d.c) also reports less differences in diurnal temperatures, suggesting increasing night temperatures in the future.

Climate change adaptation is defined as “initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects” by UN-Habitat (2011). For the built environment, this includes measures to reduce vulnerability to several aspects of climate change, such as rising temperatures, sea level rise and extreme weather events. Adaptation measures in response to overheating due to rising temperatures on a building scale include better insulation and design for effective cooling, whilst an available adaptation measure on a community scale is to increase greenery to improve the microclimate and mitigate the UHI effect (UN-Habitat, 2011). Climate change mitigation describes the strategic responses to climate change which is aimed at reducing greenhouse gas emissions (UN-Habitat, 2011), such as the reduction of energy use and improved energy efficiency. The built environment is in a position of both being a possible tool for mitigation whilst also requiring adaptation measures, and since there are both potential synergies and trade-offs between the two, they can be difficult to differentiate (Yassaghi & Hoque, 2019). A potential synergy could be illustrated by the planting of trees in urban areas; it classifies as an adaptation measure since it helps to keep a cool pedestrian comfort for the rising temperatures and during heat waves, but it could also be described as a mitigation measure due to the increased CO_2 uptake. Furthermore, a potential trade-off could be exemplified by the increase of cooling loads in a building to maintain thermal comfort as a climate adaptation measure, which in its turn increases energy use and consequently increases greenhouse gas emissions.

Mitigation and adaptation measures in the built environment can be further classified into active or passive measures. Active measures efficiently make use of building services, such as the utilization of heat recovery in the HVAC system, whilst passive measures do not require active energy use, as in the cases of natural ventilation, insulation, solar shading, change of thermal mass and change of windows and doors (Mjörnell et al, 2014; Andric et al, 2019). Some argue there is a third category of measures, labelled as “other” or “additional”, where for example change of indoor temperature comfort temperatures or clothing factors are included (Andric et al, 2019), whilst others consider these measures as coping mechanisms (Yassaghi & Hoque, 2019).

2.2 Overheating

There is no unified definition of an overheated occupied space. The Swedish National Board of Health and Welfare (SNBHW, 2005) writes that the upper temperature limit for the summer period is 26°C long-term and 28°C short term. Forum for Energy Efficient Construction (FEBY, 2018) states that the temperature should not exceed 26°C for more than 10% of the time in the most exposed apartment of the building during the cooling season, from April to September, in Sweden. The Chartered Institution of Building Services Engineers (CIBSE) defines an apartment as overheated if the temperature exceeds 28°C in living areas and 26°C in bedrooms for more than 1% of the occupied time (CIBSE, 2006). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) states that the upper limit to an acceptable temperature range inside during summer is 28°C (ASHRAE, 2004). The differences can be explained by an adaptation to the climate – in a cool Nordic climate people can be presumed to have adapted to cooler temperatures and will therefore experience greater discomfort when exposed to high temperatures.

2.3 Climate change impact on the Swedish building stock

Extensive research has been conducted globally in effort to determine the impact of climate change on the global building stock, mainly focusing on energy use. The average global trend shows a decrease in heating energy demand and increase in cooling energy demand (Andric et al, 2019). There are great differences between different climate zones, and through a review of previous research, Andric et al (2019) and Yassaghi & Hoque (2019) further exemplifies how studies of buildings in subtropical climates seem to show the most drastic shift with large reductions in heating energy demand and large increases in cooling energy demand, whilst buildings in cold climate zones have less reduction in heating energy demand as well as less increase in cooling energy demand. However, studies show that there is a large variation in the results due to modelling choices, such as building type and function, software used for energy modelling, weather data and climate projections (Andric et al, 2019).

Different case studies conducted in the Swedish context consistently show a decrease in annual space heating demands and an increase in space cooling demands for all likely climate scenarios, however, to which extent varies with the building type and method of study. Most studies which include cooling demand focus on the south part of Sweden. A summary of studies performed on buildings in Sweden is presented in Table 2.1.

Table 2.1 Summary of previous research on the impact climate change for the energy use and thermal comfort in the built environment.

Authors	Year	Type	Location	Results
Nik and Kalagasidis	2012	Building stock model	Stockholm	+10-160% of annual cooling demand on average by 2100, depending on climate model, for the building stock
Dodoo et al	2014	Multi-family residential	Växjö	+33-49% annual cooling demand in 2100 depending on scenario and building type
Dodoo and Gustavsson	2016	Multi-family residential	Växjö	+171-452% annual cooling demand in 2100 depending on building type for the RCP8.5 scenario, +14-118% peak cooling demand in 2100 depending on building type
Tettey et al	2017	Multi-family residential	Växjö	+11-44% overheating hours in 2090 depending on scenario and building type
Hosseini et al	2022	Multi-family residential	Karlshamn	+450-510% annual cooling load by 2100, +210-290% peak cooling demand in 2070, depending on scenario

Traditionally, Swedish residential buildings are not equipped with active cooling systems due to low cooling demand, but make use of natural ventilation (Van Hooff, 2015; Nik & Kalagasidis, 2012). However, results from studies are often presented in terms of cooling demand. Tettey et al (2017) have studied the effects of best available technology (BAT) and passive design measures in future climate scenarios for two types of multi-family residential buildings, a conventional building according to the 2015 building code and a passive house, both situated in Växjö, Sweden. The percentage of estimated overheating hours in future climate scenarios until 2090 for the conventional building spans between 11% and 26%, whilst the same span for the passive house is between 39 and 44% (Tettey et al, 2017). The results also show that a combination of BAT for lighting and other appliances combined with passive measures such as solar shading has the potential of almost eliminating the increased cooling demand over the next century whilst simultaneously reducing space heating demand in a RCP4.5 scenario (Tettey et al, 2017).

Dodoo et al (2014) studied temperature change for the coming century for a building built in 1995, comparing building envelope standards of a conventional building and a passive house, noting that there will be a significant increase in cooling demand, and a notably larger increase for the more well-insulated passive house standard. Dodoo and Gustavsson (2016) presents a more comprehensive study, comparing three buildings built in 1995, 2009 and 2014, including studies of the peak energy demand. The study suggests that the increase in cooling demand for the three buildings and for the RCP4.5 and RCP8.5 scenarios range from 33%-128% mid-century, and 171-452% by the end of the century, corresponding to 8-10 kWh/m^2, whilst the peak cooling increased by 14-118% until 2090 (Dodoo & Gustavsson, 2016). The study showed that solar shading and increased airing combined with solar shading were relatively effective measures in reducing annual cooling loads (Dodoo & Gustavsson, 2016). Nik and Kalagasidis (2012) modelled a representative building stock of Stockholm for a range of future climate scenarios for the coming century, showing that the increased cooling demand could be mitigated using natural ventilation for the average building stock.

A study by Hosseini et al (2022) simulated the energy use for two conventional buildings in future climate scenarios on the Swedish south coast, including microclimate effects such as UHI and extreme weather scenarios. Both annual heating demand, annual cooling demand and peak energy demand were simulated, showing an increase of 210% in peak cooling energy demand for a typical year in 2070 compared to the current climate, and during an extreme heat scenario it could increase by an additional 25% (Hosseini et al, 2022). Hosseini et al (2022) further writes that natural ventilation is an adequate strategy to mitigate the increased cooling loads for the average year in 2070 in this case study, however, not during weeks of extreme heat.

2.4 Assessing environmental impact in the building sector

The concept of Circular Economy (CE), i.e., the decoupling of economic growth from resource consumption (Ellen MacArthur Foundation, n.d.), was introduced in the building sector during the 1990s, as the attention to issues such as finite resource use was growing (Norouzi, 2021). During this period, life-cycle assessment (LCA) gained traction and became a standardised method for product environmental impact assessment, and in 2003 the Society of Environmental Toxicology and Chemistry (SETAC) published a report on the use of LCA in the building sector (Baumann & Tillman, 2004; Buyle et al, 2013). When first implemented, the environmental impact calculations were limited to the energy use of the building, and it was assumed that the environmental impact from material extraction and production was negligible in comparison (Boverket, 2020). During the most recent decade attention has been extended to the material production and building construction phases, and Boverket (2020) writes that around half of the total environmental impact of a new building is directly attributed to these life cycle-stages.

Standardising a method of calculating the life-cycle environmental impact of a building is complex due to the large scale, the extensive lifetime of the building, the varying lifetimes of separate building components, the excessive use of different materials, the geographical spread of material acquisition and production as well as the evolving function of the building (Boyle et al, 2013). However, the methodologies are constantly in development and the sustainable building certification systems LEED, BREEAM and Miljöbyggnad base the environmental impact calculations from material use on simplified variations of the LCA framework. Even though the method is complex, data and time consuming, variations of LCA are used when assessing the environmental impact of buildings and building materials, and during recent years several early-stage tools and software have been developed to aid the process.

In 2017, Boverket was appointed by the Swedish Government to develop a strategy to assess a building's environmental impact from a life-cycle perspective based on the European standard EN 15978, i.e., including environmental impact from the acquisition of raw materials, production of building materials, transportation, energy use, water use, maintenance and reparations (Boverket, 2018). An overview of the life-cycle stages of a building is shown in Figure 2.2. Boverket proposed a framework based on a simplified LCA methodology including the life-cycle phases before the building enters the operational use, i.e., of material acquisition and production, transportation, the building and installation phase, with the ability of including the operational and end-of-life phase at a later stage, and the legislation has been in effect for new buildings since the year of 2022 (Boverket, 2018). To aid in the climate declarations, Boverket (2021a) has provided a database of generic climate impact data for commonly used materials in the building industry in Sweden, with average values based on a range of Environmental Product Declarations (EPDs). The climate impact is calculated as Global Warming Potential (GWP), measured in kg CO_2e, and uses a time frame of 50 years. The environmental impact is limited to global warming potential, and excludes other types of environmental impact categories, such as eutrophication, acidification, or human toxicity.

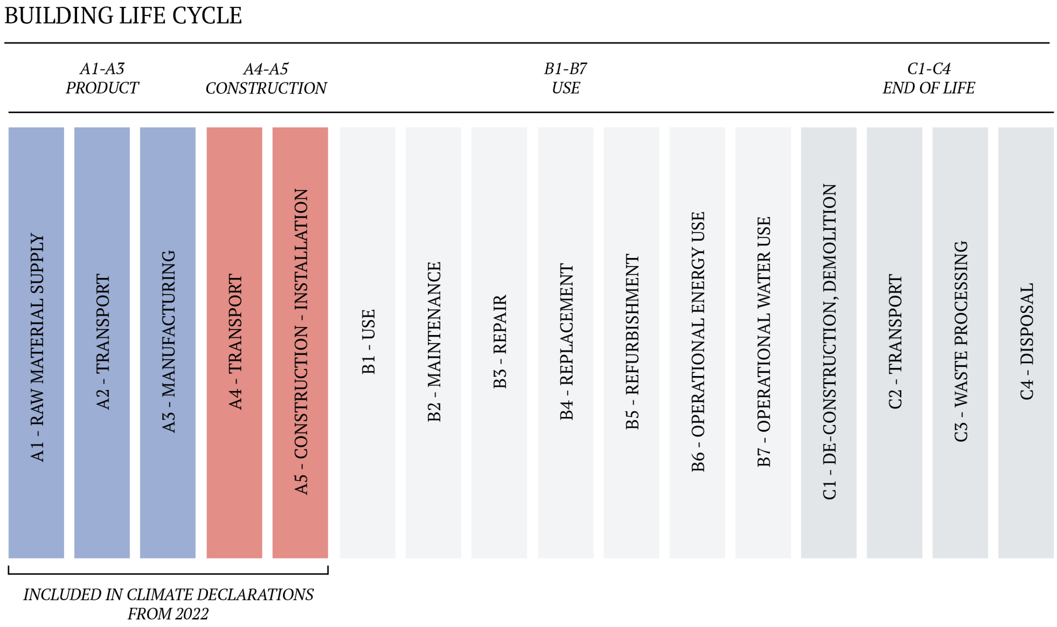


Figure 2.2 *An overview of the life cycle phases of a building. Adapted from Boverket (2018).*

2.5 Embodied carbon in building renovation

According to the national renovation strategy for the Swedish building stock, a report conducted in 2009 stated that 75% of the existing buildings will need to undergo deep renovation before 2050 for the energy savings goals in the built environment to be met (Andric et al, 2019). Furthermore, about a third of Sweden's current multi-family residential buildings was constructed during the years of 1961-1975, and since these buildings typically have a low-performing thermal envelope they represent a considerable mitigation potential (Boverket, 2003). Building renovation is a well-researched topic in Sweden, where many studies focus on improving energy efficiency for economical or environmental purposes. Hamid et al (2018) conducted a literature review which suggested that renovations predominantly are evaluated on economic profitability and energy saving potential, and more rarely is environmental impact its own performance indicator. However, as energy saving is a method of climate change mitigation due to reduced emissions associated with energy production, potential synergies can be derived.

Interdisciplinary studies quantifying possible emission reductions due to energy savings by renovation has been conducted to highlight potential synergies. A study by Mata et al (2012) showed that improving U-values and installing a heat recovery system had great potential to reduce annual energy demand, by 7% and 22% respectively, stating that the decrease in greenhouse gas emissions was negligible from a national perspective but could be relevant to decrease dependency on electricity use. La Fleur et al (2017) focused on district heating supply mixes in the Swedish and Nordic region and concluded that there is potential GHG emissions decrease of 50% in a multi-family residential building by renovation measures such as changing windows, increase insulation, and install heat recovery. Roux et al (2016) investigated changes in environmental impact from the energy use of a single-family house using projections of both climate data and electricity mixes, concluding that a passive decrease in energy use is beneficial in all scenarios.

