Assessing the Passive House regulations for future climate conditions in Swedish single family residential building

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Lund University

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

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

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Abstract

Global warming is a very much researched and debated topic in the current period as we can see the effects around us. The literature and discussions have pointed to a surface temperature rise of up to 10°C at the poles and around 4°C-7°C around the equator. The effect is more in the northern hemisphere than in southern hemisphere of our planet Earth. The effects of the warming of our environment on the buildings and the future weather patterns are being researched in many countries. This master thesis work assesses one such scenario of the effects of climate change, projected future weather patterns on the energy consumption for heating and cooling, moisture performance and mould growth of the external wall and external roof layers in four cities of Sweden namely Lulea, Stockholm, Gothenburg and Lund. The research for energy consumption was carried out with future climate data derived from the GCM's and RCM's for Extremely cold year, extremely warm year and typical downscaled year; the results from these three scenarios were clubbed together to get combined yearly energy consumption which can be comparable to the reference year data. Moisture performance was carried out only for Gothenburg using CNRM and IPSL climate data to show the effects of climate change and warming of the environment on the building outer protective layers. The results clearly show a considerably increased cooling load and decrease in heating loads in four Swedish cities over a period of next 80 years. The results for moisture performance and mould growth also shows an increase in relative humidity, temperature and water content in layers. Mould growth calculations also show an increased activity over next 80 to 100 years.

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Nomenclature

°	Degrees
C	Celsius
kWh	Kilowatt-hour
U-value	Thermal Conductance [W/m^2K]
K	Degree Kelvin
W	Watt
h	Time in Hours
Sd	Vapour diffusion thickness [m]
RH	relative humidity (%)
m	meters
m^2	area
A_{temp}	Conditioned floor area
kWh/(m^2yr)	Energy consumption
GCM	Global Climate Model
RCM	Regional Climate Model
ECY	Extremely Cold Year
EWY	Extremely Warm Year
TDY	Typical Downscaled Year
km	kilometres
yr	year
mm	millimetre
cm	centimetre
MGI	Mould growth Index

Definitions and Terminologies

The key parameters used in the work and their definitions according to Swedish building regulations (BBR) are explained below [1]–[3].

The building's energy use

The energy used by a reference building in a reference year under normal usage for heating, cooling, domestic hot water, appliances and lighting, both indoor and outdoor.

Energy for comfort cooling

The total amount of energy supplied to the reference building to keep the indoor temperatures within the comfort levels of human tolerance. Free cooling derived from the immediate surrounding environment is not taken into consideration.

Domestic energy

The electrical energy used in the building for household purposes like electrical usage for dishwasher, washing machine, dryer, cooking stoves, etc.

Indoor temperature

The intended comfort temperature which should be maintained inside the reference building during the building's occupancy.

Reference year

The arithmetic mean value of temperatures and other outdoor factors of the environment considered for an extended period of time, normally considered for a period of 30 years.

Reference year correction

Modification of the metered building's energy consumption which is created by the variation in the reference year and real climate in the specified period span for which the reference building's energy consumption is being evaluated.

Table of content

1 Introduction

Buildings in Sweden use about 48% of all the energy consumed, with 40% for the operation of buildings and 8% for their construction [4]. With the fast growing urbanisation and housing developments, the energy demand is going to increase exponentially [1]. This energy consumed by the Swedish residential building sector is dominantly for heating the occupied indoor space, as cooling demand is almost negligible. The residential buildings are rather cooled down by natural ventilation with the help of fresh, clean outdoor air; as the Swedish summer lasts, only for a brief period, the overheating issues in the buildings are rare. Yet, there exist anxieties about global warming and its impact on the building performance in the time to come. Passive houses in Sweden has grown from 0.7% to 7.2% of the total building stock in a matter of few years and has been rapidly increasing ever since[5]. Studying the long-term space conditioning analysis for some existing Swedish building stock in Stockholm, Gothenburg, Lund and Östersund has shown that the mean indoor temperature and demands of cooling loads rose depending on the climate setting whereas heating loads diminished less in 2100 CE, compared to 2011 [6]–[8].

With changes in building design, the increased sensitivity of building elements like thick walls combined and climate variation, the buildings are probable to demonstrate amplified risk of overheating and might result in devastating damages and heightened risk of moisture damage. Overheating in residential buildings has not been the concern of energy performance. Sweden`s residential housing energy use is dominated by space heating and consequently, any plans to alter strategies for new buildings, have been concentrated on minimising the space heating. The passive house buildings must have considerable low space heating loads but, due to enhanced airtightness and high-performance insulation layer, can also have higher summer temperatures unless a strategy is produced that is sensitive to these risks[9]. The concept of overheating in residential dwellings is found with different explanations in CBISE guide, which suggests that the building is overheated if more than 1% of the occupied time in indoor environment exceeds 28°C and 26°C in living areas and bedrooms respectively [4].

The general predicted lifespan of residential buildings varies from 50 to 200 years. These buildings over such a long lifespan are exposed to a lot of different climatic conditions and the building performance is directly related to the climatic variations. These anomalies in climate should also be a part of building management as the changes in climate increase the risk factors both in the building and the indoor environment in many different ways [10]. The performance of passive houses, low energy, micro energy buildings, both new and retrofitted, needs long-term perspective and it is possible by knowing the present and future conditions. Current and/or past conditions are studied using the data available in the building simulation software programs while for the future, some weather data sets provided from previous research works are used [8], [11]. Miscalculating and undermining the effects of climate change might have severe consequences and expensive damages in the future [12].

There might also the need of a guide for both existing and new buildings to cope with the future climate and its uncertainties and avoid major failures [9].

This work investigates impacts of climate change on the moisture conditions and thermal comfort of a typical passive house and performance of its building envelope in different climatic regions of Sweden. For moisture performance, critical elements of the building are considered, for thermal performance whole building is considered. Thermal performance in the building is studied through heating and cooling demands and overheating hours in the actively occupied zones of the building. Thermal performance of the building is studied for a reference year and three time periods: - 2009-2038, 2039-2068, 2069-2098. Moisture performance is studied for a reference year and three time periods 1971-1990, 2021-2050, 2071-2100 and two climate scenarios CNRM and IPSL.

1.1 Objectives:

This master thesis work aims at assessing the efficiency of the current regulation for passive houses in Sweden, considering future climatic conditions. Both the energy and moisture performance of the building will be considered in the study. For the moisture performance, sensitive parts of the building will be studied. For the study of energy performance, the whole building will be studied, investigating its energy performance and the indoor comfort.

1.2 Research methods and approach:

- Analysis of FEBY regulations for new typical single family houses
- Designing typical Swedish single family houses for the three climatic zones of Sweden.
- Simulations for moisture performance of the sensitive parts of the building.
- Thermal simulations for the whole building will be performed, investigating its thermal performance and the indoor comfort.

1.3 Expected Results:

- Suitability of the passive house designed according to current regulations, to the climatic zones of Sweden and their capability of handling the future climatic adversities.
- Possible passive house design recommendations, wall construction etc.
- Energy use affected by climate change.
- Handling the increased fluctuations/ anomalies in future climate.

2 Future climate and its models

Climate change is happening and affecting our life. The changes which occurred in the past are recorded in the geologic remains and are a proof of intense alterations which happened even before the humans came to this world, can say that they were natural forcing climate changes [13]. If the changes in the climate of the past 100's of millennia were to be understood in detail, the foretelling of the future climate patterns becomes much simpler [14]. It took about 7000 years for melting of ice sheets and it has been stable for almost 8000 years [14]. Around 20,000 years ago the mean surface temperature was around 5°C cooler than today and 1°C rise in global mean surface temperature is 20% of the rise in the temperature. The changes in temperature were more towards the earth's poles and less towards the equator and the trend is continuing today [14] The earth's atmosphere is getting warmer day by day for the past thousand years as the human doings are releasing CO_2 and other greenhouse gases, and we are about midway to the volume of CO_2 which will increase the global surface temperature by 2°C. With the projections of IPCC under RCP 8.5, the situation may be expected to reach that stage within the next 25 to 30 years at the current rate in which we are going. The global mean surface temperature has raised by about 1°C in the past 100 years and will go up by another 0.5°C in the next few years [14]–[16].

Studying the likely influences of climate change is a very interesting topic and is being researched all over the world. The pace in which climate change happens and planning to adapt for that is complex and full of uncertainties. Till now generally, Global Climate models(GCMs) or general circulation model, are used to generate the climate data and perform an impact assessment of climate change. The Regional Climate Downscaling (RCD) provide more accurate and detailed projections of local extreme climate events and the adaptation strategies for the changing climate takes place at national and regional scale [11].

Climate forecasts suggest that in Sweden and other colder countries, the temperature will rise to a considerable extent in the coming years[8], [10], [17]–[20]. The changes in climatic conditions lead to varied and widespread anomalies like untimely rains and snowfall, heat waves and increased dry periods, which leads to moisture related problems, flooding, weakening of building elements.[12], [21].

The human societies are getting more anxious about the living and working environments in the future since the structures which are built for the current or near past conditions might not be suitable for future [11], [12]. Almost all the buildings around the world are assessed and built according to the past climate and to some extent the present, but does not consider future climate scenarios [7]. The northern parts of Europe viz. Denmark, Sweden, Finland and Norway, are thought to have the least impact of the devastating effects of climate change[18], [20]. However, this region has higher chances of having increased effects of climate change like floods, storms, heat waves and on a long-term moisture and water penetration into the building elements and mould growth. Over the course of the time, the climate in the Scandinavian region shows growing trends of climate change. According to Intergovernmental Panel for Climate Change (IPCC) [17]–[19], there is a clear indication of an increase in the summer and winter mean temperatures (1-4 °C in summer and 2 -6°C in winter). The coldest days in the northernmost parts of Scandinavia might have an increase of 10°C by 2100[1] when compared to 1971-2000 mean [1], [8], [10], [19], [20].

The spatial resolution of simulated GCMs are 100-300km, the output is not good for building simulations and due to known problems in the calculation in building simulation, the direct use of GCMs is not advisable[6]. The climate scenario imitations with the help of GCMs for 20th and 21st centuries start with preindustrial conditions (1840-1860), where the human interference with atmosphere had not happened. With these initial conditions the evolving climate change and its effects, the build-up of greenhouse gas concentrations, aerosols can be imitated. The major hiccup for this as stated by researchers was the conditions during 1840-1860, as the records of climate activities does not exist for the most part of the world, except what was observed and recorded by sailors, scholars and climate enthusiasts. The testing of the climate models is initiated with the initial conditions from the pre-industrial times with random start-up conditions for GHGs, aerosol concentrations, solar constant, vegetation cover, etc. These long simulations do not display long-term tendencies rather sheds light on the inconstancies of each year and each decade [6], [23].

Future climate data sets used in the current project were received from Rossby Centre, the climate simulation unit of Swedish Meteorological and Hydrological Institute (SMHI). Weather data sets are the results of RCA3 regional climate model (RCM), where several groups of data are used in the simulation of results for the many climate models. Climate data from two GCMs have been downscaled by RCA3 and used in this work: 1) global coupled climate model developed by CERFACS in France (CNRM) and 2) Earth system model IPSL developed by IPSL labs around the world [8], [23].

There are a lot of uncertainties involved with future climate due to several factors such as different climate models, emissions scenarios etc. Future weather data sets are given for a very long period, 100- 140 years, with almost same number of days as a calendar year. More details about climate models and preparing climate files are available in [23]. The climate generated are predictions of future climate, not weather forecasts which we see every day. These are based on emission scenarios which can be obtained from the IPCC special report on Emission Scenarios, SRES [1], [23]–[25].

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[1] Colder days with temperatures of -20°C might have risen to -10°C.

2.1 Swedish climate zones

Climate zone I

Northern Regions of Sweden like- Norrbotten, Västerbotten, Jämtland fall under climate zone I. (detailed energy criteria is discussed later in the work this climate zone).

Climate zone II

Central regions of Sweden like Västernorrland, Gävleborg, Dalarna and Värmland fall under climate zone II. (detailed energy criteria is discussed later in the work this climate zone).

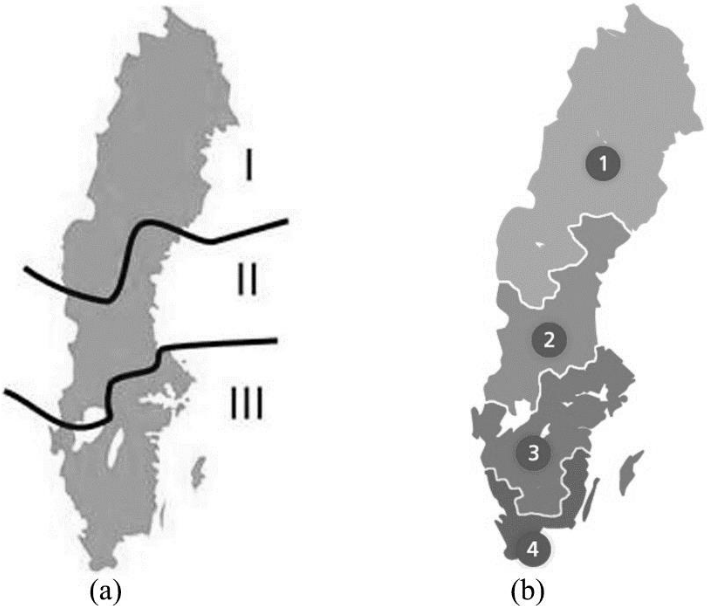

Figure 1: Climate zones of Sweden: figure a showing the three climate zones of Sweden[26]and figure b showing the four climate zones of Sweden[2] [27]

Climate zone III

The regions in the south of the Sweden like Västra Götaland, Jönköping, Kronoberg, Kalmar, Östergötland, Södermanland, Örebro, Västmanland, Stockholm, Uppsala, Skåne, Halland, Blekinge and Gotland fall under climate zone III. (detailed energy criteria is discussed later in the work this climate zone).

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[2] In this master thesis work Sweden's three climate zone classification is considered not the new four climate zones classification due to not having corresponding details for the later.

3 Passive house

The term passive house points to the thorough and careful process of designing energy efficient buildings, acting of one's own free will with a great level of excellence in cutting down the ecological footprint of the building and the impact on the environment. This process paves way for extremely low energy buildings, which consume a very small amount of energy for heating or cooling of the habitable indoor volume of the building. The scope of passive house buildings is not just restricted to residential buildings sector; it is also spread across all the sectors in building industry. By late 2008 CE and early 2009 CE, the passive house building density was around 15,000 to 20,000 for the entire world; the density of these buildings by the end of 2010 CE was around 25,000 in Europe alone; mainly in colder regions of Europe, namely Germany, Austria and Scandinavian countries [28], [29].

A Passive House according to *Swedish Centre for Zero Energy Houses (SCNH)* is a building with a very good indoor air quality, thermal comfort, and tiny energy requirement for keeping the indoors comfortable which minimises the carbon footprint. [30]. Passive houses have passed the test of practice and time with very good results across the world. The passive house allows savings of 75% to 90% for heating and cooling energies comparative to average new buildings built not just in temperate and cold climates but also in warm and hot climates [29], [31]

The energy demand for heating and cooling of indoor space in Sweden depends currently on the regulations of FEBY 2009 & FEBY 2012 which was released by SCNH. The standards for a passive house in Sweden is a combination of international principles with modifications based on the three climatic zones of Sweden as defined by *Swedish National Board of Housing Building and Planning.* The basic criteria for heating demands are listed below in Table 1 [30], [32]. The Swedish Building regulations are governed by BBR[27] where it specifies the total energy use in the building. These measures of energy performance are established on the mandate defined by the European Union and to be applied to Swedish buildings. The important reason for implementing these ordinances are not only to reduce the total energy use in buildings but also to get vital statistics of the actual energy performance of the occupied building by the occupants [33]. During the summer of 2006, the Swedish government passed a resolution to decrease 20% of the energy use in residential buildings by 2020 with reference to the consumptions in 1995, per heated floor area of the dwelling, and 50% by 2050 [1], [33].

Table 1 The Swedish criteria for passive houses. [30], [32]

Climate zone:		I	II	III
Heat load demand	kWh/(m² year)	19	17	15
For non-electric heating systems	kWh/(m² year)	63	59	55
For electric heating systems	kWh/(m² year)	31	29	27
For combination of different type of energy systems	kWh/(m² year)	78	73	68

The usage of energy in the building should not only be restricted to heating of indoor space, but also have a very low cooling needs and also very efficient appliances as it is not right in the part of designer to reduce all the heating demands and use very low efficient appliances and make up for the internal gains[34]. According to International passive house association (iPHA), passive houses are buildings which have need of very little heating and cooling when compared to conventional buildings; approximately they use only 10% of energy use of conventional buildings [35].

3.1 Specific criteria for Dwellings

According to BBR BFS 2011:26 [36], The buildings specific energy use for heating and average thermal resistance of the building envelope, should not exceed the numbers specified in the table below. During the design phase, the specific energy use for the building should be carried with suitable safety limits to make sure the all the conditions are addressed. The designs must be based on local weather patterns (meso climate), planned indoor temperatures, and typical consumption of the hot water in the building. If the indoor temperature factor is not known during calculation time, 22°C is to be considered as the average indoor temperature for energy and power calculations. [36]

Table 2: Dwellings that have a heating method other than electric heating [36]

Climate zone	I	II	III
The building's specific energy use [kWh/(m²yrA$_{temp}$)]	130	110	90
Average thermal transmittance (W/m² K)	0.40	0.40	0.40

Table 3: Dwellings with electric heating [36]

Climate zone	I	II	III
The building’s specific energy use [kWh/(m²A$_{temp}$ year)]	95	75	55
Installed power rating for heating [kW]	5.5	5	4.5
supplement when A$_{temp}$ is greater than 130 m²	0.035(A$_{temp}$-130)	0.030(A$_{temp}$-130)	0.025(A$_{temp}$-130)
Average thermal transmittance[W/m²K]	0.40	0.40	0.40

4 Analysis and visualisation of data sets

The results from the future climate scenario simulations are created on hourly or daily calculations for many decades. Even though the assessment is possible on this long period for hourly simulations, the difficulties arise in presenting the results using appropriate methods. It is almost impossible to assess the data obtained with basic methods that are commonly used in the field of building physics. Handling these enormous data requires appropriate and simplified methods. The future data is not certain. No one can be sure that the results obtained are going to happen in future or not. For this reason, the researchers base their conclusion on long time periods of 30 years or more. [23]

4.1 Boxplot

The boxplot is a unique, strong and healthy method used in the assessment of astronomical numbers of data sets. Boxplot graph compared to other modes of statistical representation is irrepressible to the existence of outliers in the experiment and gives a very clear representation of the occurrence of most the data in the data set. It is a statistical method of assessing large data sets and is built on a robust statistical method of assessment. Robust statistics is resilient to the presence of the outliers when in comparison to the old style statistical methods built on a standard distribution of data. Boxplot can give to a clear picture of the data. It is very much needed to describe and understand boxplot to assess the statistical concepts. [23]

Autonomy of boxplot [23].:

1. Quantiles: Quantiles are the steady intervals from cumulative distribution function of a variable. Quantiles are the data sets that set the boundary for consecutive sets of data. The 4 Quantile represent each part of the sampled data set. Q1- lower quartile, Q2- median quartile, Q3- upper quartile, and INTERQUARTILE- the difference between upper and lower quartiles.

2. Outliers: Outliers are the data that appears to stray significantly from the other data of the same sample in which in exists.

3. Whisker line: the line which extends up to a maximum of 1.5 times the interquartile range from either one or both ends of the box linking all the outside values which fall in the 1.5 times the box width away from the box.

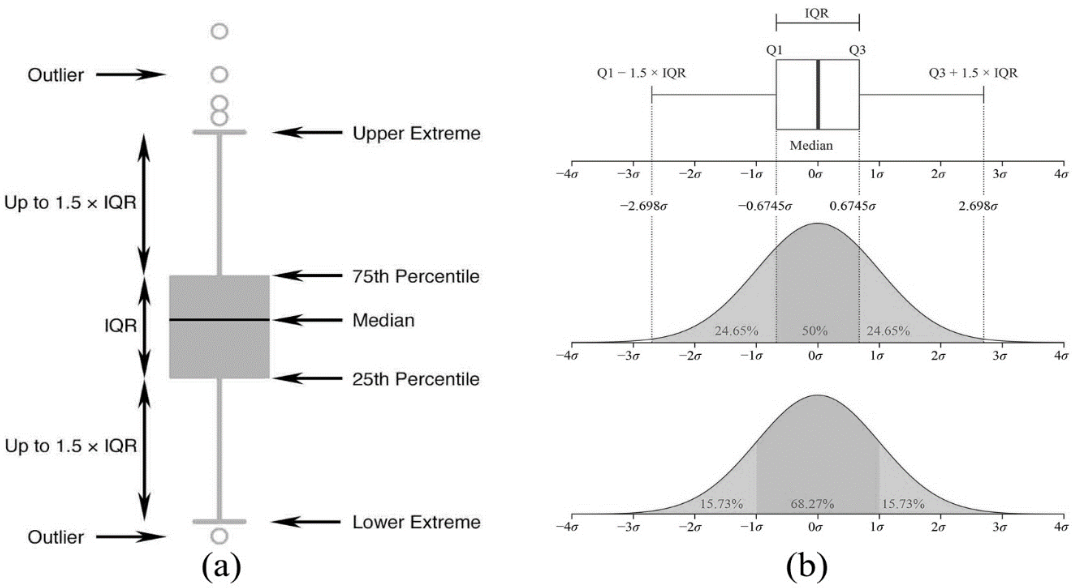

Figure 2: (a) Anatomy of a typical box and whisker plot style[37], (b) Boxplot and a probability density function (pdf) of a Normal N(0,1σ2) Population[38]

4.2 Histogram

The histogram is a very useful graphical tool for the probability distribution of numerical values. A histogram consists of bins or range values which separate the whole data into various intervals and counts the number of values in each one of the intervals. These bins are non-overlapping and consecutive. If the bins are of equal sizes, then a rectangle is constructed with height (frequency) equal to the number of cases in the bin. The histogram gives a rough estimate of the distribution of data.[23], [39].

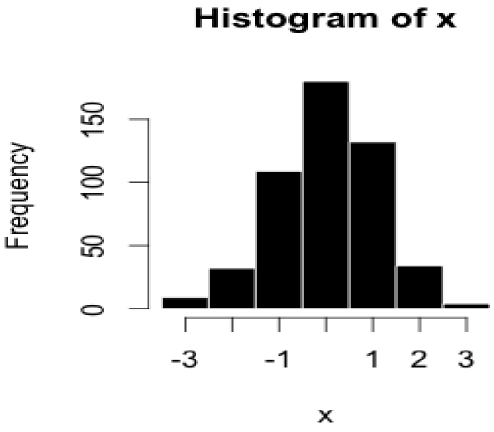

Figure 3: Typical histogram[39]

5 Energy simulation for future climate

The GCM method, forecasts for climate transformation, display variations in typical settings, inconsistencies and scale of occurrence of risky events. The converted meteorological condition statistics undervalue the influence of the climate transformation comparative to RCM, even though having alike emission and time setting. When considering the future climate scenarios, short time periods should not be relied upon but longer periods of 20-30 years should be considered which are more reliable. There exists a lot of study on effects of climate change on the energy use in cities and urban areas of energy and infrastructure planning focussing on buildings such as offices, residential hospital and supermarket. [11]

Climate data sets play a major role in the impact assessment of climate change on energy and moisture performance in buildings There is a long history of synthesised weather data sets which are used for energy simulations. The major advantage of the typical year climate data sets is the reduced time for simulation and easier data assessment and data comparison when compared to the long period of 20 to 30 years. There are several techniques in creating these typical and reference climate data sets. [40]. The credit of creating and introducing these typical climate data sets goes to Hall et al [41] where they are based on identifying typical meteorological month (TMM) for each month and all months of the year to create weather data set for one year. Different data sets of climate assessments for building simulations such as Typical reference year (TRY), weather year for calculations (WYEC) and International weather year for calculation (IWEC) are created and published by ASHRAE [42]. Although the energy calculations with typical and representative years are made easy, they also have some drawbacks such as reduction in energy saving and peak demand can be highly underestimated or overestimated and it was also concluded that the Design Summer Year continuously underestimated the discomfort level and overheating risks [43], [44]

This work takes into consideration the impact assessment of climate change on buildings and their energy performance based on three sets of weather data derived out of RCMs: (1) typical downscaled year (TDY), (2) Extreme cold year (ECY) and (3) Extreme warm year (EWY)[11]. This work uses the synthesised climate data sets which are representative of the original RCMs and their variations in different time scales. The data sets used in the work were prepared and synthesised in a way that they represent the average conditions without underestimating the climate uncertainties, extremes and variations. [11], [23]

6 Mould growth in buildings

Mould growth in the buildings is a major problem in Sweden particularly in the region of Gothenburg. Around 60% to 85% of the buildings have mould problems of some sort. Mould growth calculation is based on the functions temperature, humidity and time. Mould risk is higher with higher humidity levels >75% and optimal temperatures of -5°C to +50°C. The time taken for mould initiation to mould growth in favourable conditions is around four to eight weeks [45].

Moulds are a varied mix of microorganisms but not well categorised. Most of the mould in buildings are categorised based on their colour. Mould and other fungi affect most of the structures and materials, like roof, wall, floors, below-ground walls, doors, windows. Other than wood there are other materials which support mould growth where mould problems not as serious damage as wood and other organic materials. Mould growth in wood-based materials have been part of experiments and researches for more than 50 years now, but the results are mostly qualitative [45]–[48]. This experiment and research were conducted in response of different materials treated differently with constant temperature and relative humidity levels but not applicable to varying conditions. The models developed through the research have posed few problems are in dry periods as the knowledge from the experiments about mould growth and the effects of non-favourable conditions are limited. Researchers Viitanen and others have developed a mathematical model for mould growth on organic materials, used in the current work, based on the previous regression models for mould growth, quantification of the results is based on the mould index through visual inspection. The research is based on the differential equations explaining mould index and growth rate in varying conditions for temperature and relative humidity levels [45].

The mould growth is measured with a standard index, created by their surface appearance of the material under study [45].
0 no growth
1 little to some growth on or in the material detected only with the help of a microscope.
2 moderate growth on or in the material detected with a microscope (coverage more than 10%).
3 little to some growth on the material detected visually.
4 visually detected coverage more than 10% of the material.
5 visually detected coverage more than 50% of the material.
6 visually detected coverage 100% of the material.

Mould requires the considerable presence of moisture for its growth, controlling the moisture presence and removing the active mould colonies reduces the mould growth. The process of calculating mould index and mould growth is based on the mathematical equations developed by Viitanen and others for wooden materials [45],

[49], [50]. The calculation considers the temperature and relative humidity into the calculation. The process was carried out with programming tool Matlab from Mathworks[3]. The mould index is measured with a standard index, created on their surface appearance, measured from 0 to 6 in relation to time in days. Mould Growth and decay is measured in terms of time in days [45]. The mould index from the calculations does not reflect on the appearance of the mould to the naked eye on the material. The correct way to infer the results are mould index representative; which represents the activity of mould and other fungi on a wooden surface. Viitanen in 1997 came up with a measuring equation for the response time needed for the commencement of mould growth on wooden materials in an unchanging temperature and humidity conditions [45], [49], [50].

The moisture performance and mould calculations was performed for four cities in Sweden for reference year, namely: Lund (55°42′14″N 13°11′42″E), Gothenburg (57°42′N 11°58′E), Stockholm (59°19′46″N 18°4′7″E) and Luleå (65°35′4″N 22°9′14″E) for the future weather data for Gothenburg namely- CNRM RCP 8.5 2009 -2038, 2039-2068, 2069-2098 and IPSL RCP 8.5 2009 -2038, 2039-2068, 2069-2098

6.1 Mould growth and Mould Growth Rate

Researcher Viitanen in his work states, wood being hygroscopic material, moisture content in the wood depends on the relative humidity and temperature of the material and its surroundings, exposure time of the material to favourable and unfavourable conditions, size and shape of wooden material and absorption capacity of the wooden material; the moisture in the material can also exist in the form of free water in the pores and cracks of walls, roofs and other elements and in the living and dead cells in the materials. The humidity and temperature levels in the pores and cracks of the material are complimentary for mould growth. Mould growth and the time required for the process depends on the water levels, temperature, a period of exposure, quality of the wooden material [45], [51]–[53]

As explained by researchers Viitanen and Bjurman in the research in 1995 and 1999, growth of mould and fungi after initiation does not automatically lead to their detection to naked eye and the final overall coverage depends on the temperature, relative humidity and water content in the material and its surroundings suggesting that the measuring and limiting values exist above which the mould growth index values do not go up irrespective of conditions and time [45], [54].

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[3] The MATLAB function for calculating mould growth and mould index was developed by Vahid Nik during moisture safety design course, 2016

6.2 Model during non-favourable conditions

In his research Viitanen [49], [50] has mentioned that the collective time frames in high humidity conditions can be used to a short extent to express the commencement of mould growth, however the downside of the simplification may result in the large mould activity with repeating humidity cycles and instead of remaining certain level the mould growth would be considered as decreasing during dry spells given the fact that visual appearance might not change but a definite delay can be observed. In the research and experiments by Viitanen, he found out and concluded that mould and fungi pose a major threat to wooden structures which are exposed to excess moisture than brown rot and decay fungi; and the minimum requirement of humidity and temperature are considerably lower [45], [49], [50]. Mainly with higher temperatures, relative humidity and availability of nutrients the time required for spores to germinate and propagate is less [45].

7 Building Performance Simulation

7.1 The Studied building

The building considered for the work is a typical single-family house[4] with bedrooms, living room, family room, kitchen, toilets and store room spread across two floors with total floor area of 170m². The studied building designed is typical two level single family passive house and is assumed to be built with the best technology/ methods known to date.

The exterior wall, roof, construction was developed through discussions with architects, structural engineers, building engineers, property owners, building managers, constructors and also referring to ISOVER book and ISOVER web page where they show the standard construction details for Swedish Passive houses. [55]–[59], their properties are discussed in Table 4.

Table 4: Exterior wall details:

Element	Thickness (m)	U-value (W/m²K)
Façade element	0.015	
Airgap	0.030	
Wind barrier (expanded polystyrene)	0.050	0.04
Oriented Strand Board	0.020	0.120
Insulation	0.200	0.035
Vapor barrier	0.001 to 0.002	-
Mineral Insulation	0.070	0.035
Gypsum board	0.015	0.200
Gypsum plaster	0.015	0.200
Total	0.415	0.102

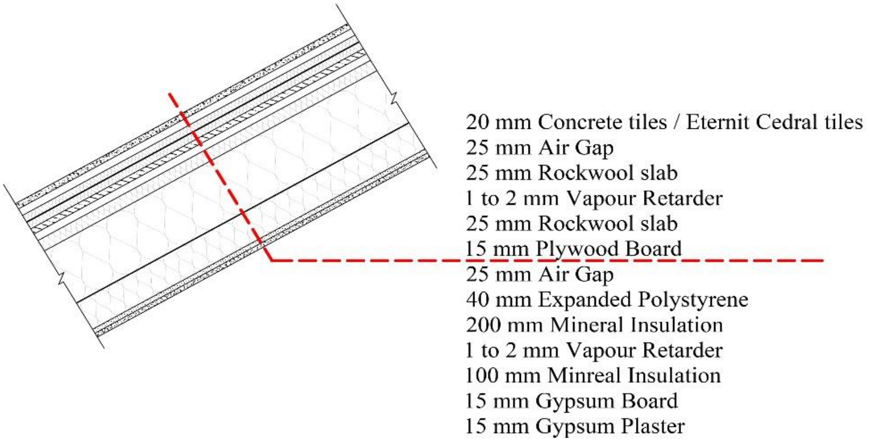

Figure 4: External roof construction

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[4] selected in careful consideration and discussions with Ar. Kenton Knoles of K2 Arkitektur

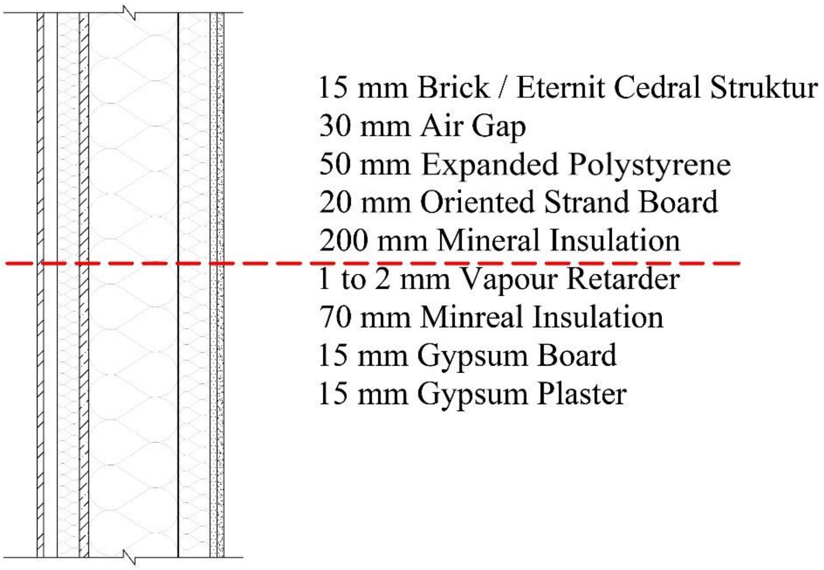

Figure 5: External Wall Construction

Table 5: Exterior roof details

Element	Thickness (m)	U-value (W/m²K)
Outer roof layer	0.020	
Air layer (in between battens)	0.025	
Rockwool insulation board	0.025	0.043
Vapor retarder	0.001 to 0.002	-
Rockwool insulation board	0.025	0.043
Ply wood board	0.015	0.100
Air layer	0.025	
Expanded polystyrene	0.040	0.040
Mineral insulation	0.200	0.031
Vapor retarder	0.001 to 0.02	-
Mineral Insulation	0.100	0.031
Gypsum board	0.015	0.2
Interior plaster	0.015	0.2
Total	0.505	0.08

Table 6: External floor details

Element	Thickness (m)	U-value (W/m²K)
Floor coating	0.005	5.0
Concrete	0.25	3.15
Insulation	0.35	0.1
Total	0.605	0.099

The building under study has an occupancy of four people, 2 adults and 2 kids. The parents are assumed to go to work on weekdays 0800-1700 and kids go to school on weekdays from 0800-1600. Weekends all the members are assumed to be at home all the time. The dwelling is assumed to be very air-tight and has minimal thermal bridges in its construction [60], [61]. The building under study is heated non-electrically.

