Assessing impacts of climate change on the energy and hygrothermal performance of detached houses in Sweden

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Najma Habibullah
Busra Duran

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

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

Master Programme in Energy-efficient and Environmental Building Design

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

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

Examiner: *Kavan Javanroodi* (*Building Physics*)

Supervisor: *Vahid Nik* (*Building Physics)*

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Abstract

Climate change is one of the most significant challenges that building sector is confronting. For example, Climate change and associated extreme events are posing a significant challenge for the building sector. Buildings should be prepared to withstand the climate changes and extreme weather that will happen in the future. Designing buildings based solely on past or average weather conditions, while neglecting the possibility of extreme weather events, is not a sustainable approach for the future.

Detached houses constitute 72% of Sweden's residential buildings, but they are more sensitive to climate fluctuations than apartment buildings. Moisture and energy performances are two key aspects that helps to identify the ability of the house to holdout extreme weather.

This study aims to investigate the hygrothermal and energy performance of detached houses in Sweden under current and future climate conditions, by using verified future weather data and past weather data. The investigation was conducted in three cities across Sweden: Lund in the south, Stockholm in the central region, and Luleå in the north. The reference detached houses were an illustration of detached houses from 1940s, 1965s and modern construction types.

For hygrothermal and energy simulations the WUFI and Rhinoceros data tools were used, and the building modelling were based on the fact obtained from literature study.

The hygrothermal results showed that all construction types were moisture safe. Despite occasional instance where the relative humidity (RH) exceeded RH critical, a thorough analysis confirmed the moisture safety of the constructions. While the energy results showed that there was a consistent behaviour of energy usage when it came to the buildings' location. An overall observation of energy load in distinct weather scenarios (past, ECY, EWY, TDY) indicates that the decrement of heating load and increment of cooling load by time in all scenarios. The obtained result showed that the cooling demand in modern construction was higher than the elder construction types, which is caused due to their high insulation material. It is the major argument for cooling system need in Swedish buildings.

Although the extreme weather conditions will never occur, still investigating these scenarios can provide building designers with a reference point for situations where climate change may cause similar conditions.

Preface

This master's thesis was completed during the spring semester of 2023 in the Master's program of *Energy Efficient and Environmental Building Design* at Lunds Tekniska Högskola and includes 30 credits points. The aim of this study is the assess impacts of climate change on the energy and hygrothermal performance of detached houses in Sweden. The study is based on theoretical and simulation data and there are a few people that helped us to carry out this study.

We would like to thank in particular our supervisor and examiner, Vahid Nik and Kavan Javanroodi, from the Division of Building Physics at LTH, who helped and guided us throughout the entire process.

Helsingborg, September 2023
Najma Habibullah, Busra Duran

Nomenclature

ASHRAE	*American Society of Heating, Refrigerating and Air-Conditioning Engineers.*
A_{temp}	*Heated area in the building*
BBR	*Boverkets byggregler*
ECY	*Extreme cold year*
$E_{kyl,i}$	*Cooling energy, kWh/year*
EP_{pet}	*Energy performance of primary energy number*
$E_{uppv,i}$	*Heating energy, kWh/year*
$E_{tvv,i}$	*Energy for domestic hot water, kWh/year*
EWY	*Extreme warm year*
F_{geo}	*Geographical correction factor*
IPCC	*Intergovernmental Panel on Climate Change*
RH	*Average relative humidity*
$RH_{critical}$	*Average critical relative humidity*
TDY	*Typical downscaled year*
VF_i	*Weighting factor (Different for different energy carriers)*

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1 Introduction

As stated in a report published by the IPCC, the effects followed by global warming are becoming increasingly apparent. Hot extreme weather events such as heat waves and cold snaps happening more frequently and will be stronger and more frequent in the future too. Even if global warming were somehow stabilized at 1.5°C, the effects would still not change. If society fails to limit temperature increases to 1.5°C and instead reaches 2°, the effects of climate change will be twice as bad, and if it reaches 3°C, the changes will be four times as bad. In fact, the intensity and frequency of hot days, hot nights, heatwaves, and other extreme heat events are expected to increase further over most tracts of land, and this is nearly certain. It is also likely that the frequency of temperature variations in most regions will be proportionate to changes in global warming and could be two to three times larger. These trends demonstrate that global warming is having an increasingly noticeable impact even in regional levels. To building sector could be redo to confronts this challenge, should this fact be considered during design phase of buildings. For example, architects and engineers might need to use more durable materials and construction techniques to ensure that structures can withstand the increasing intensity of extreme weather events triggered by global warming (IPCC, 2021).
Building sector should start the adaptation in the regional level to be able to withstand this worldwide challenge. So, building sector in Sweden has many goals to minimize the huge impact of building sector on the climate changes.
Sweden is a sparsely populated country with a large area of land, making it relatively easy purchase detached houses, even if they are located several miles away from the nearest neighbour. As a result, detached houses have remained a popular choice for homeowners in Sweden.
Detached houses constitute 72% of Sweden's residential buildings. However, they are more sensitive to climate fluctuations than apartment buildings (Hedeklint, 2022). Moisture and energy performances are two key aspects that helps to identify the ability of the house to holdout extreme weather. Moisture performance relates to the capability of the house to withstand moisture penetration and accumulation, which can result in mould problem and other structural difficulties. Energy performance relates to the ability of the building to keep a comfortable indoor temperature with the least amount of energy. As a result of their stand-alone structure and absence of shared walls, detached houses are more vulnerable to extreme weather. They are built with less insulation and less protected from outside elements specially the elder building construction that has significant less insulation material than the modern constructions, which makes them more sensitive to climate changes. As a result, detached houses use a lot more energy, and fixing climate-induced damages in these houses can be expensive. Therefore, it is preferable to come up with sustainable and cost-effective retrofitting plans, specifically with climate change. However, the overall energy usage in the housing sector can be lowered if apartment buildings or row houses are built more rather than detached houses. Which depends on that these structures have a smaller surrounding area per square meter of living space, leading to reduced energy loss (Boverket, 2009).
The main goal of urban energy solutions is to improve human comfort, and an important part of that includes providing comfortable indoor thermal comfort. For purpose of achieving this goal, it is crucial to understand the effect of high-temperature periods, such as heatwaves, which have become more prevalent since the 2003 heatwave in western Europe (Chen, 2022). High-temperature periods, such as heatwaves, can be dangerous for older people and those with disabilities. According to the website Human Rights Watch, which investigates and reports on abuses happening in all corners of the world, thousands of people died due to heatwaves in Europe. The majority of those who died were people over the age of 65 and people with underlaying medical conditions that make it hard for the body to regulate its temperature. Some diseases that have problem with regulating body temperature include diabetes and traumatic brain injuries. People with psychological problems is also included in those risk groups being affected by unusually high temperatures. Therefore, the building industry

must have effective planning in the face of the increased frequency of heatwaves to ensure the safety and comfort of all individuals (Kim, 2022).

There is a conspicuous connection between climate change and buildings. Most of the research on the impact of climate change on buildings focus on several performance indicators, such as heating energy, cooling energy, and the risk of overheating (Nik, Moazami, Carlucci, & Geving, 2019). The hygrothermal performance of buildings is also being studied under future climatic conditions, with a focus on performance indicators that depend on air temperature and moisture content. By considering a variety of climate indicators, such as air temperature, relative humidity, solar radiation, and cloudiness. By including a wider range of performance indicators might help to better understand the effects of climate change on buildings and develop effective methods to improve the thermal comfort of indoor spaces. Building materials and designs must be adapted for future climatic conditions ensure reliable and sustainable urban energy solutions (Nik, Moazami, Carlucci, & Geving, 2019).

1.2 Aim and Objectives

The aim of this degree project is to investigate the hygrothermal and energy performance of detached houses in Sweden under current and future climate conditions.

Objectives of this project is as follows:

- The hygrothermal performance of detached houses in Sweden using energy and moisture simulations under typical weather conditions.
- To assess the impact of extreme weather conditions on the hygrothermal performance of detached houses in Sweden.
- To evaluate the energy consumption of detached houses in Sweden under typical and extreme weather conditions.
- To identify and investigate the impact of climate variations on the hygrothermal and energy performance of detached houses in Sweden.
- To provide recommendations for improving the hygrothermal and energy performance of detached houses in Sweden in response to climate change.

2 Background

2.1 History of detached houses in Sweden

Due to the abundant availability of wood in Sweden, detached houses have been a popular choice with a diverse range of construction types, materials, and layouts. In the 18th century, they commonly consisted of wooden structures with thatched roofs and turf, serving a functional purpose with simple floor plans and open fireplaces. The main purpose of these houses was to fulfil the primarily function, so the floor plan was simple and consisted of just one or two rooms with an open fireplace (Svenskt trä, 2023).

During the 20th century, more developed and comfortable features were implemented in detached houses in Sweden. With these developments in the building industry, detached houses became more than just a simple shelter for families, and even a representant for cultural changes in Sweden during this period. Functionalism was one of essential architectural evolution that grew in popularity during this period. The use of rationality, clean lines and simple forms was factors that this new trend focused on. By integrating these elements into small house design, they became more practical, efficient, and comfortable for families.

National Romanticism was another trend that gained popularity and influenced the architectural design and style of detached houses during the 20th century. This trend emphasized the use of traditional materials like stone and wood to praise the cultural heritage of Sweden. Incorporation elements of this trend into small house design gave them a unique and different appearance.

Finally, the other trend that had significant impact on the design of detached houses in Sweden was Art Nouveau. This trend emphasized the use of organic shapes and decorative elements in the design of detached houses to give them more elegance and sophistication.

Overall, all these trends led to transform of detached houses in Sweden into stylish and comfortable homes that reflected the changing cultural landscape of the country (Svenskt trä, 2023).

The building industry relied heavily on manual labour before the 1960s, and the use of brick construction was common. However, as the demand of building and construction projects increased, these manual methods became impractical. The building industry executed new production methods to face this problem and even simplify and standardize the construction process. These methods opened the way for usage of new building materials such as steel, concrete, gypsum board and asfaboard. To follow these changes, more efficient methods of construction emerged in the late 1950s and early 1960s, such as prefabricated building elements. Prefabricated wall and roof elements and cast-in-place concrete frames were used as more efficient and faster building methods, which even reduced costs. Although that the prefabrication was not a new concept in the industry, it was first during this period that prefabricated detached houses became momentum. For example, prefabricated wooden wall elements were brought to the construction site and assembled to accelerate the constructing process. Then, a brick shell was added on-site completed the structure. Even pre-manufactured roof trusses were used to speed up the constructing process. These revolutions in building industry resulted in a more efficient building industry that was able to meet the growing demand of construction projects (Björk, 2012).

Sweden faced a critical lack of housing in the late 1960s. The government determined as a solution, that to construct one million new houses in just 10 years period, which later called for *Million Program* (Boverket, 2020). This program contained of two-thirds apartments and one-third single-family houses. By implementation of new building materials and construction methods, numerous small houses were rapidly constructed, so in this way the goal of the program somehow was achieved. But the production process was caried out using unsuitable construction techniques and mostly poor ground conditions. These factors in addition to the lack of knowledge about moisture had a crucial role in mismanagement of the construction process. As a result, many houses built during the 1960s have suffered from mould growth or musty odours in at least one of building component (Polarpumpen, n.d.).

The most vulnerable elements of these buildings were the foundation, exterior walls and attics. Although all the challenges faced the program, still the *Million Program* remains as remarkable achievement in Sweden's history that played a significant role in solving country's housing crisis (ÖSTMAN, 2017).

In recent years, the importance of energy-efficient construction for homes that are environmentally friendly, has increased significantly. Among several types of such house models the passive houses is one of the most popular types. Passive houses are detached small houses that are designed to reduce the carbon footprint and minimize energy consumption of homeowners. Using advanced technologies and environmentally friendly materials, in constructing of passive houses, has making them an attractive option for those who pay attention to environment. Passive houses are designed to fulfil many strict standards for energy efficiency. To be able to meet these standards, an advanced insulation, airtightness and solar system are necessary for minimizing the energy demand for heating and cooling of these houses. In this way reduces both the amount of money that homeowners spend on energy bills and even amount of released carbon emissions to the environment. Thus, the passive houses are not only environmentally friendly, even cost- effective because of their minor energy consumption. Additionally, the advanced insulation and airtightness of these houses helps to regulate the indoor temperature, provides more comfortable living conditions for residents.
Overall passive houses, by their advanced technologies and environmentally friendly materials, offer a sustainable solution to the growing problem of carbon emissions and climate change and became an attractive option in today's buildings industry (World Economic Forum, 2021).

2.2 BBR Comparison

BBR is standing for "Boverkets byggregler" which means Boverket`s building regulations for Swedish buildings, defined by Boverket. Energy performance in Swedish building standards is expressed using the primary energy number (EP_{pet}). The formula for calculating EP_{pet} can be found in chapter 9 of BBR 29 and in Equation 1 in this paper. Primary energy number is determined by energy use in the building, with the heating energy corrected by geographical correction factor (F_{geo}), multiplied by the weighting factor for energy carriers and then divided by A_{temp}, which represents the heated area in the building. The weighting factor varies for different energy carriers, with electricity heating and fossil fuels strong weighting factors. The formula is as follows:

$$EP_{pet} = \frac{\sum_{i=1}^{6}(\frac{E_{uppv,i}}{F_{geo}}+E_{kyl,i}+E_{tvv,i}+E_{f,i})\times VF_i}{A_{temp}} \qquad (1)$$

$E_{uppv,i}$: Heating energy, kWh/year
$E_{kyl,i}$: Cooling energy, kWh/year
$E_{tvv,i}$: Energy for domestic hot water, kWh/year
F_{geo}: Geographical correction factor
VF_i: Weighting factor (Different for different energy carriers)

So, the F_{geo} corrects the energy load for heating, to make the primary energy number the same for similar buildings throughout the country. The geographical correction factor is used to adjust the energy use of the buildings based on their location.

2.3 Regional variation of detached houses' construction in Sweden

There are some variations in the construction of detached houses, depending on which region in Sweden they are located, particularly between northern and southern regions. That is why Sweden is divided in four different climate zone. These variations can be associated to several factors such as climate, availability of building materials and regional architectural styles. Comprehension of these factors might help in the design and construction of detached small houses in Sweden (Scheibenpflug, 2022).

In northern regions of Sweden, where the climate is much colder and savage, the houses are typically constructed with thicker walls and roofs construction, where uses more insulation to protect from cold and keep the energy inside the houses.

Meanwhile, in the southern regions where the climate is milder, detached houses are built with thinner walls construction and larger windows to take advantage of the sunlight and warm. The availability of local building materials also plays a factor in the regional differences of detached houses in Sweden. The reason of extreme temperature variation is because of the elongated shape of the country (Scheibenpflug, 2022).

Building materials also vary dependent on the region. In southern Sweden, where there are fewer forested areas, materials such as concrete and brick are more commonly used. Conversely, in northern Sweden, where there is ample forest, wood is a very common building material for small houses. The use of wood in northern Sweden is not only because of the accessibility of forest, but also due to the cultural heritage. There is a cultural connection to the use of wood in building construction in northern Sweden, which has been passed down through generations (Scheibenpflug, 2022).

In addition to climate factor and accessibility of different building materials, regional architectural styles also influence the design of small houses. As an example, functionalist style is more common in southern Sweden, while traditional cottages with thatched or turf roofs are more prevalent in the northern Sweden (Svenskt trä, 2023).