Though this approach includes environmental impact to a degree, it runs the risk of burden shifting from one life cycle phase to another, as it only considers the operational phase of the building and ignores environmental impact associated with the materials used in the renovation. This is addressed by Ramírez-Villegas et al (2019), who calculates the embodied carbon of renovation measures and deducts the reduced embodied carbon from energy savings, showing that both building envelope improvements and the installation of heat recovery systems was beneficial in terms of limiting environmental impact during a 50-year lifespan. Österbring et al (2019) studied the environmental impact of a range of renovation measures for a building stock model in Gothenburg, including the installation of solar PV, increased insulation, change of windows and improved lighting and appliances, as well as potential synergies between measures. Setting investment capacity as the limiting factor, several environmental impact categories were assessed, showing a total reduction of GHGs by 2050 for the building stock (Österbring et al, 2019). However, Österbring et al (2019) further states the reduced GHGs are small considering the targets of GHG reduction set by the municipality.

Extending the scope to a European context, there are several studies that further supports the notion that energy saving renovation measures are beneficial in GHG reductions even when including material use. This is explored in studies in for example Serbia (Andric et al, 2017) where the measures included added thermal insulation, energy efficient glazing, and the installation of solar panels, and in Switzerland (Lasvaux et al, 2015) where the measures included added thermal insulation and added ventilation features.

2.6 Climate data projection

To be able to predict future changes in energy demand due to space heating and cooling in buildings and building stocks, regional detailed information regarding the future climate is required. Several climate models have been developed in order to simulate future weather conditions from radiative forcing scenarios. Global Climate Models (GCMs) projects future climate for different emission scenarios and considers changes in and interplay between the ocean, atmosphere, cryosphere and land surfaces (IPCC, 2013). The spatial resolution of GCMs is coarse, around 250 to 600 km horizontally, and to provide more detailed information on specific regions and localised weather events the information is downscaled. The GCMs can be downscaled dynamically using Regional Climate Models (RCMs) or through statistical morphing, i.e., combining current typical weather data for a specific location with the future projections of GCMs (Dodoo &

Gustavsson, 2015). Downscaled, regional climate data with an hourly temporal resolution is generally suitable for building energy simulations.

To create a downscaled weather data set to use in energy simulations for current and future scenarios, several techniques has been developed, such as the TMY (Typical Meteorological Year) which compounds TMMs (Typical Meteorological Month) for each month of the year (Hall et al, 1978), or the TRY (Typical Reference Year) and WYEC (Weather Year for Energy Calculations) developed by ASHRAE (Nik, 2016). In Sweden, Rossby Centre as part of the Swedish Meteorological Institute (SMHI) has developed the latest RCM which provides a spatial resolution of 50 km and a temporal resolution down to 20 minutes, and the climate data is projected using the radiation scenarios RCP2.6, RCP4.5 and RCP8.5 (Kjellström et al, 2016). Another way of indicating a future climate, i.e., a climate with higher temperatures and more frequent heat waves, is to use data from a historically hot year, as done by Pyrgou et al (2017) and Van Hooff et al (2016). There are also several weather-generator tools and software that generate TMY weather files, such as ClimGen, WeaGeats and Meteonorm (Yassaghi & Hoque, 2019). Since the climate data is based on an average year to increase credibility, the occurrences of extreme hot years, extreme cold years or extreme weather such as heat waves are rarely included.

2.7 Research gap

The continuing increase in average temperatures and the increase in length and frequency of warm periods suggests that there needs to be a larger focus on cooling in the built environment in Sweden. It will be increasingly relevant to make sure the available and implemented cooling solutions are adequate to ensure thermal comfort. Studies on how climate change impacts buildings located in Sweden have mainly been focused on how the annual energy demand will change, with a particular emphasis on heating demand. The studies have either projected energy demand for relatively new buildings, built in the 1990s or later, or in some cases an entire building stock, and there is a lack of detailed climate data projection for older buildings. Most studies indicate that the future increased annual cooling demand would be able to be mitigated by the incorporation of natural ventilation strategies (Nik & Kalagasidis, 2012; Hosseini et Al, 2022), solar shading (Dodoo & Gustavsson, 2015), or a combination of these and other measures (Dodoo et Al, 2014; Tettey et Al, 2017). Studies including extreme heat scenarios such as heat waves are scarce, and few studies include simulations of peak cooling loads. As indicated by Hosseini et al (2022), the inclusion of peak conditions when projecting climate data in energy simulations is of importance to ensure adequate climate adaptation in the built environment.

Building renovation is a well-researched topic in Sweden, where many studies focus on improving energy efficiency for economical or environmental purposes, but similarly to the assessments of how climate change impacts the Swedish building stock, studies on renovation in Sweden focus on heating and mitigation measures. Determining the mitigation potential of renovation measures is well studied, including the environmental impact of the material use. These studies, however, lack the projection of climate scenarios or climate adaptation measures.

Thus, there is a general lack of studies reviewing the environmental impact of the measures considered in the context of adapting existing buildings to future climate scenarios. There is also a lack of studies assessing climate adaptation in terms of cooling, especially peak cooling demand and cooling demand during extreme weather conditions. When renovations are considered, environmental impact is included, however, the assessments focus on heating demand reduction and climate data is rarely projected for future scenarios.

2.8 Selection of passive measures

Based on the literature review, a selection of the most relevant adaptation measures has been made. A further limited selection has been made based upon a set of criteria shaped to comply with the aims and delimitations of the study; 1) the measure is passive; 2) the measure is additive, i.e., it can be implemented in the operational life-cycle phase of the building 3) the measure is effective on a building scale; 4) it is possible to assess the embodied carbon of the measure; 5) the measure is effective when excluding microclimatic effects. Table 2.2 shows a visual representation of the considered measures. Green structures have a negligible effect on a building scale in a heating-dominating climate (Van Hooff et Al, 2015), particularly when excluding microclimate effects. In accordance with the third and fifth criteria, these measures have been excluded from the assessment. However, when studying climate adaptation on a district or city scale, these measures are of great importance for the synergy effects of increased pedestrian comfort, mitigation of UHI effects and prevention of flooding (UN-Habitat, 2011) and thus also has the potential to indirectly decrease cooling energy demand.

Increased thermal mass has not been considered as an additive measure in this case, since it is not always possible to increase the thermal mass in the operational phase of the building life cycle. Similarly, decreasing window to wall ratio is excluded since it is difficult to change in the operational life cycle phase of the building without affecting other necessary qualities, such as access to daylight. Other measures which have been excluded from the assessment is the altering of indoor comfort temperatures and clothing factors, as these are regarded as coping mechanisms. Where a measure could be described as both a mitigation and an adaptation measure, and fulfils the stated criteria, the measure has been included. The passive measures included in the study are the addition of insulation, the change to energy efficient glazing, the increase of solar reflectivity in façade material, the addition of solar shading devices, and the use of natural ventilation.

Table 2.2 *Selection criteria and the considered climate adaptation measures. The shadowed rows indicate the measures selected for the assessment.*

	Criteria				
Passive adaptation measure	1) Passive	2) Additive	3) Effective on a building scale	4) Possibility to assess embodied carbon	5) Effective when excluding microclimatic effects
Insulation + air tightness	x	x	x	x	x
Change doors & windows	x	x	x	x	x
Solar shading	x	x	x	x	x
Natural ventilation	x	x	x	x	x
Solar reflectivity	x	x	x	x	x
Thermal mass	x		x	x	x
Green structures	x	x		x	
Window to wall ratio	x		x	x	x
Solar PV		x	x	x	x
Energy efficient lighting + equipment		x	x	x	x
Heat recovery		x	x	x	x
Indoor comfort temperatures		x	x	x	x
Clothing		x			x
Smart controls		x	x		x

3 Method

The following section introduces the methodology of the thesis. Firstly, the case study is presented, followed by the climate data, the energy simulations and the environmental impact calculations. The section ends by describing the different scenarios derived from the selected passive measures and presents the developed methodology for the environmental efficiency calculations. An overview of how and when the methods have been implemented and the interplay between the methods is shown in Figure 3.1.

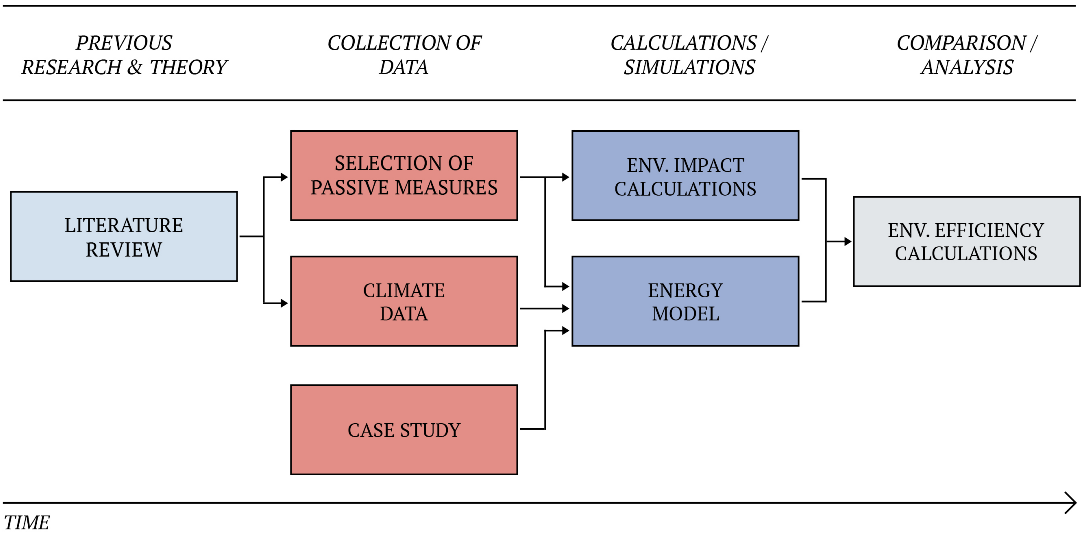


Figure 3.1 Illustration depicting the choice of methodology for different phases of the thesis as well as the interconnection between different methodologies.

3.1 Literature review

A literature review was conducted to place the study in the context of former research and related theories. Additionally, the purpose of the review was to assess the most used or planned to be used climate adaptation measures in the built urban environment. The literature review was conducted using the data bases ScienceDirect, Scopus and Google Scholar, and the search strings used are described in Table 3.1. Various reports and articles from Swedish and international organisations and governments were also reviewed.

Table 3.1 Search strings used in the strategic literature search.

Search string no.	Keywords
1 - General	("buil*" OR "renovation") AND ("climate" OR "warming" OR "*heat*") AND "adapt*"
2 - Swedish context	("buil*" OR "renovation") AND ("climate" OR "warming" OR "*heat*") AND ("Swed*" OR "Scandinavia*")
3 – Further specification	[1 or 2] + AND ("passive" OR "cooling" OR "energy" OR "power") [2] + AND ("adapt*")

3.2 Case study

To represent a building type in Sweden which typically requires large-scale renovations, a multi-family residential building built in 1970 was selected as a case study. The building is situated in Uddevalla in the region of Västra Götaland, southern Sweden, in a cool temperate climate zone. The area has less than 50% employment with average salary, and in many cases more people live in the apartments than there are designated bedrooms. The building is owned by Uddevallahem, a municipal housing company, and is part of a residential area with approximately 750 dwellings built in 1965-1975, subject to renovation in the upcoming years. The case study was chosen due to the comprehensive data availability. The increased life expectancy of the building after the planned renovation is at least 50 years. Due to the cool climate, renovation measures focus on reducing heating energy demand and planned renovation measures include added insulation, new windows and doors, and a new ventilation system with heat recovery.

The case study is a four-story building including the basement and is mainly constructed with prefabricated concrete. The building is heated with district heating and has no cooling systems installed. The ground floor consists of 250 mm concrete, the roof consists of 200 mm concrete and 400 mm insulation, the walls consist of prefabricated concrete elements with 100 mm insulation and 90 mm concrete. The doors and windows are original and were given typical values representative for windows and doors in 1970, given by Boverket (2010) and La Fleur et al (2017). The infiltration rate was estimated by Uddevallahem. See Table 3.2 for full details on construction and building information. A typical floor plan and a photo of the building is shown in Figure 3.2 and Figure 3.3.

Table 3.2 Case study building information and construction details.

Description	Parameter	Unit	Comment
Construction	Prefab concrete		
Construction year	1970		
Number of floors	4		Including basement
Number of apartments	18		3-4 rooms + kitchen
Heated floor area, A_{temp}	2526	m^2	
Heated air volume	5380	m^3	
Window area	287	m^2	
Window g-value	0.75	-	Sveby, 2012
U-values			
Roof	0.084	W/ m^2K	Calculated
Ground Floor	2.58	W/ m^2K	Calculated
Wall	0.34	W/ m^2K	Calculated
Doors	2.5	W/ m^2K	La Fleur et Al, 2017
Windows	2.8	W/ m^2K	Boverket, 2010
Infiltration	1.1	l/sm^2	Case study assumption
Mechanical ventilation	0.35	l/sm^2	Exhaust only

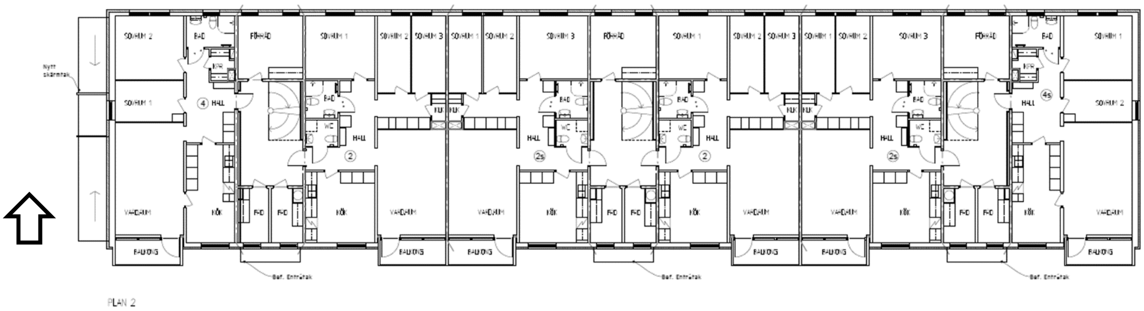


Figure 3.2 *Representative floor plan of case study building. The north facing façade is upwards, as indicated by the arrow.*

Figure 3.3 *Case study building before renovation.*

3.3 Energy model

An energy model of the case study was developed within the Rhinoceros/Grasshopper environment, using the Ladybug and Honeybee plugins which applies the EnergyPlus simulation engine. EnergyPlus is an open-source simulation engine developed and funded by U.S. Department of Energy (DOE), widely used for compliance and research (EnergyPlus, n.d.). The energy simulations were made using a bottom-up heat balance model, with information as text file inputs. The modelled geometry was based on blueprints from the planned renovation. The model was comprised of 121 thermal zones. The occupancy and equipment loads were derived from *Standardisera och Verifiera Energiprestanda i Byggnader* (In English: Standardisation and Verification of

Energy Performance in Buildings) (Sveby, 2012). The heating setpoints were estimated by Uddevallahem, the case study building owner. Key input data is presented in Table 3.3, for an overview of all input data see Appendix II – Energy model input data. Due to time limitations only one orientation was simulated, the actual orientation of the building. Similar buildings rotated 90 degrees clockwise can be found in the area, meaning the long exterior wall with the balconies could also face west instead of south. However, since the south façade has a greater exposure to solar radiation, the orientation of the case study building could be assumed to be the worst case and therefore most relevant for the assessment.