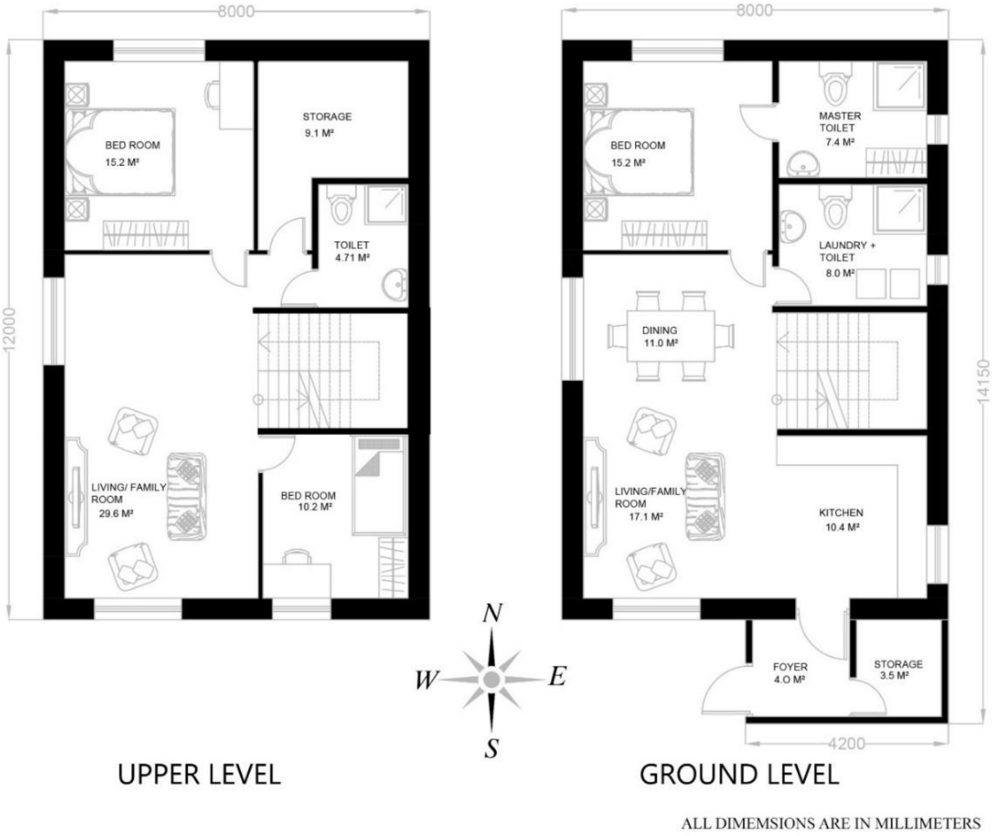

Figure 6: Plan of the Passive house under study

Figure 7: View of the Passive house

7.2 Modelling the Energy Performance

The building model under study is considered for four cities in Sweden namely, Lund, Gothenburg, Stockholm and Luleå for its energy performance and comparison with the regulations.

The energy calculation and performance of the building under study was performed with IDA ICE (IDA Indoor Climate and Energy) dynamic energy simulation software by EQUA Simulations. IDA ICE is an energy calculation program where the precise calculation of indoor climate for the whole building can be performed [62]

The energy performance in the building was analysed in three phases. The first phase was assessing the energy performance of the passive house for reference year with the conditions in present condition. The climate data used for this assessment are the ones available on EQUA Climate Data Download Centre. There are many different climate data types available. From those the IWEC2 database was chosen as the weather data for all the four cities are available.

The second phase of energy simulation was performed with CNRM and IPSL climate data for Lund for a period of 90 years with three-time spans of 2009-2038, 2039-2068 and 2069-2098. The assessment was conducted only for Lund as the time taken for simulation was too long and assessment of the enormous amount of data obtained from the simulation was very tedious and time consuming.

The third phase of the assessment was performed for all the four cities namely Lund, Gothenburg, Stockholm and Luleå, with three sets of weather data; TDY, ECY and EWY. The periods selected for the work are from 2009-2038, 2039-2068 and 2069-2098. In this method, the time taken for the assessment was reduced by almost 60% to 80% of that of the second phase and as suggested by Nik [11] the combined climate data of TDY, ECY and EWY are more reliable and they are comparable with the reference year climate data.

The building zones were simplified as it is almost impossible to ascertain the occupancy of spaces in the dwelling. Bedroom, living/family room, kitchen and staircase are in one zone in ground level and upper level; toilets and store room are in a different zone in both lower and upper zone. Foyer and outside storage at ground level are a separate zone [62]. The heating and cooling set points for the zones are set to be at 21°C and 26°C respectively.

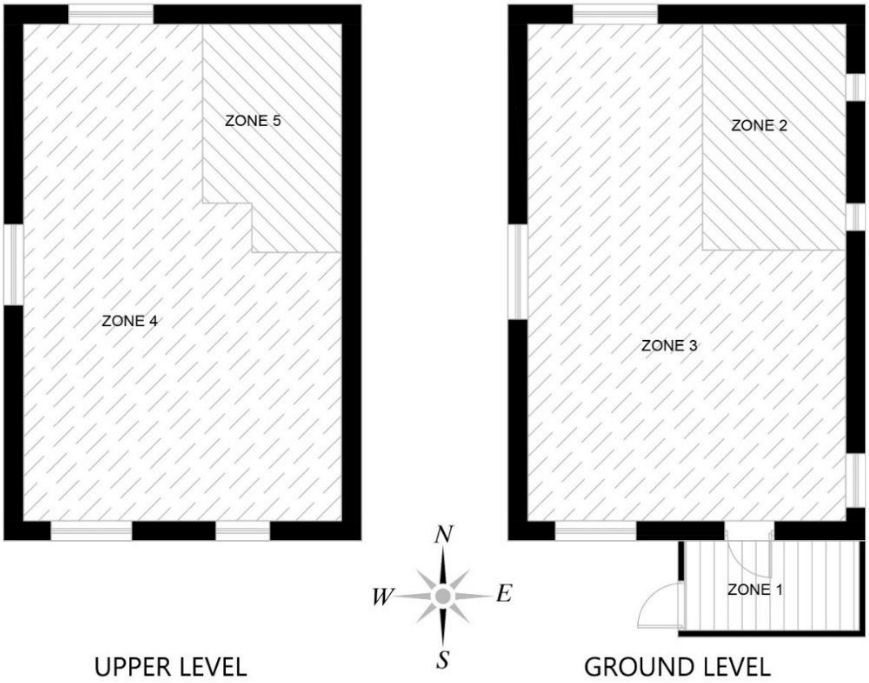

Figure 8: breakup of zones for energy consumption study in the Passive house

Table 7: Inputs for energy consumption calculation model

Element	
External roof	0.08 (W/m²K)
External wall	0.102 (W/m²K)
External floor	0.099 (W/m²K)
Windows	0.7 (W/m²K)
Internal wall	0.61 (W/m²K)
Internal floor	2.38 (W/m²K)
Window Shading	No shading
Thermal bridges	17%[5] [60]
Infiltration	0.30 L/(sm²) at 50pa pressure difference
Domestic Hot Water usage	20 kWh/(m²yrA_{temp}) (uniform usage)
Supply air temperature for AHU winter	19°C
Supply air temperature for AHU Summer	15°C
Heat exchanger	Always on
Fan operation	Always on
Heat exchanger efficiency	85%
Wind profile	suburban

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[5] best practice is between 11%to 20% of envelope transmission

7.3 Modelling the Moisture Performance

Moisture analysis was conducted in four cities, Lund, Gothenburg, Stockholm and Luleå, for the reference year climate conditions, however for future moisture performance the analysis was performed only for Gothenburg since it is the region has the maximum moisture related problems in Sweden [8], [12]. The assessment is carried out for three 30-year time periods, 1961-1990, 2021-2050 and 2071-2100 with CNRM and IPSL climate data.

The moisture performance is carried out for two façade materials for wall and two rooftop elements. Two façade elements are chosen to assess the varying moisture content in different layers of the wall. The two façade elements selected for the analysis are

1. Ventilated brick façade with 100 ach in the ventilated air gap;
2. Eternit cedral struktur façade with ventilated air cavity of 100 ach.

The motivation for the selection of two materials was to assess the moisture performance of the two popular façade elements in passive houses in Sweden[6], Brick was chosen as an inorganic material and has higher moisture storage function. Eternit cedral struktur was chosen for its fire protection properties, all weather protection properties, and it has wooden texture and strength and durability of fibre cement board [63].

The façade elements were set for south orientation for the study as South, Southwestern and Southeastern direction has a maximum impact from driving rain in Gothenburg region [12], [23].

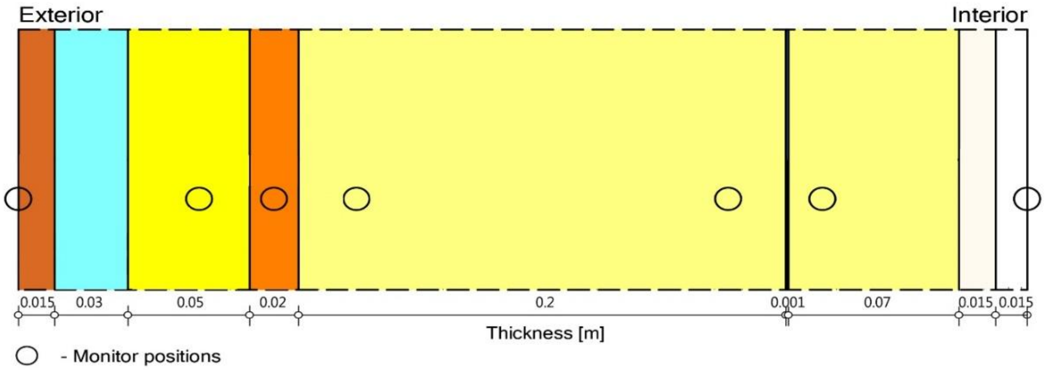

Figure 9: Monitor position in the external wall with Brick facade

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[6] discussed with few architects, façade designers, property owners, engineers, of many construction companies in Sweden and Akram Abdul Hamid of department of Building Physics at Lund University.

Table 8: Details and properties of brick facade

Façade Element	Brick
Adhering fraction of driving rain in outermost layer	1%
Orientation	South
Inclination	90°
Ground shortwave reflectance	0.2
Adhering fraction of rain	0.7
Outdoor climate, reference climate	Lund, Gothenburg, Stockholm, Lulea
Outdoor climate, future conditions	Gothenburg, CNRM and IPSL climate models
Indoor climate	EN15026 [64][65]
Calculation period, Reference year	5 years (1825 days)
Calculation period, future conditions	30 years (10950 days)

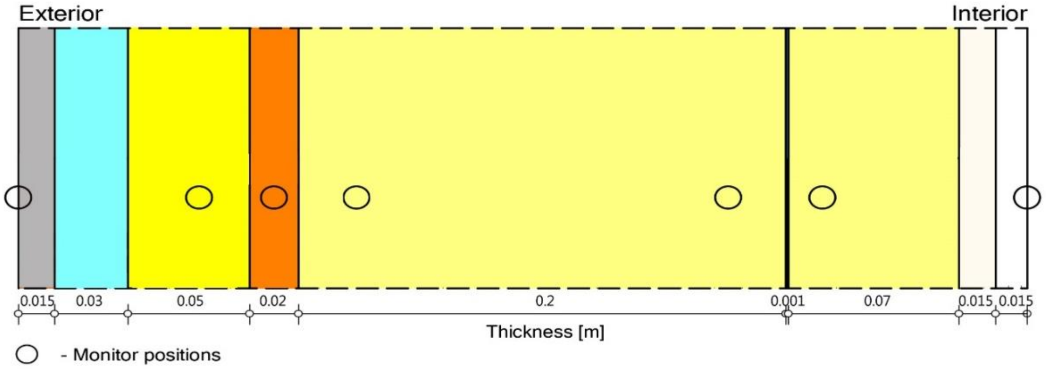

Figure 10: Monitor position in the external wall with Eternit Cedral Struktur facade

Table 9: Details and properties of Eternit cedral struktur facade

Façade Element	Eternit cedral struktur
Adhering fraction of driving rain in outermost layer	1%
Orientation	South
Inclination	90°
Ground shortwave reflectance	0.2
Adhering fraction of rain	0.7
Outdoor climate, reference climate	Lund, Gothenburg, Stockholm, Lulea
Outdoor climate, future conditions	Gothenburg, CNRM and IPSL climate models
Indoor climate	EN15026 [64]
Calculation period, Reference year	5 years (1825 days)
Calculation period, future conditions	30 years (10950 days)

The moisture performance calculation of the roof was carried out for two rooftop elements for the same time periods, first for the reference year time period, existing weather data from WUFI and for three time periods of 1961-1990, 2021-2050 and 2071-2100. The ventilated air gaps have a controlled air ventilation rate of 2.5ach;

1) External roof with Concrete roof tiles
2) External roof with Eternit cedral roof tiles

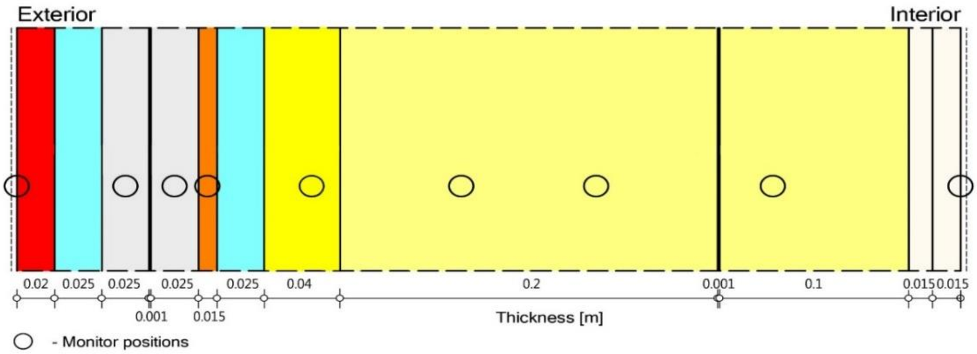

Figure 11: Monitor position in the external roof with concrete tiles

Table 10: Details and properties of roof with concrete tiles

Roof Element	Concrete tiles
Adhering fraction of driving rain in outermost layer	1%
Orientation	West
Inclination	30°
Sd- value [m]	2
Short wave radiation absorptivity	0.96
Long wave radiation absorptivity	0.9
Ground shortwave reflectance	0.2
Adhering fraction of rain	1
Outdoor climate, reference climate	Lund, Gothenburg, Stockholm, Lulea
Outdoor climate, future conditions	Gothenburg, CNRM and IPSL climate models
Indoor climate	EN15026[64]
Calculation period, Reference year	5 years (1825 days)
Calculation period, future conditions	30 years (10950 days)

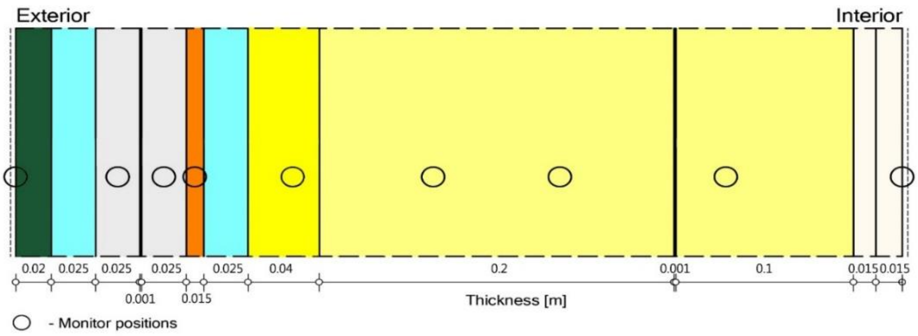

Figure 12: Monitor position in the external roof with Eternit Cedral tiles

Table 11: Details and properties of roof with Eternit roof tiles

Roof Element	Eternit Cedral Struktur
Adhering fraction of driving rain in outermost layer	1%
Orientation	West
Inclination	30°
Sd- value [m]	2
Short wave radiation absorptivity	0.96
Long wave radiation absorptivity	0.9
Ground shortwave reflectance	0.2
Adhering fraction of rain	1
Outdoor climate, present climate	Lund, Gothenburg, Stockholm, Lulea
Outdoor climate, future conditions	Gothenburg, CNRM and IPSL climate models
Indoor climate	EN15026 [64]
Calculation period, Reference year	5 years (1825 days)
Calculation period, future conditions	30 years (10950 days)

8 Results

The simulations were performed for energy consumption calculation, overheating of indoor space and for moisture performance calculation. Only selected results are presented below as sheer amount of data would be almost impossible to process and come to conclusions.

8.1 Energy Performance

In this chapter, only the heating, cooling demands and overheating[7] of indoor space are discussed as the energy consumption was constant for Lighting, Equipment and Auxiliary usage throughout the calculation period. Charts for each of the four cities are discussed in Appendix 1.

Table 12: Heating energy demand in four cities

	Lund	Gothenburg	Stockholm	Luleå
Reference year heating demand	13.8 kWh/(m²yr)	14.2 kWh/(m²yr)	14.3 kWh/(m²yr)	31.1 kWh/(m²yr)
Combined typical year heating demand 2009-2038	12.3 kWh/(m²yr)	15.3 kWh/(m²yr)	16.2 kWh/(m²yr)	26.5 kWh/(m²yr)
Combined typical year heating demand 2039-2068	12.1 kWh/(m²yr)	16 kWh/(m²yr)	16.0 kWh/(m²yr)	22.8 kWh/(m²yr)
Combined typical year heating demand 2069-2098	9.2 kWh/(m²yr)	11.6 kWh/(m²yr)	11.3 kWh/(m²yr)	19.6 kWh/(m²yr)

Table 13: Cooling energy demand in four cities

	Lund	Gothenburg	Stockholm	Luleå
Reference year cooling demand	3.3 kWh/(m²yr)	2.5 kWh/(m²yr)	6.8 kWh/(m²yr)	3.9 kWh/(m²yr)
Combined typical year cooling demand 2009-2038	8.9 kWh/(m²yr)	7.7 kWh/(m²yr)	8.0 kWh/(m²yr)	6.4 kWh/(m²yr)
Combined typical year cooling demand 2039-2068	10.2 kWh/(m²yr)	9.1 kWh/(m²yr)	9.8 kWh/(m²yr)	7.4 kWh/(m²yr)
Combined typical year cooling demand 2069-2098	10.8 kWh/(m²yr)	9.5 kWh/(m²yr)	11.6 kWh/(m²yr)	8.2 kWh/(m²yr)

In Table 12 the heating energy demands are presented for the four cities. The energy demand will decrease by 2069-2098 considerably in comparison to the reference year. The reduction in heating demand is more in northern parts of Sweden than towards central and southern Sweden. In Table 13 the cooling energy demands are presented

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[7] Cooling set point was removed and typical year climate data sets were used in the building model for the calculation of over-heating period.

which shows clearly that there is considerable rise in cooling demands in all the four cities of Sweden.

Table 14: Overheating period in ground floor of studied building (>29°C indoors)

	Lund	Gothenburg	Stockholm	Luleå
Reference year	428 hours	287 hours	1631 hours	900 hours
Typical year 2009-2038	1609 hours	1394 hours	1684 hours	1401 hours
Typical year 2039-2068	1582 hours	1677 hours	1669 hours	1636 hours
Typical year 2069-2098	1841 hours	1582 hours	2167 hours	1321 hours

Table 15: Overheating period in upper floor of studied building (>29°C indoors)

	Lund	Gothenburg	Stockholm	Luleå
Reference year	305 hours	221 hours	1498 hours	803 hours
Typical year 2009-2038	1397 hours	1178 hours	1364 hours	1072 hours
Typical year 2039-2068	1368 hours	1434 hours	1502 hours	1390 hours
Typical year 2069-2098	1653 hours	1425 hours	1977 hours	1140 hours

In Table 14 and 15 overheating periods are presented for ground floor and upper floor respectively. The trend in all the four cities is increasing overheating periods due to increase in warmer periods, which can be co-related to rising temperatures.

8.2 Moisture performance and Mould growth calculation for the reference year

Moisture Performance calculations were performed with WUFI pro software program, which is used widely for moisture performance calculations and simulations [64]. The results obtained were assessed with the help of Microsoft excel and Matlab software programs to get good graphical representations. The results obtained are categorised based on the cities and outer facade and roofing element.

8.2.1 Moisture Performance of Wall in Lund

In figure 13, left figure shows the relative humidity levels in different layers of the wall construction with outside brick surface, expanded polystyrene and oriented strand board has relative humidity levels above 75% and in top right figure the temperatures in these critical layers are varying between -10°C to +29°C, -4°C to +25°C, and -1°C to +24°C respectively. The mineral insulation layer where monitor position is 145mm from the outside surface of the wall the relative humidity level varies between 70% to 75% and temperature at the same monitor position varies between +2°C to +24°C. These relative humidity and temperature levels are most favourable for mould growth. In figure 14, there is minimal to no mould growth in expanded polystyrene layer and in oriented strand board. The highest mould index in expanded polystyrene layer is 0.12 which falls well below under MGI 1, little to some mould growth detectable only with a microscope.

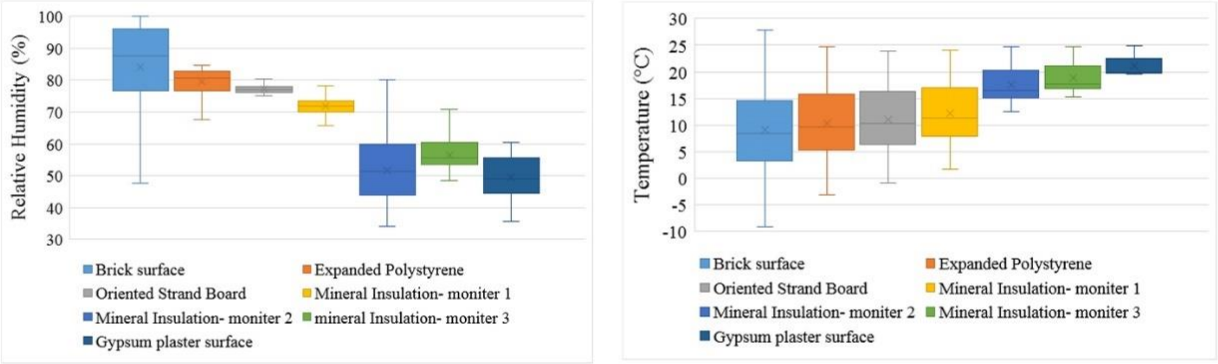

Figure 13: Moisture performance in Brick facade wall layers for Lund. Charts showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

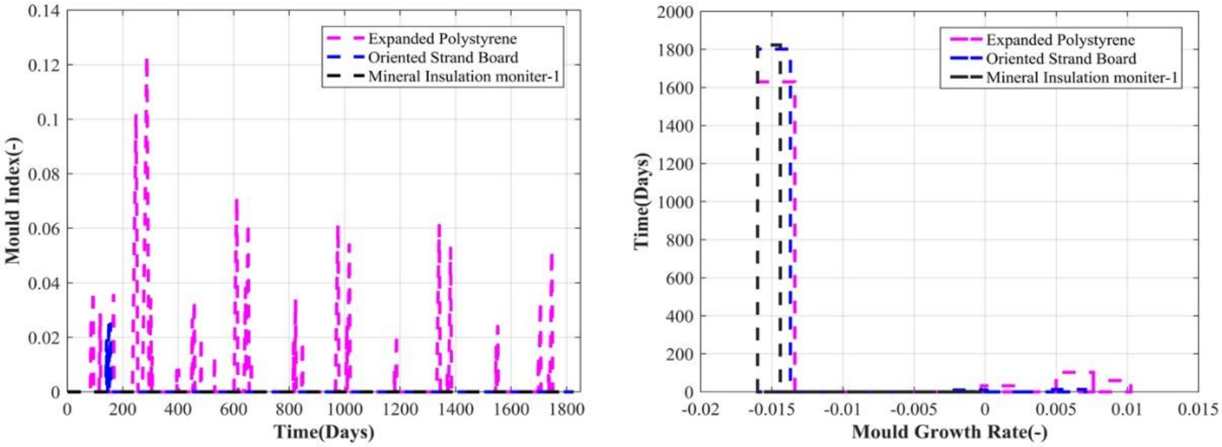

Figure 14: Mould Index(left) and Mould growth(right) in critical layers of external wall with Brick facade for Lund.

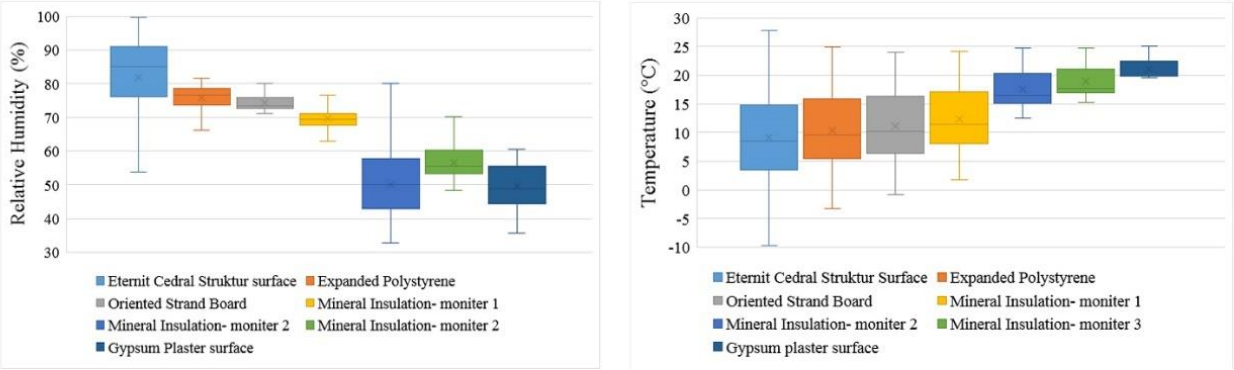

Figure 15: Moisture performance in Eternit Cedral Struktur facade wall layers for Lund. Charts showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

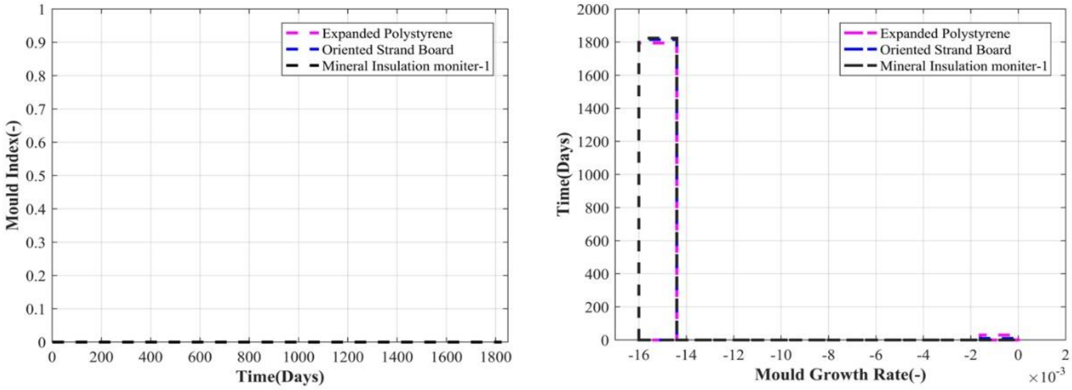

Figure 16: Mould Index(left), Mould Growth (right) in critical layers of external wall with Eternit Cedral Struktur facade for Lund.

In figure 15, left figure shows the relative humidity levels in expanded polystyrene has relative humidity levels above 75% and oriented strand board and monitor 1 of mineral insulation layer the relative humidity levels are below 75%; in right figure, the temperatures in these critical layers are varying between -10°C to +29°C, -4°C to +25°C, -1°C to +24°C and +2°C to +24°C respectively. These relative humidity and temperature levels are not favourable for mould growth. In figure 16, there is no mould growth in critical layers and the wall construction is safe for construction in the reference year.

8.2.2 Moisture Performance of Wall in Gothenburg

In figure 17, relative humidity levels and temperature levels are shown; outside brick facade surface, expanded polystyrene, oriented strand board and monitor 1 of mineral insulation have relative humidity levels of 68%-90%, 72%-80%, 72%-76% and 68%-72% respectively and temperatures in these layers are varying between -12°C to +27°C, -6°C to +25°C, -4°C to +24°C and -2°C to +24°C respectively. These relative humidity and temperature levels are not favourable for mould growth. In figure 18, there is small mould growth in expanded polystyrene layer less than MGI of 1, oriented strand board and mineral insulation layer have no mould growth and the wall construction is safe for construction in the reference year.

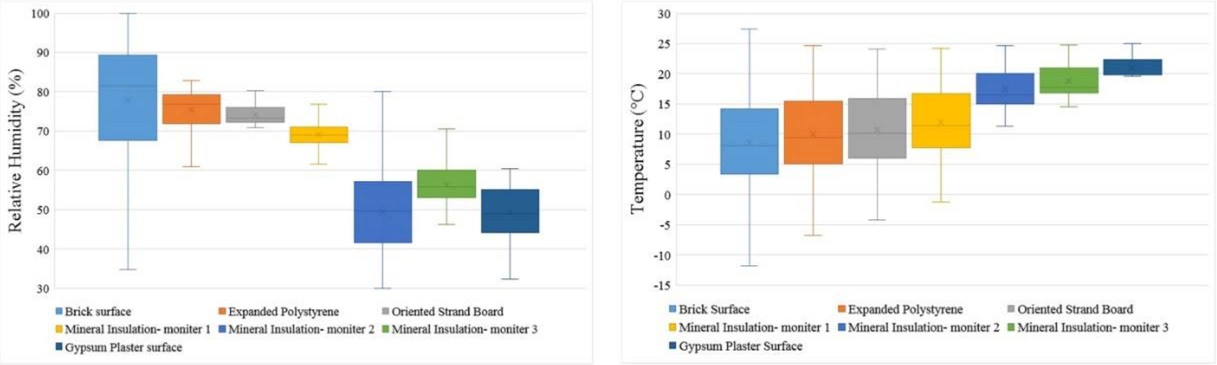

Figure 17: Moisture performance in Brick facade wall layers for Gothenburg. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

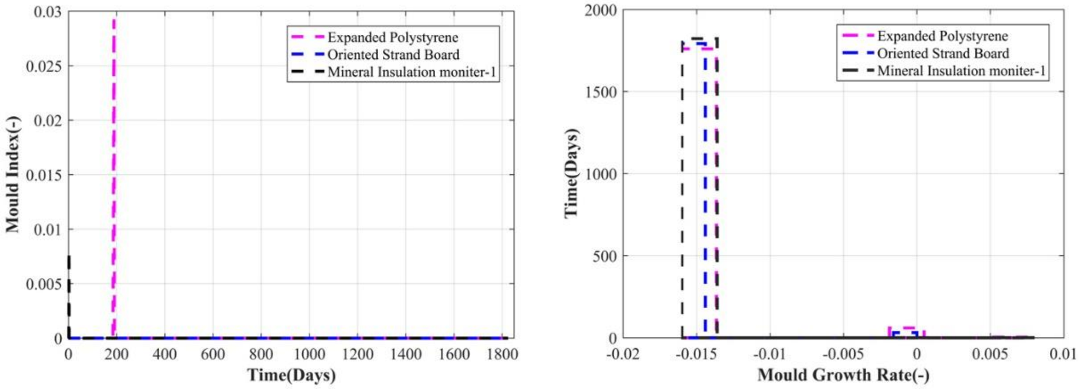

Figure 18: Mould Index(left), Mould Growth(right) in critical layers of external wall with brick facade for Gothenburg.

In figure 19, relative humidity levels and temperature levels are shown; outside Eternit Cedral Struktur surface, expanded polystyrene, oriented strand board and monitor 1 of mineral insulation have relative humidity levels of 66%-86%, 68%-73%, 68%-74% and 65%-69% respectively and temperatures in these layers are varying between -12°C to +27°C, -6°C to +25°C, -4°C to +24°C and -2°C to +24°C respectively. These relative humidity and temperature levels are not favourable for mould growth in the critical layers. In figure 20, there is no mould growth in the critical layers and the wall construction is safe for construction in the reference year.

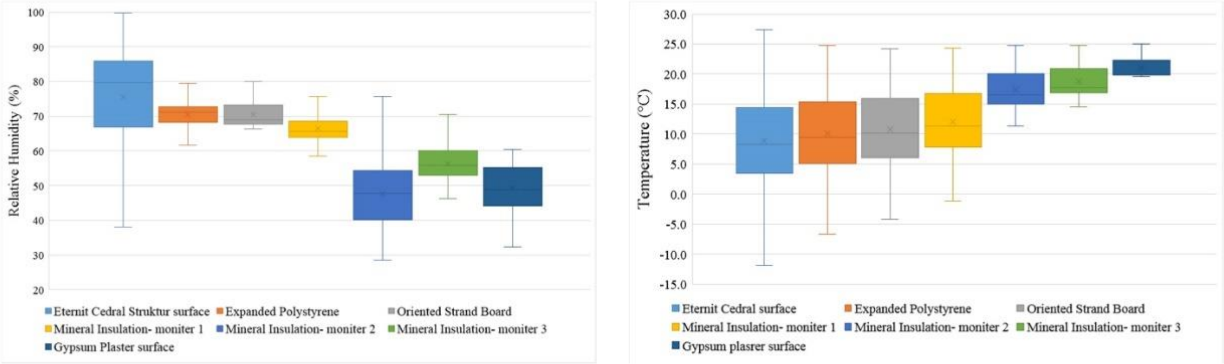

Figure 19: Moisture content in Eternit Cedral Struktur facade wall layers for Gothenburg. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

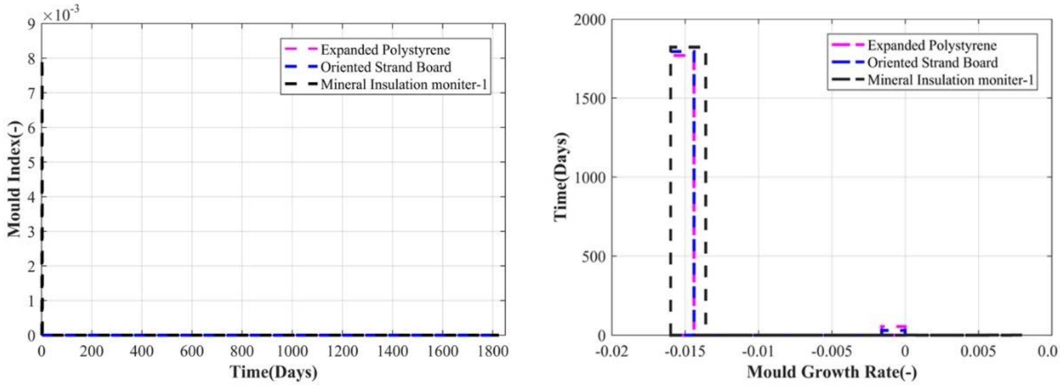

Figure 20: Mould Index(left) Mould Growth(right) in critical layers of external wall with Eternit Cedral Struktur facade for Gothenburg.