Overall, the variations in construction techniques and design of small houses between the northern and southern parts of Sweden depends on factors such as climate, availability of building materials, and different regional architectural styles. Awareness of these aspects is important when designing and constructing small houses in different regions of Sweden (Svenskt trä, n.d.).

2.4 Hygrothermal performance of detached houses in Sweden

Over time, changes can occur in building techniques, installation techniques, users' behaviour, requirements and other factors, therefore always a moisture analysis requires before we build or renovate (Bagge and Johansson, 2019).

At the time of their construction in the 1940s, houses rarely had issues with moisture and mould growth, likely due to their poor insulation which kept the concrete floors warm and dry. However, some problems with mould occurred where wooden studs were in direct contact with the concrete floors. Additional moisture problems arose when owners did not maintain their property properly. To prevent these issues, regular replacement of the roof and remaking of the drainage were necessary. Renovation of houses from the 1940s requires an overall consideration of the construction, otherwise a previously healthy house may experience moisture and mould problems with poor ventilation. Upgrading the heating system, changing the windows to new well-insulated windows, or adding more insulation can all negatively impact the ventilation system. Moisture problems were more common in attics, especially if the attic received waste heat from combustion in the past.

The behaviour of occupant was different than nowadays, during 1940s it was common to bath once a week and laundry was probably washed less often than it is today. Although the houses from the 1940s were constructed for the behaviour of occupants at that time and were not designed to handle the energy load of modern appliances, such as washing machines that are run daily and longer and more frequent bath times (polarpumpen, n.d.).

During the Million Program years, many houses were built using unproven methods, which led to significant hygrothermal problems.

According to the Emenius from Karolinska institute, these construction practices have led to a high risk of moisture damage, often affecting the health of the people who live in these houses. In general, detached houses are more prone to moisture and mould damage than apartment buildings constructed during the Million Program (Emenius,2011).

The extreme hygrothermal performance of these houses mostly depended on how they were constructed and built (polarpumpen, n.d.). For example, some of the moisture-sensitive construction solutions were used in these houses were slabs built on the ground without insulation underneath, basements without exterior insulation, wooden beams and plastic mats directly on moist concrete, flat roofs and recreational rooms etc. Another factor that led to moisture and mould growth problems in 1970s houses was the increased use of insulation material in the construction, which led to limitation of natural ventilation in these houses (polarpumpen, n.d.).

Highly insulated building envelopes can result in more sensitive constructions with greater moisture risks with a greater need for accurate moisture protection design (Bagge and Johansson, 2019). Because of the reduced margin against moisture risks, achieving good moisture protection becomes more challenging and requires smart project planning, including simulations of hygrothermal condition in the constructions. This allows solutions to be verified before construction. Not only the envelope and structure, but also the installations such as ventilation system and heat recovery must be dimensioned with consideration for hygrothermal conditions, according to Bagge and Johansson.

A common problem in the modern new-built houses is the initial construction moisture, as well as the moisture that remains in the construction after constructing. Modern construction practices have enabled us to build throughout the year, unlike in the past when buildings were only erected during the dry months. However, not all builders protect their construction projects adequately from precipitation, even as they construct tight structures. If moisture becomes trapped inside the construction, it can lead to mold growth as a consequence (polarpumpen, n.d.).

The moisture and mould issues lead to health problems for occupants, such as asthma and skin allergies, according to Emenius. Generally, households from the 1970s experienced the most health problems and bad indoor climate, while those from the 1940s had fewer health problems. So far, occupants of new houses have rarely experienced such problems, according to Emenius.

2.5 Energy performance of detached houses in Sweden

The energy performance of a building depends on its envelope, energy source and ventilation system (polarpumpen, n.d.). The detached houses build in 1940s had a huge energy usage, due to heating waste through the climate shell, which was poorly insulated and sometimes without any insulation material. They also had a high U-value windows and numerous thermal bridges. Another factor was the energy source for heating system, which was often fuel oil.

In connection with the oil crisis and the emergence of nuclear power that had the ability of mass producing of electricity, heated up the 1970s houses by the direct electricity. This changing of energy source for heating of the buildings led to problem in the classical natural ventilation phenomena, so the houses start to construct without crawl space as concrete slab on the floor. The most of these houses' energy source were changed later when the energy management requirement were stablished in 1978. There were many energy-efficient alternatives such as air heat pump to replace the direct electricity with (polarpumpen, n.d.).

The modern concept for houses' energy performance is to minimize the energy demand of houses as much as possible while the comfort takes always into the consideration. By utilizing smart and efficient construction solutions in the designing of modern houses, the energy demand can be drastically reduced to low energy, passive, or even plus energy houses. Some of these solutions include a highly insulated and airtight climate shell, Low U-value triple-glazed windows, a ventilation system with energy-recovery, and energy efficient sources such as various types of heat pumps, district heating and solar system (polarpumpen, n.d.).

When designing an energy efficient building, it is important to prioritize energy efficiency measures to reduce energy demand before installing an energy supply system that harnesses renewable energy sources (Berggren, 2019).

3 Method

The study utilized literature study, simulation results, and was conducted in three cities across Sweden: Lund placed in Climate zone 4, Stockholm in the central region is in climate zone 2, and Luleå in the northern Sweden is placed in climate zone1 as shown in Figure 1.
The workflow of this study started by gathering information about the detached houses in Sweden, to create a knowledge base for further steps in the study. By using the collected information, the location, construction, and the used material in the detached houses were selected. A wall construction was created in purpose of hygrothermal simulations, and a 3D model were designed for energy simulations.
The obtained data from hygrothermal simulations was exported to Matlab, while the data from energy simulations
were exported to Excel for reading and further analysis in Matlab.
This step was repeated for the energy simulations and future weather data was used in the second round of energy simulations. The results were compared and analysed to draw conclusions, and the report was written in parallel with the other steps.

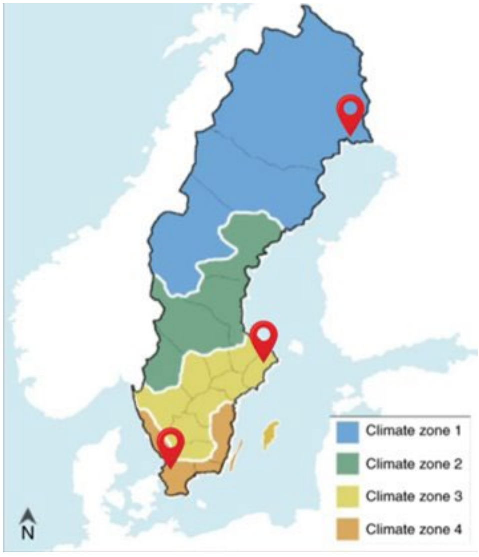

Figure 1. Different climate zones in Sweden.

The illustration in figure 2, presents the workflow of the study.

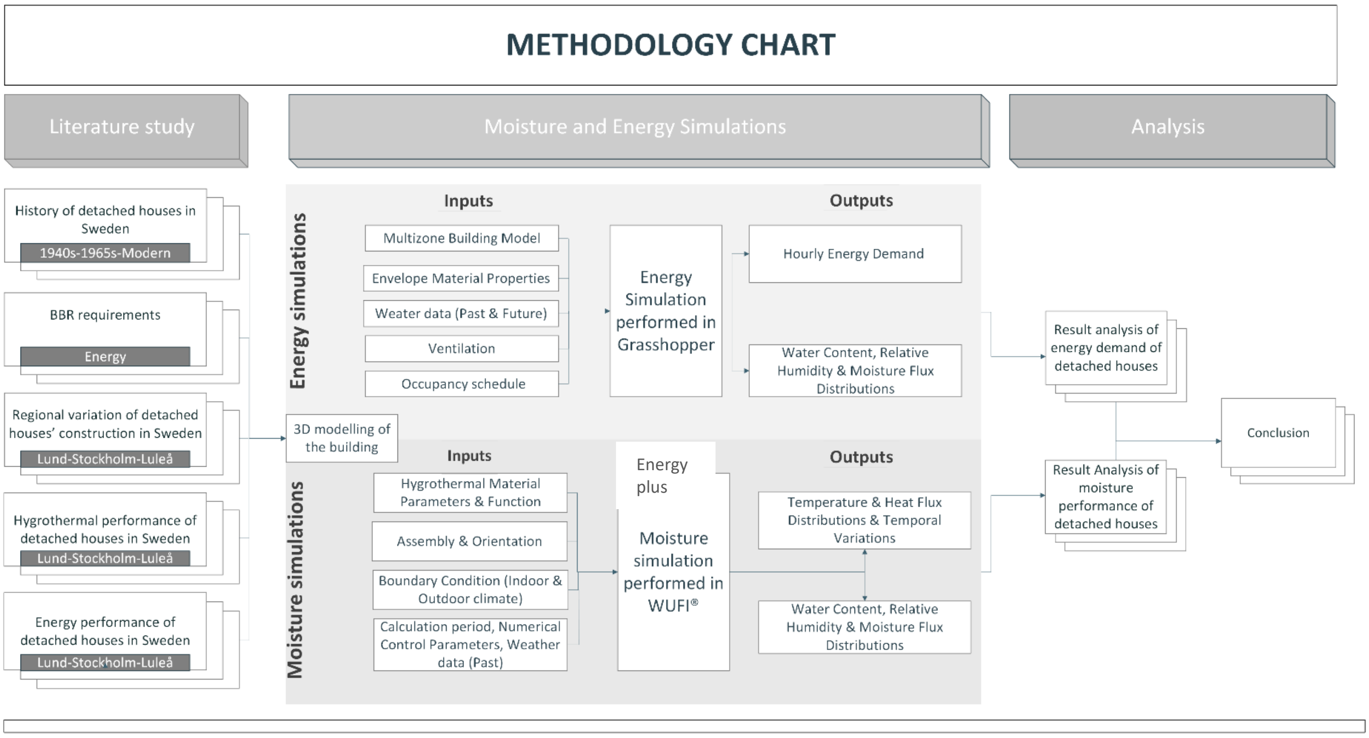

Figure 2. Illustration of the workflow of this study

1.1 Literature study

The literature study for this paper was conducted systematically and methodically, as presented in section 2, and sources was critically evaluated. The purpose of the literature review was to examine existing knowledge on the subject and establish a credible background for the work. To conduct this study, methods such as searching for information online and gathering relevant articles and literatures was employed.

1.2 Weather data

The study aimed to investigate the impact of various climate scenarios on different building constructions of detached houses. To achieve this, historical and future weather data (pessimistic) were used in simulations. All weather data used in this study were generated by Vahid Nik who is a full professor at the diffusion of Building Physics, Lund University. The received data was in the form of Energy Plus Weather Format (EPW) files. The weather data of future climate scenarios consisted of extremely cold year, extremely hot year and typical downscaled weather conditions. Each of those future scenarios were consisted of three different time periods 2010-2039, 2040-2069, 2070-2099. To create the extreme future weather data, the coldest (for ECY) and warmest (for EWY) months of a 30-year period were compiled and used to generate an annual weather forecast. Below in Figure 3 the outdoor temperature during future weather scenarios and the distinct locations are illustrated.

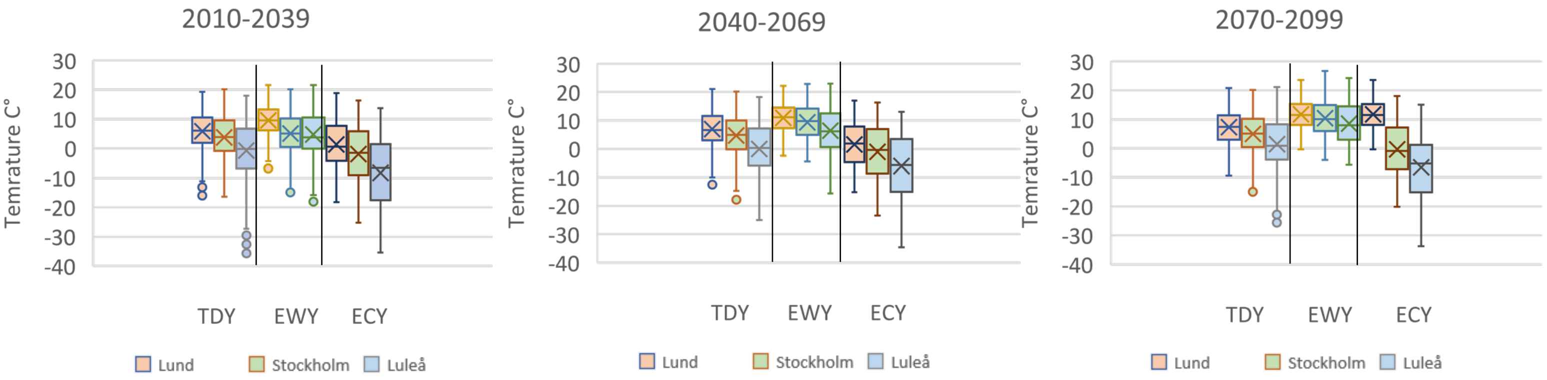

Figure 3. Shows the outdoor temperature during the future weather scenarios in the reference cities.

1.3 Simulations

The study involved two types of simulations: hygrothermal simulations and energy simulations, which will be described in detailed in the upcoming sections. The starting point for both simulations was based on a house model that was adjusted in terms of materials and construction to reflect different time periods and locations.

BBR's requirement for exterior wall construction, which varies depending on the building's location in Sweden, was taken into consideration during the construction design phase. Which appropriate the exterior wall construction's U-value, the colder the climate is in a region in Sweden, the lower U-value is required for the climate shell according to BBR. By applying more insulation can fulfil this requirement. While there are no specific U-value requirements that vary depending on the geographical location of the building, the thickness of insulation material increased by 20% for buildings further north.

During the 1940s, small wooden houses were primarily constructed using plank construction, although there was a shift towards more advanced insulation materials such as straw boards instead of sawdust (Hållahus, n.d.). For the simulations in this study, the exterior wall construction of the 1940s was modelled using plank construction. The following materials were used in each layer during the modelling phase of the simulations:

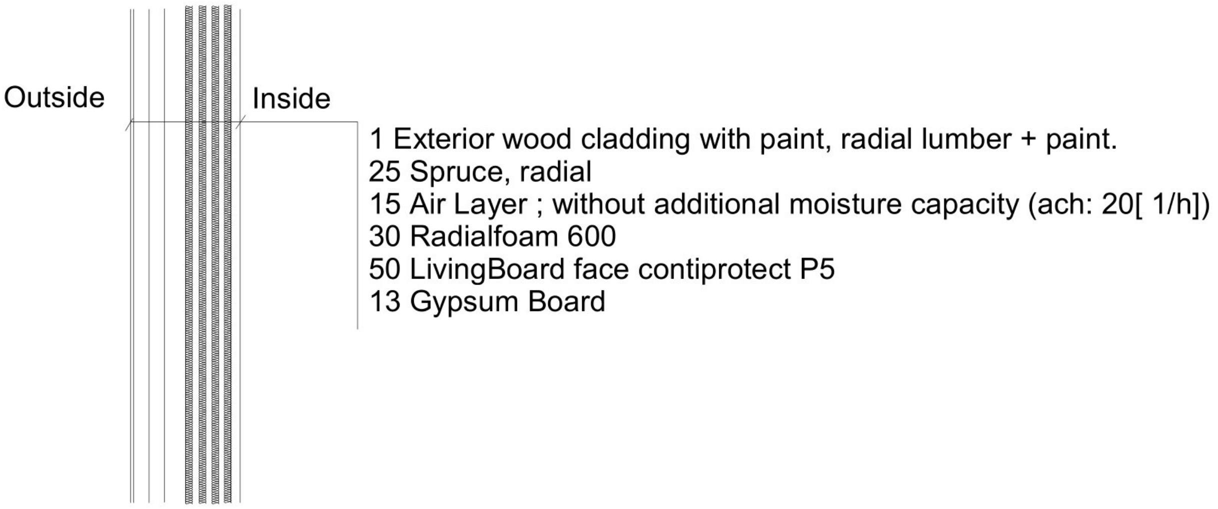

Figure 4. Wall construction representing 1940 construction.