Table 3.3 Key input data for the energy simulation model.

Description	Parameter	Unit	Comment
Occupancy			
2-bedroom apartment	2.18	ppl	Sveby, 2012
3-bedroom apartment	2.79	ppl	Sveby, 2012
Occupancy schedule	14	hrs/day	Sveby, 2012
Equipment load	2.4	W/m^2	Sveby, 2012
Natural ventilation	0.5	l/sm^2	Sveby, 2012
Schedule - Cooling period	6	hrs/day	Sveby, 2012
Heating setpoint			
Apartments	22	°C	From case study
Basement	17	°C	From case study

The model was calibrated and compared to a reference building by heating demand per meter square floor area, see Figure 3.4. The reference building is a multi-family residential building in the same area, built at the same time and with similar construction, size and layout as the case study building. The reference building has already been subject to renovations and the energy use due to heating was monitored before and after, making it a suitable object for comparison. The annual space heating demand of the model was approximately 15% smaller than the reference case, whilst the largest monthly variation was approximately 30% for the months of January and February. The variation in the cooling season, May to September, was small. Since the model was based on a TMY for 2018 in Gothenburg, and the reference values were measured between 2016-2018 on the actual case study location 90 kilometres north-east of Gothenburg, variations were within the expected range.

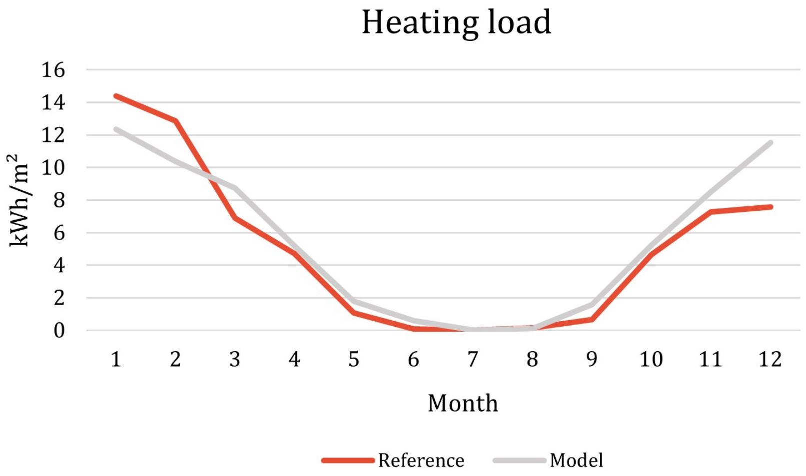


Figure 3.4 *Monthly heating demand measured for a reference building (red) and the calibrated energy model (grey).*

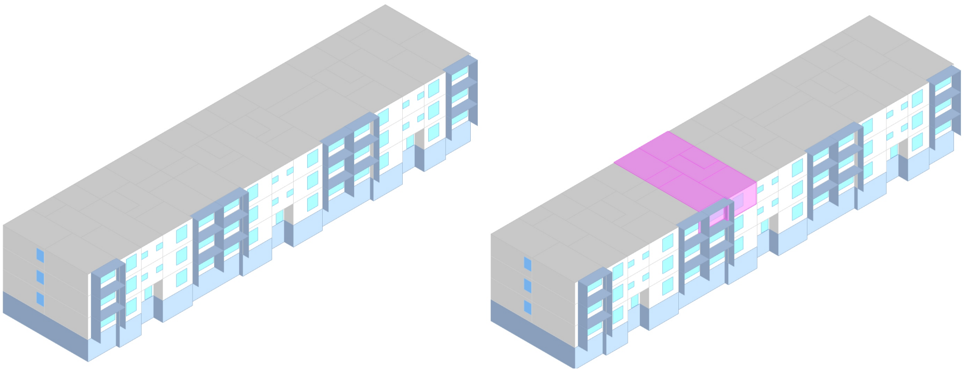


Figure 3.5 *Base geometry in energy model (left) and the assessed worst apartment (right). View from Southwest.*

The energy model was used to simulate annual cooling demand, annual heating demand, peak cooling demand, overheating hours and maximum temperature during peak conditions. Since the case study building is not equipped with a cooling system, the results show the theoretical cooling load. Overheating hours and max temperature during peak conditions were used as further indicators. The annual cooling and heating demand was assessed for the whole building, whilst the peak cooling demand, overheating hours and maximum temperature during peak conditions was assessed for the most critical apartment, identified by comparing the full set of simulation results, see Figure 3.5.

The peak condition was defined as the maximum value of cooling supplied on average across the zones in the most critical apartment. Overheating hours, defined as the percentage of hours between April and September the average temperature of the most critical apartment exceeds the temperature threshold, was assessed for two threshold cases, 26°C and 28°C. Furthermore, the hourly temperature profile of the hottest three days for the 2050 RCP4.5 scenario in the most critical apartment was assessed for all scenarios to further illustrate how peak conditions affect the thermal comfort within the building. The temperature profile was based on the average temperature profiles of the occupied zones, i.e., the living room, kitchen and bedrooms. The temperature profile of the natural ventilation scenario was further assessed due to the possible implications of modelling limitations, see section 3.6.7.

3.4 Climate data

The climate data was acquired in the form of EnergyPlus Weather (EPW) files, developed by the U.S. Department of Energy as a weather data source for energy simulations within the EnergyPlus simulation engine. Due to data availability, the geographical location of the weather data was set to Gothenburg, about 90 kilometres south of Uddevalla and the location of the case study. The historic and future climate scenarios were synthesized into EPW files using the Meteonorm software, and the climate data was in the form of TMYs. For future weather files, Meteonorm downscales climate data using ten different GCMs for the RCP2.6, RCP4.5 and RCP8.5 scenarios. TMYs of the future radiation scenario of RCP4.5 and RCP8.5 will be assessed for the year of 2030 and 2050, see Table 3.4. UHI effects were not included in the climate data.

Table 3.4 Summary of the climate scenarios used for the energy simulations.

Scenario	Location	Radiation scenario	Year	Duration	Comment
2018	Gothenburg	-	2018	1 Year	Meteonorm
2030_RCP45	Gothenburg	RCP4.5	2030	1 Year	Meteonorm
2050_RCP45	Gothenburg	RCP4.5	2050	1 Year	Meteonorm
2030_RCP85	Gothenburg	RCP8.5	2030	1 Year	Meteonorm
2050_RCP85	Gothenburg	RCP8.5	2050	1 Year	Meteonorm

3.5 Environmental impact calculations

The environmental impact of the passive measures was calculated based on the methodology presented by Boverket (2018). The data needed to assess the environmental impact of the added measures were retrieved from the open material database by Boverket (2021), see Appendix I – Environmental impact data, to enable coherency and comparisons with data from climate declarations. The environmental impact was measured in GWP using the unit of kg CO_2e, and any other climate impact were excluded. In accordance with the methodology from Boverket (2018), the end-of-life or operational phase of the product or material were not included in the environmental impact, excluding any impact from maintenance and waste. The calculations also excluded potential future changes in emissions from transportation or material extraction. No material waste is assumed. In cases where the environmental impact of a certain product is not available, such as in the case of the triple glazing scenario and solar shading scenario, the material of the product has been assessed, therefore excluding any environmental impact due to production or added material used for mounting etc. The environmental impact was calculated using the following equations:

$$A \times d \times \rho \times GWP_{norm} = GWP_{tot}$$

$$A \times \delta \times GWP_{norm} = GWP_{tot}$$

Where:

A = Area of material	[m^2]
d = Thickness of material	[m]
ρ = Density of material	[kg/m^3]
δ = Density of material	[kg/m^2]
GWP_{norm} = Normalised global warming potential	[kgCO$_2$/kg]
GWP_{tot} = Total global warming potential	[kgCO$_2$]

3.6 Scenarios

The passive climate change adaptation measures were included as parameters in the energy model by the construction of different scenarios, see Table 3.5. The scenarios included the as-built scenario as a reference, a renovated scenario which became the baseline for the cooling demand, maximum temperature and environmental impact. Scenario 1-5 represented the renovated case in addition to the selected passive measures that can be included in the renovation, and Scenario 6 represents a combination of all the assessed passive measures. The cooling power demand, maximum temperature, overheating hours, annual cooling demand and annual heating demand for all scenarios were simulated. Below follows a more detailed description of each scenario.

Table 3.5 Summary of the assessed scenarios and their parameters.

Scenario	Parameters
As-built	As-built
Renovated	+50 mm insulation, increased air tightness, double glazing, replace doors
Scenario 1	Renovated + added insulation
Scenario 2	Renovated + triple glazing
Scenario 3	Renovated + increased solar reflectivity
Scenario 4	Renovated + solar shading
Scenario 5	Renovated + natural ventilation
Scenario 6	Combination of scenario 1-5

3.6.1 As-built

The as-built scenario represents the case study building in an unrenovated state. The occupants are assumed to open the windows a few hours a day during the summer season, as estimated by Sveby (2012). Construction details and U-values are typical for 1970, see section 3.4. The input data for the as-built scenario is summarised in Table 3.6.

Table 3.6 Parameters and input values of the as-built scenario.

Parameter	Input value	Unit
Wall U-value	0.319	W/m^2K
Infiltration heating period	1.1	l/sm^2
Infiltration cooling period	1.225	l/sm^2
Window U-value	2.8	W/m^2K
Window G-value	0.75	-
Door U-value	2.4	W/m^2K
Solar reflectivity wall	0.3	-
Solar shading	No	
Natural ventilation	No	

3.6.2 Renovated

The input data for the renovated scenario is based upon the planned renovation measures for the case study, i.e., adding 50 mm insulation, increasing air tightness of the building envelope, replace the windows to better performing double glazed windows and changing to better performing doors. The ability to renovate existing windows varies between the type of window and their condition, and therefore no window renovation options will be reviewed. Since the adding of heat recovery is considered an active measure, this planned renovation measure has been excluded from the renovated scenario. This scenario is the baseline scenario for energy demand, max temperature and environmental impact, consequently, the environmental impact of the added materials in this scenario compared to the as-built case is not assessed in this study. The door U-values are improved from typical values for 1970s to a standard U-value for a current commercially available door in all further scenarios. Input data for the renovated scenario is presented in Table 3.7.

Table 3.7 Parameters and input values of the renovated scenario.

Parameter	Input value	Unit
Wall U-value	0.219	W/m²K
Infiltration heating period	0.7	l/sm²
Infiltration cooling period	0.825	l/sm²
Window U-value	1.4	W/m²K
Window G-value	0.6	-
Door U-value	1.2	W/m²K
Solar reflectivity wall	0.3	-
Solar shading	No	
Natural ventilation	No	

3.6.3 Scenario 1 - Added insulation

The first scenario consists of an extra 175 mm layer of added insulation. The additional insulation will be concentrated to the exterior walls, since the roof is already well-insulated. This option might not be beneficial in terms of cooling unless combined with a reduction of solar radiation through windows, since large heat gains risk to get trapped inside the building, exaggerating heat stress. An overview of the input data for the energy model is presented in Table 3.8, and the added materials for the added insulation scenario is presented in Table 3.9.

Table 3.8 Parameters and input values of the added insulation scenario.

Parameter	Input value	Unit
Wall U-value	0.123	W/m²K
Infiltration heating period	0.7	l/sm²
Infiltration cooling period	0.825	l/sm²
Window U-value	1.4	W/m²K
Window G-value	0.6	-
Door U-value	1.2	W/m²K
Solar reflectivity wall	0.3	-
Solar shading	No	
Natural ventilation	No	

Table 3.9 Overview of added materials in the as-built scenario.

Added materials	Area	Thickness	Volume
Insulation	837.4 m²	0.175 m	146.5 m³

3.6.4 Scenario 2 - Triple glazing

A measure that both reduces the heating and cooling load is to improve the glazing. This scenario investigates the incorporation of triple-glazed windows with low e-coating in the renovation. Compared to the double-glazed windows, this option offers further reduction of the U-value which limits heat transfer through the construction, and a further reduction of the g-value of the window, which decreases the amount of solar radiation that is let through the window and consequently reduces solar heat gains. The input data of the triple glazing scenario is presented in Table 3.10.

Since double glazing is added in the baseline renovated scenario, the added material for the triple glazing is assumed to be one extra 4 mm thick windowpane, i.e., no added material for the frame is assumed. Therefore, for the environmental impact to be valid for the triple glazing scenario, the windows need to be incorporated in the renovation so that there is no double impact from changing windows at a later point in time. An overview of the added material use for the scenario is presented in Table 3.11.

Table 3.10 Parameters and input values of the triple glazing scenario.

Parameter	Input value	Unit
Wall U-value	0.219	W/m^2K
Infiltration heating period	0.7	l/sm^2
Infiltration cooling period	0.825	l/sm^2
Window U-value	0.9	W/m^2K
Window G-value	0.45	-
Door U-value	1.2	W/m^2K
Solar reflectivity wall	0.3	-
Solar shading	No	
Natural ventilation	No	

Table 3.11 Overview of added materials in the triple glazing scenario.