8.2.3 Moisture Performance of Wall in Stockholm

In figure 21, relative humidity and temperature are shown; with outside brick facade surface, expanded polystyrene, oriented strand board and monitor 1 of mineral insulation have relative humidity levels of 70%-92%, 70%-78%, 70%-74% and 66%-69% respectively and in top right figure the temperatures in these layers are varying between -18°C to +30°C, -12°C to +25°C, -10°C to +25°C and -6°C to +25°C respectively. This relative humidity and temperature conditions are not favourable for mould growth in the critical layers. In figure 22, there is no mould growth in the critical layers and the wall construction is safe for construction in the reference year.

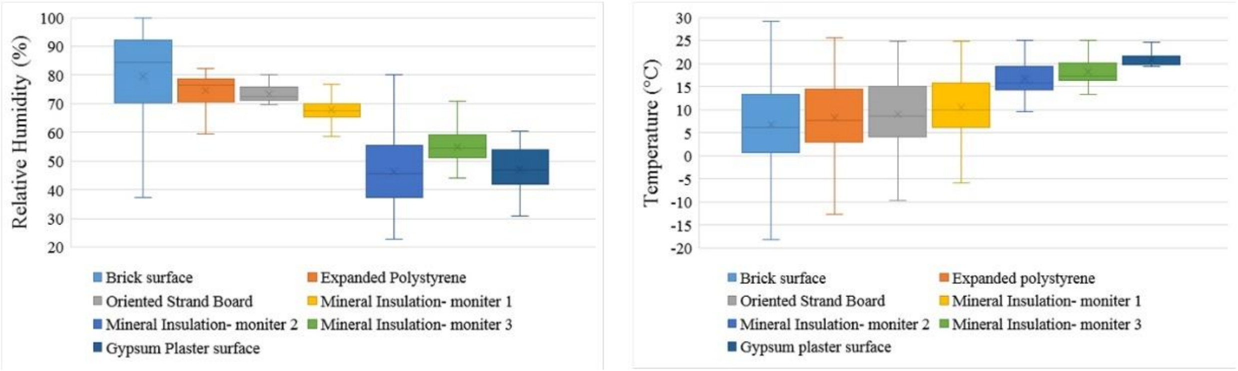

Figure 21: Moisture performance in Brick facade wall layers for Stockholm. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

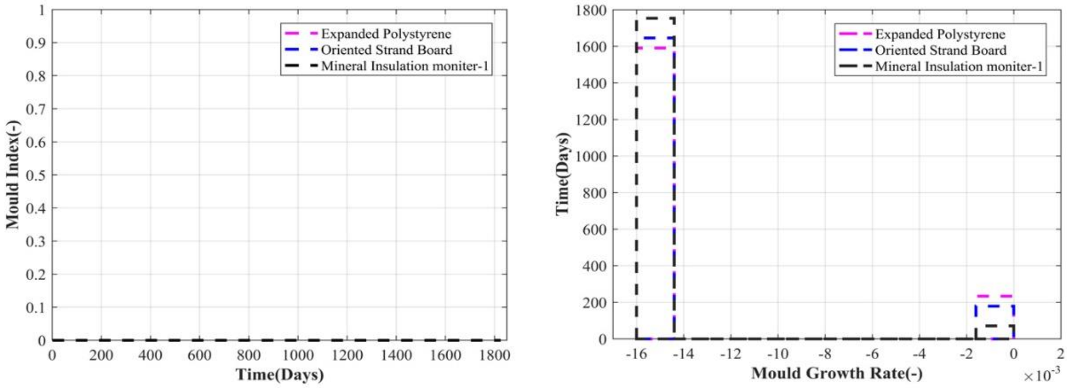

Figure 22: Mould Index(left) Mould Growth(right) in critical layers of external wall with Brick facade for Stockholm.

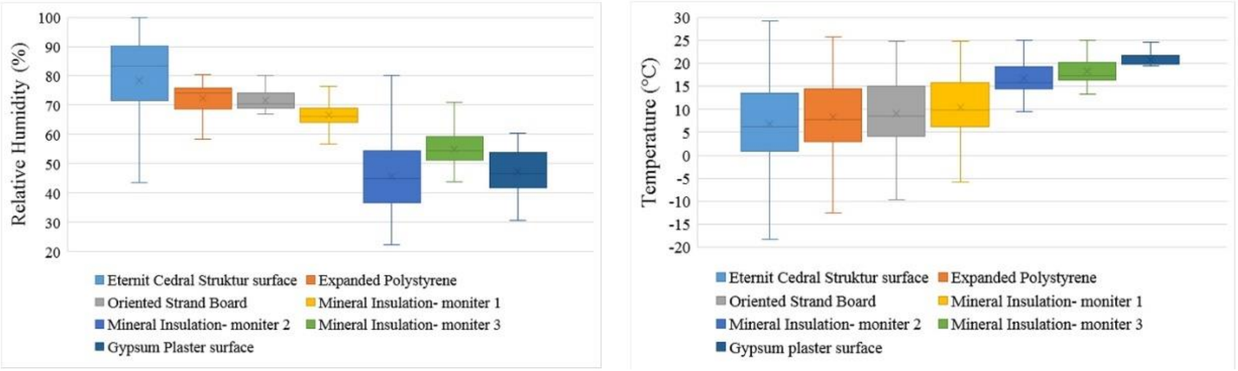

Figure 23: Moisture performance in Eternit Cedral Struktur facade wall layers for Stockholm. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

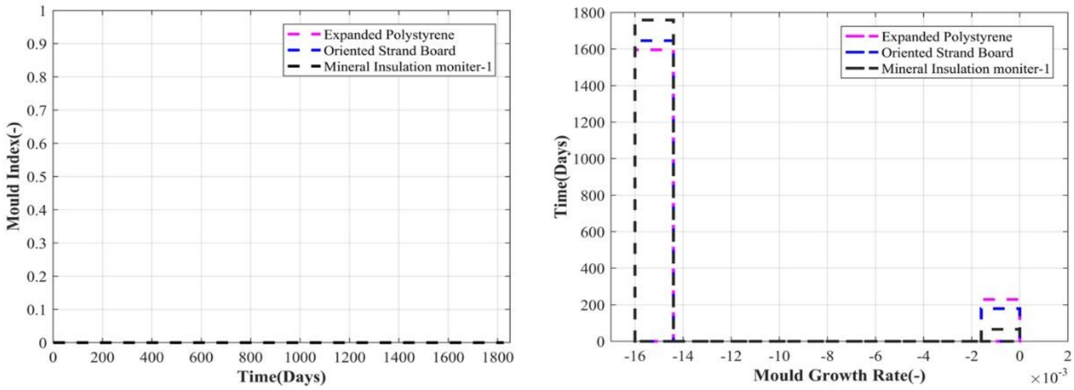

Figure 24: Mould Index(left) Mould Growth(right) in critical layers of external wall with Eternit Cedral Struktur facade for Stockholm.

In figure 23, relative humidity and temperature are shown; with outside Eternit Cedral Struktur surface 70%-90%, expanded polystyrene, oriented strand board and monitor 1 of mineral insulation have relative humidity levels less than 75% and temperatures in these layers are varying between -18°C to +30°C, -12°C to +25°C, -10°C to +25°C and -6°C to +25°C respectively. This relative humidity and temperature conditions are not favourable for mould growth in the critical layers. In figure 24, there is no mould growth in the critical layers and the wall construction is safe for construction in the reference year.

8.2.4 Moisture Performance of Wall in Lulea

In figure 25, relative humidity and temperature are shown; with outside brick facade surface 70%-90%, expanded polystyrene, oriented strand board are in 70%- 76% range and monitor 1 of mineral insulation has relative humidity levels less than 70% and temperatures in these layers are varying between -30°C to +28°C, -22°C to +25°C, -20°C to +25°C and -15°C to +25°C respectively. This relative humidity and temperature conditions are not favourable for mould growth in the critical layers. In figure 30, there is very minute mould growth in the oriented strand board layer around 180th day, after that time there is no mould growth. In figure 26, mould growth rate in oriented strand board has 500 days of minute mould growth and a decay of 1300 days; with this growth and decay there is no damage caused to the layer and the wall construction is safe for construction in the reference year.

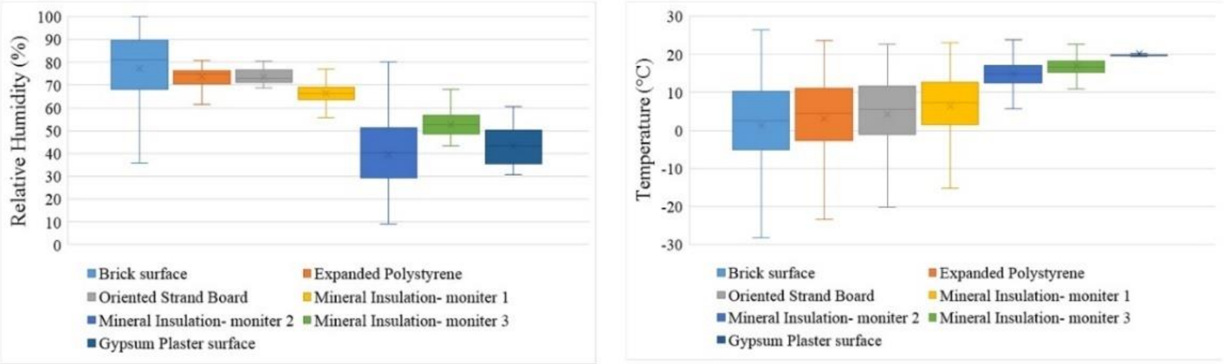

Figure 25: Moisture performance in Brick facade wall layers for Lulea. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

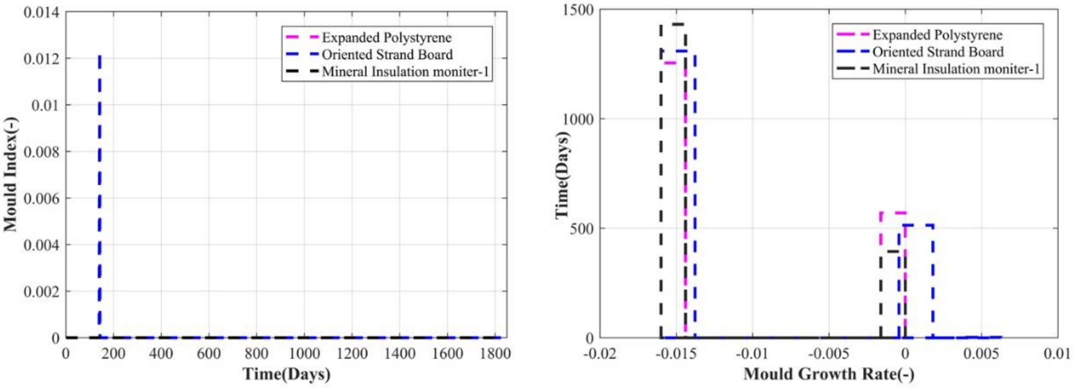

Figure 26: Mould Index(left) Mould growth(right) for critical layers in the external wall with Brick facade for Lulea.

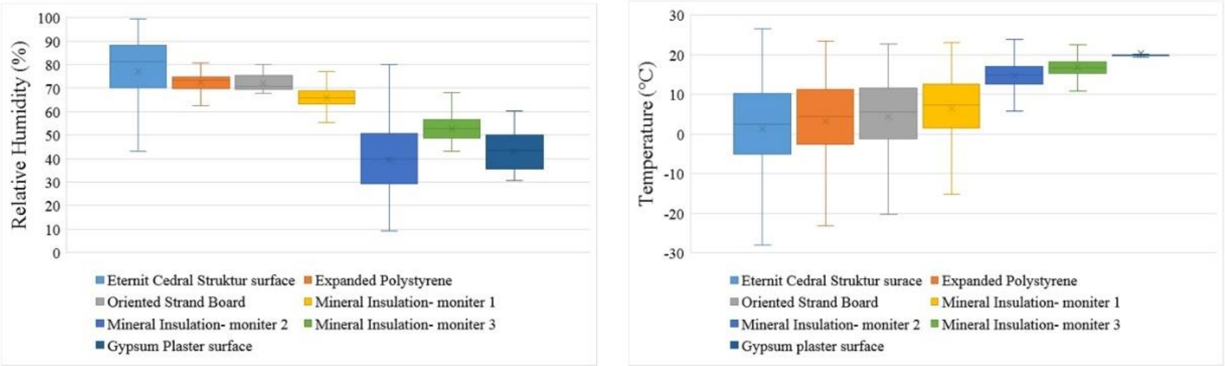

Figure 27: Moisture performance in Eternit Cedral Struktur facade wall layers for Lulea. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

In figure 27, relative humidity and temperature are shown; with outside Eternit Cedral Struktur facade surface 70%-90%, expanded polystyrene, oriented strand board are in 70%- 76% range and monitor 1 of mineral insulation has relative humidity levels less than 70% and in top right figure the temperatures in these layers are varying between -30°C to +28°C, -22°C to +25°C, -20°C to +25°C and -15°C to +25°C respectively. This relative humidity and temperature conditions are not favourable for mould growth in the critical layers and the wall construction is safe for construction in the reference year which can be seen in figure 28.

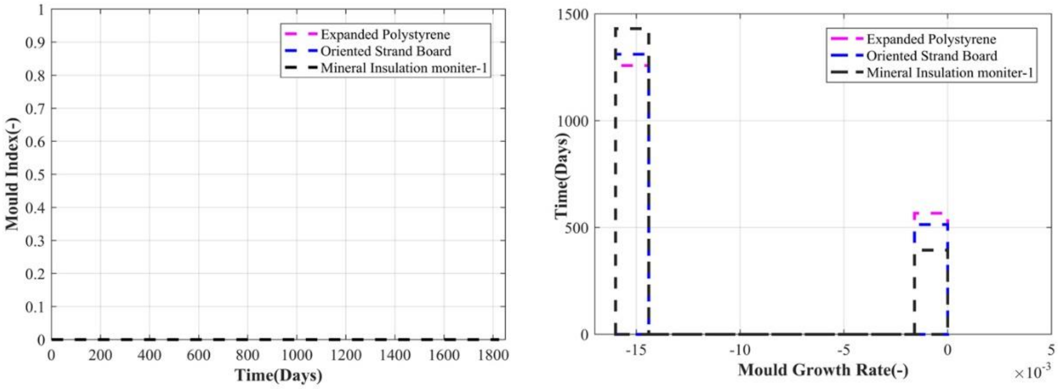

Figure 28: Mould Index(left) Mould Growth(right) for critical layers in the external wall with Eternit Cedral Struktur facade for Lulea.

8.2.5 Moisture Performance of Roof in Lund

In figure 29, relative humidity and temperature are shown; with concrete tiles roof surface 50%-78%, Getifix Rockwool slab layer-1 48%-75%, Getifix Rockwool slab layer-2, oriented strand board and expanded polystyrene layers are in 50%- 70% range and monitor 1 of mineral insulation which is 240mm from the outside surface has relative humidity levels less than 55% and in top right figure the temperatures in these layers are varying between -10°C to +40°C respectively. This relative humidity and temperature conditions are not favourable for mould growth in the critical layers which can be seen from figure 34. In figure 30, there is minute mould growth with mould index of 0.039 on the MGI, also has a decay of almost 1800 days. Therefore, the wall construction is safe for construction in the reference year.

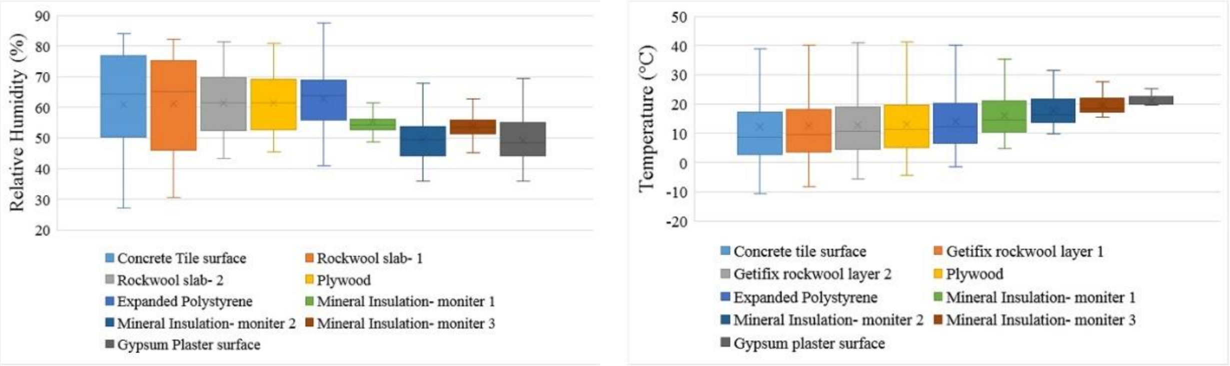

Figure 29: Moisture performance of External roof with Concrete Tiles for Lund. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

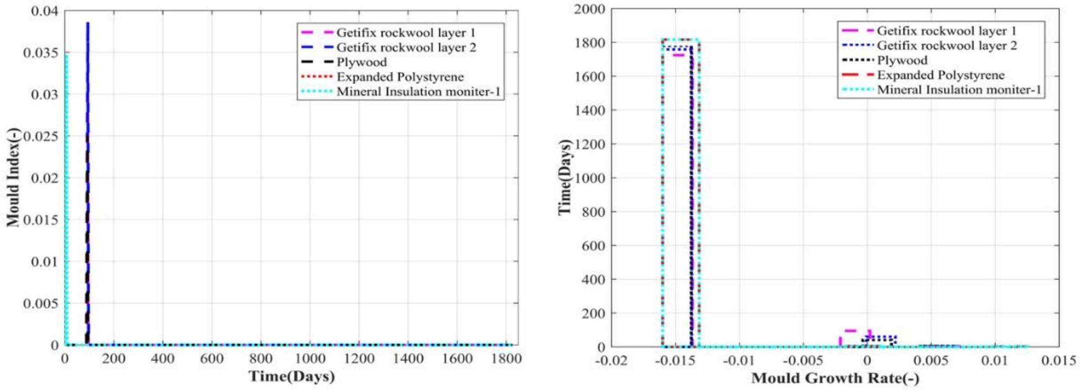

Figure 30: Mould Index(left) Mould Growth(right) in critical layers of the External roof with Concrete tile for Lund.

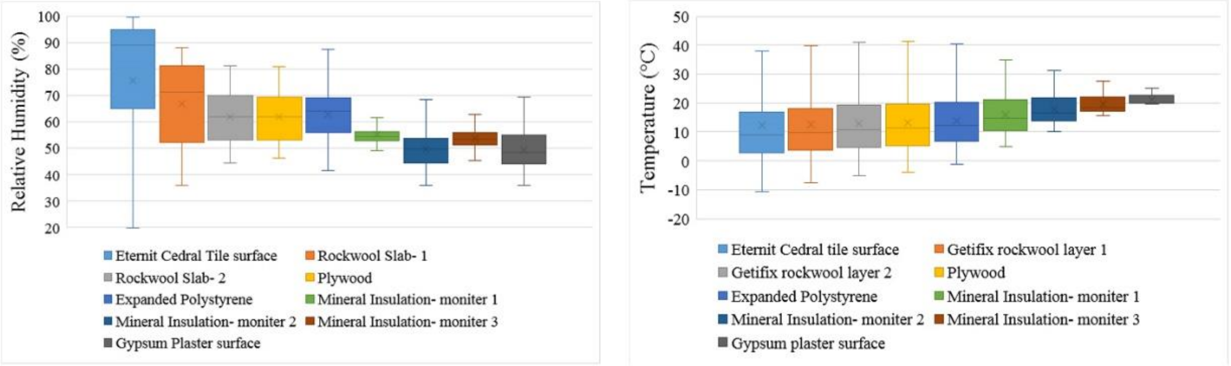

Figure 31: Moisture performance in Eternit Cedral Tile roof for Lund. Graphs showing Relative Humidity of the whole wall (left), Temperature variations in the whole wall (right)

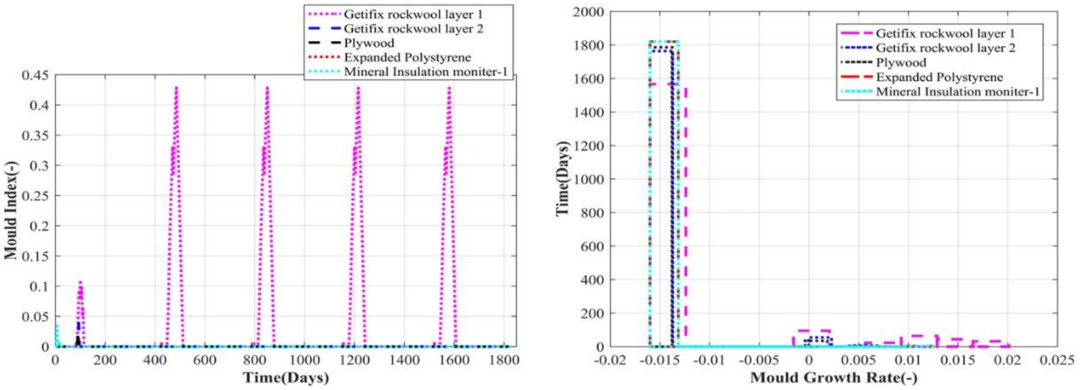

Figure 32: Mould Index(left) Mould Growth(right) in critical layers of External roof with Eternit Cedral tiles for Lund

In figure 31, relative humidity and temperature are shown; with Eternit Cedral tiles roof surface 20%-100%, Getifix Rockwool slab layer-1 40%-90%, Getifix Rockwool slab layer-2 and oriented strand board are in 45%- 80% range, expanded polystyrene layer with 40%-90% and monitor 1 of mineral insulation has relative humidity levels less than 60% and temperatures in these layers are varying between -10°C to +40°C. This relative humidity and temperature conditions are having some favourable conditions for mould growth in the critical layers which can be seen in figure 32. In figure 32, there is little to some mould growth with mould index reaching 0.45 on the MGI every 400 days, also has a decay of almost 1800 days. Therefore, the wall construction is safe for construction in reference year as the mould growth and decay cancelling out each other.

8.2.6 Moisture Performance of Roof in Gothenburg

In figure 33, relative humidity and temperature are shown; with concrete tiles roof surface 25%-85%, Getifix Rockwool slab layer-1 35%-80%, Getifix Rockwool slab layer-2 and oriented strand board are in 45%- 80% range, expanded polystyrene layer with 40%-85% and monitor 1 of mineral insulation has relative humidity levels less than 60% and temperatures in these layers are varying between -15°C to +40°C. This relative humidity and temperature conditions are not favourable conditions for mould growth in the critical layers which can be seen from figure 38. In figure 34 there is no mould growth in the layers of the roof construction. Therefore, the roof construction is safe for construction in the reference year.

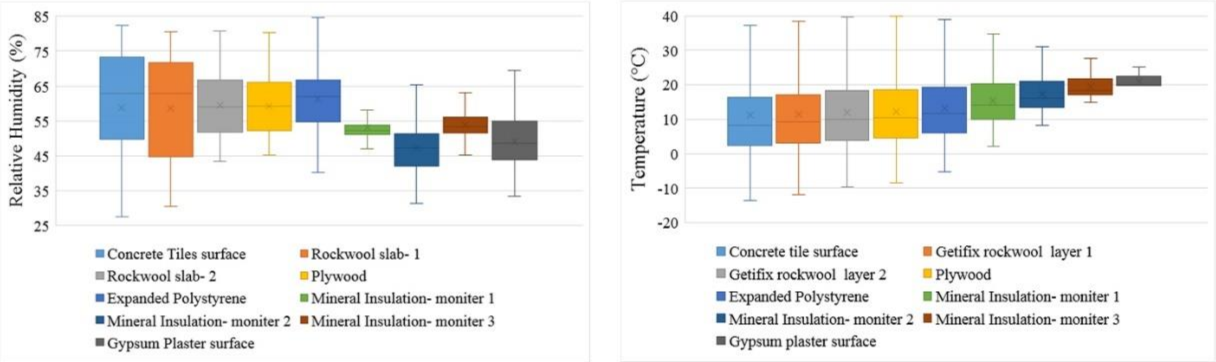

Figure 33: Moisture performance in Concrete Tile roof for Gothenburg. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

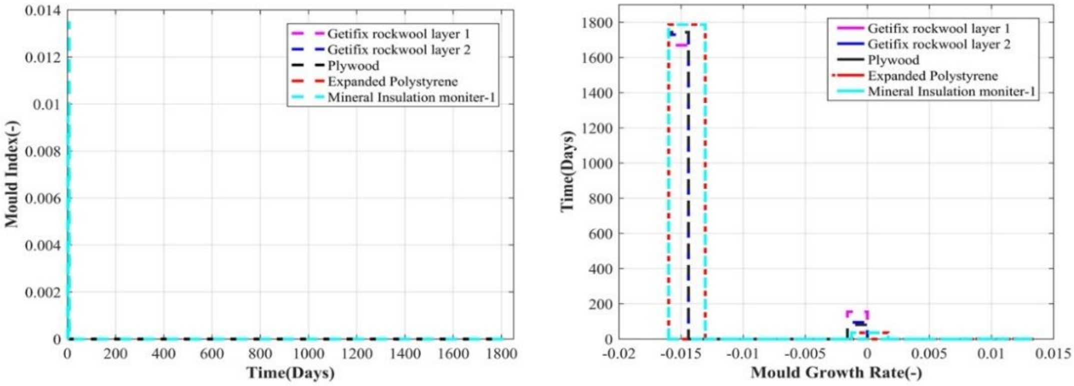

Figure 34: Mould Index(left) Mould Growth(right) in critical layers of the External roof with Concrete tiles for Gothenburg.

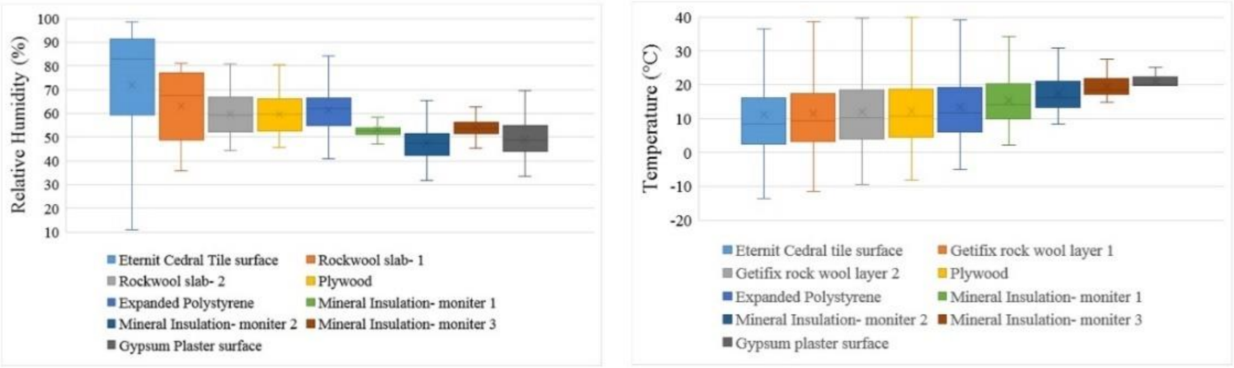

Figure 35: Moisture performance in the External roof with Eternit Cedral Tile for Gothenburg. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

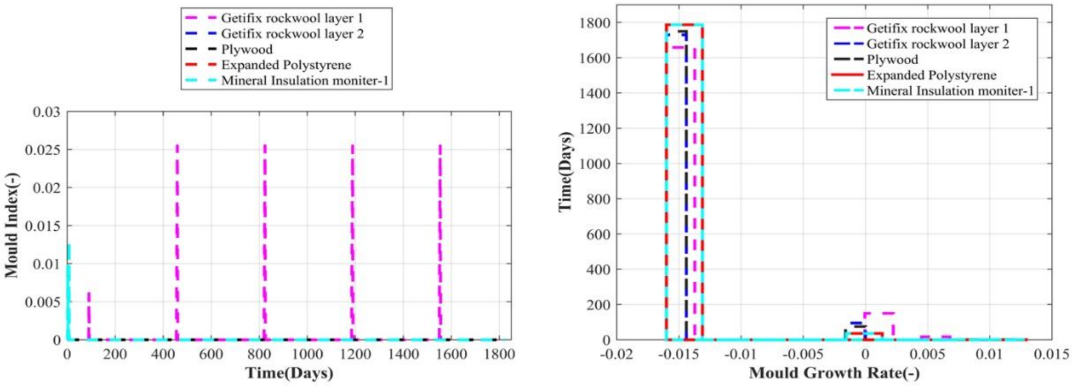

Figure 36: Mould Index(left) Mould Growth(right) in critical layers of External roof with Eternit Cedral tile for Gothenburg

In figure 35, relative humidity and temperature are shown; with Eternit Cedral tiles roof surface 10%-100%, Getifix Rockwool slab layer-1 35%-80%, Getifix Rockwool slab layer-2 and oriented strand board are in 45%- 80% range, expanded polystyrene layer with 40%-85% and monitor 1 of mineral insulation has relative humidity levels less than 60% and temperatures in these layers are varying between -15°C to +40°C. This relative humidity and temperature conditions are having some favourable conditions for mould growth in the critical layers which can be seen from figure 36. In figure 36, there is minute mould growth with mould index reaching 0.025 on MGI scale every 350 days, also has a decay of almost 1800 days. Therefore, the wall construction is relatively safe for construction in reference year as the mould growth and decay cancelling out each other.

8.2.7 Moisture Performance of Roof in Stockholm

In figure 37, relative humidity and temperature are shown; with concrete tiles roof surface 25%-85%, Getifix Rockwool slab layer-1 30%-80%, Getifix Rockwool slab layer-2 and oriented strand board are in 45%- 80% range, expanded polystyrene layer with 38%-87% and monitor 1 of mineral insulation has relative humidity levels less than 65% and temperatures in these layers are varying between -20°C to +40°C. This relative humidity and temperature conditions are not favourable conditions for mould growth in the critical layers which can be seen from figure 38. In figure 38, there is no mould growth in the layers of the roof construction. Therefore, the roof construction is safe for construction in the reference year.

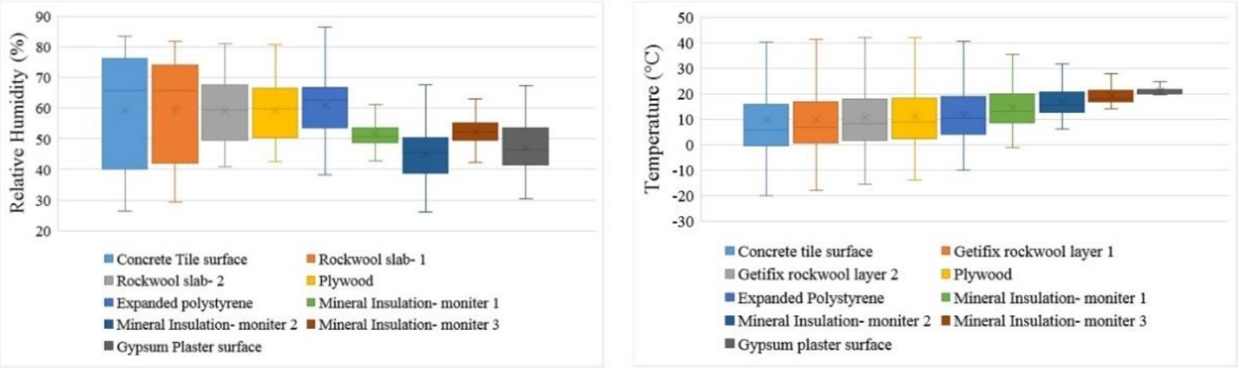

Figure 37: Moisture performance in the External roof with Concrete tiles for Stockholm. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

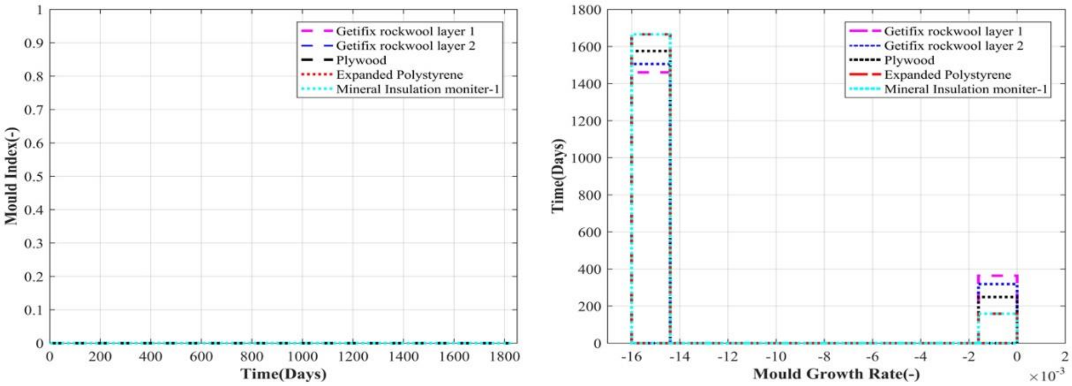

Figure 38: Mould Index(left) Mould Growth(right) in critical layers of the External roof with Concrete tiles for Stockholm.