U-value of this construction is 0.86 [W/m²K], which was used in the building model located in Stockholm.

The 1965 was the period when the *Million programme* was launched. For small wooden houses built during this period, frame construction was often used (kommun, 2020).
In the modelled house that represents architecture and construction from the 1965 period, the following materials were used:

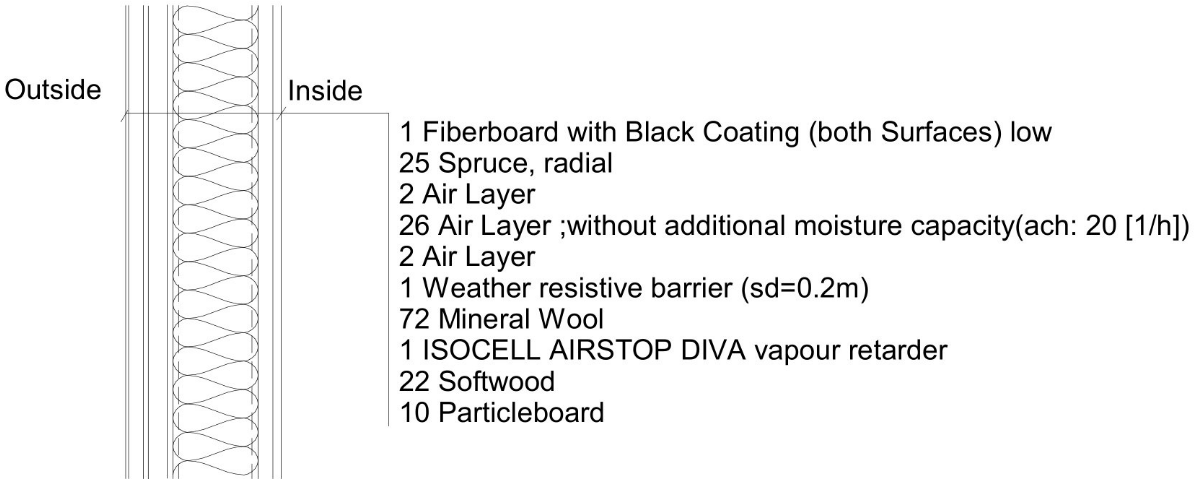

Figure 5. Wall construction in 1965.

U-value of this construction is 0.46 W/m²K, which presents the construction used in Stockholm.
During the 21st century, the multilayer principle gained popularity, which involves designing each layer to fulfil a specific task. Currently, the construction of all wooden detached houses consists of frame construction with fiberglass as the insulation material.
The model which conducts the 21st century's exterior wall construction consists of bellowing materials:

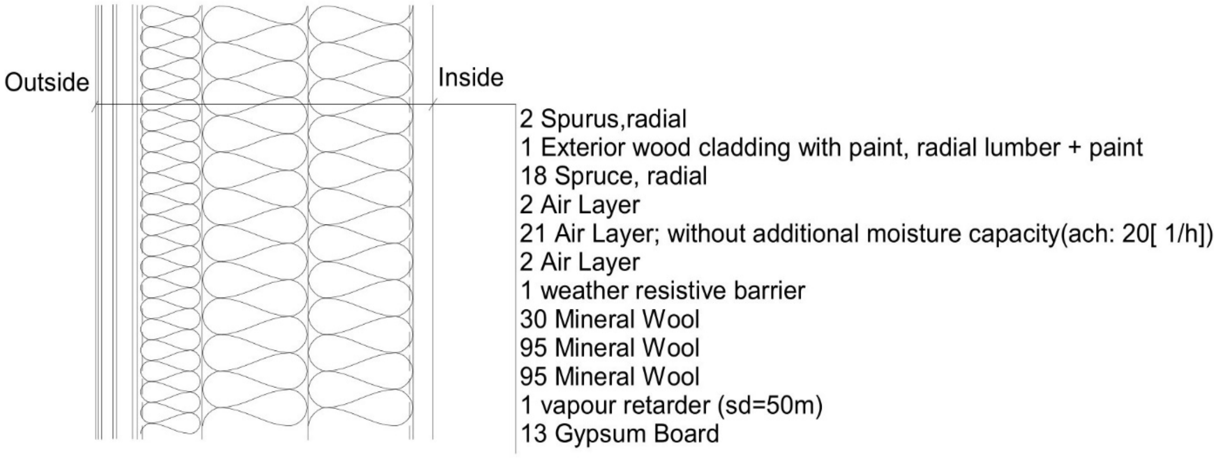

Figure 6. Modern wall construction.

U-value of this construction is 0.15 W/m²K, which presents the construction located in Stockholm.

Below in table 1, the used material in the buildings' envelope and their characteristics values is presented in detail.

Table 1. Presents the used material in the building constructions and their characteristics values.

Material	**Conductivity [W/ J*K]**	**Density [kg/ m³]**	**Specific heat capacity [J/(kg*K)]**	**Thermal absorption**	**Solar absorption**	**Visible wavelength absorption**
Ins. mat/board	0.03	140	1400	0.3	0.3	0.3
Open join cladding	0.14	500	1500	0.35	0.7	0.7
Hardboard	0.17	870	1400	0.7	0.7	0.7
Fibreboard	0.04	268	1880	0.9	0.7	0.7
Spruce	0.09	455	1400	0.7	0.7	0.7
Mineral wool	0.06	60	850	0.9	0.9	0.9
Living board	0.12	655	1400	0.9	0.9	0.9
Gypsum board	0.2	850	850	0.9	0.6	0.6
Hardwood	0.13	650	1400	0.4	0.4	0.4
Plywood	0.088	427	1400	0.4	0.4	0.4
Softwood	0.09	400	1400	0.6	0.6	0.6
Particleboard	0.14	660	1700	0.3	0.3	0.3

1.3.1 Building Modelling

In order to create a house model for the simulations, a floor plan for a typical detached house in Sweden was selected based on information gathered from the literature review. The selected floor plan consists of two rectangles with an area of approximately 150 m^2, as shown in Figure 7, and includes two bedrooms, a living room, a bathroom, a corridor and a kitchen. Each room type has different requirements, so the energy model was divided into five energy zones, as illustrated in Figure 8-12. Other characteristics of the selected house, such as the roof shape, construction, materials and façade, were not considered as they vary depending on the time period and location that were set up for this study. Therefore, the starting point for all house models is the same floor plan (Sverige, n.d.).

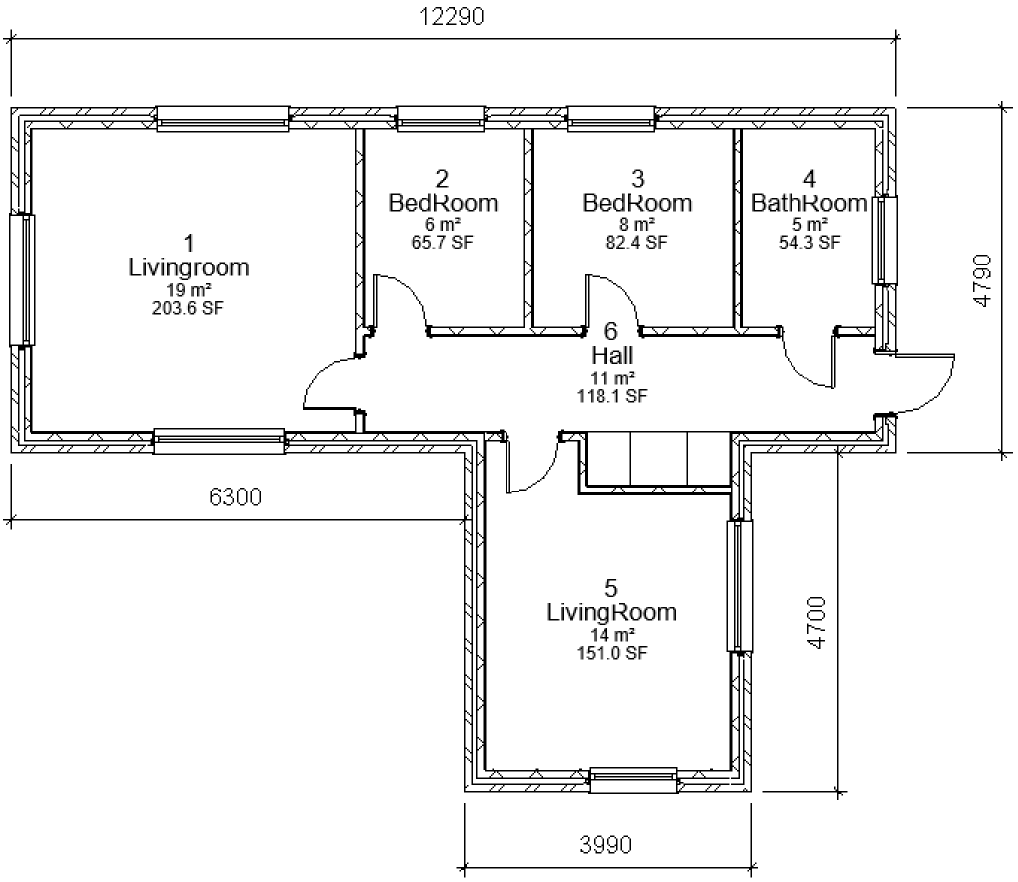

Figure 7. Illustrates the floor plan.

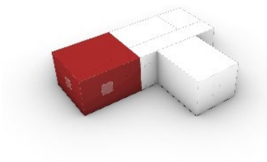

Figure 8. Livingroom

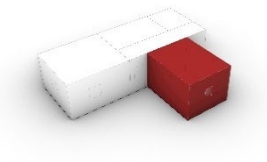

Figure 9. Kitchen

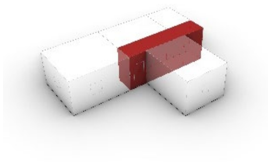

Figure 10. Corridor

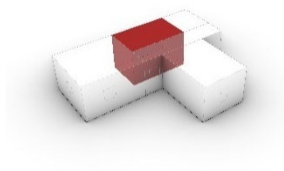

Figure 11. Bedroom

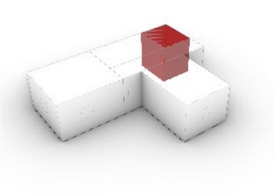

Figure 12. Bathroom

For the simulations, three distinct types of building models have been utilized, each corresponding to a different time period and different location of the detached houses: 1940, 1965, and the 21st century, as mentioned earlier. The house models have been meticulously designed to accurately reflect the change in window sizes, construction materials, and improvements made in addressing high energy consumption problems during each respective period.

The modelled house representing the 1940s period feature smaller windows and less advanced insulation materials, which result in higher energy consumption. It was common to build single-story houses with a low-pitched gable roof that were more suitable for the Swedish climate. The windows were small and not symmetrical on the facade. The houses had a rectangular floor plan and that is why the used model also had a rectangular floor plan (Byggnadsvård, 2017).

Conversely, the building models representing 21st century include modern technology, such as more energy-efficient windows and insulation materials with better thermal conductivity, to address energy consumption issues. The differences between the building models across different intervals of time

highlight the evolution of building design, construction techniques, and the importance of addressing energy consumption in modern construction practices.
In this project, in addition to three distinct building models that represent different time periods, we are even considering three different places in Sweden, which were previously mentioned in section 3.

1.3.2 Hygrothermal simulations

Hygrothermal simulations did not covered the whole outfacing construction parts, but the wall construction.
To conduct the hygrothermal simulations, WUFI and Matlab data tools were utilized. WUFI was employed to construct the wall system based on specific material properties, with consideration given to climate settings and the recommended indoor climate standard. The simulation period was set for 10 years but the weather data of 1-year repeated for 10 years. Meanwhile, Matlab was used to generate figures of the relative humidity, mould index, and mould growth rate using the data exported from WUFI.
The process of hygrothermal simulations involved designing an exterior wall construction for each period and location, with emphasis solely placed on the wall construction. Moisture assessing monitors were installed in the insulation materials. However, no evaluation of moisture was conducted on the materials used for the roof and ground.
The information about the construction design of detached houses in Sweden during the 1940s and 1965s, which were obtained through literature study, were used as reference for designing the exterior wall construction in WUFI.
For the modern construction design, the verified moisture-safe construction designs were directly used. But after running the hygrothermal simulation for this construction type, the results indicated that the RH in exterior insulation layer exceed the $RH_{critical}$ limit. Therefore, some setting changes were tested to determine the optional solution for ensuring moisture safety. After testing many values for air circulation in the air gap, the best performance for moisture safety was conducted by 15 circulation per hour[1/h], which was in the reference construction model 100 circulation per hour[1/h].
Another change to reference model was to remove the extra moisture source in the interior air layer, *2mm Air layer*.
To conduct more comprehensive analysis, an additional monitor was installed on the interior surface of the exterior insulation layer. This was done to provide greater assurance regarding the moisture safety of the construction.

In this assessment, the existing weather file of WUFI was utilized to evaluate the moisture performance of buildings in Lund, Stockholm, and Luleå. The weather data was analysed to determine the direction in which wind-driven rain is most critical. By identifying the most critical direction, the assessment was made more accurate in predicting the potential moisture risks faced by the buildings. The critical direction for buildings in Lund was found to be the Southwest, while for Stockholm, it was the Southeast, and for Luleå, the Northwest. This information provides valuable insights for architects, engineers, and builders who seek to design buildings that can withstand moisture-related challenges in these regions.

3.3.2.1 Set points and inputs

The set points and Inputs in Hygrothermal simulation varied dependent on the climate conditions, where the construction was situated. However, there may be certain setpoints that were applicable across different scenarios.
The duration time of the simulations was determined for a year, and the date was set to January 1st, 2033, to December 30th, 2033.

3.3.2.1.1 Construction setpoints

Two monitors were assembled in the moisture sensitive material in each construction, one in the exterior surface and the other one in the interior surface of this material which was usually the insulation layer.
An extra moisture source was put in the air gap layer in all of constructions. The air was distributed over the whole layer with a constant source that was mixed with the air from outdoor air. The air circulation varied between 10-20 circulation per hour[1/h], dependent on which value had best hygrothermal performance in particular construction.
For hygrothermal simulations just the exterior wall construction was considered, so the construction inclination to the ground was set to 90°, and the building height was set to low buildings/ height up to 10 m.
The initial conditions for construction were established as the median values across whole building part for initial humidity and temperature in the building part. The values for these parameters were fixed at 80% relative humidity at start and 20°C for the initial temperature in the building part.

3.3.2.1.2 Climate setpoints

The location of constructions was selected from WUFI Mapp database for Lund, Stockholm, and Luleå. By using the climate analysis in the climate section in WUFI, the windiest direction for each city was checked, to determine each constructions critical direction dependent on its location. For constructions located in Lund, the southwest direction was the windiest end the most critical orientation for wind driven rain damages. For Luleå and Stockholm, the critical direction was east and southeast, respectively. For the indoor climate condition, the ASHREA 160 standard was used, which had the heating set point of 21°C and a cooling set point of 28°C. However, the cooling set point was not applicable in this part of the study, as no cooling system was installed in any of the building types, regardless of their location.