Added materials	Area	Thickness	Volume
Floatglass	272.5 m^2	0.004 m	1.09 m^3

3.6.5 Scenario 3 - Increased solar reflectivity

The solar reflectivity, or albedo, describes how much of the solar radiation is reflected by the material surface. The non-reflected radiation is instead absorbed. Since the façade is being renovated, there is a possibility of using a highly reflective material to decrease the amount of absorbed heat in the construction. The reflective material is assumed to be light paint, reapplied once every five years to keep the solar reflectivity high. An overview of the input parameters for the energy model and added materials is presented in Table 3.12 and Table 3.13.

Table 3.12 Parameters and input values of the increased solar reflectivity scenario.

Parameter	Input value	Unit
Wall U-value	0.219	W/m^{2}K
Infiltration heating period	0.7	l/sm^2
Infiltration cooling period	0.825	l/sm^2
Window U-value	1.4	W/m^{2}K
Window G-value	0.6	-
Door U-value	1.2	W/m^{2}K
Solar reflectivity wall	0.7	-
Solar shading	No	
Natural ventilation	No	

Table 3.13 Overview of added materials in the increased solar reflectivity scenario.

Added materials	Area	No of times applied	Area
White paint exterior	837.4 m^2	10	8374 m^2

3.6.6 Scenario 4 - Solar shading

Solar shading reduces the amount of solar radiation reaching the window, limiting solar heat gains. The environmental impact from the solar shading scenario could vary to a great extent depending on material choice and design, however, for the simplicity of this study a standard solution has been assessed. The solar shading assessed is a horizontal aluminium sheet placed on the top of the window, extending 60 cm perpendicular to the exterior wall. Since automated control systems are not a passive measure, this alternative will be excluded from the scenarios. The assessed solar shading is external, since ASHRAE (2017) states that external solar shading is the most effective in reducing solar radiation. Furthermore, the scenario is based upon a standard design which does not obstruct other qualities such as daylight or view from the apartments, see Figure 3.6. Input data and material use are presented in Table 3.14 and Table 3.15.

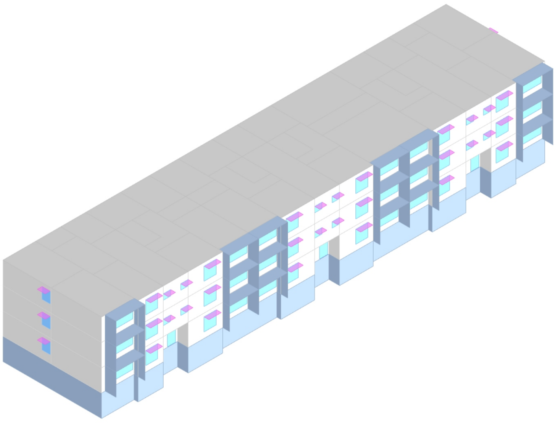


Figure 3.6 Geometry simulated for the solar shading scenario.

Table 3.14 Parameters and input values of the solar shading scenario.

Parameter	Input value	Unit
Wall U-value	0.219	W/m^2K
Infiltration heating period	0.7	l/sm^2
Infiltration cooling period	0.825	l/sm^2
Window U-value	1.4	W/m^2K
Window G-value	0.6	-
Door U-value	1.2	W/m^2K
Solar reflectivity wall	0.7	-
Solar shading	Yes	
Natural ventilation	No	

Table 3.15 Overview of added materials in the solar shading scenario.

Added materials	Area	Thickness	Volume
Aluminium sheet	26.2 m^2	0.005 m	0.13 m^3

3.6.7 Scenario 5 - Natural ventilation

Natural ventilation is the use of natural air flow to let outside air in for ventilation, which has a cooling effect if the outside air temperature is lower than the inside air temperature. Since automatic controls would not be strictly passive, the ventilation is assumed to be operated manually by occupants through opening and closing of the windows. Since the windows are operated manually, no environmental impact is assumed to be associated with this scenario. The windows are assumed to be opened if the inside air temperature exceeds 24°C and if the outside air temperature exceeds 22°C. This is due to limitations in the energy model, in which the minimum outside air temperature for natural ventilation cannot be lower than the heating setpoint, see further discussion in section 5.2. This assumption might lead to an underestimation of the efficiency of the natural ventilation, because in many cases the windows could be open during outside temperatures down to 16-18°C without causing discomfort. To further explore how this affects the efficiency of the natural ventilation scenario the peak condition is measured for two additional alternative minimum outdoor temperature setpoints, 20°C and 18°C. The openable area fraction of the windows is assumed to be 50%. Due to additional modelling limitations, if the air outside is warmer than the air inside the windows are still assumed to be opened, contributing to a heating effect. The energy simulation inputs for the natural ventilation scenario are shown in Table 3.16.

Table 3.16 Parameters and input values of the natural ventilation scenario.

Parameter	Input value	Unit
Wall U-value	0.219	W/m²K
Infiltration	0.7	l/sm²
Window U-value	1.4	W/m²K
Window G-value	0.6	-
Door U-value	1.2	W/m²K
Solar reflectivity wall	0.3	-
Solar shading	No	
Natural ventilation	Yes	
Min temperature interior	24	°C
Min temperature exterior	22	°C

3.6.8 Scenario 6 - Combination

The combined scenario explores possible synergy effects between the combination of all methods. The scenario consists of a combination of Scenario 1-5, i.e., 175 mm of added insulation, triple-glazed windows, improved solar reflectivity, added solar shading and added use of natural ventilation. Energy simulation inputs and an overview of the added materials for the scenario is presented in Table 3.17-Table 3.18.

Table 3.17 Parameters and input values of the combined scenario.

Parameter	Input value	Unit
Wall U-value	0.123	W/m²K
Infiltration heating period	0.8	l/sm²
Window U-value	0.9	W/m²K
Window G-value	0.45	-
Door U-value	1.2	W/m²K
Solar reflectivity wall	0.7	-
Solar shading	Yes	
Natural ventilation	Yes	

Table 3.18 Overview of added materials in the combined scenario.

Added materials	Area	Thickness	Volume
Insulation	837.4 m^2	0.175 m	146.5 m^3
Floatglass	272.5 m^2	0.004 m	1.09 m^3
White paint	8374 m^2		
Aluminium sheet	26.2 m^2	0.005 m	0.13 m^3

3.7 Environmental efficiency calculations

The environmental efficiency indicator was developed by the author to be able to assess the efficiency in reduced cooling demand compared to the environmental impact. The environmental efficiency is defined as the amount of environmental impact in GWP that corresponds to reducing cooling energy demand, peak (kW) or annual (kWh), or maximum temperature (°C). The environmental efficiency for a passive measure *i* is calculated according to the following equations:

$$\frac{GWP_i}{RCD_i} = EE_i$$

$$\frac{GWP_i}{RMT_i} = EE_i$$

Where:

GWP_i	= Global warming potential of scenario	[t CO_2]
RCD_i	= Reduced cooling demand for scenario	[kWh], [kW]
RMT_i	= Reduced maximum temperature during peak conditions for scenario	[°C]
EE_i	= Environmental efficiency	[t CO_2/kWh], [t CO_2/kW], [t CO_2/°C]

The environmental efficiency was calculated for the RCP4.5 climate scenario in 2050 and for all passive measures, for; 1) annual cooling [kg CO_2e per kWh reduced annually], 2) peak cooling [kg CO_2e per kW reduced during peak conditions], 3) maximum temperature during peak conditions [kg CO_2e per °C reduced].

4 Results

This section presents the results from the energy simulations and environmental impact calculations, followed by the environmental efficiency comparison.

4.1 Energy simulation results

This section presents the reduction in annual and peak cooling demand, followed by a review of the total annual energy demand. Lastly, overheating hours and temperature profiles during peak conditions are presented.

4.1.1 Annual cooling demand

The annual cooling demand was simulated for RCP4.5 and RCP8.5, the years 2018, 2030 and 2050, for all scenarios, see Figure 4.1Figure 4.2. For the renovated case, i.e. the baseline, the annual cooling demand increased with 180-230% in 2030 and 280-400% in 2050 depending on climate scenario, corresponding to 1.3-1.9 kWh/m^2. The glazing and natural ventilation options were the most effective of the individual passive measures assessed, reducing annual cooling demand with 52-56% and 24-45% for the year of 2050 respectively, depending on climate scenario. Scenario 1, 3 and 4, i.e., adding insulation, increasing the solar reflectivity and adding solar shading, showed less efficiency in reducing annual cooling demand with a possible reduction of around 4%, 8% and 14% respectively by 2050 in both the RCP4.5 and RCP8.5 climate scenario. The combined measures kept cooling at the current level in 2050 for the RCP4.5 climate scenario, and only increased by around 80% for the RCP8.5 climate scenario. This corresponded to a 66-80% decrease in annual cooling demand compared to the renovated case, depending on climate scenario, indicating a possible synergy effect when combining the individual measures.

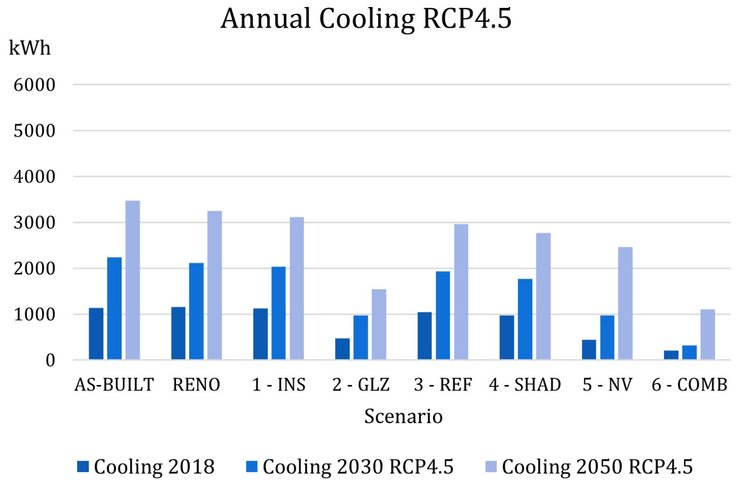


Figure 4.1 *Annual cooling energy demand for 2018, 2030 and 2050, for the RCP4.5 climate scenario.*

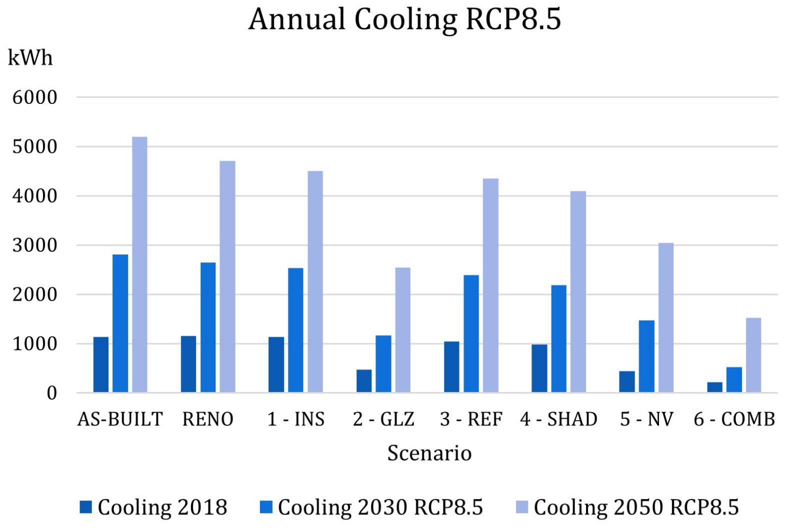


Figure 4.2 *Annual cooling energy demand for 2018, 2030 and 2050, for the RCP8.5 climate scenario.*

4.1.2 Peak cooling demand

The peak cooling demand was simulated for all passive measure and climate data scenarios. Results are presented in Figure 4.3-Figure 4.4. In the renovated scenario, the peak cooling was estimated to increase by 34-98% by 2050, depending on climate scenario, corresponding to 1.7 - 2.3 kW total cooling power demand for the worst situated apartment. The triple glazing scenario was the most effective in reducing peak cooling demand, with a reduction of 30-37% in 2030 and 36-37% in 2050 compared to the renovated case. The solar shading scenario proved to be the second most efficient measure, with the possibility of reducing the peak cooling demand with 13% by 2050 for both the RCP4.5 and RCP8.5 scenarios. The effects from the added insulation and increased solar reflectivity scenarios were negligible in terms of peak cooling reduction.

The natural ventilation case showed an increase in peak cooling, or that the decrease was small, depending on climate scenario. The peak cooling for the natural ventilation scenario occurred in early June as opposed to the other scenarios where it occurred during the warmest day of the year, i.e., 22nd of July. This suggests that the inflated peak cooling demand is due to a combination of the modelling limitations described in section 3.6.7 and a rapid increase in outside air temperature. The effects are further discussed in section 5.2. The combined case showed little to no synergy effects as the reduced peak cooling was very close to the triple glazing scenario, however, in 2050 for the RCP8.5 it showed a further reduction of 12%.