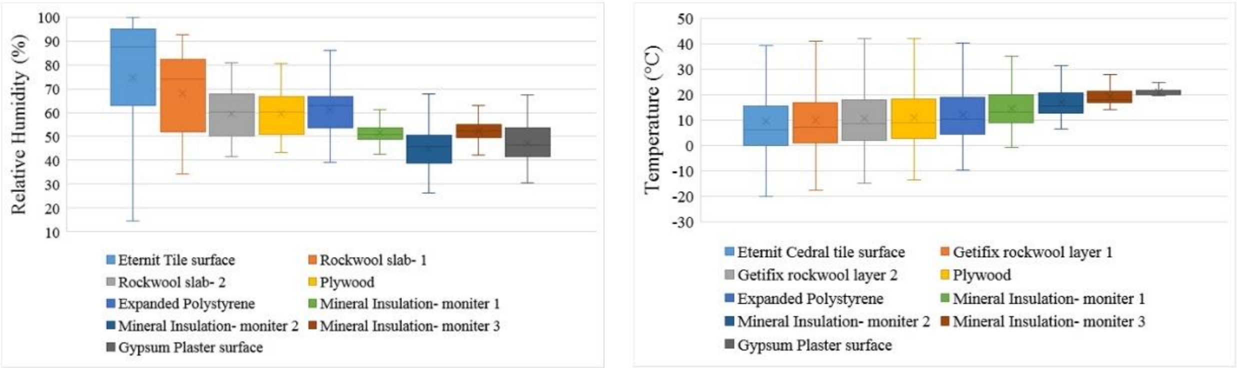

Figure 39: Moisture performance in the External roof with Eternit Cedral tiles for Stockholm. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

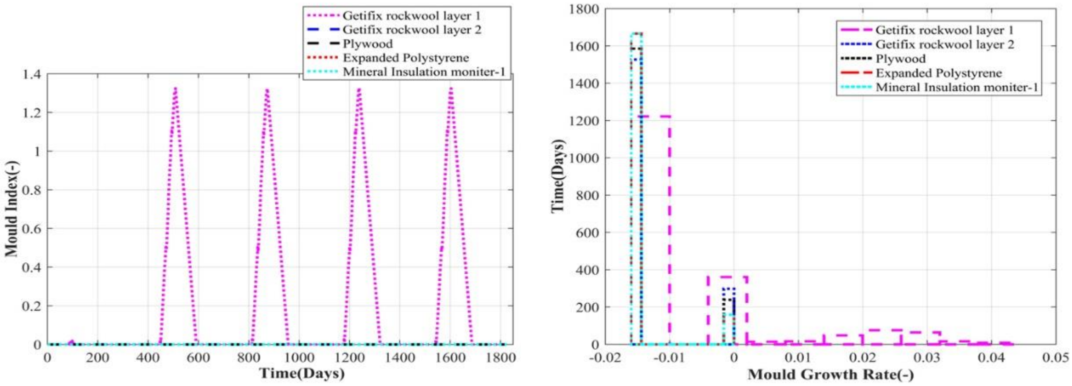

Figure 40: Mould Index(left) Mould Growth(right) in critical layers of the External roof with Eternit Cedral tile for Stockholm.

In figure 39, relative humidity and temperature are shown; with Eternit Cedral tiles roof surface 15%-100%, Getifix Rockwool slab layer-1 35%-95%, Getifix Rockwool slab layer-2 and oriented strand board are in 40%- 80% range, expanded polystyrene layer with 40%-90% and monitor 1 of mineral insulation has relative humidity levels less than 60% and temperatures in these layers are varying between -15°C to +40°C. This relative humidity and temperature conditions are having some favourable conditions for mould growth in the critical layers which can be seen from figure 44 above. In figure 40, there is some mould growth with mould index reaching 1.4 on MGI scale. Therefore, the wall construction is relatively safe for construction in reference year as the mould is detectable with a microscope and does not cause any damage to the material in the studied period of 1800 days.

8.2.8 Moisture Performance of Roof in Lulea

In figure 41, relative humidity and temperature are shown; with concrete tiles roof surface 30%-80%, Getifix Rockwool slab layer-1 30%-80%, Getifix Rockwool slab layer-2 and oriented strand board are in 45%- 80% range, expanded polystyrene layer with 40%-90% and monitor 1 of mineral insulation has relative humidity levels less than 65% and temperatures in these layers are varying between -30°C to +40°C. This relative humidity and temperature conditions are not favourable conditions for mould growth in the critical layers which can be seen from figure 42. Therefore, the roof construction is safe for construction in reference year.

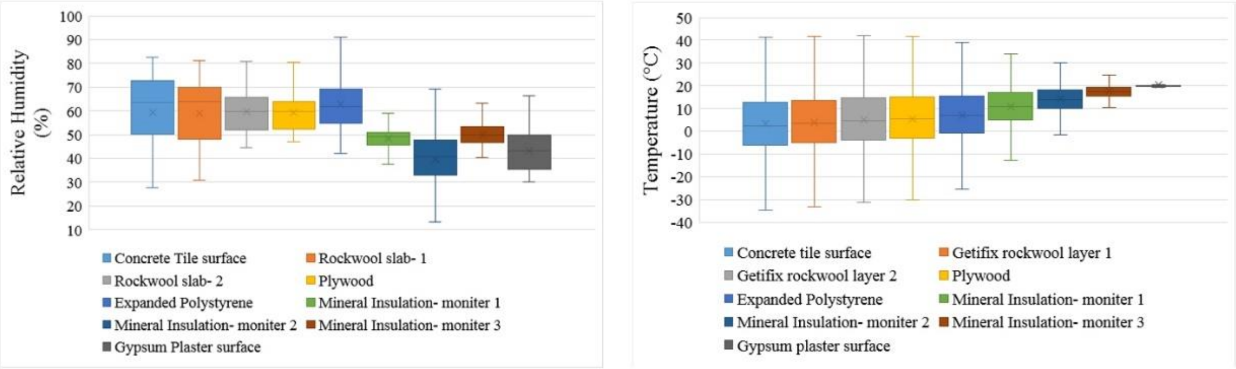

Figure 41: Moisture performance in the External roof with Concrete tiles for Lulea. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

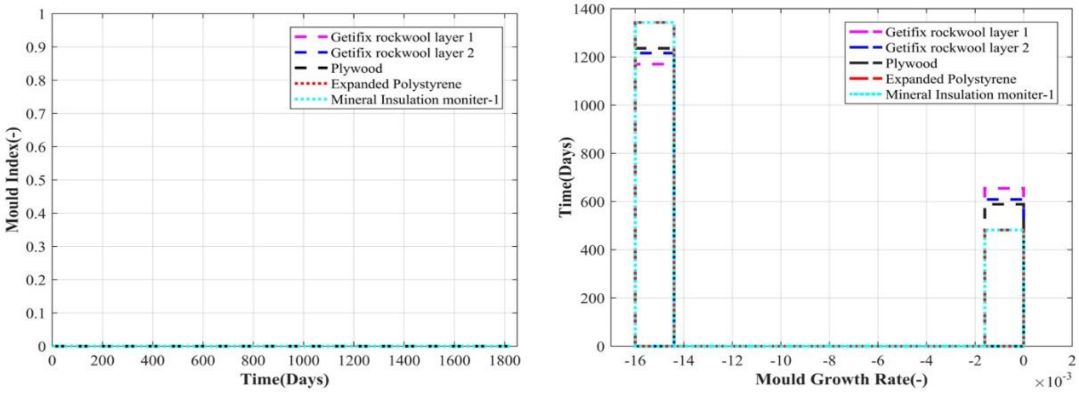

Figure 42: Mould Index(left) Mould Growth(right) in critical layers of the External roof with Concrete tiles for Lulea.

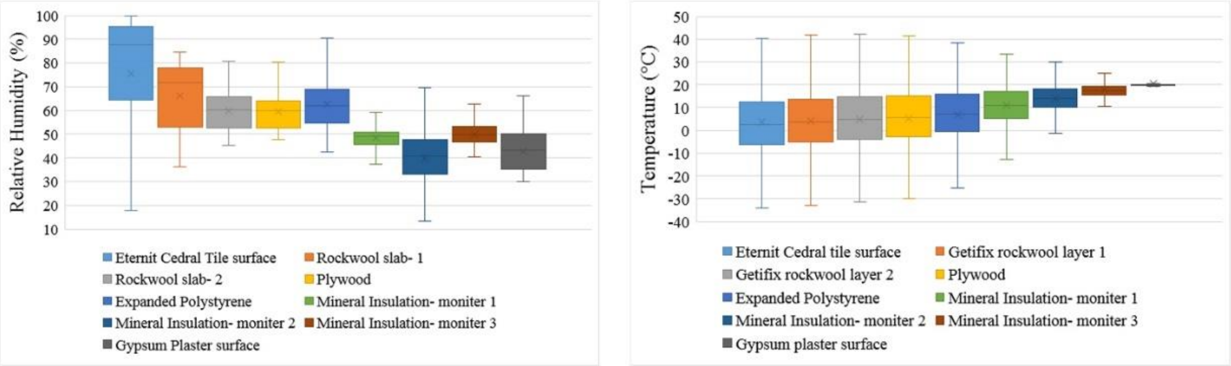

Figure 43: Moisture performance in the External roof with Eternit Cedral tiles for Lulea. Graphs showing Relative Humidity of whole wall (left), Temperature variations in the whole wall (right).

In figure 43, relative humidity and temperature are shown; with Eternit Cedral tiles roof surface 20%-100%, Getifix Rockwool slab layer-1 35%-85%, Getifix Rockwool slab layer-2 and oriented strand board are in 45%- 80% range, expanded polystyrene layer with 40%-85% and monitor 1 of mineral insulation has relative humidity levels less than 60% and temperatures in these layers are varying between -15°C to +40°C. This relative humidity and temperature conditions are having some favourable conditions for mould growth in the critical layers which can be seen from figure 44. In figure 44, there is minute to no mould growth with mould growth reaching 0.06 on MGI scale every 350 days, also has a decay of almost 1400 days. Therefore, the wall construction is relatively safe for construction in reference year as the mould growth and decay cancelling out each other.

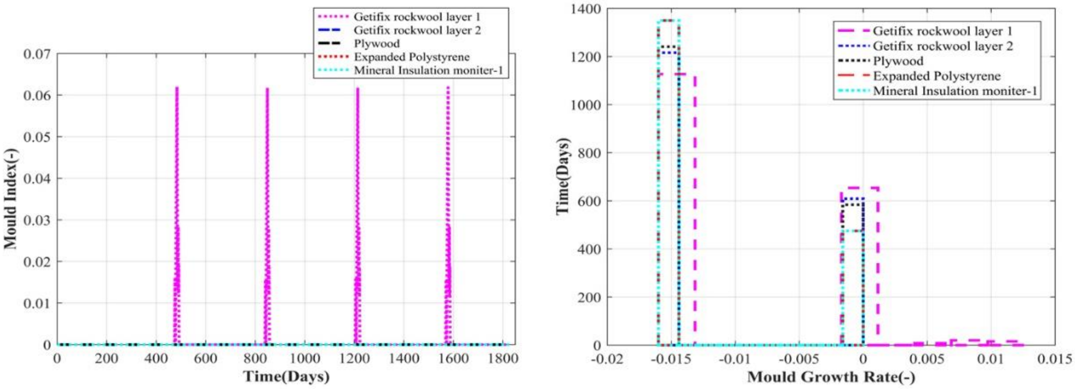

Figure 44: Mould Index(left) Mould Growth(right) in critical layers of the External roof with Eternit Cedral tile roof for Lulea.

8.3 Moisture, Mould growth calculation for future scenarios.

8.3.1 Moisture Performance of External wall with brick facade

In figure 45, relative humidity and temperature in expanded polystyrene layer are shown, they vary over time periods and climate scenarios. Relative humidity during the period of CNRM 1971-1990, 2021-2050 and 2071-2100 the values lie within 2% to 3% difference among each other but there is variation in the lower and upper quartiles. As the time progresses the density of hours around the median value increases considerably which implies that relative humidity is increasing throughout. In IPSL scenario the relative humidity median value shifts from 78% to 82%, the lower quartile shift from 74% to 78% and upper quartile shifts from 80% to 84% over the three periods of 1971-1990, 2021-2050 and 2071-2100. In figure 46, the same trend can be seen in oriented strand board, the median of CNRM scenario, relative humidity shifts from 77% in 1971-1990 to 78% in 2021-2050 and 79.5% in 2071-2100 period. In IPSL scenario the shift in median value from 73.5% in 1971-1990 to 76% in 2021-2050 to 77% in 2071-2100, which is a much greater shift. In figure 48, the mould growth in expanded polystyrene layer is seen. There is mould growth in all the time periods of CNRM scenario reaching a maximum value of 1 on MGI scale in 1971-1990, 1.4 in 2021-2050 and 2.5 in 2071-2100 time periods and the mould keeps growing and decaying throughout the studied 11000 days (30 years) in all the three time periods, whereas in IPSL scenario there is almost no mould growth in 1971-1990 and little mould growth throughout 2021-2050 and 2071-2100 periods. In figure 85, mould study for oriented strand board, there is little to no mould growth period and is less than 1 on MGI for both CNRM and IPSL scenarios for all the three time periods. In figure 47, the same trend can be seen in the mineral insulation layer, a shift in the median values can be seen for both CNRM and IPSL scenarios. In CNRM scenario the upper quartile values are below 75% which is safe for the periods1971-1990 and 2021-2050, but in 2071-2100 period the upper quartile is 75% where there might be a higher probability of mould growth. Whereas in IPSL scenario the upper quartile values are below 75% and are safe. In figure 86, for mould study of mineral insulation monitor position 1, there is no mould growth for both CNRM and IPSL scenarios for 1971-1990 and 2021-2050 time periods, in 2071-2100 period there is minimal to no mould growth in CNRM scenario. From all these figures for the critical layers of brick facade wall, there is mould growth only in the expanded polystyrene layer but the layers deeper inside the wall are safe. The mould growth in the expanded polystyrene layer is visible only through a microscope and might cover the whole layer moderately.

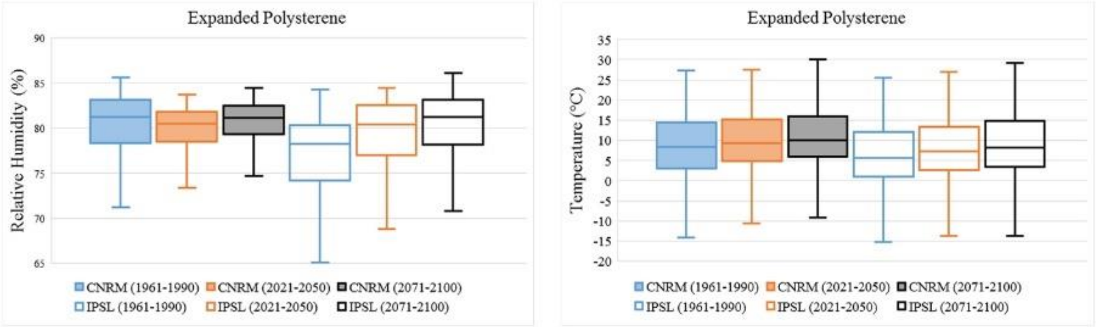

Figure 45: Moisture Performance of Expanded polystyrene layer in the External wall with Brick facade over time periods 1961-1990, 2021-2050, 2071-2100. Relative Humidity in wall layers (left), Temperature variations in layers (right).

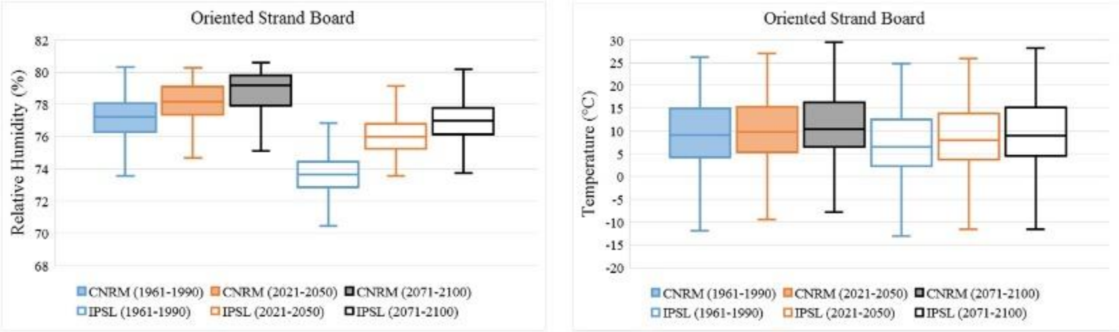

Figure 46: Moisture Performance of Oriented Strand Board layer in the External wall with Brick facade over time periods 1961-1990, 2021-2050, 2071-2100. Relative Humidity in wall layers (left), Temperature variations in layers (right).

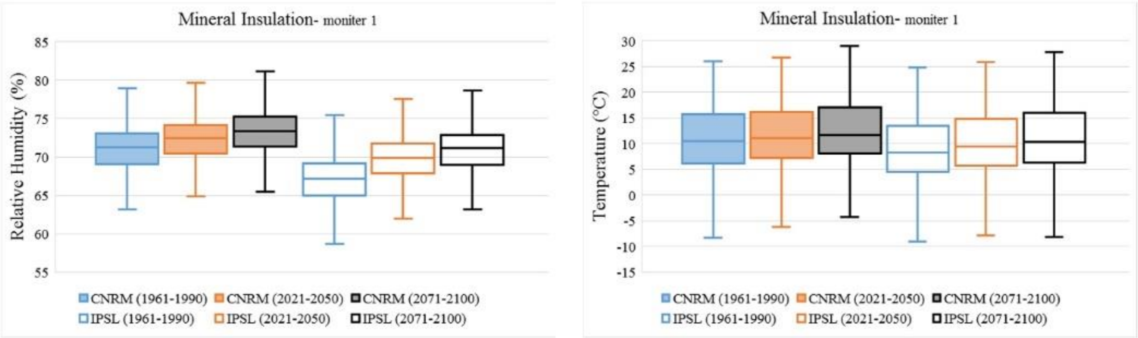

Figure 47: Moisture Performance of Mineral Insulation layer in the External wall with Brick facade over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

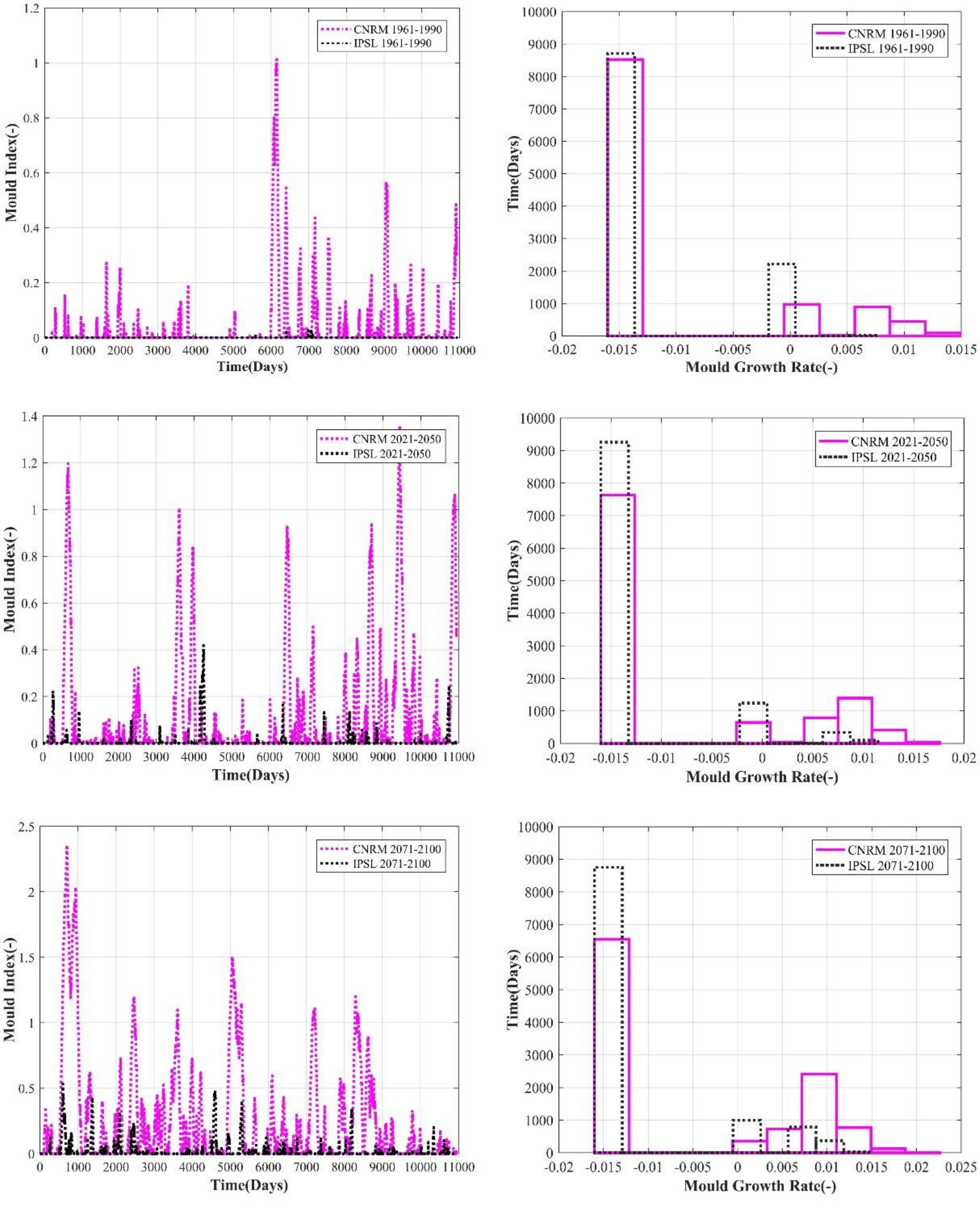

Figure 48: Mould Index (left column) and mould growth (right column) for Expanded Polystyrene layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100-time period for brick facade wall. Top row- time period 1961-1990, Middle row- time period 2021-2050, Bottom row- time period 2071-2100.

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8.3.2 Moisture performance of Eternit Cedral Struktur facade wall layers

In figure 49, relative humidity levels in expanded polystyrene layer are shown, they vary over a time period and two climate scenarios. In figure 49, CNRM scenario time period 1971-1990, 2021-2050 and 2071-2100 the median, lower and upper quartiles values lie within 2% to 3% difference among each other respectively. With time the density of hours around the median value increases which implies that relative humidity is increasing throughout. In IPSL scenario the relative humidity median value shifts from 75% to 76% to 77%, the lower quartile shift from 73% to 75% to 76% and upper quartile shifts from 76% to 79% to 80% and the lower quartiles shifts from 73% to 75% to 76% over the three time periods of 1971-1990, 2021-2050 and 2071-2100. In figure 50, the same trend can be seen in oriented strand board, the median of CNRM scenario, relative humidity shifts from 75% in 1971-1990 to 76% in 2021-2050 and 77% in 2071-2100 time period. In IPSL scenario the shift in median value from 71% in 1971-1990 to 74% in 2021-2050 to 75% in 2071-2100, which is a much greater shift. In figure 51, mineral insulation layer monitor position-1, The same trend of a shift in the median values can be seen for both CNRM and IPSL scenarios. In both CNRM and IPSL scenario the upper quartile values are below 75% which is safe for all the three time periods1971-1990, 2021-2050, 2071-2100. In figure 52, There is mould growth in all the time periods of CNRM scenario reaching a maximum value of 1.3 on standard scale for mould index in 2071-2100 time period and the mould keeps growing and decaying throughout the studied 11000 days (30 years) in all the three time periods, whereas in IPSL scenario there is almost no mould growth in all the three time periods. In figure 87, mould study for oriented strand board, there is no mould growth both CNRM and IPSL scenarios for all the three time periods. In figure 88, mould study of mineral insulation monitor position 1, there is no mould growth for both CNRM and IPSL scenarios for 1971-1990 and 2021-2050 time periods, in 2071-2100 time period there is minute to no mould growth in CNRM scenario. From all these figures of the critical layers of Eternit Cedral Struktur surface wall, there is mould growth only in the expanded polystyrene layer but the layers deeper inside the wall are safe. The mould growth in the expanded polystyrene layer is visible only through a microscope and might cover the parts of the layer or whole layer moderately.

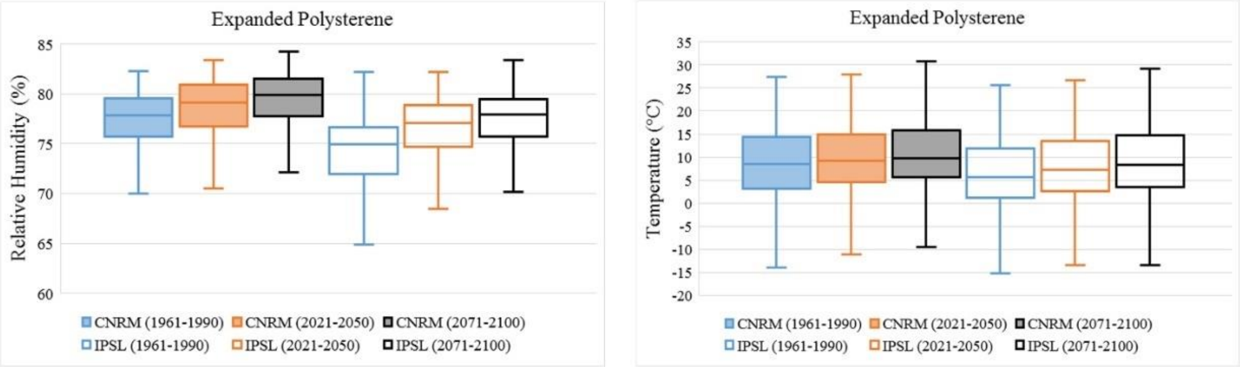

Figure 49: Moisture Performance of Expanded polystyrene layer in the External wall with Eternit Cedral Struktur facade over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

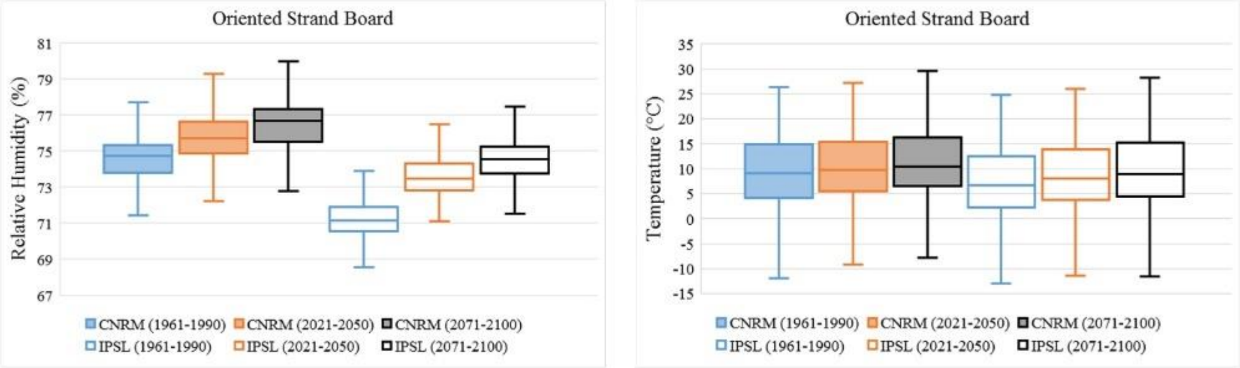

Figure 50: Moisture Performance of Oriented Strand Board layer in the External wall with Eternit Cedral Struktur facade over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

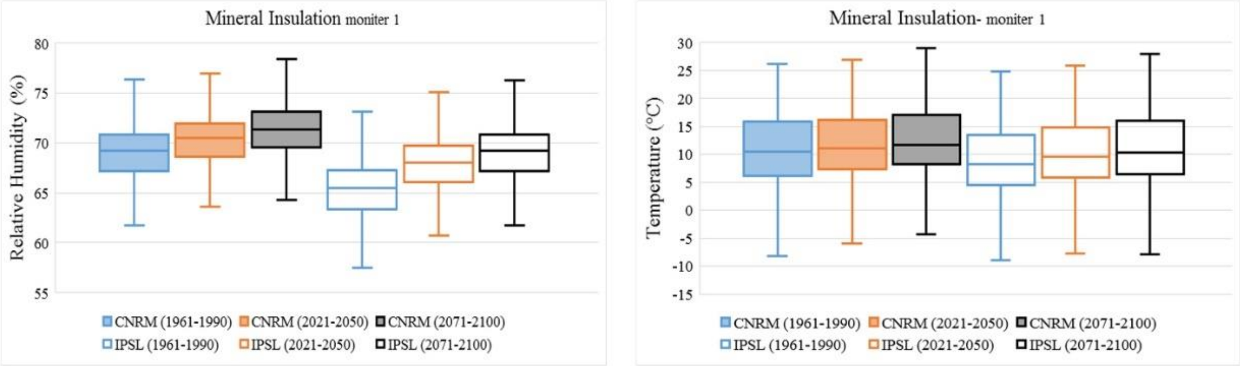

Figure 51: Moisture Performance of Mineral Insulation layer-1 in the External wall with Eternit Cedral Struktur facade over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

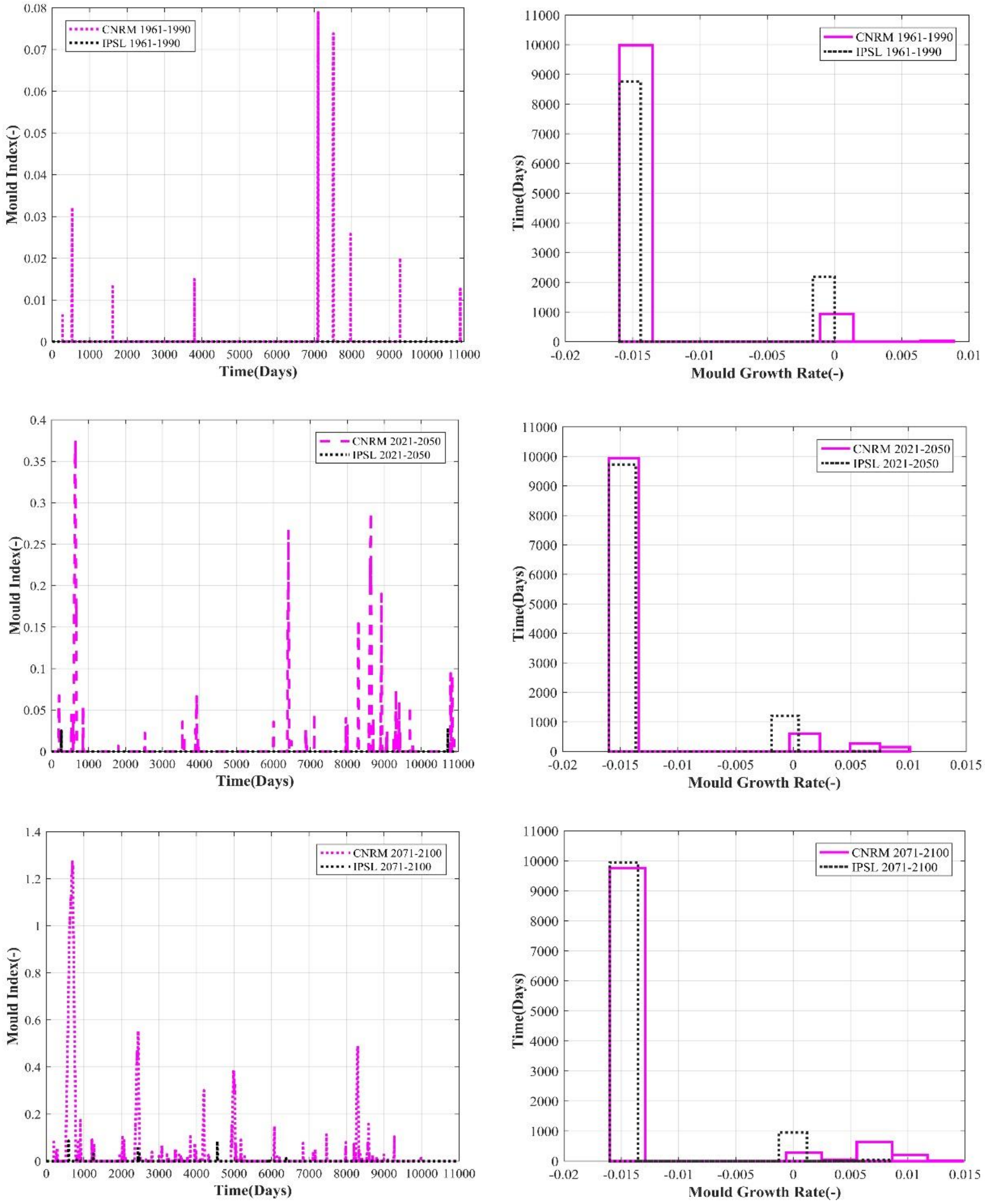

Figure 52: Mould Index and mould growth for Expanded Polystyrene layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for Eternit Cedral Struktur facade wall Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

8.3.3 Moisture Performance of Concrete tile roof layers

In figure 53, relative humidity and temperature variations in Getifix Rockwool slab layer-1 are shown. Here it can be seen that in CNRM climate scenario there is a gradual rise in relative humidity levels over the studied three time periods of 30 years each. There is only 25% of the hours above the critical level of 75% RH in 1971-1990 period, whereas in 2021-2050 and 2071-2100 periods the levels cross the critical level and upper quartile reaches 80% relative humidity and upper extreme level reaches 85% by 2071-2100 period and might cause mould problems. In IPSL scenario the same trend can be seen but the density of hours from upper quartile to upper extreme reduces and the density of hours' in-between the lower and upper quartiles increase and crosses the critical level. From figure 55, Both the scenarios CNRM and IPSL are safe during the time period 1971-1990 but in 2021-2050 period there is very minute mould growth in and large decay in CNRM scenario and no mould growth in IPSL scenario. In figure 53, 2071-2100 time period there is an increase in density of hours above the critical relative humidity level for mould growth and mould growth can be seen in figure 55, CNRM scenario has higher mould growth throughout the time period and can be seen in the mould index chart. The mould growth is less than 1 on MGI, there is no damage caused and the layer in the construction is safe.

