DEGREE PROJECT IN BUILDING TECHNOLOGY,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2021

The Effect of Global Warming on the Indoor Environment

A Simulation Study on Single-Family Houses in the Stockholm Region

JULIA ANDERSSON

FREDRIK LARSSON

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ARCHITECTURE AND THE BUILT ENVIRONMENT

Effekten av global uppvärmning på inomhusklimatet

En simuleringsstudie på småhus i Stockholmsregionen

JULIA ANDERSSON

FREDRIK LARSSON

DEGREE PROJECT IN BUILDING TECHNOLOGY FOR THE MASTER'S PROGRAMME IN CIVIL AND ARCHITECTURAL ENGINEERING

Title in Swedish: Effekten av global uppvärmning på inomhusklimatet
Title in English: The Effect of Global Warming on the Indoor Environment
Supervisor: Kjartan Gudmundsson, KTH.
Examiner: Folke Björk, KTH.

Sammanfattning

Denna uppsats huvudsakliga mål har varit att simulera och utvärdera förändringen mellan inomhusklimatet idag och år 2070 på grund av klimatförändringarna. Den skapade modellen var uppbyggd av delar valda utifrån lösningar och material som vanligtvis används vid byggandet av småhus i Stockholmsregionen 2020. Detta har gjorts genom att utvärdera statistik, litteratur, vanliga metoder och byggregler. För att simulera ett representativt hus byggdes en modell i mjukvaran IDA ICE. Modellen testades mot ett nuvarande och framtida utomhusklimat och därefter utvärderades den resulterande inomhusmiljön Det framtida utomhusklimatet har konstruerats genom prognoser baserade på scenarier som bestäms av FN:s klimatpanel (IPCC). Hypotesen var att småhus som byggds runt 2020 inte kommer att vara beboeliga år 2070 på grund av de ökade inomhustemperaturerna på sommaren, och att förändringar kan göras för att bekämpa denna potentiella uppvärmning av inomhustemperatur.

Resultaten av simuleringarna visar att inomhusmiljön var starkt beroende av utomhusklimatet, byggtekniken och designen. Vilket betyder att förändringar i byggnaden avseende design, stomme, material och installationsteknik kommer att resultera i en förändring av inomhusmiljön. Fortsatt steg inomhustemperaturerna i modellen över acceptabla nivåer, oavsett framtida scenario. Flera ändringar och tillägg till modellen har därför testats, för att undersöka om det kan leda till en sänkning av den maximala temperaturen under riktvärdet, på ett hållbart sätt.

Ingen av de individuella förändringarna minskade temperaturerna under de acceptabla nivåerna för alla scenarier samt ansågs vara ett hållbart alternativ. Några mer hållbara ändringar minskade inomhustemperaturerna under riktvärdet för de svalare scenarierna. Medan vissa mindre hållbara modifieringar minskade temperaturerna under kravet för alla scenarier. En kombination av de mer hållbara modifieringar testades också, vilket sänkte temperaturerna under tröskelvärdet för alla scenarier, utom de två mest extrema.

Det förändrade utomhusklimatet har stor inverkan på den simulerade inomhusmiljön. Detta kan ses som en stark indikation på att den verkliga inomhusmiljön och termiska komforten för småhus också kommer att påverkas i framtiden. Det är svårt att förutsäga huruvida småhus år 2070 kommer att betraktas som obeboeliga då det påverkas av många variabler. Den simulerade inomhusmiljön kan dock förbättras genom att ändra eller lägga till delar i modellen.

Abstract

In this thesis, the main objective has been to simulate and evaluate the change between the indoor climate today and 2070, due to climate change. The model created was built by parts chosen based on solutions and material commonly used when building single-family houses in the Stockholm region in 2020. This has been done by evaluating statistics, literature, common practices, and building requirements. To simulate a representative house, a model was built in the software IDA ICE where present and future climates were inserted and the resulting indoor environment evaluated. The future outdoor climate has been constructed through predictions based on scenarios determined by the Intergovernmental Panel on Climate Change (IPCC). The hypothesis was that single-family houses built in 2020 will not be habitable in 2070 due to the increased indoor temperatures in summer, and that changes can be done to combat this potential warming.

The result of the simulations shows that the indoor environment was strongly dependent on the outdoor climate, building design, and technique. Meaning that changes to the building, regarding design, structure, material, and building services will result in a change in the indoor environment. Furthermore, the indoor temperatures of the model increased above acceptable levels regardless of future scenario. Several changes and additions to the model have, therefore, been tested to examine whether they reduce the maximum temperatures below the threshold sustainably.

None of the individual changes reduced the temperatures below the acceptable levels for every single scenario and was considered a sustainable option at the same time. Some more sustainable modifications reduced the indoor temperatures below the threshold for the cooler scenarios, and some less sustainable modifications reduced the indoor temperatures below the threshold for all scenarios. A combination of more sustainable modifications was also tested, yielding a reduction in temperature beneath the threshold for all scenarios except for the two most extreme.

The changed outdoor climate has a large effect on the simulated indoor environment. This could be considered as a strong indication that the actual indoor environment and thermal comfort of single-family houses will be affected as well. It is difficult to predict whether single-family houses in 2070 will be considered unhabitable since it is determined by a wide range of variables. The simulated indoor environment can, however, be improved by changing or adding parts to the model.

Acknowledgments

First, we would like to express our great appreciation to our supervisor, Associate Professor Kjartan Gudmundsson at the Division of Sustainable Buildings, KTH, who has helped us with everything from administration and layout, to answering questions and proofreading throughout our weekly meetings. The advice and knowledge given to us has been very helpful and we are truly thankful for his time spent on this project.

Second, we would like to thank everyone who has provided us with valuable information and answered questions regarding content or software. This has enabled us to work efficiently, with facts and content from the industry, which has increased the validity of our results.

Third, we would like to thank our friends and families who have supported us throughout this period by helping us with everything from motivation to grammar. This support has been highly valuable for us to reach our final result.

Table of contents

Chapter 1

Introduction

This thesis has examined how the indoor environment may be influenced by the possible changes in outdoor climate, due to changes in climate over a 50 year period.

It is a well-known fact that the climate is changing. According to the Intergovernmental Panel on Climate Change (IPCC 2014), the global average temperatures have risen a great deal in the last century and will most likely continue rising in the foreseeable future, mostly due to the emission of greenhouse gasses. According to the Swedish Meteorological and Hydrological Institute (SMHI, 2020a), the mean temperature in Sweden has risen more than the global average in the last 30 years and since 1988. All years except two have been hotter than the 1961-1990 average, with the last summers on average being the hottest since 1860.

The average temperatures in Sweden will most likely keep on increasing even more than the global average in the future due to the rapid warming of the Arctic. This will be evident in summers with average temperatures in the Stockholm region rising from 15,4°C on average between 1961-1990 to an average of 18,4°C to 20°C at the end of the century (Asp et al. 2015). Furthermore, the number of days in a row with average temperatures exceeding 20°C will increase from 3 days in a row in 1961-1990 to between 10 to 25 days in a row at the end of the century.

Houses built in Sweden today are designed to have a structural design working life of at least 50 to 100 years (SS-EN 1990:2002), but are built in and for today's climate according to the Swedish National Board of Housing, Building and Planning (Boverket 2018). This means that houses built today are not designed for future climate changes even though they most likely will be exposed to them.

The main reason for constructing a building and creating a home is to ensure good thermal comfort and for architectural qualities to be pleasant for the users. To protect the occupants from the outdoor climate and enable thermal sensation without health complications could furthermore be the result of a well-constructed house. This means that the thermal comfort indoors is partly based on the outdoor climate conditions and the construction between indoor and outdoor spaces.

In our hectic and, in many cases, stressful life, many people today seek to improve the efficiency in every moment. The productivity of the residents can be improved by designing the homes in the best way possible when it comes to thermal comfort (Clements-Croome 2014). Due to the COVID-19 pandemic, it is possible to assume that more people will continue to work from home in the future, meaning that homes will be used more as a workplace (Markelius 2021). Consequently, the productivity of the occupants should be just as good in their homes that are designed for living and life outside of work as at their previous workplace. Even though researchers disagree on how thermal comfort is obtained, how it is defined, and how to measure it, the science within the area shows that it is an important aspect to consider during the design phase and throughout the building's lifetime. This research has been presented in section 1.1.

As previously mentioned, more time will probably be spent at home. When people spend more time at the same place, it is possible to feel that the space available is not enough and the will to have a bigger home can increase. The possibility to do more things from home will also make people want a bigger home with more potential for activities. This can be seen in Hemnet's (2020) report of the search history in 2020. The increased usage of search words as "pool" and "terrace" shows that homes with gardens or outdoor areas nearby have increased the demand for single-family houses. Homes have become the centerpiece of families' lives during 2020, because of restrictions in the community as a result of the spread of COVID-19 (Byggvärlden 2020). The demands set on the standard of buildings are, therefore, higher and more precise than ever. Hemnet (2021a) also reports an increased interest in new production during the last year, meaning that people are more willing to buy recently built houses than before. It is also noticed by experts and analysts within the area, that single-family houses are the objects with the highest increased selling prices on the market at the moment (Mäklarhuset 2020; Länsförsäkringar Fastighetsförmedling, 2021). These sources collectively show a large current interest in single-family houses that are built today, which is why it will be the main object for discussion and evaluation in this thesis.

Since the future is unknown, this thesis will not end up with just one answer to the question "What will happen in the future and how can we solve it?". One can only speculate and investigate predictions of the future climate, this work has, therefore, focused on a wide range of scenarios to cover more of the possible outcomes of the future and to be able to look at different solutions and improvements of the buildings built today.

Because the building sector is responsible for 40% of the total energy consumption and 36% of the greenhouse gas emissions in Europe, only sustainable solutions should be implemented to make sure not to harm climate development in the future (European Commission 2021). Even though the indoor climate is affected by the outdoor climate and keeping a good enough indoor climate is the main objective of the building, the environmental footprint and the future outdoor climate ought to be considered. Implementing solutions that improve the indoor climate without considering its environmental aspects might have a worsening effect on the indoor climate in the future due to the increased climate impact. To clarify, the main reason to implement a solution would be to improve or keep a good thermal climate that is economically possible, without a large negative impact on the environment. By considering the social, economic, and environmental aspects of the implementation of a suggested solution, it can be identified as a sustainable solution.

1.1 Background

Earlier research has been conducted within the area of knowledge and will be presented in this section. Both similar investigations here in Sweden, but also results from studies of indoor environments around the world.

Ambrose Dodoo and Leif Gustavsson (2016) conducted a study that included three different types of multi-family houses in Växjö, Sweden. The study investigated whether the buildings' thermal performance would change in future climate scenarios, relative to the long-term historical and recent climate. The three buildings differed in some aspects and the variations in thermal performance were presented and discussed. The risk of overheating was investigated and various solutions, such as solar shading, ventilation, and electricity supply options, were considered. All three houses had dissimilar structures: prefab concrete-frame, massive timber frame, and a light timber frame. The result presented in the report showed a significant difference when the same building in today's and historical climate was compared with the predicted future climate. Additionally, the authors concluded that heating demands would decrease while cooling demand would increase with time, for all buildings investigated. It was pointed out by the authors that the focus in the process of design and construction sector in Sweden today is to lower the heating demand as this dominates the energy demand. This study clarifies that strategies that lower the risk of overheating, but at the same time do not drastically increase the cooling demand, should be implemented in the design phase. It is a crucial point in the process of optimizing the building and restricting the impact on the environment and climate change. The results presented in this study were quite clear and as the report states, studies regarding the current building stock in Sweden are not that many or comprehensive.

An investigation of sleep quality has been made by Lan et al. (2014) to conclude whether room temperature affects sleeping. The investigation was made by taking subjective answers from the participants before and after sleeping and to assess physiological measurements of the subjects during their sleep. The study included three different temperatures; 23, 26, and 30°C, and showed that room temperature had an impact on the quality and experience of the participants' sleep. In addition, the study showed that the surroundings were experienced slightly warmer when participants walked around compared to when sleeping at the same room temperature. For example, 23°C was experienced uncomfortably cold when sleeping, but moderate when walking around.

In 2012, the World Health Organization (WHO 2012) published an assessment report from a project which included conclusions, discussion, and a result of investigations of statistical data in combination with academic research around environmental health inequalities It is clearly stated in the report that the living conditions in homes affect both the physical and mental health. Since people spend quite a lot of time at home, it is an important parameter to investigate. A variety of adverse respiratory diseases, such as asthma, pulmonary infections, and allergies were put forward as potential consequences when exposed to a bad indoor climate. Based on earlier researchers' results within the area, improvements in thermal comfort improves health – both mentally and physically.

One of several important factors in the indoor environment is the indoor temperature. Problems can occur when it is too hot or too cold. These two factors, or problems, were discussed in the report mentioned in the last paragraph. The inability to keep the building warm enough is a factor that could have serious health consequences. It has been shown that premature deaths as consequences of extreme winter temperatures occur in several European countries every year. Furthermore, non-fatal cardiovascular and respiratory diseases have been linked to colder temperatures in buildings (ibid.).

In contrast to a cold home, the indoor environment could potentially be experienced as too warm. Globally, the inability to keep the indoor environment cold enough is a larger problem than the ability to keep it warm during colder months. This shows that the rising summer temperature will become an even larger problem than previously experienced in Sweden (ibid.).

The additional investment cost is one argument against taking measures to prevent overheating or wrongly set temperature inside, could be the initial costs. In a report by David Ormandy and Véronique Ezratty (2012) it has been argued that the initial cost of, for example, extra insulation would be covered by the savings on hospital cost due to an unhealthy indoor climate. Sick people would accordingly cost society more than the cost of fixing the thermal performance of the buildings.

Petter Hellström (2018) conducted a study about one building at KTH Campus in Stockholm, and tested the thesis of the correlation between indoor climate and productivity. This study included a quantitative and qualitative investigation that mainly focused on the correlation between productivity and the subjected evaluations of the indoor climate. The outcome of this study was that the calculated thermal comfort was strongly connected to the subjective evaluation of productivity and the thermal quality of the indoor climate, which could indicate, stated by the author, that thermal parameters have a big influence when creating a productive workplace.

Better human performance can be supported and improved by better building performance which is something that Derek Clements-Croome (2015) reflected on in his article. Clements-Croome stated that the surroundings would, in some way, affect some humans more than others. He claimed that we should, when designing buildings and indoor environments, aim to satisfy the most sensitive people rather than the average preferences. The same author (2008) also wrote an article about how changes in the thermal environment, more specifically the temperature, would change human performance. The article presented results from several sources on how temperature and performance are connected. Some relevant and important results presented in the report are that laboratory studies reveal that a 10% increase in dissatisfaction decreases the performance by 1% and an increase in indoor-air temperatures above 22°C by 1°C can roughly decrease the performance of office work by 1%.

There are numerous studies and sources which have concluded that the quality of our surroundings will change and influence our behavior, mood, and motivation. This is strongly related to our motivation to work or achieve different tasks, also known as productivity. Both Cao and Wei (2005) and Cui et al. (2013) have carried out different studies and written reports showing this correlation.

Two studies published in Finland (Niemelä et. al 2002) and Japan (Tanabe et. al 2009), investigated productivity by measuring and evaluating the work in call centers. Both studies pointed out the difficulties of quantifying the effects of the indoor environmental quality on the performance of people because the performance and productivity were objectively unquantifiable. There were many ways to define productivity as a concept, which made it difficult to measure. By analyzing the call frequency and number of calls handled during a certain time, the productivity of the workers between different indoor environments with different thermal quality could be compared. In the results from the Japanese study, an increase in temperature by 1°C would result in a performance reduction of 1.9%. The Finnish study showed that the productivity decreased 5-7% when the air temperature indoors exceeded 25°C.

1.2 Objectives and hypothesis

This study aims to investigate whether buildings built today will still be habitable in the future and if they are not, investigate what can be done to make them habitable. The stipulative definition of future was created and set to 50 years since buildings built today are designed to have a working life of at least 50 years. The stipulative definition of habitable was defined as thermal comfort which in itself varies depending on air temperature, radiant temperature, air velocity, humidity, clothing insulation, and metabolic heat (SS-EN ISO 7730:2006). Thermal comfort for a body is obtained when the loss of heat to the environment is equal to the internal heat production. This thesis will however only focus on temperature changes.

The main hypothesis tested in this study was: Due to climate change, single-family houses built in the Stockholm region today will not be habitable in summertime 50 years from now, since the operative temperatures (mean radiant and ambient air temperature) will be too high and, therefore, thermal comfort too low. Sustainable changes to the building can however be done in order to increase the thermal comfort to habitable levels. To test the main hypothesis, auxiliary hypotheses have to establish according to the Duhem-Quine thesis (Grüne-Yanoff 2020).

The formed auxiliary hypotheses for this project were:

- The climate will change according to the predictions.
- The Swedish demands for indoor climate will be the same in 50 years as they are now.
- Houses built today will stand for at least 50 years.
- The model is a sufficiently valid representation of the target.

1.3 Limitations

Some limitations have been made to be able to test the hypothesis with sufficient precision and relevance. The limitations have been listed below:

- The thesis only examines changes in temperature between 2020 and 2070.
- The thesis only examines single-family houses in the Stockholm region.
- No in-depth economical evaluation has been done for the different solutions.
- Renovation needs have not been taken into consideration.
- Factors that could change the indoor environment other than the operative temperature have not been examined and have therefore been held constant.

1.4 Research Methodology

To be able to answer the previously mentioned hypothesis, a case study and model experiment containing simulation was used as the main method. This was performed with a software called IDA Indoor Climate and Energy (IDA ICE), where a digital model of a house in Stockholm was created. IDA ICE is a software where dynamic multi-zone energy simulations and calculations on thermal indoor climate can be performed and presented with sufficient precision over time. This simulation tool evaluates a building's performance partly based on the user's input of location and outdoor climate (EQUA 2020). The intervention was, therefore, to change the outdoor climate by changing the input of the climate file. Meaning that all the other factors could be held constant in all simulations.

One slightly different option to this method could have been to use another software than IDA ICE. There are other similar programs available on the market for simulation, calculations, and estimations of energy consumption and indoor climate. One such option could be to use Computational Fluid Dynamics (CFD) software. One specific example of such is Autodesk CFD for architectural and MEP applications (Autodesk n.d.a). The main use of this software is to predict the behaviour and performance of fluids (liquids and gases). Which thereafter can be used to estimate or optimize energy efficiency and indoor climate in all kinds of zones by examining the heat flow (Autodesk n.d.b).

When comparing IDA ICE with CFD-software, one should keep in mind that IDA ICE is developed to simulate buildings and present energy consumption and indoor climate for the whole building, concerning the outdoor climate (EQUA 2020). With this in mind, it can be argued that the needed input for this purpose is enough for a sufficient estimation of the indoor climate and energy demand. When gathering all wanted simulated results from the same software, background factors will be the same in all cases and the different results will therefore only depend on the intervention done by the observer. For this project, it is therefore useful to use IDA ICE, where all relevant results can be presented.

One weaker point of IDA ICE is the estimation of relative humidity (RH) indoors done by the software (Widström 2019). The RH is not correctly estimated and due to the fact that this is a factor included in the concept of thermal comfort and the quality of the indoor environment, this might lower the validity. This estimation and calculation can be performed in a CFD-software and will therefore likely be more accurate (Autodesk n.d.c). However, in SS-EN ISO 7730:2006 it is stated that the influence of relative humidity, at moderate temperatures, close to thermal comfort, is relatively small. Meaning that changes of the RH in an indoor environment will probably not have a large influence and the no-so-accurate estimation of the software IDA ICE will then be good enough to evaluate the indoor quality.

Another possible method to test the hypothesis could have been to do an observational study on a house in Stockholm and then compered the building technique with a house at a location with a climate that is similar to the predicted climate in Stockholm 50 years from now. The energy would, in this case, be quite hard to estimate. It is possible to calculate the performance, if the materials are known or can be assumed with sufficient precision, with the help of proven phenomena and knowledge in building physics. The indoor climate and thermal comfort would, in this case, be evaluated and a comparison between both cases would have been conducted and conclusions could have been drawn from that. Furthermore, to justify the second part of the hypothesis, a third house would have had to be found and observed. This house should have been located in the same climate as the second one, meaning different from the first one. In addition to that, the indoor climate had to be good enough according to the standard. Then a comparison could have been done comparing the differences in building technique and design to reach a conclusion of what changes can be done in that specific climate.

With this in mind, the chosen methodology is considered to be a suitable way of testing the hypothesis, making it possible to reject or increase the belief of the hypothesis being true.

1.5 Description of the Method

The following chapters have been arranged to follow the natural working process of developing climate models and a representative house for determining the future indoor climate. Responsible for Chapter 1, 3, and 4 is author Julia Andersson and responsible for Chapter 2, 5, and 6 is author Fredrik Larsson.