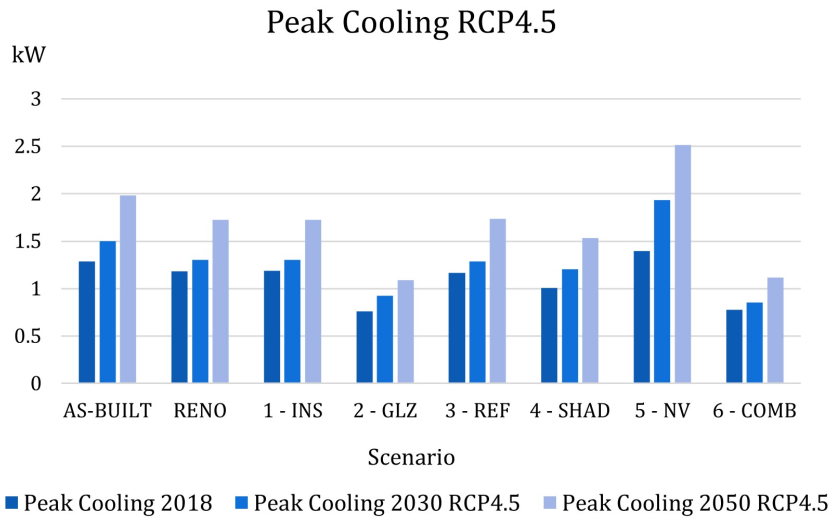


Figure 4.3 *Peak cooling energy demand for 2018, 2030 and 2050, for the RCP4.5 climate scenario.*

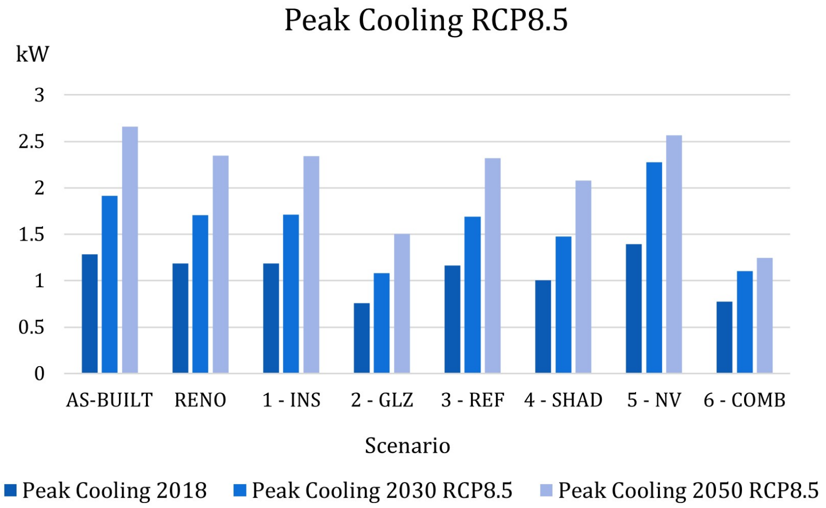


Figure 4.4 *Peak cooling energy demand for 2018, 2030 and 2050, for the RCP8.5 climate scenario.*

4.1.3 Annual energy demand due to heating and cooling

The annual heating demand was simulated to be able to detect any potential heating demand increase due to the passive cooling measures. The heating demand was reduced by 12-18% depending on climate scenario for the renovated case in 2050. As seen in Figure 4.5, the shading and increased solar reflectivity had a slight increase in heating demand compared to the renovated scenario, which also led to an increase in the combined case, however, any differences were within 0.5% compared to the renovated scenario for both the RCP4.5 and RCP8.5 climate scenario. Additionally, the total annual cooling demand in 2050 is less than 3-5% of the total annual heating demand of the same year depending on climate scenario for the renovated case, suggesting that the potential for reducing annual energy demand by reducing the cooling energy demand is small. The energy simulations showed that scenario 3, increased solar reflectivity, increased the annual energy demand with 1.2% by 2050, see Figure 4.6, due to the increase in heating demand. The solar shading option increased annual heating demand by 0.9%. The rest of the scenarios showed a net decrease of annual energy demand in 2050, due to the reduction in cooling loads. The natural ventilation and triple glazing scenario reduced the annual energy demand with 0.7% and 1% respectively. The added insulation case reduced the annual energy demand by 4.3%, however, this was mainly due to the decrease in energy demand due to heating. Similarly, the combined case reduced annual energy need by 4.5%.

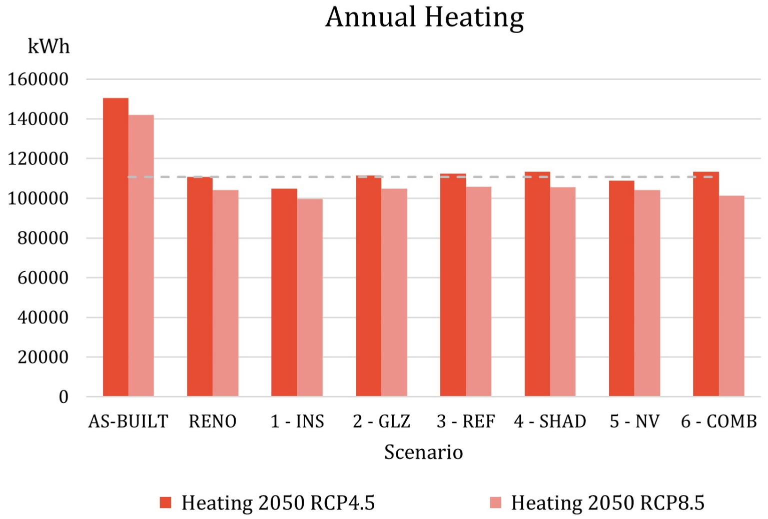


Figure 4.5 Annual heating energy demand for 2050, for the RCP4.5 and RCP8.5 climate scenarios.

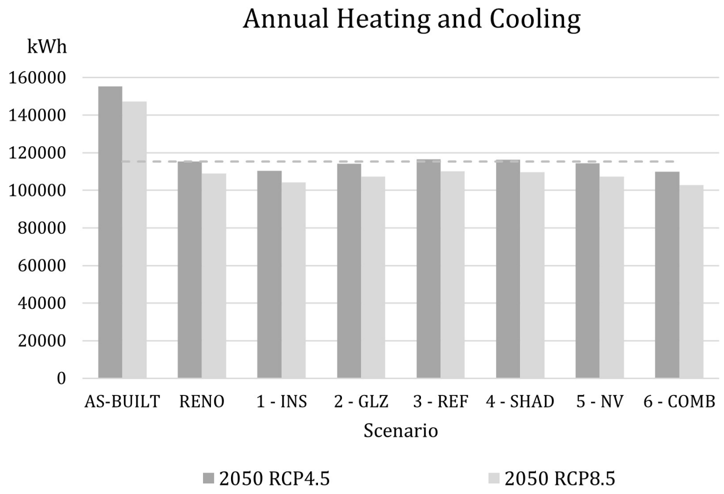


Figure 4.6 *Annual energy demand due to heating and cooling for 2050, for the RCP4.5 and RCP8.5 climate scenarios.*

4.1.4 Overheating hours

The overheating hours, i.e., the percentage of hours between April and September that exceeds 26°C or 28°C, was calculated for all climate adaptation measures in all scenarios for the worst apartment, see Figure 4.7-Figure 4.10. FEBY (2018) recommends that overheating hours should not exceed 10% for the 26°C threshold. The results showed that in 2018 the as-built and renovated case both significantly exceeded the 10% limit, with calculated overheating hours of 20% and 25% respectively. However, it should be noted that natural ventilation was not considered to be used to any greater extent in these two scenarios. Scenario 5 which included the use of natural ventilation and had the calculated overheating hours of 14% could be considered as a closer approximation of current overheating conditions. There was a small increase in overheating hours between the as-built and renovated case due to the increased air tighness and insulation trapping heat inside the apartment. Projecting the future climate data on the baseline case, i.e., the renovated case, the amount of overheating hours was estimated to increase by around 50%, reaching 38% by 2050 in both the RCP4.5 and RCP8.5 climate scenarios. Scenario 5, i.e., the case that included natural ventilation, showed an increase of 60-100% by 2050, amounting to 22-27% of overheating hours depending on climate scenario.

In terms of of reducing overheating hours the different scenarios showed similar efficiencies to the annual cooling demand results, where the triple glazing and natural ventilation were the most effective. The combined case showed a synergy effect which was effective enough to keep overheating hours below the 10% threshold for the year of 2030 and 2050 in the RCP4.5 climate scenario. In 2050 for the RCP8.5 scenario the overheating hours for the combined case exceeded the limit by 5%. For all future climate scenarios, the natural ventilation, triple glazing and the combined case showed great potential in reducing overheating hours.

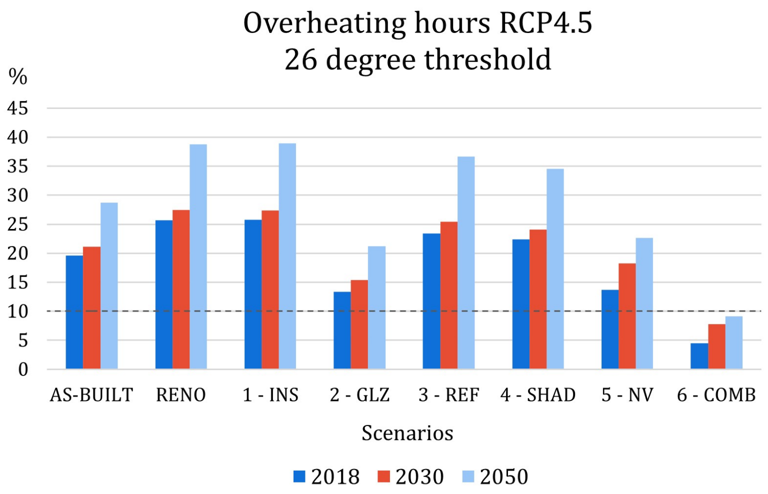


Figure 4.7 *Overheating hours considering a threshold of 26°C, for 2018, 2030 and 2050, for the RCP4.5 climate scenario. The dashed line indicates the maximum recommended overheating hours.*

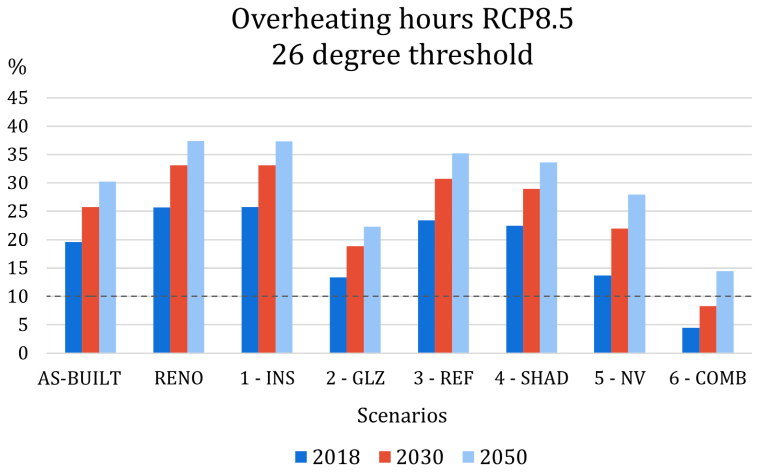


Figure 4.8 *Overheating hours considering a threshold of 26°C, for 2018, 2030 and 2050, for the RCP8.5 climate scenario. The dashed line indicates the maximum recommended overheating hours.*

The overheating hours were also assessed for the 28°C threshold, since this is a common overheating limit in building standards for slightly warmer climates. The results showed a large amount of overheating hours for the as-built and renovated cases without the use of natural ventilation, up to 14-19% by 2050 depending on climate scenario. However, when natural ventilation was used, the overheating hours was below 1% by 2050 for both climate scenarios. The triple glazing scenario continued to show a high efficiency in reducing overheating hours.

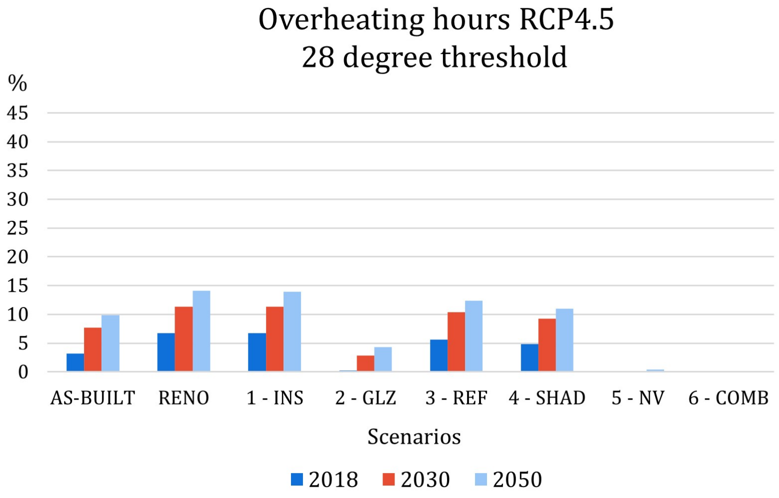


Figure 4.9 *Overheating hours considering a threshold of 28°C, for 2018, 2030 and 2050, for the RCP4.5 climate scenario.*

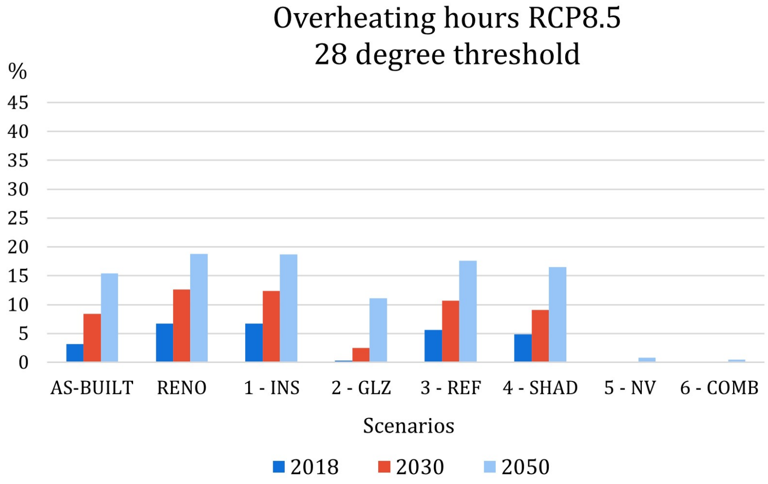


Figure 4.10 *Overheating hours considering a threshold of 28°C, for 2018, 2030 and 2050, for the RCP8.5 climate scenario.*

4.1.5 Temperatures during peak conditions

To further assess the thermal performance of the building, the average temperature for the worst apartment during peak conditions was simulated for the RCP4.5 climate scenario in 2050, see Figure 4.11. The warmest days of the TMY for 2050 were between the 21st and 23rd of July, reaching a maximum outdoor temperature of 29.5°C. Similarly to the overheating hours simulations, the natural ventilation case could be considered the closest approximation to a realistic temperature profile for the worst apartment in the building, since the apartment had openable windows. The as-built and renovated cases had an equivalent performance in terms of average temperature during peak temperatures, and in accordance with previous simulations, the added insulation and increased solar reflectivity cases showed a negligible difference. The solar shading option had the potential of reducing the maximum average indoor air temperature with around 0.6°C whilst the triple glazing option, proving more efficient, had the potential to reduce the peak temperature with 1.9°C.