3.3.3 Energy simulation

The detached houses were modelled using Rhinoceros, which was linked to Grasshopper for energy simulations. The simulations were performed via Grasshopper plugins Ladybug and Honeybee, and details about the inputs and settings is mentioned in section 2.3.2.1. For the implementation of simulations, three different building envelopes was chosen for the building model as well as three distinct locations, as previously mentioned in the section 2.3. Thus, in total nine different energy script were created in Grasshopper.
The simulation process began by utilizing relevant historical weather data for each location to run scripts created for the simulations. The weather data used for past climates were generated by Climate One Building which could be used in building performance analysis. As a result, nine distinct results were obtained, which investigated the impact of climate on the different houses with distinct construction and different locations, during recent years.
The results obtained from the simulations was exported to an Excel file and subsequently were extracted from it to Matlab for plotting and reasonable analysis.

Once the historical weather data had been obtained, it was time for the other main object of this study which was assessing the impact of extreme and typical future weather conditions on the energy consumption of detached houses in Sweden.
For the future climate, much more than nine simulations had to be conducted due to the availability of three different future weather datasets: extreme cold year, extreme warm year and typical year, as mentioned earlier in section 2.2. Each of these datasets represented approximately 90 years of weather data, which were further divided into three sets of almost 30 years each, resulting in a total of 81 simulations that needed to be performed.

The results obtained from future weather data were extracted from Grasshopper to Excel and further to Matlab to be analysed, just as the findings from historical weather data were exported for further analysis.

Down below there is an illustration of energy simulations in *Figure 13*.

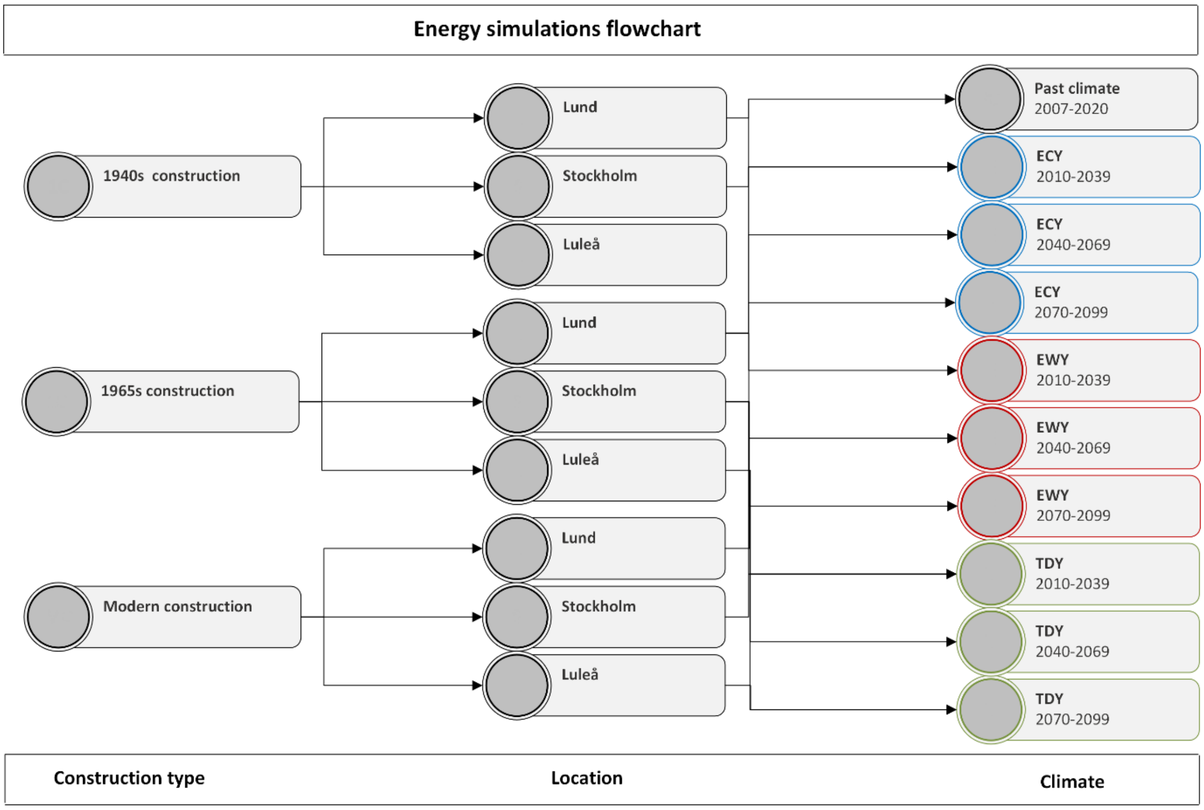

Figure 13. Illustration of the energy simulations.

3.3.3.1 Set points and inputs

The construction settings used in energy simulations were determined based on the construction details described in section 2.3. Additional settings were required to control the openings of windows to address ventilation issues. The fraction of openable window area was fixed to 0.6. In addition, the minimum outdoor and indoor temperatures were set to 25°C and 21°C respectively in ventilation control. Setting the minimum outdoor temperature ensured that ventilation cooling did not occur during winter, even if the room temperature was above the minimum indoor temperature. The minimum indoor temperature was used to initiate ventilation with values around room temperature above which the window would open.
The heating setpoint was set to 21°C and cooling the setpoints were set to 28°C, a heat pump were selected as the constructions' energy source.
The parameters for the output of the simulations included energy zone usage, HVAC energy usage and gains and losses. *Honeybee simulation controller* was used to specify the types of Energy Plus calculations to be run during the simulations.
In the next step of the energy script, the weather file for each scenario was imported into the created path for specific simulation. The obtained result was set to show the annually energy usage of the building, the total EUI, and the breakdown values for the five distinct energy usage sources: heating, cooling, lighting, electricity/equipment and hot water. Finally, to provide further clarification of the

desired results, the hourly consumption output for each of the five main energy usage was also generated.

4 Results and discussion

The analysis of the obtained results was based on comparison of graphical and statistical outputs of simulations. In this segment all results from simulations will be presented and discussed.

4.1 Hygrothermal results

The results of hygrothermal simulations represents the end year of a period of 10 years, simply put, from 2032 to 2033 as written in method part. Three different scripts for graphical outputs were written. One of those graphs shows the comparison between relative humidity and critical relative humidity in the chosen insulation layer, where the monitor was placed. The other graph shows the mould index which determines the risk of mould growth, based on the information from the previous graph where the relative humidity comparison was analysed. After creating those two graphs a boxplot was plotted in MATLAB which represents the mould growth rate.
When there was a considerable difference between relative humidity and the critical relative humidity, the mould index and mould growth rate were chosen to not be presented in this report due to no risk of mould growth.

4.1.1 Results from 1940s

In this section presents the hygrothermal condition for the house models build in 1940s. Figure 14 represents the modelled wall for the reference cities in 1940s and the monitor was placed in the only insulation layer in the wall as described earlier in the method. First step in mould growth risk assessment were made with a comparison between RH and. Based on the figure presented, the relative humidity levels remained below the critical threshold for mould growth in all three cities. As the obtained results showed that the RH in the construction in Lund reaches as highest to 78%, 67% in Stockholm and 72% in Luleå, which lies all bellow $RH_{critical}$ (80%) for mineral wool.
Therefore, there is a low risk of mould growth in the wall during the simulation period as it never exceeded the $RH_{critical}$.

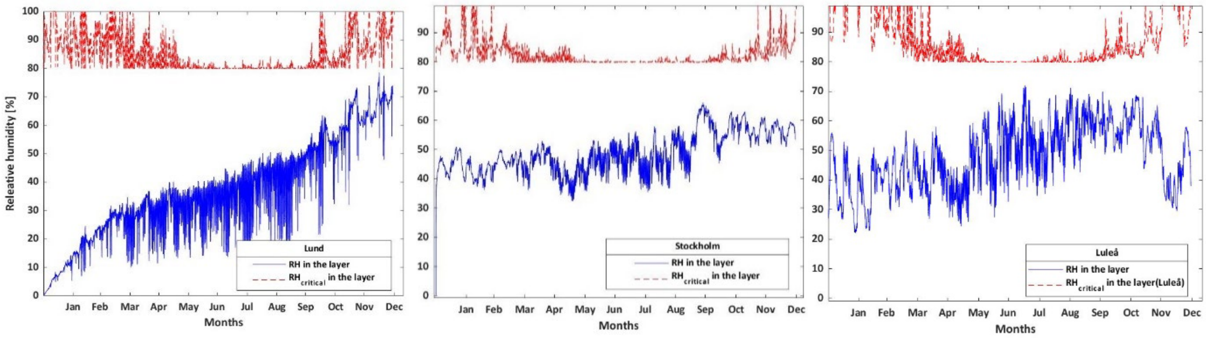

Figure 14. RH and the $RH_{critical}$ in outer surface of the insulation layer in wall representing 1940s in the reference cities.

4.1.2 Results from 1965s

The hygrothermal simulations for the detached houses from 1965s, shows that there was not any risk of mould growth in the construction's critical layer such as insulation layer, as the graphs in Figure 15 shows. Based on the data, the RH levels in this layer generally remain below the critical threshold for mould growth, which is typically around 80%. The RH in Lund reaches to 76%, 77% in Stockholm and 74% in Luleå as highest. The beginning of the simulation result indicated that the RH exceeds the $RH_{critical}$ which might have caused by the settings and inputs in the simulation tool.

It can be observed that the RH does not reach the RH$_{critical}$ in the insulation material. Although during summer and autumn the relative humidity increases compared to the rest of the year, there is still quite a margin between the RH and the RH$_{critical}$.

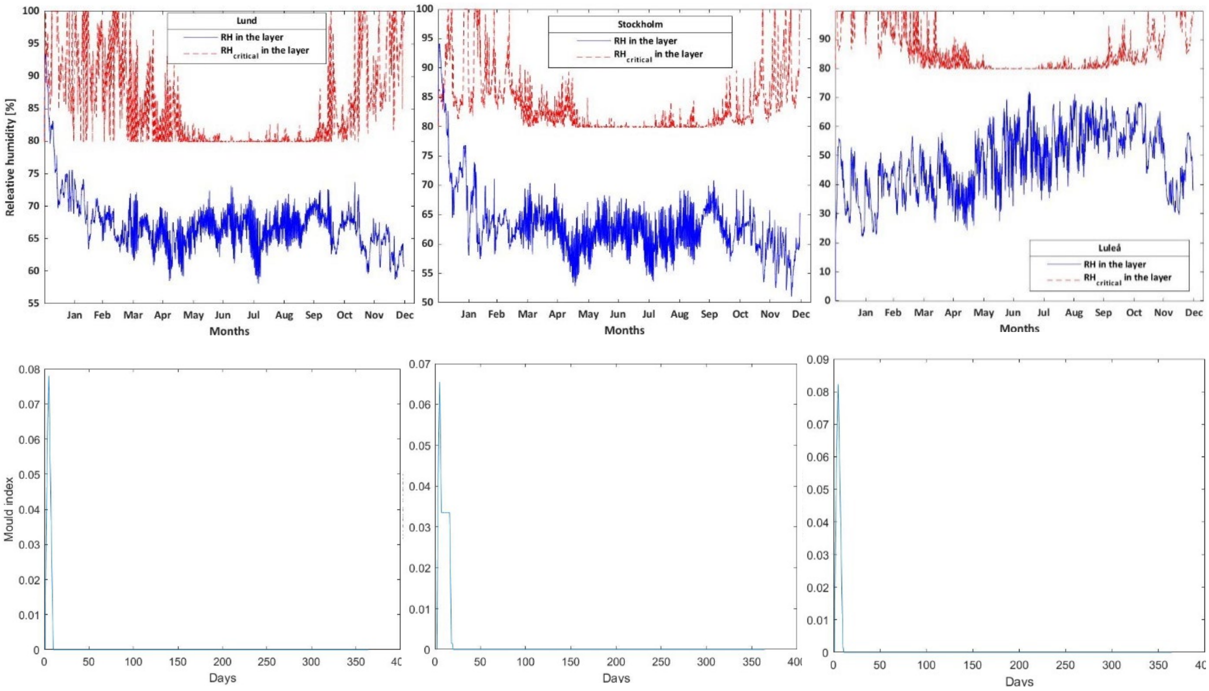

Figure 15. RH and the RH$_{critical}$ (upper) and Mould Index (down) in outer surface of the insulation layer in wall representing 1965s in the reference cities.

4.1.3 Modern constructions' results (after 2000)

The hygrothermal conditions of houses in Lund, Stockholm and Luleå, which has a modern construction design, can be observed in Figure 16. As mentioned earlier in section 3.3.2, the verified modern wall design with a few changes was used for this construction. The RH in this construction is close to the RH$_{critical}$ sometimes during winter according to this graph, but there is no risk of mould growth. To ensure that the construction is not exposed to mould growth, a further assessment was conducted.

The further assessment for moisture safety of the construction was analysing of the material's mould index which is also presented in Figure 16. As the graphical illustration of mould index shows, the risk of mould growth is zero in the material.

As Figure 16 displays the moisture content, there were periods where the humidity level exceeded the critical line (80%) in Stockholm (highest 90%) and Luleå (95%), which could potentially cause a mould growth. To confirm that there was no risk of mould growth, the interior surface of the insulation layer was analysed (for Stockholm and Luleå). The RH graphs for the interior surface are presented in Figure 17, which indicates that there is no possibility of mold growth in this construction.

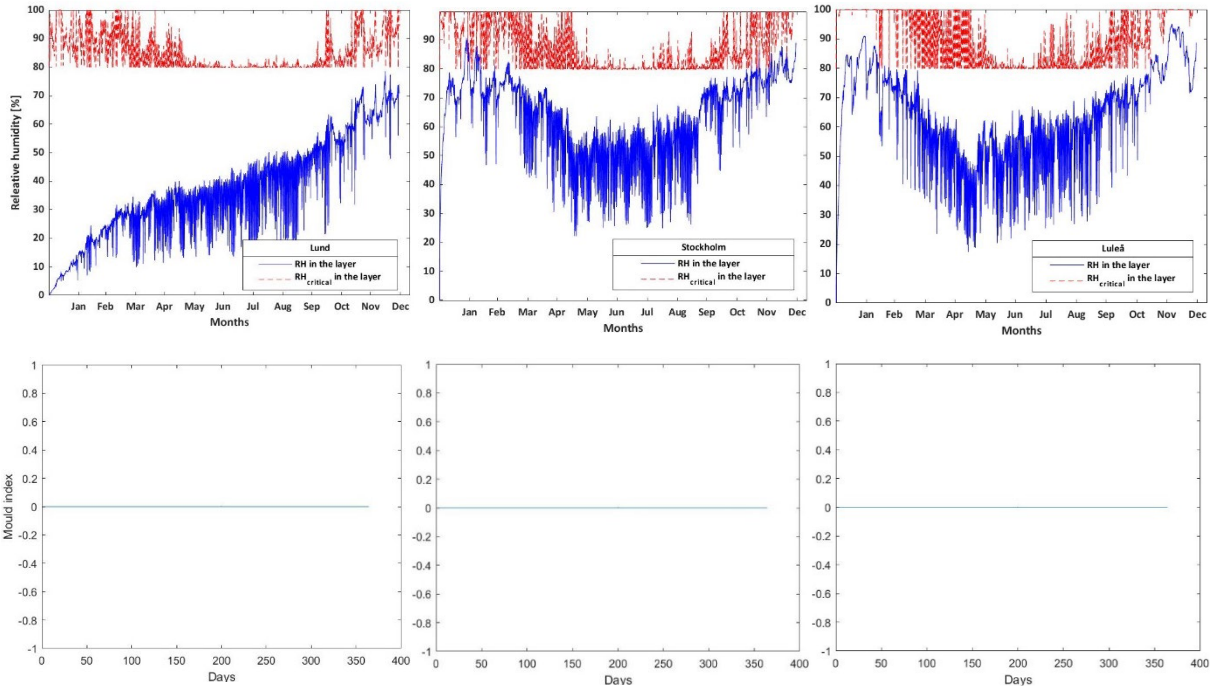

Figure 16. RH and the RH$_{critical}$ (upper) and Mould Index (down) in outer surface of the insulation layer in wall representing Modern constructions.