In Chapter 2, the present and future climate have been examined and decided through several steps by first determining how the climate in Stockholm will develop and how the current climate should be represented in an hourly climate file. In order to increase the probability that the decided future climate actually will occur, a variety of scenarios have been presented. The hourly climate file was needed for simulations in IDA ICE. Afterward, the hourly climate file was morphed according to the future predictions to represent the future hourly climate.

In Chapter 3, a representative single-family house has been decided upon and modelled. The model was optimized concerning its similarity and precision to the target. This was done by simulating the model, and subsequently the energy demand was compared to the energy usage of the model with building requirements, regulations, and data from similar buildings.

In Chapter 4, a framework for comparing the indoor environment between scenarios and to governmental requirements has been decided to easily navigate between the scenarios and modifications. The current indoor climate has, thereafter, been examined through this framework. The outcome of these different simulations was reviewed in detail and the change in indoor climate was carefully analysed.

In Chapter 5, various modifications to the model have been proposed and examined through the same framework as in Chapter 4. Energy demand and energy consumption were also considered, mainly to justify the model and compare the results with statistical data and to make sure that the proposed solutions do not have the side effects of drastically increased energy consumption. From the outputs of the simulation, conclusions were drawn according to the change of indoor climate, energy performance, and possible changes to the design were thereafter discussed. The possible changes were tested in the same original model in IDA ICE and evaluated to find whether they resulted in an improved indoor climate, meaning an improvement of the operative temperature.

Chapter 2

Changes in the Outdoor Climate

2.1 Introduction

As previously mentioned, the climate is changing, and temperatures are rising both globally and locally. These changes may have an impact on the indoor climate, especially in summers. This chapter starts broadly with a brief explanation on how the climate is predicted to be changing globally, and thereafter focuses on how this change is translated to a more local climate. Afterward, the method part explains how these local climate changes have been converted and fitted to an hourly climate file which was needed to calculate the indoor climate in IDA ICE.

2.1.1 Future climate scenarios

The IPCC (2014) has in its fifth Assessment Report (AR5) divided the possible future climate into four different scenarios called Representative Concentration Pathways (RCP). These pathways are mainly driven by economic activity, population size, energy use, lifestyle, technology, land use patterns, climate policy, and are used to assess future impacts and adaptations. One scenario (RCP 2.6) represents strict mitigation of greenhouse gases (GHG), two scenarios represent intermediate emissions of GHG (RCP 4.5 and RCP 6.0), and one with high GHG emissions (RCP 8.5). The numbers behind each RCP represent the net Radiative Forcing (RF) estimated to be absorbed by the earth around the start of the next century, in the unit Wm^{-2}. A diagram representing these pathways can be seen in Figure 1.

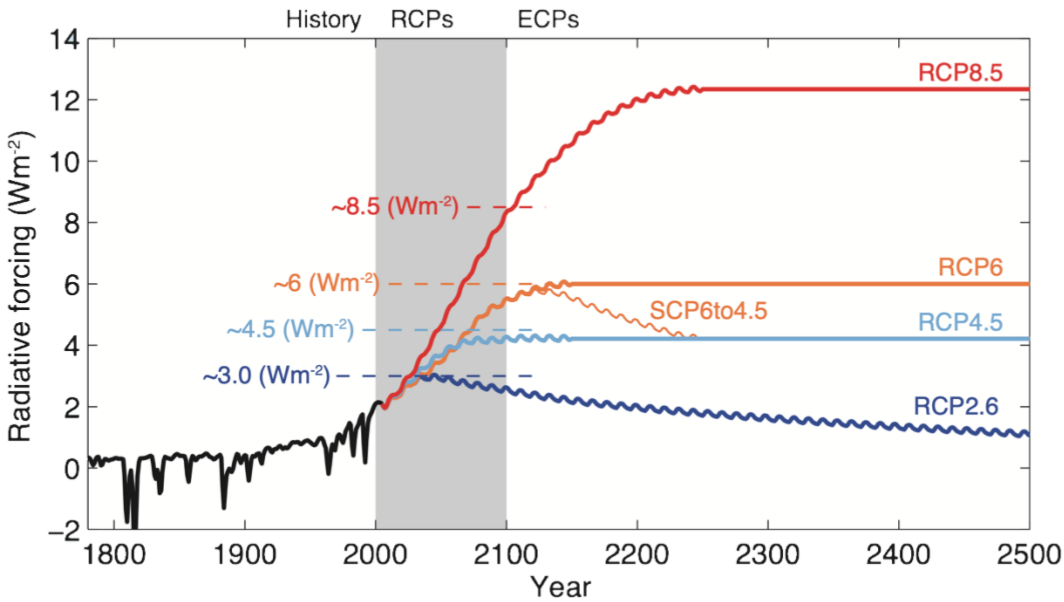

FIGURE 1: A REPRESENTATION OF THE FOUR RCP-SCENARIOS (IPCC 2013).

In the figure above, it can be seen what these four scenarios represent in terms of order and scale. These four scenarios have been constructed with intents and events in mind, which SMHI (2018) and Bjørnæs (2015) have gathered and summarized in a list that can be seen below.

RCP 2.6 – The CO_2 emissions peak around the year 2020

- The concentration of CO_2 culminates around the year 2050 and decreases thereafter to near 400 ppm year 2100.
- The emission of CO_2 is negative in 2100.
- The emission of methane decreases by 40%.
- The area of agricultural land increases due to bioenergy production.
- No vast change in pasture land area.
- The earth's population increases to 9 billion during the century.
- Decreased use of oil.
- Low energy intensity.
- A more powerful climate policy.

RCP 4.5 – The CO_2 emissions culminates around the year 2040

- The earth's population increases to slightly less than 9 billion.
- Lower areal needs for agricultural land due to larger harvests and changed consumption patterns among other instances.
- Widespread afforestation programs.
- Higher energy intensity than RCP 2.6.
- A powerful climate policy.

RCP 6.0 – The CO_2 emissions culminates around the year 2060

- The CO_2 emission reaches a level 75% above today's levels and later decreases to a level 25% below today.
- Stabilized emission of methane.
- The earth's population increases to just below 10 billion.
- The agricultural area increases but the pasture area decreases.
- Higher energy intensity than RCP 4.5.
- A large dependency on fossil fuels.

RCP 8.5 – Sustained high emission of CO_2

- No added climate policy.
- High energy intensity.
- A large dependency on fossil fuels.
- The technological development towards increased energy efficiency continues, but slowly.
- The earth's population increases to 12 billion leading to increased areas of agricultural and pasture land.
- The emission of methane increases rapidly.
- The CO_2 emissions have risen to three times the current amount around the year 2100.

The effect of the least and most extreme scenario can be seen in Figure 2 where the global average surface temperatures increase with each scenario.

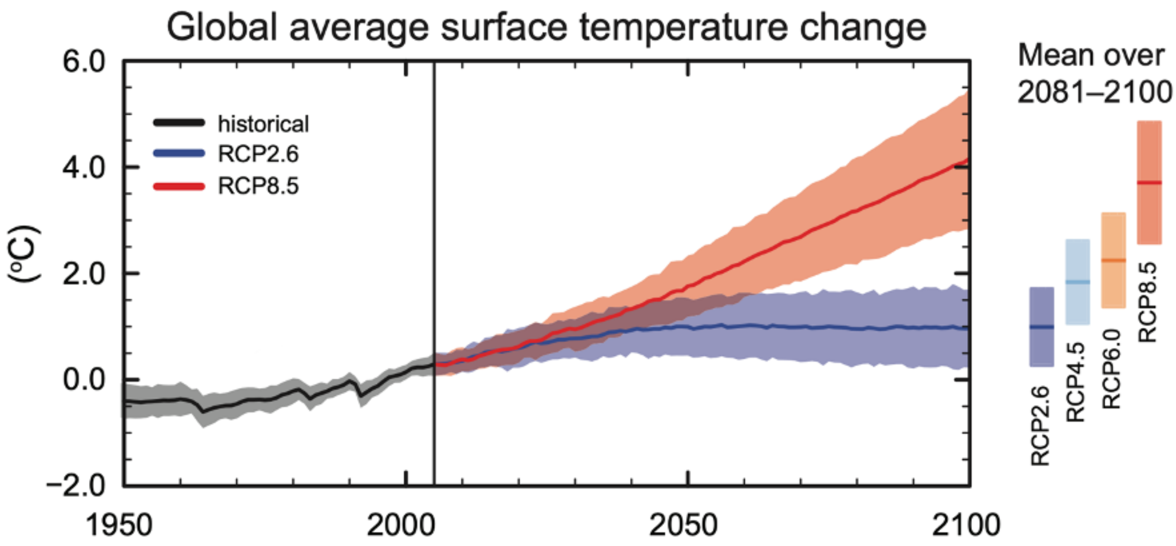

FIGURE 2: CHANGE IN GLOBAL ANNUAL MEAN SURFACE TEMPERATURE RELATIVE TO 1986–2005 (IPCC 2013).

As can be seen in the figure above, all scenarios constructed by the IPCC, result in a rise in global average surface temperature during this century.

2.1.2 Climate models for predicting the future climate

With the representative concentration pathways decided, global computational models can be created to further calculate and determine the global effect of the increased GHG emission. These models, also known as General Circulation Models (GCM), are according to SMHI (2020b) three-dimensional representations of the land, oceans, atmosphere, and their interactions. The representation is based on mathematical models describing the relationship between temperature, air pressure, humidity, and wind to name a few. A global climate model divides the atmosphere into grids of 100-300 km squares, and every known process inside and between the boxes is calculated iteratively for each RCP (Sjökvist et al. 2015).

2.1.3 Downscaling of prediction

The global climate models mentioned above are just that, global, meaning that the model is a representation of the global climate. This thesis, however, has aimed to determine the future indoor climate of a building located in the region of Stockholm. This delimitation required a downscaling of both the global model (dynamical downscaling) and the ability to fit the general result on a specific hourly climate file for further conclusions through the simulation software IDA ICE (statistical downscaling) (Moazami et. al 2019).

2.1.3.1 Dynamical downscaling
Because the resolution of global climate models can be between 100-300 km squares, information would be lost when determining the future climate of a specific place. That is where the need for higher resolution climate models becomes evident. These higher resolution models are called regional climate models (RCM) and are based on the global climate model but with one specific region simulated with higher precision (Sjökvist et al. 2015). The difference in resolution between a global climate model and a regional climate model can be seen in Figure 3.

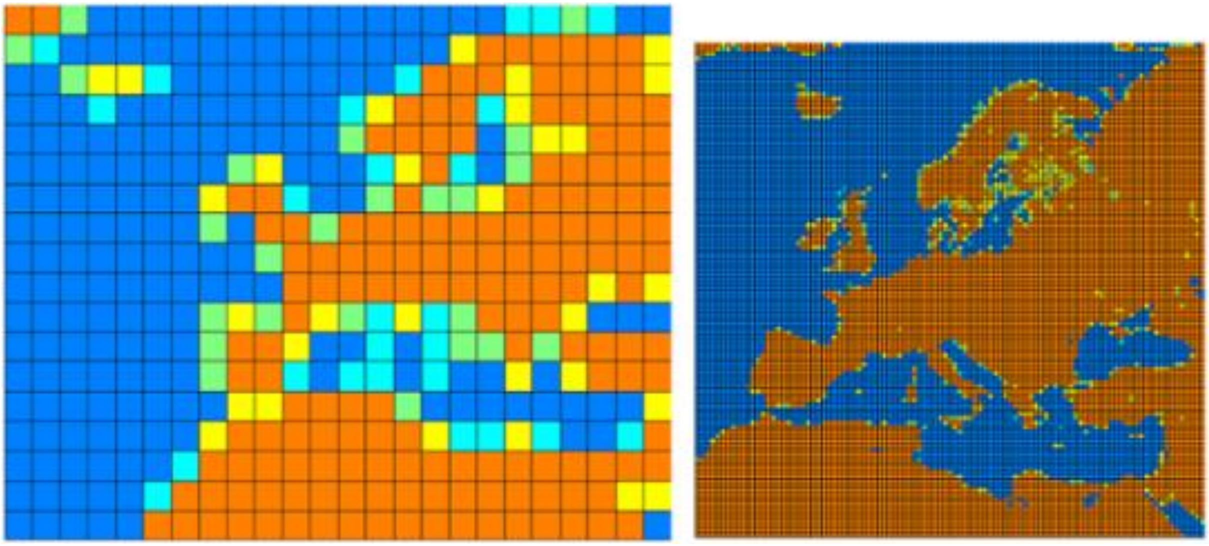

FIGURE 3: DIFFERENCE IN RESOLUTION BETWEEN A GLOBAL AND REGIONAL CLIMATE MODEL (SMHI 2020B).

2.1.3.2 Statistical downscaling
After a dynamical downscaling has been performed and depending on the time-frequency of the climate model, a statistical downscaling can be performed to further improve the accuracy of a future scenario. A statistical downscaling can be performed deterministically by morphing climate data, where monthly future trends are fitted to existing hourly climate models, with the motive that the morphed file represents both the future mean values and the future daily variance (Belcher, Hacker & Powell 2005). A statistical downscaling can also be done stochastically, where future climate models are based on a statistical analysis of existing climate data (Moazami et al. 2019).

2.2 Method

2.2.1 The global climate models and dynamic downscaling

The regional model chosen for this thesis was RCA4, developed by SMHI's research center – Rossby Centre. This model has been used to create accessible scenarios for Swedish regions based on data from an ensemble of nine different global climate models to create a more robust result. This resulted in nine different scenarios for each RCP with a grid size set for 50 km (Sjökvist et al. 2015). The RCP 6.0 has not been computed in this ensemble and will therefore not be further calculated or discussed. The global models used can be seen in Table 1 and it can also be seen that only three of the models were used for calculations of RCP 2.6.

TABLE 1: THE GLOBAL MODELS REPRESENTED IN THE ENSEMBLE (SMHI N.D.A).

Country	Institute	GCM	Source	RCP 2.6	RCP 4.5	RCP 8.5
Canada	CCCMA	CanESM2	(Chylek et. al 2011)			
France	CNRM-CERFACS	CNRM-CM5	(Voldoire et al. 2012)			
EU	EC-EARTH	EC-EARTH	(Hazeleger et al. 2010)			
France	IPSL	IPSL-CM5A-MR	(Dufresne et al. 2013)			
Japan	MIROC	MIROC5	(Watanabe et al. 2011)			
UK	Hadley Centre	HadGEM2-ES	(Collins et al. 2011)			
Germany	MPI-M	MPI-ESM-LR	(Popke, Stevens & Voigt 2013)			
Norway	NCC	NorESM1-M	(Bentsen et al. 2013)			
USA	NOAA GFDL	GFDL-ESM2M	(Dunne et al. 2012)			

The data from the ensemble can be collected at SMHI's (n.d.b) website where settings can be adjusted to obtain the parameters wanted. Some of the possible parameters that can be selected are:

- Area (world, Sweden, The Stockholm Region, etc.)
- Scenario (RCP 2.6 to 8.5)
- Season (winter, spring, summer, autumn)
- Climate index (temperature, highest daily average temperature, etc.)

An example of the result obtained from the ensemble is displayed in Figure 4 below. The only extractable outputs from this ensemble were differences in temperature and differences in length of certain periods (growth season for instance), meaning that the only variable that could be manipulated with some precision was dry-bulb temperature. Two other variables that can influence the indoor and outdoor climate are wind speeds and relative humidity. According to SMHI (2019a), future changes in wind speeds are hard to predict, and conclusions of whether they will change at all are, therefore, hard to draw. Likewise, according to SMHI (2019b), the future change in relative humidity is hard to predict since the absolute humidity and dry-bulb temperature are predicted to rise and could, therefore, cancel each other out.

2.2.2 Gathering of information from the models

According to SMHI (2015), small variations in input variables could result in substantial differences for one model. It is therefore suggested to gather the same data from all nine models to decrease variability and increase robustness as previously mentioned. The mean value of the ensemble should, thereafter, be used to further increase validity and reduce deviations. The result of this can be seen in Figure 4, where the mean value and differences are displayed through time.

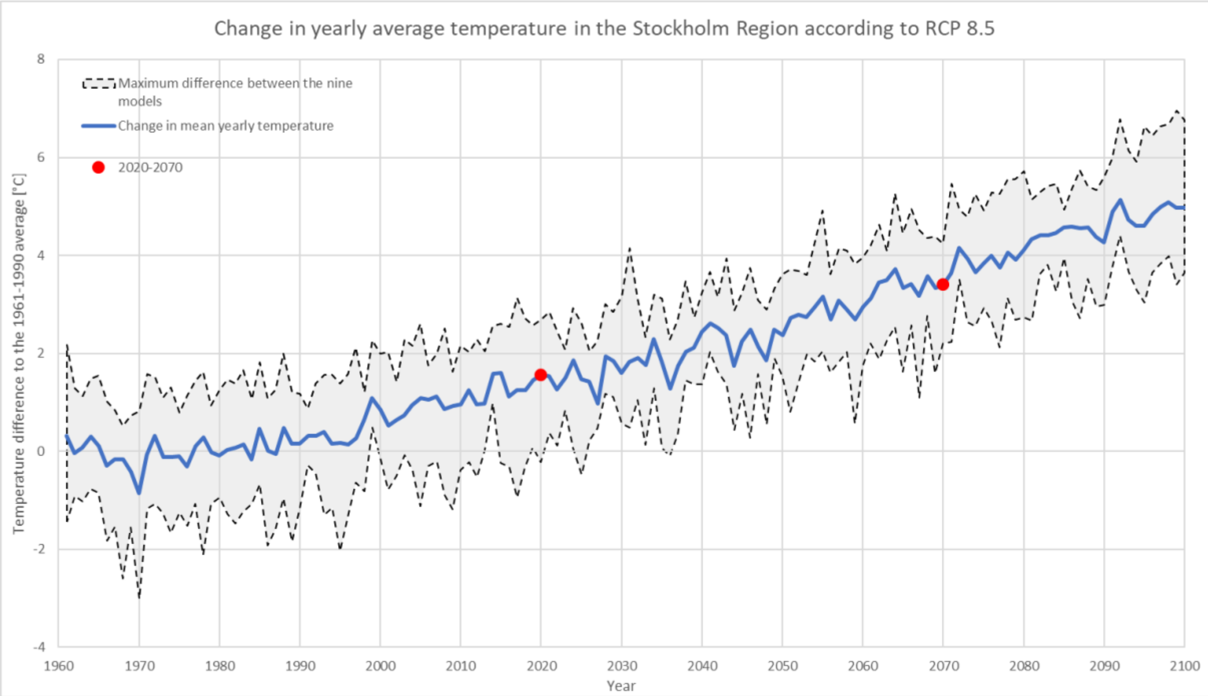

FIGURE 4: CALCULATED CHANGE IN YEARLY AVERAGE TEMPERATURE (°C) IN THE STOCKHOLM REGION FOR THE YEARS 1961-2100 COMPARED TO THE 1961-1990 AVERAGE.

The mean value shows some variations between the years, these variations should not be seen as variations in climate, but instead, as variations in the ensemble (ibid.). The mean values should, therefore, not be used to draw any short-term conclusions, but instead, for long-term trends. The diagram could thus be simplified to reduce the risk of misunderstanding what the data supports. This has been done by averaging the yearly results over a longer period which can be seen in Figure 5, where a moving thirty-year average has been applied.