The natural ventilation case had the potential of reducing the maximum average temperature with 2.2°C during the assessed peak conditions, measured at 2 PM in the afternoon on the 22nd of July. The difference in peak temperatures of the renovated case and the natural ventilation case during the 21st and 23rd of July was even greater. The combined measures showed the potential of reducing the maximum interior air temperature below outside air temperature, lowering peak temperature with 2.7°C to a maximum of 28.8°C. The combined measures were therefore the most effective in reducing maximum temperatures during peak conditions.

Between 00:00 and 07:30 on the 23rd of July, the natural ventilation was not active, since the outside air temperature subceeded 22°C. This led to an increase in inside air temperature during the night, reaching above the overheating threshold of 26°C. This scenario was further explored by simulating the peak conditions for two additional natural ventilation scenarios – with a minimum outside temperature of 20°C and 18°C, see results in Figure 4.12. The results showed that if the minimum outdoor temperature was lowered by 2-4°C, there would be a possibility to keep lower temperatures at night, reducing the amount of overheating hours. However, the scenarios showed no improvement in reducing the maximum temperature during the same period.

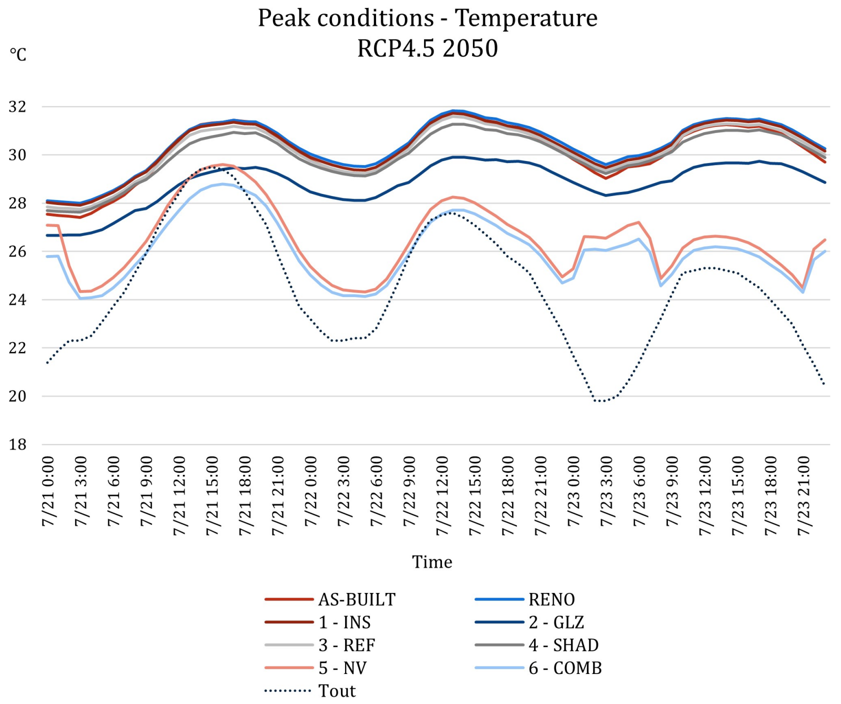


Figure 4.11 *Temperature profile during peak conditions, 21st-23rd of July, in 2050 for the RCP4.5 climate scenario. The dotted line represents the outdoor air temperature.*

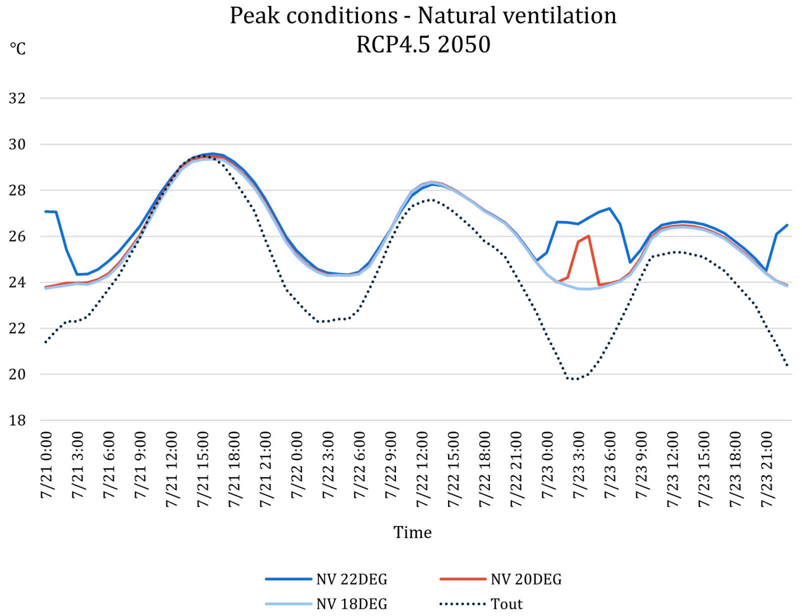


Figure 4.12 *Temperature profile of the natural ventilation scenario for a minimum outdoor temperature of 18°C, 20°C and 22°C during peak conditions, 21st-23rd of July, in 2050 for the RCP4.5 climate scenario. The dotted line represents the outdoor air temperature.*

4.2 Environmental impact

The results of the environmental impact assessment are shown in Figure 4.13. The results showed that the additional insulation, improved glazing and added shading scenarios had a similar environmental impact, around 4-6 t CO_2e. The increased solar reflectivity option had a slightly lower impact, at 2.8 t CO_2e. As previously stated, the windows were assumed to be opened manually and therefore no environmental impact was associated with the natural ventilation scenario. The combined scenario had a significantly higher impact than the other options, since the figure includes the combined impact of all the other scenarios.

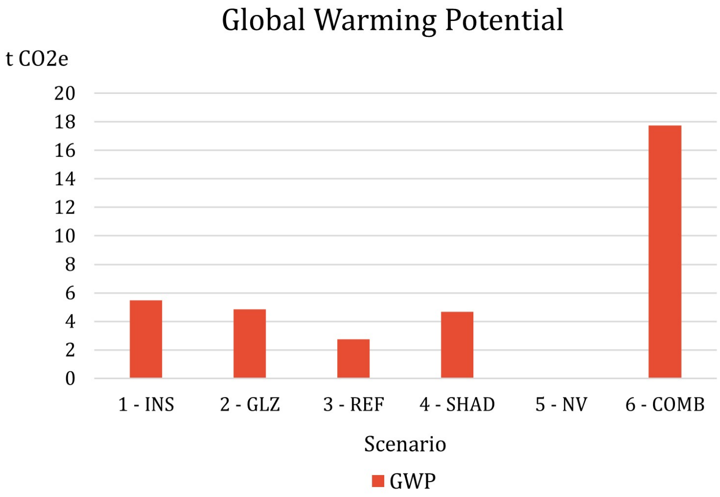


Figure 4.13 Environmental impact of the passive climate change adaptation scenarios.

4.3 Environmental efficiency

The environmental efficiency indicator was calculated for annual cooling reduction and peak cooling reduction, for all climate scenarios and passive measures in 2050. The results are presented in a dot chart, where the top left area of the chart represents environmental efficient solutions, and the bottom right area of the chart represents the most environmentally inefficient solutions. The bottom left area of the chart represents solutions with relatively small environmental impact and a small cooling reduction potential, whilst the top right area shows measures which have a high cooling reduction potential together with a high relative environmental impact. The environmental efficiencies depending on annual cooling reduction potential showed that the natural ventilation and triple glazing scenarios were the best performing alternatives, see Figure 4.14. For the RCP4.5 scenario, the triple glazing option was more than twice as effective compared to the natural ventilation option in terms of reducing annual cooling, whilst the difference was smaller in the RCP8.5 scenario. However, the natural cooling option had no associated environmental impact compared to the triple glazing option.

The combined case had the highest efficiency in cooling reduction, especially when looking at the RCP8.5 climate scenario. However, there was a large trade-off in terms of a substantial environmental impact, more than three times larger than the triple glazing option. The increased solar reflectivity option had slightly less environmental impact than the triple glazing, solar shading and added insulation options, however, both the solar shading and the triple glazing options showed a larger efficiency in reducing annual cooling demand, indicating the triple glazing option is the most environmentally efficient climate adaptation measure out of the scenarios with a mid-range environmental impact.

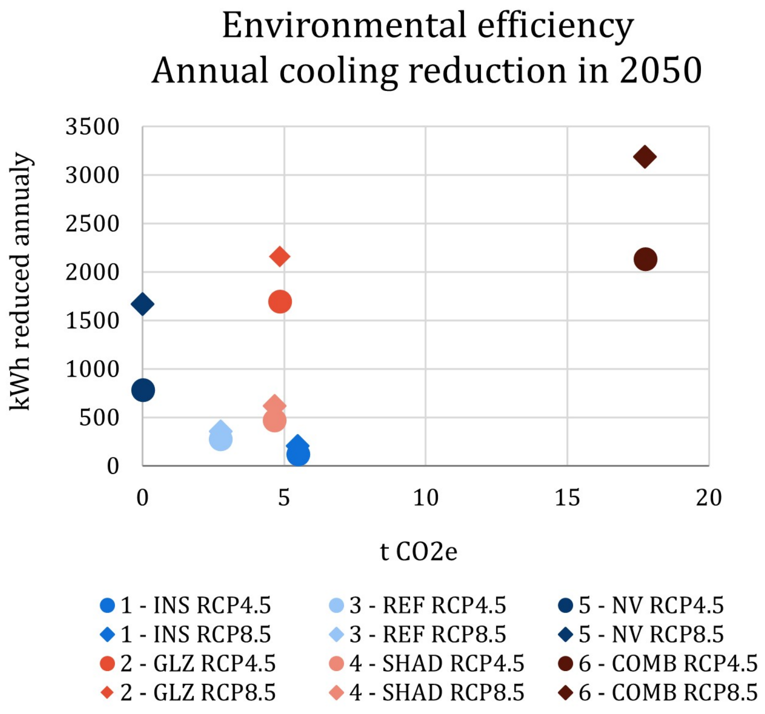


Figure 4.14 *Environmental efficiency considering annual cooling demand reduction in 2050, for the RCP4.5 and RCP8.5 climate scenarios.*

The environmental efficiency of the peak cooling simulations is shown in Figure 4.15. The results showed that the natural ventilation option did not decrease peak cooling demand. Furthermore, the results showed that the increased solar reflectivity and added insulation scenarios had no effect in reducing peak cooling demand. The solar shading and triple glazing option both showed a potential to reduce peak cooling loads, and the triple glazing option was more efficient due to a larger peak cooling reduction with similar environmental impact. For the RCP4.5 climate scenario, the combined case showed no greater potential in reducing peak cooling demand than the triple glazing option, and since it was associated with a substantially larger environmental impact, the results indicated that the combined case is an inefficient solution. In the RCP8.5 the combined case showed a slightly larger reduction potential.

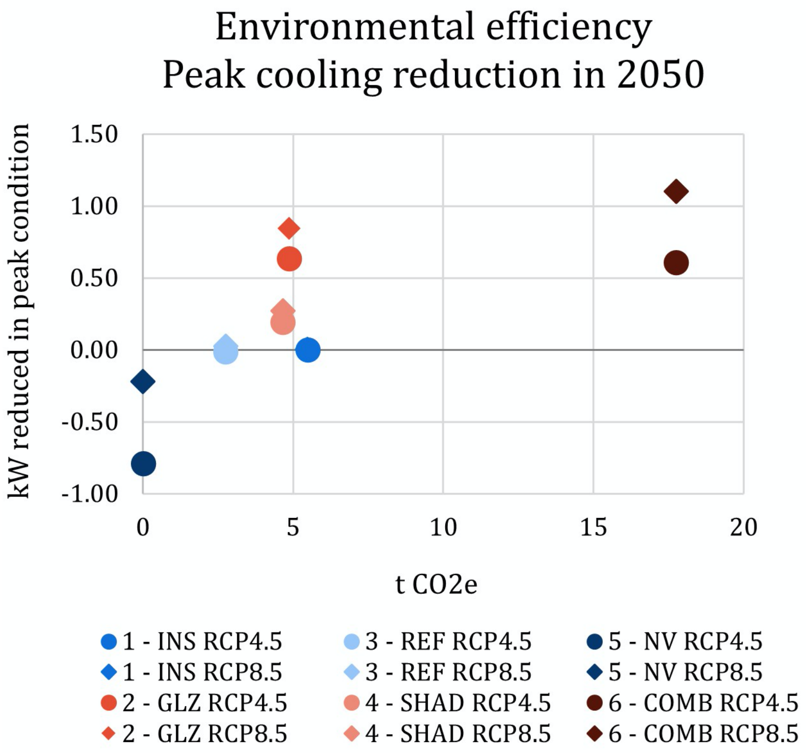


Figure 4.15 *Environmental efficiency considering peak cooling demand reduction in 2050, for the RCP4.5 and RCP8.5 climate scenarios.*

To further illustrate the potential of the natural ventilation option, the environmental efficiency was calculated for the maximum temperature reduction potential during peak conditions, i.e., the difference in maximum temperature for the passive measure scenarios compared to the renovated scenario during the 21st–23rd of July. The results are similar to the environmental peak cooling demand results, however, in this case the natural ventilation scenario shows a very high efficiency in reducing maximum temperature during peak conditions, with a greater reduction potential than the triple glazing scenario. This combined with the low environmental impact shows that it is one of the most efficient options in reducing maximum temperatures. The triple glazing scenario also shows great maximum temperature reduction, followed by the solar shading option.