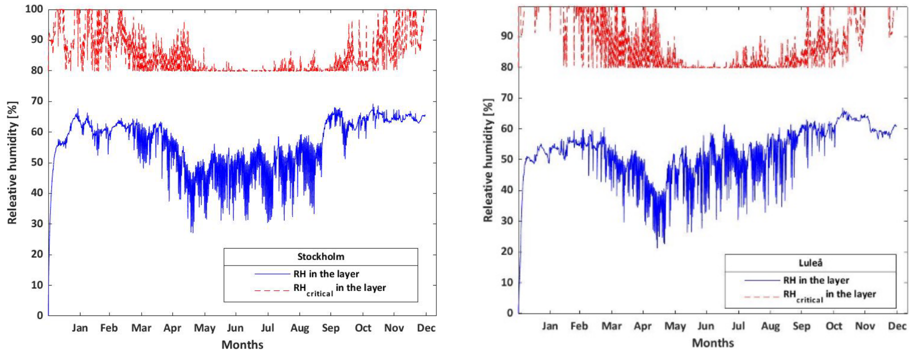

Figure 17. RH and the RH$_{critical}$ in interior surface of the insulation layer in wall representing Modern constructions.

4.1.4 Overall discussion

After analysing all construction types' hygrothermal performance, the graphs showed that all construction types were moisture safe. Although there was sometimes, some exceeding of RH through $RH_{critical}$, but still by further analysing, the moisture safety of the constructions was ensured.
The exceeding of RH depended sometimes on the initial moisture in the constructions, and sometimes on the high humidity level in the layer. The high RH depended on initial moisture was just about the inputs and settings values which the simulation tool took to consideration. So, the initial humidity is not valid in this case study, because all reference detached houses are not new built. High levels of RH in other cases were in the exterior surface of the insulation material, and after checking the interior surface of the material showed no signs of moisture penetration. Hence, we could say the constructions were moisture safe. The high level of RH occurred mostly in the modern construction types, which might depend on the existing of more amount of material in these constructions compared to the older construction types.

4.2 Energy performance results

In Figure 18, Figure 19 and Figure 20 of heating loads of periods 2010-2039, 2040-2069 and 2070-2099 are presented. The results are presented in kWh/m2. In x-axis, the division is by construction types of each weather data, TMY, ECY, TDY and EWY. The highest demand showed to be in the 1940 construction followed by 1965 and the lowest heating demand on modern construction. The trend between cities always goes from Luleå, Stockholm and Lund, from highest demand to lowest demand. Same trend follows through all three periods. The overall comparison shows that the demand is decreasing with time.

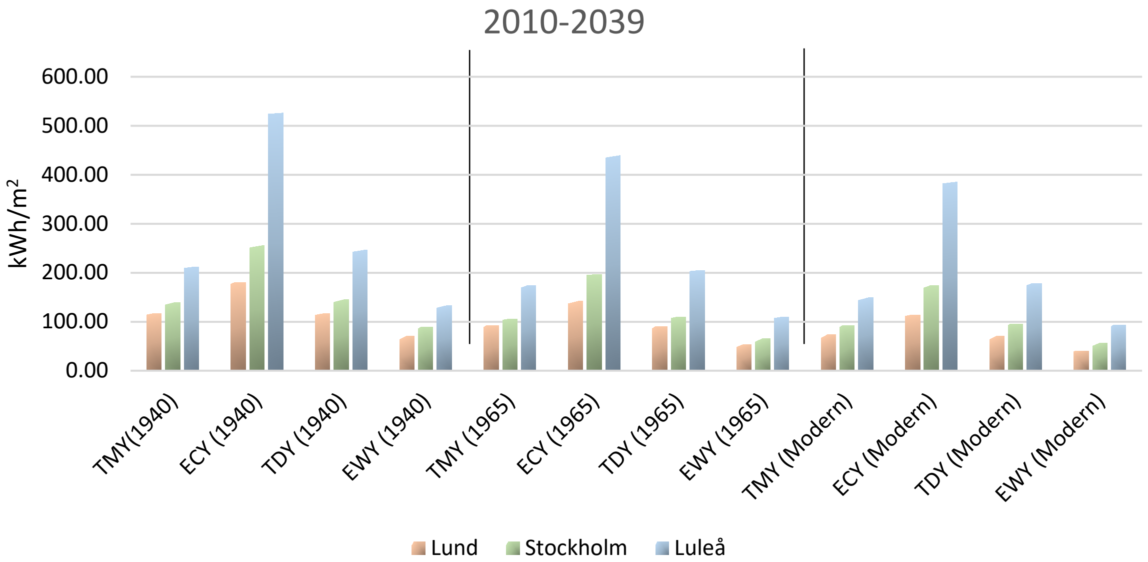

Figure 18. Heating load comparison for period 2010-2039

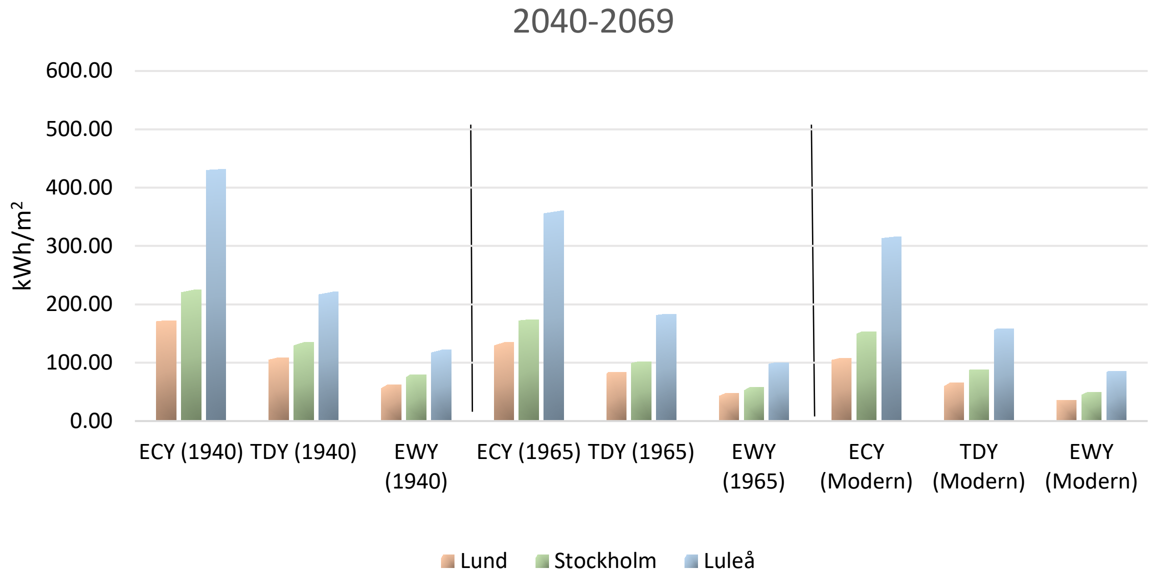

Figure 19. Heating load comparison for period 2040-2069.

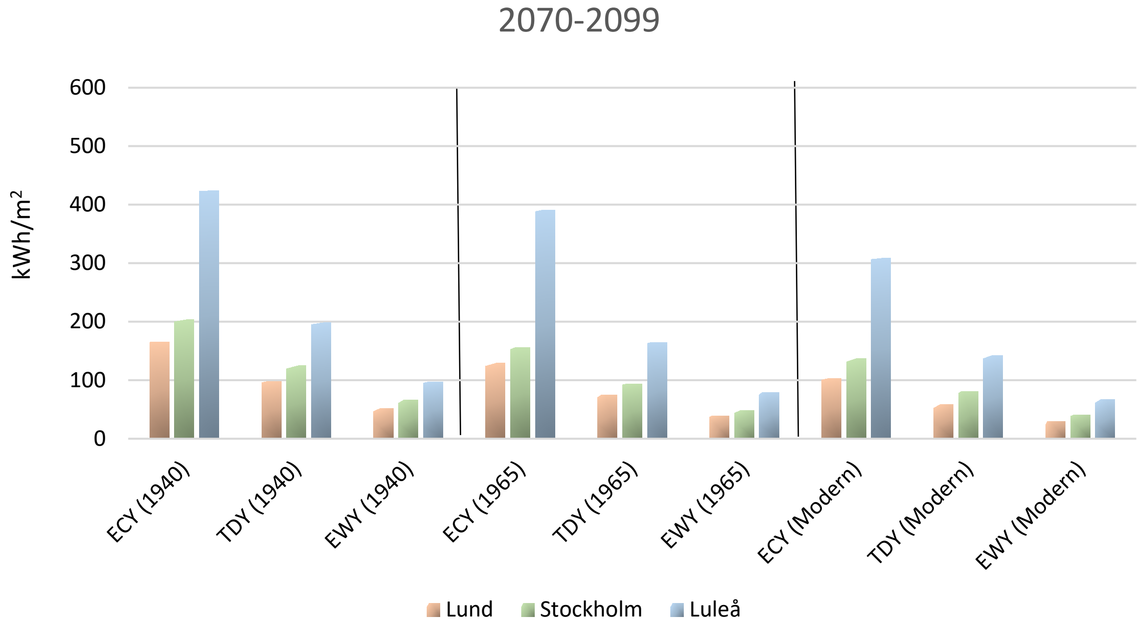

Figure 20. Heating load comparison for period 2070-2099.

Figure 21-23, are illustration of cooling loads of constructions placed in Lund, Stockholm and Luleå in periods 2010-2039, 2040-2069 and 2070-2099. The results are presented in kWh/m2. In x-axis, the division is by construction types of each weather data, TMY, ECY, TDY and EWY. The highest demand showed to be in the modern construction followed by 1965 and the lowest cooling demand on 1940s construction. The trend between cities always goes from Lund, Stockholm and Luleå, from highest demand to lowest demand. Same trend follows through all three periods. The overall comparison shows that the demand is decreasing with time.

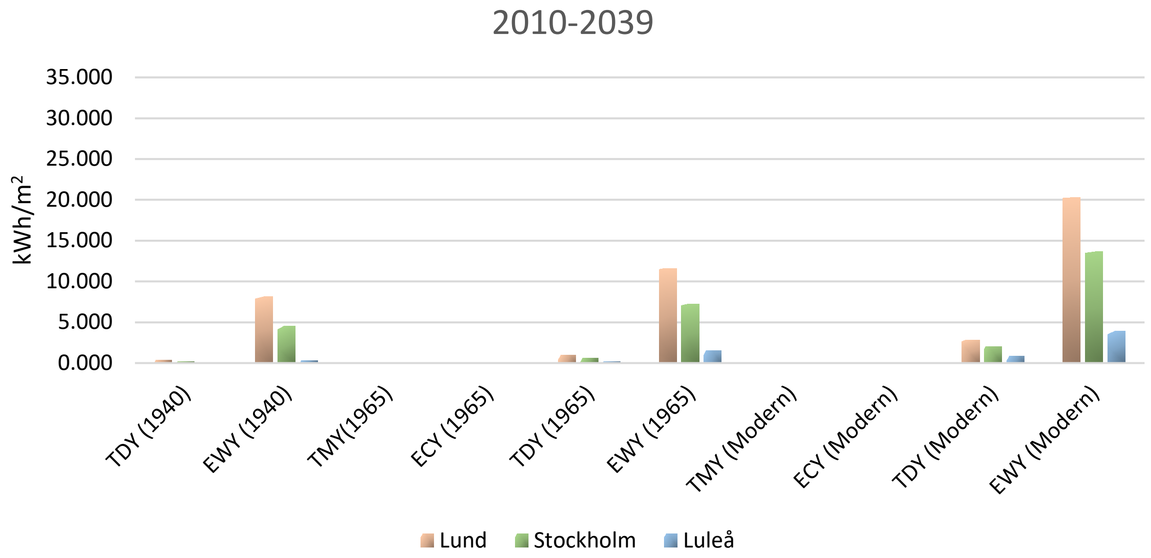

Figure 21. Cooling load comparison for period 2010-2039.

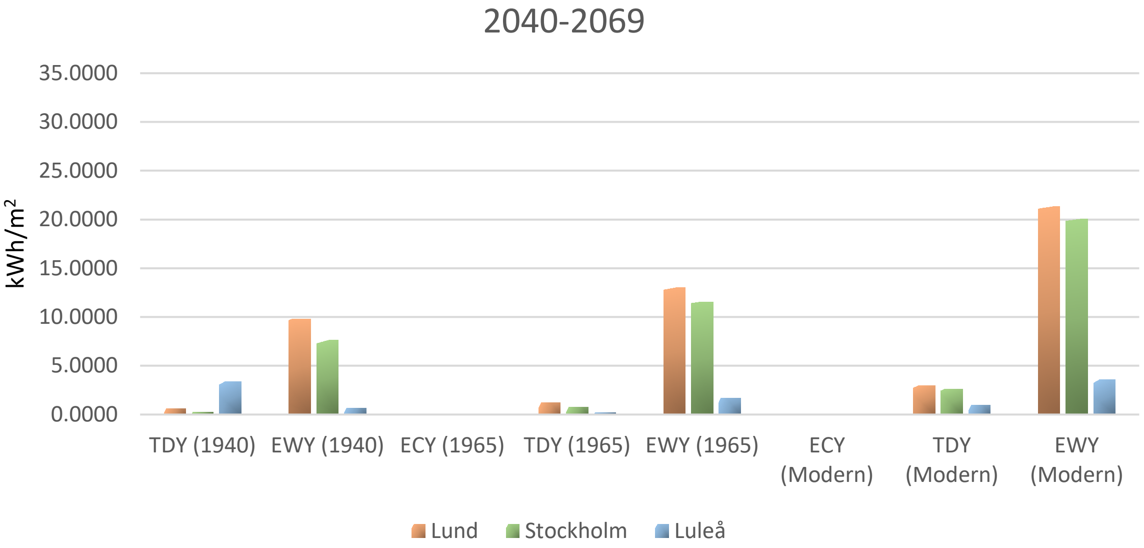

Figure 22. Cooling load comparison for period 2040-2069.