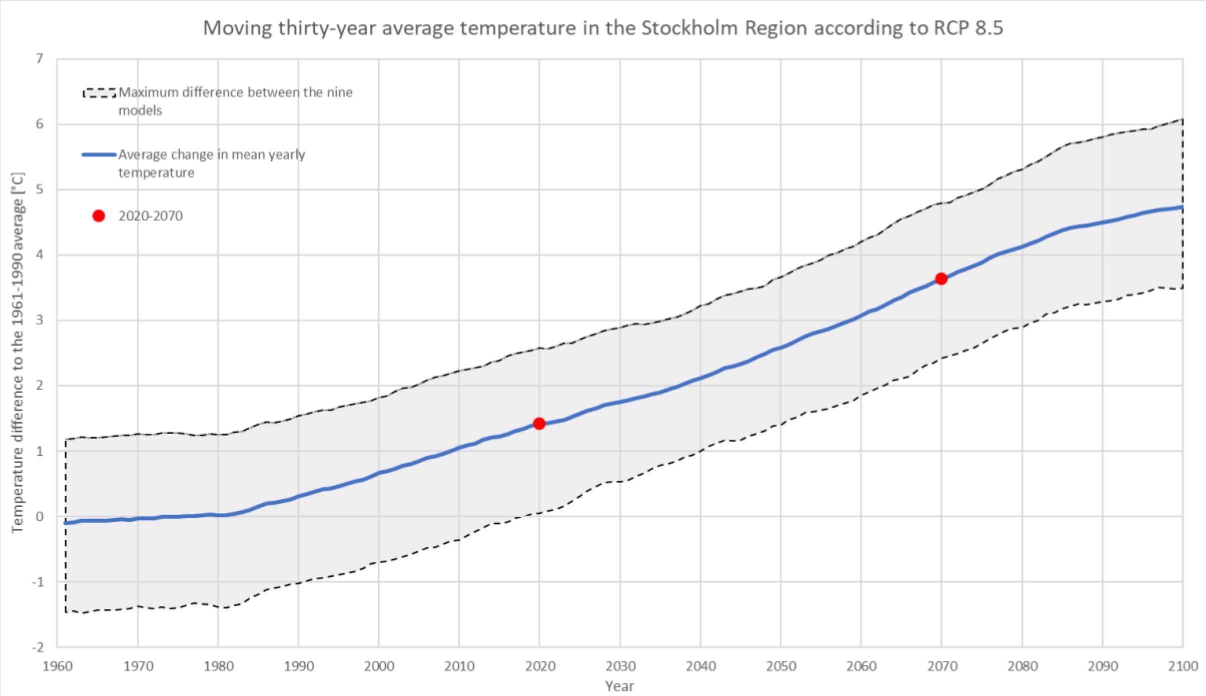

FIGURE 5: CALCULATED MOVING THIRTY-YEAR AVERAGE TEMPERATURE (°C) IN THE STOCKHOLM REGION FOR THE YEARS 1961-2100 COMPARED TO THE 1961-1990 AVERAGE.

With these changes done to the ensemble, it is possible to extract results for the statistical downscaling. The values used for the downscaling were the difference of the 2070 and 2020 averages for each set, except for one extreme scenario also being used for calculations. This scenario was used to increase the range of future possible scenarios and, therefore, the probability that the future climate fits into the range of scenarios. The scenario has also been used to more accurately represent possible future heatwaves during summers since the data on the length of future heatwaves has a great variation (Asp et al. 2015). The extreme scenario has been named "RCP 8.5 MAX" and is the difference between the 2020 ensemble average and the maximum ensemble value for 2070. The resulting scenarios analyzed were RCP 2.6, 4.5, 8.5, and 8.5 MAX.

2.2.3 The chosen hourly climate file

Before a statistical downscaling could be performed on an hourly climate file, an actual file had to be created. The climate file had to be representative of the present climate of Stockholm and, thus, a typical meteorological year (TMY) was constructed for the years 2015-2020, where data of each year has been collected from Sveby's (n.d.) website. The TMY was constructed according to SS-EN ISO 15927-4:2005, meaning that a synthetic year has been constructed from the chosen years' most statistically representative months. A ranking of the parameters: dry bulb temperature, relative humidity, solar radiation, and wind speed has been done for each month where the highest-ranking month was considered to be the most statistically representative month for that parameter. These parameters were then weighed against each other, according to Sveby (2016), where dry bulb temperature and solar radiation each were considered as two times the weight of relative humidity. The years chosen for each month can be seen in Table 2 where, for example, the most representative January is the one from 2017. The effects of leap years have been removed in all instances meaning that February 29th has been removed to reduce its effect. The first and last eight hours of each month have been changed through interpolation to assure a smoother transition between the months according to the standard.

TABLE 2: THE DIFFERENT YEARS CHOSEN FOR EACH MONTH.

Month	Most statistically representative year
January	2017
February	2016
March	2017
April	2017
May	2016
June	2018
July	2016
August	2018
September	2019
October	2018
November	2017
December	2019

The resulting TMY climate file contained hourly values for wind direction, wind speed, dry-bulb temperature, relative humidity, total cloud cover, global horizontal irradiance, direct normal irradiance, and diffuse horizontal irradiance. The hourly climate file dictating the outdoor climate in IDA ICE only accepts values for wind direction, wind speed, dry-bulb temperature, relative humidity, direct normal irradiance, and diffuse horizontal irradiance (Bring, Sahlin & Vuolle 1999). Cloud coverage and global horizontal irradiance have, therefore, not been affecting the climate in IDA ICE.

2.2.4 The statistical downscaling chosen

To create future climate files according to the RCP scenarios mentioned in section 2.2.2, the climate file has been morphed. The variable changed to morph the file was dry-bulb temperature, as mentioned earlier. It has been done in line with Belcher, Hacker & Powell (2005) and Chan (2011), with the motive that the file should be morphed to not only represent the future mean temperature, but also the future daily variance in temperature. This was done with both a shift and a stretch in temperature.

The hourly dry bulb temperature (dbt) of 2070 is, according to Belcher, Hacker & Powell (2005), determined by Equation 1. It consists of the present hourly dry-bulb temperature (dbt_0), the predicted change in seasonal mean temperature ($\Delta TEMP_m$), a scaling factor for stretch (αdbt_m), and the present seasonal mean dry bulb temperature ($\langle dbt_0 \rangle_m$).

$$dbt = dbt_0 + \Delta TEMP + \alpha dbt_m \times (dbt_0 - \langle dbt_0 \rangle_m) \tag{1}$$

The scaling factor for stretch (αdbt_m) can be seen in Equation 2 and consists of the predicted change in seasonal minimum ($\Delta TMIN_m$) and maximum ($\Delta TMAX_m$) temperature, and the present monthly mean daily maximum ($\langle dbt_{0\,max} \rangle_m$) and minimum ($\langle dbt_{0\,min} \rangle_m$) temperature. These can all be gathered from either SMHI's (n.d.b) scenario database described in sections 2.2.1 and 2.2.2 or the present climate file mentioned in section 2.2.3.

$$\alpha dbt_m = \frac{\Delta TMAX_m - \Delta TMIN_m}{\langle dbt_{0\,max} \rangle_m - \langle dbt_{0\,min} \rangle_m} \tag{2}$$

2.2.5 Justification of the chosen climate file

To justify the climate files chosen and calculated, they have been compared to the predicted resulting climate, to verify whether the seasonal and yearly mean, maximum and minimum temperatures correspond with the predicted ones. Furthermore, the climate files have been compared to three other climate indexes, namely degree-days for heating, degree-days for cooling, and heatwave. Degree-days for heating is the difference between the daily mean temperature and a threshold value of 17°C, summed for a full year (Asp et al. 2015). If the mean temperature for a single day is 10°C, the degree days for heating would be 7 degrees for that particular day. All those days are, thereafter, summed for a year. If the mean temperature is higher than the threshold, it is counted as a zero. The degree days for cooling works in the same way but for mean temperatures above the threshold of 20°C. If the mean temperature for a single day is 25°C, the degree days for cooling would be 5 degrees. Heatwave is defined as the number of days in a row with average temperatures exceeding 20°C. The indexes are in the Stockholm region for RCP 4.5 and 8.5.

2.3 Result

2.3.1 Resulting climate

The resulting average temperature difference between 2020 and 2070 can be seen in Table 3, gathered from the information gained in section 2.2.2, where necessary values for each season and scenario have been extracted to fit the equations of statistical downscaling.

TABLE 3: THE AVERAGE DIFFERENCE IN TEMPERATURE BETWEEN 2020 AND 2070 IN THE STOCKHOLM REGION DEPENDING ON THE TYPE OF SCENARIO.

Scenario	Season	Predicted change in seasonal mean temperature ($\Delta TEMP_m$)	Predicted change in seasonal maximum temperature ($\Delta TMAX_m$)	Predicted change in seasonal minimum temperature ($\Delta TMIN_m$)
RCP 2.6	Year	0,5	0,7	1,5
	Winter	0,8	0,9	1,4
	Spring	0,6	0,2	1,7
	Summer	0,5	0,7	0,2
	Autumn	0,4	0,7	0,4
RCP4.5	Year	1,3	1,0	3,0
	Winter	1,6	1,5	2,8
	Spring	1,4	1,2	3,4
	Summer	1,0	1,0	1,2
	Autumn	1,1	0,9	1,4
RCP 8.5	Year	2,2	1,8	5,6
	Winter	2,7	2,3	5,4
	Spring	2,2	1,7	4,4
	Summer	1,9	1,8	1,8
	Autumn	2,1	2,0	2,3
RCP 8.5 MAX	Year	3,4	4,8	10,7
	Winter	5,1	4,6	10,6
	Spring	3,7	4,3	9,7
	Summer	3,7	4,8	4,5
	Autumn	3,8	4,5	5,1

2.3.2 The resulting climate files

The resulting climate file used for simulations of today's climate (dbt_0) and for morphing the future climate (dbt) based on the TMY 2015-2020 and the result from Table 3, can be seen in Figure 6 represented as the monthly mean for the hourly climate file of each scenario.

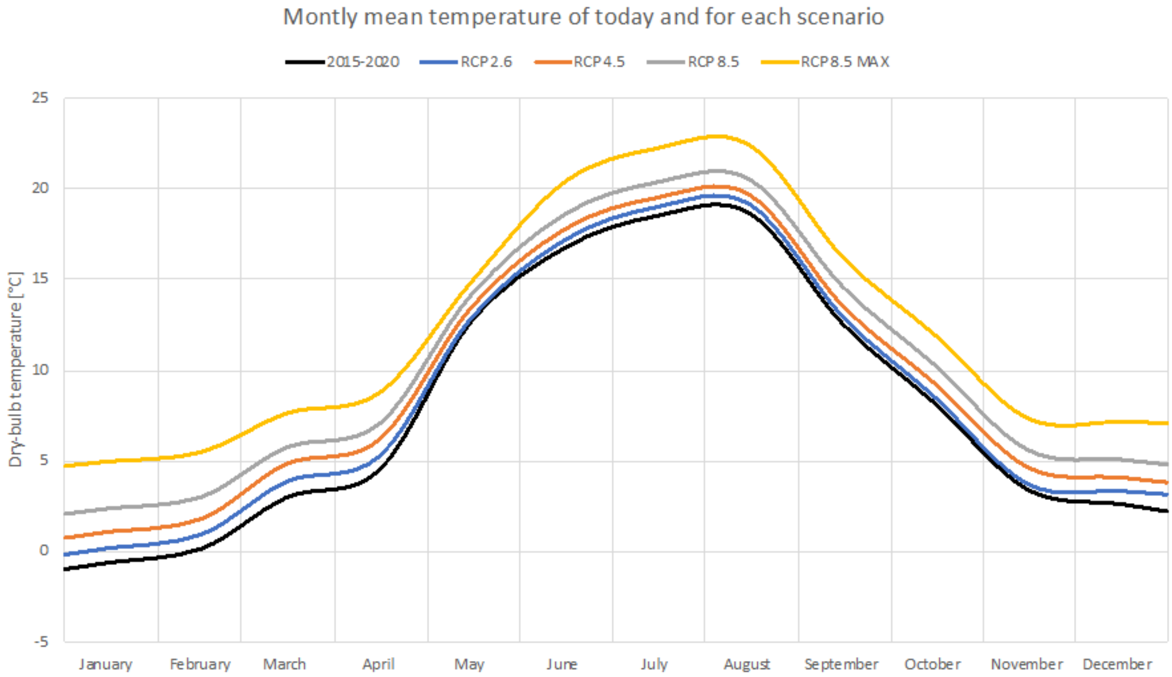

FIGURE 6: MONTHLY AVERAGE TEMPERATURE OF TODAY AND FOR EACH SCENARIO.

Figure 6 shows that the average temperatures will increase with every scenario and that the temperature increases differently depending on the season. The difference between each scenario and today's temperature can be seen more clearly in Figure 7.

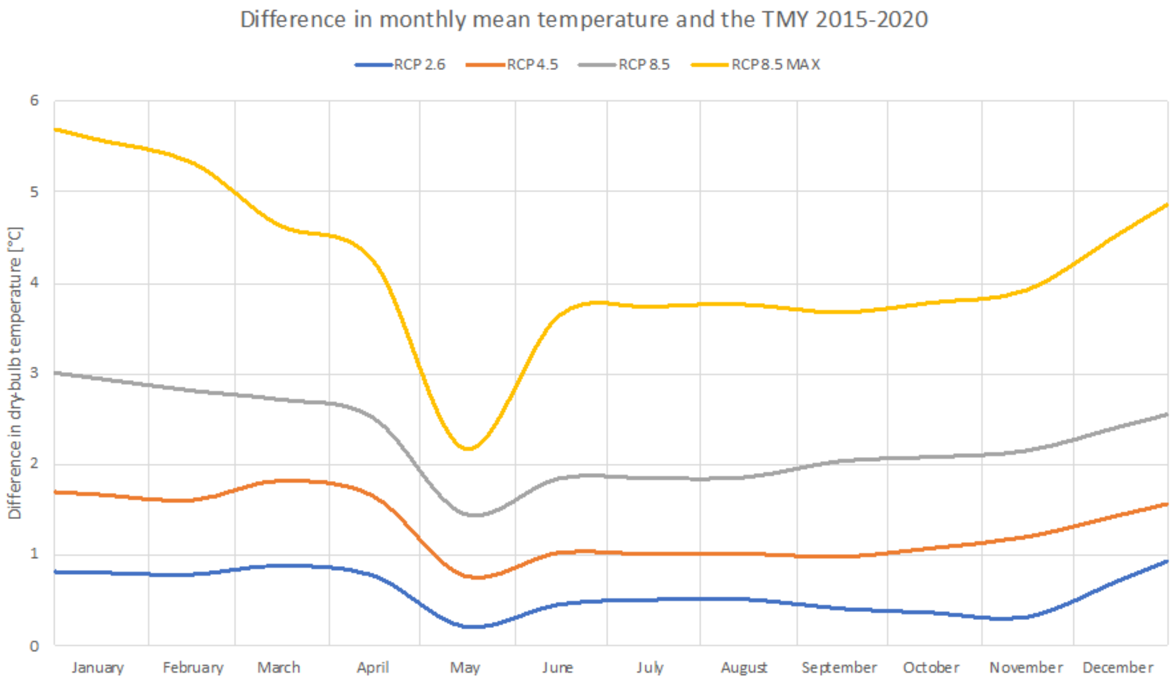

FIGURE 7: DIFFERENCE IN MONTHLY MEAN TEMPERATURE BETWEEN EACH SCENARIO AND TODAY.

2.3.3 Justification of the climate files chosen

To easily spot the difference between the resulting climate files and the predicted scenario, a similar table as Table 3 is presented in Table 4, but with differences in temperatures. Differences larger than 1 degree have been highlighted in red.

TABLE 4: THE DIFFERENCE BETWEEN THE RESULTING CLIMATE FILES AND THE PREDICTED FUTURE CLIMATE.

Scenario	Season	Difference in seasonal mean temperature compared to the predicted change	Difference in seasonal maximum temperature compared to the predicted change	Difference in seasonal minimum temperature compared to the predicted change
RCP 2.6	Year	0,0	0,0	-0,4
	Winter	0,0	-0,3	-0,3
	Spring	0,0	-0,5	-0,5
	Summer	0,0	0,0	0,0
	Autumn	0,0	-0,2	-0,2
RCP4.5	Year	0,0	-0,2	-1,0
	Winter	0,0	-0,4	-0,8
	Spring	0,0	-1,1	-1,0
	Summer	0,0	-0,2	0,0
	Autumn	0,0	-0,1	0,1
RCP 8.5	Year	0,0	0,0	-1,3
	Winter	0,0	-0,8	-1,1
	Spring	0,0	-1,1	-1,0
	Summer	0,0	0,0	0,2
	Autumn	0,0	-0,1	0,1
RCP 8.5 MAX	Year	0,7	-0,7	-2,1
	Winter	0,0	-1,8	-2,1
	Spring	0,0	-3,8	-3,7
	Summer	0,0	-0,7	-1,1
	Autumn	0,0	-1,0	-0,9

As can be seen in the table above, the mean temperatures were not deviating at all from the predicted climate, just as supposed. However, the model does not fully represent the predicted changes in maximum and minimum temperature for the two more aggressive scenarios (8.5 and 8.5 MAX). One of the most accurately modeled seasons was summer, which is suitable for the overheating focus of this study.

The climate files can, furthermore, be justified by comparing them to the climate indexes presented in section 2.2.5. The predicted values have been presented by Asp et al. (2015). Table 5 displays these comparisons.

TABLE 5: THE DIFFERENCE BETWEEN CALCULATED AND PREDICTED VALUES FOR FURTHER CLIMATE INDEXES.

		Calculated value from hourly climate files	**Predicted value from Asp et al. (2015)**
Degree-days for heating	Today	3292	
	RCP 2.6	3120	
	RCP 4.5	2891	3223
	RCP 8.5	2615	2923
	RCP 8.5 MAX	2107	
Degree-days for cooling	Today	43	
	RCP 2.6	56	
	RCP 4.5	65	47
	RCP 8.5	101	87
	RCP 8.5 MAX	210	
Heatwave	Today	4	
	RCP 2.6	4	
	RCP 4.5	5	10
	RCP 8.5	17	17
	RCP 8.5 MAX	27	

As can be seen in the table above, all calculated values were, somewhat, close to the predicted mean values that originated from an ensemble of nine models. This means that there exists a deviation in which the calculated values exist. Additionally, all predicted values exist in the span of the climate files.

Chapter 3

The Representative House

3.1 Introduction

There are various solutions, designs and systems used when building single-family houses today. People without professional knowledge or experience within the area of building techniques have a quite large influence when designing their future homes. This means that the outcome of every house in the building stock today can differ plenty. The building design of these types of buildings has changed during the years, following the overall development of society and technical progress, but also influenced by new knowledge within the area of building technique and design. To be able to answer the research questions and test the hypothesis, a model representing the typical house built today, with a system and solutions in line with the requirements has been created.

3.2 Method

The creation of a mirrored model of the representative house built today has been done by choosing materials and solutions from a variety of sources which have been presented later on in the thesis. The section below is divided into the different building parts, systems, and parameters that were important for the validity of the model and the result. The sources have been a mixture of current properties for sale on the market in the nearest area of Stockholm, combined with literature and among current producers and professionals within the area of building techniques and energy systems. Further justification of the model can be found in section 3.3.7 where values required results from the simulations were compared to statistics and Swedish building regulations.

3.3 Result

3.3.1 Roof

The roof of the house has been constructed as a “cold roof” of the type saddle roof, meaning that the outer half of the roof is uninsulated and at an angle of 27 degrees, while the other half is flat and insulated. This part of the roof has an inclination of 27 degrees and the second half of the roof, the isolated ceiling to the second level to the house is flat. This is the common solution for single-family houses today which is why it has been chosen (Boverket 2010). The roof structure can be seen in Table 6.

TABLE 6: MATERIAL IN THE ROOF STRUCTURE.

Material	Thickness [mm]
Concrete tiles	32
Counter battens, 25x38 c/c 375	25
Battens, 25x23 c/c 450	25
Waterproofing membrane	1
Tongued and grooved board	22
Wooden studs 220x70 C24, c/c 600	220
Light insulation	150
Wooden studs, 220x70 C24, with insulation c/c 600	220
Plywood	12
Gypsum	13

3.3.2 Outer wall

The structure of the wall was in line with current producers of single-family houses on the market and the heat transfer coefficient (U) of the entire wall structure was compared to building regulations, see section 3.3.7. According to Boverket (2010), most façades of single-family houses are made of wood and it has therefore been chosen for this building. The wall structure can be seen in Table 7.

TABLE 7: MATERIAL IN THE OUTER WALL STRUCTURE FROM INSIDE TO OUTSIDE.

Material (inside to outside)	Thickness [mm]
Gypsum	13
Plywood	12
Wooden studs 70x45 with insulation C24 c/c 600 (installation layer)	70
PE-foil, vapor barrier	0.2
Wooden studs with insulation 195x45 C24 c/c 600	195
Wind breaking membrane, wind barrier	0.2
Battens 28x45 c/c 600	28
Wooden facade	22

3.3.3 Windows

According to the Swedish window supplier Elitfönster, a trend of increased window area in the production of single-family houses has been noticed. Even though a wall structure has a better heat transfer coefficient than windows, an increased use of windows can be seen in the stock of villas in the Stockholm region. The increased usage of windows will demand higher quality windows to fulfill the energy consumption requirements and the development of a more sustainable living (Svantesson 2021).

The number of windows chosen for this model has been based on Boverket's building regulations (BFS 2011:6), which states that the window area should be at least 10% of the floor area, representing a daylight factor of 1%. This has also been compared to data from Boverket (2010), where average window areas have been collected. The window sizes have been chosen according to the floor plan and previously mentioned average window areas. The size 0.8 m x 0.8 m has been chosen in all rooms except the bathrooms and the laundry room, where smaller windows of 0.8 m x 0.5 m were used. The window placement has been chosen to naturally follow the floorplan and symmetry in the façade was considered when possible. To further improve the validity of the model and the result of the simulation the heat transfer coefficient has been tested against BFS 2011:6, see section 3.3.7.

3.3.4 Foundation and intermediate floor

The foundation has been constructed as a slab and consists of 250 mm extruded polystyrene with 120 mm of concrete on top, directly placed on a flat ground of gravel and macadam, which is a commonly used solution for single-family houses in Sweden (Berg 2013). The flooring material chosen was parquet for all rooms except the two bathrooms and the laundry room where clinker tiles were used. Table 8 presents the construction of the foundation in, for example, the living room.

TABLE 8: MATERIAL IN THE FOUNDATION.

Material	Thickness [mm]
Parquet flooring	15
Acoustic mat combined with a vapor barrier	3
Concrete	120
Extruded Polystyrene	250

The intermediate floor has been constructed with wooden beams (70x220 mm of C24) as the load-bearing structure, with insulation in between. Underneath the load-bearing structure, a ceiling consisting of battens and gypsum boards has been chosen. The flooring on the upper floor was similar to the flooring on the entrance floor, see the previous piece about the foundation. The structure of the intermediate floor can be seen in Table 9.

TABLE 9: MATERIAL IN THE INTERMEDIATE FLOOR STRUCTURE.

Materia	Thickness [mm]
Parquet flooring	15
Acoustic mat	3
Wooden beams with insulation, 220x70 C24, c/c 600	220
Battens 25x38 c/c 600	25
Gypsum	13

3.3.5 Floorplan and area

The chosen habitable area of the house has been based on sources about the average area of newly built single-family houses in the Stockholm region. Swedish Energy Agency (Energimyndigheten 2020) has reported that most single-family houses in the Stockholm region are 101-150 m^2 and Boverket (2010) reported an average of 137 m^2 for buildings built between 2000-2005. Most of the buildings in the same source consist of two floors, which is why the model has been constructed as a two-story building. Furthermore, Statistics Sweden (Statistiska Centralbyrån, SCB, n.d.) justify the chosen area of 130 m^2, where the most common range has been reported to be 111-130 m^2 for single-family houses in the Stockholm region.

When it comes to the design of the rooms and floorplan, the chosen solution has been based on current selling objects on the market and suggested floorplans from producers of single-family houses in Sweden today. The floorplan was, thereafter, compared and adjusted to the standard for new production (SS 91 42 21:2006). The house and the combination and number of rooms should be in line with how many occupants the house is designed for. The number of occupants has been acquired from SCB (n.d.). An additional source that was used to further justify the chosen floorplan for the model was “Så byggdes villan” (Björk, Nordling & Reppen 2015), which is a book including information about how houses are built during different times in Sweden. All sources used support that the floorplan created possibly could have been built in 2020, in the Stockholm region.

The distribution of rooms has been presented in Figure 8. The entrance can be found in the north close to the kitchen. On the first floor, one can find a kitchen, dining area, living room, bathroom, laundry room, and a staircase leading up to the second floor. An additional door has been placed on the living room's east wall, to be able to reach a potential garden or terrace. On the second floor, two bedrooms of the same size, a smaller bathroom, and a big second living room can be found. The outer dimensions of the house are roughly 10,7 m long and 7,2 m wide, making the living area inside approximately 130 m^2. The floorplan is quite open and social, with bedrooms separated from the social areas downstairs and placed in the north direction to avoid too much sun. The house has been designed for three occupants, with social spaces designed for more. An illustration of the final model of the house can be seen in Figure 9.

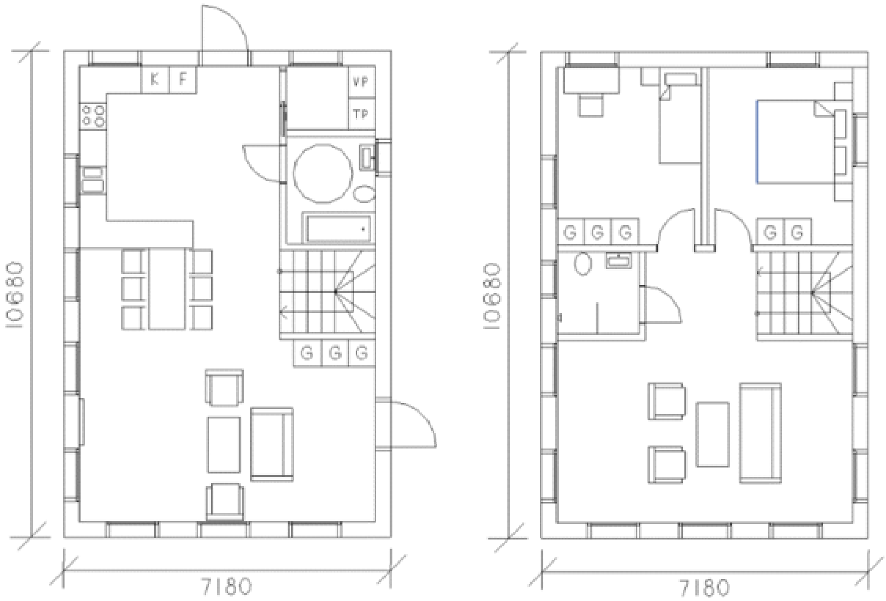

FIGURE 8: CHOSEN FLOORPLAN FOR THE BUILDING

FIGURE 9: ILLUSTRATION OF THE HOUSE.

3.3.6 Ventilation and heating system

Different systems for heating and ventilation can be used when planning and constructing a new home, and some of the systems can be integrated to decrease the total energy demand. Looking at current objects on the market within the nearest area of Stockholm, different solutions and combinations can be identified (Hemnet n.d.). Producers of single-family houses have as their “standard solution” in many cases chosen a heat pump, which can be combined with the ventilation or geothermal heating if possible at the site.

According to Energimyndigheten (2020), the most common source for heating single-family houses built after 2011 in the Stockholm region is electricity, both direct and indirect. The most common type of electrical heating is a water-based system, which includes exhaust air heat pumps and air to water heat pumps. According to Boverket (2010), the most common system for ventilation and heating is an exhaust air heat pump. Suppliers of heating and ventilation systems, NIBE and IVT, are confirming this data (Carlholmer 2021; Åkesson 2021).

The chosen system for the model is an exhaust air ventilation system in combination with an exhaust air heat pump that uses the heat from the exhaust air to heat the indoor environment again through liquid floor heating and radiators. The distribution of the heat throughout the house is done with liquid floor heating on the first floor and radiators placed underneath most windows on the second floor. Exhaust valves for ventilation have been placed in the bathrooms, the laundry room, and the kitchen. The kitchen fan is an additional separate exhaust duct. The supply valves have been placed on the outer wall to let outdoor air into the house due to the pressure difference created by the ventilation system. The supply valves have been placed in the living rooms and bedrooms. The placement of valves and calculation of flow have been done according to BFS 2011:6 and Boverket’s old building regulations (BFS 1998:38).

3.3.7 Justification of the model

To justify the model, different parameters have been compared to statistical data, regulations, and requirements for new production of single-family houses in Sweden. This was done to make sure that the particular model could have been built today, in real life, and that it is a representative house of what is normally built in 2020. To improve the external validity, parameters as requirements for energy demand and heat transfer coefficient for different building parts were found in BFS 2011:6. The simulated energy consumption has also been compared with Energimyndigheten’s (2020) statistics of energy consumption for newly-built single-family houses in 2018. The statistic shows that a normal energy consumption for heating and domestic hot water is 59 kWh/m^2, year (±8 kWh/m^2, year), which could be compared to our simulated value of 52 kWh/m^2, year. When only observing water-based systems with electricity as a source, the normal consumption is 40 kWh/m^2, year (±8 kWh/m^2, year). The simulated value for the energy consumption is located in the middle of these two statistical values and could, therefore, be argued to be a good representation in terms of energy consumption.

The model has also been compared to statistics on energy for heating, domestic hot water, and facility electricity which is 76 kWh/m^2, year (±8 kWh/m^2, year) (ibid.). The simulated value of 79 kWh/m^2, year was close to this and within the deviation. BFS 2011:6 limits the allowed specific energy consumption of single-family houses to 95 kWh/m^2, year for this size of house and this location. The model’s specific energy consumption has been calculated according to the equation described and presented in BFS 2011:6, which outputs a value of 93 kWh/m^2, year. To simulate and calculate the specific energy consumption, a different climate file has been used. This climate file has been based on a TMY for 1980-2010 which is supposed to be used when calculating the energy consumption of houses today according to BFS 2011:6.

Boverket (2010) has also provided statistical data for the heat transfer coefficient (U) of buildings built between 2000 and 2005 in Sweden, which is the latest accessible data. The reported values have been compared to the model values, see Table 10. Note that the heat transfer coefficients of the building parts should be kept below the BFS 2011:6 limits.

TABLE 10: COMPARISON OF HEAT TRANSFER COEFFICIENT (U) FOR JUSTIFICATION OF THE MODEL.

Building Part	BFS 2011:6	From Sources	Model Values
Slab on ground	0.15	0.14 (Boverket 2010)	0.14
Outer wall	0.18	0.16 (Boverket 2010)	0.17
Roof	0.13	0.11 (Boverket 2010)	0.11
Window	1.2	1.0 (Svantesson 2021)	1.0

One additional parameter that has been checked was thermal bridges, which have been assumed to be and set to "normal" in the simulation software. According to Sweden Green Building Council (SGBC 2020), thermal bridges could be assumed to be 30% of the transmission losses for the lowest level of certification. This certification system has three levels; gold, silver, and bronze, and for the two lowest levels, 30% can be assumed. For the highest level, the thermal bridges must be calculated further. For this model, thermal bridges could be assumed to be approximately 30% for the representative house. The model's total thermal bridges were calculated to be 29.95% of the total transmission losses, which further strengthened the validity of the model.

Chapter 4

Indoor Environment

4.1 Introduction

As presented in Chapter 1, the indoor climate influences the way inhabitants feel and perform throughout the day. To evaluate the indoor environment, an operationalization has been made and limited to only assess operative temperature. This chapter aims to decide and simulate an acceptable indoor environment. It has been done in the model established in Chapter 3, with the outdoor climate established in Chapter 2. This has been done by first deciding what an acceptable indoor climate is, and thereafter simulating and presenting the data for the present and future climate.

4.2 Method

4.2.1 Demands and definitions

The indoor climate can be evaluated according to the standard SS-EN ISO 7730:2006, where the parameters Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) are mainly used to measure it. The PMV is calculated through a formula where the variables; air temperature, radiant temperature, air velocity, humidity, clothing insulation, and metabolic heat, are used to determine the average vote for a large group of people in the same environment. PPD is calculated through a formula fully dependent on PMV and results in a prediction of the percentage of people dissatisfied with the thermal environment. This thesis has focused on the change in dry-bulb temperature. Air velocity, humidity, clothing insulation, and metabolic heat have, therefore, been held constant through all simulations.

To get a result from the simulation, the built structure of the house should be complemented with standardized user data (Sveby n.d.). This data ought to be in line with the chosen parameters and user of the constructed representative house that the model is mirroring. However, as mentioned before, the only parameter manipulated was dry-bulb temperature. Mainly because of that, the change in indoor climate has been evaluated based on the change in operative temperature for every room. Since other parameters that potentially could change the indoor climate were held constant in the climate file, the effect of these have not been considered when evaluating the change for this case. Other standardized user data has also been held constant in all the simulations.

The demand and guidelines of the indoor environment have been presented in BFS 2011:6 where further information can be found in the Public Health Agency of Sweden’s (Folkhälsomyndigheten, FoHM) advice concerning indoor temperature (FoHMFS 2014:17). The guidelines have been summed up in Table 11 and apply for rooms where people reside more often than temporarily.

TABLE 11: GUIDING OPERATIVE TEMPERATURES.

Operative temperature	Heating season	Summer
Permanent	≥ 18°C	≥ 18°C
Short term	≤ 26°C	≤ 28°C
Long term	≤ 24°C	≤ 26°C

To assess the result of the simulations, the terms temporarily, short term, and long term must be defined. The rooms where people reside more than temporarily were all except the laundry room and the stairs, meaning that the operative temperatures in those two rooms have been neglected. Short-term has been defined as the number of continuous days with temperatures exceeding the threshold value. The limit has been set to three days with the argument that the risk of health issues increases noticeably for the elderly when the temperatures exceed 26°C for more than three days in a row (FoHM 2015). Furthermore, SMHI (n.d.c) issue public messages when temperatures exceed 26°C for three consecutive days and warnings when temperatures exceed 30°C for three or more consecutive days due to increased stress on the human body.

4.2.2 Collection of data

The main method used to evaluate the indoor environment was to, as described in Chapter 1, build the model in software IDA ICE. To be able to evaluate the indoor climate, or more precisely the operative temperature, the temperature for all rooms was gathered from the simulation with the climate file representing today's climate and the climate files representing the predicted climate in the year 2070 for all four scenarios. These results have been presented in Table 12-16. To analyze and evaluate the building in general, the worst room for maximum operative temperature, daily average temperature, and days in a row was selected and has been presented in section 4.3.1.

4.3 Result

The tables that summarize the simulations have been presented below. Each table represents a scenario, each row represents a room, and each column represents a targeted value mentioned in section 4.2.1 To further simplify the tables, operative temperature has been shortened to T_o and the daily average operative temperature has been shortened to $\bar{T}_o$. Furthermore, to increase visibility, the cells with values larger than the threshold have been highlighted red.

TABLE 12: RESULT FROM SIMULATION OF TODAY'S INDOOR CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,8	25,1	6	0	0	3	0	0
	Bathroom	26,0	25,3	1	0	0	1	0	0
	Livingroom	26,9	25,2	7	0	0	3	0	0
Upper Floor	Bedroom	27,5	25,9	9	0	0	3	0	0
	Master bedroom	26,6	25,8	8	0	0	3	0	0
	Bathroom	27,2	25,7	11	0	0	3	0	0
	Livingroom	27,3	25,98	9	0	0	3	0	0

TABLE 13: RESULT FROM SIMULATION OF YEAR 2070´S INDOOR CLIMATE FOR RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,2	25,5	8	0	0	3	0	0
	Bathroom	26,3	25,6	3	0	0	2	0	0
	Livingroom	27,3	25,7	8	0	0	3	0	0
Upper Floor	Bedroom	28,0	26,4	14	0	1	4	0	1
	Master bedroom	27,1	26,3	9	0	2	3	0	2
	Bathroom	27,6	26,1	14	0	1	4	0	1
	Livingroom	27,7	26,4	11	0	2	3	0	1

TABLE 14: RESULT FROM SIMULATION OF YEAR 2070´S INDOOR CLIMATE FOR RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,4	25,7	10	0	0	3	0	0
	Bathroom	26,5	25,8	5	0	0	2	0	0
	Livingroom	27,5	25,8	10	0	0	3	0	0
Upper Floor	Bedroom	28,2	26,6	15	2	2	4	1	1
	Master bedroom	27,2	26,4	11	0	2	4	0	2
	Bathroom	27,8	26,3	19	0	2	5	0	1
	Livingroom	27,7	26,6	12	0	3	4	0	2

TABLE 15: RESULT FROM SIMULATION OF YEAR 2070´S INDOOR CLIMATE FOR RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,0	26,3	12	0	2	4	1	1
	Bathroom	27,0	26,3	7	0	3	3	0	2
	Livingroom	28,1	26,4	16	2	3	5	1	2
Upper Floor	Bedroom	28,8	27,2	20	4	3	4	3	2
	Master bedroom	27,9	27,0	13	0	3	4	0	2
	Bathroom	28,4	26,8	22	4	4	6	2	2
	Livingroom	28,5	27,1	18	3	5	5	2	2

TABLE 16: RESULT FROM SIMULATION OF YEAR 2070´S INDOOR CLIMATE FOR RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	29,4	27,7	28	6	8	11	3	4
	Bathroom	28,5	27,8	17	4	9	5	2	4
	Livingroom	29,5	27,9	30	6	8	11	3	4
Upper Floor	Bedroom	30,6	28,8	41	9	11	11	3	4
	Master bedroom	29,8	28,9	28	6	11	8	3	4
	Bathroom	30,0	28,5	36	7	10	12	3	4
	Livingroom	30,0	28,6	42	9	14	23	4	5

4.3.1 Summary and comparison

To create a clear and structured summary and comparison of the results from the different scenarios, the largest value for every column in the tables above has been presented in Table 17. This was done to evaluate the house and discuss potential improvements. The weakest part of the house should be considered first and by improving the worst room, the house will most likely improve overall as well.

Table 17: Summarizing table for the maximum values from table 12-16.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,5	25,98	11	0	0	3	0	0
RCP 2.6	28,0	27,0	14	1	4	4	1	2
RCP 4.5	28,0	27,0	14	1	4	4	1	2
RCP 8.5	28,8	27,2	22	4	5	6	3	2
RCP 8.5 MAX	30,6	28,9	42	9	14	23	4	5

Table 18 display the energy consumptions of 2020 and all four scenarios for the year 2070. The total value in the table differs from section 3.3.7, since lighting and equipment have not been displayed in the table since there is no difference in these between the scenarios.

Table 18: Energy consumption of the reference house.

[kWh/m^2]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
HVAC aux	2,8	2,6	2,5	2,3	2,1
Electric heating	15,1	14,9	14,6	14,1	13,2
Top up heating	28,5	25,1	21,2	16,7	8,7
Total	46,3	42,6	38,2	33,1	24,0

Chapter 5

Improvements to the Building

5.1 Introduction

As seen in the results for the various scenarios presented in Table 17, there exists a correlation between the indoor climate and outdoor climate, and depending on scenario, the temperatures inside rise to high levels over long periods. Additionally, the temperatures and days in a row with high temperatures exceed the threshold in all future climate scenarios. This chapter focus on reducing the future indoor temperatures and heatwaves to levels beneath the threshold in a sustainable way. Different solutions have, therefore, been tested to investigate the possibility of implementation to prevent an unwanted negative change of the indoor climate.

5.2 Method

The same main method as used in Chapter 4 of using IDA ICE to simulate the indoor environment has been used in this chapter. Starting with the reference house and its result presented in Chapter 4, a selection of different modifications to the design and building physics have been implemented to the model. The new model has thereafter been simulated with the same climate files described in Chapter 2 to easily investigate whether the modifications have worsened or improved the indoor climate. The output from the simulations can be found in Appendix 1-11 and in section 5.3 where a summary and comparison to the reference house has been presented.

5.3 Result

In this section, three tables for each tested solution have been presented. The first table presents the new highest operative temperatures and longest periods for every scenario simulated, similar to Table 17, where values above the threshold have been highlighted red.

The second table presents the difference between the values generated by the modified house and the reference house. Meaning that if the modification yields cooler temperatures or fewer days with hot temperatures than the reference, the table will display the difference as negative, and this will further be shown with green highlights. If the modification yields higher temperatures or longer periods, the cells will be highlighted red. The first table was used to investigate whether the purposed solution yields temperatures and periods lower than the threshold. The second table indicates whether the purposed solution yields better results than the reference house.

The third table displays the energy performance and difference between the modified house and the reference house. The only values presented were the summary of HVAC aux, Electric heating, Top-up heating, and cooling since the other parts have not been affected by the changes. The difference was, thereafter, taken and presented as kWh/m^2, year. Red cells indicate increases in energy consumption, and green cells indicate decreases in energy consumption, compared to the reference house's energy performance, described in Chapter 4.

5.3.1 External shading

5.3.1.1 Drop arm awning covering all windows

This modification utilizes drop arm awning as external shading. These were placed on all windows and were drawn according to a macro that shades the windows whenever it was hit by direct sunlight. However, the macro was only active between the 1st of April to the 30th of September, because the sun should be considered as beneficial to the energy consumption in wintertime. See a summary of the result in the tables below. The complete result can be found in Appendix 1.

TABLE 19: SUMMARY OF WORST VALUES WITH DROP ARM AWNING.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,3	25,8	8	0	0	3	0	0
RCP 2.6	27,8	26,3	11	0	2	4	0	1
RCP 4.5	28,0	26,5	14	0	2	4	0	1
RCP 8.5	28,6	27,0	18	4	4	4	3	2
RCP 8.5 MAX	30,5	28,6	40	9	11	11	4	5

TABLE 20: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING DROP ARM AWNING.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,2	-0,2	-3	0	0	0	0	0
RCP 2.6	-0,2	-0,1	-3	-1	0	0	-1	-1
RCP 4.5	-0,2	-0,1	-5	-2	-1	-1	-1	-1
RCP 8.5	-0,2	-0,2	-4	0	-1	-2	0	0
RCP 8.5 MAX	-0,1	-0,3	-2	0	-3	-12	0	0

TABLE 21: ENERGY CONSUMPTION FOR THE DROP ARM AWNING.

[kWh/m^2, yr]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	46,9	43,1	38,6	33,5	24,3
Difference	0,6	0,5	0,4	0,4	0,3

5.3.1.2 Larger roof overhang and adding cantilever roof

This modification was completely passive, and it was essentially an extension of the roof and an installation of cantilever roofs halfway up the building, see Figure 10. This has been done to maximize shading of the façade in summer when the solar height is high and minimize it in wintertime when it is low. The overhang for both the cantilever and regular roof was 1 m on all sides. The cantilever roofs were placed at the same height as the intermediate floor and covered the perimeter of all façades except the northern one. See a summary of the result in the tables below. The complete result can be found in Appendix 2.

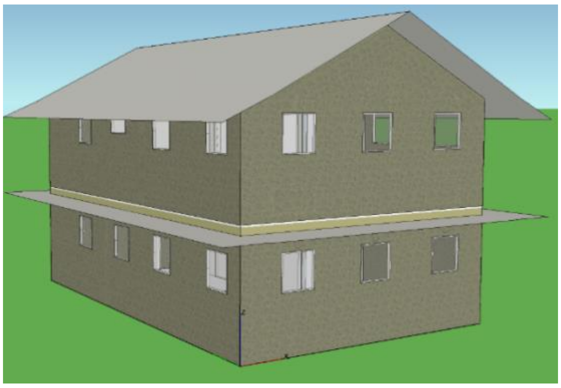

FIGURE 10: ILLUSTRATION OF THE HOUSE WITH EXTENDED OVERHANG OF ROOF AND ADDED CANTILEVER ROOF

Table 22: Summary of worst values with larger roof and cantilever roof.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,3	25,9	8	0	0	3	0	0
RCP 2.6	27,9	26,3	11	0	1	4	0	1
RCP 4.5	28,1	26,5	13	1	2	4	1	1
RCP 8.5	28,7	27,1	18	4	4	4	3	2
RCP 8.5 MAX	30,5	28,6	40	9	10	11	4	5

Table 23: Difference between reference house and implementing roof overhang and cantilever roof.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,2	-0,1	-3	0	0	0	0	0
RCP 2.6	-0,1	-0,1	-3	-1	-1	0	-1	-1
RCP 4.5	-0,1	-0,1	-6	-1	-1	-1	0	-1
RCP 8.5	-0,1	-0,1	-4	0	-1	-2	0	0
RCP 8.5 MAX	-0,1	-0,3	-2	0	-4	-12	0	0

Table 24: Energy consumption for roof overhang and balcony.

[kWh/m^2, yr]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	47,9	44,0	39,5	34,2	24,9
Difference	1,6	1,4	1,3	1,1	0,9

5.3.2 Windows

5.3.2.1 New windows

One possible solution tested was to change all the windows to better ones available on the market. The window tested was a window produced by Pilkington in their SunCool series, which was developed specifically to prevent overheating due to too much solar heat gain (Pilkington n.d.). Meaning that the values for solar radiation and daylight transmission were changed in the model. In addition, the chosen window had a lower heat transfer coefficient (U) of 0.5 W/m²K, but the value for the frame and frame fraction was still the same. The new total heat transfer coefficient for the window was therefore 0.64 W/m²K. The solar heat gain coefficient (G) was changed from 0.6 to 0.24 and the solar transmittance (T) was changed to 0.21 from 0.4. See a summary of the result in the tables below. The complete result can be found in Appendix 3.

Table 25: Summary of worst values with new windows.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,1	25,6	7	0	0	3	0	0
RCP 2.6	27,6	26,1	8	0	1	3	0	1
RCP 4.5	27,8	26,2	11	0	1	4	0	1
RCP 8.5	28,4	26,8	14	3	3	4	2	2
RCP 8.5 MAX	30,2	28,3	34	8	9	11	3	4

Table 26: Difference between reference house and implementing new windows.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,4	-0,4	-4	0	0	0	0	0
RCP 2.6	-0,4	-0,3	-6	-1	-1	-1	-1	-1
RCP 4.5	-0,4	-0,4	-8	-2	-2	-1	-1	-1
RCP 8.5	-0,4	-0,4	-8	-1	-2	-2	-1	0
RCP 8.5 MAX	-0,4	-0,6	-8	-1	-5	-12	-1	-1

Table 27: Energy consumption for implementing new windows.

[kWh/m²]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	47,4	43,7	39,3	34,0	24,9
Difference	1,1	1,1	1,1	0,9	0,9

5.3.2.2 Changed position of current windows

This modification covers moving all windows placed on the south wall to the west and east wall. The same window area as before has been used with a dissimilar distribution between the walls. The windows have been placed to match the floor plan. See a summary of the result in the tables below. The complete result can be found in Appendix 4.

TABLE 28: SUMMARY OF WORST VALUES WITH CHANGED POSITION OF WINDOWS.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,9	26,1	16	0	1	4	0	1
RCP 2.6	28,4	26,5	19	4	3	5	2	2
RCP 4.5	28,6	26,7	22	4	4	6	2	2
RCP 8.5	29,2	27,3	26	6	6	6	3	3
RCP 8.5 MAX	30,9	28,9	48	17	16	23	4	5

TABLE 29: DIFFERENCE BETWEEN REFERENCE HOUSE AND CHANGING POSITION OF CURRENT WINDOWS.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	0,4	0,1	7	0	1	1	0	1
RCP 2.6	0,4	0,1	5	3	1	1	1	0
RCP 4.5	0,4	0,1	3	2	1	1	1	0
RCP 8.5	0,4	0,1	4	2	1	0	0	1
RCP 8.5 MAX	0,3	0	6	8	2	0	0	0

TABLE 30: ENERGY CONSUMPTION FOR CHANGED POSITIONS OF CURRENT WINDOWS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Reference	46,3	42,6	38,2	33,1	24,0
Modified	47,4	43,7	39,3	34,1	24,7
Difference	1,1	1,1	1,1	1,0	0,7

5.3.2.3 Using the windows for night-ventilation

This modification utilizes the cooling potential at night in summers. Some windows were opened when there was a need for cooling inside, and a cooling potential outside. The windows equipped with these macros were windows that maximize the cross-breeze potential. See a summary of the result in the tables below. The complete result can be found in Appendix 5.

TABLE 31: SUMMARY OF WORST VALUES WITH NIGHT VENTILATION.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,0	25,1	5	0	0	3	0	0
RCP 2.6	27,5	25,6	5	0	0	3	0	0
RCP 4.5	28,1	25,9	7	1	0	3	1	0
RCP 8.5	28,7	26,6	10	2	3	4	1	2
RCP 8.5 MAX	30,8	28,3	24	7	6	7	3	4

TABLE 32: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING NIGHT-VENTILATION.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,5	-0,9	-6	0	0	0	0	0
RCP 2.6	-0,5	-0,8	-9	-1	-2	-1	-1	-2
RCP 4.5	-0,1	-0,7	-12	-1	-3	-2	0	-2
RCP 8.5	-0,1	-0,6	-12	-2	-2	-2	-2	0
RCP 8.5 MAX	0,2	-0,6	-18	-2	-8	-16	-1	-1

TABLE 33: ENERGY CONSUMPTION FOR IMPLEMENTING NIGHT-VENTILATION.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Reference	46,3	42,6	38,2	33,1	24,0
Modified	46,5	42,8	38,3	33,2	24,2
Difference	0,2	0,2	0,1	0,1	0,2

5.3.3 Ventilation System

5.3.3.1 Change of ventilation system to a balanced ventilation system

In this modification, the central air handling unit (AHU) has been changed from an exhaust AHU with liquid heat recovery, to a balanced AHU with an air-to-air heat recovery system. The recovery system was set to have an efficiency of 85%. Furthermore, all rooms with outdoor fresh air supply valves have been provided with an air supply connected to the AHU. Since the liquid heat recovery has been removed, the base heating has been changed to an air-to-liquid heat pump. The output and coefficient of performance (COP) have, however, been unchanged to reduce the number of variables. See a summary of the result in the tables below. The complete result can be found in Appendix 6.

TABLE 34: SUMMARY OF WORST VALUES WITH BALANCED VENTILATION SYSTEM.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,4	25,9	12	0	0	3	0	0
RCP 2.6	27,9	26,3	15	0	1	4	0	1
RCP 4.5	28,1	26,5	19	0	3	5	0	2
RCP 8.5	28,7	27,0	22	4	5	6	2	2
RCP 8.5 MAX	30,6	28,8	41	9	13	23	4	5

TABLE 35: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING BALANCED VENTILATION.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,1	-0,1	1	0	0	0	0	0
RCP 2.6	-0,1	-0,1	1	-1	-1	0	-1	-1
RCP 4.5	-0,1	-0,1	0	-2	0	0	-1	0
RCP 8.5	-0,1	-0,2	0	0	0	0	-1	0
RCP 8.5 MAX	0	-0,1	-1	0	-1	0	0	0

TABLE 36: ENERGY CONSUMPTION FOR IMPLEMENTING BALANCED VENTILATION.

[kWh/m^2, yr]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	30,1	27,9	25,5	22,8	24,3
Difference	-16,2	-14,7	-12,7	-10,3	0,3

5.3.3.2 Change of constant airflow to variable airflow

In this modification, the central AHU has the same features and specifications as in section 5.3.3.1 with one exception. The airflow, which used to be continuous, has now been modified to be variable depending on the temperature and CO_2-levels inside. Meaning that the AHU can vary the airflow from 0.3 to 7 l/s, m^2. See a summary of the result in the tables below. The complete result can be found in Appendix 7.

TABLE 37: SUMMARY OF WORST VALUES WITH VARIABLE AIRFLOW.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	28,0	26,1	20	0	1	5	0	1
RCP 2.6	28,2	26,3	24	2	5	6	1	2
RCP 4.5	28,2	26,5	27	3	5	6	2	3
RCP 8.5	28,7	27,1	33	5	8	8	3	3
RCP 8.5 MAX	30,5	28,6	56	14	18	24	4	4

TABLE 38: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING BALANCED VENTILATION WITH VARIABLE AIRFLOW.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	0,5	0,1	9	0	1	2	0	1
RCP 2.6	0,2	-0,1	10	1	3	2	0	0
RCP 4.5	0	-0,1	8	1	2	1	1	1
RCP 8.5	-0,1	-0,1	11	1	3	2	0	1
RCP 8.5 MAX	-0,1	-0,3	14	5	4	1	0	-1

TABLE 39: ENERGY CONSUMPTION FOR IMPLEMENTING BALANCED VENTILATION WITH VARIABLE AIRFLOW.

[kWh/m^2, yr]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	24,2	22,3	20,4	18,3	15,8
Difference	-22,1	-20,3	-17,8	-14,8	-8,2

5.3.4 Insulation

5.3.4.1 Added insulation

For this modification, 295 mm of extra insulation have been added to the exterior walls. Same properties as the current insulation have been used in this case. The added layer was placed on the outside of the current layer of 195 mm of insulation. The result of the difference has been presented below. See a summary of the result in the tables below. The complete result can be found in Appendix 8.

TABLE 40: SUMMARY OF WORST VALUES WITH ADDED INSULATION.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,4	25,9	15	0	0	4	0	0
RCP 2.6	27,9	26,3	18	0	2	5	0	1
RCP 4.5	28,0	26,4	21	1	3	6	1	2
RCP 8.5	28,7	26,9	24	5	5	6	3	2
RCP 8.5 MAX	30,5	28,8	47	9	13	24	4	5

TABLE 41: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING MORE INSULATION.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,1	-0,1	4	0	0	1	0	0
RCP 2.6	-0,1	-0,1	4	-1	0	1	-1	-1
RCP 4.5	-0,2	-0,2	2	-1	0	1	0	0
RCP 8.5	-0,1	-0,3	2	1	0	0	0	0
RCP 8.5 MAX	-0,1	-0,1	5	0	-1	1	0	0

TABLE 42: ENERGY CONSUMPTION FOR IMPLEMENTING MORE INSULATION.

[kWh/m^2, yr]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	37,9	34,7	31,2	27,2	20,3
Difference	-8,4	-7,7	-7,0	-5,9	-3,7

5.3.4.2 Less insulation

For this modification, the thicker insulation layer of 195 mm was removed from all exterior walls. The only layer of insulation remaining in the construction was the insulating layer of 70 mm mineral wool which also includes installations such as electricity and plumbing. See a summary of the result in the tables below. The complete result can be found in Appendix 9.

TABLE 43: SUMMARY OF WORST VALUES WITH LESS INSULATION.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,8	26,2	12	0	2	4	0	1
RCP 2.6	28,4	26,7	15	4	3	4	2	2
RCP 4.5	28,6	26,9	18	5	3	5	3	2
RCP 8.5	29,3	27,6	26	7	8	8	3	4
RCP 8.5 MAX	31,3	29,3	46	15	16	24	4	5

TABLE 44: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING LESS INSULATION.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	0,3	0,2	1	0	2	1	0	1
RCP 2.6	0,4	0,3	1	3	1	0	1	0
RCP 4.5	0,4	0,3	-1	3	0	0	2	0
RCP 8.5	0,5	0,4	4	3	3	2	0	2
RCP 8.5 MAX	0,7	0,4	4	6	2	1	0	0

TABLE 45: ENERGY CONSUMPTION FOR IMPLEMENTING LESS INSULATION.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Reference	46,3	42,6	38,2	33,1	24,0
Modified	80,5	74,6	67,6	59,2	43,5
Difference	34,2	32,0	29,4	26,1	19,5

5.3.5 Cooling system

In this case, air conditioning units have been added to the house to improve the thermal comfort inside. The units have been placed in the living rooms, kitchen, and bedrooms upstairs. Different units and systems could be used to remove heat but would result in different energy consumptions and different times to reach the required indoor climate. The result presented below is an example of units with an energy efficiency ratio (EER) of 6,3 and a maximum effect of 3,4 kW, which can be found on the market today when searching for units suitable for this floor area. For this simulation, all the windows have been closed with the assumption that the users will not have the windows open and use the air conditioning at the same time. See a summary of the result in the tables below. The complete result can be found in Appendix 10.

TABLE 46: SUMMARY OF WORST VALUES WITH AIR CONDITION.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	24,7	24,3	0	0	0	0	0	0
RCP 2.6	24,7	24,3	0	0	0	0	0	0
RCP 4.5	24,7	24,3	0	0	0	0	0	0
RCP 8.5	24,7	24,3	0	0	0	0	0	0
RCP 8.5 MAX	24,8	24,4	0	0	0	0	0	0

TABLE 47: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING AIR CONDITIONING.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-2,8	-1,7	-11	0	0	-3	0	0
RCP 2.6	-3,3	-2,1	-14	-1	-2	-4	-1	-2
RCP 4.5	-3,5	-2,3	-19	-2	-3	-5	-1	-2
RCP 8.5	-4,1	-2,9	-22	-4	-5	-6	-3	-2
RCP 8.5 MAX	-5,8	-4,5	-42	-9	-14	-23	-4	-5

TABLE 48: ENERGY CONSUMPTION FOR IMPLEMENTING AIR CONDITIONING.

[kWh/m^2, yr]	Today	RCP 2.6	RCP 4.5	RCP 8.5	RCP 8.5 MAX
Reference	46,3	42,6	38,2	33,1	24,0
Modified	47,4	44,1	40,1	35,7	28,1
Difference	1,1	1,5	1,9	2,6	4,1

5.3.6 Combination of earlier presented modifications

Sometimes modifications can be combined to reach full potential, which is something that has been tested in this section. When combining modifications, it is important to make sure that the different types do not work against each other. In this section, a combination of improvements has been tested. The changes done to the model in this combined solution were extended overhang of the roof and cantilever roof (see section 5.3.1.2), new windows (see section 5.3.2.1), night ventilation (see section 5.3.2.3), and lastly, added insulation (see section 5.3.4.1). See a summary of the result in the tables below. The complete result can be found in Appendix 11.

TABLE 49: SUMMARY OF WORST VALUES WITH COMBINED SOLUTION.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,0	24,7	5	0	0	3	0	0
RCP 2.6	27,5	25,1	5	0	0	3	0	0
RCP 4.5	27,7	25,3	6	0	0	3	0	0
RCP 8.5	28,5	25,9	9	2	0	3	1	0
RCP 8.5 MAX	29,9	27,4	20	7	4	6	3	2

TABLE 50: DIFFERENCE BETWEEN REFERENCE HOUSE AND IMPLEMENTING THE COMBINED SOLUTION.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	-0,5	-1,3	-6	0	0	0	0	0
RCP 2.6	-0,5	-1,3	-9	-1	-2	-1	-1	-2
RCP 4.5	-0,5	-1,3	-13	-2	-3	-2	-1	-2
RCP 8.5	-0,3	-1,3	-13	-2	-5	-3	-2	-2
RCP 8.5 MAX	-0,7	-1,5	-22	-2	-10	-17	-1	-3

TABLE 51: ENERGY CONSUMPTION FOR IMPLEMENTING THE COMBINED SOLUTION.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Reference	46,3	42,6	38,2	33,1	24,0
Modified	39,5	36,4	32,6	28,4	21,6
Difference	6,8	6,2	5,6	4,7	2,4

Chapter 6

Discussion

6.1 Changed outdoor climate

As can be seen in the result of Chapter 2, the temperatures in the Stockholm region will most likely keep on rising regardless of the scenario chosen. This is one of the reasons for displaying multiple scenarios of the possible future climate, because there is a wide range of possibilities that all depend on how the world, as a whole, acts to combat the increase in greenhouse gas emissions. No one knows what the future holds or what path will be taken. This is one of multiple reasons for adding the fourth and most extreme scenario (RCP 8.5 MAX) to the number of possible scenarios. That scenario might not be the most probable over a whole year in 2070, but it can be a representation of a summer with longer heat waves. The scenario could further be a good representation of a year closer to the end of the century since most houses probably stand longer than 50 years.

The scenarios are important factors for deciding the future climate, but the impact of these can only be somewhat predicted by the implementation of global and regional circulation models. The reliability of the results depends on the reliability of the models, scenarios and climate files they were built on, meaning that choosing global and regional models could have a fairly large influence on the absolute numbers of the result. This has been taken into consideration when choosing models, which is why, for example, the average of an ensemble of nine models has been chosen to increase the validity of the results.

Another variable determining the absolute value of the future climate file, is the chosen present climate file. If the hourly temperature changes in the present file, the hourly value in the future file will roughly vary with corresponding degrees. That is why the significance of a representative climate file is of importance and why a typical meteorological year was constructed of the latest years.

The morphing of the final hourly climate file into a future climate file can be done in various ways, returning various results. The method chosen delivered four morphed climate files with fairly small differences to the predicted climate scenarios when focusing on the most important months, namely the summer months. To further justify the morphing method, the four morphed climate files were compared to three other climate indexes for the predicted climates in which all fall into the span of the morphed files.

6.2 The representative house

Many factors could change the result of these simulations, one of them being the studied house. The building consists of many parts with even more alternative modifications that would change the outcome of these kinds of simulations. To be able to create a complete house to study, many choices of systems and materials had to be made. These choices have been based on statistics, research, facts, and requirements that support the chosen solutions. Meaning that there exist other solutions that could have been used in the same situation, which would have achieved the targeted values in the requirements. With this in mind, it can be argued that the studied house could be built around 2020, but do not represent all houses built today, just a percentage of them presented together in a complete house.

The option for people without professional knowledge of building design or building techniques to create and design their own house today makes the variation on the market quite large, hard to predict, and to cover with one building. Therefore, every part of the construction must be evaluated, chosen separately, and then tested together concerning the regulations. Section 3.3.7 show that it would be possible to build this house, with all parts set together, today, when considering the requirements and data for energy consumption. If materials and systems were to be changed, the result would of course also change, but the results in this thesis are based on the same original house. Meaning that the proportions showing in the result of the indoor environment and the outcome of the improvements can be used for discussion and conclusions with well-founded arguments.

6.3 Indoor environment

As described before, the indoor environment will be influenced by more parameters than solely the operative temperature, but the operative temperature has been argued to have a big influence on the experienced thermal comfort of the occupants. As presented in Chapter 1, the operative temperature will affect the feel and productivity of inhabitants, making this an important parameter to investigate. However, high temperatures do not automatically indicate a low thermal comfort, it is rather an indication that the comfort could be low. For example, there may exist shorter periods where both temperatures and air velocities are high, which might have a counterbalancing effect. The threshold values of the operative temperatures decided could have been different. This, however, would not have changed the actual result of the simulations but merely the discussion around the values.

The result of the simulations shows that the building designed in Chapter 3 with the 2020 outdoor climate of Chapter 2, passes the threshold values decided on for every room in the house. For RCP 2.6 and 4.5, however, all rooms on the bottom floor passed the threshold but not the upper floor. Further, none of the rooms in RCP 8.5 and 8.5 MAX passed the threshold. The energy demand decreased with each scenario probably because each scenario is warmer than the other.

6.4 Improvements to the building

6.4.1 External Shading

Different solutions using external shading were tested to evaluate the difference and the possibility to improve different parameters during the critical months without worsening the energy demand.

6.4.1.1 Drop arm awning covering all windows

The addition of drop arm awnings has resulted in lower overall temperatures probably due to the shading. The addition has, however, increased the overall energy performance and not lowered the temperatures below any threshold. The increased energy performance is likely due to the electrical motors controlling the sunshades. This implementation requires an initial cost for purchasing, mounting, and wiring. Furthermore, maintenance and electricity will be a recurring cost throughout its lifetime which is something to consider for both economic and ecological sustainability. A benefit this implementation brings beyond the lowered temperatures is its flexibility, the awnings can be drawn or raised depending on the user’s desire. The drawback of this flexibility is reliability where parts might break if not used correctly or simply by ware.

6.4.1.2 Larger roof overhang and adding cantilever roof

The larger roof and added cantilever roof have resulted in lower temperatures for all scenarios probably due to the shading potential it gives. The implementation has, however, not lowered the temperatures below the threshold values for the future scenarios and can therefore not be seen as a sole solution to the overheating problem. Furthermore, the implementation increases the energy consumption compared to the reference house probably due to shading in wintertime. The energy performance will likely increase in real life since the cantilever roof contributes to a thermal bridge. This implementation requires a high initial cost for purchasing and constructing, but afterward, the recurring cost for maintenance should be lower than for active solutions. Another profit this implementation brings is that it shelters the façade and windows from rain and sunshine, reducing these eroding forces. It can furthermore be seen as a sustainable modification to the building as it is completely passive, reduces indoor temperatures, and is of low maintenance.

6.4.2 Windows

6.4.2.1 New windows

The modification with new windows specifically designed to minimize the solar heat gain has resulted in better values in all rooms. This was considered as an advantage and could be considered as an option to improve the house. The negative aspect is the increased energy consumption, as can be seen in Table 25. This was probably since that the house loses the incoming solar heat during wintertime, making the demand for heating larger during the colder months than before, resulting in an increased total energy demand.

The benefit of active external shading was that it could be removed to absorb the “free heat” during heating season, which was not an option when changing the windows to reflect the sunlight. This disadvantage makes the modification better to combine with other options that could compensate for this increased energy consumption. It is probably possible to purchase windows with an even better heat transfer coefficient (U) to minimize the risk of an increased energy consumption. This will then probably be a question of economics with a potential higher initial investment. One option to reduce that cost could be to only change the windows that are the most exposed to sunshine and possibly select a cheaper alternative for the more shaded parts. This could be in different latitudes or if there is external shading in the garden around the house, for example, trees or other buildings, where regular windows can be used to lower the initial costs. The geometry of the house will also influence where there is more sunlight reaching inside.

6.4.2.2 Changed position of current windows

Lowered temperatures could not be noticed by changing the position of the windows. The window area has been kept the same and the difference in position was small due to the small surrounding area of the house, making the possible placement windows quite limited. With a larger house, the façade area for possible window placement would be larger and could possibly influence the operative temperature inside. Another option could be to remove some unnecessary windows entirely instead of rearranging them. That would probably lead to a decreased energy usage since the overall mean heat transfer coefficient (U) would decrease due to increased wall area and reduced window area.

6.4.2.3 Using the windows for night-ventilation

The implementation of nighttime ventilation reduces the temperatures a great deal and can potentially be seen as a sole solution for the overheating problem in RCP 2.6. It could further be discussed if the thermal comfort of the inhabitants increases more than what can be seen in the reduced temperatures. The ventilation does in fact increase the air velocity, which is a variable in the thermal comfort equation as stated earlier. Night ventilation does, however, increase the energy usage, which is probably due to the automation installed. It requires an initial cost of mounting, wiring, and testing, and it will probably require maintenance and compatibility updates throughout its lifetime. Another benefit of implementing night ventilation macros is that it is almost invisible. However, this modification has been done by opening the windows which could be a security problem for instance. The modification does, fortunately, not have to be implemented on windows, it could for instance be implemented on smaller hatches or ducts instead.

6.4.3 Ventilation system

6.4.3.1 Change of ventilation system to a balanced ventilation system

The change of ventilation system brought mixed results, the temperatures did decrease but not by much, and the number of hot days increased for some scenarios. The energy consumption was, however, reduced for all scenarios except the most extreme one, possibly due to the higher efficiency air-to-air heat exchanger. The reason why the energy consumption increased in RCP 8.5 MAX might be because although the efficiency of the air-to-air heat exchanger is higher it has little to no benefit in summertime when temperatures are high enough. The air-to-water heat exchanger does, however, heat the consumable hot water in summers as well, making it useful all year round. A balanced ventilation system comes with a higher initial cost than an exhaust system, but since the energy consumption is reduced, it might pay itself off after some years. Further benefits are that other factors of the air can be controlled when the inlet is controlled, such as temperature, humidity, and cleanliness.

6.4.3.2 Change the constant airflow to variable airflow
The implementation of adding control over the airflow did not improve the temperatures, but it did reduce the energy consumption more than for the constant airflow. This is probably because the ventilation is reduced to a level below the constant airflow when ventilation is not needed. The initial cost does, however, probably increase with this modification compared to the constant airflow. This since each room with ventilation also needs sensors that measure the carbon dioxide and temperature. Further, the automation and air handling unit probably cost more as well. But there might, however, exist a break-even point for this modification as well.

6.4.4 Insulation

6.4.4.1 Added insulation
When adding insulation, the maximum temperature decreased some, but the number of days in a row with hot temperatures increased. Probably because added insulation causes less heat flow through the wall, resulting in less heat entering the building but further causing extended containment periods. This modification by itself might not be optimal, due to the increase of days with higher temperatures, but to lower the maximum average temperatures, this could be considered an option. In addition to the improved temperatures, the energy consumption decreased, strengthening the argument for adding insulation being a sustainable improvement. This even though adding insulation entails a high initial cost and an increased material usage.

6.4.4.2 Less insulation
When observing warmer climates, it is possible to conclude that less insulation would be needed to reduce the highest peaks in temperature, since it is a common sight closer to the equator. With the results presented it can be determined that such a conclusion would be false. The maximum temperature was not reduced, and the energy consumption increased dramatically, probably due to an increased heating demand during wintertime. Just because the climate might become warmer, Stockholm will probably still have a relatively high heating demand. The maximum temperatures were higher than for the reference house, and the combination with the drastically increased energy consumption have made this a poor modification to improve the indoor climate sustainably. Additionally, with that drastically increased energy demand, the building would possibly not be permitted due to the strict energy requirements.

6.4.5 Cooling system

The implementation of a cooling system was dependent on the actual units and components of the system. It was possible to reach low enough temperatures for quite dramatic weather conditions, but the sustainability aspect should carefully be considered. Firstly, the efficiency of the system varied some and was mostly dependant on the initial cost, making it a question of economical sustainability. It can be seen in Table 48, that the difference in energy consumption between the modified house and the reference house increased with warmer scenarios, even though the heating demand decreased. The results further indicate that the difference in energy consumption would increase with time when a cooling system was installed compared to the reference house, even if the proportions would differ depending on the efficiency of the system and units installed. There exists a risk that the increased energy consumption exceeds the energy requirements of BFS 2011:6. If that would be the case, more modifications will have to be done to lower the consumption beneath the requirements.

The consideration of economical sustainability is important throughout its lifetime because of the technical knowledge needed and potential maintenance. In addition to economic and environmental sustainability, social sustainability should also be considered. For this case, the units were installed in several rooms, which probably changed the interior appearance. The visual appearance and discretion are, in many cases, dependant on the price, which shows that the three parts of sustainability often is connected and dependent on each other. For example, a more expensive system could have a more discrete implementation and appearance.

6.4.6 Combination of earlier presented modifications

This final modification was a combination of an extended overhang of the roof and cantilever roof, new windows, night ventilation, and added insulation. The separate changes have been discussed above, and together they reduce the maximum temperatures, periods of heatwave, and at the same time, reduce the energy consumption. As mentioned earlier, the absolute energy consumption depends on initial conditions, but a trend can be seen in the result making it clear that the indoor environment could be improved with these passive strategies without drastically increasing the consumption. The combined modification could be seen as a solution to the overheating problem for RCP 2.6 and 4.5, and with some adjustments possibly even RCP 8.5. When comparing the combined modifications to the installation of a cooling system, it can be seen that the combination reduces the energy consumption and improves the maximum indoor temperatures, unlike the air conditioning that reduces temperatures in exchange for higher energy consumption. All these changes do, however, most likely come with a higher initial cost than air conditioning, which might be the reason for many owners taking that route. Furthermore, these combined modifications require knowledge in multiple different areas unlike the instalment of most air conditioning units.

As stated in Chapter 1, a reduction of the operative temperature as shown in Table 50 can make a difference in the wellbeing of the occupants, and also the risk of other health issues. Trends of an increased cooling demand and decreasing heating demand have been identified from the results and are in line with the conclusion drawn in the studies presented in section 1.1. Meaning that the trend of future increased temperatures will continue, as well as the risk of a worsened wellbeing and health of inhabitants.

Chapter 7

Conclusion and future research

The main hypothesis tested in this thesis has been discussed and concluded in the following paragraphs.

As can be seen in Chapter 2, the climate both globally and regionally will become warmer, the only question is - at what pace? Furthermore, it can be seen in Chapter 4 that this, most probably, has a large effect on the simulated indoor environment of a model built on statistics of houses built today. The simulated indoor environment could be considered as a strong indication that the actual indoor environment and thermal comfort of single-family houses will be affected as well. It is difficult to predict whether single-family houses in 2070 will be considered unhabitable, since it is determined by a wide range of variables. But thermal comfort is one of the variables and operative temperature a large part of thermal comfort. Since the operative temperature increases, there is a risk of future indoor climates not being habitable.

As can be seen in the results of Chapter 5, the simulated indoor environment can be improved by changing or adding parts to the model. It has further been noticed that several modifications can be implemented without drastically increasing the energy consumption, which is one part of the sustainability requirement. Furthermore, it can be difficult to evaluate whether a modification is sustainable in all aspects, but some aspects have been discussed in Chapter 6. The combination of improvements, in particular, (section 5.3.6 and 6.4.6) have yielded results indicating that a sustainable solution can be implemented to increase the thermal comfort to habitable levels in a majority of the scenarios.

The results presented in this thesis imply that quite simple modifications can be made to a house in order to improve the indoor environment sustainably. Therefore, further research can be made to inspect whether and how simple solutions can be implemented early in the building process to increase a building's resistance to changes in climate and to reduce energy consumption. Finally, several modifications can be done to a building in order to change the results. This thesis only covers a few basic modifications without variations, meaning that it is possible that the best solutions have not been found yet.

References

Asp, M., Berggreen-Clausen, S., Berglöv, G., Björck, E., Johnell, A., Mårtensson, A., Nylén, L., Ohlsson, A., Persson, H. & Sjökvist, E. (2015). *Klimatologi nr 21: Framtidsklimat i Stockholms län - enligt RCP-scenarier*. ISSN: 1654-2258

Autodesk (n.d.a). *CFD Features 2019*. https://www.autodesk.com/products/cfd/features [2020-12-02].

Autodesk (a.d.b). *Autodesk CFD | Overview.* https://www.autodesk.com/products/cfd/overview [2020-12-02].

Autodesk (n.d.c). *Humidity.* https://knowledge.autodesk.com/support/cfd/learn-explore/caas/CloudHelp/cloudhelp/2019/ENU/SimCFD-UsersGuide/files/GUID-599627EC-C556-42DC-9415-BB50BFCBFFC8-htm.html [2020-12-02].

Belcher, S., Hacker, J. & Powell, D. (2005). Constructing design weather data for future climates. *Building Services Engineering Research and Technology*, 26(1), pp. 49–61, doi:10.1191/0143624405bt112oa.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C. & Kristjánsson, J. E. (2013). The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate. *Geoscientific Model Development*, 6(3), pp. 687–720, doi:10.5194/gmd-6-687-2013.

Berg, S. A. (2013). *Grundläggning och undergrund*. Stockholm: Lärnö. ISBN: 978-91-977925-6-1

BFS 1998:38. *Boverkets byggregler (föreskrifter och allmänna råd).* Karlskrona: Boverket

BFS 2011:6. *Boverkets byggregler (föreskrifter och allmänna råd) - med ändringar till och med BFS 2020:4.* Karlskrona: Boverket

Björk, C., Nordling, L. & Reppen, L. (2015). *Så byggdes villan: svensk villaarkitektur från 1890 till 2010*. 2nd ed. Stockholm: Svensk Byggtjänst. ISBN: 978-91-7333-689-5

Bjørnæs, C. (2015). *A guide to Representative Concentration Pathways - Cicero*. https://www.cicero.oslo.no/en/posts/news/a-guide-to-representative-concentration-pathways [2021-02-16].

Boverket (2010). Energi i bebyggelsen - tekniska egenskaper och beräkningar, resultat från projektet BETSI, Karlskrona: Boverket.

Boverket (2018). *Boverkets byggregler och klimatanpassning*. Karlskrona: Boverket. No. 2018:10. Karlskrona: Boverket. ISBN: 978-91-7563-543-9

Bring, A., Sahlin, P. & Vuolle, M. (1999). *Models for Building Indoor Climate and Energy Simulation*. Stockholm: Kungliga Tekniska Högskolan. No. 1.02.

Byggvärlden (2020). Pandemin har drivit upp bostadsmarknaden. *Byggvärlden*. https://www.byggvarlden.se/pandemin-har-drivit-upp-bostadsmarknaden-183782/nyhet.html [2021-03-26]

Cao, M. & Wei, J. (2005). Stock market returns: A note on temperature anomaly. *Journal of Banking & Finance*, 29(6), pp. 1559–1573, doi:10.1016/j.jbankfin.2004.06.028.

Carlholmer, R. (2021). RE: Examensarbete byggteknik. [email]

Chan, A. L. S. (2011). Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong. *Energy and Buildings*, 43(10), pp. 2860–2868, doi:10.1016/j.enbuild.2011.07.003.

Chylek, P., Li, J., Dubey, M. K., Wang, M. & Lesins, G. (2011). *Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2*. Aerosols/Atmospheric Modelling/Troposphere/Physics (physical properties and processes). preprint.

Clements-Croome, D. (2014). *Sustainable Intelligent Buildings for Better Health, Comfort and Well-Being*. https://derekcroome.com/document-files/DENZERO.pdf [2021-03-21]

Clements-Croome, D. (2015). Creative and productive workplaces: a review. *Intelligent Buildings International*, 7(4), pp. 164–183, doi:10.1080/17508975.2015.1019698.

Clements-Croome, D. (2008). Work performance, productivity and indoor air. *Scandinavian Journal of Work, Environment and Health, Supplement*, (4), pp. 69–78.

Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A. & Woodward, S. (2011). Development and evaluation of an Earth-System model – HadGEM2. *Geoscientific Model Development*, 4(4), pp. 1051–1075, doi:10.5194/gmd-4-1051-2011.

Cui, W., Cao, G., Park, J. H., Ouyang, Q. & Zhu, Y. (2013). Influence of indoor air temperature on human thermal comfort, motivation and performance. *Building and Environment*, 68, pp. 114–122, doi:10.1016/j.buildenv.2013.06.012.

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

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N. & Vuichard, N. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Climate Dynamics*, 40(9–10), pp. 2123–2165, doi:10.1007/s00382-012-1636-1.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., Stouffer, R. J., Cooke, W., Dunne, K. A., Harrison, M. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Phillipps, P. J., Sentman, L. T., Samuels, B. L., Spelman, M. J., Winton, M., Wittenberg, A. T. & Zadeh, N. (2012). GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. *Journal of Climate*, 25(19), pp. 6646–6665, doi:10.1175/JCLI-D-11-00560.1.

Energimyndigheten (2020). Energistatistik för småhus 2019. https://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/energistatistik-for-smahus/?currentTab=0#mainheading [2021-03-02]

EQUA (2020). *IDA ICE - Simulation Software*. https://www.equa.se/en/ida-ice [2020-11-30].

European Commission (2021). *Energy performance of buildings directive*. https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en [2021-03-26].

FoHMFS 2014:17. *Folkhälsomyndighetens allmänna råd om temperatur inomhus*. Stockholm: Folkhälsomyndigheten

Folkhälsomyndigheten (FoHM) (2015). *Hälsoeffekter av höga temperaturer. En kunskapssammanställning*. Folkhälsomyndigheten. ISBN: 978-91-7603-487-3

Grüne-Yanoff, T. (2020). Experiments, models and methodology.

Hazeleger, W., Severijns, C., Semmler, T., Ştefănescu, S., Yang, S., Wang, X., Wyser, K., Dutra, E., Baldasano, J. M., Bintanja, R., Bougeault, P., Caballero, R., Ekman, A. M. L., Christensen, J. H., van den Hurk, B., Jimenez, P., Jones, C., Kållberg, P., Koenigk, T., McGrath, R., Miranda, P., van Noije, T., Palmer, T., Parodi, J. A., Schmith, T., Selten, F., Storelvmo, T., Sterl, A., Tapamo, H., Vancoppenolle, M., Viterbo, P. & Willén, U. (2010). EC-Earth: A Seamless Earth-System Prediction Approach in Action. *Bulletin of the American Meteorological Society*, 91(10), pp. 1357–1364, doi:10.1175/2010BAMS2877.1.

Hellström, P. (2018). *Assessing the impact of the indoor environment on productivity*. Stockholm: Kungliga Tekniska Högskolan. TRITA-ABE-MBT-18181

Hemnet (n.d.). *Nyproduktion till salu - Stockholms län*. Nyproduktion till salu - Stockholms län. https://www.hemnet.se/bostader?location_ids%5B%5D=17744&item_types%5B%5D=villa&new_construction=only [2021-03-02].

Hemnet (2020). *Efter covid-19 – förändrat sökbeteende på Hemnet*. Hemnet. https://www.hemnet.se/artiklar/bostadsmarknaden/2020/09/22/efter-covid-19-annorlunda-sokbeteende-pa-hemnet [2021-03-26].

Hemnet (2021a). *Hemnet om bostadsmarknaden i december 2020*. Hemnet. https://www.hemnet.se/artiklar/bostadsmarknaden/2021/01/13/hemnet-om-bostadsmarknaden-i-december-2020 [2021-03-26].

IPCC (2013). *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2014). *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.

Lan, L., Pan, L., Lian, Z., Huang, H. & Lin, Y. (2014). Experimental study on thermal comfort of sleeping people at different air temperatures. *Building and Environment*, 73, pp. 24–31, doi:10.1016/j.buildenv.2013.11.024.

Länsförsäkringar Fastighetsförmedling (2021). *Ett år med coronapandemin – så påverkades bostadsmarknaden.*

Mäklarhuset (2020). *Skifte på bostadsmarknaden – villaägare vinnare under 2020*. https://www.mynewsdesk.com/se/maklarhuset/pressreleases/skifte-paa-bostadsmarknaden-villaaegare-vinnare-under-2020-3054819 [2021-03-26].

Markelius, A. (2021). *COVID-19 har gjort hemmet till den nya marknadsplatsen*. Accenture. https://www.accenture.com/se-en/about/newsroom/company-news-release-covid-consumer-research [2021-03-26].

Moazami, A., Nik, V. M., Carlucci, S. & Geving, S. (2019). Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions. *Applied Energy*, 238, pp. 696–720, doi:10.1016/j.apenergy.2019.01.085.

Niemelä, R., Hannula, M., Rautio, S., Reijula, K. & Railio, J. (2002). The effect of air temperature on labour productivity in call centres—a case study. *Energy and Buildings*, 34(8), pp. 759–764, doi:10.1016/S0378-7788(02)00094-4.

Ormandy, D. & Ezratty, V. (2012). Health and thermal comfort: From WHO guidance to housing strategies. *Energy Policy*, 49, pp. 116–121, doi:10.1016/j.enpol.2011.09.003.

Pilkington (n.d.). *Pilkington Suncool^{TM}-serien*. http://www.pilkington.com/sv-se/se/products/funktionsomrade/solskydd/pilkington-suncool [2021-05-10].

Popke, D., Stevens, B. & Voigt, A. (2013). Climate and climate change in a radiative-convective equilibrium version of ECHAM6: RCE WITH ECHAM6. *Journal of Advances in Modeling Earth Systems*, 5(1), pp. 1–14, doi:10.1029/2012MS000191.

Sjökvist, E., Axén Mårtensson, J., Dahné, J., Köplin, N., Björck, E., Nylén, L., Berglöv, G., Brunell Tengdelius, J., Nordborg, D., Hallberg, K., Södling, J. & Berggreen Clausen, S. (2015). *Klimatologi nr 15: Klimatscenarier för Sverige: Bearbetning av RCP-scenarier för meteorologiska och hydrologiska effektstudier*. Norrköping: Sveriges meteorologiska och hydrologiska institut. No. 15.

SMHI (n.d.a). *Klimatscenarier Om analysen*. https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier/info/haag#omens [2021-03-01].

SMHI (n.d.b). *Klimatscenarier*. https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier/ [2021-03-10].

SMHI (n.d.c). *Varningsdefinitioner*. https://www.smhi.se/vader/varningar-och-risker/varningsdefinitioner [2021-04-08].

SMHI (2015). *Hur ska scenariodata tolkas?* https://www.smhi.se/klimat/framtidens-klimat/vagledning-klimatscenarier/hur-ska-scenariodata-tolkas-1.80286 [2021-03-9].

SMHI (2018). *Vad är RCP?* Vad är RCP? https://www.smhi.se/klimat/framtidens-klimat/vagledning-klimatscenarier/vad-ar-rcp-1.80271 [2021-02-16].

SMHI (2019a). *Vind*. https://www.klimatanpassning.se/hur-klimatet-forandras/klimateffekter/vind-1.21290 [2021-05-7].

SMHI (2019b). *Luftfuktighet*. https://www.klimatanpassning.se/hur-klimatet-forandras/klimateffekter/luftfuktighet-1.35753 [2021-05-7].

SMHI (2020a). *Klimatindikator - temperatur*. https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/klimatindikator-temperatur-1.2430 [2020-11-29].

SMHI (2020b). *Hur fungerar en klimatmodell?* https://www.smhi.se/kunskapsbanken/klimat/klimatmodeller-och-scenarier/hur-fungerar-en-klimatmodell-1.470 [2021-02-25].

SS 91 42 21 (2006). *Building design – Housing – Interior dimensions*. 5th ed. Stockholm: Swedish Standards Institute (SIS).

SS-EN 1990 (2002). *Grundläggande dimensioneringsregler för bärverk*. Stockholm: Swedish Standards Institute (SIS).

SS-EN ISO 7730 (2006). *Ergonomi för den termiska miljön - Analytisk bestämning och bedömning av termisk komfort med hjälp av indexen PMV och PPD samt kriterier för lokal termisk komfort*. Stockholm: Swedish Standards Institute (SIS).

SS-EN ISO 15927-4 (2005). *Fukt- och värmetekniska egenskaper hos byggnader – Klimatdata – Del 4: Timbaserade data för att bestämma årlig energianvändning för uppvärmning och kylning*. 1st ed. Stockholm: Swedish Standards Institute (SIS).

Statistiska centralbyrån (SCB) (n.d.). *Antal lägenheter efter region, hustyp och bostadsarea. År 2013-2019*. https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BO__BO0104__BO0104D/BO0104T5/ [2021-03-2].

Svantesson, M. (2021). Den representativa villan 2021 - Examensarbete KTH. [email]

Sveby (n.d.). *Sveby | Branchstandard för energi i byggnader*. http://www.sveby.org/ [2021-03-26].

Sveby (2016). *Klimatdatafiler för Sveriges kommuner*. Stockholm: Sveby.

Sweden Green Building Council (SGBC) (2020). Miljöbyggnad 3.1 - Nybyggnad. https://www.sgbc.se/app/uploads/2020/05/Miljöbyggnad-3.1-Nybyggnad.pdf [2021-03-02]

Tanabe, S., Kobayashi, K., Kiyota, O., Nishihara, N. & Haneda, M. (2009). The effect of indoor thermal environment on productivity by a year-long survey of a call centre. *Intelligent Buildings International*, 1(3), pp. 184–194, doi:10.3763/inbi.2009.0005.

Voldoire, A., Sanchez-Gomez, E., Salas y Mélia, D., Decharme, B., Cassou, C., Sénési, S., Valcke, S., Beau, I., Alias, A., Chevallier, M., Déqué, M., Deshayes, J., Douville, H., Fernandez, E., Madec, G., Maisonnave, E., Moine, M.-P., Planton, S., Saint-Martin, D., Szopa, S., Tyteca, S., Alkama, R., Belamari, S., Braun, A., Coquart, L. & Chauvin, F. (2012). The CNRM-CM5.1 global climate model: description and basic evaluation. *Climate Dynamics*, 40(9–10), pp. 2091–2121, doi:10.1007/s00382-011-1259-y.

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., Nozawa, T., Kawase, H., Abe, M., Yokohata, T., Ise, T., Sato, H., Kato, E., Takata, K., Emori, S. & Kawamiya, M. (2011). *MIROC-ESM: model description and basic results of CMIP5-20c3m experiments*. Climate and Earth System Modeling. preprint.

World Health Organization (WHO) (2012). *Environmental health inequalities in Europe: assessment report*. Copenhagen: World Health Organization, Regional Office for Europe. ISBN: 978-92-890-0260-8

Widström, T. (2019). *Simulation of historic buildings for enhancement of preservation and energy performance – issues and methods*. Doctoral Thesis. Stockholm: Kungliga Tekniska Högskolan

Åkesson, Å. (2021). VB: Lead IVT.se. [email]

Appendix

Appendix 1 – External shading

TABLE 52. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C
Ground Floor	Kitchen	26,5	25,0	3	0	0	2	0	0
	Bathroom	25,2	24,6	0	0	0	0	0	0
	Livingroom	26,5	25,1	3	0	0	2	0	0
Upper Floor	Bedroom	27,3	25,8	8	0	0	3	0	0
	Master bedroom	26,1	25,4	2	0	0	2	0	0
	Bathroom	26,0	25,2	0	0	0	0	0	0
	Livingroom	26,9	25,8	7	0	0	3	0	0

TABLE 53. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C
Ground Floor	Kitchen	26,9	25,4	6	0	0	3	0	0
	Bathroom	25,6	24,9	0	0	0	0	0	0
	Livingroom	26,9	25,5	7	0	0	3	0	0
Upper Floor	Bedroom	27,8	26,3	11	0	1	4	0	1
	Master bedroom	26,6	25,9	4	0	0	2	0	0
	Bathroom	26,3	25,6	2	0	0	1	0	0
	Livingroom	27,4	26,2	8	0	2	3	0	1

TABLE 54. VALUES FROM SIMULATIONS FOR YEAR 2070 FOR SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,1	25,6	7	0	0	3	0	0
	Bathroom	25,8	25,1	0	0	0	0	0	0
	Livingroom	27,1	25,7	7	0	0	3	0	0
Upper Floor	Bedroom	28,0	26,5	14	0	2	4	0	1
	Master bedroom	26,8	26,1	5	0	1	3	0	1
	Bathroom	26,5	25,7	4	0	0	2	0	0
	Livingroom	27,6	26,4	10	0	2	4	0	1

TABLE 55. VALUES FROM SIMULATIONS FOR YEAR 2070 FOR SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,7	26,2	8	0	2	3	0	1
	Bathroom	26,3	25,6	4	0	0	2	0	0
	Livingroom	27,7	26,3	9	0	2	3	0	1
Upper Floor	Bedroom	28,6	27,0	18	4	3	4	3	2
	Master bedroom	27,3	26,6	10	0	3	4	0	2
	Bathroom	27,0	26,2	5	0	2	3	0	1
	Livingroom	28,1	26,9	12	1	4	4	1	2

TABLE 56. VALUES FROM SIMULATIONS FOR YEAR 2070 FOR SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	29,0	27,5	23	4	5	8	2	3
	Bathroom	27,7	26,9	9	0	5	4	0	3
	Livingroom	29,0	27,6	24	4	7	8	2	4
Upper Floor	Bedroom	30,5	28,6	40	9	9	11	3	4
	Master bedroom	29,1	28,3	20	5	8	5	3	4
	Bathroom	28,6	27,8	12	4	5	4	2	3
	Livingroom	29,6	28,3	33	8	11	11	4	5

TABLE 57. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,3	25,8	8	0	0	3	0	0
RCP 2.6	27,8	26,3	11	0	2	4	0	1
RCP 4.5	28,0	26,5	14	0	2	4	0	1
RCP 8.5	28,6	27,0	18	4	4	4	3	2
RCP 8.5 MAX	30,5	28,6	40	9	11	11	4	5

TABLE 58. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,8	2,6	2,5	2,3	2,1
Electric heating	15,3	15,1	14,8	14,3	13,4
Top up heating	28,9	25,4	21,4	16,9	8,8
Equipment	17,3	17,3	17,3	17,3	17,3
Total	74,4	70,6	66,1	60,9	51,8

Appendix 2 – Extended roof and cantilever roof

TABLE 59. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,5	25,0	4	0	0	2	0	0
	Bathroom	25,5	24,8	0	0	0	0	0	0
	Livingroom	26,6	25,1	4	0	0	2	0	0
Upper Floor	Bedroom	27,3	25,9	8	0	0	3	0	0
	Master bedroom	26,1	25,4	1	0	0	1	0	0
	Bathroom	26,0	25,1	0	0	0	0	0	0
	Livingroom	26,9	25,7	7	0	0	3	0	0

TABLE 60. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,0	25,4	7	0	0	3	0	0
	Bathroom	25,9	25,3	0	0	0	0	0	0
	Livingroom	27,0	25,5	7	0	0	3	0	0
Upper Floor	Bedroom	27,9	26,3	11	0	1	4	0	1
	Master bedroom	26,6	25,8	3	0	0	2	0	0
	Bathroom	26,4	25,5	2	0	0	1	0	0
	Livingroom	27,3	26,0	8	0	1	3	0	1

TABLE 61. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,2	25,6	8	0	0	3	0	0
	Bathroom	26,1	25,5	2	0	0	2	0	0
	Livingroom	27,2	25,7	8	0	0	3	0	0
Upper Floor	Bedroom	28,1	26,5	13	1	2	4	1	1
	Master bedroom	26,8	26,0	5	0	1	3	0	1
	Bathroom	26,6	25,7	4	0	0	2	0	0
	Livingroom	27,5	26,3	8	0	2	3	0	1

TABLE 62. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,6	26,2	10	0	2	3	0	1
	Bathroom	26,6	26,0	5	0	0	3	0	0
	Livingroom	27,8	26,3	10	0	2	3	0	1
Upper Floor	Bedroom	28,7	27,1	18	4	3	4	3	2
	Master bedroom	27,3	26,6	10	0	3	4	0	2
	Bathroom	27,1	26,2	6	0	1	3	0	1
	Livingroom	28,1	26,8	11	1	4	4	1	2

TABLE 63. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	29,1	27,5	24	4	6	8	2	3
	Bathroom	28,1	27,4	11	1	5	5	1	3
	Livingroom	29,1	27,6	25	4	7	8	2	4
Upper Floor	Bedroom	30,5	28,6	40	9	9	11	3	4
	Master bedroom	29,0	28,2	19	5	7	5	3	4
	Bathroom	28,6	27,7	12	4	5	4	2	3
	Livingroom	29,5	28,2	30	8	10	11	4	5

TABLE 64. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,3	25,9	8	0	0	3	0	0
RCP 2.6	27,9	26,3	11	0	1	4	0	1
RCP 4.5	28,1	26,5	13	1	2	4	1	1
RCP 8.5	28,7	27,1	18	4	4	4	3	2
RCP 8.5 MAX	30,5	28,6	40	9	10	11	4	5

TABLE 65. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,8	2,7	2,5	2,3	2,1
Electric heating	15,4	15,2	14,9	14,4	13,6
Top up heating	29,6	26,2	22,1	17,4	9,2
Equipment	17,3	17,3	17,3	17,3	17,3
Total	75,3	71,5	66,9	61,6	52,3

Appendix 3 – New Windows

TABLE 66. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,1	24,7	2	0	0	2	0	0
	Bathroom	25,1	24,7	0	0	0	0	0	0
	Livingroom	26,1	24,8	3	0	0	2	0	0
Upper Floor	Bedroom	27,1	25,6	7	0	0	3	0	0
	Master bedroom	25,8	25,2	0	0	0	0	0	0
	Bathroom	25,9	25,0	0	0	0	0	0	0
	Livingroom	26,5	25,4	3	0	0	2	0	0

TABLE 67. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,4	25,1	3	0	0	2	0	0
	Bathroom	25,4	24,8	0	0	0	0	0	0
	Livingroom	26,5	25,2	3	0	0	2	0	0
Upper Floor	Bedroom	27,6	26,1	8	0	1	3	0	1
	Master bedroom	26,2	25,6	1	0	0	1	0	0
	Bathroom	26,3	25,4	3	0	0	2	0	0
	Livingroom	26,9	25,8	7	0	0	3	0	0

TABLE 68. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,6	25,3	4	0	0	2	0	0
	Bathroom	25,6	25,0	0	0	0	0	0	0
	Livingroom	26,7	25,4	5	0	0	2	0	0
Upper Floor	Bedroom	27,8	26,2	11	0	1	4	0	1
	Master bedroom	26,4	25,8	3	0	0	2	0	0
	Bathroom	26,4	25,6	4	0	0	2	0	0
	Livingroom	27,1	25,9	7	0	0	3	0	0

TABLE 69. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,2	25,8	7	0	0	3	0	0
	Bathroom	26,1	25,5	1	0	0	1	0	0
	Livingroom	27,2	25,9	7	0	0	3	0	0
Upper Floor	Bedroom	28,4	26,8	14	3	2	4	2	1
	Master bedroom	26,9	26,3	6	0	2	3	0	2
	Bathroom	26,9	26,1	5	0	1	2	0	1
	Livingroom	27,6	26,5	9	0	3	4	0	2

TABLE 70. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,6	27,1	15	4	5	5	2	3
	Bathroom	27,5	26,8	8	0	5	4	0	3
	Livingroom	28,6	27,2	16	4	5	5	2	3
Upper Floor	Bedroom	30,2	28,3	34	8	9	10	3	4
	Master bedroom	28,6	27,9	13	2	6	4	2	4
	Bathroom	28,6	27,5	13	4	5	4	2	3
	Livingroom	29,0	27,9	22	4	8	11	2	4

TABLE 71. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,1	25,6	7	0	0	3	0	0
RCP 2.6	27,6	26,1	8	0	1	3	0	1
RCP 4.5	27,8	26,2	11	0	1	4	0	1
RCP 8.5	28,4	26,8	14	3	3	4	2	2
RCP 8.5 MAX	30,2	28,3	34	8	9	11	3	4

TABLE 72. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,8	2,6	2,5	2,3	2,1
Electric heating	15,7	15,6	15,2	14,8	13,9
Top up heating	28,9	25,5	21,6	16,9	8,9
Equipment	17,3	17,3	17,3	17,3	17,3
Total	74,9	71,2	66,7	61,5	52,3

Appendix 4 – Changed position of current windows

TABLE 73. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,4	25,4	9	0	0	3	0	0
	Bathroom	26,2	25,4	2	0	0	2	0	0
	Livingroom	27,5	25,5	12	0	0	3	0	0
Upper Floor	Bedroom	27,5	25,9	10	0	0	4	0	0
	Master bedroom	26,6	25,8	8	0	0	3	0	0
	Bathroom	27,4	25,8	14	0	0	3	0	0
	Livingroom	27,9	26,1	16	0	1	4	0	1

TABLE 74. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,7	25,8	13	0	0	3	0	0
	Bathroom	26,5	25,7	4	0	0	2	0	0
	Livingroom	27,9	25,9	16	0	0	5	0	0
Upper Floor	Bedroom	28,0	26,4	14	1	1	4	1	1
	Master bedroom	27,1	26,2	9	0	2	3	0	2
	Bathroom	27,8	26,2	17	0	2	4	0	1
	Livingroom	28,4	26,5	19	4	3	5	2	2

TABLE 75. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,9	25,9	15	0	0	5	0	0
	Bathroom	26,7	25,9	6	0	0	3	0	0
	Livingroom	28,1	26,2	18	1	1	6	1	1
Upper Floor	Bedroom	28,2	26,6	15	2	2	4	1	1
	Master bedroom	27,2	26,4	11	0	2	4	0	2
	Bathroom	28,1	26,4	21	1	2	6	1	1
	Livingroom	28,6	26,7	22	4	4	6	2	2

TABLE 76. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,4	26,6	19	3	3	6	2	2
	Bathroom	27,2	26,4	9	0	3	3	0	2
	Livingroom	28,6	26,7	22	4	4	6	2	2
Upper Floor	Bedroom	28,8	27,2	20	5	3	4	3	2
	Master bedroom	27,8	27,0	13	0	3	4	0	2
	Bathroom	28,6	26,9	22	5	4	6	2	2
	Livingroom	29,2	27,3	26	6	6	6	3	3

TABLE 77. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	30,0	28,1	35	9	9	12	3	4
	Bathroom	28,8	27,9	22	5	9	5	3	4
	Livingroom	30,2	28,3	41	11	9	14	4	4
Upper Floor	Bedroom	30,7	28,8	41	9	11	11	3	4
	Master bedroom	29,7	28,8	28	5	10	8	3	4
	Bathroom	30,3	28,6	38	9	10	12	4	4
	Livingroom	30,9	28,9	48	17	16	23	4	5

TABLE 78. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,9	26,1	16	0	1	4	0	1
RCP 2.6	28,4	26,5	19	4	3	5	2	2
RCP 4.5	28,6	26,7	22	4	4	6	2	2
RCP 8.5	29,2	27,3	26	6	6	6	3	3
RCP 8.5 MAX	30,9	28,9	48	17	16	23	4	5

TABLE 79. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,8	2,7	2,5	2,3	2,1
Electric heating	15,0	14,8	14,5	14,1	13,3
Top up heating	29,6	26,2	22,3	17,7	9,3
Equipment	17,3	17,3	17,3	17,3	17,3
Total	74,8	71,1	66,7	61,6	52,2

Appendix 5 – Night-ventilation through windows

TABLE 80. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,3	24,5	1	0	0	1	0	0
	Bathroom	25,4	24,7	0	0	0	0	0	0
	Livingroom	26,3	24,5	1	0	0	1	0	0
Upper Floor	Bedroom	27,0	25,1	5	0	0	3	0	0
	Master bedroom	26,0	25,1	1	0	0	1	0	0
	Bathroom	26,3	25,0	3	0	0	2	0	0
	Livingroom	26,6	25,0	3	0	0	2	0	0

TABLE 81. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,8	25,1	3	0	0	2	0	0
	Bathroom	25,8	25,2	0	0	0	0	0	0
	Livingroom	26,8	25,1	3	0	0	2	0	0
Upper Floor	Bedroom	27,5	25,6	5	0	0	3	0	0
	Master bedroom	26,4	25,5	1	0	0	1	0	0
	Bathroom	26,8	25,4	4	0	0	2	0	0
	Livingroom	27,1	25,5	3	0	0	2	0	0

TABLE 82. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\overline{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\overline{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\overline{T}_o >$ 26°C
Ground Floor	Kitchen	26,9	25,2	3	0	0	2	0	0
	Bathroom	26,0	25,3	0	0	0	0	0	0
	Livingroom	26,9	25,3	4	0	0	2	0	0
Upper Floor	Bedroom	28,1	25,9	7	1	0	3	1	0
	Master bedroom	26,6	25,7	2	0	0	2	0	0
	Bathroom	27,0	25,6	5	0	0	2	0	0
	Livingroom	27,2	25,7	4	0	0	2	0	0

TABLE 83. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\overline{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\overline{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\overline{T}_o >$ 26°C
Ground Floor	Kitchen	27,5	25,8	5	0	0	2	0	0
	Bathroom	26,5	25,8	4	0	0	2	0	0
	Livingroom	27,6	25,9	7	0	0	3	0	0
Upper Floor	Bedroom	28,7	26,5	10	2	2	3	1	1
	Master bedroom	27,4	26,6	5	0	1	3	0	1
	Bathroom	27,8	26,4	8	0	3	4	0	2
	Livingroom	28,1	26,6	8	1	2	3	1	1

TABLE 84. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,9	27,2	14	4	4	4	2	2
	Bathroom	27,8	27,1	8	0	5	4	0	3
	Livingroom	29,0	27,4	15	4	4	4	2	2
Upper Floor	Bedroom	30,8	28,3	24	7	5	7	3	3
	Master bedroom	29,1	28,2	9	4	6	4	2	4
	Bathroom	29,5	27,8	21	5	5	5	3	3
	Livingroom	29,5	28,1	19	4	6	5	2	4

TABLE 85. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,0	25,1	5	0	0	3	0	0
RCP 2.6	27,5	25,6	5	0	0	3	0	0
RCP 4.5	28,1	25,9	7	1	0	3	1	0
RCP 8.5	28,7	26,6	10	2	3	4	1	2
RCP 8.5 MAX	30,8	28,3	24	7	6	7	3	4

TABLE 86. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,8	2,6	2,5	2,3	2,1
Electric heating	15,2	15,0	14,7	14,2	13,3
Top up heating	28,5	25,2	21,2	16,7	8,8
Equipment	17,3	17,3	17,3	17,3	17,3
Total	73,9	70,2	65,8	60,7	51,7

Appendix 6 – Balanced ventilation with constant air volume

TABLE 87. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,8	25,1	5	0	0	2	0	0
	Bathroom	26,0	25,2	0	0	0	0	0	0
	Livingroom	26,9	25,3	8	0	0	3	0	0
Upper Floor	Bedroom	27,4	25,9	9	0	0	3	0	0
	Master bedroom	26,5	25,7	6	0	0	2	0	0
	Bathroom	27,2	25,7	12	0	0	3	0	0
	Livingroom	27,2	25,9	9	0	0	3	0	0

TABLE 88. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,2	25,5	8	0	0	3	0	0
	Bathroom	26,2	25,5	2	0	0	2	0	0
	Livingroom	27,2	25,6	8	0	0	3	0	0
Upper Floor	Bedroom	27,9	26,3	14	0	1	4	0	1
	Master bedroom	27,0	26,1	9	0	1	3	0	1
	Bathroom	27,6	26,1	15	0	1	4	0	1
	Livingroom	27,6	26,3	11	0	2	3	0	1

TABLE 89. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,4	25,7	9	0	0	3	0	0
	Bathroom	26,4	25,7	3	0	0	2	0	0
	Livingroom	27,4	25,8	10	0	0	3	0	0
Upper Floor	Bedroom	28,1	26,5	16	2	2	4	1	1
	Master bedroom	27,1	26,3	9	0	2	3	0	2
	Bathroom	27,8	26,2	19	0	3	5	0	2
	Livingroom	27,8	26,5	13	0	3	4	0	2

TABLE 90. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,9	26,3	12	0	2	4	0	1
	Bathroom	26,9	26,1	6	0	2	3	0	2
	Livingroom	27,9	26,4	16	0	3	5	0	2
Upper Floor	Bedroom	28,7	27,0	20	3	3	4	2	2
	Master bedroom	27,8	26,9	12	0	3	4	0	2
	Bathroom	28,3	26,7	22	4	4	6	2	2
	Livingroom	28,4	27,0	19	3	5	5	2	2

TABLE 91. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C
Ground Floor	Kitchen	29,3	27,7	28	5	7	11	2	4
	Bathroom	28,4	27,7	17	4	7	5	2	4
	Livingroom	29,5	27,9	30	6	8	12	3	4
Upper Floor	Bedroom	30,6	28,8	39	9	10	11	3	4
	Master bedroom	29,7	28,8	27	5	10	8	3	4
	Bathroom	30,0	28,6	36	6	10	12	3	4
	Livingroom	29,9	28,5	41	9	13	23	4	5

TABLE 92. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C
Today	27,4	25,9	12	0	0	3	0	0
RCP 2.6	27,9	26,3	15	0	1	4	0	1
RCP 4.5	28,1	26,5	19	0	3	5	0	2
RCP 8.5	28,7	27,0	22	4	5	6	2	2
RCP 8.5 MAX	30,6	28,8	41	9	13	23	4	5

TABLE 93. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m², yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	6,0	5,9	5,9	5,8	5,9
Electric heating	11,5	11,4	11,1	10,7	11,4
Top up heating	12,7	10,6	8,5	6,3	7,0
Equipment	17,3	17,3	17,3	17,3	17,3
Total	57,6	55,3	52,9	50,2	51,8

Appendix 7 – Balanced ventilation with variable air volume

TABLE 94. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,3	25,7	8	0	0	3	0	0
	Bathroom	26,7	25,9	8	0	0	3	0	0
	Livingroom	27,4	25,7	8	0	0	3	0	0
Upper Floor	Bedroom	27,7	25,9	12	0	0	3	0	0
	Master bedroom	26,9	26,0	12	0	1	3	0	1
	Bathroom	28,0	26,1	20	0	1	5	0	1
	Livingroom	27,6	26,0	12	0	0	4	0	0

TABLE 95. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,6	25,8	8	0	0	3	0	0
	Bathroom	26,9	26,1	10	0	2	3	0	2
	Livingroom	27,7	25,9	12	0	0	4	0	0
Upper Floor	Bedroom	28,0	26,3	15	0	1	4	0	1
	Master bedroom	27,2	26,2	16	0	4	4	0	2
	Bathroom	28,2	26,3	24	2	5	6	1	2
	Livingroom	27,9	26,3	14	0	3	4	0	2

Table 96. Values from simulations for year 2070 and scenario RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,7	26,0	11	0	1	3	0	1
	Bathroom	27,0	26,2	11	0	3	3	0	2
	Livingroom	27,8	26,1	15	0	1	4	0	1
Upper Floor	Bedroom	28,1	26,5	17	2	4	4	2	3
	Master bedroom	27,4	26,4	18	0	6	6	0	3
	Bathroom	28,2	26,5	27	3	5	6	1	2
	Livingroom	28,0	26,5	18	0	5	5	0	2

Table 97. Values from simulations for year 2070 and scenario RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,2	26,5	17	1	3	5	1	2
	Bathroom	27,5	26,8	20	0	5	5	0	2
	Livingroom	28,3	26,6	23	3	3	8	2	2
Upper Floor	Bedroom	28,8	27,1	23	6	6	7	3	3
	Master bedroom	27,9	27,0	25	0	8	7	0	3
	Bathroom	28,7	27,1	33	5	8	8	2	3
	Livingroom	28,6	27,1	26	4	7	8	2	3

TABLE 98. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	29,4	27,8	38	5	9	12	2	4
	Bathroom	28,4	27,8	38	4	15	14	2	5
	Livingroom	29,5	27,9	41	7	10	23	3	4
Upper Floor	Bedroom	30,5	28,6	45	10	12	24	3	4
	Master bedroom	29,3	28,4	43	5	18	14	3	4
	Bathroom	30,0	28,4	56	14	16	24	4	4
	Livingroom	29,9	28,5	49	10	14	23	4	4

TABLE 99. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	28,0	26,1	20	0	1	5	0	1
RCP 2.6	28,2	26,3	24	2	5	6	1	2
RCP 4.5	28,2	26,5	27	3	5	6	2	3
RCP 8.5	28,7	27,1	33	5	8	8	3	3
RCP 8.5 MAX	30,5	28,6	56	14	18	24	4	4

TABLE 100. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	1,7	1,9	2,0	2,3	3,3
Electric heating	11,2	11,1	10,8	10,3	9,2
Top up heating	11,2	9,4	7,6	5,7	3,3
Equipment	17,3	17,3	17,3	17,3	17,3
Total	51,6	49,8	47,8	45,8	43,3

Appendix 8 – Added insulation

TABLE 101. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,8	25,0	6	0	0	3	0	0
	Bathroom	25,9	25,2	0	0	0	0	0	0
	Livingroom	26,8	25,1	7	0	0	3	0	0
Upper Floor	Bedroom	27,4	25,9	9	0	0	3	0	0
	Master bedroom	26,6	25,8	8	0	0	3	0	0
	Bathroom	27,4	25,7	15	0	0	4	0	0
	Livingroom	27,2	25,9	9	0	0	3	0	0

TABLE 102. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,1	25,4	8	0	0	3	0	0
	Bathroom	26,1	25,4	2	0	0	2	0	0
	Livingroom	27,1	25,5	8	0	0	3	0	0
Upper Floor	Bedroom	27,9	26,3	14	0	1	4	0	1
	Master bedroom	26,9	26,2	9	0	1	3	0	1
	Bathroom	27,8	26,0	18	0	2	5	0	1
	Livingroom	27,6	26,2	11	0	2	3	0	1

TABLE 103. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,2	25,6	8	0	0	3	0	0
	Bathroom	26,3	25,6	3	0	0	2	0	0
	Livingroom	27,3	25,7	10	0	0	3	0	0
Upper Floor	Bedroom	28,0	26,4	16	1	2	4	1	1
	Master bedroom	27,1	26,4	11	0	2	4	0	2
	Bathroom	27,9	26,2	21	0	2	6	0	1
	Livingroom	27,8	26,4	12	0	3	4	0	2

TABLE 104. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,8	26,1	12	0	2	4	0	1
	Bathroom	26,8	26,1	6	0	2	3	0	2
	Livingroom	27,9	26,2	15	0	2	5	0	1
Upper Floor	Bedroom	28,7	26,9	21	4	3	4	3	2
	Master bedroom	27,8	26,9	13	0	3	4	0	2
	Bathroom	28,5	26,8	24	5	4	6	2	2
	Livingroom	28,3	26,9	18	3	5	5	2	2

TABLE 105. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	29,2	27,6	28	5	7	11	2	4
	Bathroom	28,3	27,6	17	2	8	5	1	4
	Livingroom	29,3	27,7	29	5	8	11	2	4
Upper Floor	Bedroom	30,5	28,6	43	9	10	24	3	4
	Master bedroom	29,6	28,8	28	5	11	8	3	4
	Bathroom	30,1	28,5	47	8	10	12	4	4
	Livingroom	29,8	28,4	42	9	13	23	4	5

TABLE 106. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,4	25,9	15	0	0	4	0	0
RCP 2.6	27,9	26,3	18	0	2	5	0	1
RCP 4.5	28,0	26,4	21	1	3	6	1	2
RCP 8.5	28,7	26,9	24	5	5	6	3	2
RCP 8.5 MAX	30,5	28,8	47	9	13	24	4	5

TABLE 107. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,4	2,3	2,2	2,1	2,0
Electric heating	14,6	14,4	14,1	13,6	12,5
Top up heating	20,9	18,0	14,9	11,5	5,8
Equipment	17,3	17,3	17,3	17,3	17,3
Total	65,3	62,2	58,7	54,6	47,7

Appendix 9 – Less insulation

TABLE 108. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,5	25,4	8	0	0	3	0	0
	Bathroom	26,7	25,6	5	0	0	2	0	0
	Livingroom	27,6	25,5	10	0	0	3	0	0
Upper Floor	Bedroom	27,8	26,1	11	0	1	3	0	1
	Master bedroom	27,1	25,9	10	0	0	3	0	0
	Bathroom	27,4	25,8	9	0	0	3	0	0
	Livingroom	27,8	26,2	12	0	2	4	0	1

TABLE 109. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	27,9	25,8	11	0	0	3	0	0
	Bathroom	27,0	25,9	6	0	0	3	0	0
	Livingroom	28,0	25,9	13	1	0	3	1	0
Upper Floor	Bedroom	28,4	26,6	15	4	2	4	2	1
	Master bedroom	27,6	26,5	12	0	2	4	0	2
	Bathroom	27,8	26,3	13	0	2	3	0	1
	Livingroom	28,3	26,7	13	3	3	4	2	2

TABLE 110. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,1	26,1	13	2	1	3	2	1
	Bathroom	27,2	26,2	9	0	2	3	0	2
	Livingroom	28,2	26,2	17	3	2	5	2	1
Upper Floor	Bedroom	28,6	26,8	18	5	2	4	3	1
	Master bedroom	27,8	26,7	12	0	3	4	0	2
	Bathroom	28,0	26,5	15	1	2	4	1	1
	Livingroom	28,5	26,9	18	4	3	4	2	2

TABLE 111. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	28,7	26,7	18	4	4	5	2	2
	Bathroom	27,8	26,8	13	0	4	4	0	2
	Livingroom	28,8	26,8	21	5	4	6	2	2
Upper Floor	Bedroom	29,3	27,5	22	6	4	6	3	2
	Master bedroom	28,4	27,4	17	2	5	4	2	2
	Bathroom	28,7	27,1	19	4	4	5	2	2
	Livingroom	29,2	27,6	26	7	8	8	3	4

TABLE 112. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	30,4	28,4	38	9	8	12	3	4
	Bathroom	29,5	28,5	30	6	10	11	3	4
	Livingroom	30,5	28,5	41	11	9	12	4	4
Upper Floor	Bedroom	31,3	29,3	46	15	12	24	4	4
	Master bedroom	30,4	29,2	38	9	12	14	4	4
	Bathroom	30,5	28,8	36	10	10	23	4	4
	Livingroom	30,9	29,2	46	14	16	23	4	5

TABLE 113. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	27,8	26,2	12	0	2	4	0	1
RCP 2.6	28,4	26,7	15	4	3	4	2	2
RCP 4.5	28,6	26,9	18	5	3	5	3	2
RCP 8.5	29,3	27,6	26	7	8	8	3	4
RCP 8.5 MAX	31,3	29,3	46	15	16	24	4	5

TABLE 114. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m², yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	5,4	4,7	4,1	3,6	2,8
Electric heating	16,2	16,0	15,7	15,3	14,6
Top up heating	58,9	54,0	47,7	40,4	26,2
Equipment	17,3	17,3	17,3	17,3	17,3
Total	107,9	102,1	95,0	86,7	71,0

Appendix 10 – Cooling system

TABLE 115. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	24,4	24,1	0	0	0	0	0	0
	Bathroom	24,4	24,1	0	0	0	0	0	0
	Livingroom	24,6	24,2	0	0	0	0	0	0
Upper Floor	Bedroom	24,6	24,3	0	0	0	0	0	0
	Master bedroom	24,5	24,3	0	0	0	0	0	0
	Bathroom	24,5	24,2	0	0	0	0	0	0
	Livingroom	24,7	24,3	0	0	0	0	0	0

TABLE 116. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	24,4	24,1	0	0	0	0	0	0
	Bathroom	24,4	24,1	0	0	0	0	0	0
	Livingroom	24,6	24,2	0	0	0	0	0	0
Upper Floor	Bedroom	24,6	24,3	0	0	0	0	0	0
	Master bedroom	24,5	24,3	0	0	0	0	0	0
	Bathroom	24,5	24,2	0	0	0	0	0	0
	Livingroom	24,7	24,3	0	0	0	0	0	0

TABLE 117. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	24,4	24,1	0	0	0	0	0	0
	Bathroom	24,4	24,1	0	0	0	0	0	0
	Livingroom	24,6	24,2	0	0	0	0	0	0
Upper Floor	Bedroom	24,6	24,3	0	0	0	0	0	0
	Master bedroom	24,5	24,3	0	0	0	0	0	0
	Bathroom	24,5	24,2	0	0	0	0	0	0
	Livingroom	24,7	24,3	0	0	0	0	0	0

TABLE 118. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	24,4	24,2	0	0	0	0	0	0
	Bathroom	24,4	24,1	0	0	0	0	0	0
	Livingroom	24,6	24,2	0	0	0	0	0	0
Upper Floor	Bedroom	24,6	24,3	0	0	0	0	0	0
	Master bedroom	24,5	24,3	0	0	0	0	0	0
	Bathroom	24,5	24,2	0	0	0	0	0	0
	Livingroom	24,7	24,3	0	0	0	0	0	0

TABLE 119. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	24,4	24,2	0	0	0	0	0	0
	Bathroom	24,4	24,2	0	0	0	0	0	0
	Livingroom	24,6	24,3	0	0	0	0	0	0
Upper Floor	Bedroom	24,6	24,3	0	0	0	0	0	0
	Master bedroom	24,6	24,4	0	0	0	0	0	0
	Bathroom	24,5	24,2	0	0	0	0	0	0
	Livingroom	24,8	24,4	0	0	0	0	0	0

TABLE 120. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	Maximum		Total number of days			Maximum days in a row		
	T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Today	24,7	24,3	0	0	0	0	0	0
RCP 2.6	24,7	24,3	0	0	0	0	0	0
RCP 4.5	24,7	24,3	0	0	0	0	0	0
RCP 8.5	24,7	24,3	0	0	0	0	0	0
RCP 8.5 MAX	24,8	24,4	0	0	0	0	0	0

TABLE 121. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m², yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
Electric cooling	2,6	2,8	3,1	3,6	4,8
HVAC aux	2.7	2,6	2,4	2,3	2,1
Electric heating	14,5	14,3	14,0	13,6	12,9
Top up heating	27,6	24,4	20,6	16,2	8,3
Equipment	17,3	17,3	17,3	17,3	17,3
Total	74,8	71,5	67,5	63,1	55,5

Appendix 11 – Merging of passive solutions

TABLE 122. VALUES FROM SIMULATIONS WITH TODAY´S CLIMATE.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	25,5	24,2	0	0	0	0	0	0
	Bathroom	24,3	23,9	0	0	0	0	0	0
	Livingroom	25,5	24,2	0	0	0	0	0	0
Upper Floor	Bedroom	27,0	24,7	5	0	0	3	0	0
	Master bedroom	24,9	24,3	0	0	0	0	0	0
	Bathroom	24,9	24,2	0	0	0	0	0	0
	Livingroom	25,7	24,4	0	0	0	0	0	0

TABLE 123. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 2.6.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	25,7	24,4	0	0	0	0	0	0
	Bathroom	24,6	24,1	0	0	0	0	0	0
	Livingroom	25,7	24,4	0	0	0	0	0	0
Upper Floor	Bedroom	27,5	25,1	5	0	0	3	0	0
	Master bedroom	25,4	24,8	0	0	0	0	0	0
	Bathroom	25,3	24,6	0	0	0	0	0	0
	Livingroom	26,1	24,9	1	0	0	1	0	0

TABLE 124. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 4.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	25,8	24,5	0	0	0	0	0	0
	Bathroom	24,8	24,3	0	0	0	0	0	0
	Livingroom	25,8	24,5	0	0	0	0	0	0
Upper Floor	Bedroom	27,7	25,3	6	0	0	3	0	0
	Master bedroom	25,7	25,2	0	0	0	0	0	0
	Bathroom	25,3	24,6	0	0	0	0	0	0
	Livingroom	26,1	25,0	1	0	0	1	0	0

TABLE 125. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5.

	Room	Maximum		Total number of days			Maximum days in a row		
		T_o	$\bar{T}_o$	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C	$T_o >$ 26°C	$T_o >$ 28°C	$\bar{T}_o >$ 26°C
Ground Floor	Kitchen	26,2	24,8	2	0	0	1	0	0
	Bathroom	25,1	24,6	0	0	0	0	0	0
	Livingroom	26,2	24,9	2	0	0	1	0	0
Upper Floor	Bedroom	28,5	25,9	9	2	0	3	1	0
	Master bedroom	26,2	25,6	1	0	0	1	0	0
	Bathroom	25,7	25,0	0	0	0	0	0	0
	Livingroom	26,7	25,4	3	0	0	2	0	0

TABLE 126. VALUES FROM SIMULATIONS FOR YEAR 2070 AND SCENARIO RCP 8.5 MAX.

	Room	**Maximum**		**Total number of days**			**Maximum days in a row**		
		T_o	$\bar{T}_o$	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C
Ground Floor	Kitchen	27,6	26,2	7	0	3	4	0	2
	Bathroom	26,5	25,9	5	0	0	3	0	0
	Livingroom	27,6	26,3	7	0	2	4	0	1
Upper Floor	Bedroom	29,9	27,4	20	7	4	6	3	2
	Master bedroom	27,5	26,9	6	0	4	4	0	2
	Bathroom	27,1	26,3	5	0	3	3	0	1
	Livingroom	28,1	26,8	8	1	4	4	1	2

TABLE 127. SUMMARY OF THE MAXIMUM VALUES FOR EVERY SCENARIO FROM THE TABLES ABOVE.

Scenario	**Maximum**		**Total number of days**			**Maximum days in a row**		
	T_o	$\bar{T}_o$	T > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C	T_o > 26°C	T_o > 28°C	$\bar{T}_o$ > 26°C
Today	27,0	24,7	5	0	0	3	0	0
RCP 2.6	27,5	25,1	5	0	0	3	0	0
RCP 4.5	27,7	25,3	6	0	0	3	0	0
RCP 8.5	28,5	25,9	9	2	0	3	1	0
RCP 8.5 MAX	29,9	27,4	20	7	4	6	3	2

TABLE 128. ENERGY CONSUMPTION FOR ALL SCENARIOS.

[kWh/m^2, yr]	**Today**	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**RCP 8.5 MAX**
Lighting	10,1	10,1	10,1	10,1	10,1
HVAC aux	2,4	2,3	2,2	2,1	2,0
Electric heating	15,6	15,4	15,0	14,6	13,5
Top up heating	21,5	18,7	15,4	11,7	6,1
Equipment	17,3	17,3	17,3	17,3	17,3
Total	67,0	63,8	60,1	55,8	49,1

TRITA-ABE-MBT-21524