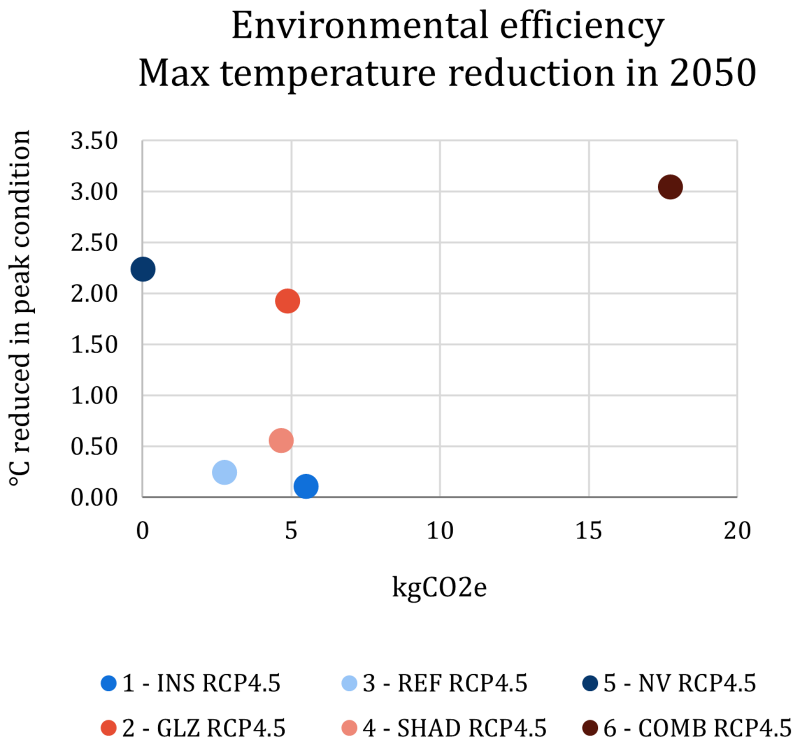


Figure 4.16 Environmental efficiency considering maximum temperature reduction during peak conditions in 2050, for the RCP4.5 climate scenario.

4.4 Scenario comparison and summary

Overall, the triple glazing scenario and the natural ventilation scenario proved to be the two most environmentally efficient solutions in reducing annual energy cooling demand, overheating hours and maximum temperature during peak conditions. The triple glazing scenario was also the most environmentally efficient solution for peak cooling reduction. In addition, the natural ventilation and triple glazing scenarios showed no increase in total annual energy demand. The combined scenario showed a greater efficiency in cooling demand reduction for all simulated energy performance indicators; however, the measure was associated with a substantially larger environmental impact. On the other hand, the combined scenario was the only assessed option which kept the overheating hours below or close to below 10% for the 26°C threshold in 2050 depending on climate scenario.

The added insulation scenario shows close to no reduction in either peak cooling demand or annual cooling demand. Moreover, the heating demand reduction is 4.3%, i.e., far less than the heating demand reduction seen between the as-built case and the renovated case. This combined with the associated environmental impact suggests that Scenario 1, i.e., added insulation, is one of the most inefficient scenarios assessed when it comes to reducing cooling demand when no possible synergies are considered. Scenario 3, i.e., increased solar reflectivity, has a slightly lower environmental impact and a higher efficiency in reducing annual cooling and maximum temperature during peak conditions. However, compared to the natural ventilation and triple glazing scenarios the efficiency is very low. Additionally, the increased solar reflectivity increases the heating demand during the warming season, resulting in a small net increase in total annual energy demand. The solar shading scenario, i.e., Scenario 4, also brings a small net increase in annual cooling demand and compared to the triple glazing and natural ventilation scenarios the maximum temperature and annual cooling demand reduction is substantially lower. However, it has a higher efficiency of reducing annual cooling demand, overheating hours, peak cooling as well as maximum temperature during peak conditions compared to Scenario 1 and 3, with a similar environmental impact.

5 Discussion

This section presents the discussion of the methodology and results from the literature review, energy simulations, EI and eco-efficiency calculations.

5.1 Efficiency of passive climate adaptation measures

The literature study showed that there is a research gap in interdisciplinary assessments including environmental impact when assessing the efficiency of climate adaptation measures in the built environment in Sweden. The purpose of this study was to introduce the inclusion of environmental impact when assessing the efficiency of passive cooling measures, to be able to explore potential synergies between cooling demand reduction and environmental impact. The most common passive cooling measures that can be included in a retrofit was selected based on the literature review, i.e., added insulation, triple glazing, increased solar reflectivity, added solar shading and natural ventilation. A combination of above stated measures was also included in the assessment.

The results from the energy simulations show that there will be a substantially increased cooling demand in 2050, around 180-400% for annual cooling demand and 34-98% for peak cooling demand. The results are based on climate data for an average year, meaning potential peak and annual cooling energy demand for unusually hot years or heat waves are disregarded. In general, the results conform with previous research, indicating both an increase in annual and peak cooling and that thermal comfort can be kept with a combination of one or more common passive measures. Scenario 2, triple glazing, and Scenario 5, natural ventilation, are the two most environmentally effective solutions in reducing annual energy cooling demand and maximum temperature during peak conditions according to the developed assessment method. The triple glazing option is also the most environmentally efficient when it comes to reducing peak cooling loads. The combined scenario, although it is associated with great environmental impact, performed best in all options and was the only scenario which kept overheating hours below 10%, which suggests that a combination of passive measures could be necessary to achieve an adequate thermal comfort in a future climate scenario.

Especially considering the simulated peak cooling demand, the risks associated with only implementing the natural ventilation scenario as suggested by a few previous studies that focused on annual cooling demand are highlighted. To mitigate future cooling needs during peak conditions, results indicate that further passive cooling measures should be considered. Moreover, the study suggests that there is a large difference in environmental efficiency between the available passive measures, indicating that environmental impact assessments of the considered options are relevant.

The methodology to calculate the environmental efficiency was developed by the author to include environmental impact when assessing the efficiency of climate adaptation measures as a response to an identified research gap. Since the methodology is not commonly known, certain aspects regarding uncertainty of method are appropriate to consider. For instance, the narrow scope of the study poses a potential risk of finding a circumstantial optimal solution that would have been non-optimal if the scope was extended to include active measures, microclimate effects or pedestrian comfort, as well as if the measures were considered on a district scale. For instance, the use of green structures on a district scale might locally reduce the air temperature to reduce cooling energy demand as efficiently as the assessed passive cooling measures, whilst also increasing the pedestrian comfort and local air quality. If these aspects were included, the increased solar reflectivity might also provide a synergy effect in increased pedestrian comfort which would increase the environmental efficiency of the option and possibly lead to other conclusions.

5.2 Energy modelling and input data

This section will focus on discussing the potential impact on the results that could be derived from limitations in the energy model and input data. Although the EnergyPlus energy simulation engine is widely used in previous research, it poses certain limitations, especially when it comes to energy simulations for the natural ventilation scenario. The performance during peak conditions was assessed in two ways, by simulating the temperature profile for the warmest three consecutive days, referred to as peak conditions, and measuring the reduction of maximum temperature, and by simulating the estimated peak cooling with an annual simulation period. The natural ventilation option showed an increase in peak cooling demand by 2050, whilst the maximum temperature reduction during peak conditions was substantial and natural ventilation is estimated to be one of the most efficient scenarios. Furthermore, an increase in peak cooling demand due to the use of natural ventilation is contradictive to previous research.

The peak cooling demand for the natural ventilation option occurs during a hot day in June, whereas the other scenarios have peak hours during the peak conditions, i.e., 21st - 23rd of July. This is likely due to the modelling limitations introduced in section 3.1.7, suggesting that the opening of windows occur when the outside air temperature is warmer than the inside air temperature, leading to a rapid warming effect. This could be avoided by opening windows during the night to precool the space and consequently reduce the peak cooling, or by keeping windows closed during the day to theoretically achieve the same peak cooling demand as in the renovated scenario. However, manually operated natural ventilation will perform inconsistently due to the dependence on occupancy behaviour. For instance, residents may not occupy the space at optimal hours to control the opening and closing of windows. Moreover, residents may not have the desired knowledge to optimally control the opening and closing of windows. Other aspects that suggest an inconsistent performance of natural ventilation implemented on a larger scale is for instance the risk of compromised air quality, noise and safety. Considering the many examples of limiting factors to an optimal implementation of natural ventilation controlled manually, the inconsistent results is still relevant for the comparison of passive cooling measures.

The overheating hours associated with the natural ventilation scenario is another inconsistent result, as indicated in section 4.1.2. Due to the 22°C minimum outside air temperature modelling limitation, windows are closed at night-time during peak conditions, causing a slight overestimation of overheating hours. However, the aforementioned limiting factors associated with natural ventilation indicate that these results are of interest. If natural ventilation is not an available option to the residents during night-time due to for example safety or noise, the implementation of other adaptation measures becomes increasingly important in a future climate scenario to sustain a low percentage of overheating hours.

According to the results, the solar shading option is a rather inefficient option, at least in comparison with natural ventilation or the implementation of triple glazing. However, the efficiency of solar shading largely depends on the design and placement. Although it is outside the scope of this study, the solar shading alternative might have performed better if a solar shading design optimisation was performed. For instance, the current type and placement does not effectively reduce the solar radiation when the sun is at a low angle, i.e., during morning or afternoon hours.

Finally, the uncertainties regarding the projected climate data are addressed. There are large uncertainties in climate models, such as the extent of future GHG accumulation, the climate's response to GHG accumulation, the natural variations occurring in the climate and the condensation of data to representative climate models, implying that results based on climate data projection should not be considered as definite but rather be viewed as an indicator for future trends. However, the models to predict future climate data have been improved during recent years and to design a building with high functionality throughout its lifetime a projection of the future climate is crucial.

5.3 Environmental impact

The environmental impact is calculated according to the methodology developed by Boverket (2018) and the input data is retrieved from the database developed for climate declarations. The environmental impact is therefore limited to global warming potential, which excludes other important categories such as eutrophication, acidification and resource depletion. Consequently, an incomplete view of the environmental impact associated with the different climate adaptation measures is presented. Furthermore, the global warming potential is based upon an average of EPDs for materials or building components, meaning that the individual variation can be large depending on supplier. Other assumptions have been made that are likely to lead to an underestimation of the environmental impact were made, for example, no material waste was assumed and the operational and end-of-life life-cycle phases were excluded.

Further uncertainties can be related to the triple glazing and added solar shading scenarios as there was no available data for the specific building component, meaning the environmental impact was based merely on the environmental impact associated with the material. This could have led to an underestimation of the environmental impact of these two alternatives, since environmental impact associated with the production and transportation of the component is excluded, as well as the impact from any other materials used, e.g., for mounting. However, the assessments of environmental impact associated with building materials and components are still under development, and the results are in accordance with the climate declaration legislation currently in practice. Additionally, conducive to the aims and limitations of the study the results are relevant as a simplified approximation of the environmental impact associated with different climate adaptation measures, useful for a comparative study.

5.4 Delimitations and future research

Since the efficiency of the individual measures has a large variation, another suggested further development of the study is to explore more combinations of passive measures, for example the natural ventilation case combined with the triple glazing case, to assess if an efficiency close to the combined case can be achieved with a lower environmental impact. Moreover, due to the delimitations of the study, several environmental impact categories were excluded, as well as several life-cycle phases. Hence, the accuracy of the environmental impact assessment could be further developed for added detail.

The delimitations stated the exclusion of other building types, and it would be useful to develop the study further in the investigation of further building types, e.g., single-family homes, offices and commercial buildings, which would increase the possibility of assessing the impact on a larger scale. Recommended further research includes assessing active measures and coping mechanisms, assessing microclimate effects, and expanding the assessment to a district scale implementation. Another aspect to explore in further research or implementation is the economical aspect, for instance to assess the cost-effectiveness of the passive measures' ability to reduce cooling demand alongside the environmental impact to facilitate further comparative factors.

6 Conclusions

The peak energy demand due to cooling increases by around 34-98% and the annual energy demand due to cooling increases by around 180-400% by 2050, depending on climate scenario. The selection of common passive cooling measures which can be implemented in an existing building is comprised of additional insulation, change to triple glazed windows, increased solar reflectivity of façade material, the use of solar shading and the use of natural ventilation.

Natural ventilation shows a significant synergy between low environmental impact and high potential of annual cooling demand reduction and maximum temperature reduction during peak conditions, as the option is associated with no environmental impact. When including peak cooling demand and considering other potential limitations to the use of natural ventilation, complementary passive measures would be beneficial to ensure thermal comfort. When accounting for the environmental impact and cooling demand reduction potential of different passive cooling measures, the triple glazing proved most efficient when including environmental impact, followed by the adding of solar shading. A combination of all measures proved to be associated with the highest cooling demand reduction potential in all scenarios, however, there is a great trade-off considering the large environmental impact. A further exploration of different combinations of passive measures is recommended as a development of the study.

Since the annual cooling demand constitutes a small portion of the annual energy demand, 3-5% in 2050, there are cases where the passive measures lead to a net increase in annual energy demand due to an increase in heating demand during the heating season. The increased solar reflectivity and the solar shading options are examples of passive measures which lead to an increase in annual energy use compared to the renovated baseline scenario. However, the two most environmentally efficient options, natural ventilation and triple glazing, decrease the annual energy demand with 0.7% and 1% respectively, further emphasising the benefits of these passive cooling measures.

References

Andric, I., Muammer, K., G. Al-Gamdi, S. (2019). A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries. *Journal of Cleaner Production,* 211, 83-102. Doi: 10.1016/j.jclepro.2018.11.128.

Andric, I., Pina, A., Ferrão, P., Fournier, J., Lacarrière, B., Le Corre, O. (2017). The impact of climate change on building heat demand in different climate types. *Energy and Buildings,* 149, 225-234. Doi: 10.1016/j.enbuild.2017.05.047

ASHRAE. (2004). *Thermal Environmental Conditions for Human Occupancy.* ASHRAE, Atlanta. Retrieved 2022-04-12 from http://arco-hvac.ir/wp-content/uploads/2015/11/ASHRAE_Thermal_Comfort_Standard.pdf

ASHRAE. (2017). *Handbook: Fundamentals*. SI Edition, ASHRAE.