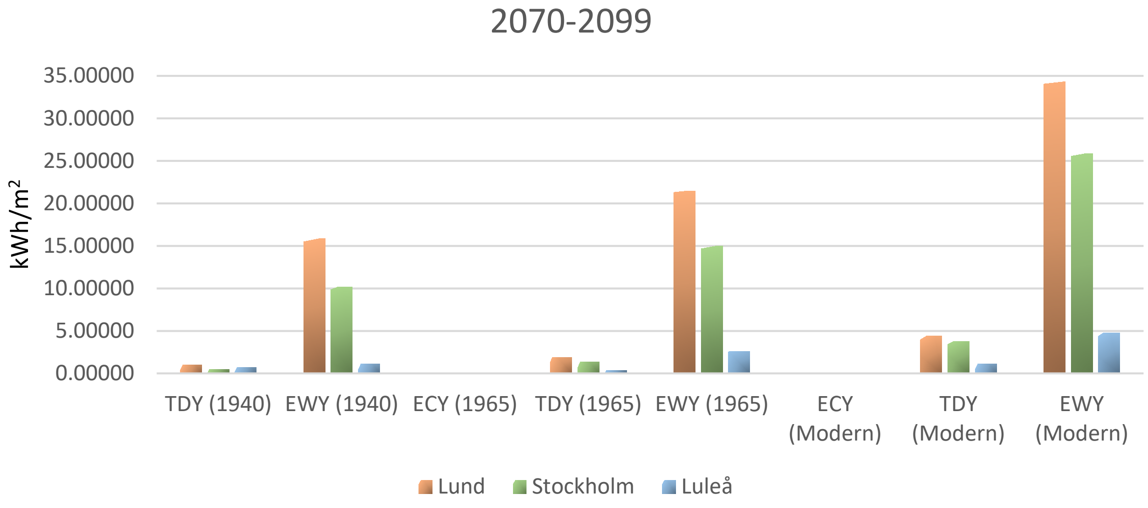

Figure 23. Cooling load comparison for period 2070-2099.

4.2.1 1940s constructions

4.2.1.1 Past climate (2007-2020)

The heating load of reference buildings located in Lund, Stockholm and Luleå is presented in , which is simulated using weather data from the past climate between 2007 and 2020. Highest heating demand occurs in January in these three reference cities. The heating load in Lund in January reaches 2767,8 kWh/m^2, in Stockholm 3546 kWh/m^2 and in Luleå it is 4059 kWh/m^2. Heating demand may still be present during summers, depending on the climatic conditions and the heating setpoint used in the simulations script.

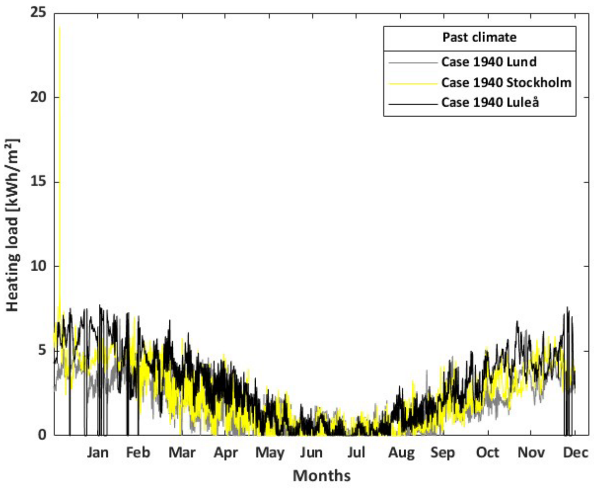

Figure 24. Heating load of houses from 1940s, located in Lund, Stockholm and Luleå using the past weather data.

4.2.1.2 Extreme cold year (ECY)

Heating loads in detached houses in three reference cities (Lund, Stockholm and Luleå) of ECY (2010-2099) are presented in Figure 25. As this was an extremely cold year, the heating load was higher compared to the past climate. The path of the heating load in these three periods shows that the heating load reduces slightly by time (during November and December months). The highest monthly heating load for this scenario is presented in Figure 25.

Table 2. Highest monthly heating load of detached houses from 1940s, placed in Lund, Stockholm and Luleå; simulated using weather data ECY.

			HEATING	
		Period	Month	Load [kW/m^2]
LUND		2010-2039	January	4062,6
		2040-2069	January	4221,8
		2070-2099	January	3739,3
STOCKHOLM		2010-2039	March	6179
		2040-2069	January	6615,5
		2070-2099	February	4675,9
LULEÅ		2010-2039	January	16358
		2040-2069	January	14336
		2070-2099	February	13778

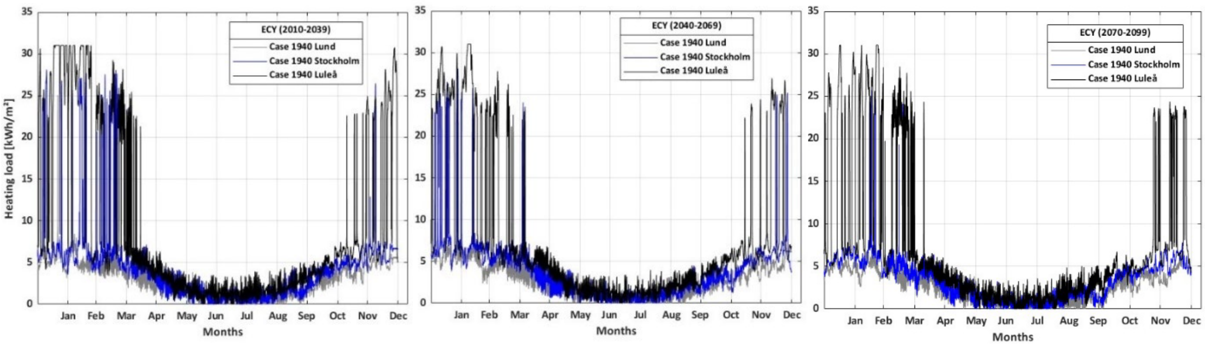

Figure 25. Heating load of detached houses placed in Lund, Stockholm and Luleå simulated using weather data ECY.

4.2.1.3 Extreme warm year (EWY)

Heating and cooling loads of extremely warm years (EWY) in 1940s construction type are presented in Figure 26. Since the EWY is a data collection of highest temperatures during this period, cooling demand increases, and heating demand decreases during this year. Comparing the different period in this scenario, the heating load decreases, and cooling load slightly increases even by time (in the future). In Table 3 the presented heating and cooling load shows these changing in the future.

Table 3. Highest monthly heating- and cooling load of detached houses from 1940s, placed in Lund, Stockholm and Luleå;

		HEATING		**COOLING**	
	Period	Month	Load [kW/m^2]	Month	Load [kW/m^2]
LUND	2010-2039	January	1919,6	July	670,6108
	2040-2069	January	1869,7	July	740,8739
	2070-2099	November	1400	August	1046,1
STOCKHOLM	2010-2039	January	2486,2	July	267,16
	2040-2069	January	2214,3	July	794,01
	2070-2099	January	1929,2	July	681,18
LULEÅ	2010-2039	January	2871,8	July	18,1501
	2040-2069	January	3043,7	July	46,2977
	2070-2099	January	2453,1	July	62,3162

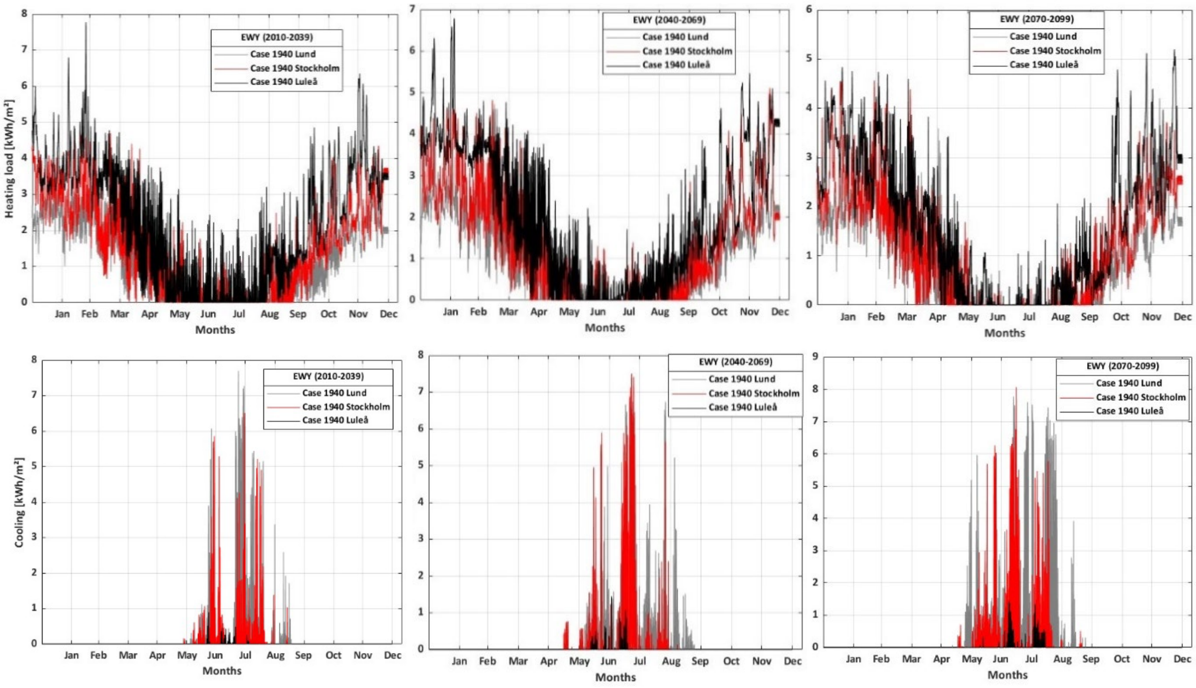

Figure 26. Heating load (upper) and Cooling load (lower) of buildings from 1940s placed in Lund, Stockholm and Luleå simulated using EWY.

4.2.1.4 Typical Downscaled Year (TDY)

The heating and cooling loads in a typical down scaled year during the periods 2010-2099 for the construction type of 1940 are represented by Figure 27. The results closely resemble historical climate results for the same building type, albeit with slightly increased heating requirements during the winter months. Cooling load during the summer months occurs in all three reference cities in this scenario. In the Figure 27 it is possible to see that, there is some cooling demand on some days during the summer. The Figure 27 presents the highest monthly heating and cooling load during the typical downscaled year.

Table 4. Highest monthly heating- and cooling load of detached houses from 1940s, placed in Lund, Stockholm and Luleå;

		HEATING		**COOLING**	
	Period	Month	Load [kW/m^2]	Month	Load [kW/m^2]
LUND	2010-2039	January	2806,7	July	29,52
	2040-2069	January	2649,7	July	47,14
	2070-2099	January	2442,6	August	66,8671
STOCKHOLM	2010-2039	January	3434,8	July	10,42
	2040-2069	January	3348	July	27,12
	2070-2099	January	3147,8	July	62,49
LULEÅ	2010-2039	January	6806,2	July	1,06
	2040-2069	January	5807,2	July	0,45
	2070-2099	January	5256,2	July	4,06

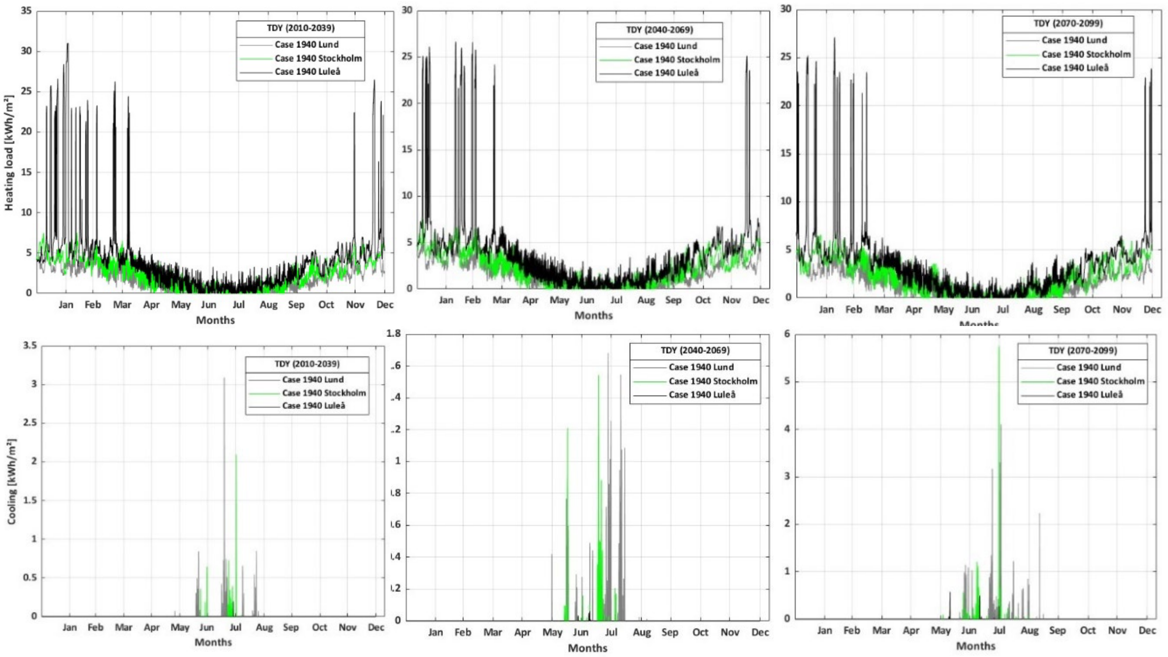

Figure 27. Heating load (Upper) and Cooling load (down) of buildings from 1940s placed in Lund, Stockholm and Luleå simulated using TDY.

4.2.2 1965s constructions

This section presents the energy results obtained for the construction type from the 1965.

4.2.2.1 Past climate

For existing detached houses in Sweden, there is typically no cooling system, so the results from the past climate are only for heating load. Figure 28 presents the heating demand of the reference constructions in Lund, Stockholm and Luleå. The heating demand in the coldest month, January. during the simulation period 2007-2020, reached 2247 kWh/m^2 for Lund, 2762,7 kWh/m^2 for Stockholm, and 3431,2 kWh/m^2 for Luleå.

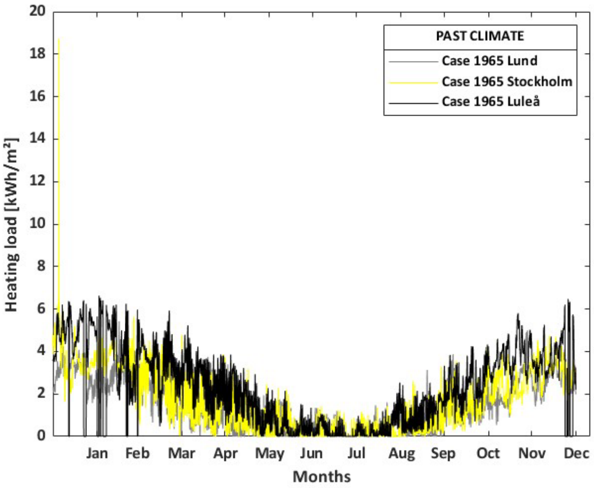

Figure 28. Heating load of buildings placed in Lund, Stockholm and Luleå simulated with past climate.

4.2.2.2 Extreme cold year (ECY)

In the future weather scenarios, in addition to heating demand, cooling demand was also taken into consideration. Figure 29 shows the heating load of the detached house from the 1965 in the reference cities during the extreme cold years (2010- 2099). Since the simulation was for an extreme cold year, there was no cooling demand.

The results of all three periods follow the same trend but with a decreasing of heating load by time, as the Figure 29 shows. Table 5 presents the highest monthly heating load during this scenario.

Table 5. Highest monthly heating load of detached houses from 1965s, placed in Lund, Stockholm and Luleå; simulated using weather data ECY.

		HEATING		
	Period	Month	Load [kW/m^2]	
LUND	2010-2039	January	3300,80	
	2040-2069	January	3423,70	
	2070-2099	January	3023,40	
STOCKHOLM	2010-2039	January	4813,4	
	2040-2069	January	5201,9	
	2070-2099	February	3656,90	
LULEÅ	2010-2039	January	13824	
	2040-2069	January	12054	
	2070-2099	January	2410,7	

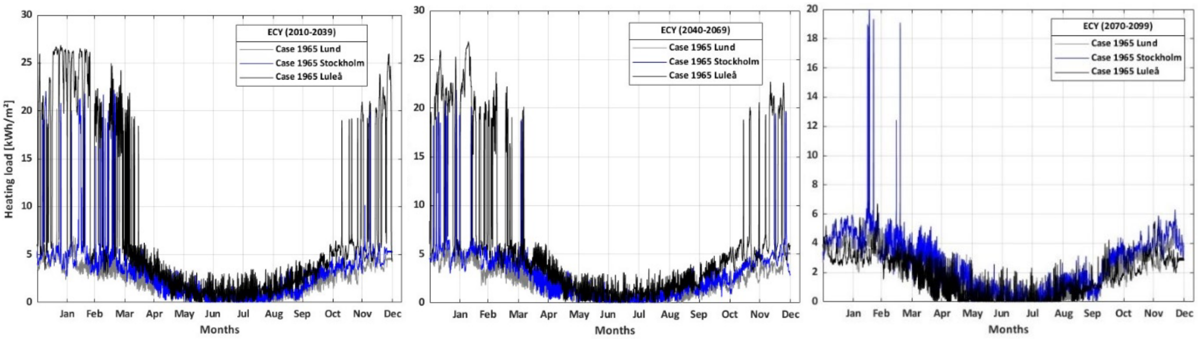

Figure 29. Heating load of buildings from 1965s placed in Lund, Stockholm and Luleå simulated using ECY.

4.2.2.3 Extreme warm year (EWY)

In this section of the report, the results from EWY for the detached house model from 1965s in Lund, Stockholm and Luleå will be presented. Figure 30 illustrates the heating- and cooling load of the reference construction during period 2010-2099. It can be observed from the graphs that the heating demand in all reference cities is less compared to the heating demand in ECY scenario, as expected. However, both the cooling demand and the number of days requiring cooling being higher, increases slightly by time when compare different time period. The highest monthly heating- and cooling loads are presented in Table 6.

Table 6. Highest monthly heating and cooling loads of detached houses from 1965s, placed in Lund, Stockholm and Luleå; simulated using weather data EWY.

		HEATING		**COOLING**	
	Period	Month	Load [kW/m^2]	Month	Load [kW/m^2]
LUND	2010-2039	January	1503,70	July	905,07
	2040-2069	January	1470,70	July	945,65
	2070-2099	November	1093,10	July	1034,40
STOCKHOLM	2010-2039	January	1892,8	July	403,14
	2040-2069	January	1684,6	July	1114,60
	2070-2099	January	1455,30	July	967,18
LULEÅ	2010-2039	January	1617,9	June	0,19
	2040-2069	January	2560,5	July	102,13
	2070-2099	January	2048,1	July	131,01

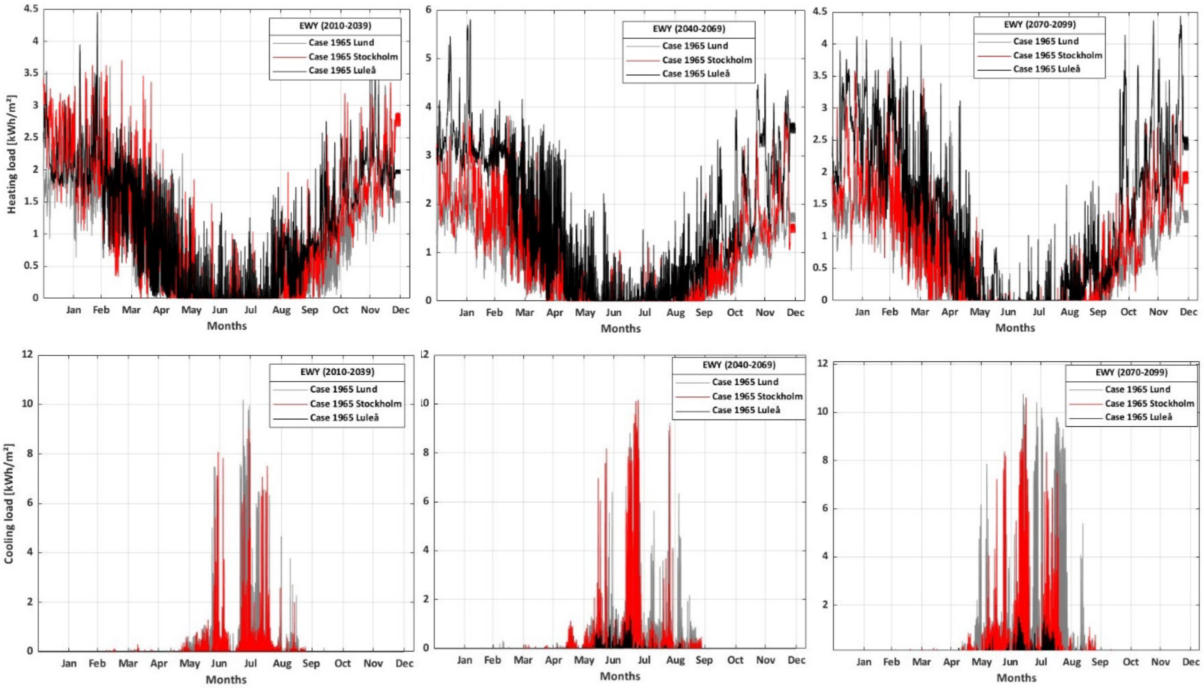

Figure 30. Heating load (upper) and Cooling load (down) of buildings from 1965s placed in Lund, Stockholm and Luleå simulated using EWY.

4.2.2.4 Typical Downscaled Year (TDY)

As the graphs in Figure 31 shows, the result in this scenario is closer to the ECY results than EWY results. The graphs follow the same path with a slightly lower average value of heating loads in different time periods. The cooling peak loads and the number of days that cooling demand requires increases by time even in this scenario. *Table 7* presents the highest monthly heating and cooling load for TDY.

Table 7. Highest monthly heating- and cooling load of detached houses from 1965s, placed in Lund, Stockholm and Luleå; simulated using weather data TDY.

		HEATING		**COOLING**	
		Month	Load [kW/m^2]	Month	Load [kW/m^2]
LUND	2010-2039	January	2248,50	July	58,90
	2040-2069	January	2119,00	July	77,11
	2070-2099	January	1937,60	July	86,28
STOCKHOLM	2010-2039	January	2667,10	July	37,90
	2040-2069	January	2603,20	July	61,70
	2070-2099	January	2441,70	July	109,43
LULEÅ	2010-2039	January	5753,10	July	15,93
	2040-2069	January	4900,80	July	14,77
	2070-2099	January	4442,4	July	24,24

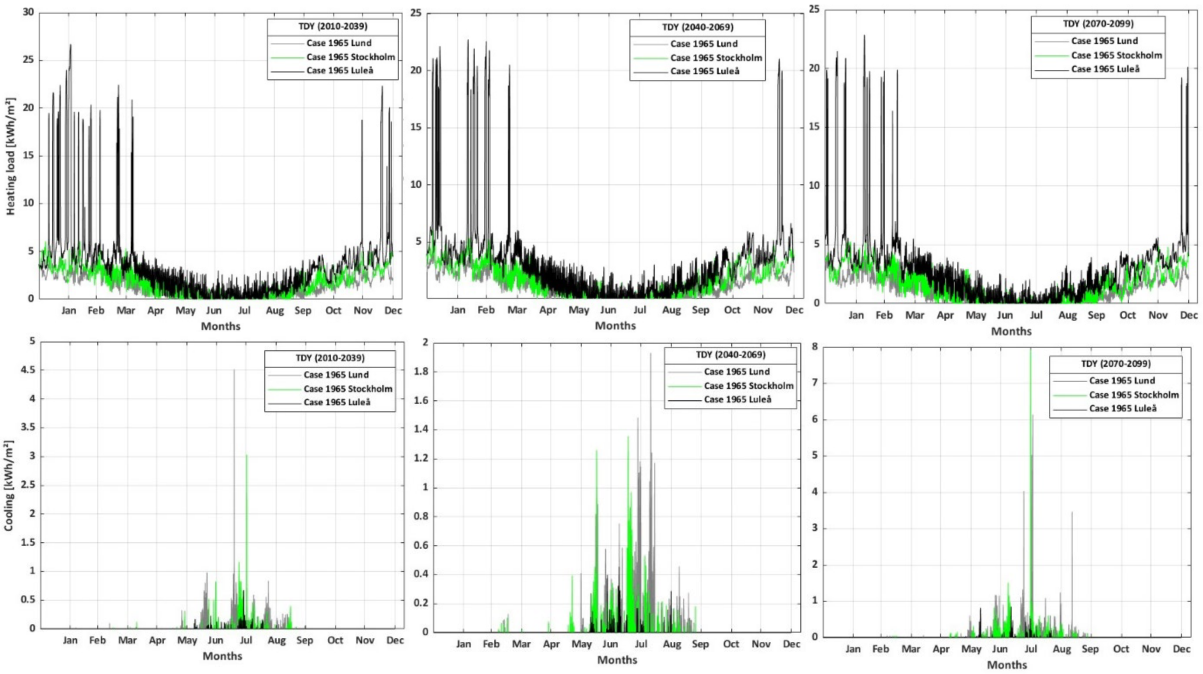

Figure 31. Heating load (upper) and Cooling load (down) of buildings from 1965s placed in Lund, Stockholm and Luleå simulated using TDY.

4.2.3 Modern constructions (after 2000)

In this division of the paper energy results of the modern construction in the reference locations will be presented.

4.2.3.1 Past Climate (2007-2020)

The energy performance of a detached house built using modern techniques between years 2007 and 2020 is shown in Figure 32. The highest heating demand occurred in January with approximately 3094,50 kWh/m^2 in Luleå. The heating load was around 2511,90 kWh/m^2 in Stockholm and 2595.9 kWh/m^2 in Lund.

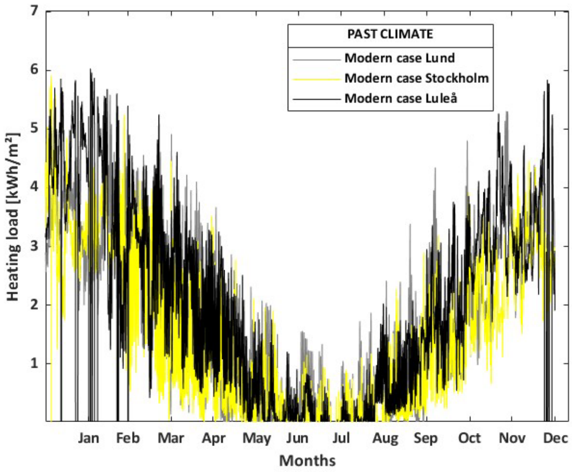

Figure 32. Heating load of buildings placed in Lund, Stockholm and Luleå simulated with past climate.

4.2.3.2 Extreme cold year (ECY)

The heating loads for detached houses during the period ECY 2010-2099 are illustrated in Figure 33 and the peak monthly heating demand are presented in Table 8. There is a clear difference between the current scenario and past climate scenario; the heating load during ECY 2010-2099 period is higher compared to the past climate scenario.

Table 8. Highest monthly heating load of detached houses after 2000s, placed in Lund, Stockholm and Luleå; simulated using weather data ECY.

		HEATING	
	Period	Month	Load [kW/m^2]
LUND	2010-2039	January	2785,40
	2040-2069	January	2882,1
	2070-2099	January	2536,40
STOCKHOLM	2010-2039	January	2907,10
	2040-2069	January	3113,50
	2070-2099	January	3205,50
LULEÅ	2010-2039	January	12330,00
	2040-2069	January	10752,00
	2070-2099	February	10347,00

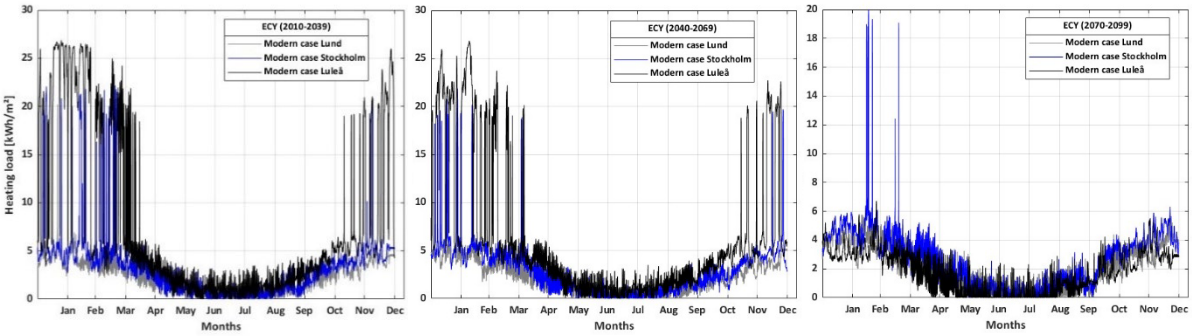

Figure 33. Heating load of Modern buildings in Lund, Stockholm and Luleå simulated using ECY.

4.2.3.3 Extreme warm year (EWY)

In this section the heating and cooling load of the detached house model in the reference locations using the EWY weather data, will be presented. As the graphs in Figure 34 displays, the average heating load in Lund, Stockholm and Luleå is much lower in comparison to the ECY results.
For the same scenario, there is a cooling need for all locations which shows even in Figure 34.
The peak cooling demand for the last time period in this scenario does not exceed the cooling peak load of the first simulation period (2010-2039), but the number of days that there is a need for cooling have increased compared to the start of this time period. Also, in the first time period there is no cooling load for Luleå, while in the next time periods there is a significant cooling requirement even in Luleå.
The cooling load graph shows that the cooling load increases by the time, because both number of days which needs cooling load and even the amount of the cooling need at the same time has increased. Table 9 presents all monthly peak heating and cooling demand during EWY.

Table 9. Highest monthly heating- and cooling load of detached houses after 2000s, placed in Lund, Stockholm and Luleå; simulated using weather data EWY.

		HEATING		**COOLING**	
	Period	Month	Load [kW/m^2]	Month	Load [kW/m^2]
LUND	2010-2039	January	1221,90	July	1477,00
	2040-2069	January	1201,00	July	1467,50
	2070-2099	January	882,98	August	2188,4
STOCKHOLM	2010-2039	January	1699,20	July	711,43
	2040-2069	January	1509,90	July	1787,20
	2070-2099	January	1293,30	July	1603,70
LULEÅ	2010-2039	January	2137,80	July	171,34
	2040-2069	January	2272,60	July	179,23
	2070-2099	January	1806,00	July	225,07

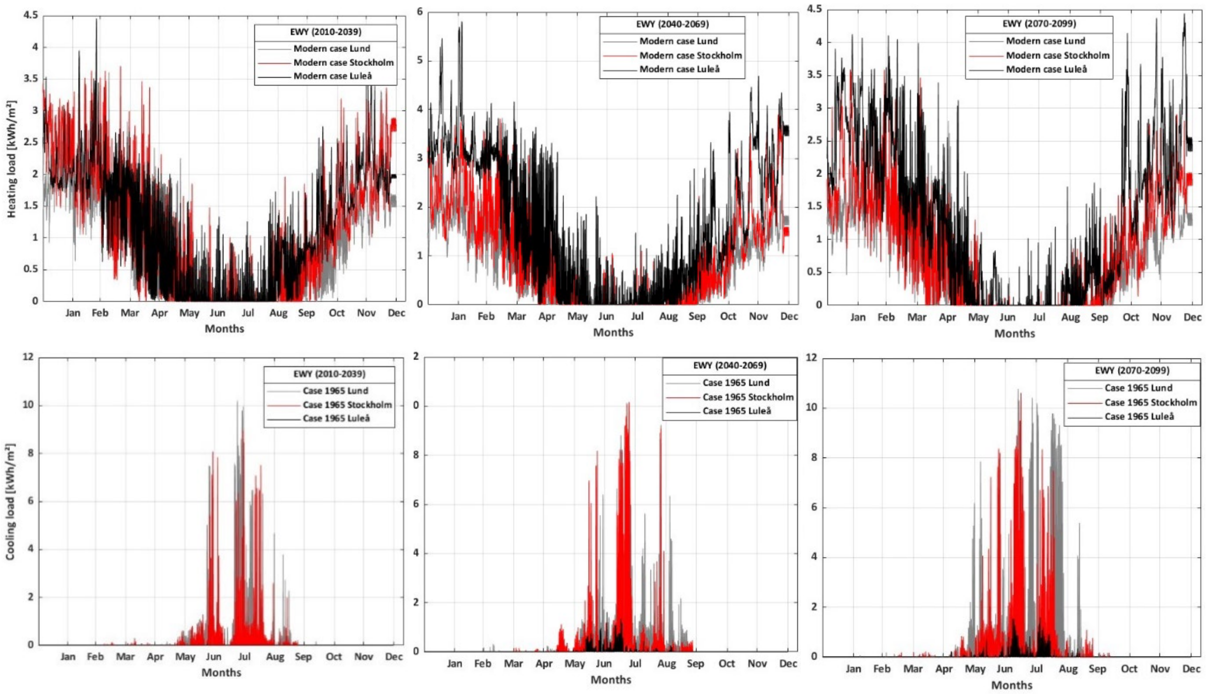

Figure 34. Heating load (upper) and Cooling load (down) of buildings after 2000s placed in Lund, Stockholm and Luleå simulated using EWY.

4.2.3.4 Typical Downscaled Year (TDY)

This section presents the results of the modern construction in Lund, Stockholm and Luleå, using the TDY weather data. The heating- and cooling loads for this scenario are illustrated in figure 35. The graph displays that the heating load in this scenario lies between the result from ECY and EWY, which make sense. As shown in figure 35, the cooling load is much lower than the cooling load which was needed during EWY period. The peak monthly loads are presented in Table 10. Highest monthly heating- and cooling load of detached houses after 2000s, placed in Lund, Stockholm and Luleå; simulated using weather data TDY.

Table 10. Highest monthly heating- and cooling load of detached houses after 2000s, placed in Lund, Stockholm and Luleå; simulated using weather data TDY.

		HEATING		**COOLING**	
	Period	Month	Load [kW/m^2]	Month	Load [kW/m^2]
LUND	2010-2039	January	1876,80	July	145,48
	2040-2069	January	1754,60	July	169,03
	2070-2099	January	1593,40	August	232,2106
STOCKHOLM	2010-2039	January	2417,10	July	111,64
	2040-2069	January	2368,30	July	168,34
	2070-2099	January	2222,70	July	238,90
LULEÅ	2010-2039	January	5125,60	July	48,52
	2040-2069	January	4368,00	July	50,57
	2070-2099	January	3961,00	July	64,51

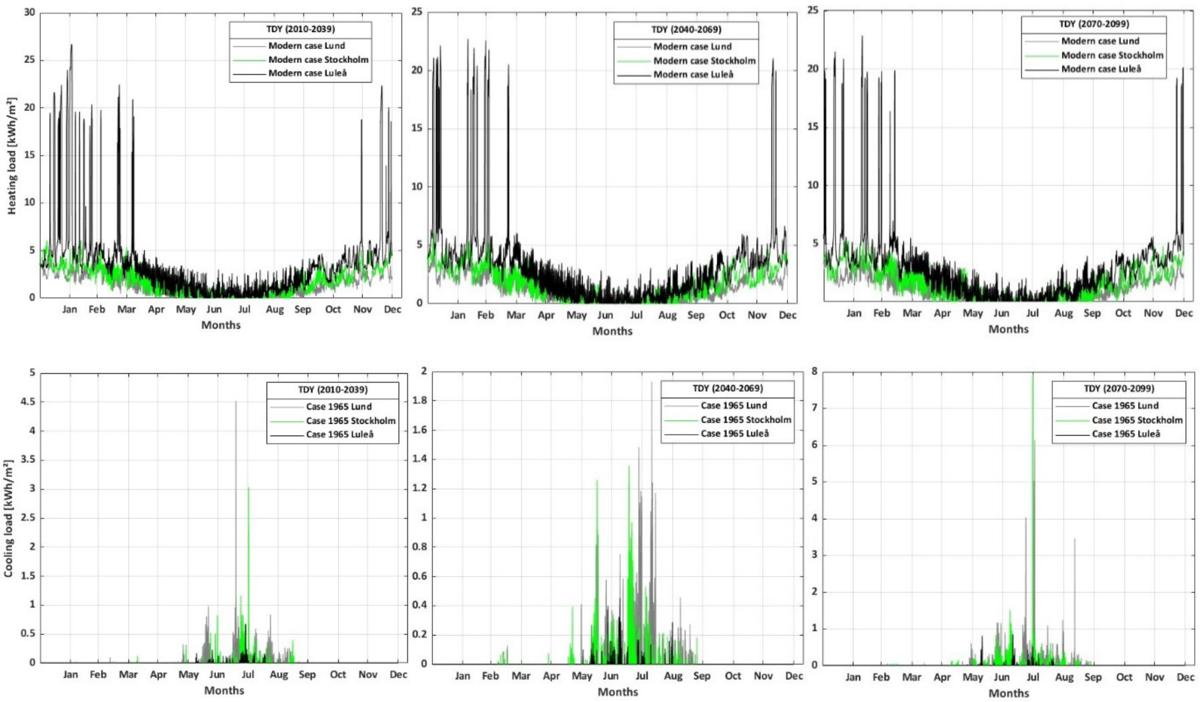

Figure 35. Heating load (upper) and Cooling load (down) of buildings after 2000s placed in Lund, Stockholm and Luleå simulated using TDY.

4.2.4 Overall discussion

The analysis of all scenario's results for energy performance of detached houses in Sweden, showed a consistent behaviour of energy usage across different building types and weather conditions. The building model located in Luleå had the highest heating demand and lowest cooling need during summer compared to Stockholm and Lund. Between Stockholm and Lund, Stockholm generally had a higher heating demand, but there were times when the heating peak load and energy demand of detached house in Stockholm were lower than Lund's heating demand. The same pattern is observed between Lund and Stockholm when it comes to cooling demand, although the cooling demand in Lund was mostly higher than Stockholm but there were some occurrences of higher cooling demand in Stockholm.

An overall observation of energy load in distinct weather scenarios (past, ECY, EWY, TDY) indicates that the energy demand in TDY scenario lies between ECY and EWY. But we can say that the energy demand for TDY in most cases was closer to the ECY than EWY.

Upon closer examination the energy demand pattern in each weather scenario, it becomes clear that the heating demand decreases, and cooling demand increases by time in the future.

To assess the realism and reliability of future weather data, the results of past climate with the results of future weather data were compared. The past climate data is what was happened, so it can be a reference to compare the future data with. But, since the extreme scenarios (EWY and ECY) will never happen, the comparison can be only between past climate and the TDY weather data. The results from TDY weather data compared to past climate, indicates that what happened in reality (past) were lower energy need for the detached houses than the results obtained from TDY weather data.

Comparing the detached houses by the period of constructing, the houses build after 2000s had the best energy performance when it comes to heating load as graphs in figures 18-20 displayed. Modern construction showed a lower heating load than the other types of detached houses (1940s and 1965s

construction). While when it comes to the cooling demand, the best performance belongs to construction from 1940s due to its minimal insulation material. So, the highest cooling demand belongs to the modern constructions, and it obviously depend on the high amount of insulation material in these types of constructions.
In Figure 36, Figure 37 and Figure 38 there is a comparison between different time periods and distinct construction type in Lund, Stockholm and Luleå. These figures indicated how the heating demand decreases by time in all of construction types.

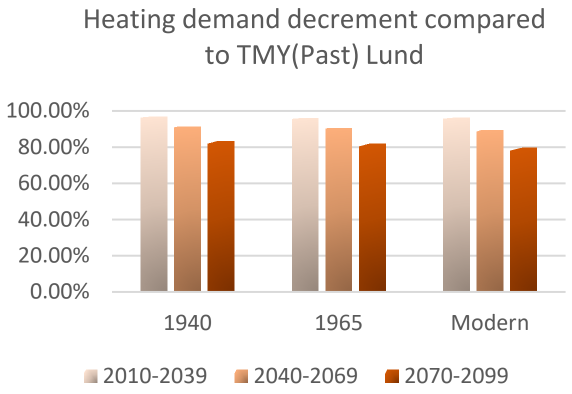

Figure 36. Heating demand decrement compared to TMY (Past) for the building placed in Lund.

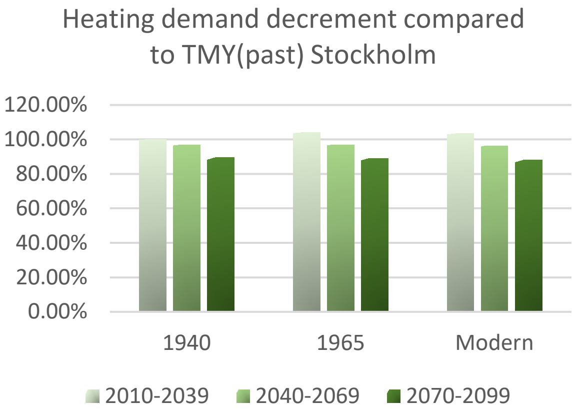

Figure 37. Heating demand decrement compared to TMY (Past) for the building placed in Stockholm.

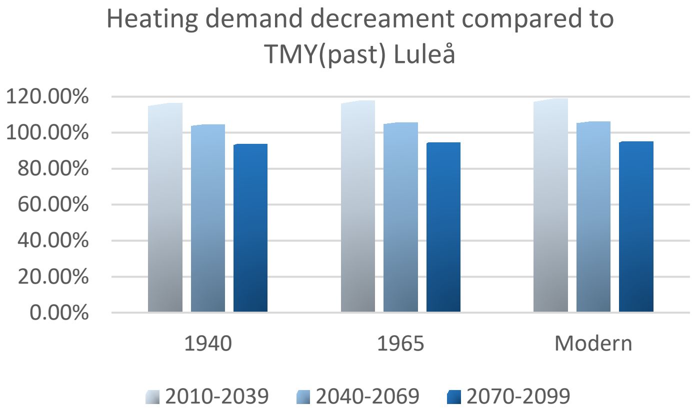

Figure 38. Heating demand decrement compared to TMY (Past) for the building placed in Luleå.

The increment of cooling load in future in Lund is illustrated in Figure 39 . The increment of cooling load was largest in buildings placed Lund, and there was a cooling demand increment in all three-time period. As the cooling demand increment were negligible in Stockholm and Luleå compared to Lund s there is an illustration of this increment in Lund. It means that the implementing of cooling system in buildings, especially in southern Sweden is necessary.

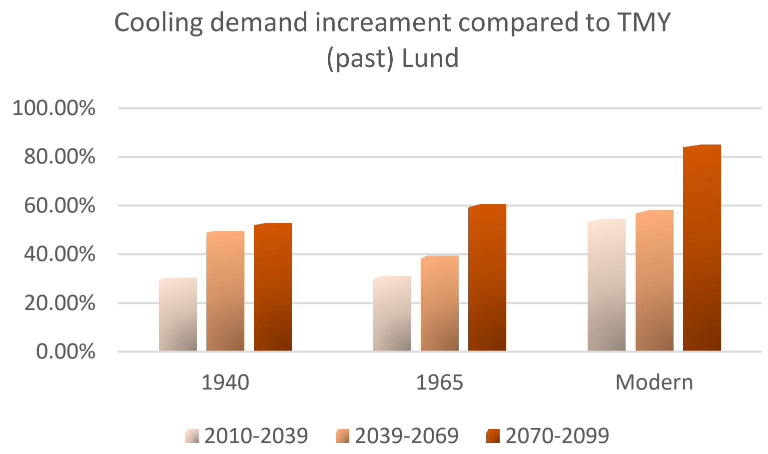

Figure 39 39. Cooling demand increment compared to TMY (past) for the building placed in Lund.

5 Conclusion

This paper aimed to provide an overview of detached houses' hygrothermal and energy performance under extreme and typical weather conditions, to be able to investigate possible solutions for more robust construction design that can have an enhanced hygrothermal and energy performance in the fact of future climate impacts.
To be able to reach the objective of the study, hygrothermal and energy performance of distinct constructions placed in reference cities were analysed with methods which was described in Section 3.2.

The obtained results from this study showed that the modern building constructions are more suitable and sustainable in an energy performance perspective. But as the climate changes challenges buildings, the high amount of insulation causes overheating in this type of constructions. The increase in insulation material does not necessarily result in a decrease in energy consumption.
After a certain amount of increasing insulation material, the extra material has not any effect on decrement of energy demand, the inverse effect of it might lead to increment of cooling load during summer.

The findings of this study indicated, was the decrement of heating load and increment of cooling load across all scenarios. The building industry in Sweden especially in Southern part, should be alert to the need for accommodating building designs that can withstand future climate changes. This may require incorporating adapted cooling systems into building designs to ensure that they remain habitable and comfortable in the face of rising temperatures.
Although the extreme weather conditions will never occur, still investigating these scenarios can provide building designers with a reference point for situations where climate change may cause similar conditions. This can help assuredness of that buildings are designed to withstand future climate impacts, even if they do not reach the level of extreme scenarios.
This study is an example of the energy and hygrothermal analyses, which might be an essential part in the building project planning, that can help the constructors to have an overview if the building is able to withstand the future climate change and provide thermal comfort for the inhabitants.

6 Further studies

The unfeasibility of the extreme weather data (EWY and ECY) and some simplification and assumption that was used in this method, underlies the applicability and feasibility of this study.

The approach can be used at the very beginning of process in the building projects, to take the future climate issues into the consideration while designing and renovating of buildings.

This study has only examined the method on the reference detached houses by using distinct weather and distinct locations in Sweden. Applying this method to other locations and other building types can therefore give a deeper and even new knowledge about the future building designing and their robust performance.

In this study the future hygrothermal performance of the reference buildings were not included, and it can be an interesting option to analyse for further study in this field. Another fascinating option for further studies in this field can be the construction materials obsolescence by exhaustion and time. Since the obsolescence of material was not taken into consideration at all in this study.

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LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services
Department of Building and Environmental Technology