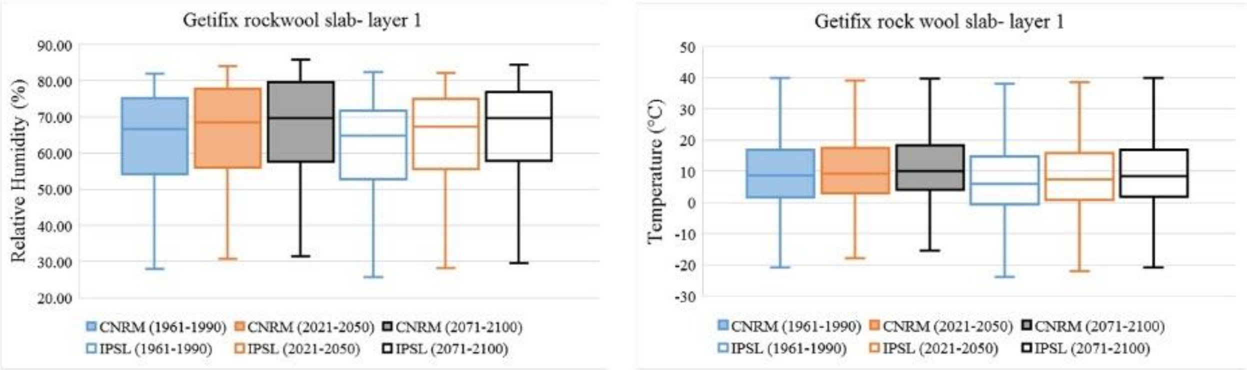

Figure 53: Moisture Performance of Getifix Rockwool slab layer-1 in the External roof with Concrete tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

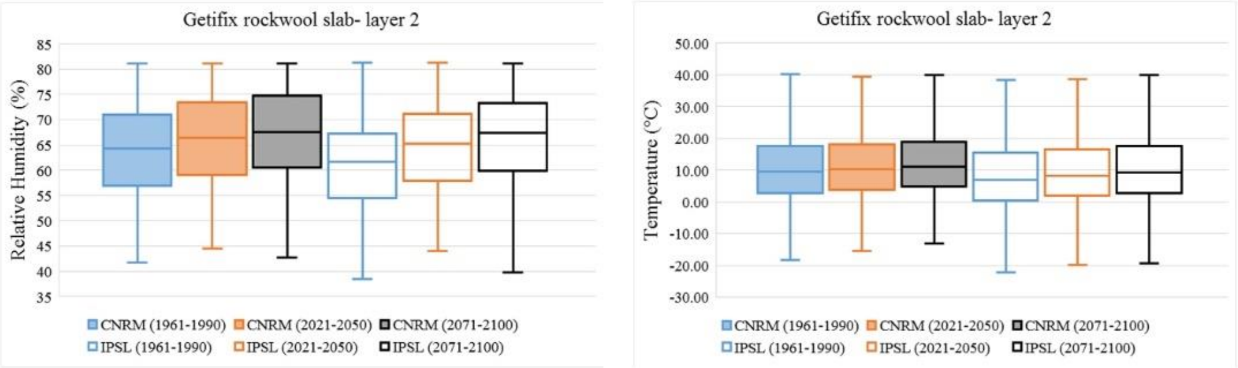

Figure 54: Moisture Performance of Getifix Rockwool slab layer-2 in the External roof with Concrete tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

Figure 54, shows the relative humidity and temperature in Getifix Rockwool slab layer-2, the density of hours below the critical relative humidity level of 75% is more than 75% of the total hourly values, the probability of mould growth in the layer is very less in both CNRM and IPSL scenarios for all the three time periods, which can be seen in figure 89. In figure 89, in CNRM scenario 2071-2100 time period there is a minute to no mould growth of about 500 days and measures 0.012 on the MGI around 5000th day of the time period. This layer also has a mould decay of more than 10000 days of the simulation period. This mould growth and mould decay balance out and there is no damage caused by the mould in the layer.

Figures 56, 57, 58, shows relative humidity and temperature variations in plywood, expanded polystyrene and mineral insulation monitor position-1, majority of hourly values are below the critical humidity level and the probability of mould growth in the layers is almost absent except for few hours in 2071-2100 time period of CNRM scenario, can be seen in figure 90 and 91. When there is abundant mould decay in the material there is no damage is caused to the material and also the wooden elements in the layer.

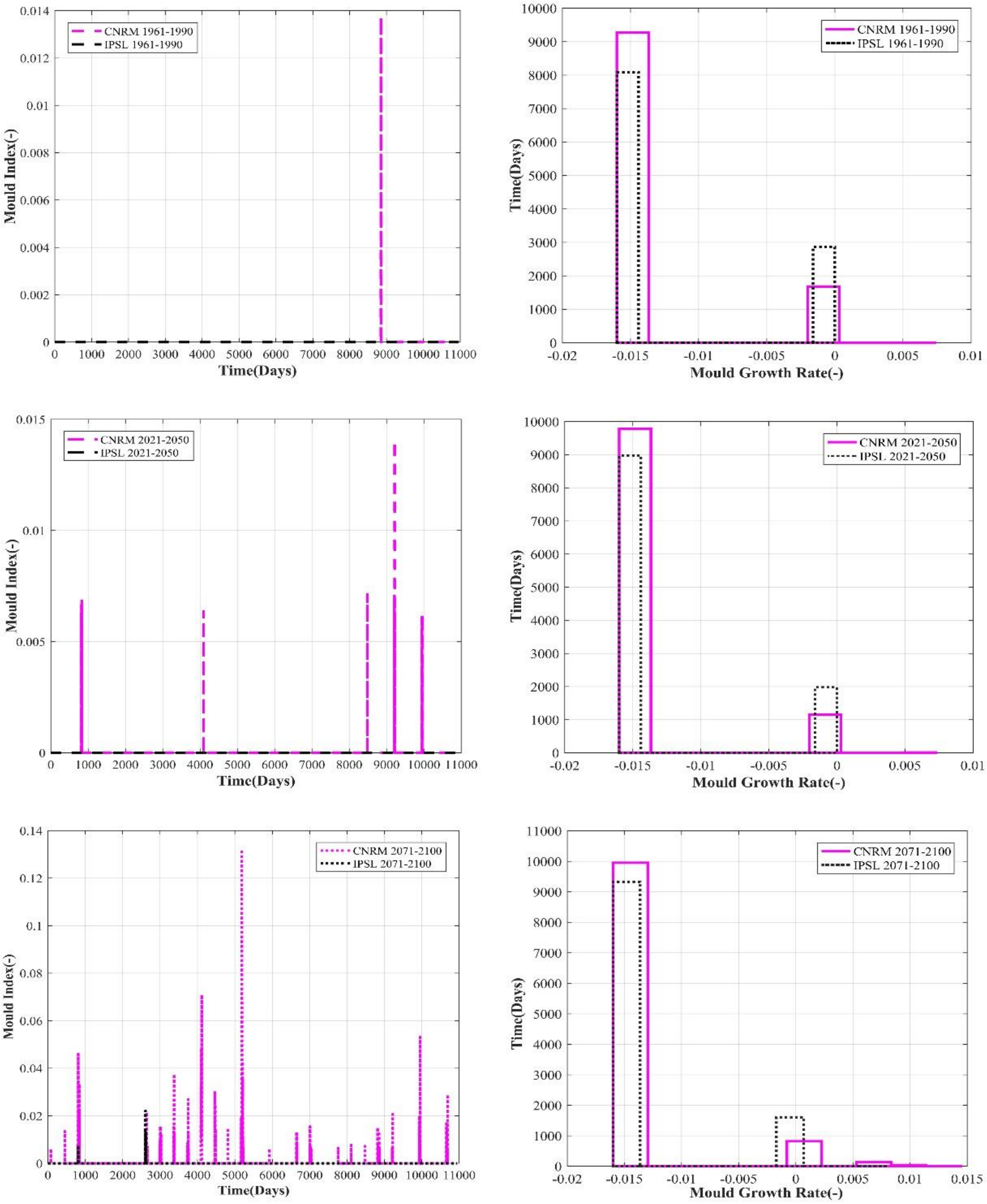

Figure 55: Mould Index and mould growth for Getifix Rockwool slab layer-1 in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Concrete tiles Top- time period 1961-1990. Middle- time line- 2021-2050, Bottom- time period 2071-2100.

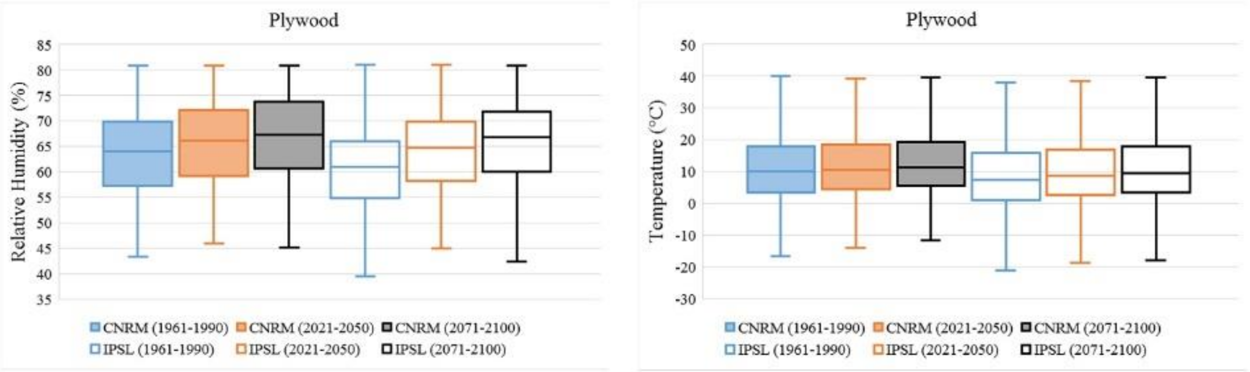

Figure 56: Moisture Performance of plywood layer in the External roof with Concrete tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

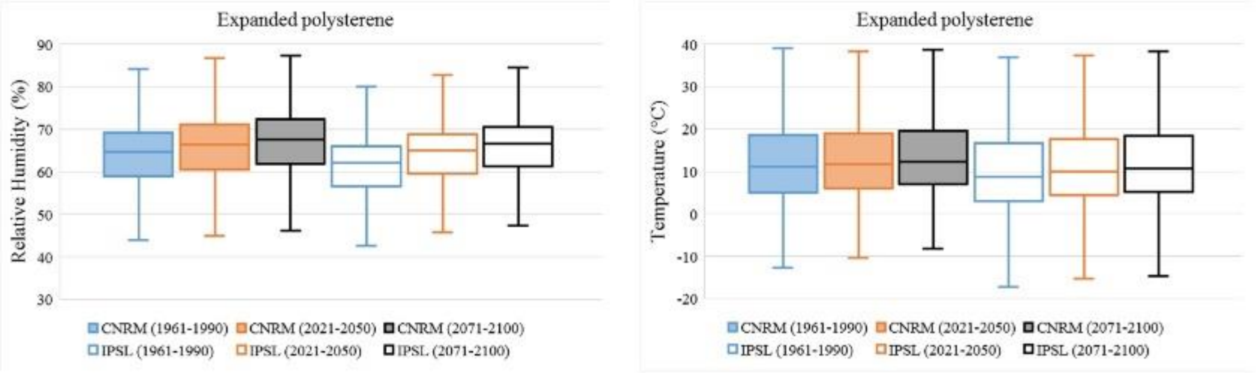

Figure 57: Moisture Performance of Expanded Polystyrene layer in the External roof with Concrete tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

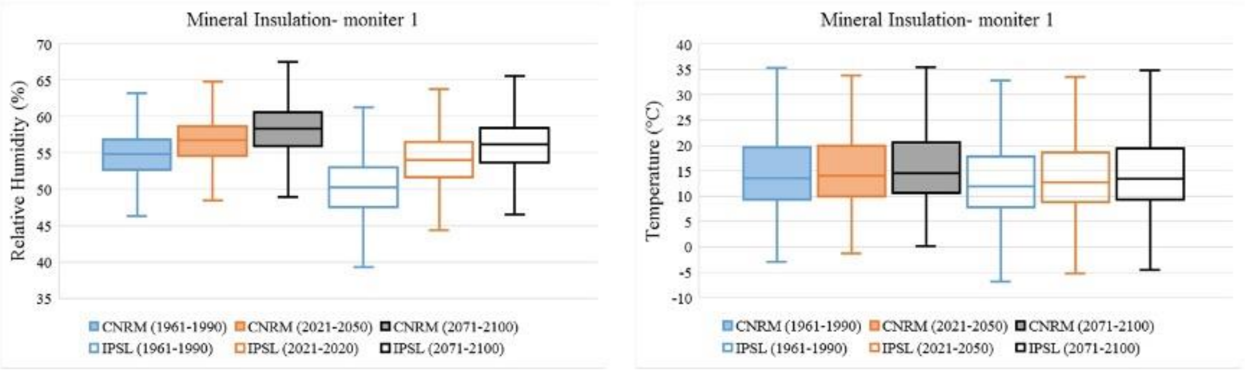

Figure 58: Moisture Performance of Mineral insulation layer-1 in the External roof with Concrete tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

8.3.4 Moisture Performance Eternit Cedral tile roof layers

Figure 59 shows the relative humidity and temperature variation in Getifix Rockwool slab layer-1, 80% density of relative humidity hourly values are above the critical relative humidity level in CNRM scenario, in IPSL scenario the density of hours between the lower and upper quartiles shifts above the critical level in the three time periods of 1971-1990, 2021-2050, 2071-2100. From figure 59, there is the very high probability of mould damage in the layer. In figure 62, mould study in the layer, there is very high mould growth in both CNRM and IPSL scenarios. In CNRM scenario of 1971-1990, 2021-2050, 2071-2100 time periods, the mould index value is above 3 on MGI all the time, this is very dangerous as this situation gives rise to mould and rot in the material and the wooden elements in the material. In mould growth rate chart, there is high growth and very little decay, which causes a lot of issues related to the mould damage and causes structural damage to the layer. In IPSL scenario of 1971-1990, there is lower mould growth when compared to CNRM scenario, the mould growth on the standard index is around 1 on MGI for the whole time, but there are few days where the index reads 4 and 6 where there is higher damage caused by mould and rot. In 2021-2050 and 2071-2100 time periods there is extensive mould growth in the material reaching the upper value of 6 on the mould index scale often. This can cause extensive damage to the material and the wooden elements in the material.

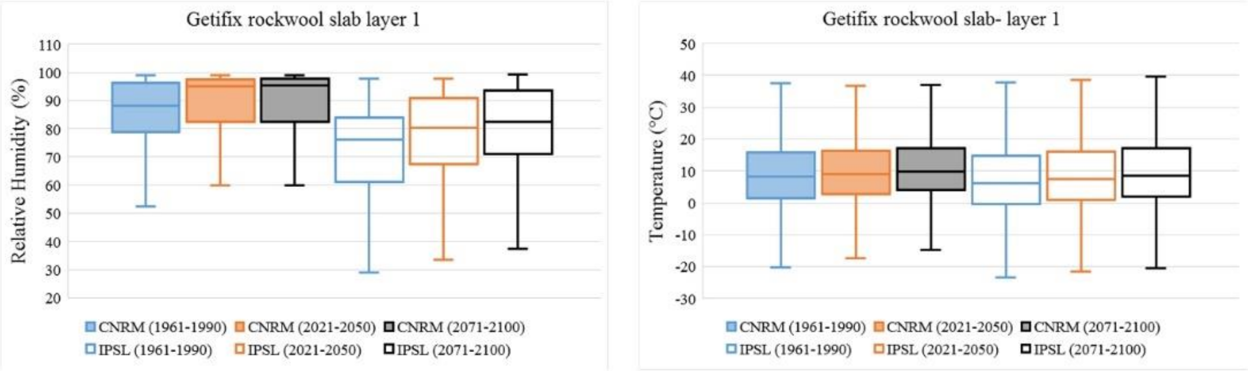

Figure 59: Moisture Performance of Getifix Rockwool slab layer-1 in the External roof with Eternit Cedral tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

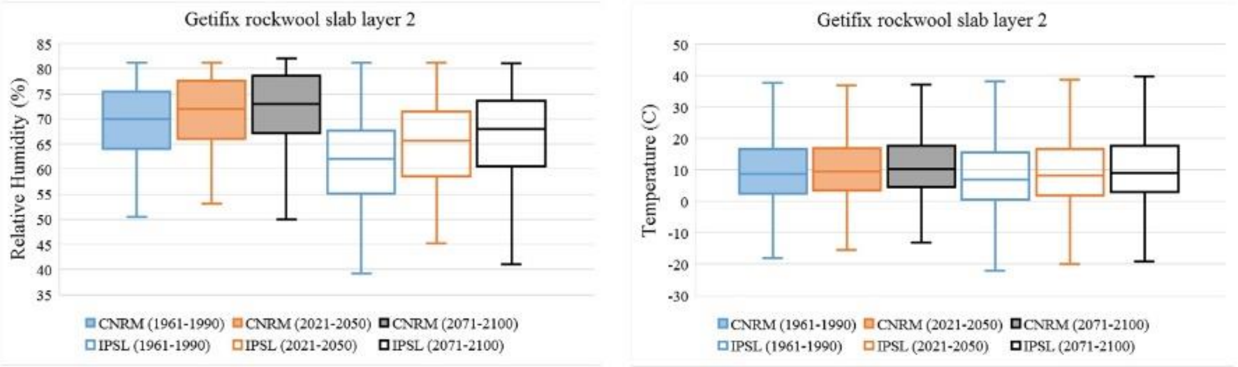

Figure 60: Moisture Performance of Getifix Rockwool slab layer-2 in the External roof with Eternit Cedral tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

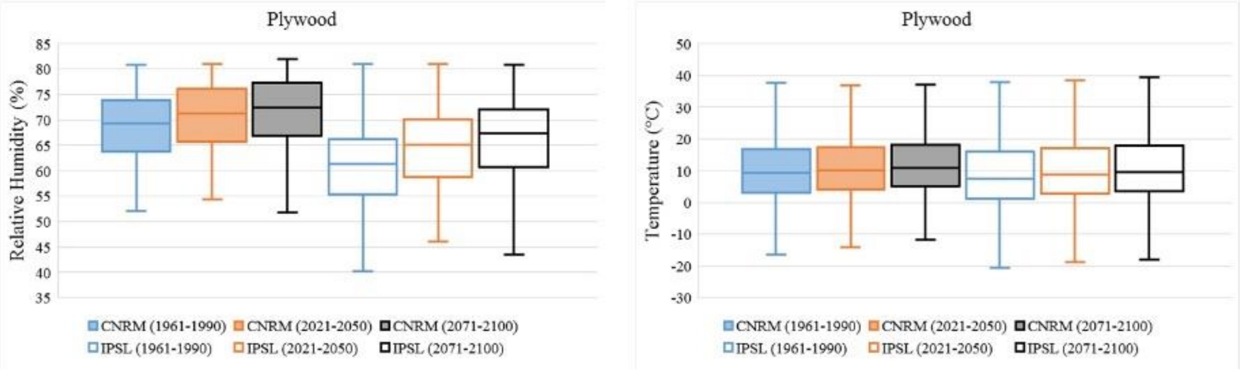

Figure 61: Moisture Performance of Plywood layer in the External roof with Eternit Cedral tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

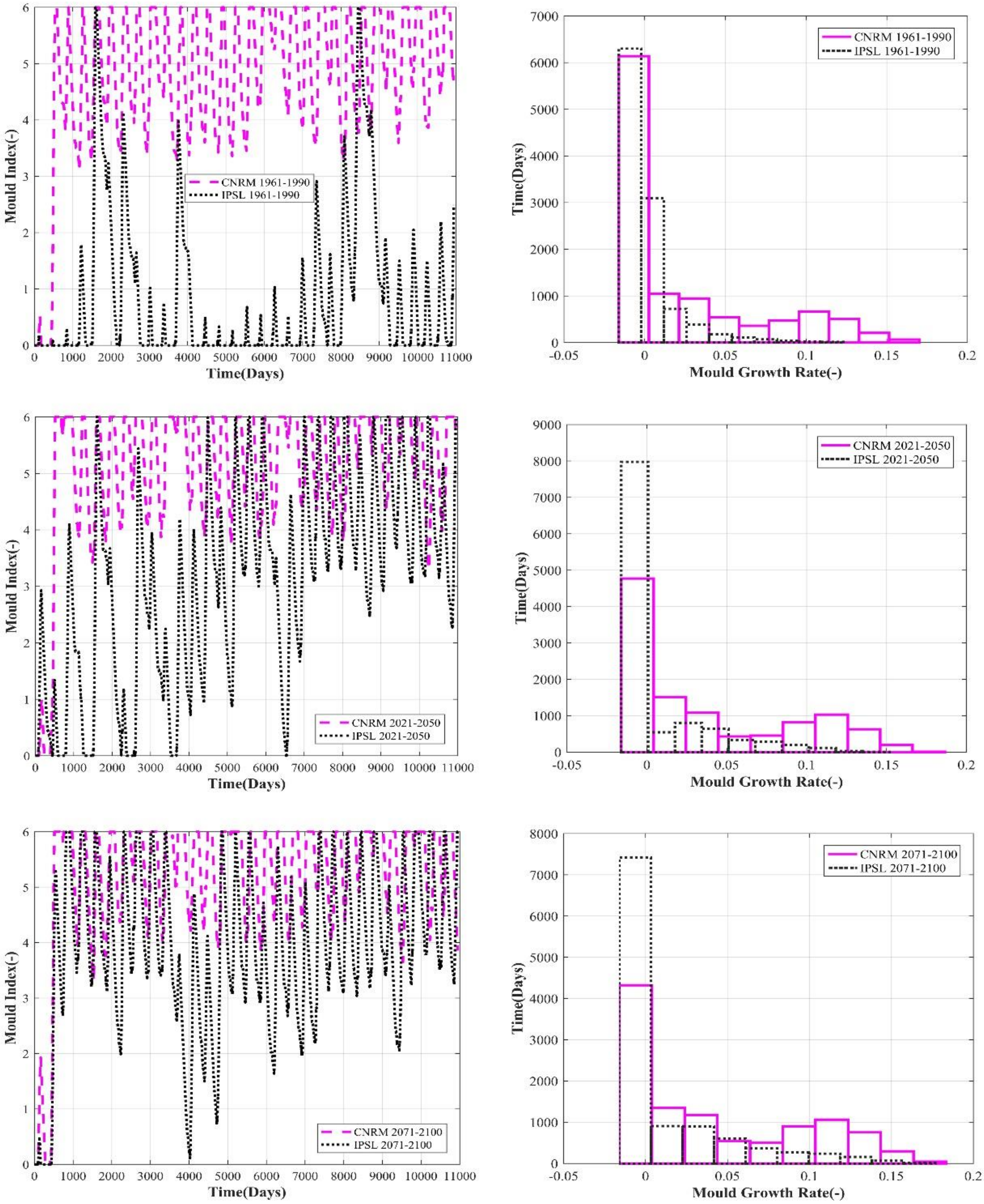

Figure 62: Mould Index and mould growth for Getifix Rockwool slab layer-1 in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Eternit Cedral tiles Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

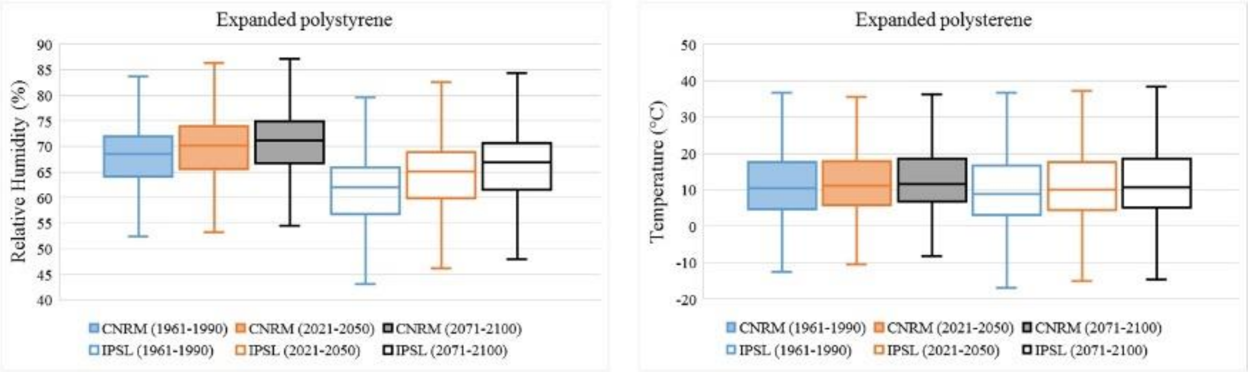

Figure 63: Moisture Performance of Expanded Polystyrene layer in the External roof with Eternit Cedral tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

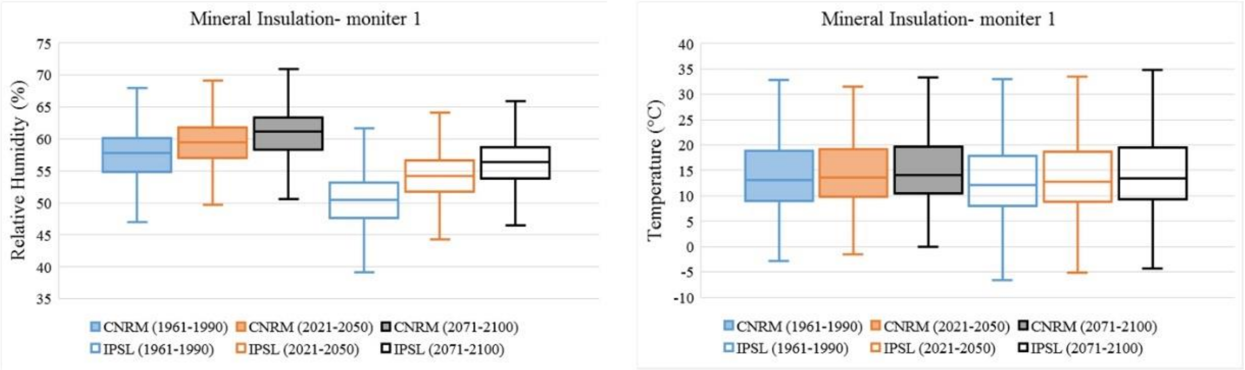

Figure 64: Moisture Performance of Mineral insulation layer-1 in the External roof with Eternit Cedral tiles over time periods 1961-1990, 2021-2050, 2071-2100 Relative Humidity in wall layers (left), Temperature variations in layers (right).

Figure 60, the density of relative humidity hours above the critical level of 75% is less in CNRM scenario where as in IPSL the density is less than 20% of the values. This indicates lower probability for mould growth in the layer. In figure 92, there is no mould growth in the material in both CNRM and IPSL 1971-1990 time period, whereas in 2021-2050 there is little to no mould growth in CNRM scenario and IPSL scenario has no mould growth. In 2071-2100 time period there is little to no mould growth in the material which grows in intermittent periods. As the mould growth on the MGI scale is less than 1, this mould growth will not harm the material and the layer.

Figure 61, the trend of the previous Getifix Rockwool slab layer-2 is observed. The mould index study in figure 93 also shows similar results with little mould growth in 2071-2100 time period of CNRM scenario. The mould growth is balanced out by a large amount of mould decay and does not cause any kind of damage in the material.

In figure 63, less than 25% of the relative humidity hours are above the critical level, the probability of mould growth in the layer is very less. This is confirmed in figure 94, that there is no mould growth in the material.

In figure 64, the relative humidity in both CNRM and IPSL scenarios are well below the critical relative humidity level and the conditions for mould growth do not exist.

9 Conclusion

This master thesis work analysed the energy performance, moisture performance and the indoor climate of a typical two stories single family passive house designed for a reference year and its feasibility for future climate uncertainties. This study of energy consumption and overheating in the building was based on ECY, TDY, EWY and their combinations for 2009-2038, 2039-2068 and 2069-2098. For moisture performance of the critical parts over the next 100 years, CNRM and IPSL climate scenarios were analysed and the three time periods for the study were 1971-1990, 2021-2050 and 2071-2100. The reference year calculation was compared with the results from the different future scenarios and time periods. The results show a decrease in heating demand and increase in cooling demand. The risk of overheating is increased in future climate scenarios. Uncertainties of the future climate projections and the climate data may affect the simulations.

The main conclusions drawn from the master thesis work are:

- The heating demand in the typical two stories single family passive house is going to decrease and cooling demand is going to increase in all the four studied cities of Sweden, namely Lund Gothenburg, Stockholm and Lulea.
- In Lund, the southern city selected for the study, the variations in heating demand were found to decrease from 12kWh/(m²year) in 2009-2038 to 9kWh/(m²year) by 2069-2098, which is a 33% decrease in heating demand compare to the reference year; whereas the variation in cooling demand was found to be much higher, reaching 9kWh/(m²year) in 2009-2038 to 10 kWh/(m²year) in 2039-2069 and 11kWh/(m²year) in 2069-2098 which is 170%, 208% and 226% rise in comparison to reference year cooling demands respectively. When compared to FEBY regulations of 2011 there is a decrease in heating demand of 20% in 2009-2038 and 40% by 2069-2098. The overheating(>29°C) hours in the living areas increased from 428 hours in reference year to 1927 hours in 2069-2098, which is 350% increase in their comparison and 2100% increase as per the regulations.
- For Gothenburg, the heating demand rises to 15kWh/(m²year) in 2009-2038 and 16kWh/(m²year) 2039-2068 and then decreases to 12kWh/(m²year) in 2069-2098; whereas the cooling demand increases in all the three time periods from 8kWh/(m²year) in 2009-2038 to 9kWh/(m²year) in 2039-2068 and to 11kWh/(m²year) in 2069-2098, which is 207%, 264% and 279% increase to reference year cooling demand. The overheating hours of the indoor living areas increase to 480% by 2069-2098 in comparison to reference year, when compared with the regulations it is 1700% increase.
- In Stockholm, the same trend continues, heating demand drops from 16 kWh/m²year in 2009-2038 to 11kWh/(m²year) in 2069-2098 and cooling increases from 8kWh/(m²year) in 2009-2038 to 11kWh/(m²year) in 2069-2098. Heating and cooling demands are the almost same by 2069-2098. The overheating hours increases from 1600 hours to 2000 hours.

- In Lulea, the design and construction of passive house are very difficult as it has the influence of arctic zone and falls under sub-arctic climate. There is no recorded passive house built in Lulea. The study also confirms that it is difficult to design a passive house. The heating demand in the studied building is 31kWh/(m²year) in reference year which is almost 1.5 times the allowable heating demand as per the FEBY regulations. The heating demand in this city also decreases from 26.5kWh/(m²year) in 2009-2038 to 19.5kWh/(m²year) in 2069-2098. Cooling demand rises from 6kWh/(m²year) in 2009-2038 to 8kWh/(m²year) in 2069-2098. The overheating hours increases from 900 hours in reference year to 1400 in 2069-2098, which is 55% increase. Based on the results of energy performance study for Lulea, there is a higher possibility of designing passive house by 2030-2040 as the heating demand will reduce and the use of better insulation material in design and construction can decrease the heating demand even further.
- Over-heating hours in ground floor of the studied Passive house is more than the over-heating hours in upper floor, the reason behind this might be that the energy model developed might not have taken the convection of heat into consideration.
- The over-heating period in Stockholm and Lulea are more compared to Lund mainly because of the simple reason that architectural and other technical design parameters used. With the obtained results, it can be concluded that the passive house design is location specific and the same parameters used in warmer location of Sweden will not give same results in colder regions of Sweden, instead causes over-heating problems.
- From the energy calculations for the four cities in Sweden, namely Lund Gothenburg, Stockholm and Lulea, there is a clear indication of rising in cooling demand in the years to come and drop in heating demand. The author also feels that cooling demand in the buildings should also be taken into consideration in the regulations.
- The wall and roof of the studied passive house were found to be safe for the reference year climatic scenario, with some mould growth only detectable through microscopic analysis.
- The relative humidity and water content in the critical layers rose considerably, from 15% to 25% over next 90 years. This rise in relative humidity and optimal temperatures in the critical layers of the wall were studied for Gothenburg, where it was found that wall construction with brick facade had mould growth in expanded polystyrene layer during all the studied three time periods. The mould growth was found to be moderate but still can cause problems and other critical layers were found to be safe throughout. In Eternit Cedral external wall there was less mould growth in expanded polystyrene layer and other layers are safe.
- The relative humidity and water content in the roof were also found to increase over the three time periods of 1971-1990, 2021-2050 and 2071-2100. It was

found from the study that the rise in relative humidity levels gave rise to mould problems in Eternit Cedral roof. The mould problems were found to extensive and can cause major damages to the building and its occupants. Whereas the concrete tile roof was much resilient to the changes and there is no noticeable mould growth or problems in the critical layers.

- Overall, it can be said that the concrete tiles can be preferred for construction of roofs in Sweden as they are sturdier. Eternit Cedral facade is suitable for passive houses in Sweden.
- The studied building is designed as per the current FEBY and passive house regulations perform well for the reference year climatic conditions. When the future climatic scenarios are considered the building has very low heating demand and very high cooling demand in Lund and Stockholm, whereas Gothenburg shows an increase in cooling demand and a slight reduction in heating demand. Lulea has the influence of sub-arctic climate has a very high heating demand for reference year in comparison to FEBY and passive house regulations; under the influence of climate change the heating demand in Lulea reduces over the next 90 years reaches the current passive house regulations.
- Considering the results from the simulations it can be noted that the current regulations for Zone III need to be worked on and possibly a reduction in heating demand and a limit on cooling demand can be introduced for future scenarios. For Zone II around the region of Gothenburg cooling demand limitations can be introduced in the regulations. For Zone II around the region of Stockholm both heating and cooling demand limitations can be introduced. For Zone I, around the region of Lulea, the heating demands in future scenarios is matching the current regulations and the cooling demand is minimal, therefore there is no need to change any limitations and current criteria can be applicable for future scenarios.
- The main challenge for the designers in the passive house will be the overheating periods in the future scenarios. This might be overcome by opening of the windows during the summer months or by the introduction of cooling coils in the ventilation system of the passive house, especially in Zone III. In Zone II only window openings might reduce the indoor temperatures during the summer months. In Zone-I, there is little cooling demand and this can be overcome by the opening of windows during the warmest periods.
- Use of solar shading devices in the buildings can have a great impact in reducing the cooling demands in all the four cities which were studied. Addition of ventilators, which are mainly used in tropical countries, with time or temperature schedules, for natural ventilation during warm periods can reduce the operative temperatures indoors.
- The introduction of Trombe wall, the Phase Change Material in passive houses of Zone II and III may reduce the heating and cooling demands and may also aid in reducing the overheating in the buildings.

- Reducing the insulation thickness and increasing the U-values of walls and windows may also aid in reducing the cooling demands and overheating hours in the future.

10 Future research

From the research, the author has understood that there is a potential for future research. The future research on single family residential buildings can include different orientation of the building model, active and passive solar shading technologies, different construction methodologies, roof and wall inclination, construction materials, wind profiles, other cities in Sweden, material degradation, life cycle costing and assessment and environmental certifications.

The future research can also include multifamily residential buildings, office buildings, restaurants, hotels, industrial and wear-house buildings.

11 Summary

Global warming is a very much researched and debated topic in the current period as we can see the effects around us. The literature and discussions have pointed to a surface temperature rise of up to 10°C at the poles and around 4°C-7°C around the equator. The effect is more in the northern hemisphere than in southern hemisphere of our planet Earth. The effects of the warming of our environment on the buildings and the future weather patterns are being researched in many countries.

This master thesis work assesses one such scenario of the effects of climate change, projected future weather patterns on the energy consumption for heating and cooling, moisture performance and mould growth of the external wall and external roof layers in four cities of Sweden namely Lulea, Stockholm, Gothenburg and Lund. The research for energy consumption was carried out with future climate data derived from the GCM’s and RCM’s for Extremely cold year, extremely warm year and typical downscaled year; the results from these three scenarios were clubbed together to get combined yearly energy consumption which can be comparable to the reference year data. Moisture performance was carried out only for Gothenburg using CNRM and IPSL climate data to show the effects of climate change and warming of the environment on the building outer protective layers.

The results clearly show a considerably increased cooling load and decrease in heating loads in four Swedish cities over a period of next 80 years. The results for moisture performance and mould growth also shows an increase in relative humidity, temperature and water content in layers. Mould growth calculations also show an increased activity over next 80 to 100 years.

Results from the simulation of typical passive house shows the current regulations for Zone III need to be worked on and possibly a reduction in heating demand and a limit on cooling demand can be introduced for future scenarios. For Zone II around the region of Gothenburg cooling demand limitations can be introduced in the regulations. For Zone II around the region of Stockholm both heating and cooling demand limitations can be introduced. For Zone I, around the region of Lulea, the heating demands in future scenarios is matching the current regulations and the cooling demand is minimal, therefore there is no need to change any limitations and current criteria can be applicable for future scenarios.

It can be concluded that the heating demand in the typical two stories single family passive house is going to decrease and cooling demand is going to increase in all the four studied cities of Sweden. Overheating periods in the passive houses are also going to increase, which corresponds to higher cooling demands. Moisture related problems such as mould and rot growth is going to increase due to warmer and wetter climatic conditions. Attics and roof elements are more susceptible to mould damage than wall.

It was also seen that concrete and brick were more resilient and protect the roof and wall from moisture related problems.

Some of the methodologies which can be used to reduce over heating periods are solar shading devices, addition of ventilators for natural ventilation during warm periods, using phase change materials in the construction.

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13 Appendix 1: Energy performance

13.1.1 Lund

Table 16: Energy consumption distribution in a passive house in reference year climate conditions for Lund.

	Energy Consumption	
	kWh	kWh/(m²yr)
Auxiliary energy	649	3.7
Cooling energy	580	3.3
Heating energy	2420	13.8
Domestic Hot Water	3646	20.8
Lighting	1137	6.5
Equipment	2127	12.2
Grand total	10559	60.3

In figure 65, the top left figure shows the variation in energy consumption for heating and cooling of indoor space in the studied passive house with reference year heating and cooling demand to ECY, TDY and EWY of 2009-2038, 2039-2068 and 2069-2098. The top right figure shows the comparative analysis of heating and cooling energy consumption of typical combined years and reference year. Here it can be seen that, in comparison with the reference year and typical combined years, there is a considerable rise in cooling energy demand from 3.3kWh/(m²yr) in reference year to 8.9kWh/(m²yr), 170% in 2009-2038 to 10.2kWh/(m²yr), 208% in 2039-2068 and 10.8kWh/(m²yr), 226% in 2069-2098. In the same figure, the heating demand is reducing from 12.3kWh/(m²yr) in 2009-2038 to 12.1kWh/(m²yr) in 2039-2068 and reducing further to 9.2kWh/(m²yr) in 2069-2098 which is 11% reduction during 2009-2038, 12.5% reduction in 2039-2068 and 33% reduction in heating energy demand in combined year in 2069-2098 in comparison with reference year heating demand of 13.8kWh/m²yr. The bottom row in the figure shows the operative temperatures in the living areas of ground floor and upper floor of the studied passive house. Here it can be seen that there is a considerable rise in the temperatures indoors especially above 29°C in both ground level, from 428 hours in reference year to 1609 in 2009-2038 to1582 hours in 2039-2068 to1841 hours in 2069-2098 and, upper floor living areas, from 305 hours in reference year to 1397 in 2009-2038 to 1368 hours in 2039-2068 to 1653 hours in 2069-2098, which directly co-relates to the very high cooling energy demands of 2009-2038, 2039-2068, 2069-2098 to reference year.

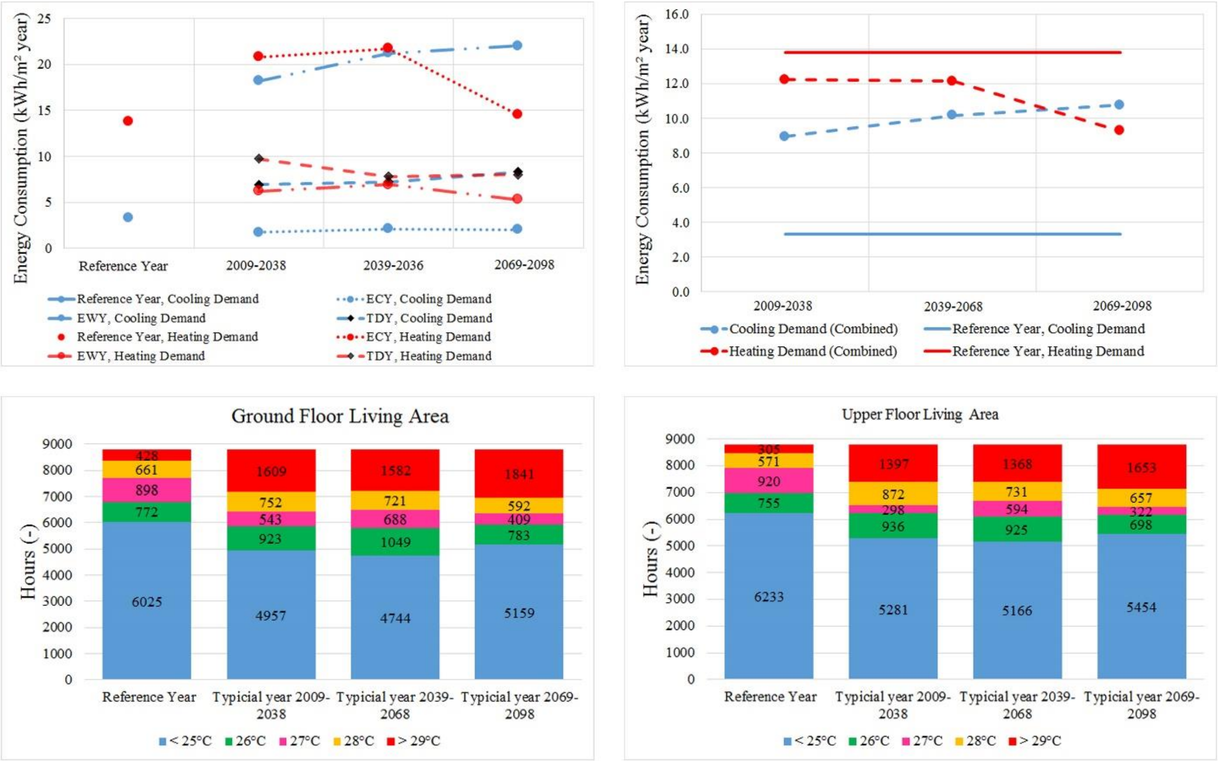

Figure 65: Comparative analysis of Energy consumption for heating and cooling and operative temperature hours for Lund with ECY, TDY, EWY, reference year, and Combined year.

13.1.2 Gothenburg

Table 17: Energy consumption distribution in a passive house in reference year climate condition for Gothenburg.

	Energy Consumption	
	kWh	kWh/(m²yr)
Auxiliary energy	648	3.7
Cooling energy	441	2.5
Heating energy	2487	14.2
Domestic Hot Water	3646	20.8
Lighting	1136	6.5
Equipment	2126	12.2
Grand total	10484	59.9

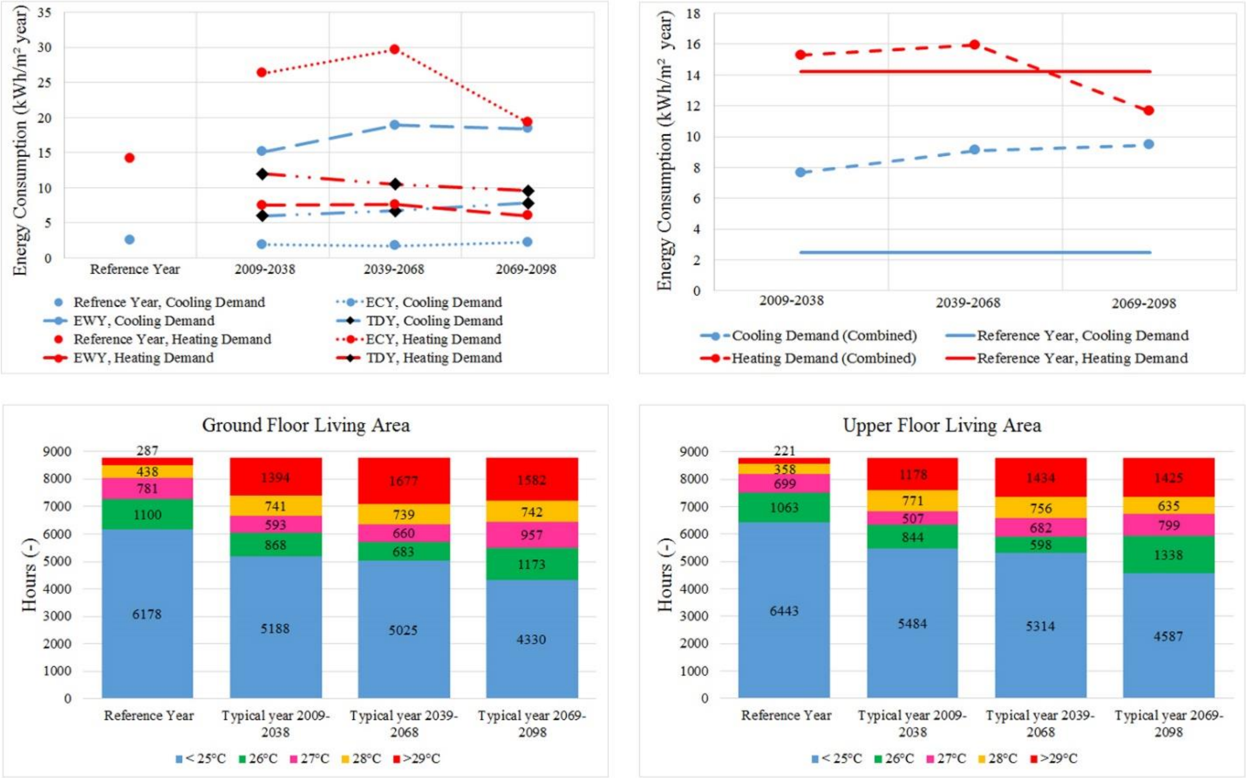

Figure 66: Comparative analysis of Energy consumption for heating and cooling and operative temperature hours for Gothenburg with ECY, TDY, EWY, reference year, and Combined year.

In figure 66, top right and top left figures show the variation in energy consumption in different scenarios. Top right figure there is an increase in cooling energy demand from 7.7kWh/(m²yr) in 2009-2038 to 9.1kWh/(m²yr) in 2039-2068 and 9.47kWh/(m²yr) in 2069-2098 in comparison with reference year cooling demand of 2.5kWh/(m²yr) which is 207%, 264% and 279% respectively for 2009-2038, 2039-2068, 2069-2098. In the same figure, the heating demand increasing to 15.3kWh/(m²yr) in 2009-2038 and to 16kWh/(m²yr) in 2039-2068 and reduces considerably to 11.6kWh/(m²yr) in 2069-2098, which is 18% reduction in 2069-2098, in comparison with reference year heating demand of 14.2kWh/(m²yr). The bottom row in the figure shows the operative temperature hours. Here it can be seen that there is a considerable rise in the temperatures indoors especially above 29°C at ground level, from 287 hours in reference year to 1394 in 2009-2038 to 1677 hours in 2039-2068 to 1582 hours in 2069-2098, and upper floor living areas, from 221 hours in reference year to 1178 hours in 2009-2038 to 1434 hours in 2039-2068 to 1425 hours in 2069-2098.

13.1.3 Stockholm

Table 18: Energy consumption distribution in a passive house in reference year climate condition for Stockholm.

	Energy Consumption	
	kWh	kWh/(m²yr)
Auxiliary energy	648	3.7
Cooling energy	1182	6.8
Heating energy	2497	14.3
Domestic Hot Water	3646	20.8
Lighting	1136	6.5
Equipment	2125	12.1
Grand total	11234	64.2

In figure 67, top right and top left figures show the variation in energy consumption for heating and cooling. There is an increase in cooling energy demand from 6.8 kWh/(m²yr) in reference year to 8kWh/(m²yr), 18% in 2009-2038 to 9.8kWh/(m²yr), 44% in 2039-2068 and 11.6kWh/(m²yr), 71% in 2069-2098. In the same figure, the heating demand increases to 16.2kWh/(m²yr) in 2009-2038 and to 16kWh/(m²yr) 2039-2068 and then reduces to 11.3kWh/(m²yr) in 2069-2098 which is 21% reduction in 2069-2098, in comparison with reference year heating demand of 14.3kWh/(m²yr). The bottom row in the figure shows the operative temperature hours in the living areas. There are slight fall and rise in the temperatures indoors especially above 29°C at ground level, from 1631 hours in reference year to 1684 in 2009-2038 to 1669 hours in 2039-2068 to 2167 hours in 2069-2098 and, upper floor living areas, from 1498 hours in reference year to 1364 hours in 2009-2038 to 1502 hours in 2039-2068 to 1977 hours in 2069-2098.

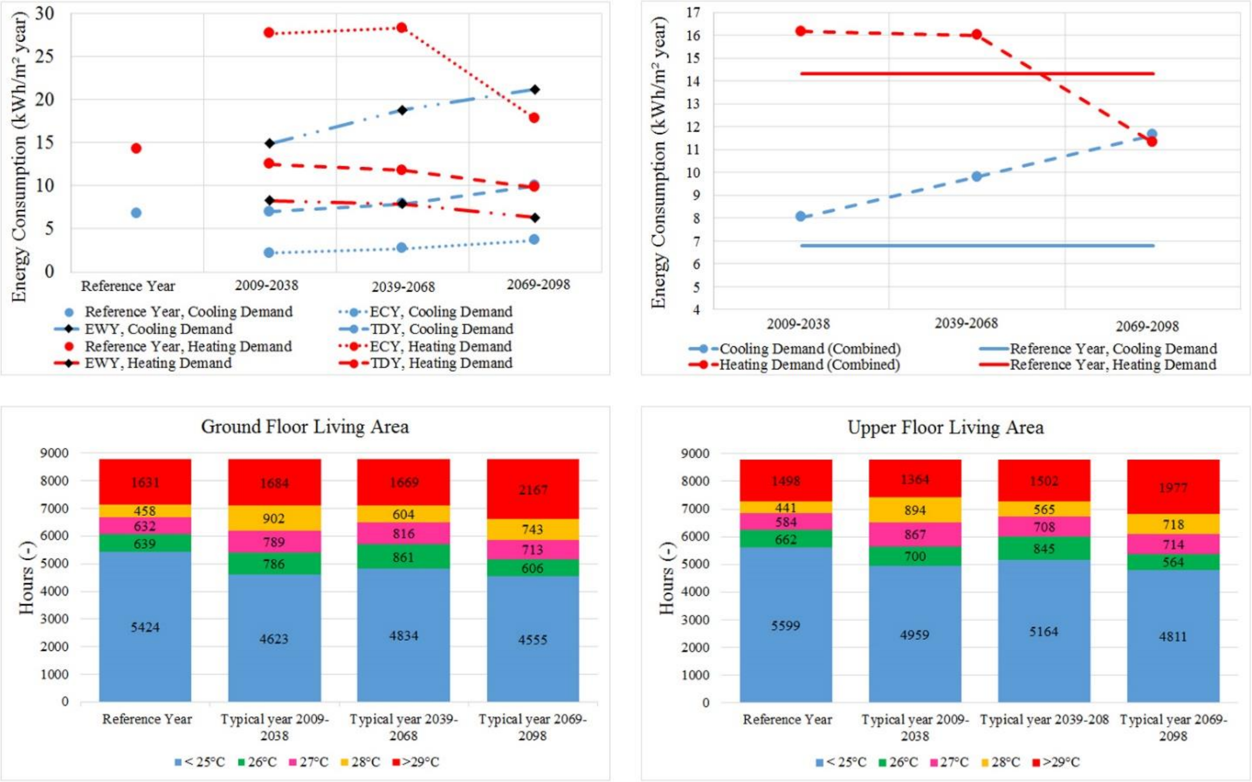

Figure 67: Comparative analysis of Energy consumption for heating and cooling and operative temperature hours for Stockholm with ECY, TDY, EWY, reference year, and Combined year.

13.1.4 Luleå

Table 19: Energy consumption distribution in a passive house in reference year climate condition for Lulea.

	Energy Consumption	
	kWh	kWh/(m²yr)
Auxiliary energy	647	3.7
Cooling energy	677	3.9
Heating energy	5437	31.1
Domestic Hot Water	3646	20.8
Lighting	1136	6.5
Equipment	2126	12.2
Grand total	13669	78.1

In figure 68, top right and top left figures show the variation in energy consumption for heating and cooling. There is an increase in cooling energy demand from 3.9kWh/(m²yr) in reference year to 6.4kWh/(m²yr), 64% in 2009-2038 to 7.4kWh/(m²yr), 91% in 2039-2068 and 8.2kWh/(m²yr), 110% in 2069-2098. In the same figure, the heating demand decreasing to 26.5kWh/(m²yr) in 2009-2038 to

22.8kWh/(m²yr) in 2039-2068 to 19.6kWh/(m²yr) in 2069-2098 which is 37% reduction in 2069-2098, in comparison with reference year heating demand of 31.1kWh/(m²yr). The bottom row in the figure shows the operative temperature hours. Here it can be seen that there is an increase in the temperatures indoors especially above 29°C at ground level, from 900 hours in reference year to 1401 hours in 2009-2038 to 1636 hours in 2039-2068 to 1321 hours in 2069-2098 and, upper floor living areas, from 803 hours in reference year to 1072 hours in 2009-2038 to 1390 hours in 2039-2068 to 1140 hours in 2069-2098.

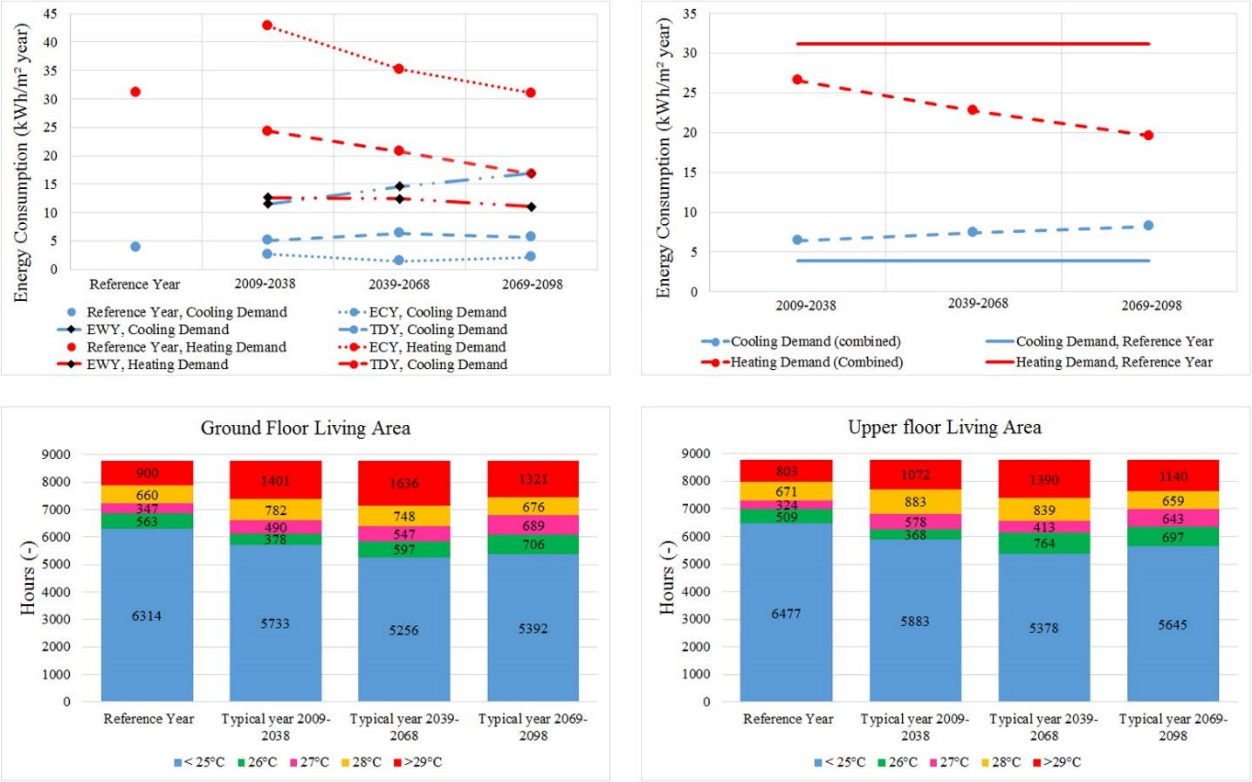

Figure 68: Comparative analysis of Energy consumption for heating and cooling and operative temperature hours for Lulea with ECY, TDY, EWY, reference year, and Combined year.

14 Appendix 2: Moisture performance for reference year

14.1.1 Moisture Performance of Wall in Lund

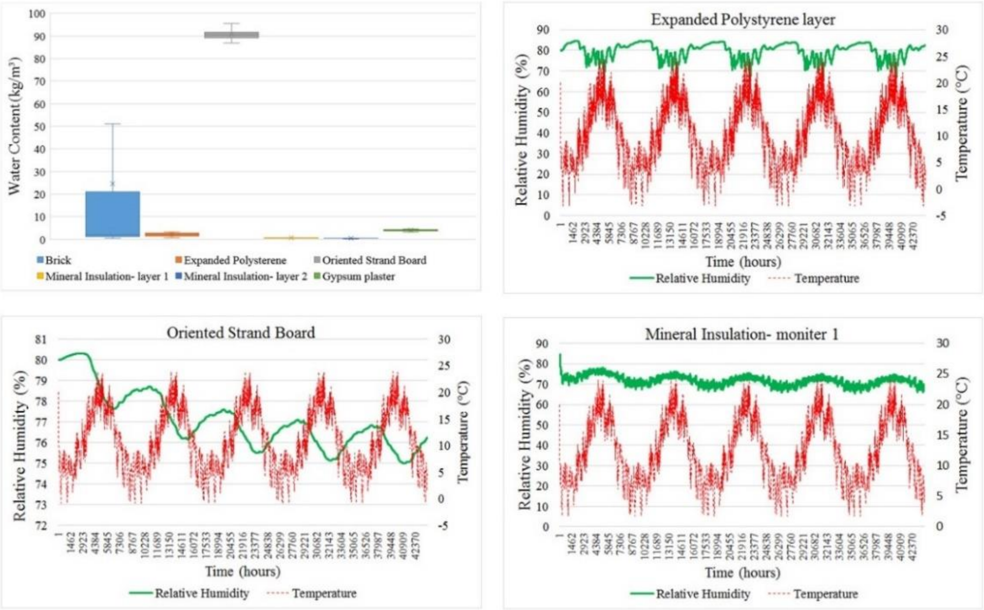

Figure 69: Moisture performance in Brick facade wall layers for Lund. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row, right and bottom row).

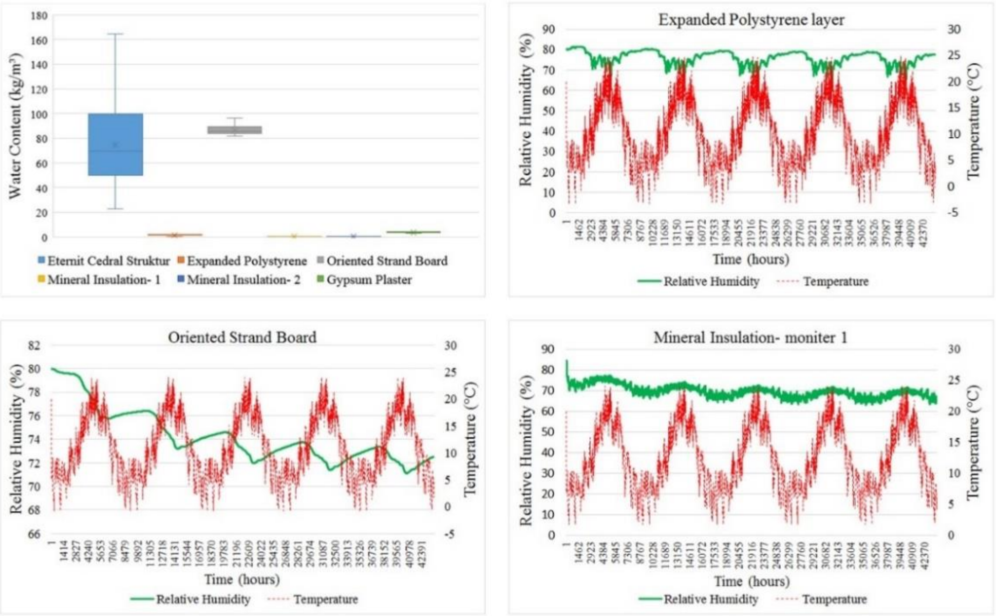

Figure 70: Moisture performance in Eternit Cedral Struktur facade wall layers for Lund. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row, right and bottom row).

14.1.2 Moisture Performance of Wall in Gothenburg

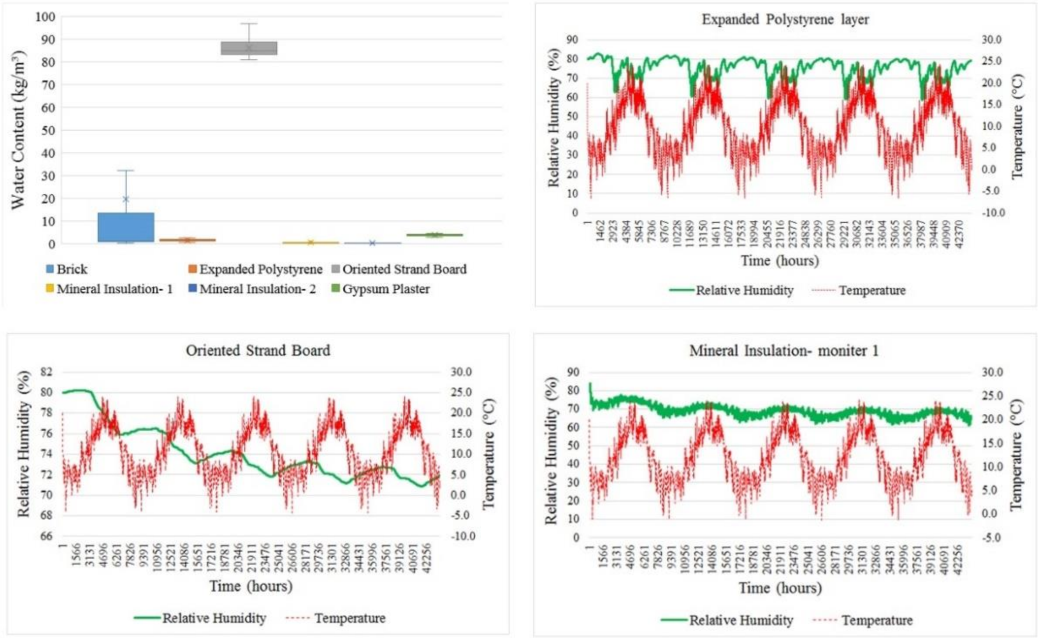

Figure 71: Moisture performance in Brick facade wall layers for Gothenburg. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right and bottom row).

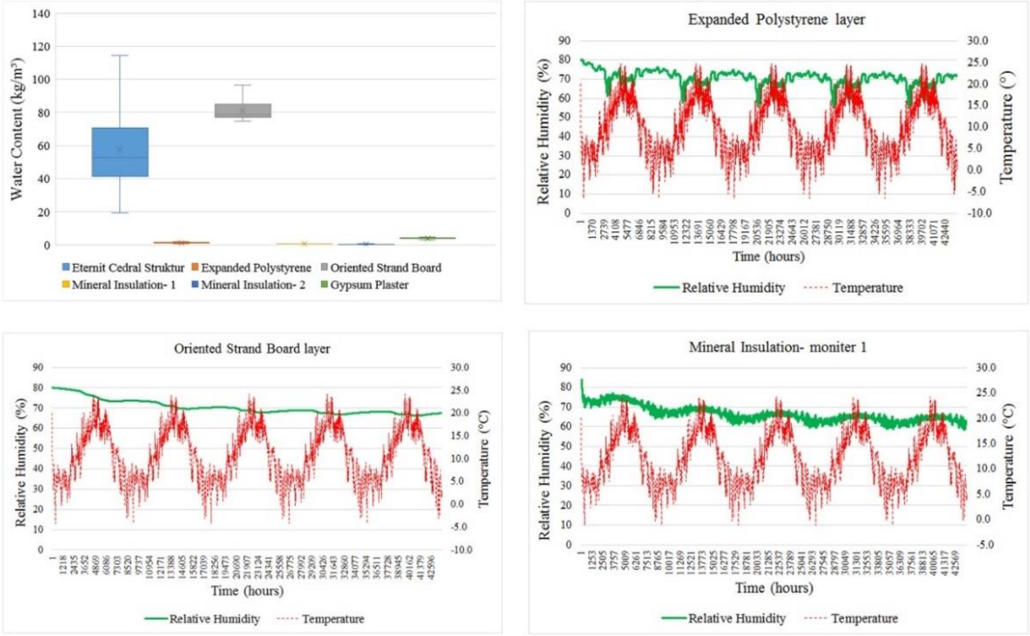

Figure 72: Moisture content in Eternit Cedral Struktur facade wall layers for Gothenburg. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right and bottom row).

14.1.3 Moisture Performance of Wall in Stockholm

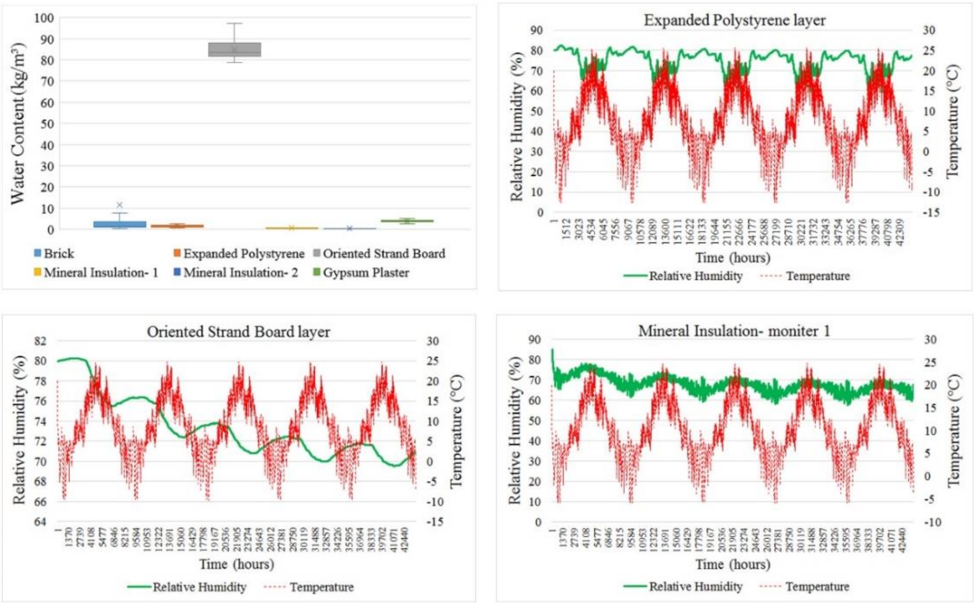

Figure 73: Moisture performance in Brick facade wall layers for Stockholm. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right and bottom row).

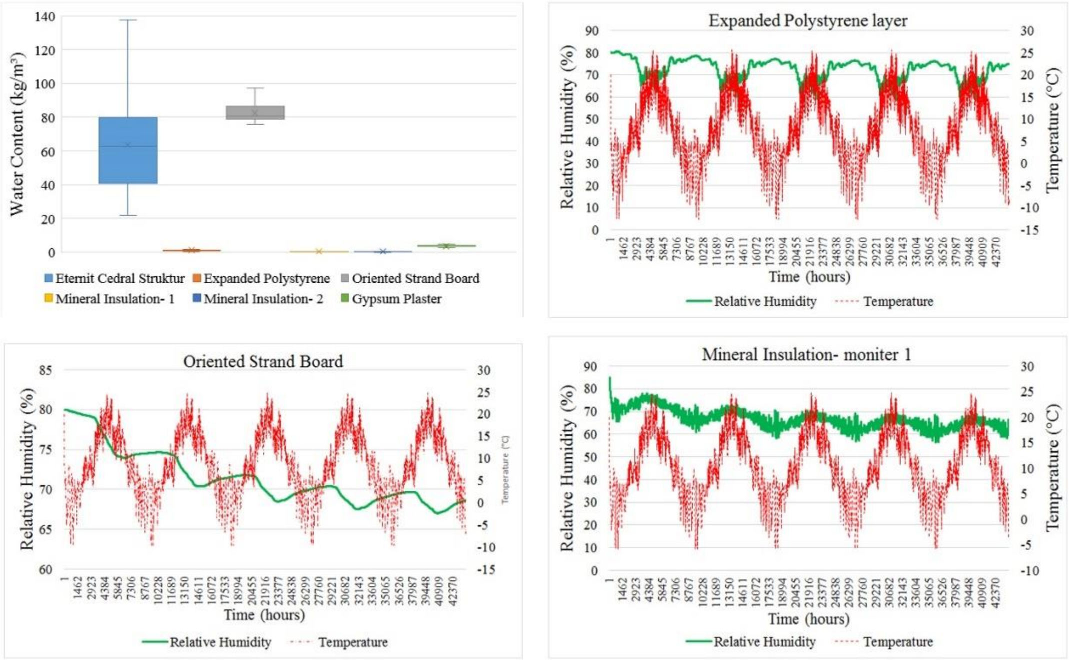

Figure 74: Moisture performance in Eternit Cedral Struktur facade wall layers for Stockholm. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row, right and bottom row).

14.1.4 Moisture Performance of Wall in Lulea

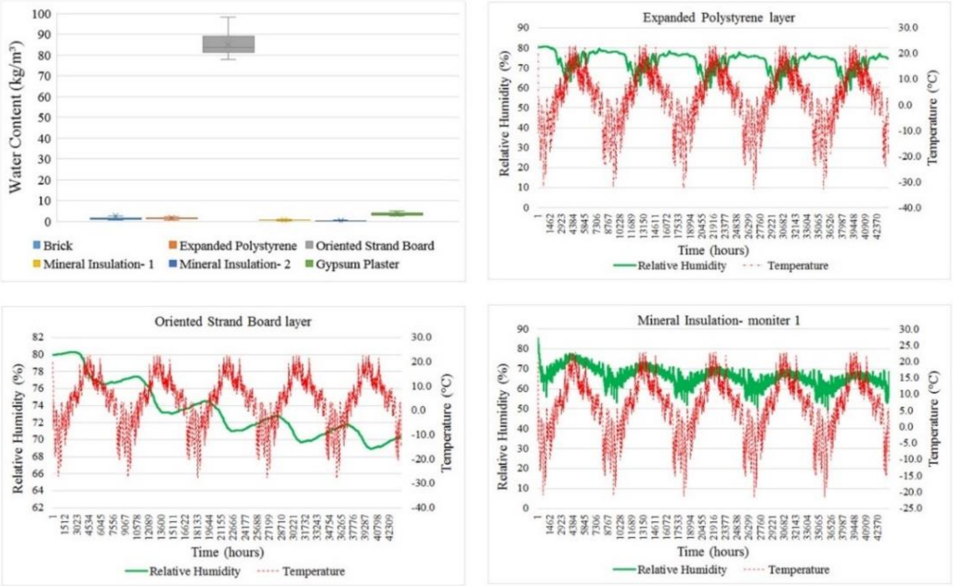

Figure 75: Moisture performance in Brick facade wall layers for Lulea. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right and bottom row).

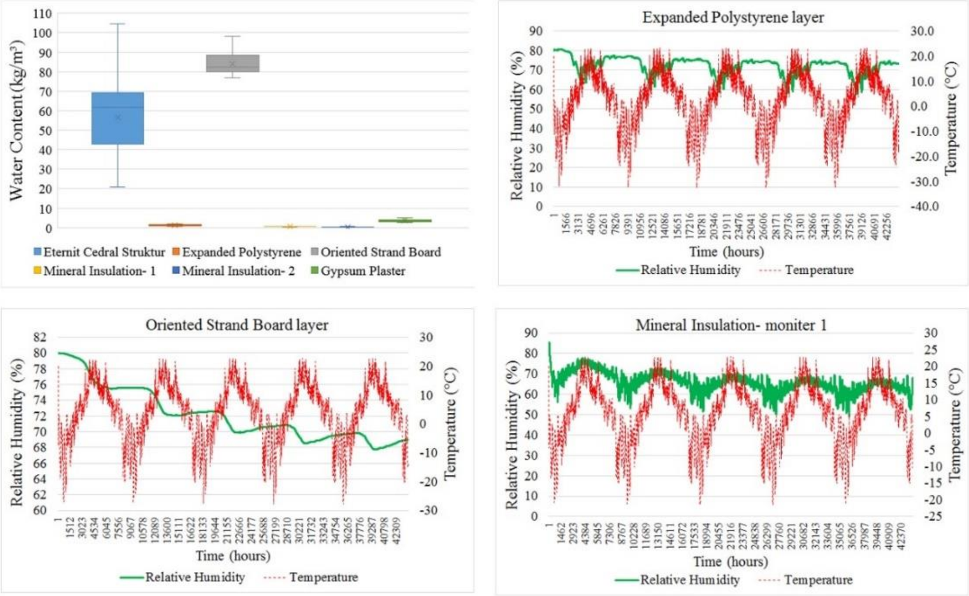

Figure 76: Moisture performance in Eternit Cedral Struktur facade wall layers for Lulea. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right and bottom row).

14.1.5 Moisture Performance of Roof in Lund

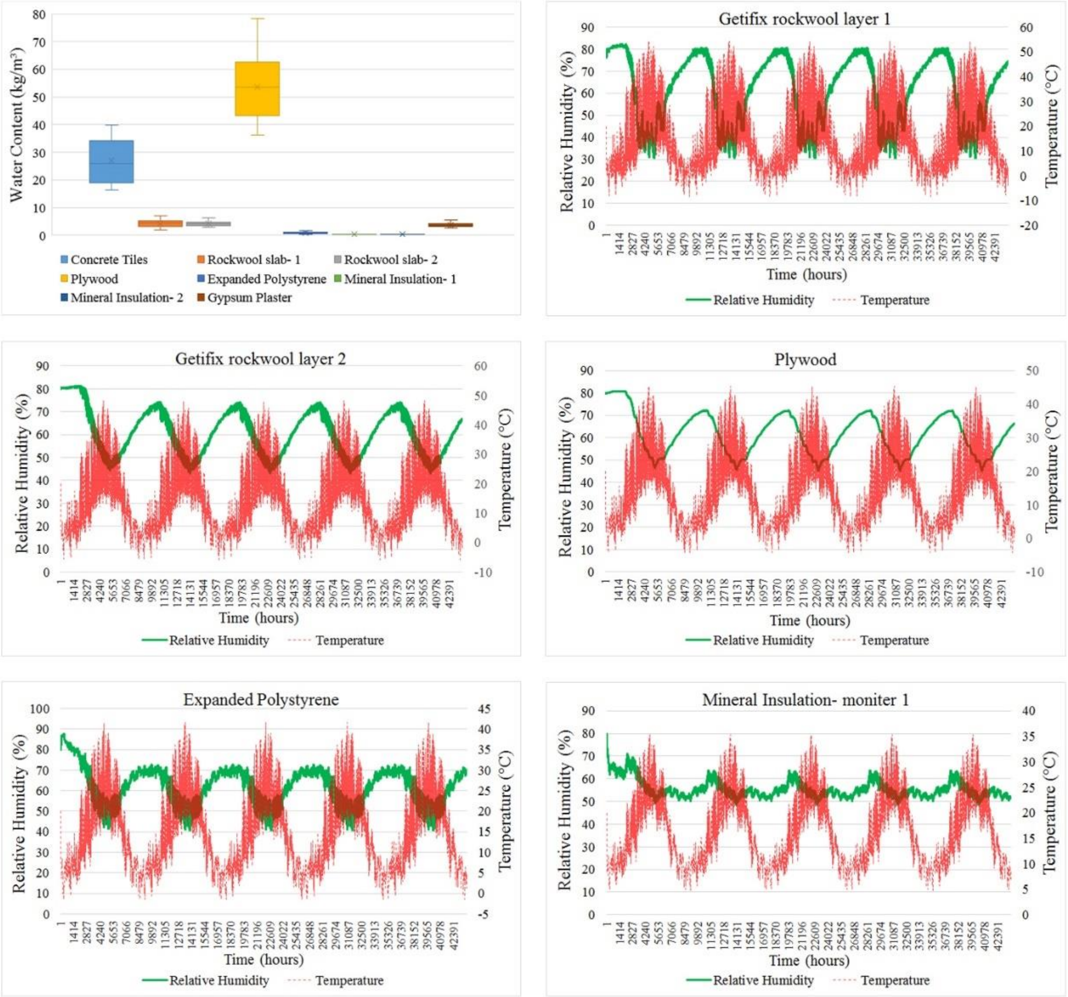

Figure 77: Moisture performance of External roof with Concrete Tiles for Lund. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

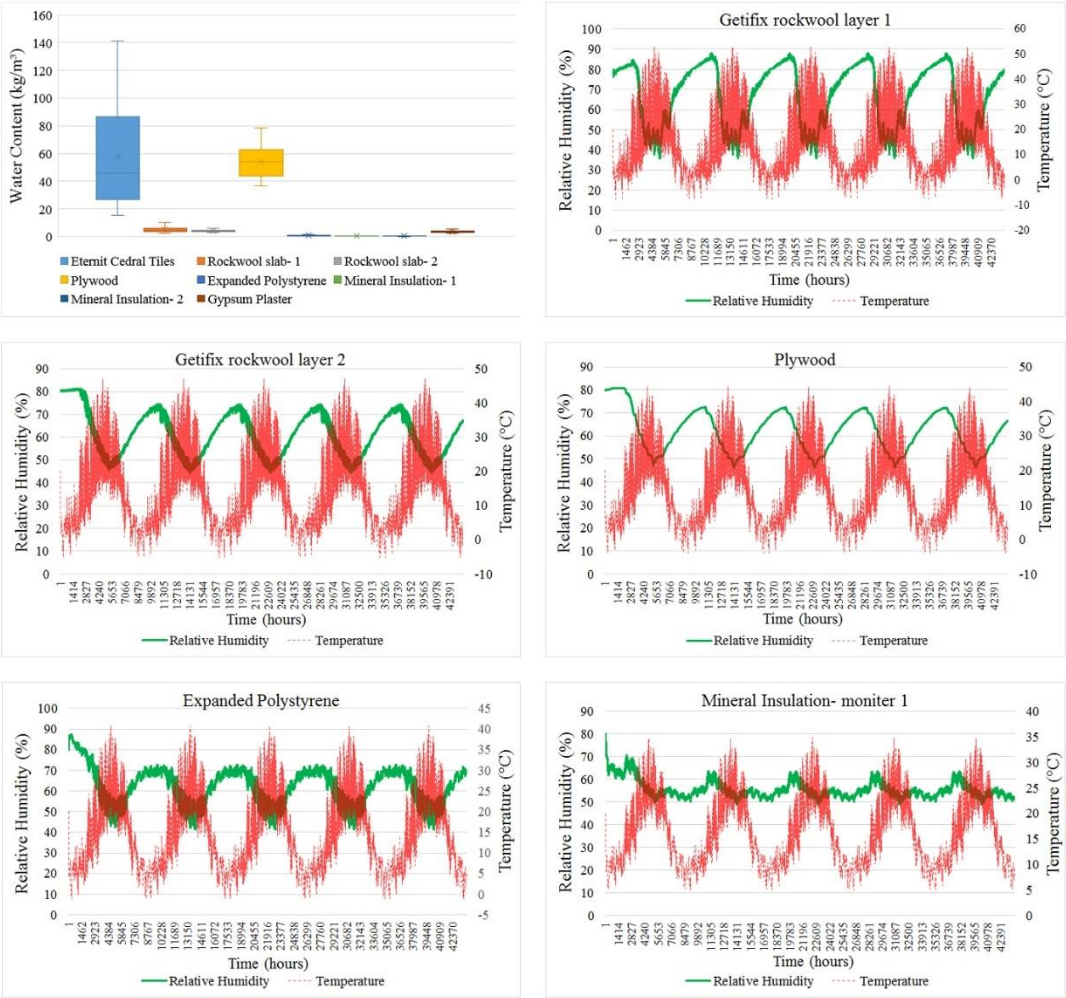

Figure 78: Moisture performance in Eternit Cedral Tile roof for Lund. Graphs Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

14.1.6 Moisture Performance of Roof in Gothenburg

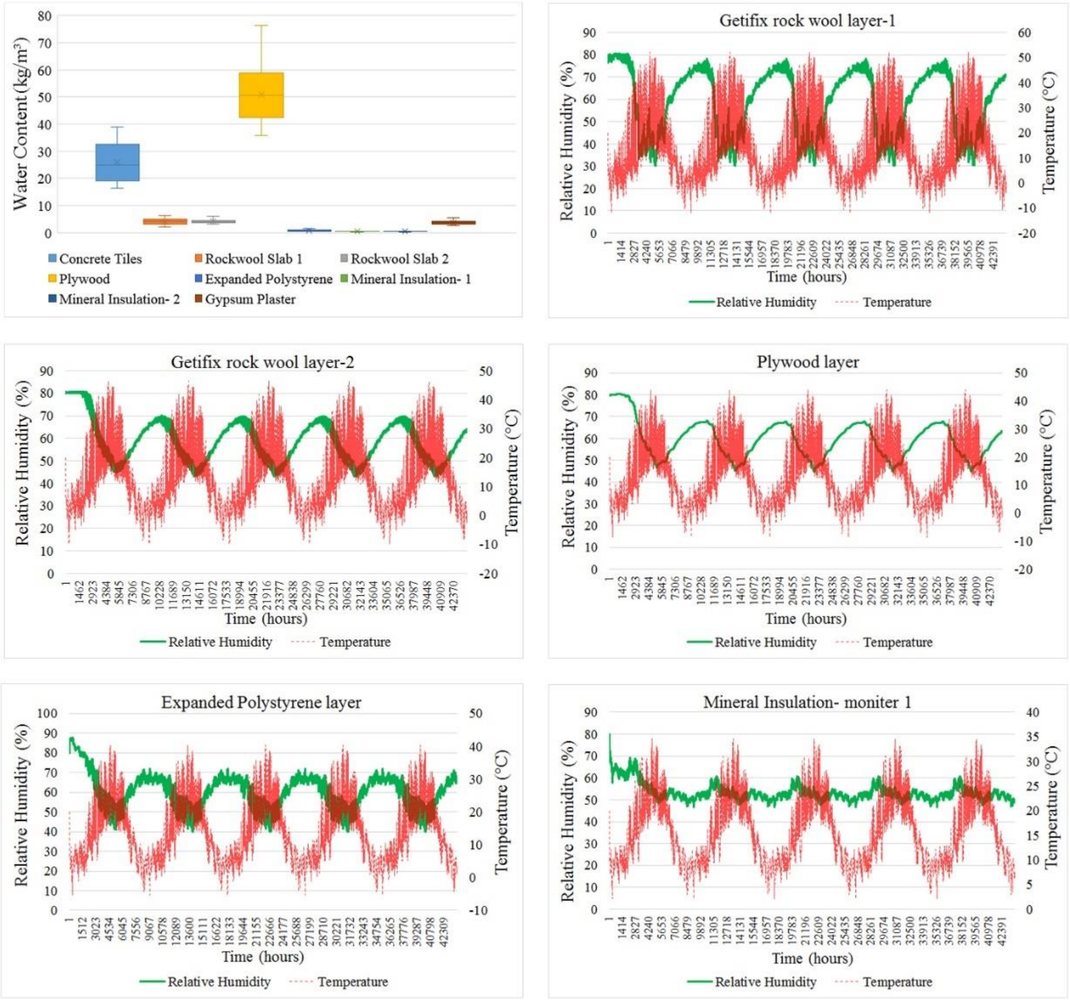

Figure 79: Moisture performance in Concrete Tile roof for Gothenburg. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

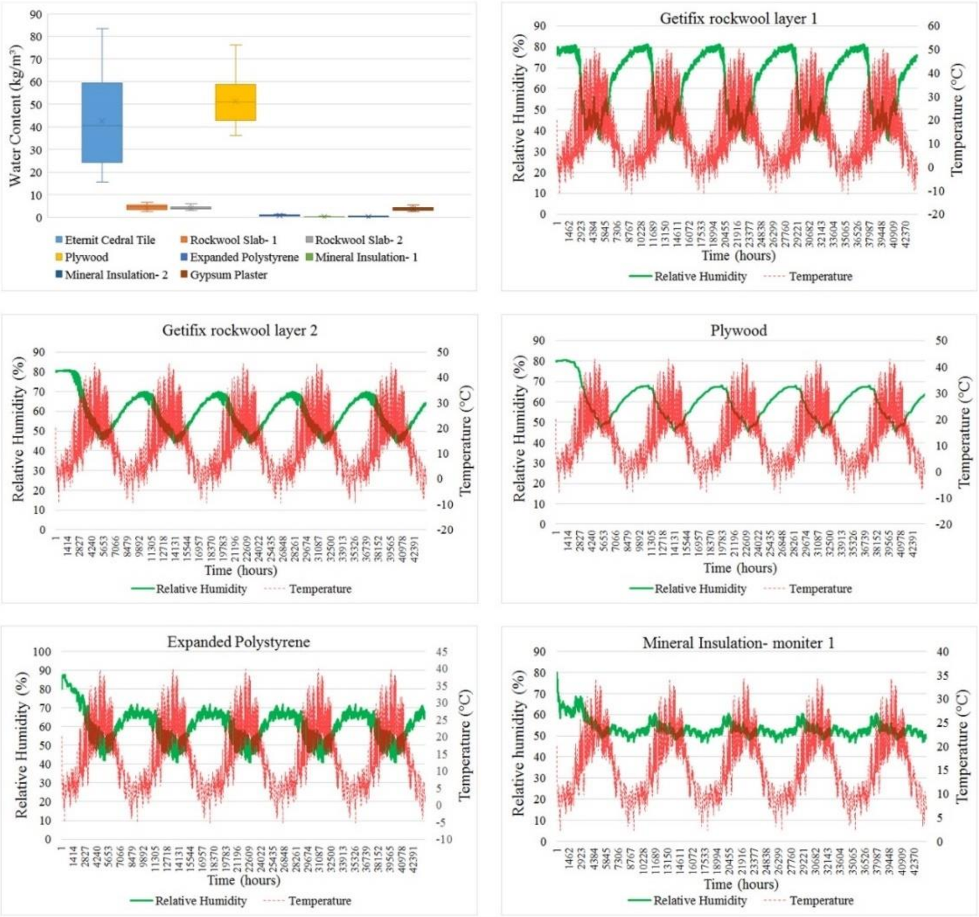

Figure 80: Moisture performance in the External roof with Eternit Cedral Tile for Gothenburg. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

14.1.7 Moisture Performance of Roof in Stockholm

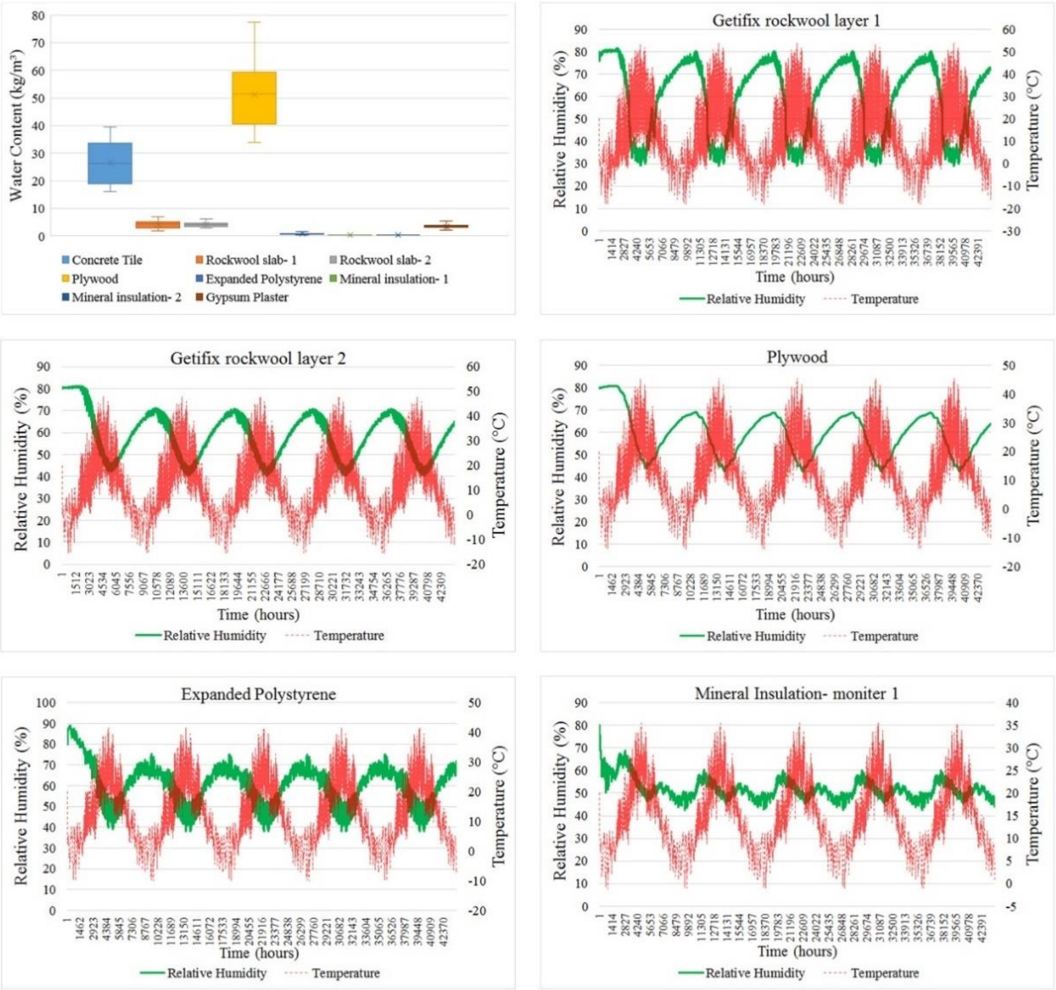

Figure 81: Moisture performance in the External roof with Concrete tiles for Stockholm. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

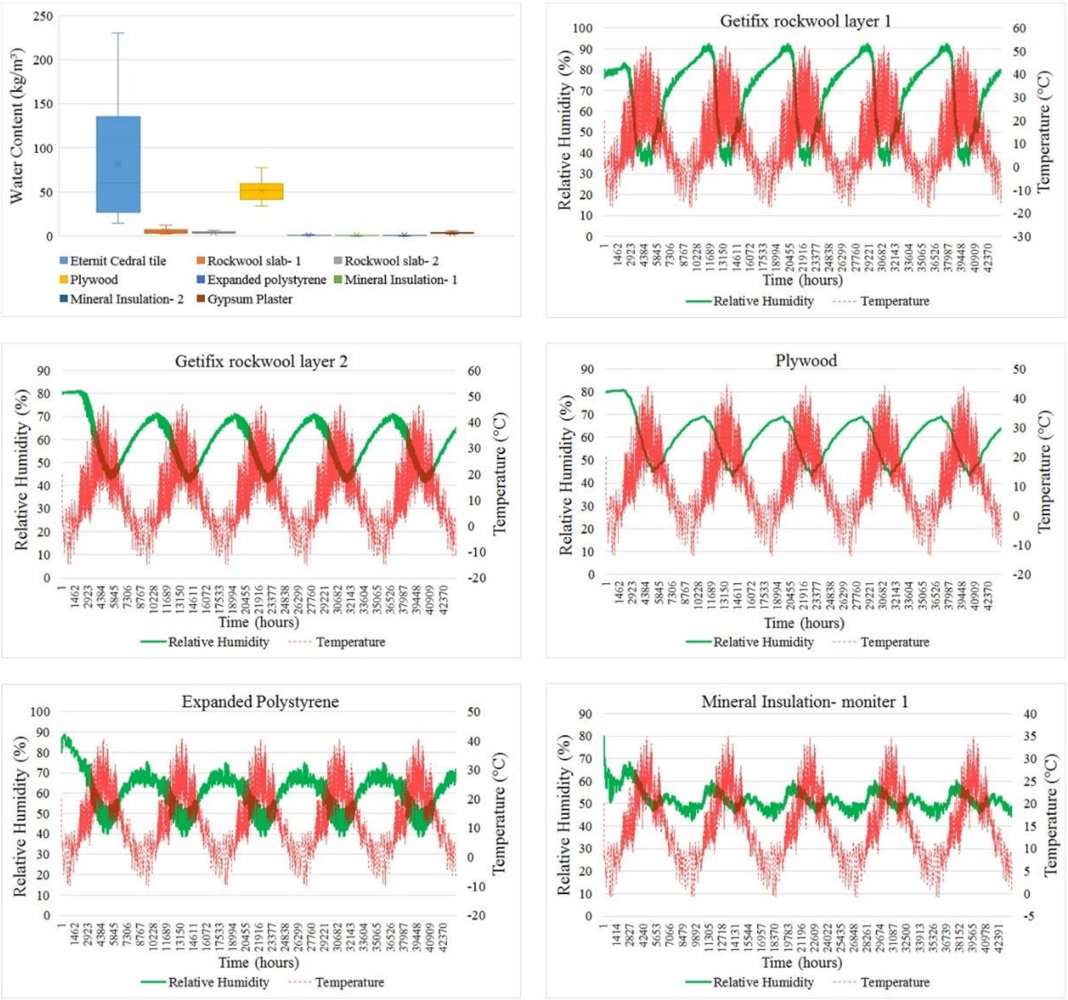

Figure 82: Moisture performance in the External roof with Eternit Cedral tiles for Stockholm. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

14.1.8 Moisture Performance of Roof in Lulea

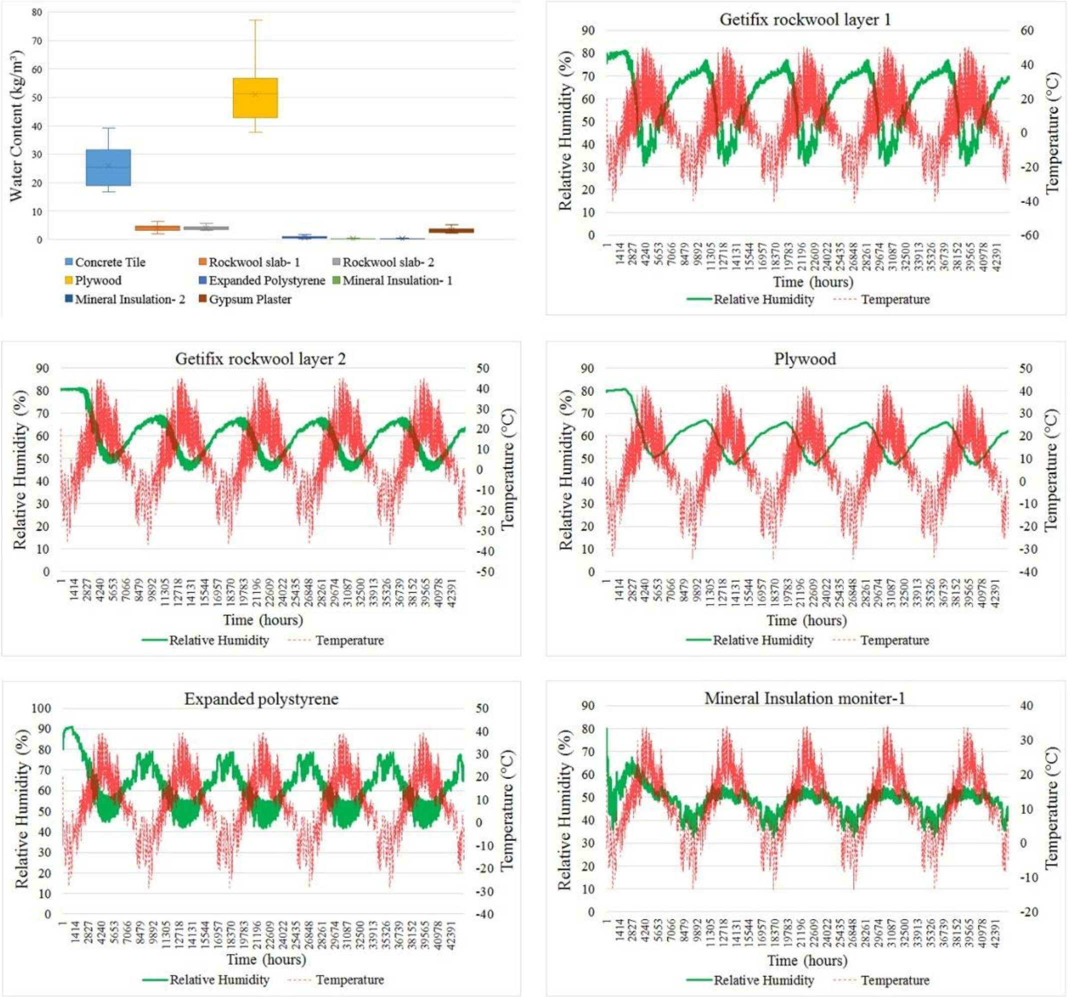

Figure 83: Moisture performance in the External roof with Concrete tiles for Lulea. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

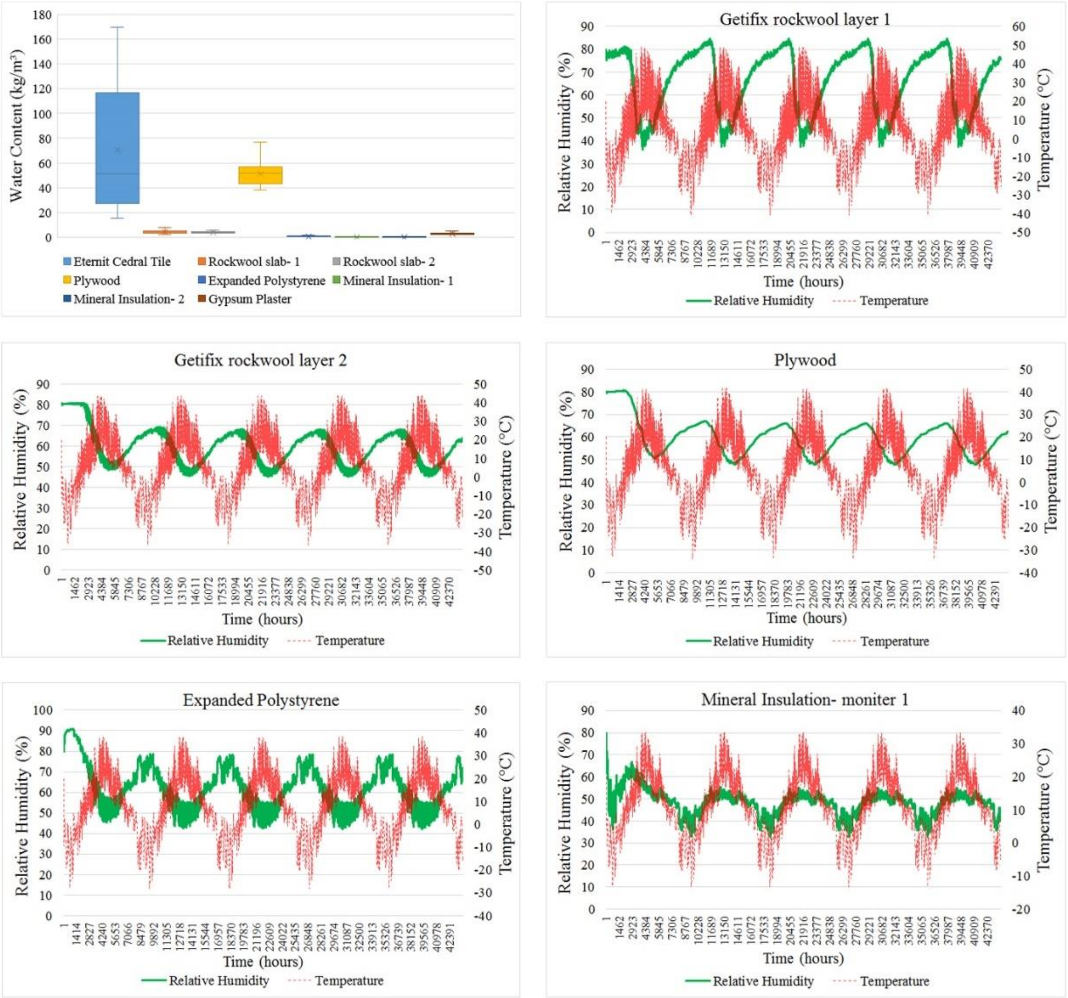

Figure 84: Moisture performance in the External roof with Eternit Cedral tiles for Lulea. Graphs showing Water content variations in the whole wall (top row, left), Temperature and Relative Humidity variation with time in critical layers (top row right, middle row and bottom row).

15 Appendix 3: Moisture performance, Mould growth calculations for future climate condition

15.1.1 Mould growth calculations in external wall with brick facade

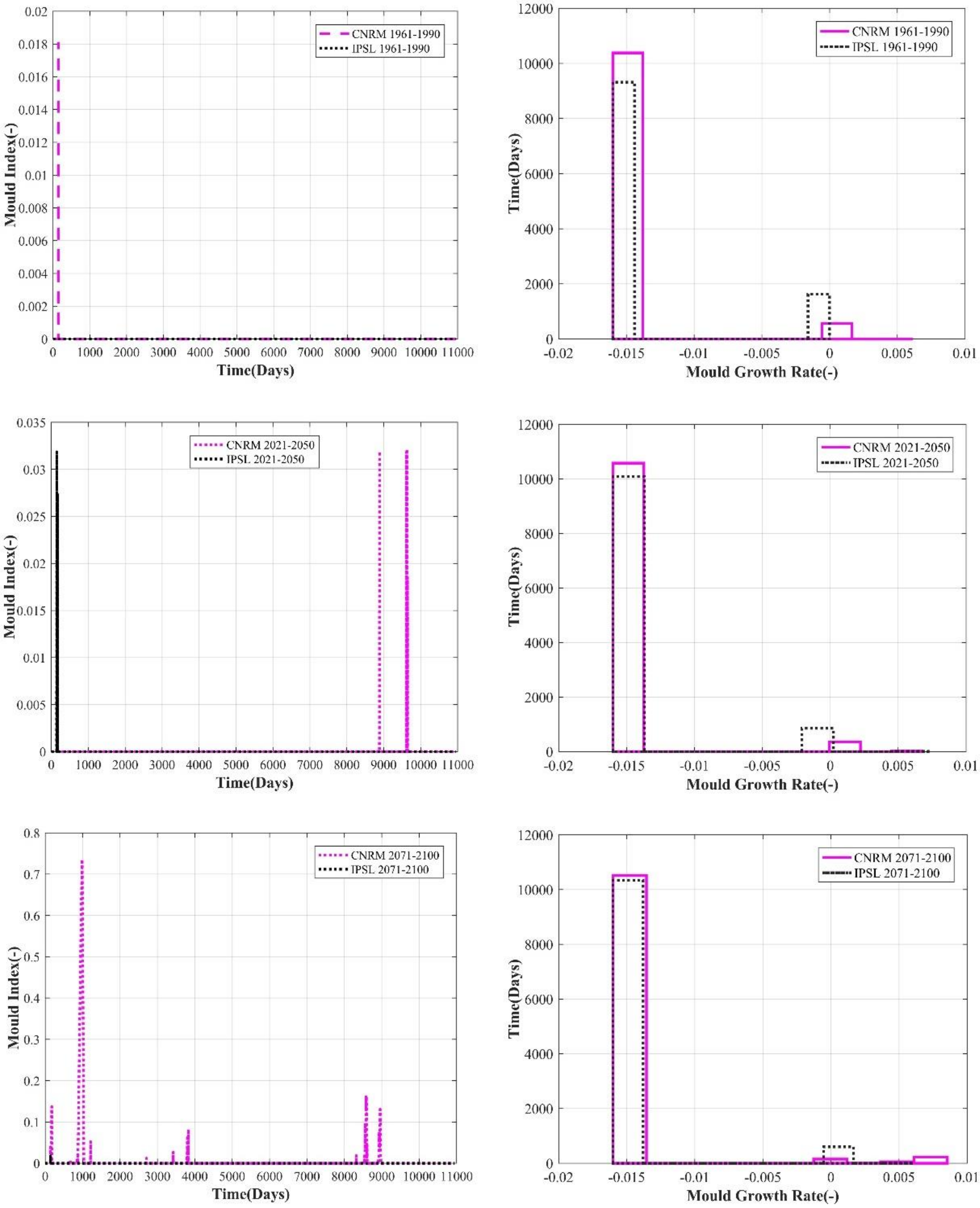

Figure 85: Mould Index and mould growth for Oriented Strand Board layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for brick facade wall Top row- time period 1961-1990, Middle row- time 2021-2050, Bottom row- time period 2071-2100.

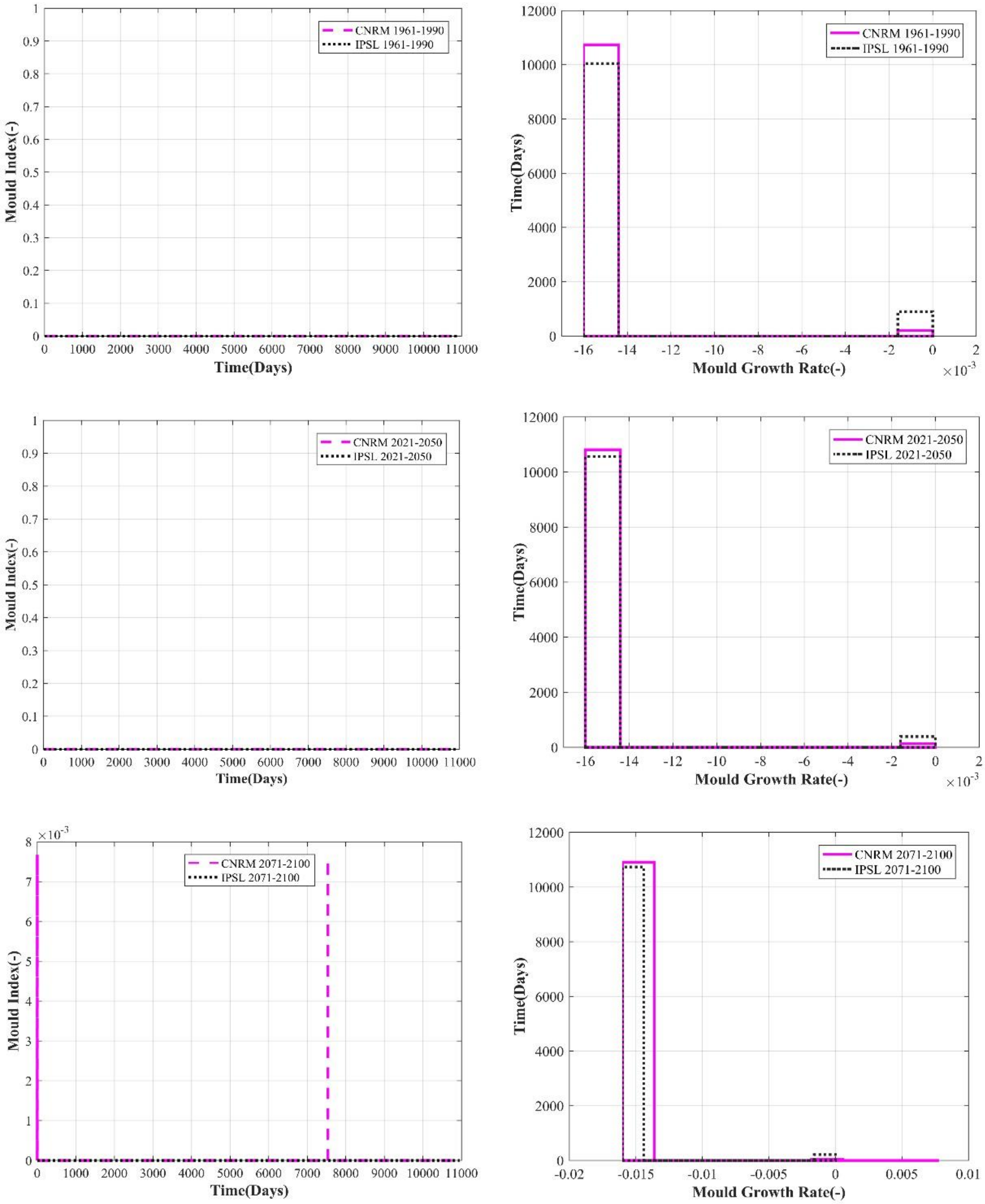

Figure 86: Mould Index and mould growth for Mineral Insulation layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for brick facade wall Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

15.1.2 Mould growth calculations in Eternit cedral structure facade wall layers

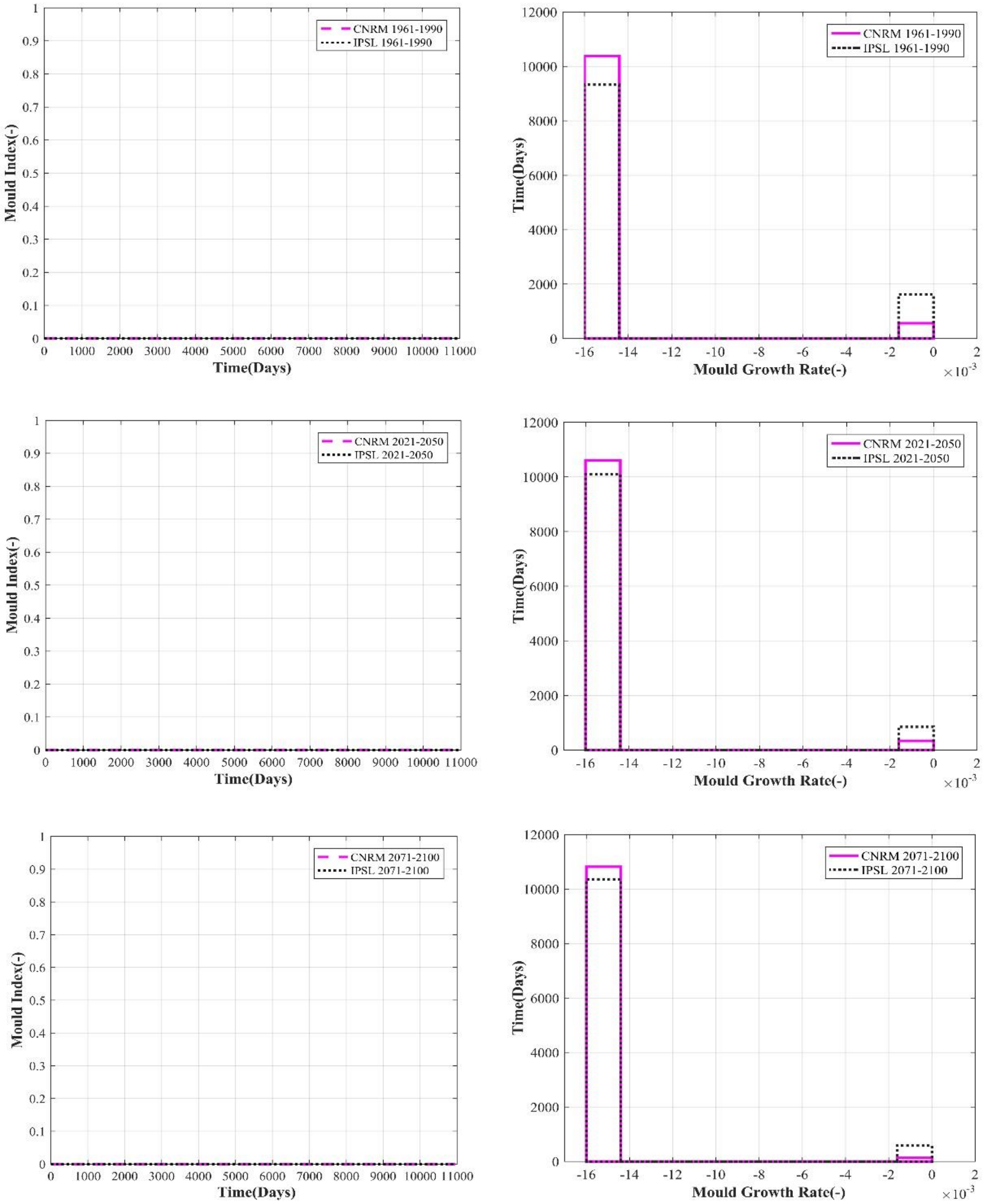

Figure 87: Mould Index and mould growth for Oriented Strand Board layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for Eternit Cedral Struktur facade wall Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

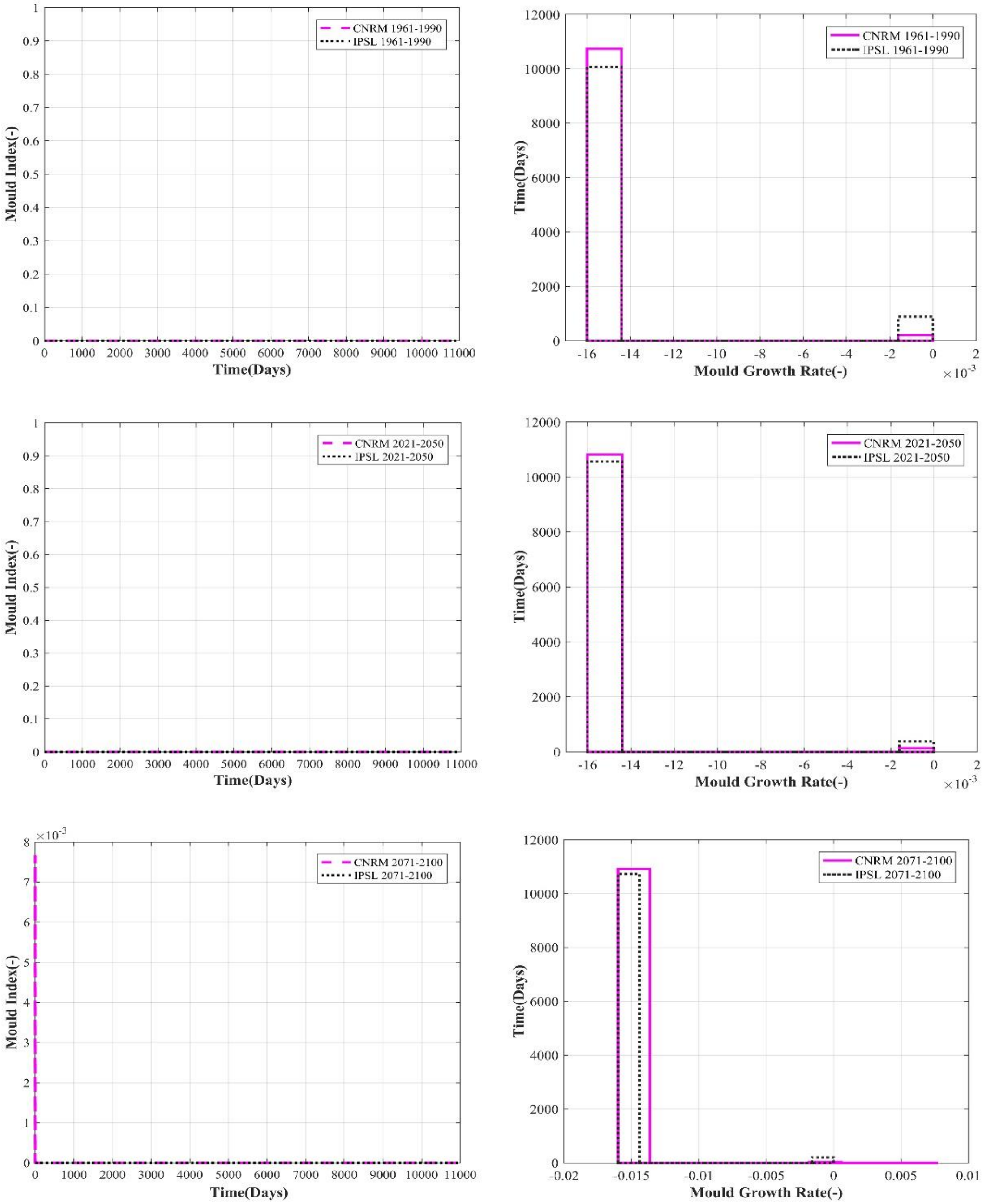

Figure 88: Mould Index and mould growth for Mineral Insulation layer-1 in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for Eternit Cedral Struktur facade wall Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

15.1.3 Mould growth calculations in Concrete tile roof layers

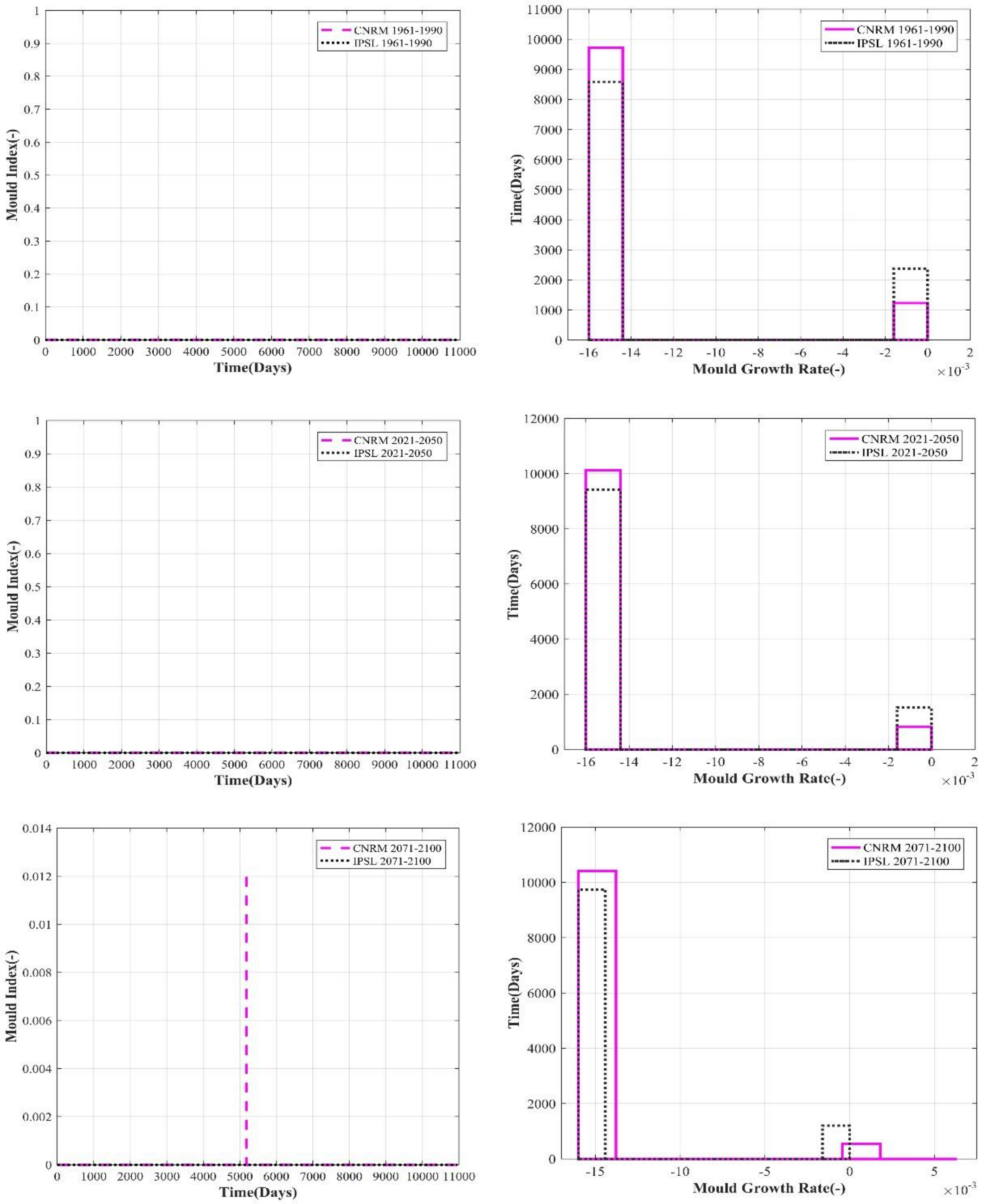

Figure 89: Mould Index and mould growth for Getifix Rockwool slab layer-2 in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Concrete tiles Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

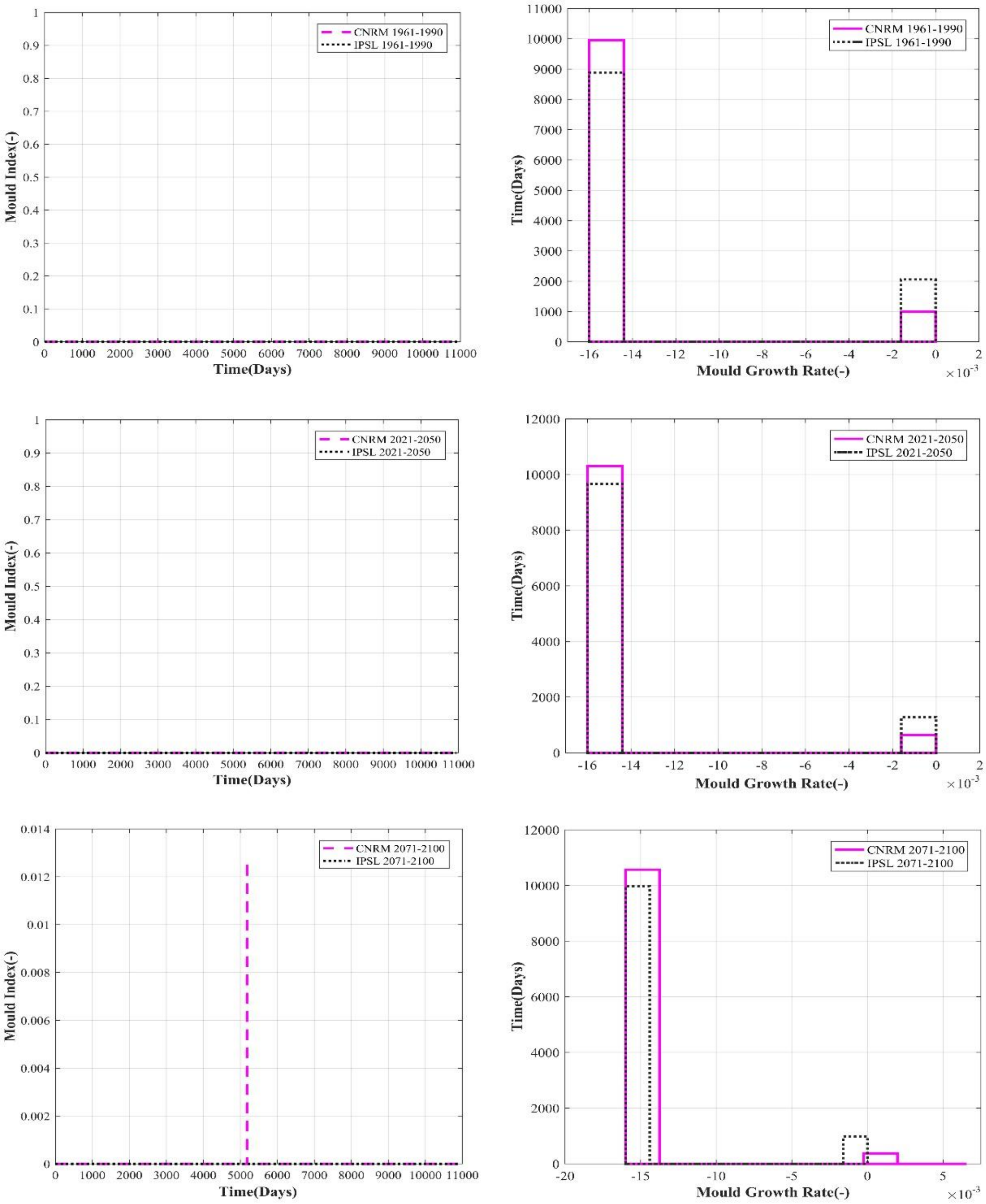

Figure 90: Mould Index and mould growth for plywood layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Concrete tiles Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

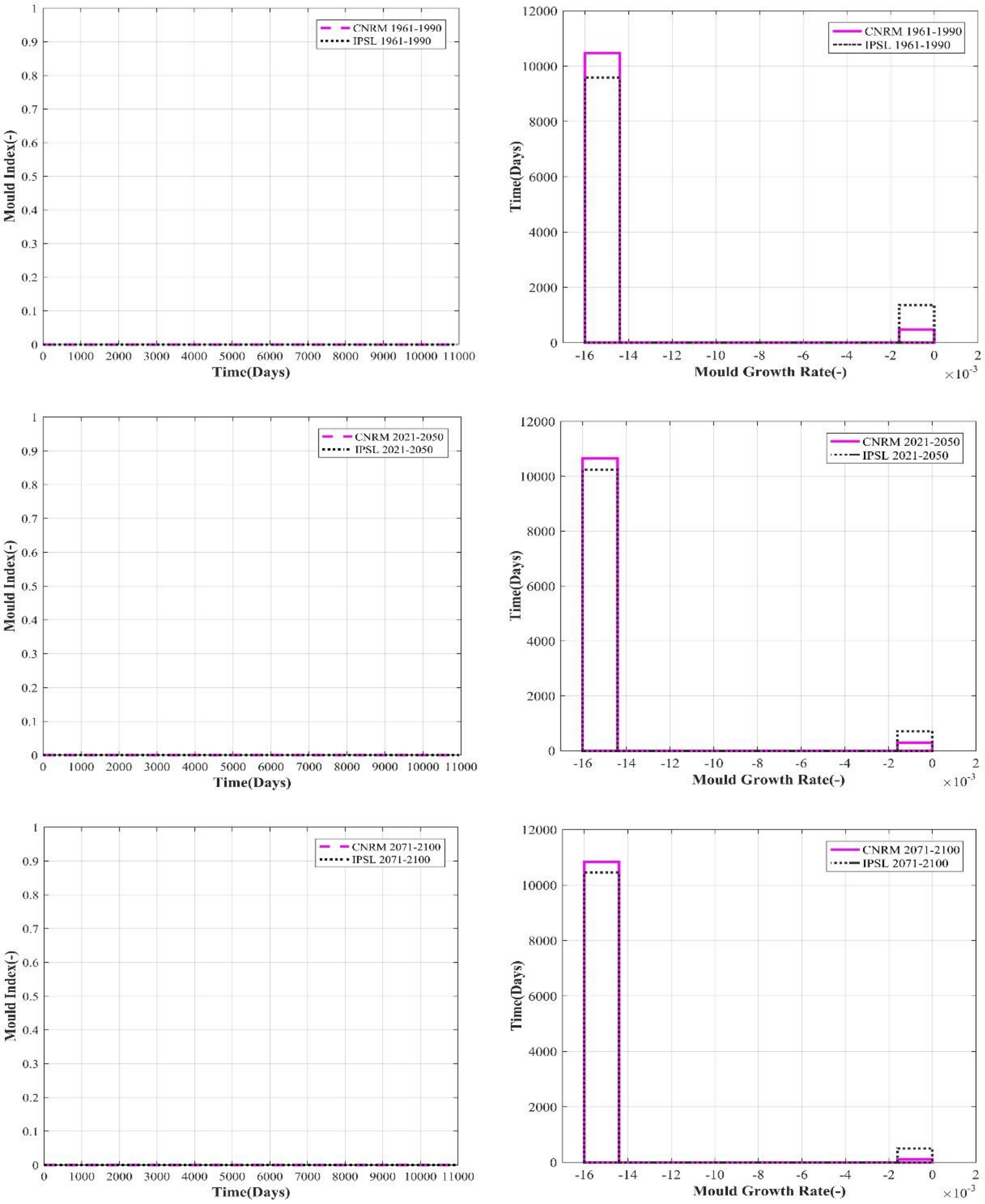

Figure 91: Mould Index and mould growth for Expanded Polystyrene layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Concrete tiles Top- time period 1961-1990. Middle- time line- 2021-2050, Bottom- time period 2071-2100.

15.1.4 Mould growth calculations in Eternit Cedral tile roof layers

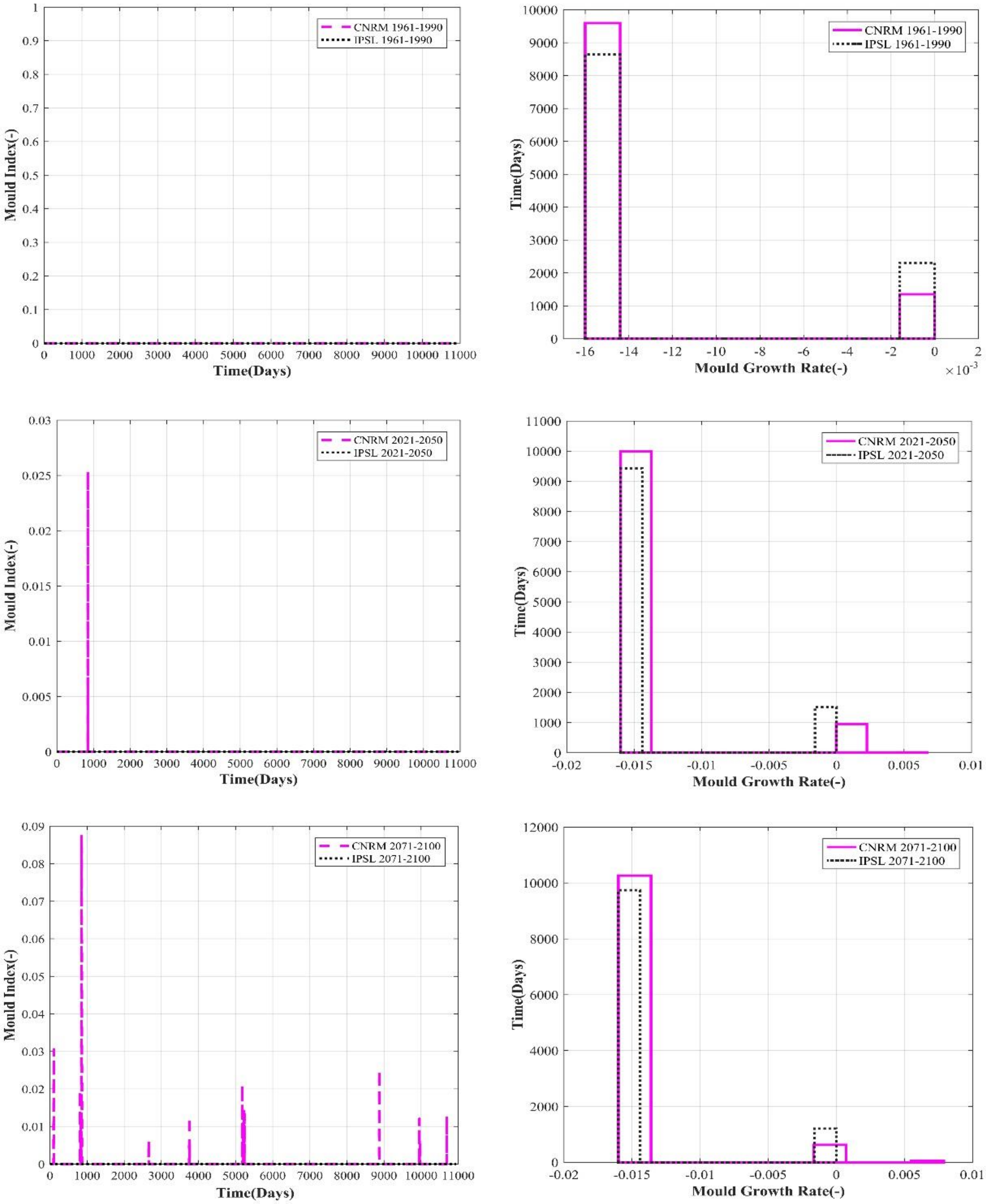

Figure 92: Mould Index and mould growth for Getifix Rockwool slab layer-2 in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Eternit Cedral tiles Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

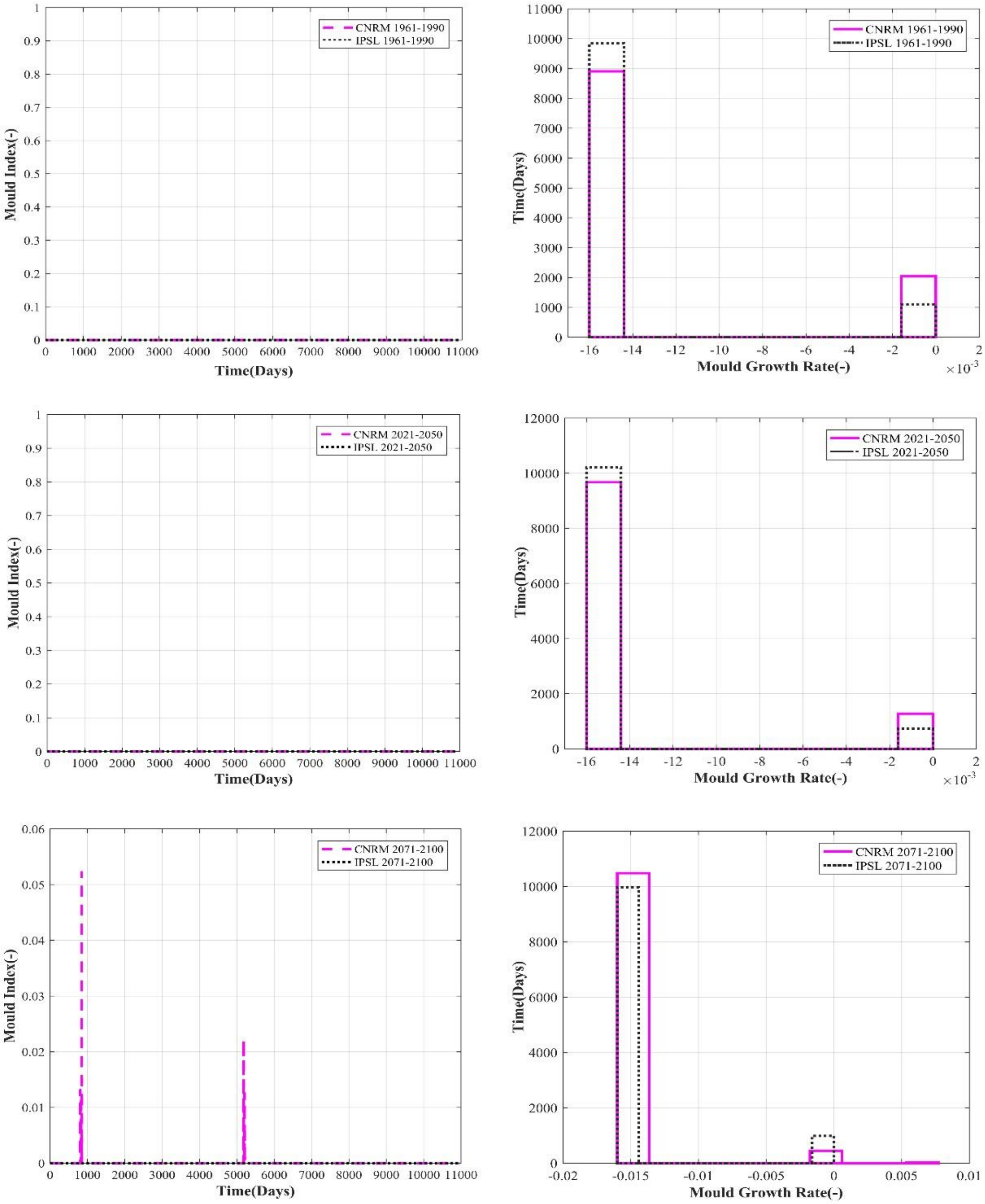

Figure 93: Mould Index and mould growth for Plywood layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Eternit Cedral tiles Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

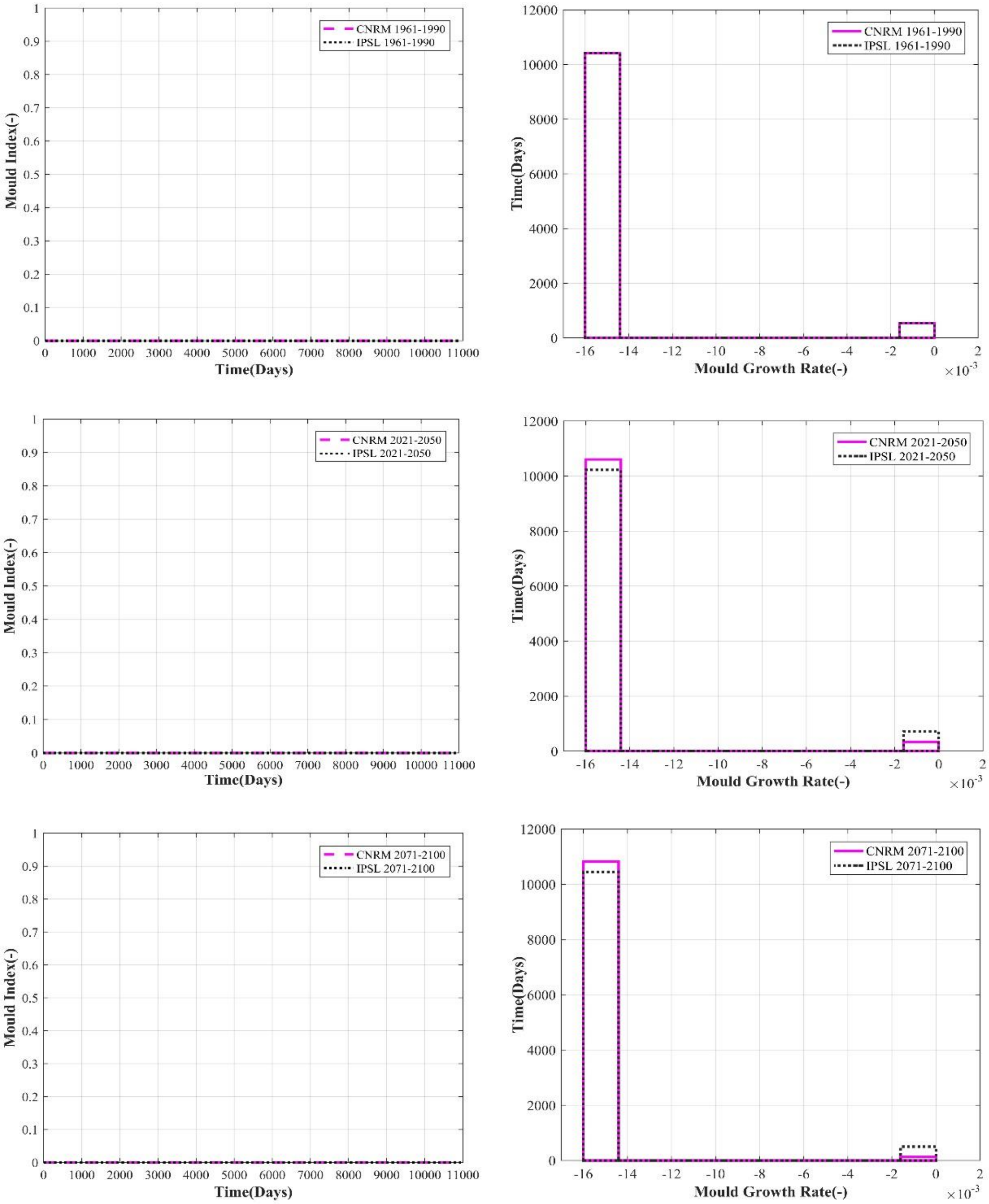

Figure 94: Mould Index and mould growth for Expanded polystyrene layer in CNRM and IPSL climate data for 1961-1990, 2021-2015 and 2071-2100 time period for the External roof with Eternit Cedral tiles Top- time period 1961-1990. Middle- time period- 2021-2050, Bottom- time period 2071-2100.

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Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services