Baumann, H. & Tillman, A. (2004). *The Hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application (1. ed.)*. Lund: Studentlitteratur.

Boverket. (2003). *Bättre koll på underhåll* (In English: Better track keeping of maintenance). Retrieved 2022-04-19 from https://www.boverket.se/globalassets/publikationer/dokument/2003/battre_koll_pa_underhall.pdf

Boverket. (2018). *Klimatdeklaration av byggnader* (In English: Climate Declarations of Buildings). Retrieved 2022-04-12 from https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2018/klimatdeklaration-av-byggnader2/

Boverket. (2020). *Regulation on climate declarations for buildings.* Retrieved 2022-04-12 from https://www.boverket.se/globalassets/publikationer/dokument/2020/regulation-on-climate-declarations-for-buildings.pdf

Boverket. (2021a). *Boverkets klimatdatabas* (In English: The National Board of Housing, Building and Planning's Climate Database). Retrieved 2022-03-09 from https://www.boverket.se/sv/klimatdeklaration/klimatdatabas/

Boverket. (2021b.). *Syftet med att klimatdeklarera byggnader.* Retrieved 2022-04-20 from https://www.boverket.se/sv/klimatdeklaration/om-klimatdeklaration/syfte/

Buyle, M., Braet, J., Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews,* 26, 379-388. Doi: 10.1016/j.rser.2013.05.001

CIBSE. (2006). *Guide A: Environmental Design*. Chartered Institution of Building Services Engineers, London.

Dodoo, A. (2020). Energy and indoor thermal comfort performance of a Swedish residential building under future climate change conditions. *E3S Web of Conferences,* 172, 02001. Doi: 10.051/e3sconf/202017202001

Dodoo, A., Gustavsson, L. (2016). Energy use and overheating risk of Swedish multi-storey residential buildings under different climate scenarios. *Energy,* 97, 534-548. Doi: 10.1016/j.energy.2015.12.086

Dodoo, A., Gustavsson, L., Bonakdar, F. (2014). Effects of future climate change scenarios on overheating risk and primary energy use for Swedish residential buildings. *Energy Procedia*, 61, 1179-1182.

Ellen MacArthur Foundation. (n.d.). *Circular Economy Introduction.* Retrieved 2022-04-20 from https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

EnergyPlus. (n.d.) *EnergyPlus*. Retrieved 2022-04-20 from https://energyplus.net/

Energimyndigheten. (2019). *Sveriges miljö- och klimatmål* (In English: Environment and climate goals in Sweden). Retrieved 2022-04-12 from https://www.energimyndigheten.se/klimat--miljo/sveriges-energi--och-klimatmal/

Engineering ToolBox. (n.d.) *Materials, light reflecting factors*. Retrieved 2022-04-13 from https://www.engineeringtoolbox.com/light-material-reflecting-factor-d_1842.html

EU. (2021a). *Buildings Renovation: Data Supporting Investment Measures*. Retrieved 2022-01-17 from https://ec.europa.eu/jrc/en/news/buildings-renovation-data-supporting-investment-measures

EU. (2021b). *Heating and cooling degree days – statistics*. Retrieved 2022-02-09 from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Heating_and_cooling_degree_days_-_statistics#By_Member_State

FEBY. (2018). *Kravspecifikation för energieffektiva byggnader, bostäder och lokaler* (In English: Requirements for Energy Effective Buildings, Residential and Commercial). Retrieved 2022-04-12 from https://www.feby.se/files/2019-01/kravspecifikation-feby18.pdf

Hamid, AA., Farsäter, K., Wahlström, Å., Wallentén, P. (2018). Literature review on renovation of multifamily buildings in temperate climate conditions. *Energy & Building,* 172, 414-431. Doi: 10.1016/j.enbuild.2018.04.032

Hosseini, M., Javanroodi, K., Nik, VM. (2022). High-resolution impact assessment of climate change on building energy performance considering extreme weather events and microclimate – Investigating variations in indoor thermal comfort and degree-days. *Sustainable Cities and Society,* 78, 103634. Doi: 10.1016/j.scs.2021.103634

IEA. (2018). *The Future of Cooling.* IEA, Paris. Retrieved 2022-04-11 from https://www.iea.org/reports/the-future-of-cooling

IPCC. (2013). *What is a GCM?* Retrieved 2022-02-14 from https://www.ipcc-data.org/guidelines/pages/gcm_guide.html

IPCC. (2014a). *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press.

IPCC. (2014b). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)*. IPCC, Geneva, Switzerland, 151 pp.

IPCC. (2021). C*limate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)*. Cambridge University Press. In Press.

Kjellström, E., Bärring, L., Nikulin, G., Nilsson, C., Persson, G., Strandberg, G. (2016). Production and use of regional climate model projections – A Swedish perspective on building climate services. *Climate Services,* 2-3, 15-29.
Doi: 10.1016/j.cliser.2016.06.004

La Fleur, L., Moshfegh, B., Rohdin, P. (2017). Measured and predicted energy use and indoor climate before and after a major renovation of an apartment building in Sweden. *Energy and Building,* 146, 98-110. Doi: 10.1016/j.enbuild.2017.04.042

Lasvaux, S., Favre, D., Périsset, B., Bony, J., Hildbrand, C., Citherlet, S. (2015). Life cycle assessment of energy related building renovation: methodology and case study. *Energy Procedia,* 78, 3496-3501. Doi: 10.1016/j.egypro.2016.10.132.

Mata, É., Kalagasidis, AS., Johnsson, F. (2012). Energy usage and technical potential for energy saving measures in the Swedish residential building stock. *Energy Policy,* 55, 404-414. Doi: 10.1016/j.enpol.2012.12.023

Mjörnell, K., Boss, A., Lindahl, M., Molnar, S. (2014). A Tool to Evaluate Different Renovation Alternatives with Regard to Sustainability. *Sustainability,* 6, 4227-4245.
Doi: 10.3390/su6074227

Nik, VM., Kalagasidis, AS. (2012). Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties. *Building and Environment*, 60, 291-304.
Doi: 10.1016/j.buildenv.2012.11.005

Nik, VM. (2016). Making energy simulation easier for future climate – Synthesizing typical and extreme weather data sets out of regional climate models (RCMs). *Applied Energy*, 177, 204-226. Doi: 10.1016/j.apenergy.2016.05.107

Norouzi, M., Chafér, M., Cabeza, LF., Jiménez, L., Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering*, 44, 102704. Doi: 10.1016/j.jobe.2021.102704.

Pyrgou, A., Castaldo, VL., Pisello, AL., Cotana, F., Santamouris, M. (2017). On the effect of summer heatwaves and urban overheating on building thermal-energy performance in central Italy. *Sustainable Cities and Society*, 28, 187-200. Doi: 10.1016/j.scs.2016.09.012

Ramírez-Villegas, R., Eriksson, O., Olofsson, T. (2019). Life Cycle Assessment of Building Renovation Measures–Trade-off between Building Materials and Energy. *Energies*, 12, 344. Doi: 10.3390/en12030344

Roux, C., Schalbart, P., Assoumou, E., Peuportier, B. (2016). Integrating climate change and energy mix scenarios in LCA of buildings and districts. *Applied Energy,* 184, 619-629. Doi: 10.1016/j.apenergy.2016.10.043

Santamouris, M. (2019). Recent Progress on Urban Overheating and Heat Island Research. Integrated Assessment of the Energy, Environmental, Vulnerability and Health Impact. Synergies with the Global Climate Change. *Energy & Buildings*, 207. Doi: 10.1016/j.enbuild.2019.109482

SMHI. (n.d.a) *Fördjupad klimatscenariotjänst* (In English: Improved Climate Scenario Service). Retrieved 2022-04-20 from https://www.smhi.se/klimat/framtidens-klimat/fordjupade-klimatscenarier/met/sverige/medeltemperatur/rcp45/2071-2100/year/anom

SMHI. (n.d.b) *Fördjupad klimatscenariotjänst* (In English: Improved Climate Scenario Service). Retrieved 2022-04-20 from https://www.smhi.se/klimat/framtidens-klimat/fordjupade-klimatscenarier/met/sverige/longestheat/rcp45/2071-2100/year/anom

SMHI. (n.d.c) *Fördjupad klimatscenariotjänst* (In English: Improved Climate Scenario Service). Retrieved 2022-04-20 from https://www.smhi.se/klimat/framtidens-klimat/fordjupade-klimatscenarier/met/sverige/temprange/rcp45/2071-2100/year/anom

Socialstyrelsen. (2005). *Temperatur inomhus* (In English: Interior temperatures). Retrieved 2022-04-20 from https://www.folkhalsomyndigheten.se/contentassets/a22abd3cdc1042e195d50fe4484a7fb9/temperatur-inomhus.pdf

Sveby. (2012). *Brukarindata bostäder* (In English: User behaviour data for dwellings). Retrieved 2022-03-10 from https://www.sveby.org/wp-content/uploads/2012/10/Sveby_Brukarindata_bostader_version_1.0.pdf

Tettey, U., Dodoo, A., Gustavsson, L. (2017). Energy use implications of different design strategies for multi-storey residential buildings under future climates. *Energy*, 138, 846-860. Doi: 10.1016/j.energy.2017.07.123

UN-Habitat. (2011). *Cities and climate change global report on human settlements 2011*. Earthscan.

Van Hooff, T., Blocken, B., Timmermans, HJP., Hensen, JLM. (2016). Analysis of the predicted effect of passive climate adaptation measures on energy demand for cooling and heating in a residential building. *Energy*, 94, 811-820.
Doi: 10.1016/j.energy.2015.11.036

Wu A, Pett J. (2006). *Cold Comfort for Kyoto?*. London, ACE.

Yassaghi, H., Hoque, S. (2019). An Overview of Climate Change and Building Energy: Performance, Responses and Uncertainties. *Buildings*, 9, 166. Doi: 10.3390/buildings9070166

Österbring, M., Mata, E., Thuvander, L., Walbaum, H. (2019). Explorative life-cycle assessment of renovating existing urban housing-stocks. *Building and Environment*, 165, 106391. Doi: 10.1016/j.buildenv.2019.106391

Appendix I – Environmental impact data

Table A 1 Environmental impact data by product / material.

Material / Product	Global warming potential [kg CO_2e/kg]			Conversion value
	A1-A3	A4	A5	
Glasswool, blowing wool, wall	1.2	0.0345	0.01235	30 kg/m^3
Door, external, wood, massive	1.875	0.0324	0.0	27.7 kg/m^2
Window, wood/aluminium, side-hung, 3-glass	2.875	0.042	0.0	39.2 kg/m^2
Floatglass	1.45	0.0345	0.2969	2500 kg/m^3
Paint, acrylic, water-borne for exterior use	3.125	0.0345	0.12638	0.1 kg/m^2
Aluminium sheet, primary	12.5	0.0495	0.62748	2700 kg/m^3

Table A 2 Environmental impact data by scenario.

Scenario	Added material	Amount	Conversion value	Mass [kg]	GWP [kg CO_2e/kg]	GWP Material [kg CO_2e]	GWP Scenario [kg CO_2e]
1	Glasswool, blowing wool, wall	146.5 m^3	30 kg/m^3	4396.4	1.24685	5481.6	5481.6
2	Floatglass	1.09 m^3	2500 kg/m^3	2725	1.78140	4854.3	4854.3
3	Paint, acrylic, water-borne for exterior use	8374 m^2	0.1 kg/m^2	837.4	3.28588	2751.6	2751.6
4	Aluminium sheet, primary	0.131 m^3	2700 kg/m^3	353.7	13.17698	4660.7	4660.7
5	-	-	-	-	-	-	0
6	Glasswool, blowing wool, wall	146.5 m^3	30 kg/m^3	4396.4	1.24685	5481.6	17748.2
	Floatglass	1.09 m^3	2500 kg/m^3	2725	1.78140	4854.3	
	Paint, acrylic, water-borne for exterior use	8374 m^2	0.1 kg/m^2	837.4	3.28588	2751.6	
	Aluminium sheet, primary	0.131 m^3	2700 kg/m^3	353.7	13.17698	4660.7	

Appendix II – Energy model input data

Table A 3 Roof, construction all scenarios.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorbtivity
Concrete	100	0.55	2000	Medium Rough	0.7
Insulation	400	0.0345	60	Medium Rough	0.6

Table A 4 Ground construction, all scenarios.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorptivity
Concrete	250	0.63	2000	Medium Rough	0.7

Table A 5 Basement wall construction, all scenarios.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorptivity
Concrete	250	0.78	2000	Medium Rough	0.7

Table A 6 Wall construction, as-built scenario.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorbtivity
Concrete	90	0.65	2000	Medium Rough	0.7
Insulation	100	0.0345	60	Medium Rough	0.6
Concrete	90	0.65	2000	Medium Rough	0.7

Table A 7 Wall construction, renovated scenario, scenario 2 – triple glazing, scenario 4 – solar shading, scenario 5 – natural ventilation.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorbtivity
Concrete	90	0.65	2000	Medium Rough	0.7
Insulation	150	0.0345	60	Medium Rough	0.6
Concrete	90	0.65	2000	Medium Rough	0.7

Table A 8   Wall construction, scenario 1 – added insulation.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorbtivity
Concrete	90	0.65	2000	Medium Rough	0.7
Insulation	275	0.0345	60	Medium Rough	0.6
Concrete	90	0.65	2000	Medium Rough	0.7

Table A 9   Wall construction, scenario 3 – increased solar reflectivity.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorbtivity
Concrete	90	0.65	2000	Medium Rough	0.7
Insulation	150	0.0345	60	Medium Rough	0.6
Concrete	90	0.65	2000	Medium Rough	0.3

Table A 10   Wall construction, scenario 6 – combined.

Construction layer	Thickness [mm]	Conductivity [W/mK]	Density [kg/m^3]	Roughness	Solar Absorbtivity
Concrete	90	0.65	2000	Medium Rough	0.7
Insulation	275	0.0345	60	Medium Rough	0.6
Concrete	90	0.65	2000	Medium Rough	0.3

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF ARCHITECTURAL THEORY AND METHODS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY