MASTERARBEIT

THERMAL COMFORT IN NATURALLY VENTILATED OFFICES IN AUSTRIAN AND GREEK CLIMATE

Ausgeführt zum Zwecke der Erlangung des

akademischen Grades eines Diplom-Ingenieurs

unter der Leitung von

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ABSTRACT

Indoor spaces are an important part of daily life where various activities are accommodated. On the one hand many studies have proved that poor indoor conditions affect health, productivity and comfort of occupants. For this reason, thermal comfort nowadays is a very crucial issue and a lot of work on this field has been done in order to determine the parameters which affect it and also to propose building design-oriented solutions for its improvement. On the other hand, global warming and elevated temperatures affect not only the outdoor thermal conditions but also the indoor thermal comfort, increasing even more the energy demand for cooling. Exploring passive strategies to address the impacts of climate change is unavoidable.

During the last decade several standards have been created, which determine the Indoor Environmental Quality (IEQ) of the buildings. The EN 15251 adaptive thermal comfort model provides a thermal comfort evaluation method valid throughout Europe. The purpose of this work is to evaluate the thermal comfort of a virtual naturally ventilated cellular office room in the climates of Vienna, Austria and Athens, Greece, by following the assessment method of EN 15251 standard. For each country, the impact of changes in typical construction characteristics as well as global warming induced changes in climate data were considered and simulated using the IDA ICE (Indoor Climate and Energy) thermal simulation software. Scenarios with modified building design parameters were examined and a comparison of their effectiveness in the current local climates was carried out. The process was repeated in the second part of this work for a short-term and a long-term scenario using the climate data projections for the years 2030 and 2070. The resulting changes of comfort levels are presented and the effectiveness of the proposed design features in the future scenarios is discussed.

Predicting thermal comfort through simulations that consider future climate change scenarios can lead to suitable construction decisions in the early stages of building design.

Keywords

adaptive thermal comfort, IDA ICE, naturally ventilated buildings, building simulation, global warming, effect on thermal comfort

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KURZFASSUNG

Innenräume sind ein wichtiger Teil des täglichen Lebens, in denen verschiedene Aktivitäten ausgeübt werden. Einerseits haben viele Forschungen bewiesen, dass schlechte Innenraumbedingungen die Gesundheit, die Produktivität und den Komfort der Nutzer beeinträchtigen. Aus diesem Grund ist die thermische Behaglichkeit heutzutage ein entscheidendes Thema, und es wurde bereits viel auf diesem Gebiet gearbeitet, um die Parameter zu bestimmen, die sich auf sie auswirken, und auch, um gebäudedesignorientierte Lösungen für ihre Optimierung vorzuschlagen. Andererseits beeinflussen die globale Erwärmung und die erhöhten Temperaturen nicht nur die thermischen Bedingungen im Freien, sondern auch die thermische Behaglichkeit in Innenräumen, wodurch der Energiebedarf für die Kühlung noch weiter steigt. Die Erforschung passiver Strategien zur Bewältigung der Auswirkungen des Klimawandels ist unumgänglich.

Im Laufe des letzten Jahrzehnts wurden mehrere Normen erstellt, die die Innenraumqualität (IEQ) von Gebäuden bestimmen. Das adaptive thermische Behaglichkeitsmodell EN 15251 bietet eine europaweit gültige Methode zur Bewertung der thermischen Behaglichkeit. Ziel dieser Arbeit ist es, die thermische Behaglichkeit eines virtuellen, natürlich belüfteten, zellularen Büroraums in den Klimazonen von Athen, Griechenland und Wien, Österreich, zu bewerten, indem die Bewertungsmethode der Norm EN 15251 befolgt wird. Für beide Länder wurden die Auswirkungen von Änderungen der typischen Konstruktionsmerkmale sowie der durch die globale Erwärmung verursachten Änderungen der Klimadaten berücksichtigt und mit der thermischen Simulationssoftware IDA ICE (Indoor Climate and Energy) simuliert. Es wurden Szenarien mit veränderten Gebäudeauslegungsparametern untersucht und ein Vergleich ihrer Wirksamkeit in den aktuellen lokalen Klimazonen durchgeführt. Der Prozess wurde im zweiten Teil dieser Arbeit für ein Kurzzeit- und ein Langzeitszenario unter Verwendung der Klimadatenprojektionen für die Jahre 2030 und 2070 wiederholt. Die sich daraus ergebenden Änderungen der Komfortniveaus werden dargestellt und die Wirksamkeit der vorgeschlagenen Konstruktionsmerkmale in den zukünftigen Szenarien wird diskutiert.

Die Vorhersage der thermischen Behaglichkeit durch Simulationen, die zukünftige Klimawandelszenarien berücksichtigen, kann zu geeigneten Konstruktionsentscheidungen in den frühen Phasen der Gebäudeplanung führen.

Schlüsselwörter

adaptiver thermischer Komfort, IDA ICE, natürlich belüftete Gebäude, Gebäudesimulation, globale Erwärmung, Auswirkung auf die thermische Behaglichkeit

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CONTENTS

1 introduction 7

1.1 Overview 7

1.2 Motivation 8

1.3 Research objectives 8

1.4 Hypothesis 9

1.5 Methodology 9

1.6 Background 10

1.6.1 Indoor climate 10

1.6.2 The concept of thermal comfort 10

1.6.3 Comfort indices 12

1.6.4 Adaptive thermal comfort model 13

1.6.5 Adaptive thermal comfort model according to DIN EN 15251: 2007-08 14

1.6.6 Indoor air temperature 17

1.6.7 Case studies in literature related to thermal comfort 18

2 Method 20

2.1 Overview 20

2.2 Location and climate classification 20

2.2.1 Locations' selection 20

2.2.2 Climate classification 21

2.3 Climate data 23

2.4 Case scenarios and design strategies 26

2.4.1 Case studies and configuration scenarios 26

2.4.2 Thermal comfort in future climate data projections 28

2.4.3 Office room geometry 28

2.4.4 Envelope construction and thermal mass 30

2.4.5 Building occupancy 32

2.4.6 Artificial lighting and equipment 33

2.4.7 Air exchange rates and window opening behaviour 35

2.5 The selected configuration scenarios 37

2.5.1 Configuration scenario variation 1 – Night ventilation 37

2.5.2 Configuration scenario variation 2 – Shading and shading control 38

2.5.3 Configuration scenario variation 3 – Glazing 40

2.5.4 Configuration scenario variation 4 – Thermal mass and exterior insulation 41

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3 Results 43
3.1 Overview 43
3.2 Thermal comfort evaluation criteria and assumptions 43
3.3 Simulation results 44
3.3.1 Evaluation of the basic scenario 44
3.3.2 Evaluation of configuration scenario 1 – Night ventilation 47
3.3.3 Evaluation of configuration scenario 2 – Shading and shading control 50
3.3.4 Evaluation of configuration scenario 3 – Glazing 55
3.3.5 Evaluation of configuration scenario 4 – Thermal mass - exterior insulation 58
3.4 Summary of results 61
4 Discussion 69
4.1 The influence of building design 69
4.2 The influence of the climate change 71
5 Conclusion 76
5.1 Natural ventilation comfort levels with adapted building configurations 76
5.2 Building design and climate change 77
5.3 Limitations of this work 78
5.4 Suggestions for further research 78
Index 80
Abbreviations 80
List of Figures 81
List of Tables 83
Literature 84
Appendix 87
A. “Meteonorm 8” climate data for Vienna and Athens 87
B. Graphs of mean air and operative temperatures 111

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1 INTRODUCTION

1.1 Overview

Thermal comfort plays a very important role regarding the satisfaction of occupants in their working environments. In 2007 the European Committee for Standardization (CEN) created several standards to help EU member countries comply with the European Directive for Energy Performance of Buildings (EPBD), including the European standard of comfort, EN 15251, "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" (CEN Standard EN 15251 2007). According to the EN 15251 standard the energy consumption of buildings depends significantly on the indoor environment (temperature, ventilation and lighting) as well as the building design and operation.

As Lan et al. (2012) describes, small improvements of Indoor Environmental Quality (IEQ) in office buildings can significantly increase the productivity resulting to substantial economic benefits. The above reason as well as the need to reduce energy consumption in buildings both explain why recently an adaptive approach to thermal comfort has gained unprecedented exposure for the evaluation of naturally ventilated buildings.

As a first research question, this work investigates the impact of design parameters on the thermal comfort of a naturally ventilated typical office room for the climates of Athens, Greece and Vienna, Austria, taking into account the typical construction characteristics of each country, using the thermal simulation software IDA ICE (Indoor Climate and Energy). The second research question investigates the effectiveness of the proposed design parameters in a short- and a long-term climate scenario, taking global warming into account.

The first chapter provides the motivation and background information, in particular regarding thermal comfort standards, focusing on the principles of the European standard EN 15251, while the second chapter describes the applied methods to achieve the objectives of this work. The categorization of the building simulation assumptions in two groups as well as the simulation parameters are described in this chapter in detail. In chapter 3 the results of the accomplished simulations and the effectiveness of the configurations for each scenario are presented. In chapter 4 the results are discussed and interpreted, illustrating the changes in thermal comfort under different circumstances and the sensitivity of the thermal comfort parameter with respect to changes in different design parameters. In the final chapter potential research topics contributing to the further development of the topic are proposed.

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1.2 Motivation

Establishing Indoor Environmental Quality (IEQ) in buildings is of primary importance. For many years, the energy consumption has not been a primary concern, due to the low cost of energy and low sustainability awareness. As these topics have become the focus of many stakeholders, the question of how the design of naturally ventilated buildings can provide acceptable comfort levels in different climates has been raised.

In Mediterranean climates such as that of Greece, the majority of office buildings are operated in mixed mode, using a cooling system only for the warm period of the year while for the rest of the year they are operated in naturally ventilated mode. On the other hand, in more northern climates such as the Austrian, the buildings are typically operated as free-running buildings. However due to climate change, the use of systems to avoid overheating in working spaces has increased rapidly during the last decade (Roetzel 2008). In view of the impending global warming, immediate decisions must be taken to reduce CO_2 emissions.

Thus, the energy consumption of the buildings needs to be addressed through fundamental design characteristics favoring the use of natural ventilation and leading to a drastic reduction of mechanical cooling.

1.3 Research objectives

In this work, two main research objectives will be addressed in relation to naturally ventilated office buildings and the fulfilment of acceptable indoor thermal comfort conditions.

The first research objective investigates how effective typical and adapted building design configurations are in maintaining thermal comfort with natural ventilation in different climates.

Furthermore, due to the climate change and increase in greenhouse gas emissions in the past few decades, projections predict global warming of about 0.2°C per decade for the next two decades in the 21st century (IPCC 2015).

Therefore, the second research objective to be answered is how effective these measures and configurations are in view of climate predictions regarding global warming during the summer months.

This project demonstrates the sensitivity in which the results for thermal comfort react to changes in various parameters (e.g. orientation, natural ventilation, shading, glazing, thermal mass) and investigates the consequences of these changes and their significance in the user's potential satisfaction. The results of this study can provide a knowledge platform for

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engineers, contractors or future researchers and can affect the design criteria for naturally ventilated office buildings in an early stage of design.

1.4 Hypothesis

The international literature demonstrates that thermal comfort in office buildings with natural ventilation can be achieved through design features, reducing or even eliminating the building's energy consumption e.g. required for mechanical cooling. However, the effectiveness of these features could be affected dramatically by the local climate conditions. It is also questionable to what extent these design features will be sufficient in the future, given the predictions of a continuous increase in global temperature.

The hypothesis in this work is that thermal comfort in a virtual cellular office room located in Temperate and Mediterranean climates can be achieved during warm periods thanks to design features and natural ventilation, without the use of mechanical cooling in current climate conditions, but thermal comfort cannot be maintained in future climate conditions based on the current climate projections.

1.5 Methodology

In this work the thermal comfort in naturally ventilated buildings is examined, focusing on office spaces in two cities with different climate characteristics (Vienna, Austria and Athens, Greece). A virtual cellular office room was designed in the thermal simulation software IDA ICE (Indoor Climate and Energy) and thermal comfort was evaluated according to EN 15251 Standard. The office construction configurations have been selected based on the construction characteristics of the typical building patterns in each country.

While investigating the first research objective, simulations were performed on the basic model examining thermal comfort of the occupants in each climate. The simulations were followed by a combination of building configuration scenarios described in EN 15251 and applied to the basic model to investigate their effectiveness in each climate.

Exploring the second research objective, the effectiveness of the configuration scenarios on impending global warming was examined. For this reason, the climate data with the maximum climate deterioration for a short-term (2030) and a long-term (2070) scenario were selected, and dynamic simulations were carried out, observing whether the proposed configurations can provide acceptable levels of thermal comfort in predicted future climate conditions.

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1.6 Background

1.6.1 Indoor climate

There are several parameters that directly or indirectly affect the physical well-being of people indoors and they are defined under the term Indoor Environmental Quality (IEQ). According to United States Green Building Council (USGBC 2002), IEQ encompasses the conditions inside a building -air quality, lighting, thermal conditions, ergonomics- and their effects on occupants or residents. Better indoor environmental quality can enhance the lives of building occupants, increase the resale value of the building, and reduce liability for building owners. Thermal comfort is one of the important factors affecting the quality of the indoor environment and is the main focus of this work.

Ventilation is important for ensuring both a good indoor climate and air quality. In buildings without mechanical ventilation systems, natural ventilation is the only means of meeting indoor air quality needs. Natural ventilation is, however, a difficult process to control and to combine with the achievement of thermal comfort conditions. In Papadopoulos and Avgelis (2016) field studies confirmed the dissatisfaction of occupants regarding the control of thermal comfort conditions using natural ventilation but also demonstrated the role of natural ventilation in reducing CO_2 and particulate matter concentrations.

1.6.2 The concept of thermal comfort

Thermal comfort is defined as the mind's condition in which it expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55 1992). A model for thermal comfort was developed by P.O. Fanger using heat-balance equations and empirical studies about skin temperature to define comfort. Fanger's equations are used to calculate the Predicted Mean Vote (PMV) of a group of subjects for a particular combination of parameters such as air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. Fanger also developed another equation to relate the PMV to the Predicted Percentage of Dissatisfied (PPD). This relation was based on studies that surveyed subjects in a chamber where the indoor conditions could be precisely controlled (Fanger 1970).

ASHRAE Standard 55 uses the PMV model to set the requirements for indoor thermal conditions. It specifies the combinations of indoor thermal environmental factors and personal factors, which will produce thermal environmental conditions acceptable to a majority of the occupants within the space. Specifically, the comfort zone is considered to be sufficiently comfortable if at least 80% of its occupants are expected not to disapprove of their

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ambient condition, meaning that the majority are between -0.5 and 0.5 on the PMV scale (ANSI/ASHRAE Standard 55 2004). The calculation is based on the thermal interaction of the human body with its environment and the human ability of thermoregulation (Figure 1).

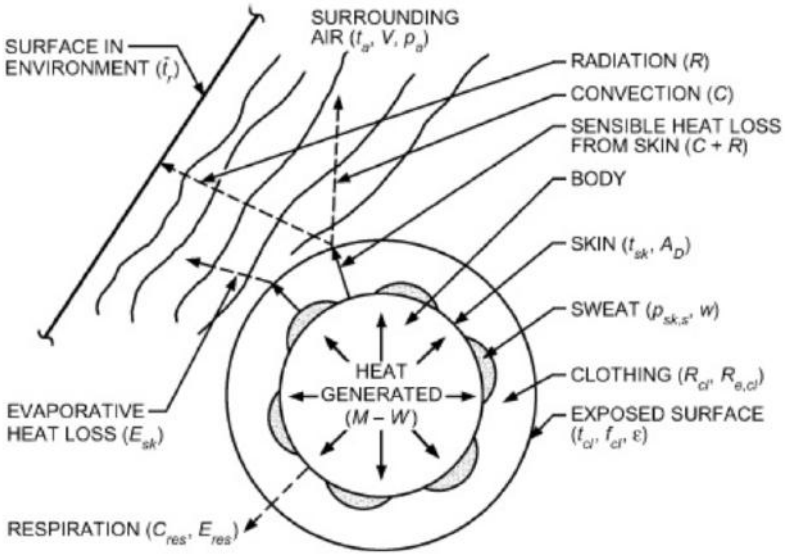

Figure 1. Thermal interaction of the human body and environment (ASHRAE HANDBOOK 2005)

According to the above definition, thermal comfort has a subjective character, in the sense that in a particular space it may occur that one person feels satisfied with the relative thermal conditions, while another feels discomfort. For this reason, a scientific objective assessment of thermal comfort requires the identification of the physical, biological and external parameters that influence it (Table 1).

Table 1. Parameters affecting thermal comfort (ANSI/ASHRAE Standard 55 2004)

1. Environmental factors
Air temperature [^{0}C] - The air contact temperature measured by the dry bulb temperature (DBT)
Average radiant temperature of indoor surfaces [^{0}C] - The temperature of a person's surroundings. This is generally expressed as mean radiant temperature (MRT), which is a weighted average of the temperature of the surfaces surrounding a person and any strong mono-directional radiation, such as the solar radiation.
Relative air humidity [RH] - The ratio between the current amount of vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature, expressed as a percentage
Indoor air velocity [m.s^{-1}] - The air contact velocity
Spatial distribution of the above quantities
2. Personal factors
Clothing - Clothes insulate a person from exchanging heat with the surrounding air and surfaces [clo] (1clo= 0,155 m^2 ^{0}C/W) (ANSI/ASHRAE Standard 55 2004)
Metabolic heat - The heat produced by physical activity. Usually, a person who stays still feels cooler than those who are moving [met] (1 met= 58,20 W.m^{-2}) (ANSI/ASHRAE Standard 55 2004)

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These factors, and primarily physical factors, affect the flow of energy in the form of heat from humans to the environment and vice versa. The human body has mechanisms (metabolism and perspiration) through which a constant thermal state of the body is maintained and adapted to the conditions of the environment (Avgelis and Papadopoulos 2004).

1.6.3 Comfort indices

The response to a hot or cold environment depends mainly on the combined effect of the factors mentioned in Table 1. Understanding how the various parameters affect thermal comfort has been used to formulate thermal indices and thermal scales, which indicate the effects of combinations of the various comfort factors.

It is a fact that thermal comfort cannot be defined by temperature alone, as has been widely misinterpreted by many building occupants. This misinterpretation often leads to overuse of heating and cooling systems, which, on the one hand, may temporarily improve indoor air temperature levels, but at the same time may lead to a reduction in IAQ (e.g. increase of CO_2 levels) and more often to increased energy consumption. When operating an air conditioning unit in a working place, it is very common that some people feel comfortable whereas others may be in discomfort.

Fanger introduced two thermal comfort indicators, to allow to predict the thermal comfort of an indoor climate.

PMV

The PMV (Predicted Mean Vote) is an index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale, as described in Table 2.

Table 2. Thermal sensation scale of PMV (ANSI/ASHRAE Standard 55 2004)

PMV Scale	Thermal sensation
+ 3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

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The PMV is calculated from Fanger's comfort equation, which is based on the heat balance of the human body and a statistical analysis of experiment results in special climate-controlled chambers (skin temperature and sweating rate values expressed as functions of the metabolic rate).

A PMV equal to zero represents thermal neutrality and the comfort zone is defined by possible combinations of the six parameters mentioned above, for which the PMV is within the recommended limits of -0.5 < PMV < +0.5 (ANSI/ASHRAE Standard 55 2004).

PPD

In addition to the PMV index, Fanger also created the PPD (Predicted percentage dissatisfied) index that expresses the predicted percentage of unsatisfied individuals in specific thermal conditions. The PPD index depends on the value of the PMV index and decreases as PMV tends to 0, i.e. thermal neutrality, but never reaches below 5%, as it is impossible to fully satisfy a large number of people in the same thermal environment. The relationship between the two indices is shown in Figure 2.

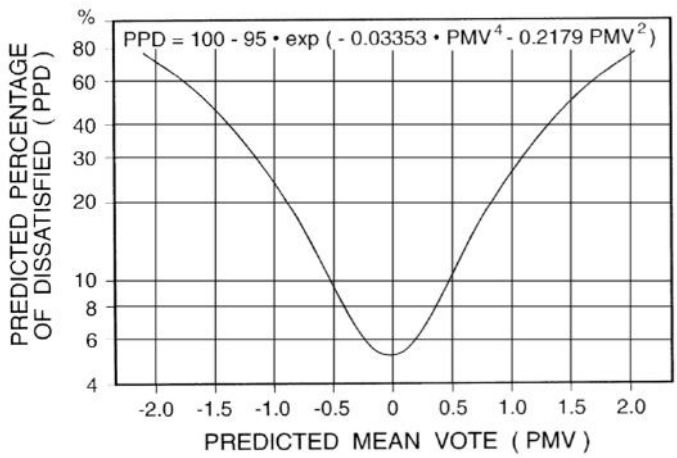

Figure 2. PPD as a function of PMV (ANSI/ASHRAE Standard 55 2004)

1.6.4 Adaptive thermal comfort model

The adaptive approach is based on the idea that outdoor climate influences indoor comfort because humans can adapt to different temperatures during different times of the year. In ANSI/ASHRAE Standard 55 (2004) the adaptive model is described as “a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters”. In naturally ventilated buildings, the preferred thermal sensation of occupants is not a fixed neutral temperature but varies depending on one side on indoor and outdoor temperature and on the other side on the degree of personal control, expectation, and adaptation possibilities.

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Adaptive models of thermal comfort are also implemented in other standards such as the ISO 7730 and the European EN 15251 Standard. The exact derivation methods and results are slightly different from the ASHRAE 55 adaptive standard, but they are based on the same principles and share many common features. A main difference lies in the application of the directive, as the ASHRAE 55 adaptive standard only applies to buildings without mechanical cooling installed, whereas EN 15251 can be applied also to mixed-mode buildings (CEN Standard EN 15251 2007).

Also, in the EN 15251 Standard unlike ISO 7730:2005 and ASHRAE 55-2004, criteria related to local thermal discomfort such as airflow, radiant temperature asymmetry, vertical temperature difference and floor surface temperature are not included. In all three models (ASHRAE 55-2004, ISO 7730:2005 and EN 15251) the operative temperatures are plotted against comfort limits based on the outdoor mean temperature but calculated according to different equations. In addition, the three models differ in terms of categorization, allowance for excess hours and requirements for building controls.

1.6.5 Adaptive thermal comfort model according to DIN EN 15251: 2007-08

The CEN Standard EN 15251 specifies how design criteria can be established and used for the dimensioning of systems, it defines how to use the input parameters for building energy calculations and finally identifies parameters to be used for monitoring and displaying the indoor environment as recommended in the EPBD. The occupants have access to operable windows, and they are free to adjust clothing insulation (Halawa and van Hoof 2012).

According to EN 15251 (2007) “adaptation is the physiological, psychological or behavioural adjustment of building occupants to the interior thermal environment in order to avoid discomfort. In naturally ventilated buildings these are often in response to changes in indoor environment induced by outside weather conditions”.

The EN 15251 standard introduces an adaptive thermal comfort evaluation method based on operative indoor temperatures and using a classification into four categories as they are described in Table 3. The operative temperature or sensation temperature is a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and air speed. In EN 15251 (2007) as optimal operative temperature is described the operative temperature where a maximum number of the occupants can be expected to feel the indoor temperature acceptable. As recommended in EN 15251 for the evaluation of thermal comfort, a maximum of 5% overheating hours is permitted for each category.

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Table 3. Description of the applicability of the categories used in EN15251 (2007)

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside of the previous categories. This category should only be accepted for a limited part of the year

The EN 15251 standard divides buildings into two categories, those with mechanical cooling-ventilation systems and those without.

For buildings without mechanical cooling systems, the criteria are differentiated due to the different expectations of individuals and the phenomenon of adaptation. The criteria do not relate to the sizing of mechanical systems, since they do not exist, but to the design of the buildings (orientation, sun protection, insulation, natural ventilation, etc.) in order to avoid overheating of the interior spaces. In EN 15251, the operating temperature levels are related to the weekly running average outdoor air temperature, unlike ASHRAE 55-2004, which uses the monthly running average outdoor air temperature. This variation is due to the fact that people seem to determine their behavior (clothing choice and adaptation) based more on the previous and consecutive day's temperature than on the average monthly temperature.

In Figure 3 acceptable summer indoor temperatures (cooling season) are presented for buildings without mechanical cooling systems. The operative temperatures (room temperatures) presented in this figure are valid for office buildings, where there is easy access to operable windows and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions (EN 15251 2007). The temperature limits apply only when the thermal conditions in the rooms in question are mainly controlled by the occupants through the opening and closing of windows.

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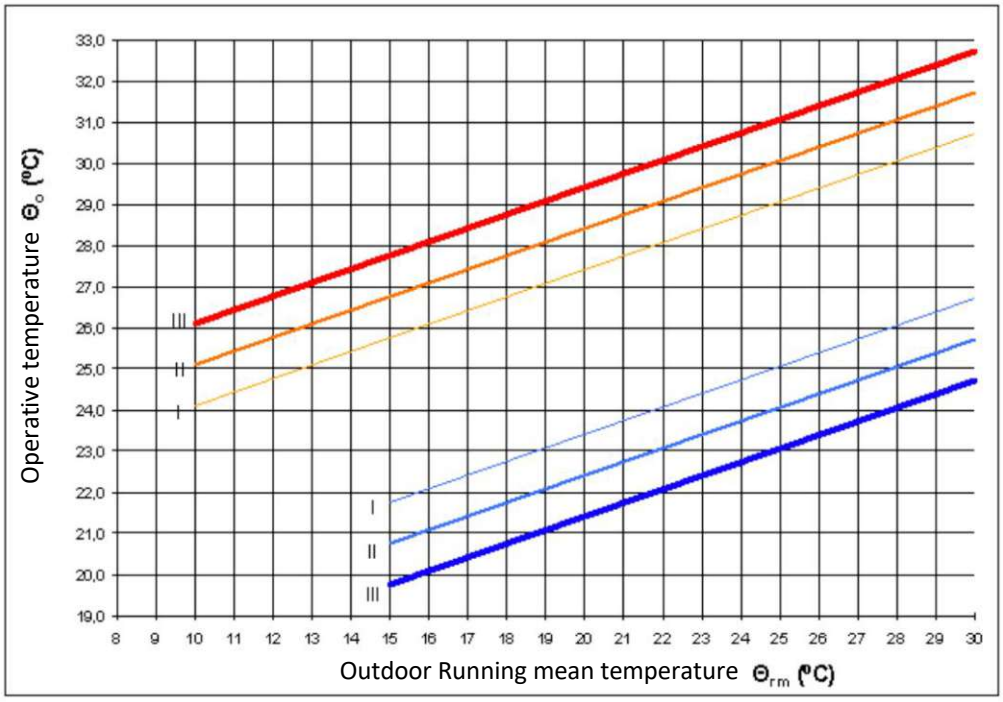

Figure 3. Acceptable indoor temperatures for design of natural ventilation buildings
Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature (CEN Standard EN 15251 2007)

As illustrated in Figure 3, this standard includes three categories of temperature limits for use. These three categories correspond to the categorisation described in Table 3. Category IV exceeds the thermal comfort limits. The allowable indoor operative temperatures in Figure 3 are plotted against the outdoor running mean temperature Θ_{rm}. This is defined as the exponentially weighted running average of the daily outdoor temperature (EN 15251 2007).

The exponentially weighted running mean of the daily mean external air temperature Θ_{ed} is such a series, and is calculated from the following formula, as described in EN 15251 (2007):

$\Theta_{rm} = (1-\alpha) \cdot \{\Theta_{ed-1} + \alpha\Theta_{ed-2} + \alpha^2\Theta_{ed-3}.....\}$ This equation can be simplified to

$\Theta_{rm} = (1-\alpha)\Theta_{ed-1} + \alpha . \Theta_{rm-1}$

Where:

Θ_{rm} = Running mean temperature for today.

Θ_{rm-1} = Running mean temperature for previous day.

Θ_{ed-1} is the daily mean external temperature for the previous day.

Θ_{ed-2} is the daily mean external temperature for the day before and so on.

α is a constant between 0 and 1. Recommended to use 0.8.

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The equations representing the lines in Figure 4 are (EN 15251 2007):

Category I	upper limit:	$\Theta_{i\,max} = 0.33\ \Theta_{rm} + 18.8 + 2$
	lower limit:	$\Theta_{i\,min} = 0.33\ \Theta_{rm} + 18.8 - 2$
Category II	upper limit:	$\Theta_{i\,max} = 0.33\ \Theta_{rm} + 18.8 + 3$
	lower limit:	$\Theta_{i\,min} = 0.33\ \Theta_{rm} + 18.8 - 3$
Category III	upper limit:	$\Theta_{i\,max} = 0.33\ \Theta_{rm} + 18.8 + 4$
	lower limit:	$\Theta_{i\,min} = 0.33\ \Theta_{rm} + 18.8 - 4$

where:

Θ_i = limit value of indoor operative temperature, °C

Θ_{rm} = running mean outdoor temperature. These limits apply when $10 < \Theta_{rm} < 30$ °C for upper limit and $15 < \Theta_{rm} < 30$ °C for lower limit.

According to EN 15251 (2007), the temperature limits shown in Figure 4 should be used for the sizing of passive means to avoid overheating in summer conditions, e.g. the dimensions and orientation of windows, the dimensions of sun protection and the thermal capacity of the building structure. Where the adaptive temperature limits shown in Figure 3 cannot be ensured by passive means, mechanical cooling should be used.

In this work, the thermal comfort is simulated and evaluated according to EN 15251 (2007), taking into account that no mechanical systems are used, but only design parameters, as suggested by the standard, while the level of clothing and metabolism of the users is determined.

1.6.6 Indoor air temperature

A decisive parameter, concerning the indoor environment of the building, is the indoor air temperature. The indoor air temperature affects the thermal comfort in many ways and is, in combination with other factors, the key to energy balance, sensation of the thermal environment, comfort, discomfort and the perception of indoor air quality.

The parameters affecting air temperature inside buildings (Table 4) which are naturally ventilated can be grouped into two categories: the external factors and the building design and occupants' behaviour. The problem in examining air temperature as a parameter of thermal comfort lies in the fact that there is no single value of temperature that is the optimal choice, but a range of values determined by many parameters.

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Table 4. Parameters affecting the air temperature inside a natural ventilated building
Self-created according to Avgelis and Papadopoulos (2004)

1. External factors
The climate conditions
2. Building design and occupants' behaviour
The orientation of the building
The construction materials and thermal insulation materials of the building
The design of a naturally ventilated building
The number and type of electrical appliances, machinery or office equipment present in the building that generate heat (e.g. computer monitors)
The way the building and the ventilation are operated by the building occupants

In addition to the parameters in Table 4, the way in which indoor air temperature affects the human body and the energy exchange functions, in the form of heat, with the environment should be considered. In particular, an increase in air temperature leads to a decrease in conduction and radiative heat losses, while perspiration increases heat losses. Besides, air temperature affects the average skin temperature, which is a physical quantity to be taken into account in order to obtain a better assessment of thermal comfort. The findings of Höppe's investigations (Höppe 1988), carried out using the mathematical model M.E.M.I. (Munich Energy Balance Model for Individuals), show that the average skin temperature depends on the air temperature.

1.6.7 Case studies in literature related to thermal comfort

Many studies have been done in the field of thermal comfort and how it can be affected by the building design and climate change.

In Alexandre et al. (2011) the EN 15251 Standard was used for the evaluation of national comfort requirements for an office building case study in Porto, Portugal. It was found that improvement of comfort category increases the energy demand of the building.

In Lan et al. (2012) the effects of indoor air temperature on human performance through the selection of different categories of indoor environment, as prescribed by the EN 15251, are discussed. The results show that the lower category of thermal environment causes reduced performance of office work and potential increase of the energy demand in mixed-mode buildings.

In Fabbri and Tronchin (2011) the relationship between IEQ index and indoor air temperature trend in moderate thermal environments, in low-energy demand buildings with reference to

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EPBD, is investigated. The case study is located in Ravenna, Italy. The results show that buildings of Category I, according to EN 15251 could achieve a high level of thermal comfort.

In Baranova et al. (2017) the IDA ICE software was used for dynamic simulation of a two-storey building situated in Baltic Sea. The results show that in case of natural ventilation a satisfying level of thermal comfort can be achieved opening windows in summer from 8 am till 6 pm. This type of ventilation has also a good impact on the room oriented to the north.

In Roetzel et al. (2014) the impact of building design and occupancy on office comfort and energy performance in the climates of Hamburg and Athens is examined. It was found that building design has a significant influence on adaptive thermal comfort in offices. Moreover, the results show that the maximum comfort values could be achieved if occupants a) operate windows during the day and leave them open during night, b) actively operate blinds, c) actively operate artificial lighting and d) operate office equipment in a low power consumption.

In Rijal et al. (2007) the implementation of the "Humphreys adaptive algorithm", which was created for the prediction of human behaviour for windows opening, in a simulated office, concludes that improved building design leads to improved comfort, reduced adaptive behavioural use of windows and a reduction in annual energy demand.

In Kuczyński et al. (2021) the effectiveness of night ventilation, external blinds and thermal mass on the summer thermal performance of a building in a temperate climate was examined. It was found that increasing the thermal mass was very effective in reducing the maximum temperatures during the day, while activating the night ventilation effectively reduced the temperature during the night hours. Closing the external blinds was more effective during the daytime.

Finally, in Hopfe et al. (2009) the impact of future climate scenarios on decision making in building performance simulation was investigated. The research shows the chosen climate scenarios affect the uncertainty of the simulation outcomes as well as the choices at the design decision making.

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2 METHOD

2.1 Overview

This chapter describes the method applied to achieve the objectives of this thesis. In this work the thermal comfort in naturally ventilated buildings is examined, focusing on office spaces. Two cities with different climate characteristics (Athens, Greece and Vienna, Austria) have been selected for this research.

The investigations are based on a parametric study for a typical cellular office room, using the thermal simulation software IDA ICE (Indoor Climate and Energy). Thermal comfort is evaluated according to EN 15251. For a more realistic approach, the construction layers of the office shell have been selected based on the typical construction characteristics of the building patterns in each country.

Thermal simulations are first performed on the basic model, assuming that no previous design intervention has been made that could improve the thermal comfort of the occupants. Then alternative scenarios with a combination of parameters described in EN 15251 are applied and their effectiveness in each climate is observed.

In a subsequent step the effectiveness of these scenarios on impending global warming is examined. For this reason, the climate data with the maximum climate deterioration for a short-term (2030) and a long-term (2070) scenario were selected, and dynamic simulations were carried out, observing whether the proposed configurations can provide acceptable levels of thermal comfort in predicted future climate conditions.

The following sections describe the climate data of the two cities selected for the case study. The methodology and the thermal simulation software used are then explained, and the office design and equipment as well as the environmental and personal factors taken into account as parameters for the simulations are described.

2.2 Location and climate classification

2.2.1 Locations' selection

For the purpose of this work, the two European cities, Vienna (Austria) located in central Europe and Athens (Greece) in south Europe were selected to carry out the thermal comfort evaluations according to the European EN 15251 Standard (2007). The reason why these areas were chosen for the evaluation is their different climate characteristics.

Additionally, in Greece, the Greek building regulation refers to the EN 15251 (2007) for the evaluation of thermal comfort. As mentioned earlier, this standard introduces an adaptive

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thermal comfort model for buildings with natural ventilation and a static model for buildings with mechanical ventilation. An initial study for more northern climates (Hamburg, Germany) as well as similar studies in Vienna, Austria showed that the requirements following this model are partially met even in a moderate climate for south-facing spaces (Roetzel 2009). This current study investigates, therefore, whether naturally ventilated offices in the temperate climate of Vienna, Austria, as well as in the more southern region of Athens, Greece, with hot and dry climate can meet the requirements according to the adaptive thermal model EN 15251 (2007).

2.2.2 Climate classification

The climate classification in this work is based on the Köppen Climate Classification System (Figure 4). The system divides climates into five main climate groups, with each group being divided based on seasonal precipitation and temperature patterns. These groups are represented by capital letters A, B, C, D and E, all of which, except for B, are defined by temperature criteria.

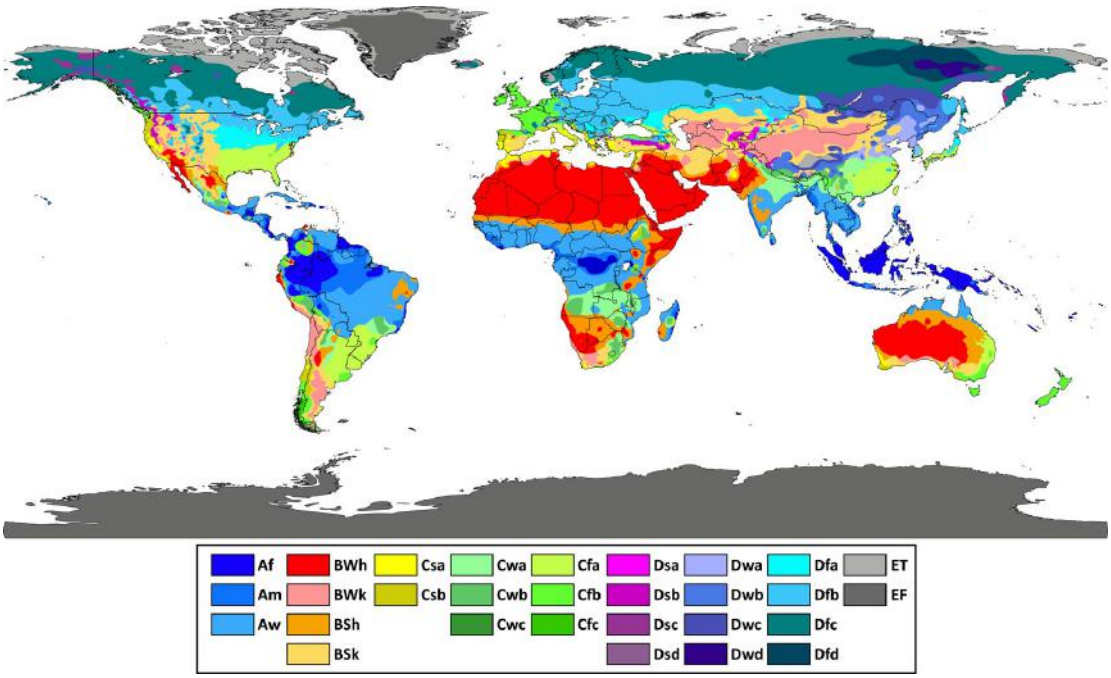

Figure 4. The Köppen Climate Classification System, (Peel et al. 2007)

The city of Vienna has a temperate oceanic climate (Cfb), which means that it is moderately continental, with cold winters and warm summers. The average day temperatures from May to October range from approximately 10.9°C minimum to 21.6°C maximum. Vienna has a significant amount of rainfall during the year, even for the driest month. The city is located near the 48th parallel north.

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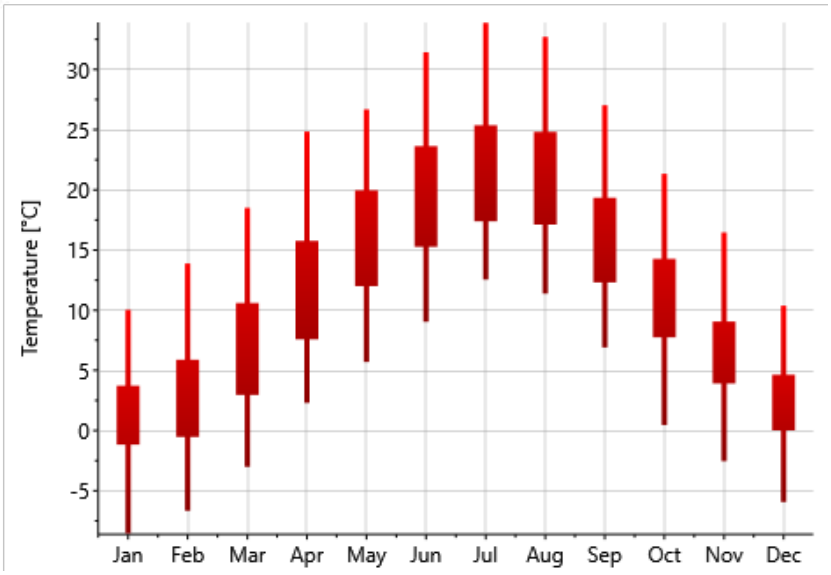

Figure 5. Average monthly temperatures for Vienna, (Meteonorm 8 2020)

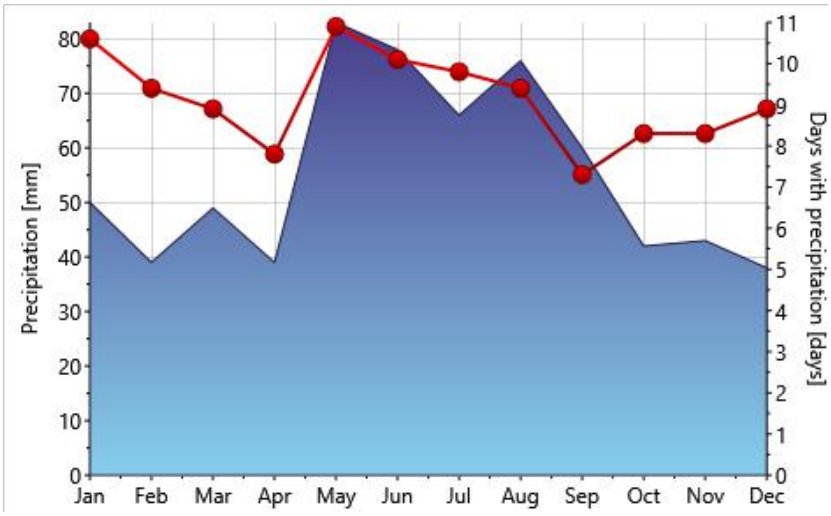

Figure 6. Average monthly precipitation for Vienna, (Meteonorm 8 2020)

According to the updated map of world climates (Peel et al. 2007), the climate in Athens can be categorized as Csa, which means Mediterranean climate with hot and dry summers. The main characteristics of the Athens climate vary with season. During winter, the main parameters are sunshine duration, cloudiness, relative humidity, daily temperature range and wind speed. During summer, the typical parameters are cloudiness, humidity, evaporation and wind speed and the daily temperature range (Bartzokas and Metaxas 1995).

The average day temperatures from May to October range from approximately 19.7°C minimum to 28.8°C maximum. The city is located near the 38th parallel north.

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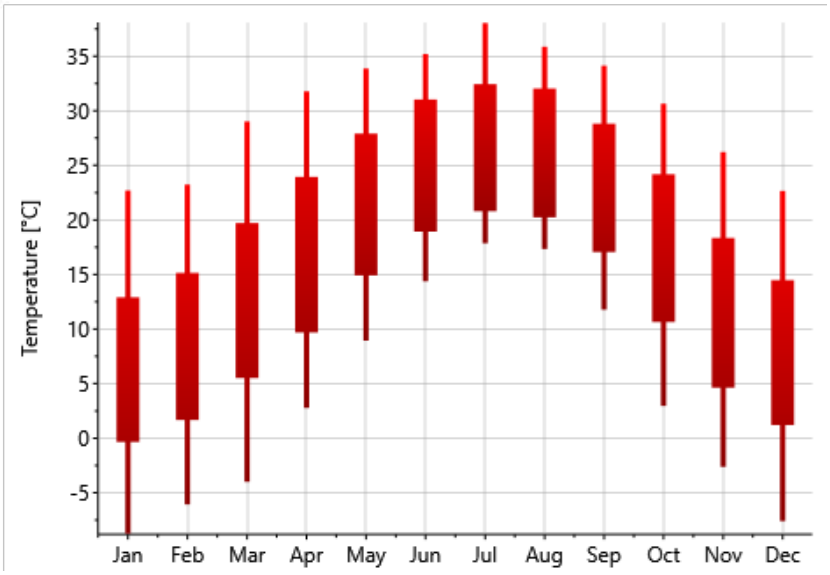

Figure 7. Average monthly temperatures for Athens, (Meteonorm 8 2020)

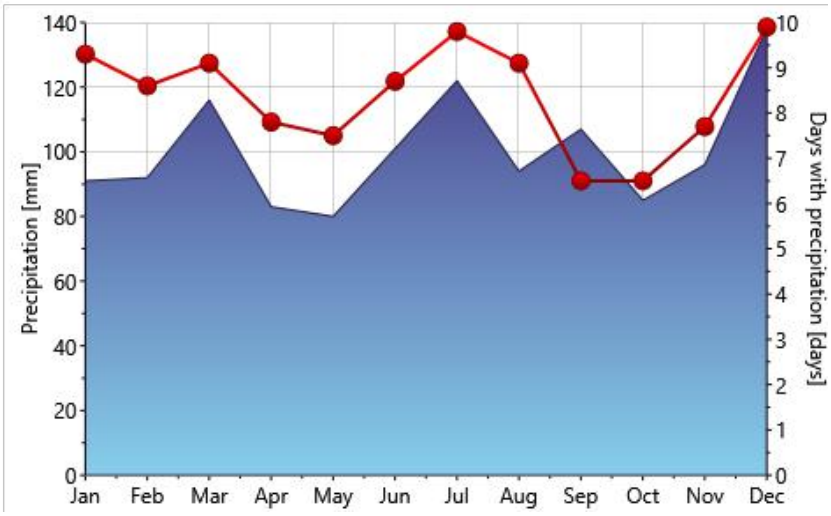

Figure 8. Average monthly precipitation for Athens, (Meteonorm 8 2020)

2.3 Climate data

All the climate datasets used for this work were obtained from the climate data base of the software Meteonorm 8 (2020). The calculations are based on hourly climate data. The climate data for the test reference year 2020 are based on multi-year measurements. The datasets used are accordingly based on long-term averages.

For Vienna the climate data was retrieved from the weather station Hohe Warte located approximately 6 km northwest of Vienna's city center (Station details: Vienna-Hohe Warte, 48.25 Latitude [°N], 16.367 Longitude [°E], 209 Altitude [m a.s.l.]) and for Athens simulations the climate data collected from the regional weather station situated in Hellenikon (Station details: Athinai/Hellenkion, 37.9 Latitude [°N], 23.733 Longitude [°E], 15 Altitude [m a.s.l.]) was used.

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Anthropogenic greenhouse gas (GHG) emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy (IPCC 2015). Due to the increase in GHG emissions in the past few decades, projections by the IPCC (2007) predict global warming of about 0.2°C per decade for the next two decades in the 21st century. This work investigates the effectiveness of the proposed design parameters in terms of thermal comfort in naturally ventilated offices, considering a contemporary as well as a short- and a long-term climate scenario for the years 2030 and 2070 respectively.

The calculations with future climate data for 2030 and 2070 were based on the scenario datasets of the 2014 IPCC report "AR5". The Representative Concentration Pathways (RCPs), which are used for making projections based on these factors, describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use (IPCC 2015). The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5). In this work, the RCP8.5 scenario was selected for 2030 and 2070 respectively, representing the highest GHG emissions.

A set of future forecast weather data including the RCP8.5 scenario for Vienna and Athens was extracted from Meteonorm 8 and was applied for the simulation. Table 5 provides an overview of the changes of the selected climate scenarios and in Figure 9 the mean annual air temperature increase for the years 2020, 2030 (RCP8.5) and 2070 (RCP8.5) for both cities is compared.

Table 5. Mean annual values for the Vienna and Athens climate (Meteonorm 8 2020)

Vienna Wien - Hohe Warte	Air Temperature [°C]	Relative Humidity [%]	Irradiation of global radiation horizontal [kWh.m^{-2},a^{-1}]	Irradiation of diffuse radiation horizontal [kWh.m^{-2}.a^{-1}]
2020	11.4	69.2%	1196	602
2030 RCP8.5	12.4	69.6%	1229	596
2070 RCP8.5	15.0	69.9%	1258	595
Athens **Athinai - Hellenkion**				
2020	18.8	58.9%	1723	649
2030 RCP8.5	19.7	59.3%	1732	646
2070 RCP8.5	22.1	59.4%	1755	651

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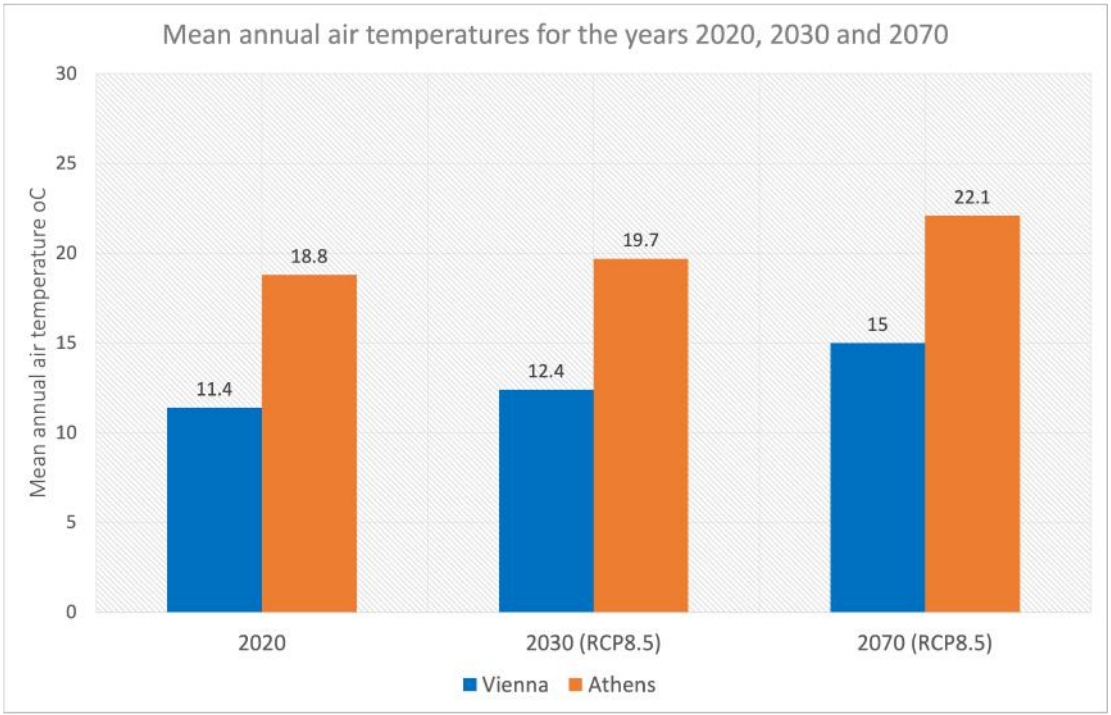

Figure 9. Mean annual air temperature for 2020, 2030 and 2070 in Vienna and Athens

Climate change is expected to initially affect areas with a hot and dry climate, such as Athens, which is expected to cause a deterioration of thermal comfort conditions in buildings. Researches of Founda and Giannakopoulos (2009) and Founda (2011) shows that hot periods and heat waves, which are characteristic of the Greek climate, are becoming more intense and longer in duration. However, it is indicated that people have the ability to acclimatize to heat waves and especially in offices, short-term adaptations to hot spells may be able to influence thermal perception and preference.

Another climate phenomenon that affects comfort and energy efficiency in offices is the "urban heat island" (UHI) effect. As described in Aleksandrowicz et al. (2017), the UHI effect describes the tendency of urban areas to experience higher outdoor air temperature levels (up to 12 K higher) compared to the neighboring rural region. In Makropoulou and Gospodini (2016) is mentioned that the unique microclimate of an urban area is mainly determined by the complex built environment, human activities and the lack of cooling planted surfaces. Particularly in urban neighborhoods in Greece, the microclimate is mainly influenced by parameters such as topography, urban morphology, soil structure and paved surfaces.

Therefore, future thermal comfort evaluation should consider the increasing temperatures and heat waves due to climate change as well as the UHI effect. As demonstrated by Aleksandrowicz et al. (2017), UHI mitigation strategies are attracting increasing interest from scientists worldwide, reflecting concerns about the impacts of increased global urbanization trends and global warming challenges. Furthermore, the use of natural ventilation and

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improvement of the building design configurations could contribute to the increase of thermal comfort in offices and reduction of energy consumption and CO_2 emissions.

2.4 Case scenarios and design strategies

In this work, the effectiveness of certain parameters is investigated, followed by an analysis below, concerning a typical cellular office room with natural ventilation in the climate of Vienna, Austria and Athens, Greece, in terms of thermal comfort. The study was carried out with the thermal simulation software IDA ICE (Indoor Climate and Energy).

IDA ICE is a building energy simulation tool, which can predict and analyse the energy performance of buildings. IDA ICE creates a mathematical model where simultaneous dynamic simulation of airflow and heat transfer is provided. Thus, thermal comfort is predicted based on the equations of ISO 7730 as well as EN 15251.

2.4.1 Case studies and configuration scenarios

In the first part of this work a virtual cellular office building is used, whose shape derives from a preliminary design study of an actual office project in Vienna. First, a 3D model of the whole building was built in the IDA ICE and four office spaces were added on the top floor, each of them corresponding to a thermal zone (see Figure 10). Each zone faces a different orientation. Later in this chapter, thermal comfort is also considered for future climate scenarios. Fagan (2008) states that global warming is projected to lead to prolonged warm periods.

For the natural ventilation of a building the critical time of the year is the hot period. In this research the indoor climate conditions were examined during an extended summer period, which was defined for the purpose of this work from 01 May to 31 October. For the needs of the simulation, fixed parameters as well as variable parameters were defined and the effectiveness of the variable parameters in optimizing thermal comfort was analyzed.

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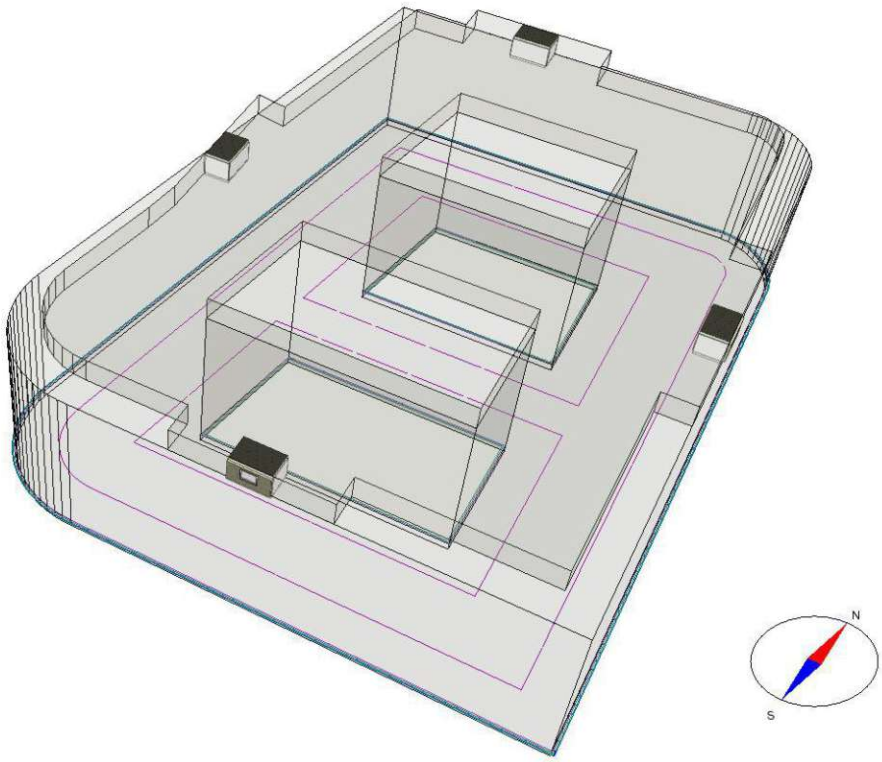

Figure 10. 3D model of the office building envelope, created in IDA ICE

The same fixed parameters were applied both for the case study in Vienna and Athens. The differentiation between the two models lies in the construction materials of the individual elements and their thermal mass, trying to approximate as closely as possible the typical construction methods in both countries. Specifically, in the Vienna case study a precast external reinforced concrete wall with external insulation was applied and in the case study of Athens a cavity wall was implemented. A cavity wall is a type of wall that has a hollow center. Masonry is considered to be applied to the outer layers and the cavity is filled with insulation. Each office room construction is described in detail in chapter 2.5.3 Office room geometry.

The configuration scenarios were subsequently defined based on the EN 15251 Standard (2007) recommendations. For the case of Vienna, night ventilation was chosen as the initial configuration scenario followed by the scenario of installing external blinds. In each case a simulation was carried out during the cooling period defined above and the climate data for 2020 was applied. Finally, the hours each thermal zone was in Category IV i.e., in an unacceptable thermal comfort state, were recorded.

The same procedure was adopted for the case study of Athens. Due to the different type of typical construction and more specifically the less energy-efficient windows in Athens, a third configuration scenario was chosen, applying the same window with improved thermal

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characteristics as in the case study of Vienna. Finally, as a fourth configuration scenario, it was decided to modify the thermal mass of the exterior brick wall to prefabricated concrete wall with external insulation, as applied in the Vienna case study. The four scenarios with combination of configurations and their application to each case study can be summarized as follows:

- Configuration scenario variation 1 – Night ventilation (applied in Vienna and Athens)
- Configuration scenario variation 2 – Night ventilation and shading - shading control (applied in Vienna and Athens)
- Configuration scenario variation 3 – Night ventilation, shading - shading control and energy efficient glazing (applied in Athens)
- Configuration scenario variation 4 – Night ventilation, shading - shading control, energy efficient glazing and thermal mass - exterior insulation (applied in Athens)

The fixed as well as the variation parameters applied for the design of the office model in IDA ICE are presented in detail in this chapter.

2.4.2 Thermal comfort in future climate data projections

At the second part of this work the simulations were focused on the future climate data projections. The same simulations that were run for the climate data of the year 2020, were performed again applying the climate data with the highest greenhouse gas emissions RCP8.5 scenarios of 2030 and 2070. For each scenario the climate data was extracted from the software “Meteronorm 8”. The effects of climate in the case studies of Vienna and Athens were investigated and analyzed. The outcomes of the simulations were summarized, and the results of the analysis are presented in Chapter 3.

2.4.3 Office room geometry

The investigated room is a typical cellular office room located in a virtual office building. It is assumed to have one façade, equipped with a central window 2.10m wide and 1.60m high, positioned 0.90m from the floor. The room is assumed to be surrounded by rooms with similar temperature, therefore the interior walls are described in the software as adiabatic. The area of the windows is about 23% of the area of the façade, which is considered sufficient for proper illumination of the room with daylight. According to EN 15251 (2007) windows which are too small may be a problem (not enough daylight, impaired well-being, etc) and, on the other hand, windows that are unprotected and are too big can also be a problem in terms of overheating. Also, field studies (Galasiu and Veitch 2006) conclude that occupants tend to

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prefer horizontal windows compared to vertical openings and would accept a minimum window area of 20%-30% as satisfactory.

The room width is 5.40m, the depth 3.50m and the height 2.70m, as illustrated in Figure 11. These dimensions are identical with the reference office for simulation of lighting and energy as developed in IEA task 27 and 31 (van Dijk 2001). The dimensions also correlate with ergonomic guidelines in Europe to provide 8-10/10 m^2 of office space per person (Roetzel et al. 2014).

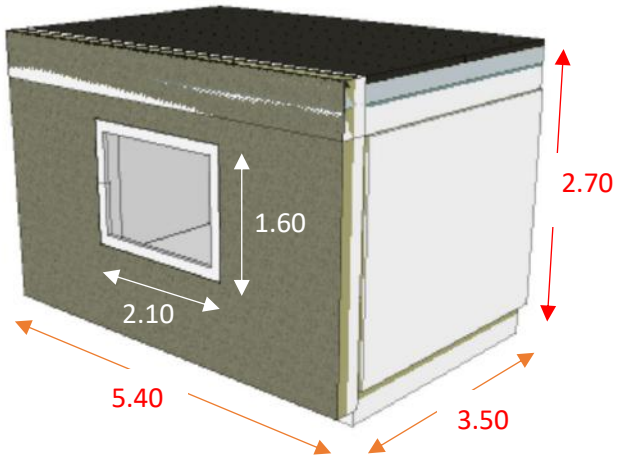

Figure 11. Office room geometry, created in IDA ICE

The simulated office in this work investigates all orientations, with the room facing the south (thermal zone 1), the west (thermal zone 2), the north (thermal zone 3) and the east (thermal zone 4), as shown in Figure 12. The effect of the orientation in accordance with the configuration parameters on the thermal comfort of the space is investigated and the results are analysed in Chapter3.

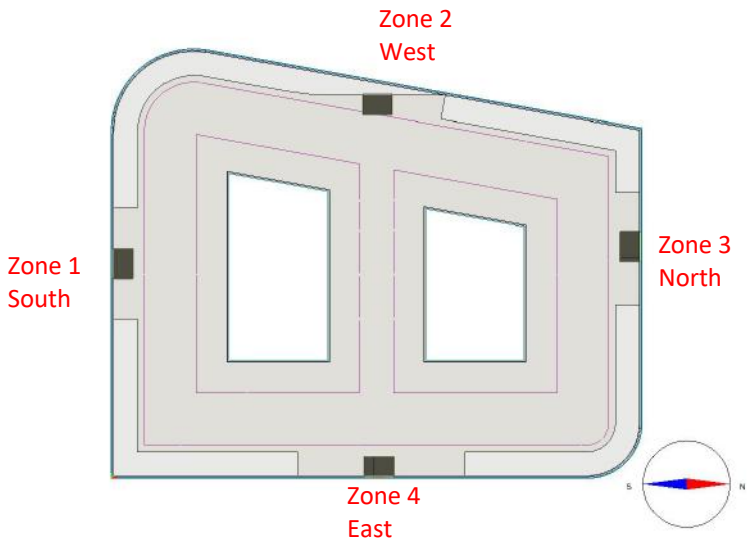

Figure 12. Floor plan illustrating the 4 office rooms, created in IDA ICE

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2.4.4 Envelope construction and thermal mass

During the construction of a building, the main stakeholders (most of whom are the owners - investors of the property) mainly influence the design of the building taking into account the material costs. Based on this assumption, the choice of the criteria for the materials selection for the envelope construction in this work is based on the current real estate market and standard technologies in Vienna and Athens.

The wall construction for the case study of Vienna from inside to outside is: 'external wall' precast external reinforced concrete wall (18 cm), expanded polystyrene insulation foam (16 cm) with thermal conductivity 0.032 $W.m^{-1}.K^{-1}$ and plaster (0.5 cm). The heat transfer coefficient calculated of IDA ICE to be 0.1905 $W.m^{-2}.K^{-1}$. The wall specification is described in Figure 13. The roof construction from outside to inside is: Gravel (8 cm), separating layer (0.5 cm), extruded polystyrene (19 cm), sealing (1.5 cm), screed (3 cm) and concrete (28 cm). The heat transfer coefficient for the roof is 0.1763 $W.m^{-2}.K^{-1}$. The roof specification can be seen in Figure 14.

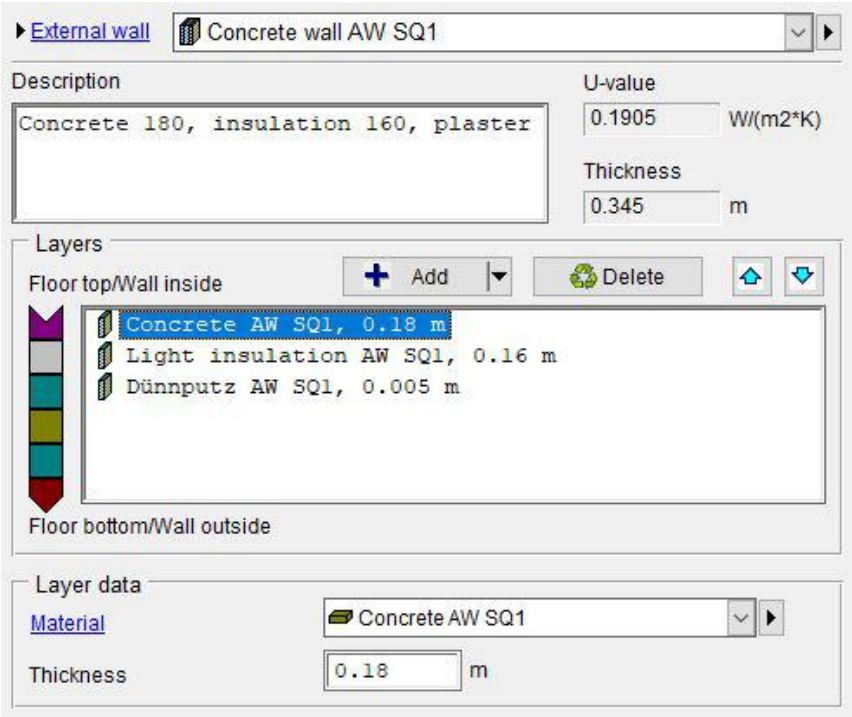

Figure 13. Wall construction specification - Vienna, created in IDA ICE

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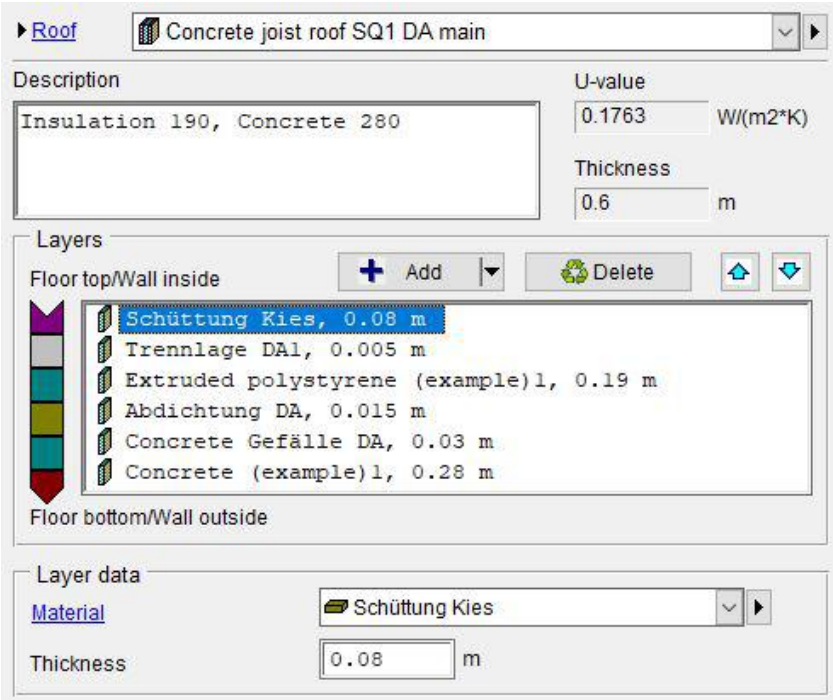

Figure 14. Roof construction specification - Vienna, created in IDA ICE

For the case of Athens, a cavity wall is a typical wall construction type. The wall construction from inside to outside is: plaster (2 cm), brick (9 cm), expanded polystyrene insulation foam (5 cm), brick (9 cm) and plaster (2 cm). The heat transfer coefficient calculated of IDA ICE to be 0.521 $W.m^{-2}.K^{-1}$. The wall specification is described in Figure 15. In Figure 16 is illustrated a typical cavity wall in Athens (Roetzel 2009).

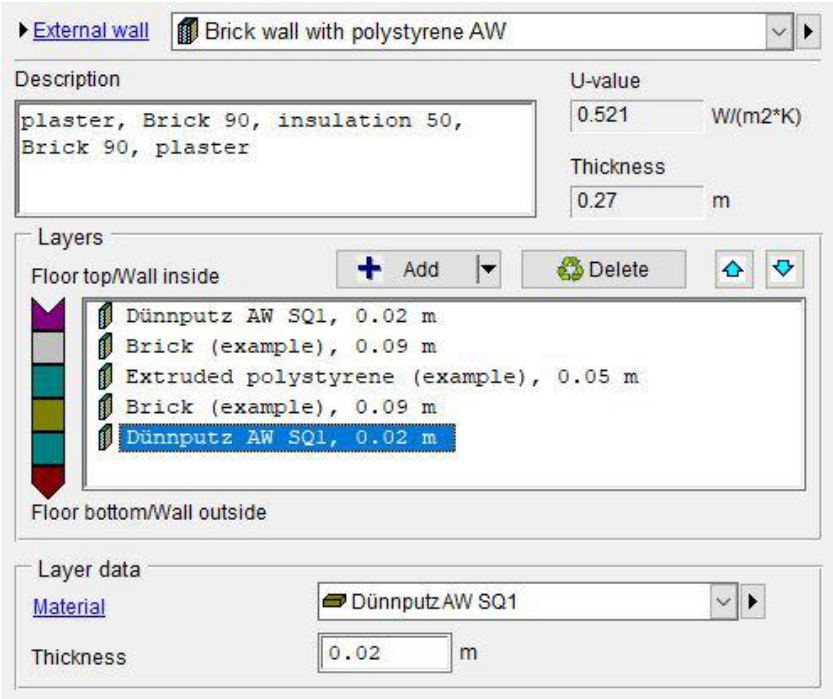

Figure 15. Wall construction specification - Athens, created in IDA ICE

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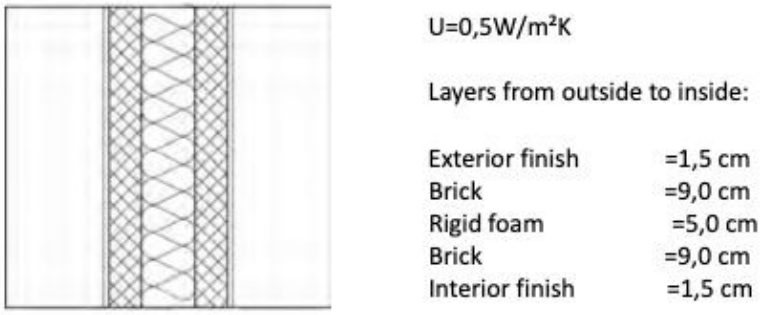

Figure 16. Example of an exterior cavity wall in Athens, (Roetzel, 2009)

The roof construction from outside to inside is: ceramic tiles (2 cm), concrete (3 cm), separating layer (0.5 cm), extruded polystyrene (6 cm), sealing (1.5 cm), screed (3 cm) and concrete (25 cm). The heat transfer coefficient for the roof is 0.4626 $W.m^{-2}.K^{-1}$. The roof specification can be seen in Figure 17.

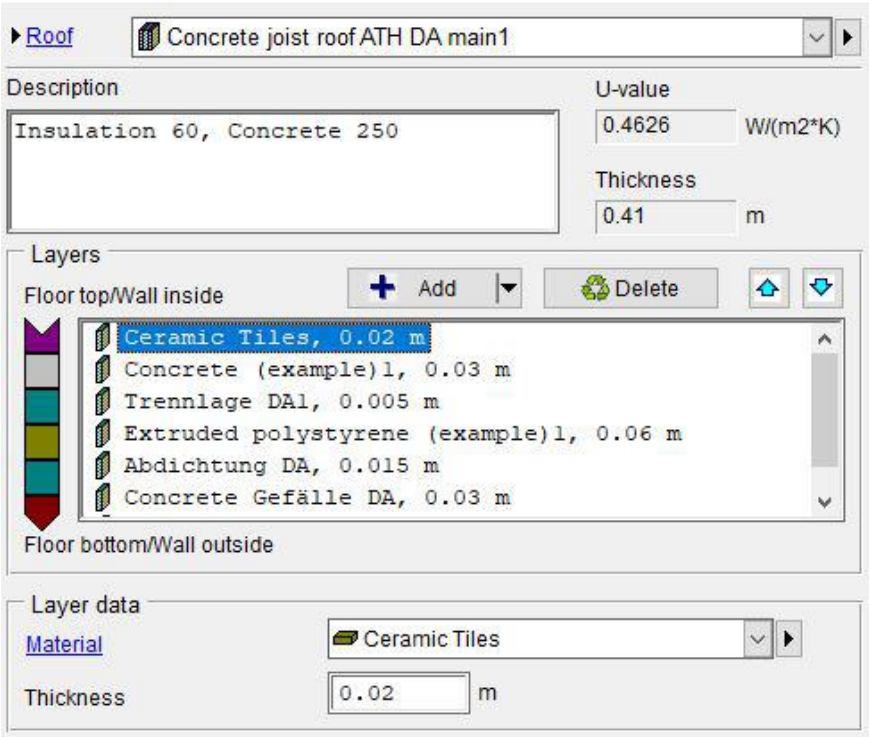

Figure 17. Roof construction specification - Athens, created in IDA ICE

The internal walls are considered as gypsum walls and the floor as concrete floor with screed. As already mentioned, both internal walls and the floor are applied to the software as adiabatic.

2.4.5 Building occupancy

The investigated office is assumed to be occupied by two persons. For the purposes of this study, an occupancy schedule from 08 am to 05 pm for the weekdays was applied. According to EN 15251, the recommended clothing level for summer (clo-value) and activity level (met-

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value) for a single office (cellular office) is 0.5 CLO and 1.2 MET respectively (EN 15251 2007). For the purpose of the simulations, it was assumed that users are dressed in light clothing and are seated, so an activity level of 1.2 MET and a clothing level of 0.7 CLO was applied, which can be automatically adapted ± 0.25 between the limits to obtain comfort. The applied parameters are illustrated in Figure 18.

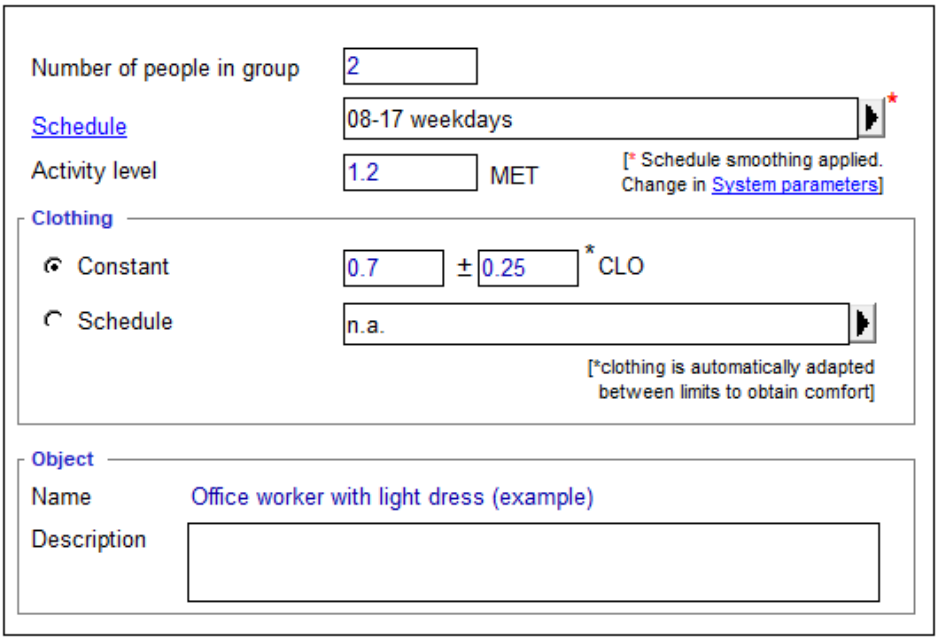

Figure 18. Occupancy profile for the office room, created in IDA ICE

2.4.6 Artificial lighting and equipment

The typical heat producers in any given indoor space, apart from the occupants, are lighting and the equipment. In the case studies two lighting bulbs of 60W have been used with luminous efficacy of 12lm.W^{-1}. The old light bulbs were selected as they represent the worst case with respect to internal heating. The operational hours are defined as from 8am to 5pm during weekdays. The applied parameters are illustrated in Figure 19.

The heat generation from equipment in a zone can vary depending on the purpose of use. Typical equipment in an office space is usually computers and printers, which generate heat. In this work, two computers are selected as the main equipment, one for each user, with a standard 17-inch monitor in continuous operation. The computers can operate in energy saver mode of 20W (ASHRAE RP-1055 1999). The heat gain by each unit is 125 W. The equipment is assumed to operate at the same time as the occupants' working hours i.e. 08am to 05pm in weekdays (Figure 20).

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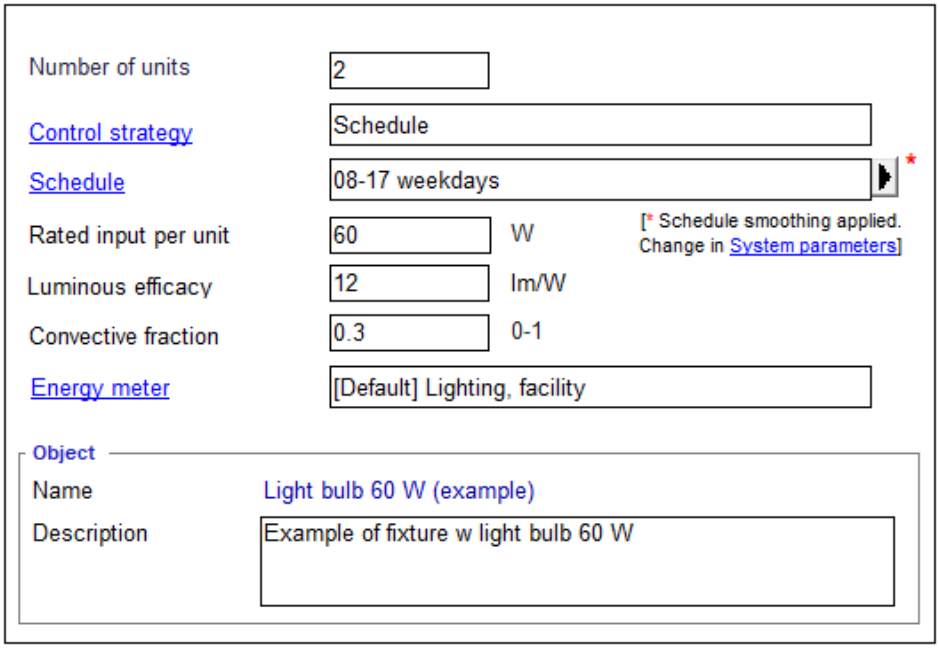

Figure 19. Artificial lighting profile for the office room, created in IDA ICE

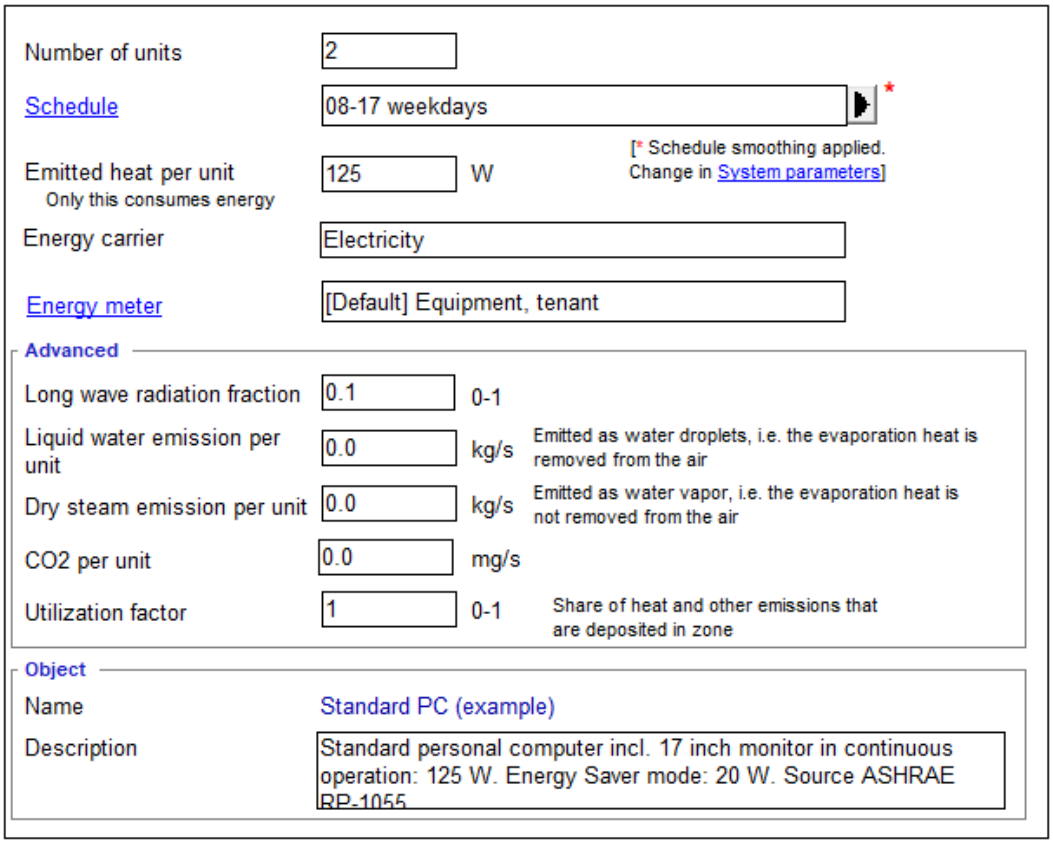

Figure 20. Standard equipment profile for the office room, created in IDA ICE

The office is considered to be equipped with 2 wooden worktables with a surface area of $2m^2$ each. In the simulation they are placed opposite each other in the center of the room. The convective heat transfer coefficient is considered 6 $W.m^{-2}.K^{-1}$.

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2.4.7 Air exchange rates and window opening behaviour

The air exchange rate is assumed to be a constant 0.1 h^{-1} over the course of the year. Infiltration air is another input for the simulation, which has been estimated an air tightness of 1.0 ACH at pressure difference of 50 Pa.

Typically for thermal comfort simulations, air exchange rates are assumed to be constant during occupancy, as well as at nights or weekends. The usual values for natural ventilation through a façade can be assumed 1 h^{-1} (Roetzel 2009). However, it should be mentioned that in studies regarding naturally ventilated office rooms, the values of air exchange rates can vary significantly during day or night, as they are affected by the differences between indoor and outdoor temperatures, wind speed-direction and -fluctuation, placement of windows within the façade, cross- sectional area for air exchange of ventilation openings, horizontal and vertical arrangement of ventilation openings, depth of window reveal, placement of heating devices related to windows, window decoration, and window opening behaviour of occupants (Richter et al. 2003).

According to simulation-based measurements, it was found that air exchange rates are strongly affected by the differences between indoor and outdoor temperatures (Richter et al. 2003). In this work, the case studies simulated with IDA ICE and the weather data applied from Meteonorm 8 (2020), provide hourly values for outdoor air temperature and room air temperature. The air exchange rates were adapted automatically from IDA ICE regarding the difference in air temperatures.

Another important aspect of natural ventilation with manually operated windows is occupants' opening behaviour. Based on field studies during occupancy hours, Rijal et al. (2007) showed that the time factor of opened windows is a function of indoor and outdoor temperature. It has been found that the occupants are more likely to open the windows when both outdoor and indoor temperatures are high as well as when they are not satisfied with the indoor air quality (air age, CO_2, relative humidity). Other field experiments have shown that the thermal responses of occupants in such spaces differ from the thermal responses of occupants in buildings with HVAC systems, mainly due to differences in thermal experience, availability of control, and changes in occupant expectations (EN 15251 2007).

In this work the office room is equipped with one operable window and is assumed that it opens to the outdoors and that can be easily opened and adjusted by the occupants of the space. For the window opening behaviour, the maximum setpoints were assumed to be according to EN 15251 (2007):

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- Indoor operative temperature 26°C
- relative humidity 70%
- CO_2 concentration 800ppm

Figure 21 illustrates the effect of the window opening to the indoor air quality of the office room in Vienna for the week between 06/07/2020 until 12/07/2020 for the Zone 1 (south).

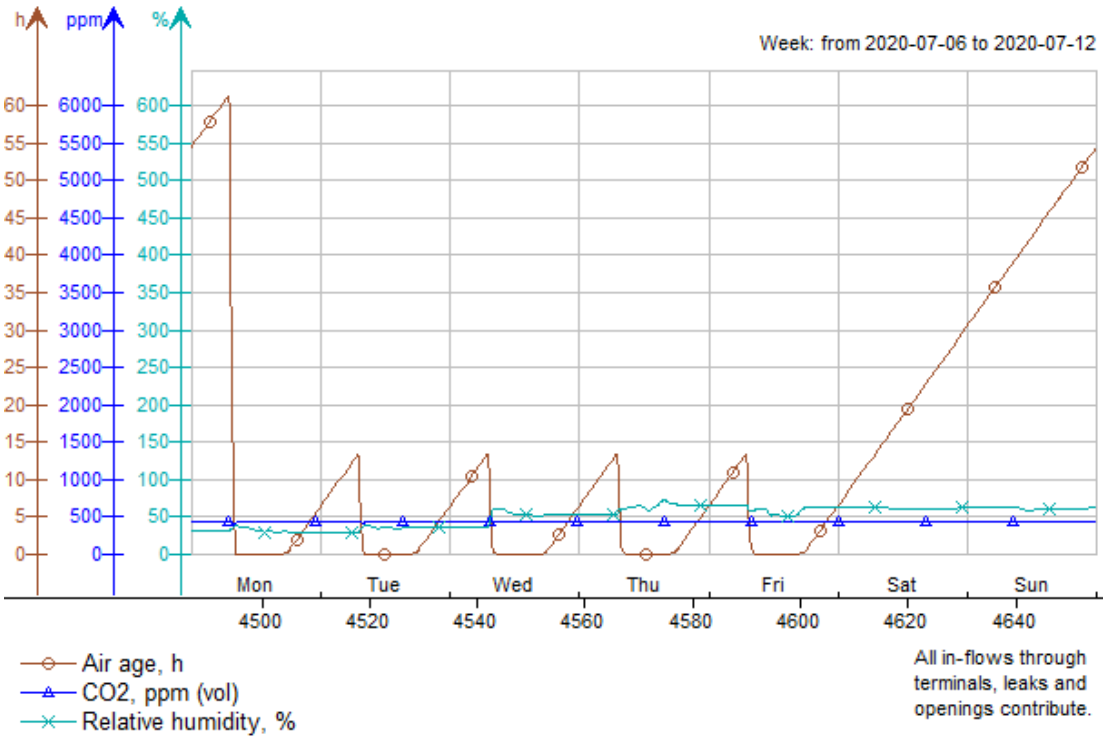

Figure 21. Indoor air quality for a week in Vienna. Basic scenario, Zone 1 (south)

According to the EN 15251, a mechanical cooling system must not be operated in the room. Mechanical ventilation with unconditioned air during summer period could be used, but the opening and closing of windows should be of primary importance as a means of regulating the thermal conditions in the space. In this work no mechanical cooling or ventilation system has been applied for the simulations.

In the investigated case studies, the opening behaviour was simulated from the software. For the standard scenario a window opening schedule was applied for the occupancy periods i.e., 08am until 17pm through the weekdays, without night ventilation. Figure 22 presents the ventilation air flows in Vienna for a single day, with the window opening from the occupants during the working hours.

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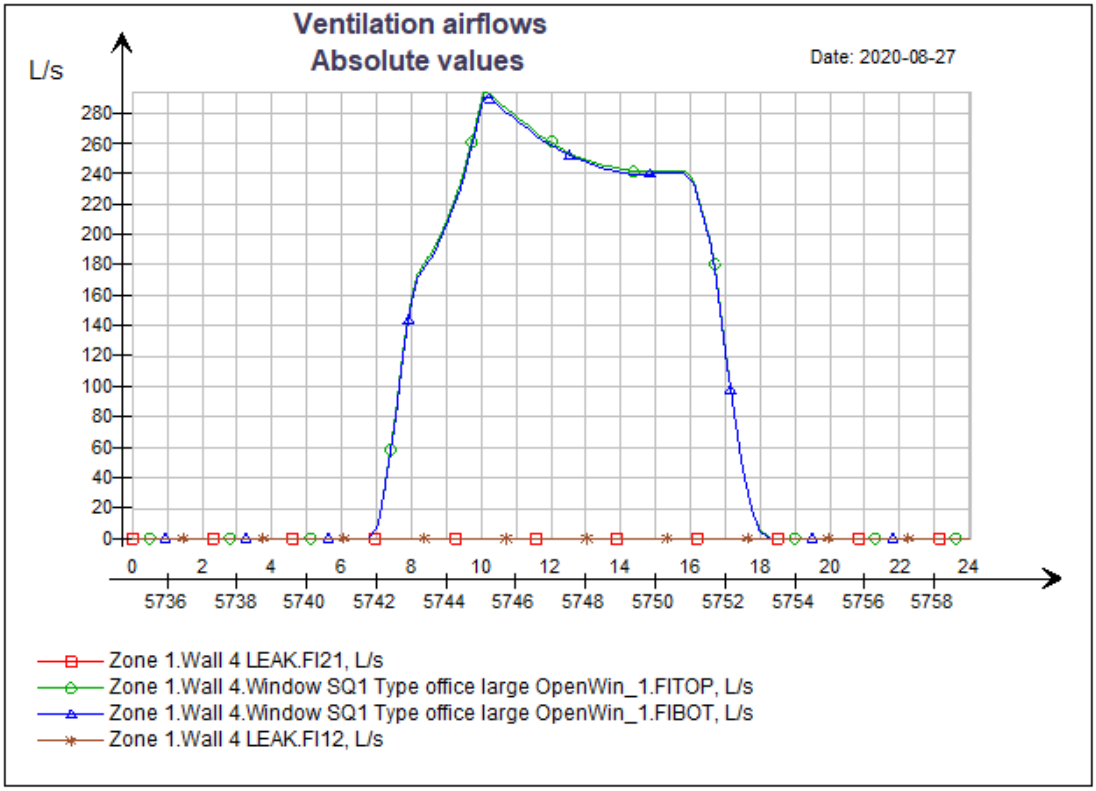

Figure 22. Ventilation air flows for a single day in Vienna without night ventilation

As can be seen from the diagram, shortly before the start of occupancy, ventilation air flows are detected. The reason is because according to the EN 15251 Standard (2007), in order to ensure good IAQ at the beginning of occupancy, ventilation should be started before occupancy, or a minimum ventilation rate should be provided during non-occupied hours. In particular, an outdoor air flow equivalent to 2 air volumes of the ventilated space shall be provided to the space prior to occupancy. Infiltration was calculated as a part of this ventilation.

2.5 The selected configuration scenarios

2.5.1 Configuration scenario variation 1 – Night ventilation

To evaluate the effectiveness of natural ventilation in offices, the possibility of night ventilation is an important aspect. It is a fact though that the use of night ventilation implies an increase in the security problems of the building and thus required the implementation of additional security systems. Nowadays, the potential for the implementation of security scenarios in a building is quite extensive. In the context of this research, we assume that appropriate security systems are implemented in the building and that the users take into account the use of night ventilation and leave the windows open after they leave the room.

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For each field survey, the night ventilation scenario was additionally applied to the original baseline ventilation scenario that provided for opening windows only during working hours. This configuration scenario was then simulated with the weather data for 2030 and 2070. The diagram below in Figure 23 shows the ventilation air flows for one day in Vienna with the weather data of 2020. As can be noticed, the air flow rates decrease during the night as temperatures drop and gradually increase again in the early morning hours.

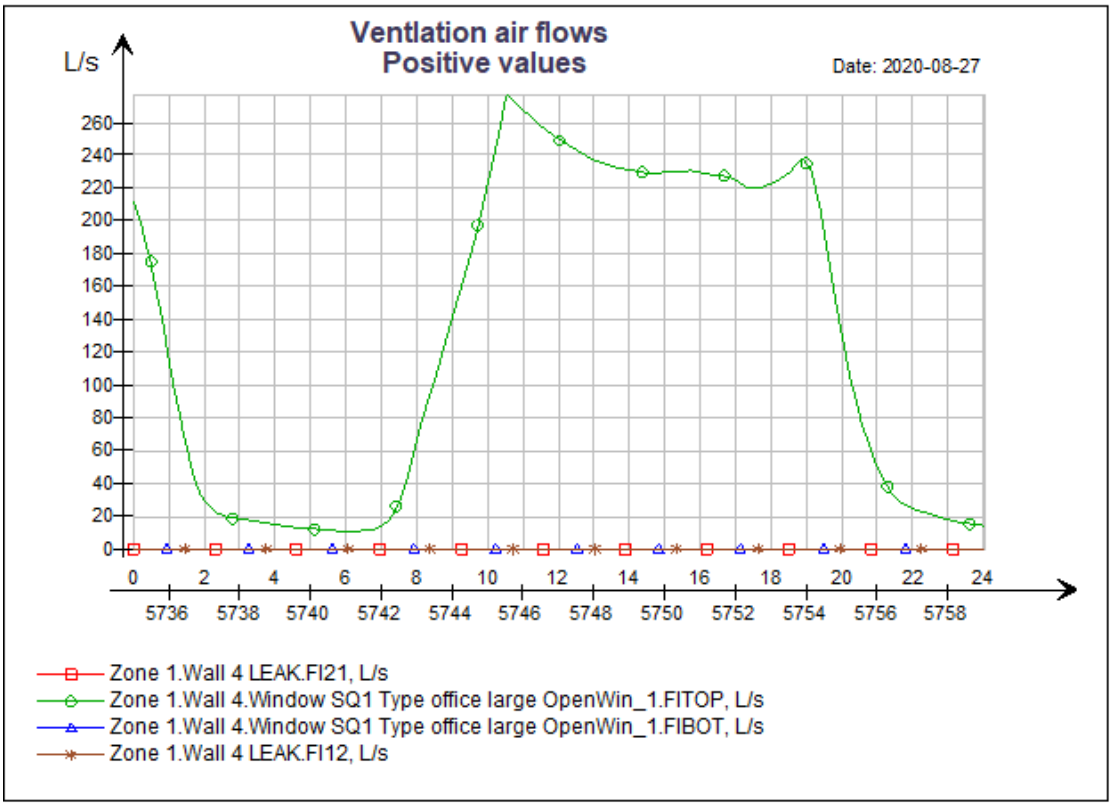

Figure 23. Ventilation air flows for a single day in Vienna with night ventilation

2.5.2 Configuration scenario variation 2 – Shading and shading control

According to EN 15251 Standard (2007) another method of improving the thermal comfort of a room is the application of shading devices. Of course, their application and use are directly related to the orientation of the room, and it is expected that in the north orientation their use will be limited or will be omitted.

For the purposes of this parametric study, it is assumed that all windows are not shaded by opposite buildings or trees, etc. This may not be realistic for all city centre locations, but it does result in higher solar heat gains and is therefore a safe assumption in terms of assessing thermal comfort.

In this scenario, the night ventilation scenario was adapted, using a shading device. The shading under consideration for the room is an external blind (BRIS), integrated at the

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window. The shading was applied to all windows, albeit knowing that its effectiveness at the north windows is minimal. The blinds are considered to be either fully down or fully retracted.

As Rea (1984) describes, there are a variety of factors that affect the handling of window blinds by users, such as the orientation of the window, time of day, weather conditions, latitude, workstation location, user habits and interior lighting. On average, users tend to control shading in order to block solar radiation (heat and light).

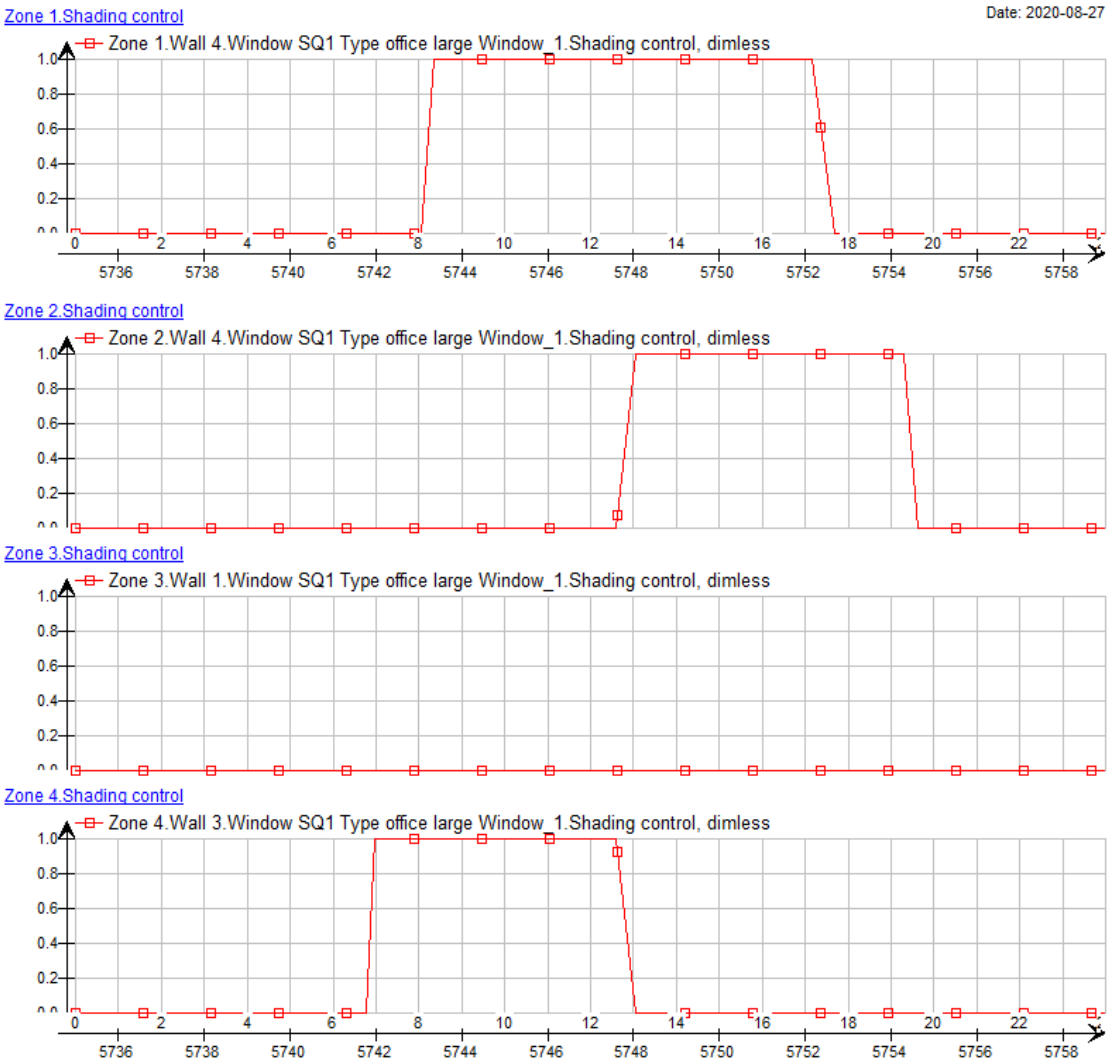

Figure 24. Shading control for a single day in Vienna

In building simulation, it is very difficult to take all these interdependencies into account. Therefore, a shading schedule was applied for the office occupancy hours, considering the glare as well as the heat criterion for closing the shading device. In general, it could be assumed that in Vienna the solar gains are normally welcome in the office spaces, but on the other hand during the summertime the room overheating due to direct solar radiation is a very typical phenomenon. Therefore, it is considered that glare is more likely to occur when the sun is shining on the façade, so this was chosen as the glare criterion for closing the

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shading system. In terms of the heat discomfort criterion, it is considered that both room air temperature above 26.0°C and simultaneous direct solar radiation on the façade will lead the occupant to close the blind. As can be seen in the diagram of Figure 24, the shading is fully closed during the hours of direct solar radiation or with an indoor room temperature over 26.0°C.

This configuration scenario was simulated again using the RCP8.5 weather data for the years 2030 and 2070.

2.5.3 Configuration scenario variation 3 – Glazing

This configuration scenario applied only in the case study of Athens. For the basic scenario in Athens a double-glazed window was chosen, which is typical for an office building in Greece. The U-value of the frame is 1.5 $W.m^{-2}$ °C while for the glazing it is 2.9 $W.m^{-2}.K^{-1}$. The solar heat gain coefficient (SHGC) is g: 0.76 (Figure 25).

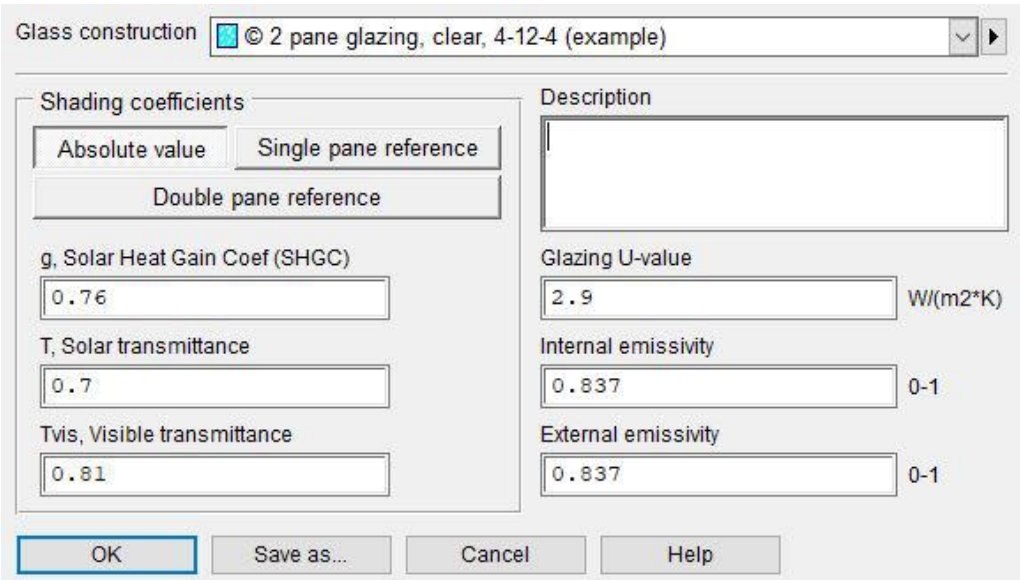

Figure 25. Glass construction and specification for the standard window in Athens

Solar heat gain coefficient is the fraction of solar radiation admitted through a window either transmitted directly or absorbed, and subsequently released as heat inside the room. The lower the SHGC, the less solar heat it transmits. A product with a high SHGC rating is more effective at collecting solar heat during the winter. A product with a low SHGC rating is more effective at reducing cooling loads during the summer by blocking heat gain from the sun.

The standard window applied in the case study of Vienna is a high energy efficient product with a double structure thermal insulation glass and U-value 0.6 $W.m^{-2}.K^{-1}$ as well as g: 0.37 (Figure 26). This glazing is more expensive but provides better thermal protection in case of high solar gains. This glazing is preferred nowadays in Austria due to the rapid increase of

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office buildings requesting sustainability certifications (ÖGNI, BREEAM, LEED) and thermal comfort is an important part of the certification criteria.

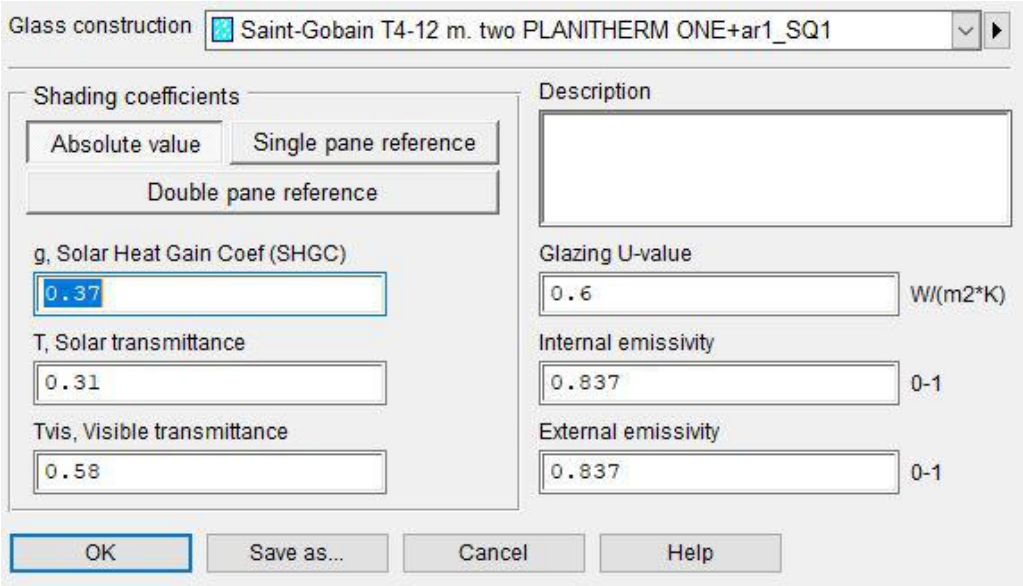

Figure 26. Glass construction and specification for the optimized window in Athens

In this scenario, in the case of Athens, where the incident solar radiation is much higher than in Austria (Table 5), the window used in the Vienna simulation building is applied together with the two previous scenarios (night ventilation and shading). It is expected that the cost of such a window exceeds the initial budget cost for the state of the art in Greece, but in the future such measures will be necessary in order to reduce the cooling energy consumption for the building as well as the CO_2 emissions.

This configuration scenario was simulated again using the RCP8.5 weather data for the years 2030 and 2070.

2.5.4 Configuration scenario variation 4 – Thermal mass and exterior insulation

Thermal mass is the ability of a material to absorb and store thermal energy. High-density materials such as concrete and bricks are considered to have a high thermal mass. Lightweight materials such as timber have a low thermal mass.

A high thermal mass building needs to gain or lose a large amount of energy to change its internal temperature, whereas a light building requires only a small gain or loss of energy to change the air temperature. This is an important factor to consider when selecting building systems and evaluating climate change adaptation.

For buildings, which are externally insulated with internal exposed mass, both Thermal Time Constant (representative of the effective thermal capacity of a building and defined as the

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product of the heat capacity (Q) and the resistance (R) to heat transmission) and Diurnal Heat Capacity (a measure of the building's capacity to absorb solar energy coming into the interior of the space, and to release the heat to the interior during the night hours) are high. When the building is ventilated at night and closed during the day, it can absorb the heat in the mass with relatively small indoor temperature rise (Givoni 1998) and this could be considered as an efficient proposal for hot-dry regions such as Athens, Greece.

In this scenario the thermal mass of the external wall and the external insulation of the case study of Vienna applies in the previous scenario of Athens case study. The construction of the wall from inside to outside is: concrete wall (18 cm), external insulation (16 cm) and plaster (0.5 cm).

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3 RESULTS

3.1 Overview

In this chapter the results of the accomplished simulations are displayed. The results investigate to what extent naturally ventilated offices in Vienna, Austria and Athens, Greece can meet the requirements according to EN 15251 (2007) and how certain building configurations can improve adaptive thermal comfort, minimizing the need for cooling systems.

Initially, the criteria and assumptions regarding the assessment of thermal comfort are identified. The basic scenarios are compared through diagrams for the case studies of Vienna and Athens. Then the results from the first configuration scenario concerning night ventilation are presented, and subsequently the second scenario considering the implementation of a shading system in the previous scenario. Finally, the results of the third and fourth scenarios, regarding the window replacement and the thermal mass change, which are considered only in the Athens case study, are presented. In addition, in the fourth scenario the positioning of the insulation is changed.

3.2 Thermal comfort evaluation criteria and assumptions

Thermal comfort in this work is evaluated according to the adaptive thermal comfort model as described in EN 15251-2007 Standard. According to the adaptation principle, assuming that in naturally ventilated buildings the preferred thermal sensation of occupants varies according to indoor and outdoor temperature, the amount of personal control provided, expectations and adaptation possibilities. This work examines the percentage of hours in Category IV for all scenario variations, i.e., the percentage when thermal comfort conditions are completely unacceptable. As recommended in EN 15251 (2007), for each category a maximum of 5% overheating hours are allowed and the aim of the standard is to achieve Category II.

For the adaptive model to be applicable, the room under examination must not have mechanical cooling and the occupants' use of the window (opening or closing) must be the main means of regulating thermal conditions. Night ventilation is automated, considering windows open during the unoccupied hours. The area under investigation is a cellular office room, so the simulation model is designed for occupants involved in sedentary physical activities with a metabolic rate of 1.2 MET as mentioned in the previous chapter, and where the occupants can freely adjust their clothing.

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The results of all simulations refer to a standard configuration of parameters, which have been simulated based on input data in chapter 2. All configurations are ventilated by natural ventilation and applied in the same way for all four thermal zones.

The order of the configuration scenarios was chosen according to the realistic cost of implementing the parameter, from the most affordable to the most expensive solution for the stakeholder.

3.3 Simulation results

3.3.1 Evaluation of the basic scenario

The basic scenario considers all the main parameters as described in the previous chapter for both case studies in Vienna, Austria and Athens, Greece, using the meteorological data for the year 2020, as derived from Meteonorm 8 for each city. Simulations were carried out for each thermal zone of the building and then compared according to the EN 15251 comfort zone definition in the following graph (Figure 27).

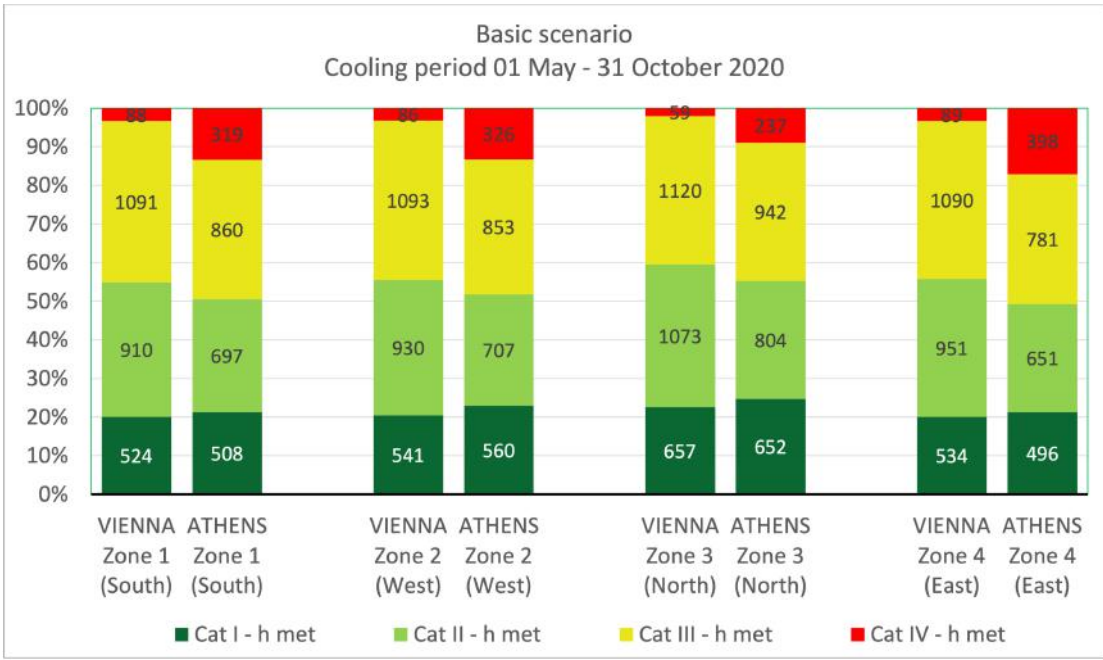

Figure 27. Basic scenario 2020
Cooling period 01/05/2020 – 31/10/2020 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

At a first glance the graph shows that in both cities some hours were recorded that the room exceeded the thermal comfort range of Category III and was in category IV. However, in the case study of Vienna this overlapping does not exceed the upper limit of 5% and the room is in the range of Category III in all zones. Nevertheless, there is a marked difference between the 2 case studies, with Athens showing almost four times as many hours of unacceptable thermal comfort as Vienna. The comparison shows the impact of the selected meteorological

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data as well as the different room envelope design to simulate summer comfort and indicates a significant effect on the thermal comfort of the room.

According to Givoni (1998), when a window is not shaded, its quantitative effect on indoor temperature depends on its orientation, relative to daily and annual patterns of solar radiation intensity on vertical surfaces. The different patterns of radiation at different orientations depend on the latitude of the building's location.

In the current case studies the basic scenario does not provide shading at the windows. Regarding the percentage of working hours that meet the thermal comfort criteria according to EN 15251, the results show that the orientation is the main factor affecting the results in each case study. For Vienna the highest percentages occur on the north side, followed by a small difference in percentages by the west, east and south side. However, the differences are greatest on the north side, while the east, south and west sides result in relatively similar percentages. In the case of Athens, the results show that the highest rates of working time meeting the thermal comfort criteria also occur on the north side, followed by the west, south and finally the east. However, all zones exceed significantly the defined 5% overlapping of Category III according to EN 15251, meaning unacceptable thermal comfort conditions with natural ventilation.

The above simulations were subsequently carried out again using the climate data for the year 2030 with the extreme scenario RCP8.5. The results are displayed in the diagram in Figure 28.

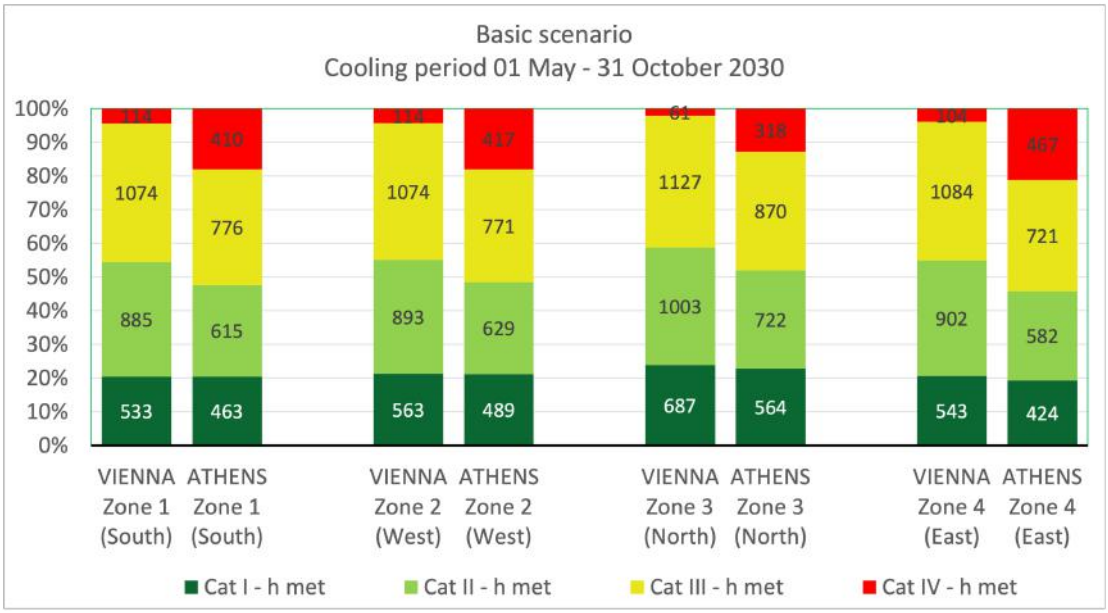

Figure 28. Basic scenario 2030
Cooling period 01/05/2030 – 31/10/2030 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

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The graph shows a slight deterioration of the results with a decrease in the number of working hours within the range of thermal comfort of Category III. This slight deterioration can be explained by the increase of the outdoor temperature. In the case study of Vienna, the results show that in all zones the room stays in the range of Category III, while in the case of Athens all zones are in Category IV. The eastern side shows the most negative results but compared to the basic scenario the differences are not that significant.

Finally, the same simulations concerning the basic room model were carried out once again taking into account the long-term future scenario using the climate data for the year 2070 with the extreme GHG emissions scenario RCP8.5. The results are displayed in the diagram in Figure 29.

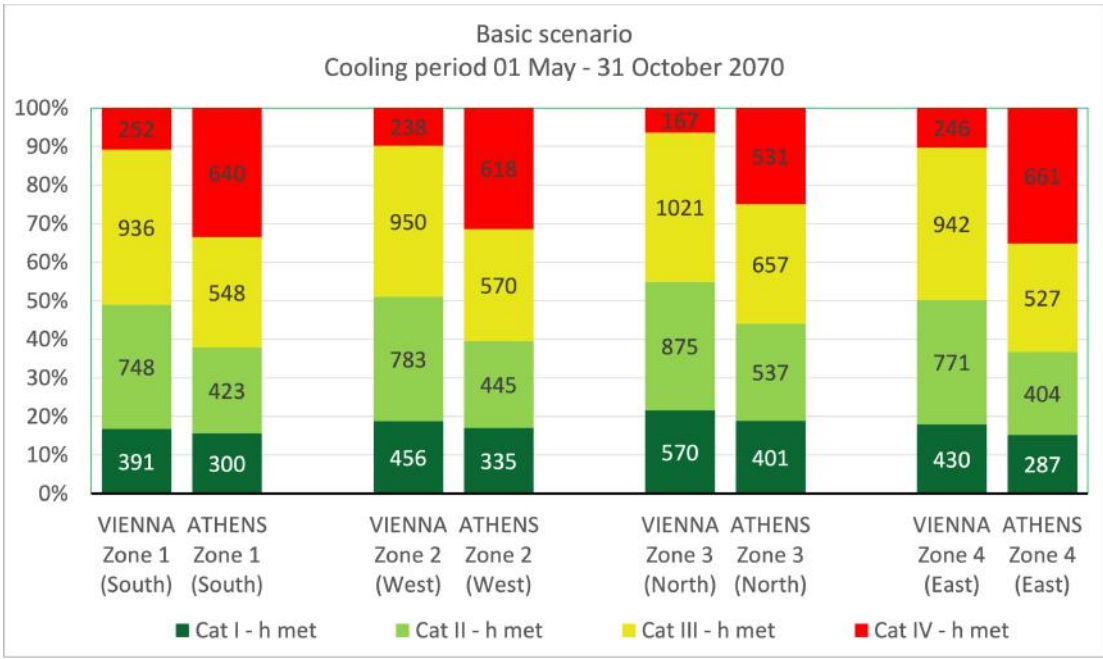

Figure 29. Basic scenario 2070
Cooling period 01/05/2070 – 31/10/2070 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

In this scenario the impact of climate change on space is apparent. In the case of Vienna almost 90% of the working hours remain in Categories I - III and approximately 10% of the working hours are out of the range of thermal comfort conditions, with the north side remaining the most thermally comfortable, as it also receives the least incident solar radiation. In contrast, the Athens case study shows a significant deviation from the simulated contemporary data (2020), with the east, south and west sides approaching almost 35% of the working hours out of thermal comfort.

From the above results it is obvious that the selected configurations in the particular climate conditions require the use of mechanical cooling systems, in order to allow users to feel

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thermally comfortable in the room. In the following chapters, the results from the configuration scenarios in each city are analyzed.

3.3.2 Evaluation of configuration scenario 1 – Night ventilation

As already mentioned in the previous chapters, the use of night ventilation is an efficient scenario concerning the reduction of peak cooling loads during the night (Kuczyński et al. 2021). According to Schuss (2011), natural ventilation during the night could be used to cool the internal thermal mass of the building and, in combination with an effective shading control and reduction of unnecessary internal loads, could essentially be used as a passive cooling system. It is one of the methods recommended also by EN 15251 and can be considered one of the least expensive configurations in a building, with a necessary implementation of a security system.

The effect of night ventilation on the cooling loads of the room is illustrated in the PMV/PPD diagrams below. In this example, the case study of Vienna in a very hot week between 06/07/2020 and 12/07/2020 was chosen. As can be seen comparing the Fanger's indices in the diagram in Figure 30 between the basic scenario and the one with the night ventilation, when using night ventilation in the room, the PMV/PPD values improve significantly.

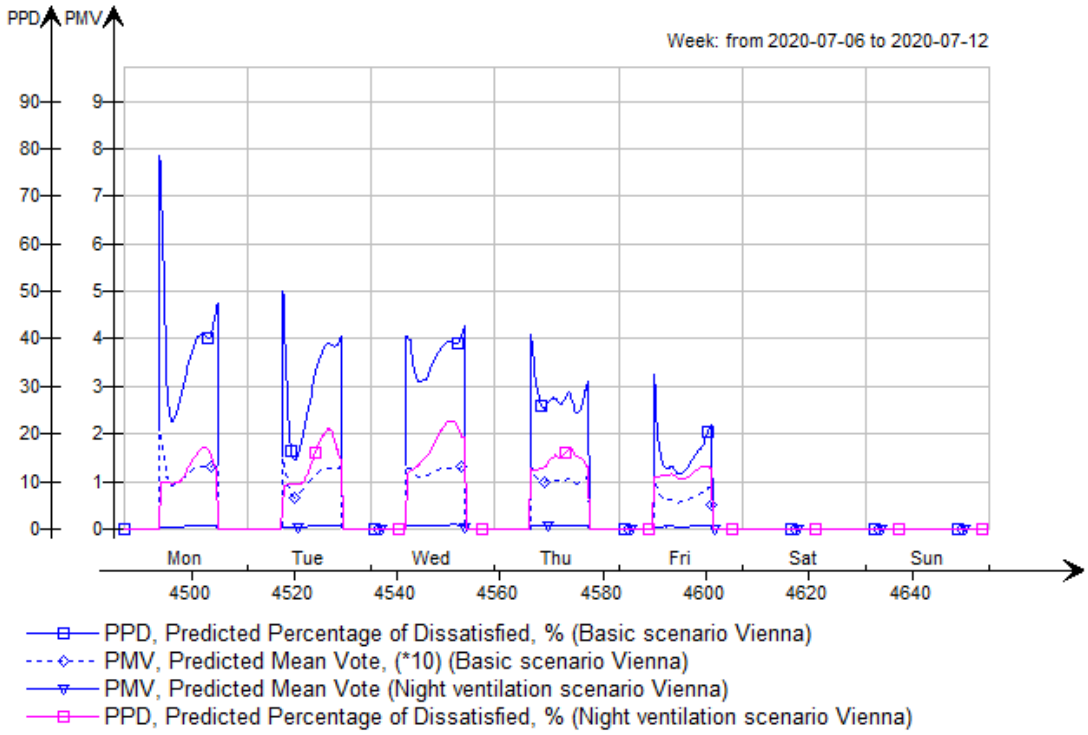

Figure 30. PMV/PPD indicators, comparison of 2 scenarios in Vienna, Zone 1 (south) Comparison of the basic scenario and the night ventilation scenario in Vienna, Zone 1 (south)

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The results of the simulations comparing the two case studies with the application of night ventilation in the office room for the year 2020 are presented in the diagram in Figure 31.

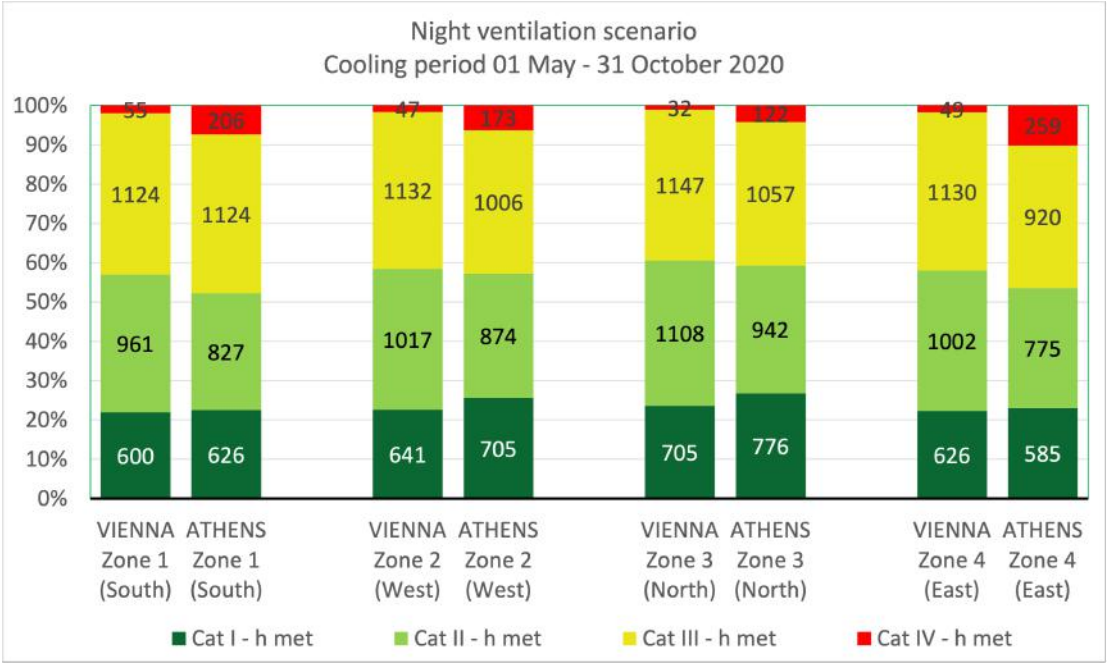

Figure 31. Night ventilation scenario 2020
Cooling period 01/05/2020 – 31/10/2020 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

Applying night ventilation to the Vienna case study shows that all working hours outside thermal comfort have been reduced considerably, with all zones being within the thermal comfort range of Category III.

On the other hand, in the Athens case study the cooling loads were reduced, but the night ventilation was not enough for zones to reach Category III. Zone 1, 2 and 4 exceed the range and only Zone 3 on the north side is in the range of Category III with 122 working hours out of the limit. This does not exceed the accepted 5% overlapping. In this case it is obvious again that even when cooling the internal thermal mass through night ventilation, the overheating through direct solar radiation on the exterior surfaces affect thermal comfort.

The thermal comfort results of the simulations through night ventilation, using the climate data of the year 2030 with the extreme scenario RCP8.5 are presented in the diagram in Figure 32.

The results for the year 2030 show for the case of Vienna that there is relatively little deterioration in conditions, but nevertheless all zones remain in class III. The South façade is slightly under the limit of category IV. Conversely, in the case of Athens, all zones are in the range of Category IV, even the Zone 3 on the north façade, which was in the thermal comfort

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range in the contemporary climate scenario. Therefore, also for this short-term scenario of 2030 other configurations should be applied to improve thermal comfort.

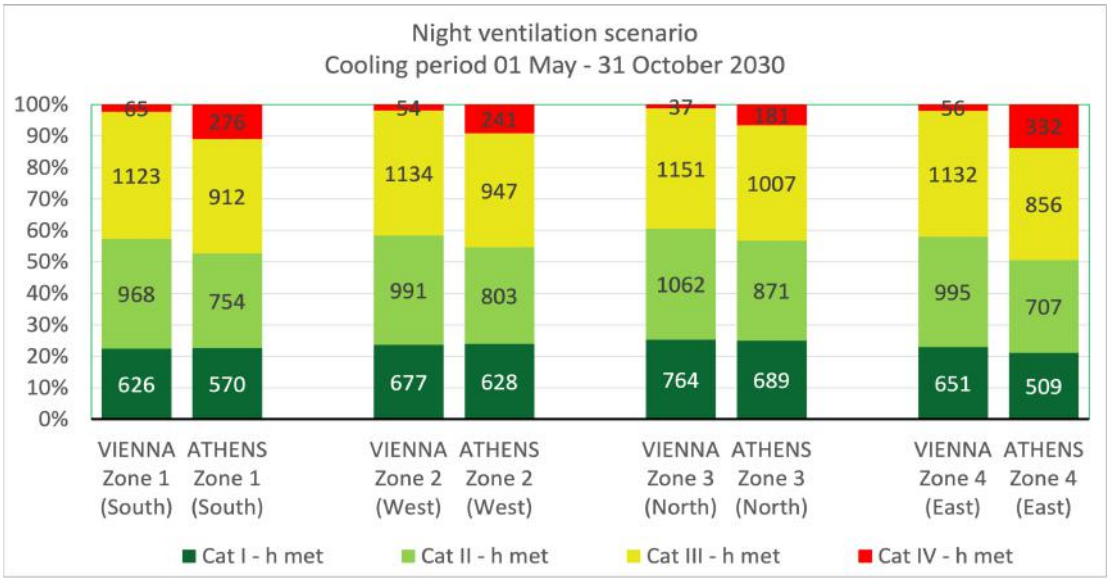

Figure 32. Night ventilation scenario 2030
Cooling period 01/05/2030 – 31/10/2030 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

Finally, for the night ventilation scenario simulations were carried out with the climate data of 2070. The results are presented in the diagram of Figure 33.

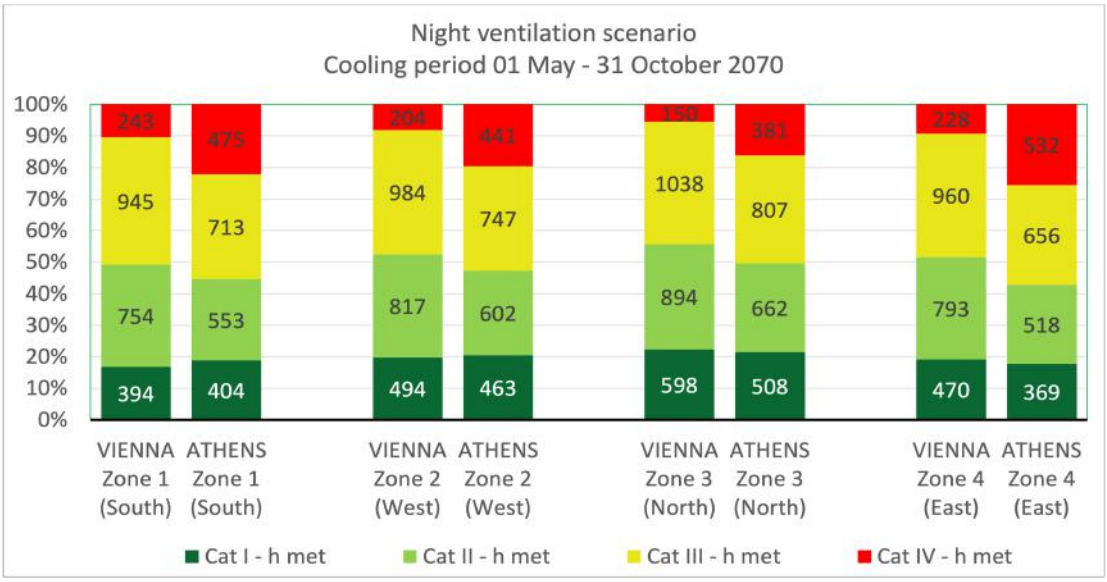

Figure 33. Night ventilation scenario 2070
Cooling period 01/05/2070 – 31/10/2070 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

In the long-term scenario of 2070, it seems that night ventilation is not sufficient even in the case of Vienna. The northern zone, which shows the best results, lies 150 working hours above the limit, followed by the south with 243 hours, the west with 204 hours and finally the east zone with 228 hours.

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In the Athens case study, the results are slightly better than the basic scenario in the year 2070, but all the zones remain within unacceptable conditions, significantly far from the Category III range.

3.3.3 Evaluation of configuration scenario 2 – Shading and shading control

The effect of window orientation on indoor temperatures is largely determined by the ventilation and shading conditions of the window. When windows are not shaded or when shading is not effective, solar radiation enters through the windows and directly heats the interior of the building. The amount and daily pattern of penetrating radiation depend on the orientation of the windows. The effect of penetrating radiation on indoor temperatures depends, in turn, on the ventilation conditions. Therefore, there are strong interactions between the effect of the orientation of a window and the shading and ventilation conditions of the office room in question.

The shading control of the users is another important parameter. As stated in Humphreys and Nicol (1998) if a change is such that causes discomfort, people react in ways that aim at restoring their comfort.

In this configuration scenario, the night ventilation scenario was adapted as previously, adding at the same time an external blind (BRIS) as shading device, integrated at the window as described in chapter 2. The shading was applied to all windows, despite knowing that its effectiveness at the north window is minimal. The blinds are considered to be either fully down or fully retracted. A shading schedule was applied for the office occupancy hours, considering the glare (when the sun is shining on the façade) as well as the heat criterion (room air temperature above 26.0°C) for closing the shading device. The occupants' behaviour can be seen in Figure 24.

The use of a shading system obviously affects the incident luminance in the office as well as the amount of luminous flux spread on the working surfaces. The diagrams in Figures 34 and 35 illustrate the illuminance on a user's desktop during a selected week between 06/07/2020 and 12/07/2020 in the office case study of Vienna. The zone under consideration is the eastern zone.

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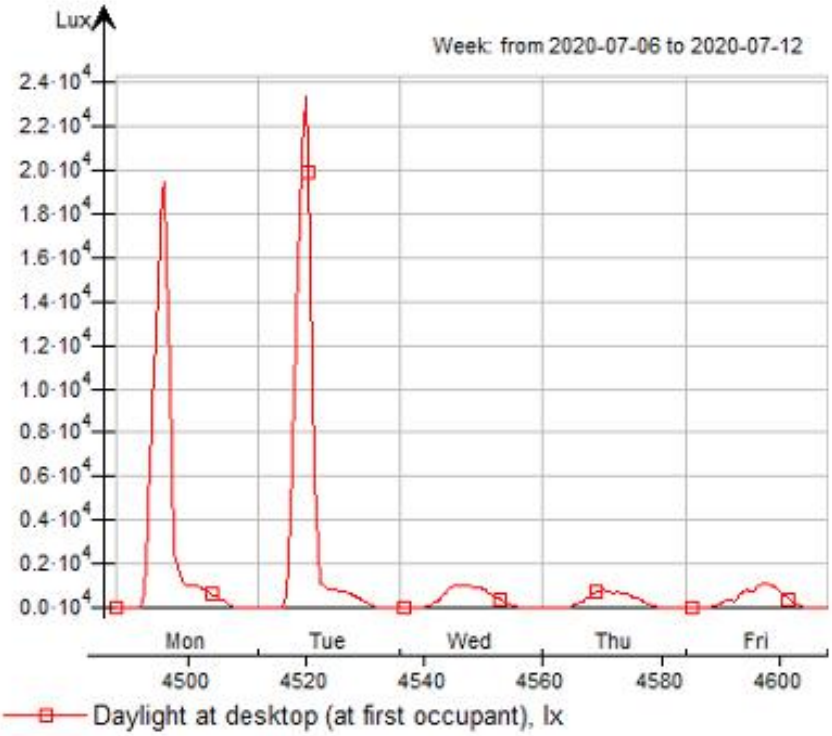

Figure 34. Daylight at a desktop - basic scenario Vienna, Zone 4 (East)

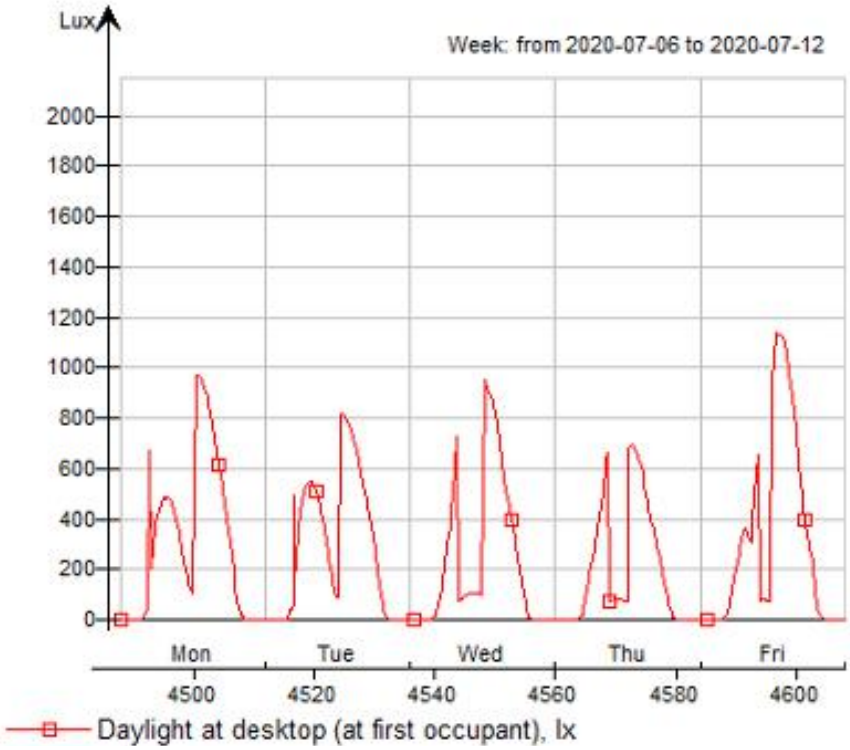

Figure 35. Daylight at a desktop - night ventilation and shading, Vienna, Zone 4 (East)

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In the basic scenario we can see that during the day the daylight incident on the working surface increases exponentially and steadily, reaching at the brightest moment of the day its peak, up to 23000 lx, a value considered too high to be able to work efficiently. In more cloudy days the maximum illuminance reaches up to approximately 1500 lx. In contrast, in the scenario where the shading system is applied, we observe that the user adjusts the shades at regular intervals, resulting in better control of the illumination levels on the working surface. In this case, the maximum illuminance reaches up to approximately 1100 lx with an average of approximately 600 - 700 lx.

But apart from the levels of visual comfort provided by external shading, the benefits in terms of thermal comfort are also important. Comparing the Fanger's indices in the diagram in Figure 36 between the basic scenario and the one with the night ventilation and applied shading, we notice that the PMV/PPD values improve significantly with the use of shading.

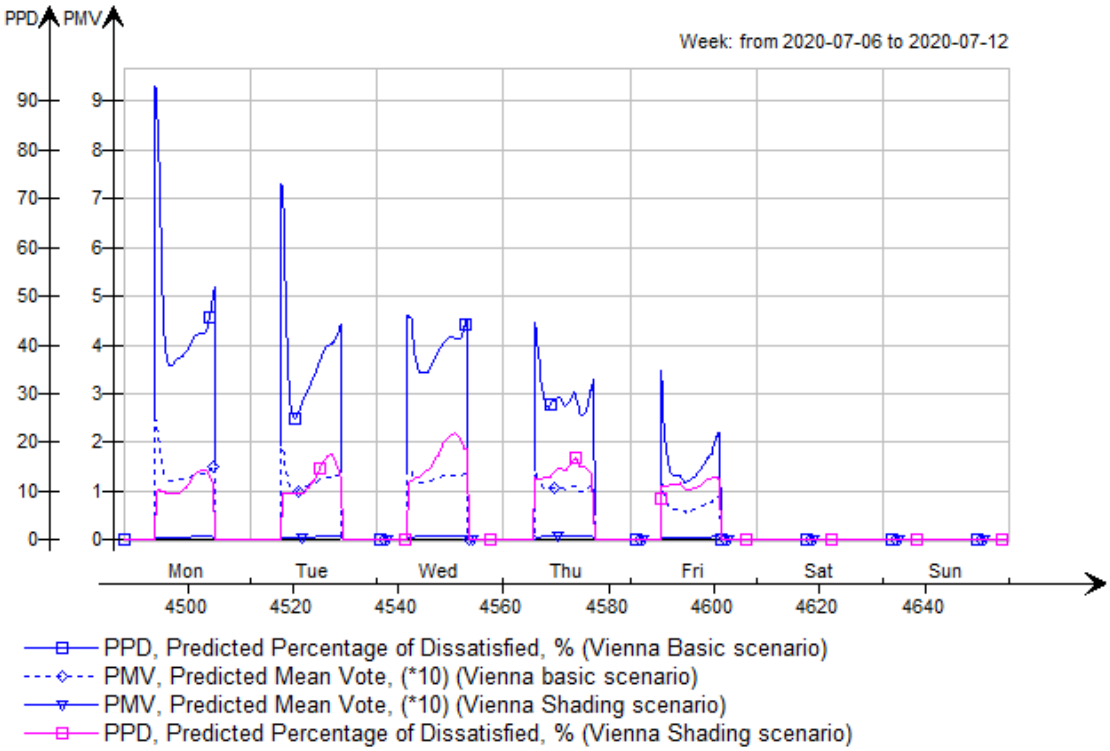

Figure 36. PMV/PPD comparison of 3 scenarios in Vienna, Zone 4 (East)
Comparison of the basic scenario and the scenario with night ventilation and a shading device

The results of the simulations comparing the two case studies with the application of night ventilation and a shading system in the office room for the year 2020 are presented in the diagram in Figure 37.

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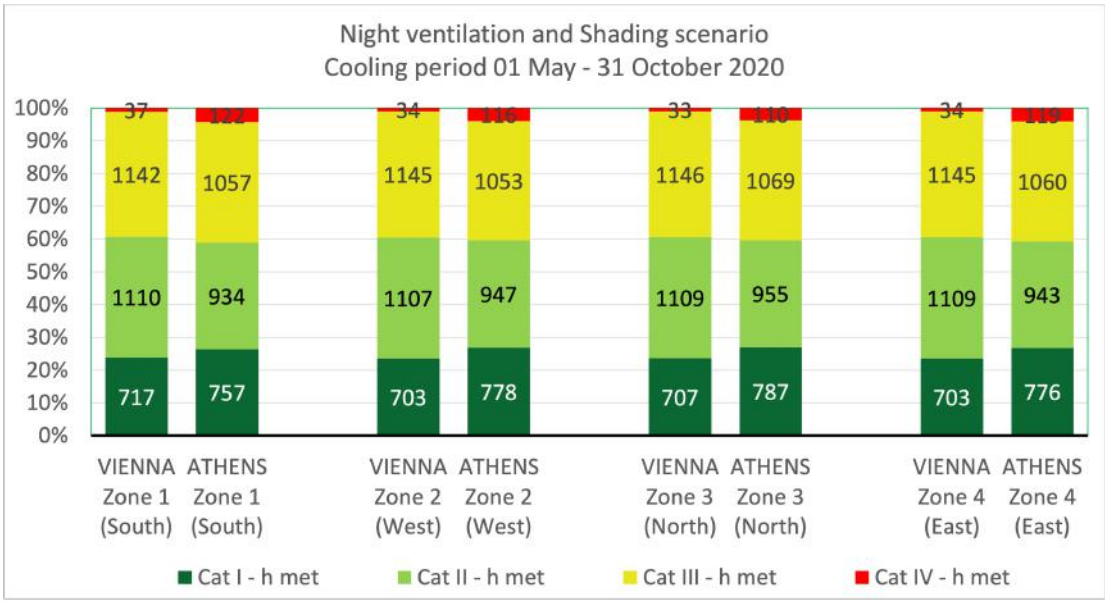

Figure 37. Night ventilation and shading scenario 2020
Cooling period 01/05/2020 – 31/10/2020 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

In the Vienna case study, the improvement is significant, and all four zones lie in Category III, overlapping Category III maximum approximately 1%. Thus, we can assume that in today's conditions, the chosen building envelope characteristics with the addition of night ventilation and a shading system are suitable to provide sufficient thermal comfort conditions in the office space.

In the case of Athens, the addition of shading significantly improves thermal comfort and puts all zones in the Category III range, with approximately only 2-4% of the working hours overlapping Category III.

The simulation results of the thermal comfort optimization through night ventilation, using the climate data of the year 2030 with the extreme scenario RCP8.5, are presented in the diagram in Figure 38.

In the 2030 short-term scenario it appears that the office room in the Vienna case study meets Category III in all four zones. Therefore, in this scenario too, it seems that climate change in the next 10 years may not be a turning point for the studied construction method.

The Athens case study shows a minimal deterioration. All zones are in Category IV, with zone 3 (north) to exceed slightly the 5% limit.

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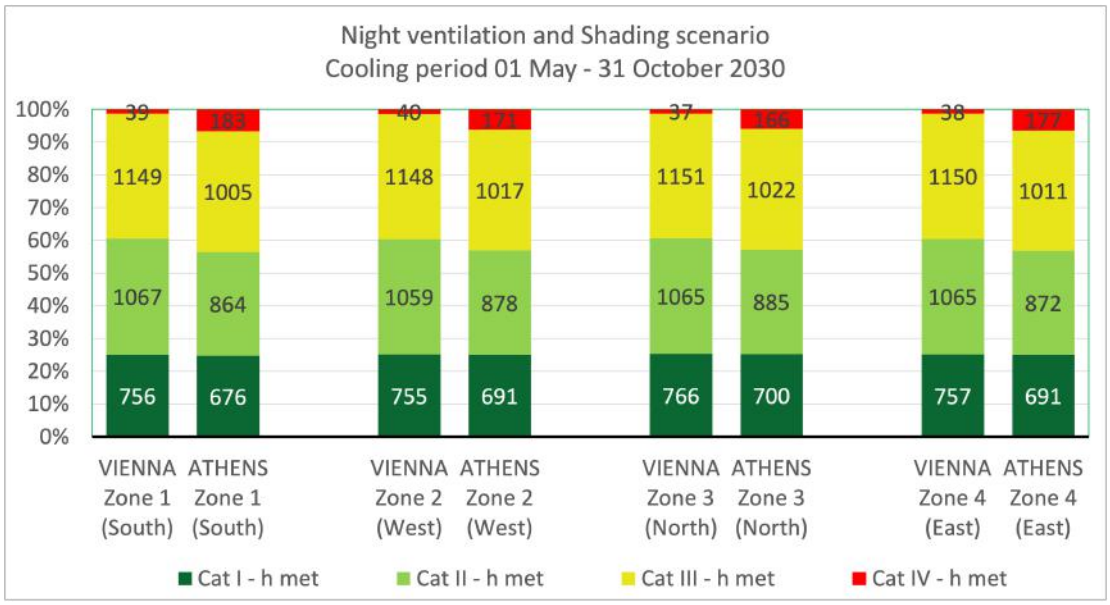

Figure 38. Night ventilation and shading scenario 2030
Cooling period 01/05/2030 – 31/10/2030 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

Finally, for this scenario, simulations were carried out with the climate data of 2070. The results are presented in the diagram of Figure 39.

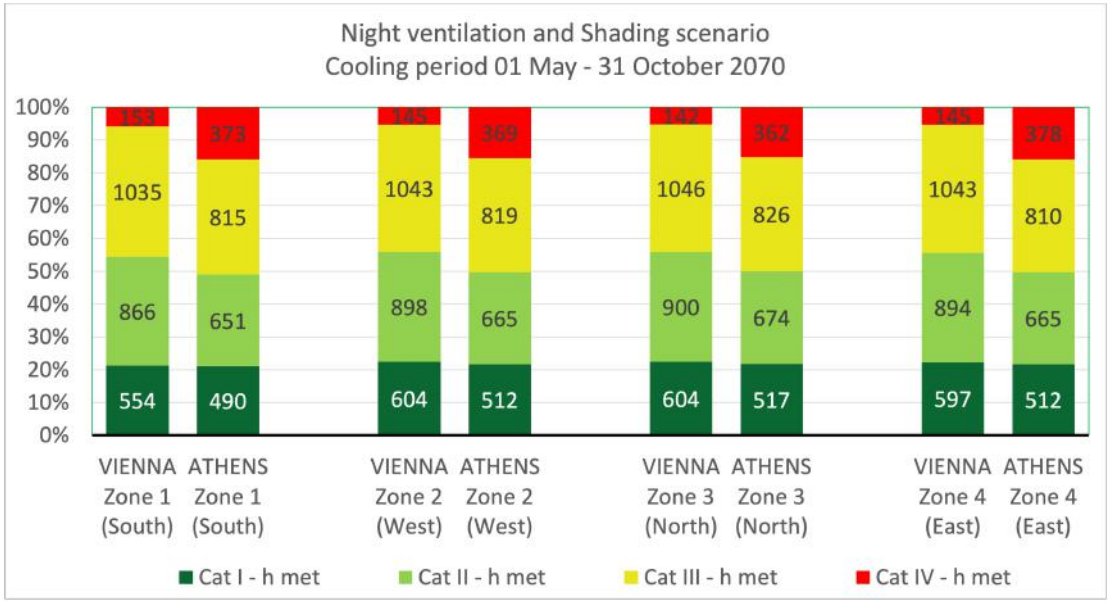

Figure 39. Night ventilation and shading scenario 2070
Cooling period 01/05/2070 – 31/10/2070 comparing thermal comfort in Vienna and Athens according to EN 15251 Standard (2007)

In this long-term scenario it seems that the Vienna case study fails to meet the thermal comfort criteria in all four zones. However, all zones lie slightly over Category III. As it can be seen from the diagram, the south, west and east orientations are more burdened, while the north orientation seems to have slightly fewer working hours outside thermal comfort. Nevertheless, the discrepancy is not significant, and we can assume that with the appropriate

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design approach and modest changes to the building configurations, suitable thermal comfort conditions can be achieved.

In the case study of Athens, it appears that more than 15% of the total working hours on average are in category IV. It is obvious that the typical construction method in Athens does not adequately meet the required levels of thermal comfort under the current climate conditions and the deviation is obviously much greater for future climate scenarios. In the context of this work, two more configuration scenarios for the office room in Athens were investigated. Taking into account the positive results from the simulations of the Vienna case study, in the next two chapters, the effectiveness of the window glazing, and thermal mass of Vienna's building will be investigated in the case study of Athens.

3.3.4 Evaluation of configuration scenario 3 – Glazing

Although windows glazing is not the main determinant affecting adaptive thermal comfort, when their internal surfaces are very hot, solar radiation through the window is very high and when the position of the building occupant is very close to the window, their effect could become significant.

This configuration scenario applied only in the case study of Athens. As analysed in chapter 2, for the basic scenario in Athens a double-glazed window was chosen, which is typical for an office building in Greece. The U-value of the glazing is 2.9 $W.m^{-2}.K^{-1}$ and the solar heat gain coefficient (SHGC) is g 0.76.

In this scenario the window used in the Vienna simulation building is applied together with night ventilation and a shading system. It is a high energy efficient window with a double structure thermal insulation glass and U-value 0.6 $W.m^{-2}K^{-1}$ as well as g 0.37.

Comparing the Fanger's indices in the diagram in Figure 40 between the basic scenario, the one with night ventilation and the shading and finally the one with all previous parameters and additionally an energy efficient window glazing, we can notice that the PMV/PPD values improve in each scenario. However, the improvement applying the glazing together with the shading is not that efficient considering the high investment cost of this type of glazing.

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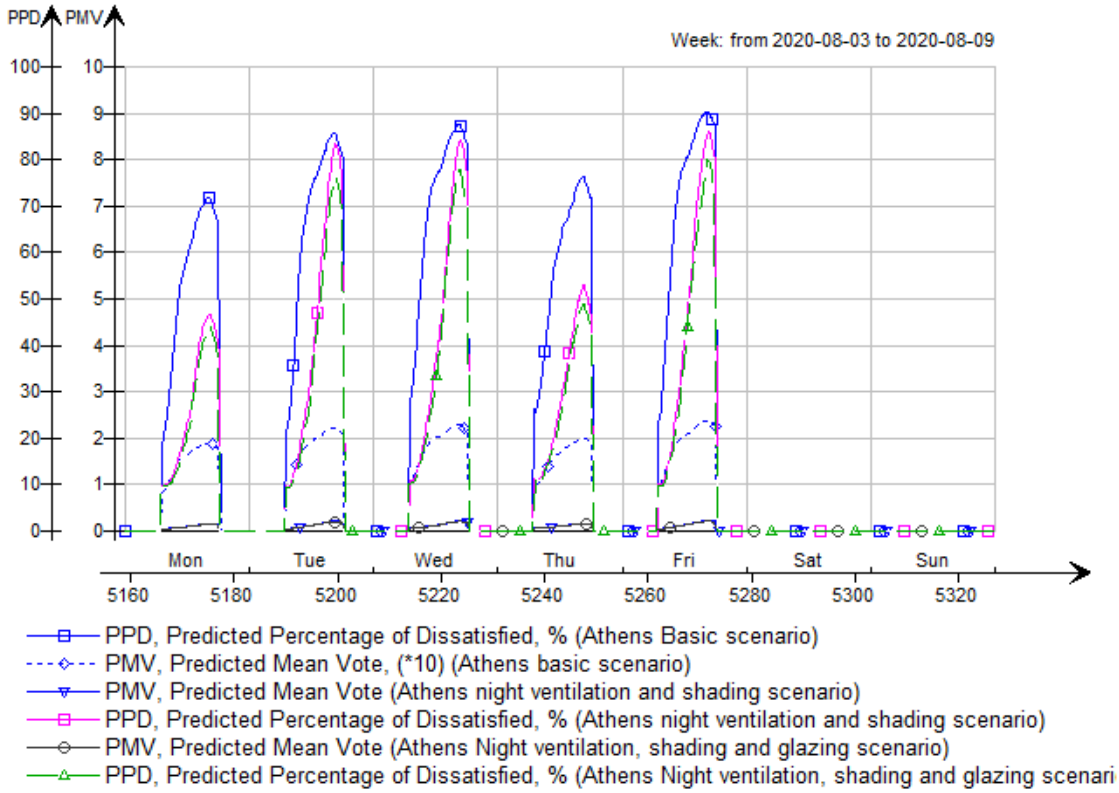

Figure 40. PMV/PPD comparison of 3 scenarios in Athens, Zone 4 (East)
Comparison of the basic scenario and the scenarios with night ventilation and a shading device as well as with night ventilation, a shading device and energy efficient glazing

The results of the simulations comparing the four thermal zones with the application of the double structure thermal insulation glass on the previous scenario in the office room for the year 2020 are presented in the diagram in Figure 41.

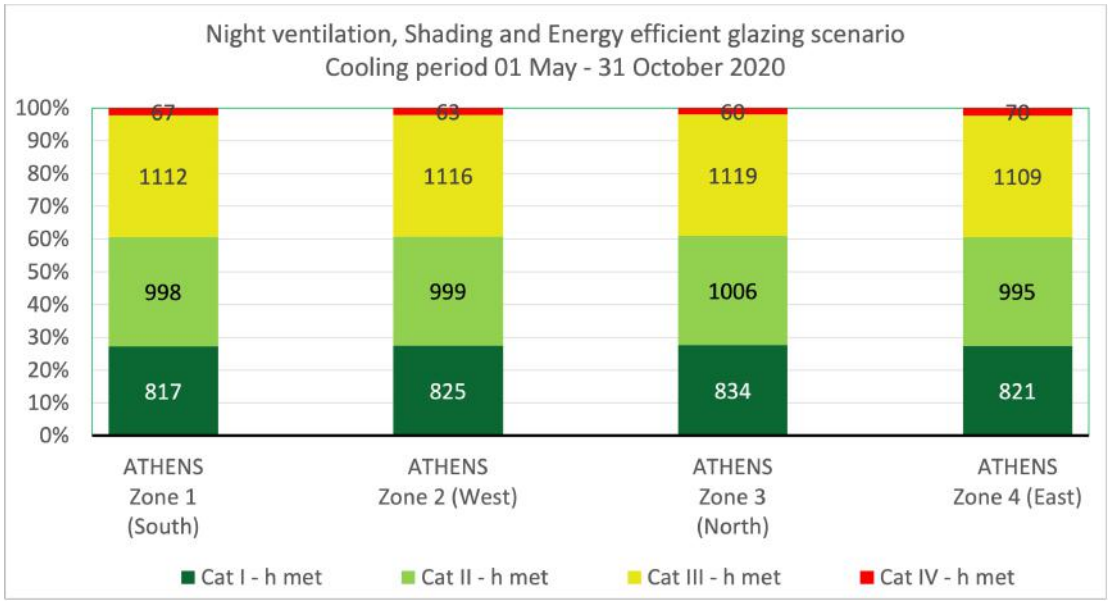

Figure 41. Night ventilation, shading and energy efficient glazing Scenario 2020
Cooling period 01/05/2020 – 31/10/2020 in Athens according to EN 15251-2007 Standard

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The results show an improvement of the working hours lying within the range of Category III. However, the results show that the improvement compared to the previous scenarios is not that significant.

The thermal comfort results of the simulations using the climate data of the year 2030 with the extreme scenario RCP8.5 are presented in the diagram in Figure 42.

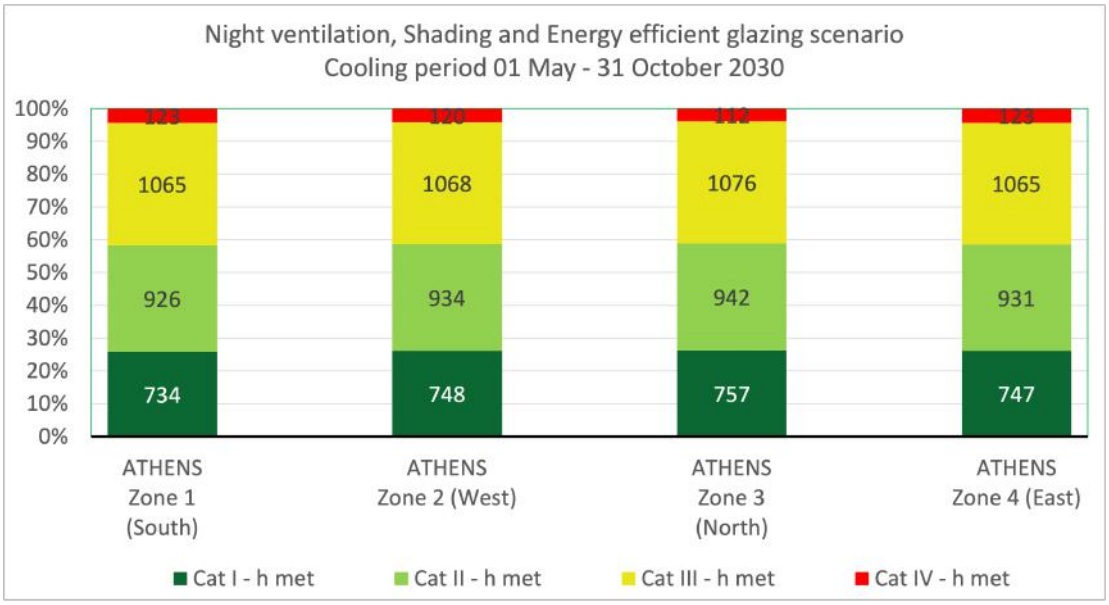

Figure 42. Night ventilation, shading and energy efficient glazing scenario 2030 Cooling period 01/05/2030 – 31/10/2030 in Athens according to EN 15251-2007 Standard

In this case, the results show that in this short-term climate scenario, the use of energy efficient glazing affects the thermal comfort of every zone, reaching Category III. For this scenario less than 5% of the working hours lie in Category IV, therefore mechanical cooling is not considered necessary.

Finally, for this scenario, simulations were carried out with the climate data of 2070. The results are presented in the diagram of Figure 43.

In this long-term scenario it seems that the office room fails to meet the thermal comfort needs with more than 10% of the total working hours on average overlap Category III.

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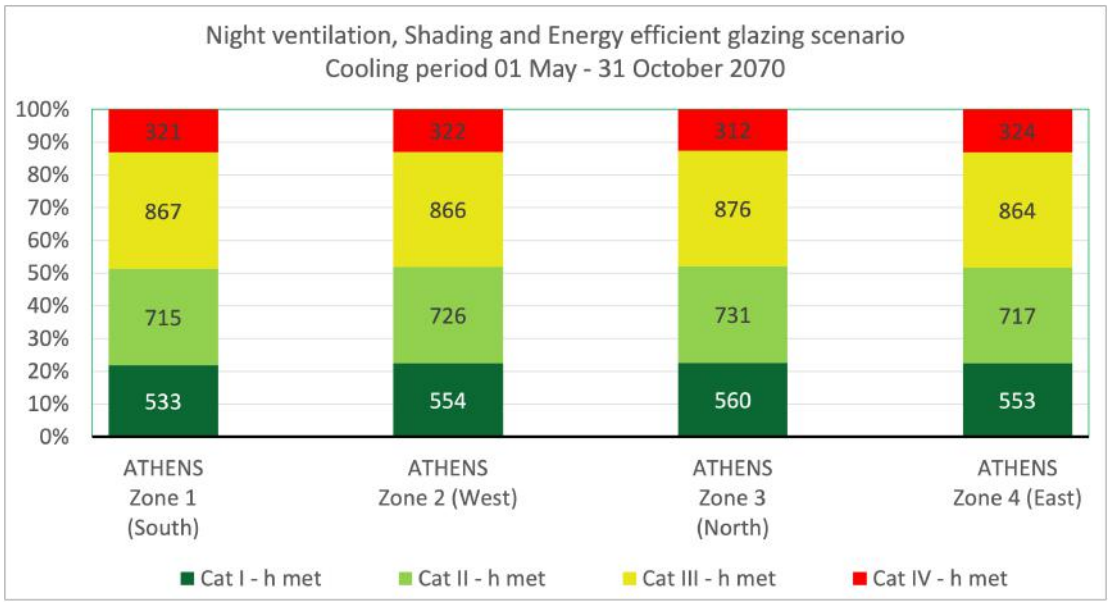

Figure 43. Night ventilation, shading and energy efficient glazing scenario 2070 Cooling period 01/05/2070 – 31/10/2070 in Athens according to EN 15251-2007 Standard

3.3.5 Evaluation of configuration scenario 4 – Thermal mass - exterior insulation

The thermal storage potential in a building material can affect the energy consumption, energy demand and thermal comfort of a building. Thus, another important influence on thermal comfort in offices is thermal mass, and the different wall, floor and ceiling constructions of "light", "medium" and "heavy" lead to a different classification of thermal comfort. A high thermal mass building is less likely to be affected by local climate variability than less robust buildings. In terms of providing adaptive thermal comfort according to EN15251 (2007), the building's robustness is a key parameter. In terms of climate variability, resilient buildings that are well protected from solar thermal gains and provide high thermal mass are more likely to provide satisfactory thermal comfort conditions for occupants without the need for a mechanical cooling system.

Another important parameter is the positioning of the insulation. An analytical solution for the response of a simple building exposed to periodic temperature conditions shows that the most effective wall systems are walls where the thermal mass is in good contact with the interior of the building and insulation on the exterior (Kossecka and Konsy 1998).

As described in chapter 2, in this scenario the change of thermal mass of the external wall only in the Athens case study is proposed, by replacing the cavity wall with a concrete wall with external insulation as designed in the Vienna office room scenario.

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Comparing the Fanger's indices in the diagram in Figure 44 between the basic scenario, the previous configuration scenario and finally the one with additionally applying also thermal mass, we can notice that the PMV/PPD values improve in each scenario.

At this point it should be mentioned that the present scenario concerns only buildings that have not been constructed, but are in the design phase, as the complete conversion of the thermal mass as described here is not feasible.

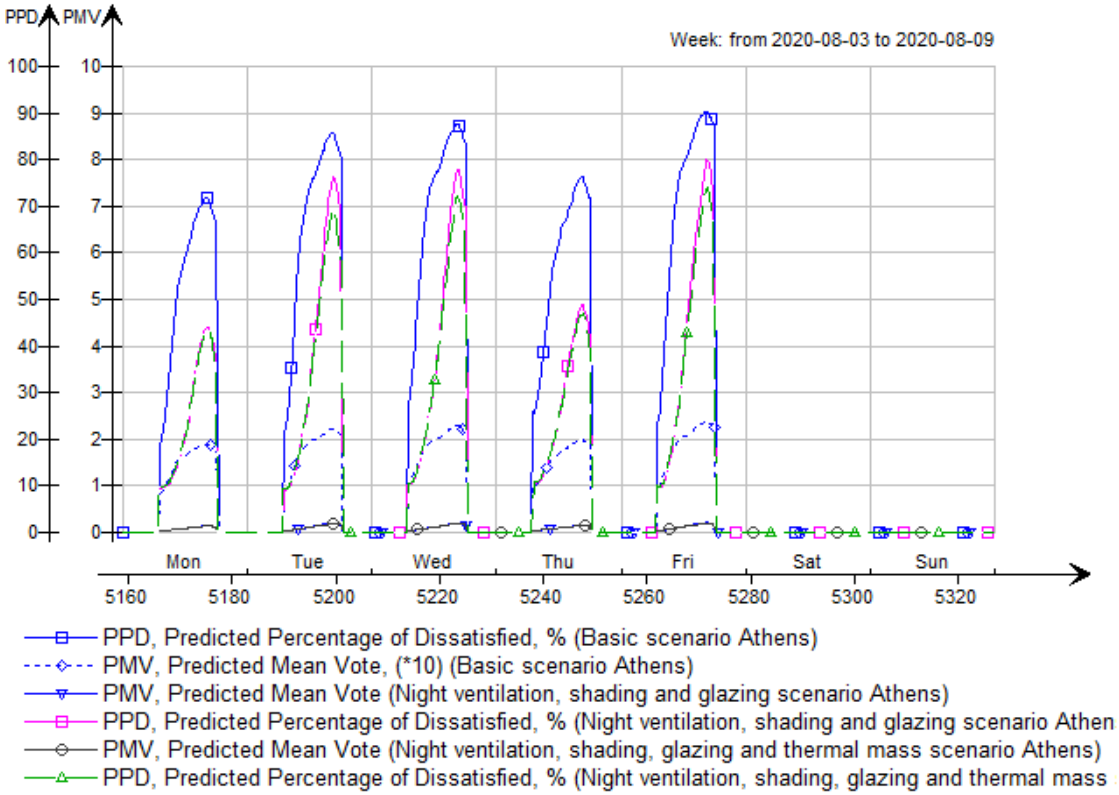

Figure 44. PMV/PPD comparison of 4 scenarios in Athens Zone 4 (East)
Comparison of the basic scenario and the scenarios with night ventilation, a shading device and energy efficient glazing as well as with night ventilation, shading device, energy efficient glazing and thermal mass

The results of the simulations comparing the four thermal zones with the application of the double structure thermal insulation glass on the previous scenario in the office room for the year 2020 are presented in the diagram in Figure 45.

The diagram shows that by changing the thermal mass only on the building façade and applying the external insulation, all four zones can achieve Category III in this scenario, only with a few hours out of the range.

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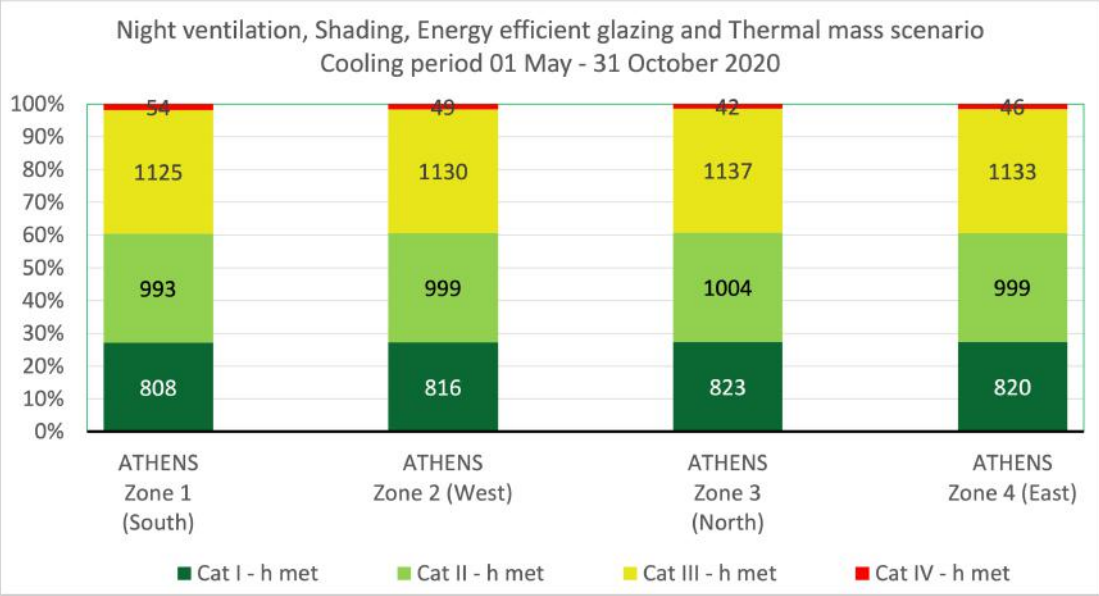

Figure 45. Night ventilation, shading, glazing and thermal mass scenario 2020
Cooling period 01/05/2020 – 31/10/2020 in Athens according to EN 15251-2007 Standard

The thermal comfort results of the simulations using the climate data of the year 2030 with the extreme scenario RCP8.5 are presented in the diagram in Figure 46.

Looking at the results from this diagram, it is clear that all zones are still within Category III.

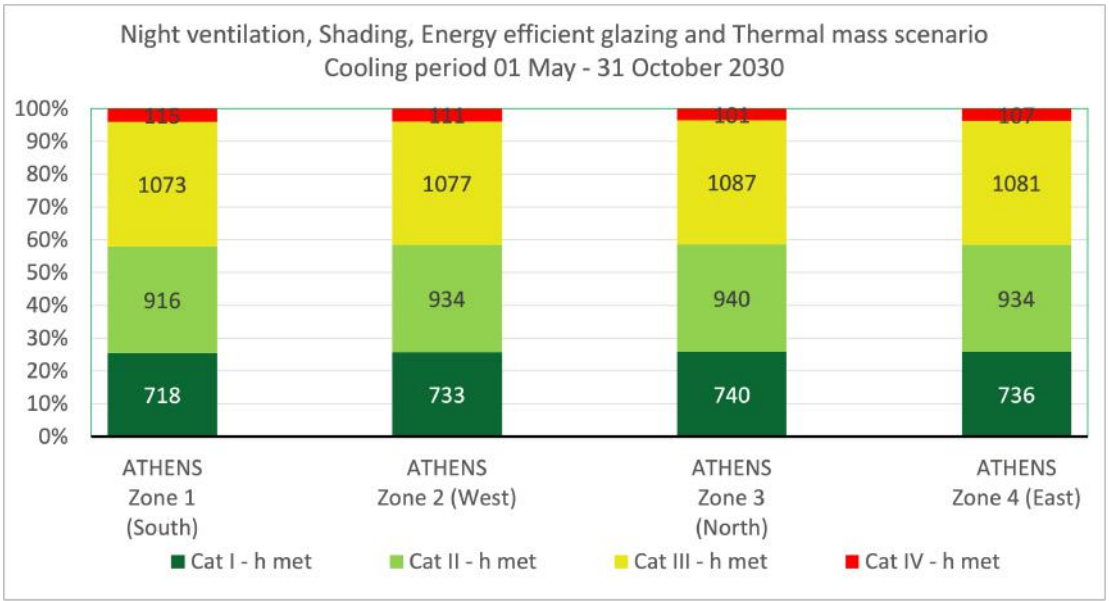

Figure 46. Night ventilation, shading, glazing and thermal mass scenario 2030
Cooling period 01/05/2030 – 31/10/2030 in Athens according to EN 15251-2007 Standard

Finally, for this scenario, simulations were carried out with the climate data of 2070. The results are presented in the diagram of Figure 47.

The results show that even with this configuration scenario, the climate conditions of 2070 in Athens are not recommended for an office building that uses only natural ventilation and is without a mechanical cooling system. Evidently, there is a need for engineers and architects

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to examine and design more efficient building configuration scenarios, in order to optimize thermal comfort in the space and to avoid the use of mixed cooling systems.

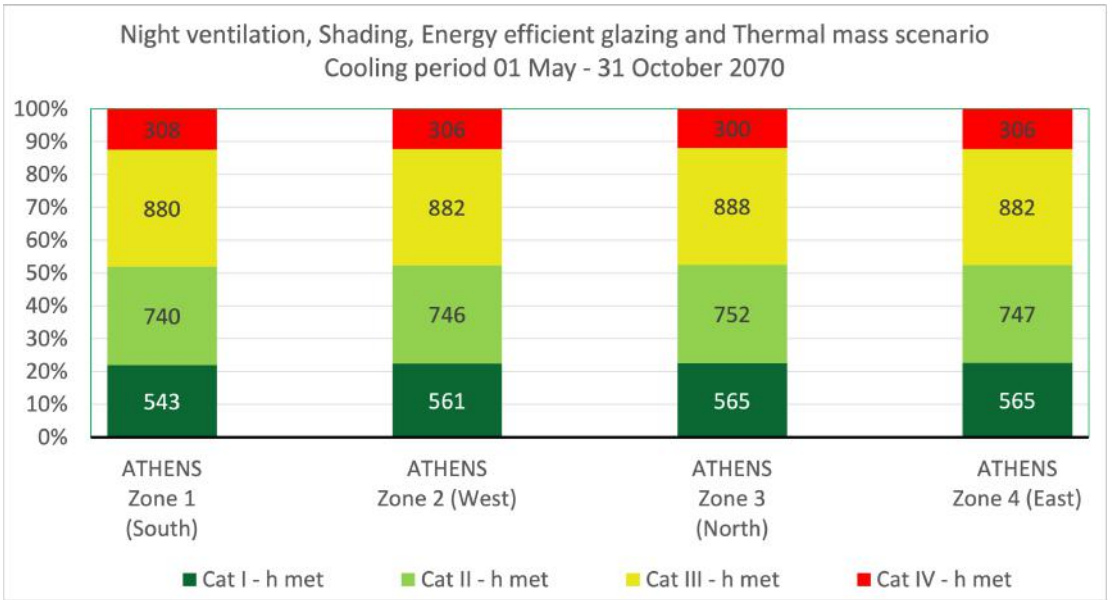

Figure 47. Night ventilation, shading, glazing and thermal mass scenario 2070 Cooling period 01/05/2070 – 31/10/2070 in Athens according to EN 15251-2007 Standard

3.4 Summary of results

The performance of the room is evaluated by calculating the number of actual hours converted into a % of the time during which the criteria are met or not. As described in the previous chapter, deviations from the selected criteria can be allowed. According to EN 15251 Standard (2007), some national criteria express acceptable deviations as an acceptable number of hours outside the criteria based on a yearly evaluation. In this work no national criteria for deviations have been considered. For the purposes of this study, as suggested in EN 15251, a maximum of 5% of working hours outside the limits of each category was considered acceptable.

Basic scenario in Vienna and Athens

In this chapter, the results of the simulations of the basic scenario for the case studies of Vienna and Athens are presented, comparing all building orientations in all future scenarios. In the tables below, the scenarios where the room does not exceed 5% of working hours outside category III are marked in bold and those that exceed this percentage are marked in grey.

As depicted in Table 6, the typical Vienna construction can provide acceptable thermal comfort conditions using natural ventilation in all building orientations for the years 2020 and 2030. From the percentages of exceeding Category III limits, in the first decade the discomfort

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in the room increases only slightly and therefore an additional mechanical cooling system could be avoided.

However, looking at the results for the year 2070, we see that the dissatisfaction in the space exceeds the 5% threshold by a considerable amount. The North zone is in a sufficiently better condition due to its orientation, however, even in this case the use of a mechanical cooling system is recommended.

Table 6 also presents the results from the typical Athens construction with the climate data of the region. In this case, the results show that in all orientations and in the contemporary as well as in all future scenarios, space overheating is very frequent and particularly in the long-term scenario of the year 2070, the use of mechanical cooling for about 25-35% of the occupied hours is deemed unavoidable.

Regarding the impact of the climate data compared to the basic building design configurations in each city, the results show that the Vienna construction could be acceptable for the next 10 years, but in the near future more drastic implementations are needed in terms of reducing energy consumption from the use of mechanical cooling. On the other hand, in the hot and dry climate of Athens, current standard construction methods are far from being considered efficient.

Table 6. Overlapping Category III – Vienna-Athens basic scenario
Percentage of overlapping Category III according to EN 15251-2007

Vienna basic scenario
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	524	2089	80%	910	1179	45%	1091	88	**3%**	88
Zone 1 - 2030	533	2073	80%	885	1188	46%	1074	114	**4%**	114
Zone 1 - 2070	391	1936	83%	748	1188	51%	936	252	**11%**	252
ZONE 2 - WEST										
Zone 2 - 2020	541	2109	80%	930	1179	44%	1093	86	**3%**	86
Zone 2 - 2030	563	2081	79%	893	1188	45%	1074	114	**4%**	114
Zone 2 - 2070	456	1971	81%	783	1188	49%	950	238	**10%**	238
ZONE 3 - NORTH										
Zone 3 - 2020	657	2252	77%	1073	1179	41%	1120	59	**2%**	59
Zone 3 - 2030	687	2191	76%	1003	1188	41%	1127	61	**2%**	61
Zone 3 - 2070	570	2063	78%	875	1188	45%	1021	167	**6%**	167
ZONE 4 - EAST										
Zone 4 - 2020	534	2130	80%	951	1179	44%	1090	89	**3%**	89
Zone 4 - 2030	543	2090	79%	902	1188	45%	1084	104	**4%**	104
Zone 4 - 2070	430	1959	82%	771	1188	50%	942	246	**10%**	246

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Athens basic scenario
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	508	1876	79%	697	1179	49%	860	319	13%	319
Zone 1 - 2030	463	1803	80%	615	1188	52%	776	412	18%	412
Zone 1 - 2070	300	1611	84%	423	1188	62%	548	640	33%	640
ZONE 2 - WEST										
Zone 2 - 2020	560	1886	77%	707	1179	48%	853	326	13%	326
Zone 2 - 2030	489	1817	79%	629	1188	52%	771	417	18%	417
Zone 2 - 2070	335	1633	83%	445	1188	60%	570	618	31%	618
ZONE 3 - NORTH										
Zone 3 - 2020	652	1983	75%	804	1179	45%	942	237	9%	237
Zone 3 - 2030	564	1910	77%	722	1188	48%	870	318	13%	318
Zone 3 - 2070	401	1725	81%	537	1188	56%	657	531	25%	531
ZONE 4 - EAST										
Zone 4 - 2020	496	1830	79%	651	1179	51%	781	398	17%	398
Zone 4 - 2030	424	1770	81%	582	1188	54%	721	467	21%	467
Zone 4 - 2070	287	1592	85%	404	1188	63%	527	661	35%	661

Night ventilation scenario in Vienna and Athens

The results of the application of night ventilation in the room are presented below. As can be seen in Table 7, in the case of Vienna the space meets the criteria for Category III for the years 2020 and 2030, having slightly improved the thermal comfort conditions compared to the basic scenario. However, the cooling of the thermal mass in the evening hours does not seem to be sufficient for the 2070 future scenario, as the space in all orientations remains slightly outside Category III with north zone to be more beneficial.

In the Athens case study, the results show that night ventilation is not able to create satisfactory thermal comfort conditions during working hours. Only in one case, on the north side in the year 2020, the space is marginally within Category III.

However, observing the results in the Table 7, is obvious that the percentage of improvement of the working hours that meet the thermal comfort conditions is significantly higher in the case of Athens. It seems that cooling the thermal mass during the evening hours in hot and dry climates contributes sufficiently to delay overheating during very hot days.

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Table 7. Overlapping Category III – Vienna-Athens night ventilation scenario
Percentage of overlapping Category III according to EN 15251-2007

Vienna configuration scenario 1: Night ventilation scenario
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	600	2140	78%	961	1179	43%	1124	55	**2%**	55
Zone 1 - 2030	626	2156	77%	968	1188	43%	1123	65	**2%**	65
Zone 1 - 2070	394	1942	83%	754	1188	51%	945	243	**10%**	243
ZONE 2 - WEST										
Zone 2 - 2020	641	2196	77%	1017	1179	42%	1132	47	**2%**	47
Zone 2 - 2030	677	2179	76%	991	1188	42%	1134	54	**2%**	54
Zone 2 - 2070	494	2005	80%	817	1188	48%	984	204	**8%**	204
ZONE 3 - NORTH										
Zone 3 - 2020	705	2287	76%	1108	1179	39%	1147	32	**1%**	32
Zone 3 - 2030	764	2250	75%	1062	1188	39%	1151	37	**1%**	37
Zone 3 - 2070	598	2082	78%	894	1188	44%	1038	150	**6%**	150
ZONE 4 - EAST										
Zone 4 - 2020	626	2181	78%	1002	1179	42%	1130	49	**2%**	49
Zone 4 - 2030	651	2183	77%	995	1188	42%	1132	56	**2%**	56
Zone 4 - 2070	470	1981	81%	793	1188	48%	960	228	**9%**	228

Athens configuration scenario 1: Night ventilation
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	626	2157	78%	827	1330	48%	1124	206	**7%**	206
Zone 1 - 2030	570	1942	77%	754	1188	47%	912	276	**11%**	276
Zone 1 - 2070	404	1741	81%	553	1188	55%	713	475	**22%**	475
ZONE 2 - WEST										
Zone 2 - 2020	705	2053	74%	874	1179	43%	1006	173	**6%**	173
Zone 2 - 2030	628	1991	76%	803	1188	45%	947	241	**9%**	241
Zone 2 - 2070	463	1790	79%	602	1188	53%	747	441	**20%**	441
ZONE 3 - NORTH										
Zone 3 - 2020	776	2121	73%	942	1179	41%	1057	122	**4%**	122
Zone 3 - 2030	689	2059	75%	871	1188	43%	1007	181	**7%**	181
Zone 3 - 2070	508	1850	78%	662	1188	50%	807	381	**16%**	381
ZONE 4 - EAST										
Zone 4 - 2020	585	1954	77%	775	1179	46%	920	259	**10%**	259
Zone 4 - 2030	509	1895	79%	707	1188	49%	856	332	**14%**	332
Zone 4 - 2070	369	1706	82%	518	1188	57%	656	532	**26%**	532

Night ventilation and shading system scenario in Vienna and Athens

The results of the application of an additional shading system in the previous scenario are presented below. Table 8 shows that in the case of Vienna, there is a slight improvement in all zones except the north. South zone 1 shows the highest percentage of improvement with

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the application of the shading system. It is also important to note that in the future climate scenario for the year 2070 the present configuration of the building prove to be sufficient to achieve Category III except of the south zone 1. However, zone 1 is slightly overlapping the 5% maximum deviation of Category III. Global warming slightly affects this building configuration.

In the Athens case study, the results show that the shading system is very efficient. All zones improve and reach Category III in the year 2020. In the year 2030 all zones exceed Category III, while the north zone is slightly above the allowed deviation of 5%. Thus, these building configurations natural ventilation is not sufficient and mechanical cooling is required for the years 2030 and 2070.

At this point it should be emphasized that the shading function is user adjustable and as mentioned in a previous chapter the parameters that affect the opening or closing of the shading are glare and temperature. It is considered that glare is more likely to occur when the sun is shining on the façade. Therefore, on the north zone where direct sunlight is minimal, it is reasonable that there is very little improvement in the thermal comfort of the space with the application of shading. On the other hand, the south façade appears to have the greatest benefits in this scenario.

Table 8. Overlapping Category III – Vienna-Athens night ventilation-shading scenario Percentage of overlapping Category III according to EN 15251 -2007

Vienna configuration scenario 2: Night ventilation + Shading
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	717	2289	76%	1110	1179	39%	1142	37	**1%**	37
Zone 1 - 2030	756	2255	75%	1067	1188	39%	1149	39	**1%**	39
Zone 1 - 2070	554	2054	79%	866	1188	46%	1035	153	**6%**	153
ZONE 2 - WEST										
Zone 2 - 2020	703	2286	76%	1107	1179	39%	1145	34	**1%**	34
Zone 2 - 2030	755	2247	75%	1059	1188	40%	1148	40	**1%**	40
Zone 2 - 2070	604	2086	78%	898	1188	44%	1043	145	**5%**	145
ZONE 3 - NORTH										
Zone 3 - 2020	707	2288	76%	1109	1179	39%	1146	33	**1%**	33
Zone 3 - 2030	766	2253	75%	1065	1188	39%	1151	37	**1%**	37
Zone 3 - 2070	604	2088	78%	900	1188	44%	1046	142	**5%**	142
ZONE 4 - EAST										
Zone 4 - 2020	703	2288	76%	1109	1179	39%	1145	34	**1%**	34
Zone 4 - 2030	757	2253	75%	1065	1188	39%	1150	38	**1%**	38
Zone 4 - 2070	597	2082	78%	894	1188	44%	1043	145	**5%**	145

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Athens configuration scenario 2: Night ventilation + Shading
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	757	2113	74%	934	1179	41%	1057	122	**4%**	122
Zone 1 - 2030	676	2052	75%	864	1188	44%	1005	183	**7%**	183
Zone 1 - 2070	490	1839	79%	651	1188	51%	815	373	**16%**	373
ZONE 2 - WEST										
Zone 2 - 2020	778	2116	73%	947	1169	40%	1053	116	**4%**	116
Zone 2 - 2030	691	2066	75%	878	1188	43%	1017	171	**6%**	171
Zone 2 - 2070	512	1853	78%	665	1188	50%	819	369	**16%**	369
ZONE 3 - NORTH										
Zone 3 - 2020	787	2134	73%	955	1179	40%	1069	110	**4%**	110
Zone 3 - 2030	700	2073	75%	885	1188	43%	1022	166	**6%**	166
Zone 3 - 2070	517	1862	78%	674	1188	50%	826	362	**15%**	362
ZONE 4 - EAST										
Zone 4 - 2020	776	2122	73%	943	1179	41%	1060	119	**4%**	119
Zone 4 - 2030	691	2060	75%	872	1188	43%	1011	177	**6%**	177
Zone 4 - 2070	512	1853	78%	665	1188	50%	810	378	**16%**	378

Night ventilation, shading and energy efficient glazing scenario in Athens

Considering that the Athens case study with the above building characteristics does not correspond to the climate conditions of 2070, two additional configuration scenarios were tested for Athens and the results of the first scenario are presented in Table 9. Considering that the building characteristics of the Vienna case study seem to be more effective to climate change, as a third scenario was chosen to use the window with energy efficient glazing in the Athens case study.

The results show that the performance improved and the office space for the years 2020 and 2030 lies in Category III in all orientations. Although the percentages improved, neither this scenario is satisfactory for the year 2070. This configuration cannot handle future global warming.

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Table 9. Overlapping Category III – Athens night ventilation-shading-glazing scenario Percentage of overlapping Category III according to EN 15251 -2007

Athens configuration scenario 3: Night ventilation + Shading + Energy efficient glazing
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	817	2177	73%	998	1179	39%	1112	67	**2%**	67
Zone 1 - 2030	734	2114	74%	926	1188	42%	1065	123	**4%**	123
Zone 1 - 2070	533	1903	78%	715	1188	49%	867	321	**13%**	321
ZONE 2 - WEST										
Zone 2 - 2020	825	2178	73%	999	1179	39%	1116	63	**2%**	63
Zone 2 - 2030	748	2122	74%	934	1188	41%	1068	120	**4%**	120
Zone 2 - 2070	554	1914	78%	726	1188	48%	866	322	**13%**	322
ZONE 3 - NORTH										
Zone 3 - 2020	834	2185	72%	1006	1179	39%	1119	60	**2%**	60
Zone 3 - 2030	757	2130	74%	942	1188	41%	1076	112	**4%**	112
Zone 3 - 2070	560	1919	77%	731	1188	48%	876	312	**13%**	312
ZONE 4 - EAST										
Zone 4 - 2020	821	2174	73%	995	1179	39%	1109	70	**2%**	70
Zone 4 - 2030	747	2119	74%	931	1188	41%	1065	123	**4%**	123
Zone 4 - 2070	553	1905	78%	717	1188	48%	864	324	**13%**	324

Night ventilation, shading, energy efficient glazing and thermal mass scenario in Athens

As a final and hypothetical scenario, the change of thermal mass on the external façade of the office room was chosen and an exterior wall as in the Vienna case study was applied. The results in Table 10 show that the thermal comfort improved, and this high optimized building configurations scenario is efficient to the climate conditions of the years 2020 and 2030. However, in the year 2070 the room lies within Category IV. This configuration is not effective to the global warming climate predictions for 2070. In any case, the option of changing thermal mass could only be applied to buildings that are in the design process and not to existing buildings.

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Table 10. Overlapping Category III – Athens night ventilation-shading-glazing-thermal mass scenario
Percentage of overlapping Category III according to EN 15251 -2007

Athens configuration scenario 4: Night ventilation, Shading, Energy efficient glazing, Thermal mass and increase of insulation
Investigated cooling period 01 May - 31 October

	Cat I - Max. 5% Overlapping			Cat II - Max. 5% Overlapping			Cat III - Max. 5% Overlapping			Cat IV (unacceptable)
	h met	h not met	percent not met	h met	h not met	percent not met	h met	h not met	percent not met	h met
ZONE 1 - SOUTH										
Zone 1 - 2020	808	2172	73%	993	1179	40%	1125	54	**2%**	54
Zone 1 - 2030	718	2104	75%	916	1188	42%	1073	115	**4%**	115
Zone 1 - 2070	543	1928	78%	740	1188	48%	880	308	**12%**	308
ZONE 2 - WEST										
Zone 2 - 2020	816	2178	73%	999	1179	39%	1130	49	**2%**	49
Zone 2 - 2030	733	2122	74%	934	1188	42%	1077	111	**4%**	111
Zone 2 - 2070	561	1934	78%	746	1188	48%	882	306	**12%**	306
ZONE 3 - NORTH										
Zone 3 - 2020	823	2183	73%	1004	1179	39%	1137	42	**1%**	42
Zone 3 - 2030	740	2128	74%	940	1188	41%	1087	101	**4%**	101
Zone 3 - 2070	565	1940	77%	752	1188	47%	888	300	**12%**	300
ZONE 4 - EAST										
Zone 4 - 2020	820	2178	73%	999	1179	39%	1133	46	**2%**	46
Zone 4 - 2030	736	2122	74%	934	1188	42%	1081	107	**4%**	107
Zone 4 - 2070	565	1935	77%	747	1188	48%	882	306	**12%**	306

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4 DISCUSSION

In this study, the adaptive thermal comfort model of EN 15251 (2007) was applied for different configurations of a virtual cellular office room in Vienna and Athens, considering the behaviour of the occupants. In addition, the influence of a contemporary, a medium- and long-term climate forecast and typical weather prediction dataset for each location was compared.

The simulations showed that thermal comfort in office spaces is highly dependent on the properties of the building as well as on the orientation.

Buildings with implemented night ventilation as a cooling strategy and protection from solar heat gains through shading systems, energy efficient glazing and the provision of high thermal mass, are less likely to be affected by local climate variability than less thermally protected buildings. They are more likely to provide satisfying thermal comfort conditions for occupants, without the need of a mechanical cooling system.

In any case, in terms of comfort assessment, the climate dataset should be carefully selected according to the focus of the study. The use of different climate datasets for the building simulation shows that local climate variability can have a significant impact on thermal comfort in office buildings. Moreover, the research shows that in future climate scenarios, which consider a high degree of deterioration due to global warming, the typical building technology used nowadays is far from able to meet the thermal comfort needs in the long-term climate scenario of 2070, especially in hot and dry climates, such as that of Athens. In more temperate climates, such as in Vienna, thermal comfort conditions are far better, but still marginal and overheating is observed more frequently than in the contemporary scenarios, while for the 2070 scenario thermal comfort conditions cannot be achieved.

4.1 The influence of building design

The graphs in Figures 48 and 49 show the working hours in the office room in Vienna and Athens that exceed the thermal comfort zone and are therefore classified in Category IV according to the EN 15251 Standard (2007). Comparing the results of the simulations for the cooling period 01/05/2020 - 31/10/2020 the results show that in the case study of Vienna even without adaptations, it was possible to meet the criteria of the adaptive thermal comfort model of EN15251 of Category III, as shown in Tables 6. With minor adaptations such as the implementation of night ventilation and a shading system, it was possible to improve thermal comfort, therefore a mechanical cooling system is not considered necessary.

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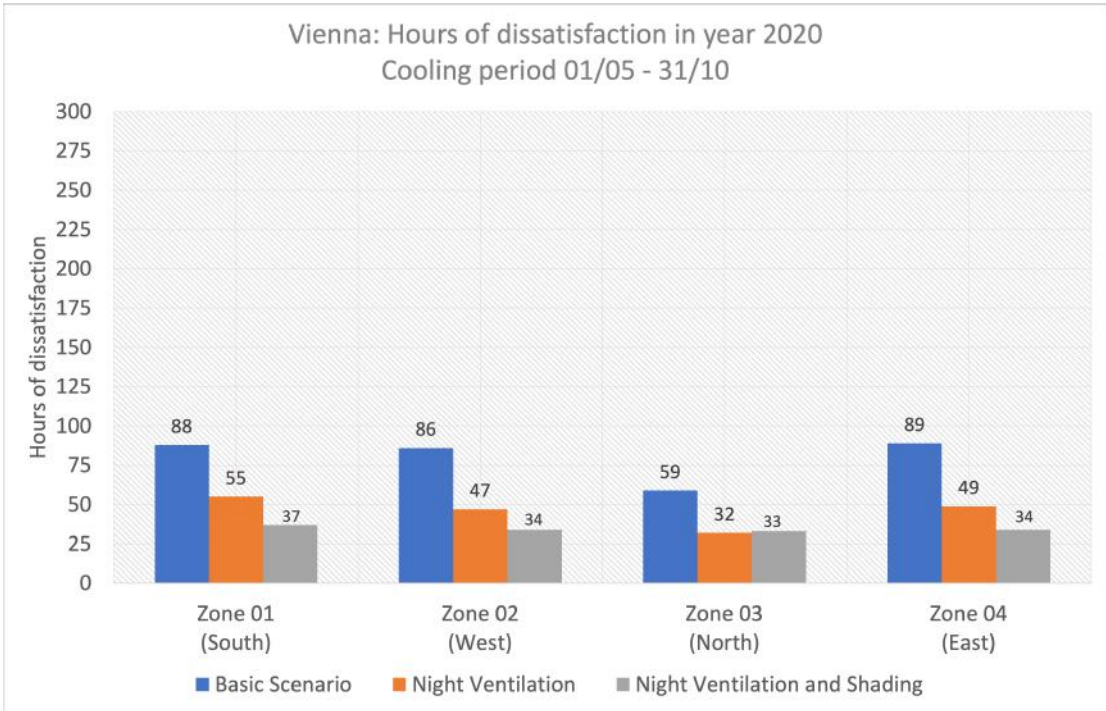

Figure 48. Working hours of thermal discomfort in Vienna, scenario 2020 Cooling period 01/05/2020 - 31/10/2020

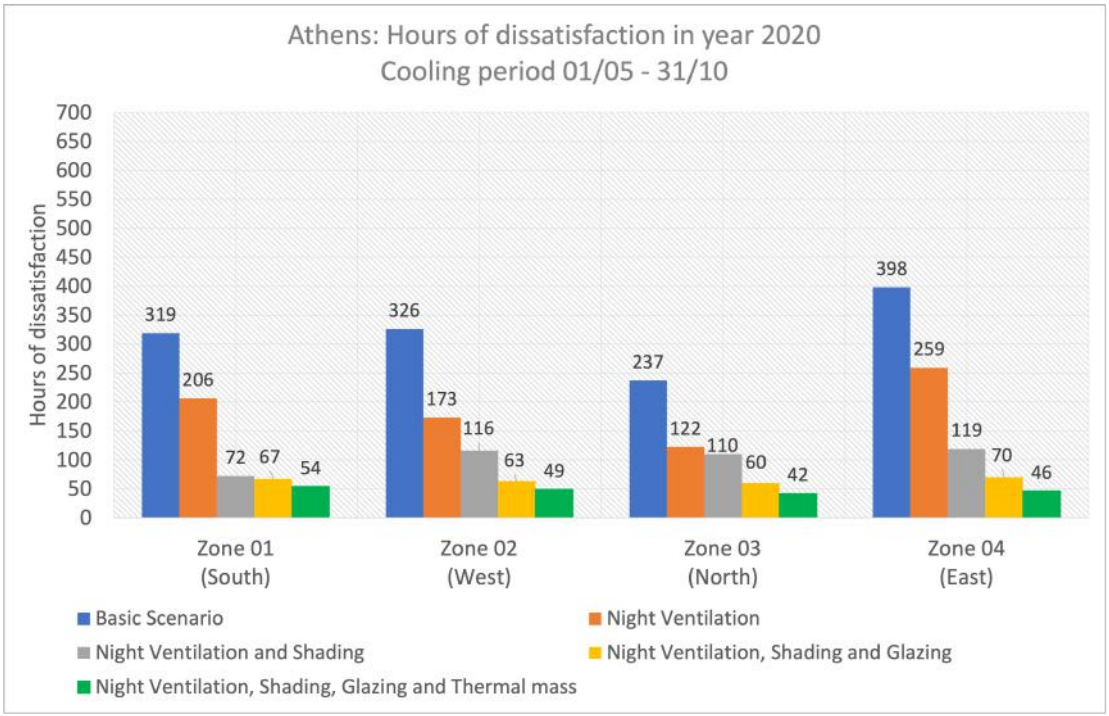

Figure 49. Working hours of thermal discomfort in Athens, scenario 2020 Cooling period 01/05/2020 - 31/10/2020

Furthermore, the results of the above figures show that the north-facing façade, provides more acceptable thermal comfort conditions compared to all other orientations. However, it was found that the use of a shading system is more effective on the south- and east-facing façade than on the north-facing façade where direct radiation is minimal.

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On the contrary, in the case study of Athens it seems that meeting the criteria of Category III for the adaptive thermal comfort model of EN 15251 was only possible for a highly optimized building. However, this configuration is not the most likely variant in an existing office environment, as it takes thermal mass into account and thermal mass adaptation in existing buildings is uncommon or a high-cost configuration that is not preferred by the stakeholders. This combination of configurations could be more fitting in new buildings, or buildings which are in the design process, where all the above parameters will be considered and adapted to the building design. Thus, it is likely that nowadays most office buildings with natural ventilation in Athens do not meet the requirements of the adaptive thermal comfort model of EN 15251.

Furthermore, assuming that internal thermal mass could also be beneficial, the problem in this configuration scenario would be that in office walls the additional flexibility required in terms of potentially changing the layout with each tenant change is not feasible. In addition, lightweight walls are more cost effective than solid walls, a parameter that stakeholders consider important. For this reason, although it could have a significant positive effect on thermal comfort (Roetzel 2009), a heavy construction is usually hardly realistic in office buildings.

4.2 The influence of the climate change

In order to assess the impact of climate change and projected climate data on thermal comfort, the percentage of working time that does not meet the criteria for comfort Category III according to EN 15251 was compared with the climate data of the years 2030 and 2070. Figures 50, 51, 52 and 53 show the working hours that the user are in thermal discomfort for the years 2030(RCP8.5) and 2070(RCP8.5) respectively for the Vienna and Athens case studies.

The strongest impact of future climate data is observed in the case study of Athens, as even for the highly optimized variation, the total hours of discomfort are almost twice as high as for the highly optimized variation in Vienna.

Analyzing the simulation results, it was found that the office in the case study of Vienna with the optimized configuration, could maintain the range of Category III of the EN 15251 Standard for the scenario of 2030, although for the year 2070 it exceeds the limits in the first two scenarios. However, in the third scenario, it is within the thermal comfort limits except for the southern zone 1 which exceeds 5%. In all cases the northern orientation is the most advantageous in contrast to the southern orientation, which appears to be the most unpleasant from thermal point of view.

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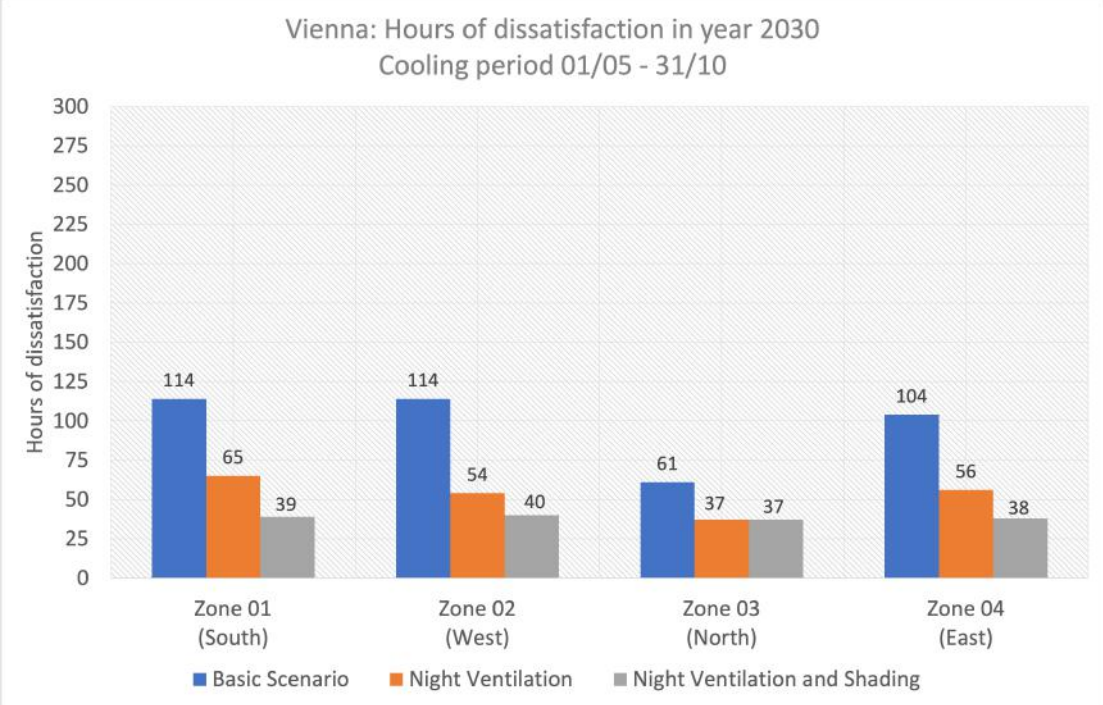

Figure 50. Working hours of thermal discomfort in Vienna, scenario 2030 Cooling period 01/05/2030 - 31/10/2030

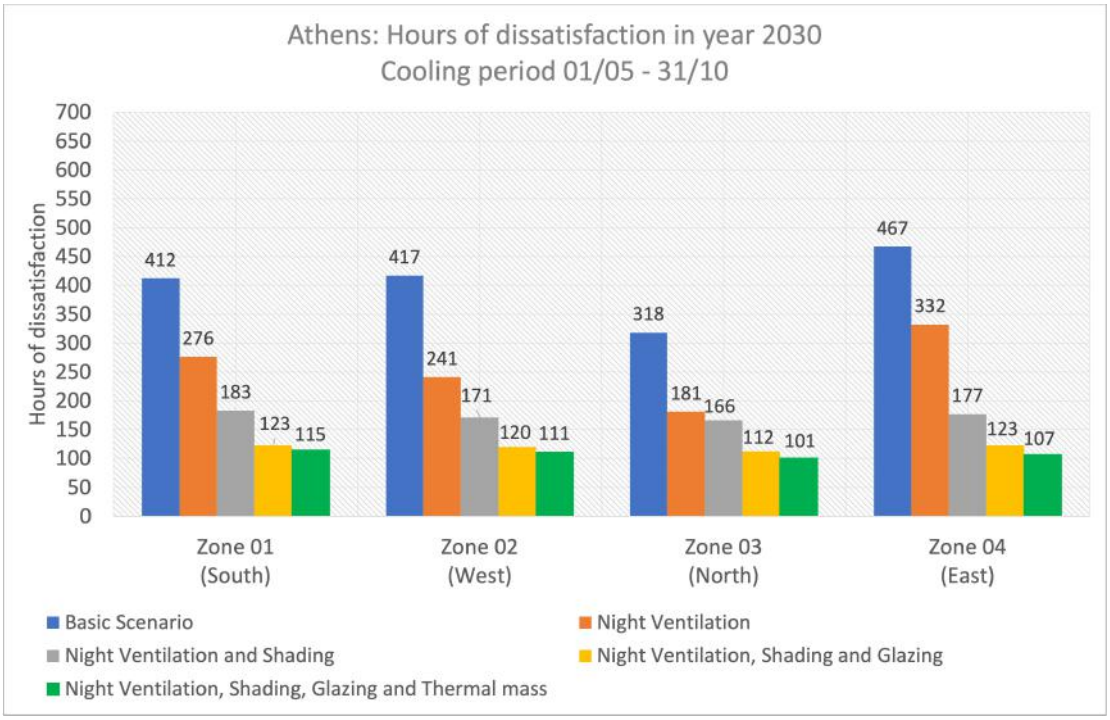

Figure 51. Working hours of thermal discomfort in Athens, scenario 2030 Cooling period 01/05/2030 - 31/10/2030

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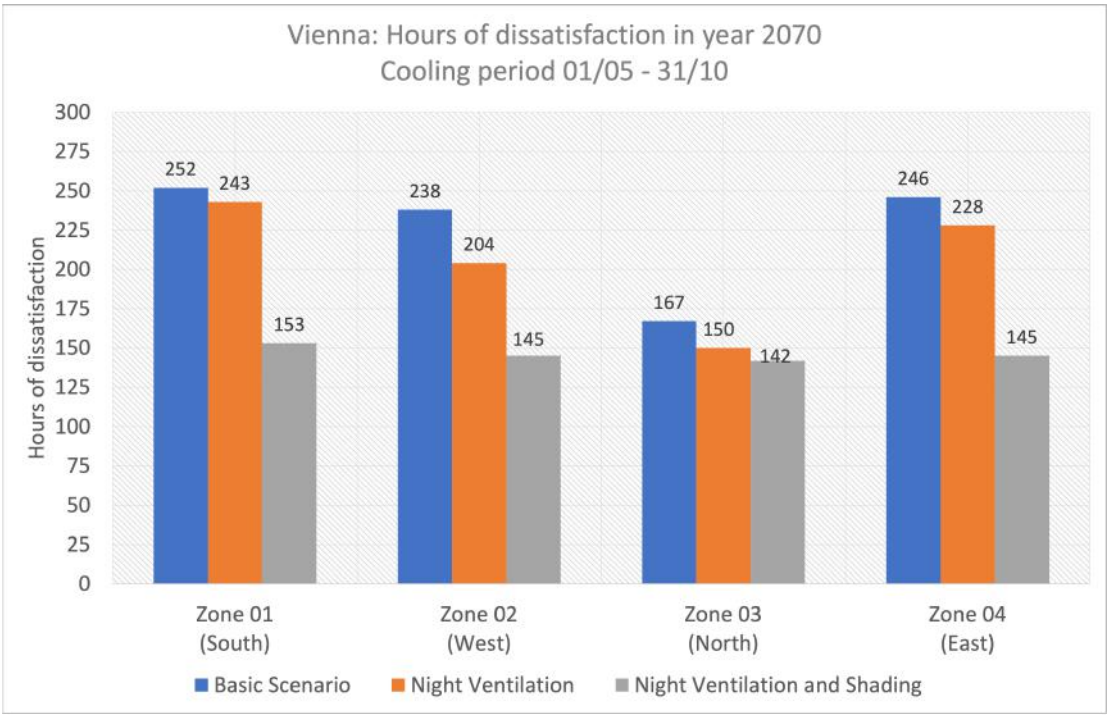

Figure 52. Working hours of thermal discomfort in Vienna, scenario 2070 Cooling period 01/05/2070 - 31/10/2070

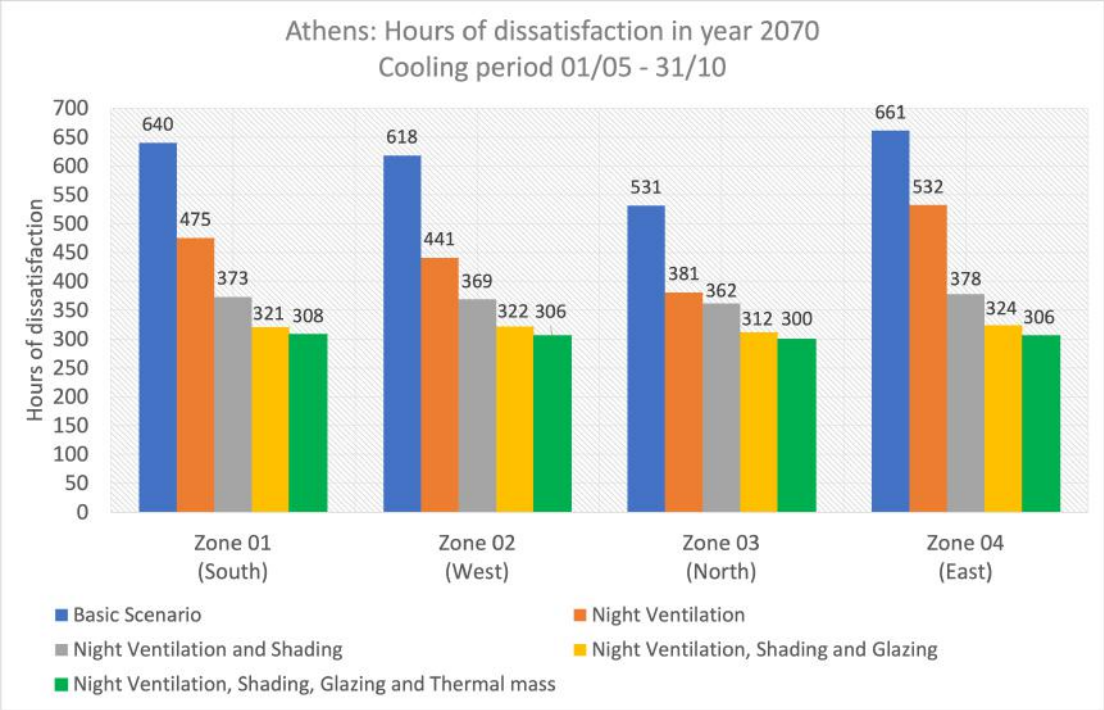

Figure 53. Working hours of thermal discomfort in Athens, scenario 2070 Cooling period 01/05/2070 - 31/10/2070

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Regarding the Athens case study, the office building cannot meat Category III after applying night ventilation and a shading system in contrast to the Vienna case study. However, with the implementation of energy efficient glazing and thermal mass on the façade, the results show that it meets the criteria for Category III for the year 2030 but is far from the thermal comfort limits for the future scenario of 2070.

This raises the question as to what extent the use of mechanical cooling systems could be reduced in the climate of Athens, if at the same time it seems almost impossible to achieve thermal comfort Category III in naturally ventilated buildings, even after implementing multiple variations of building configurations. However, as stated in EN 15251 (2007), comfort limits above a current average outdoor temperature are based on a limited database. Further research would be needed to determine whether the occupants of naturally ventilated buildings in Athens and in general in hot and dry climates are more tolerant of high temperatures than assumed in EN 15251. Further field research would be needed regarding this assumption.

Moreover, as for the façade orientation as an important influencing parameter to thermal comfort, the future impacts of climate change and the associated increase in temperatures, it is essential that high internal thermal loads should be avoided. Where this is not possible, energy-consuming operations would be recommended to locate on the north side of the building.

Looking at the above graphs, it can be concluded that the higher the solar gains and the less resistant the building is in preventing overheating, the warmer climate conditions in future climate scenarios will reduce the percentage of working hours under thermal comfort sensation in the office, using only natural ventilation.

The building sector has a significant share of total GHG emissions and most countries are continuously adapting the energy requirements of buildings in order to reduce emissions and mitigate climate change. A careful combination of all the parameters of the building design, offers wider configuration possibilities that could help to avoid mechanical cooling in offices. However, this possibility can only be beneficial for a specific building if parameters such as building configurations as well as the needs of future users are considered already in the early stages of design in combination with the appropriate selection and prevention of future climate characteristics.

It is a fact that the climate is changing globally, leading to rising temperatures. This change is directly related to the building design and affects the thermal comfort conditions of the users. Our knowledge of future climate data is limited only to predictive models, which can be used

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by designers to simulate the energy and thermal comfort needs of buildings in future scenarios. In addition, during the design process it must be considered that the lifespan of a building is significantly long, therefore it is important for the designer to simulate future climate scenarios so that the building can provide the required thermal comfort over time and with the least possible use of mechanical cooling energy consumption.

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5 CONCLUSION

The purpose of this work was to evaluate the thermal comfort of a virtual cellular natural ventilated office room without mechanical cooling systems in the climates of Vienna, Austria and Athens, Greece, by following the assessment method of the adaptive thermal comfort model of EN 15251 standard.

The research focused on two main topics. The first topic investigated the correlation between design configurations that could increase thermal comfort levels in spaces such as office buildings and how effective they are in different climates, and the second topic examined how effective these configurations are in view of climate predictions regarding global warming during the summer months.

5.1 Natural ventilation comfort levels with adapted building configurations

For the purpose of this work, in the first part of the research, the virtual cellular office room was designed and the typical construction characteristics as well as the contemporary local climate data of each country were simulated using the IDA ICE (Indoor Climate and Energy) thermal simulation software. Various scenarios of adapted building configurations were applied and the possibilities to optimize users' thermal comfort through these scenarios in the context of naturally ventilated offices were investigated.

Comparing the different scenarios, it can be concluded that the higher the solar gains and the less protected the building is through passive cooling systems, the worse the thermal comfort conditions become. Thermally robust buildings, which are well protected from solar heat gains, are more likely to provide satisfying thermal comfort conditions for occupants, without the need for a mechanical cooling system.

Furthermore, the use of different meteorological data sets and the orientation of the room seem to have a significant impact on the thermal comfort of office users. In the climate of Vienna, the results show better thermal comfort conditions compared to the climate of Athens. Also, the typical building construction of Vienna is thermally more efficient compared to the typical construction of Athens. In the case study of Vienna, even in the basic scenario (without night ventilation and shading system), the office room lies within the thermal comfort range of Category III for the adaptive thermal comfort model of EN 15251 Standard in the contemporary climate and in all orientations. In the case study of Athens, it was found that only by applying night ventilation and a shading system was it possible to meet the criteria of Category III in the contemporary climate.

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The general characteristics regarding the distribution of thermal comfort exceeding hours seem to be predetermined by climate. The magnitude as well as the range of room temperatures during the year are mainly influenced by the combination of the building configuration scenario.

The thoughtful combination of all building design parameters offers broader optimization possibilities, which could help to avoid mechanical cooling in offices. However, this potential can only be beneficial if the building configuration and the needs of future users are considered from the early design stages, together with appropriate selection and prevention of local climate characteristics.

5.2 Building design and climate change

In the second part of the study, the combination of the proposed parameters was applied to a short-term climate scenario for the year 2030 and a long-term scenario for the year 2070. The climate data were extracted from the “Meteonorm 8” software database considering the worst-case scenario with very high GHG emissions (RCP8.5).

The use of different climate datasets for building simulation shows that climate variability can have a significant impact on thermal comfort in office buildings. For the climate scenario of 2030 the study shows that the highly optimized office rooms could be in the range of Category III for all directions. The north direction is always the more beneficial in contrast to the east and south façade orientations.

Furthermore, the simulation results show that the typical building technology used today, without using passive cooling systems, is unable in any case to meet the thermal comfort needs in all climate scenarios in the hot and dry climate of Athens. In the temperate climate of Vienna, thermal comfort conditions are much better, but still marginal. In the 2070 scenario thermal comfort conditions cannot be achieved and mechanical cooling systems should be applied in all cases.

According to the results of this work, the selected building configurations proposed that also comply with EN 15251 are not effective in terms of thermal comfort for naturally ventilated offices against global warming in both climates of Vienna and Greece.

The thorough combination of all building design parameters and the consideration of the users' behaviour, offer broader possibilities to optimize the thermal comfort of an office space. If the above parameters in combination with predictions of future climate data could be considered from the early stages of the design of a building, through the use of thermal

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simulation software, it is possible to replace mechanical cooling with natural ventilation in offices.

Climate change is directly linked to building design and affects the thermal comfort conditions of occupants. Our knowledge of future climate data is limited only on predictive climate models. It is important that building designers simulate combinations of building configurations along with future climate scenarios so that the building can provide the required thermal comfort over time and with the lowest possible mechanical cooling energy consumption.

5.3 Limitations of this work

Although modern building simulation software has come a long way and can provide a wide range of tools that help the designer to better understand the energy design needs of a building, the field study often offers much more reliable results. In building simulation, it is very difficult to consider all the interdependencies that can affect thermal comfort. Therefore, it is proposed that the results of this research should be examined and compared further through field studies.

In particular, the literature shows that regarding occupant-controlled light switching as well as window opening, the variety of individual influences is very difficult to reflect in building simulation, since the parameters are limited to physically measurable variables, without considering each individual behavior in the space. Studies attempt to investigate at an appropriate level of analysis the combined effects of inaccuracies due to simulation algorithms and weather prediction on the reliability of control system recommendations (Mahdavi et al. 2009).

Furthermore, this work shows that the weather dataset for use in building simulation should be carefully selected according to the focus of the study. The reliability of the thermal comfort simulation results depends on the accuracy of the weather predictions. Further research should analyze in a detailed and quantitative manner whether weather datasets including climate change scenarios and heat island effects are reliable. More detailed and comprehensive studies are required.

5.4 Suggestions for further research

This work has revealed areas of research that would be worth exploring further. The concerns and research ideas that emerged from this work are presented below.

- Real estate market and costs are very often a critical parameter, which is directly reflected to building design. How the stakeholders and the mechanisms of real estate

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market affect the building design configuration could be investigated. Further research would be needed to examine promotion strategies of green office buildings.

- In EN 15251 standard (2007) it is stated that comfort limits above a current average outdoor temperature are based on a limited database. Further research would be needed to determine whether the occupants of naturally ventilated buildings in hot and dry climates are more tolerant of high temperatures than assumed in EN 15251. Further field research would be needed regarding this assumption.
- Strategies should be developed to assess the potential and limitations of adaptive thermal comfort in relation to building design characteristics and future climate changes at early design stages.

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INDEX

Abbreviations

ACH	Air Changes per Hour
BRIS	Brise Soleil
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CO_2	Carbon dioxide
DBT	Dry Bulb Temperature
EN	European Norm / European Standard
EPBD	Energy Performance of Buildings
GHG	Greenhouse Gas
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IAQ	Indoor Air Quility
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
MRT	Mean Radiant Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RCP	Representative Concentration Pathway
RH	Relative Humidity
SHGC	Solar Heat Gain Coefficient
UHI	Urban Heat Island
USGBC	United States Green Building Council

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List of Figures

Figure 1. Thermal interaction of the human body and environment 11
Figure 2. PPD as a function of PMV (ANSI/ASHRAE Standard 55 2004) 13
Figure 3. Acceptable indoor temperatures for design of natural ventilation buildings ... 16
Figure 4. The Köppen Climate Classification System, (Peel et al. 2007) 21
Figure 5. Average monthly temperatures for Vienna, (Meteonorm 8 2020) 22
Figure 6. Average monthly precipitation for Vienna, (Meteonorm 8 2020) 22
Figure 7. Average monthly temperatures for Athens, (Meteonorm 8 2020) 23
Figure 8. Average monthly precipitation for Athens, (Meteonorm 8 2020) 23
Figure 9. Mean annual air temperature for 2020, 2030 and 2070 in Vienna and Athens 25
Figure 10. 3D model of the office building envelope, created in IDA ICE 27
Figure 11. Office room geometry, created in IDA ICE 29
Figure 12. Floor plan illustrating the 4 office rooms, created in IDA ICE 29
Figure 13. Wall construction specification - Vienna, created in IDA ICE 30
Figure 14. Roof construction specification - Vienna, created in IDA ICE 31
Figure 15. Wall construction specification - Athens, created in IDA ICE 31
Figure 16. Example of an exterior cavity wall in Athens, (Roetzel, 2009) 32
Figure 17. Roof construction specification - Athens, created in IDA ICE 32
Figure 18. Occupancy profile for the office room, created in IDA ICE 33
Figure 19. Artificial lighting profile for the office room, created in IDA ICE 34
Figure 20. Standard equipment profile for the office room, created in IDA ICE 34
Figure 21. Indoor air quality for a week in Vienna. Basic scenario, Zone 1 (south) 36
Figure 22. Ventilation air flows for a single day in Vienna without night ventilation 37
Figure 23. Ventilation air flows for a single day in Vienna with night ventilation 38
Figure 24. Shading control for a single day in Vienna 39
Figure 25. Glass construction and specification for the standard window in Athens 40
Figure 26. Glass construction and specification for the optimized window in Athens 41
Figure 27. Basic scenario 2020 44
Figure 28. Basic scenario 2030 45
Figure 29. Basic scenario 2070 46
Figure 30. PMV/PPD indicators, comparison of 2 scenarios in Vienna, Zone 1 (south) 47
Figure 31. Night ventilation scenario 2020 48
Figure 32. Night ventilation scenario 2030 49
Figure 33. Night ventilation scenario 2070 49
Figure 34. Daylight at a desktop - basic scenario Vienna, Zone 4 (East) 51

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The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek WIEN Your knowledge hub

Figure 35. Daylight at a desktop - night ventilation and shading, Vienna, Zone 4 (East) ...51
Figure 36. PMV/PPD comparison of 3 scenarios in Vienna, Zone 4 (East) 52
Figure 37. Night ventilation and shading scenario 2020 53
Figure 38. Night ventilation and shading scenario 2030 54
Figure 39. Night ventilation and shading scenario 2070 54
Figure 40. PMV/PPD comparison of 3 scenarios in Athens, Zone 4 (East) 56
Figure 41. Night ventilation, shading and energy efficient glazing Scenario 2020.....56
Figure 42. Night ventilation, shading and energy efficient glazing scenario 2030.....57
Figure 43. Night ventilation, shading and energy efficient glazing scenario 2070.....58
Figure 44. PMV/PPD comparison of 4 scenarios in Athens Zone 4 (East) 59
Figure 45. Night ventilation, shading, glazing and thermal mass scenario 2020 60
Figure 46. Night ventilation, shading, glazing and thermal mass scenario 2030 60
Figure 47. Night ventilation, shading, glazing and thermal mass scenario 2070 61
Figure 48. Working hours of thermal discomfort in Vienna, scenario 2020 70
Figure 49. Working hours of thermal discomfort in Athens, scenario 2020 70
Figure 50. Working hours of thermal discomfort in Vienna, scenario 2030 72
Figure 51. Working hours of thermal discomfort in Athens, scenario 2030 72
Figure 52. Working hours of thermal discomfort in Vienna, scenario 2070 73
Figure 53. Working hours of thermal discomfort in Athens, scenario 2070 73

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The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU WIEN Bibliothek Your knowledge hub

List of Tables

Table 1. Parameters affecting thermal comfort (ANSI/ASHRAE Standard 55 2004) 11

Table 2. Thermal sensation scale of PMV (ANSI/ASHRAE Standard 55 2004) 12

Table 3. Description of the applicability of the categories used in EN15251 (2007) 15

Table 4. Parameters affecting the air temperature inside a natural ventilated building 18

Table 5. Mean annual values for the Vienna and Athens climate (Meteonorm 8 2020) 24

Table 6. Overlapping Category III – Vienna-Athens basic scenario 62

Table 7. Overlapping Category III – Vienna-Athens night ventilation scenario 64

Table 8. Overlapping Category III – Vienna-Athens night ventilation-shading scenario 65

Table 9. Overlapping Category III – Athens night ventilation-shading-glazing scenario 67

Table 10. Overlapping Category III – Athens night ventilation-shading-glazing-thermal mass scenario 68

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APPENDIX

A. "Meteonorm 8" climate data for Vienna and Athens

Wien-Hohe Warte
Location name

48.25
Latitude [°N]

16.367
Longitude [°E]

110350
WMO

209
Altitude [m a.s.l.]

III, 3
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2000–2019
Temperature period

1991–2013
Radiation period

Additional information

Uncertainty of yearly values: Gh = 5%, Bn = 10%, Ta = 0,3 °C
Trend of Gh / decade: 3,3%
Variability of Gh / year: 6,0%
P90 and P10 of yearly Gh, referenced to average: 92,1%, 108,2%

Month	Ta	H_Gh	Td	RH	H_Dh	FF	Lin	PP
	[°C]	[kWh/m2]	[°C]	[%]	[kWh/m2]	[m/s]	[kWh/m2]	[hPa]
January	1.0	28,6	-2.7	76.1	20,4	3.8	199	988
February	2.5	49,9	-2.1	71.4	25,8	3.8	180	988
March	6.6	88,5	0.6	65.4	50,0	3.8	211	989
April	12.0	133,8	5.0	62.0	59,9	3.5	220	989
May	16.1	171,0	9.2	63.7	79,7	3.6	245	989
June	20.0	176,1	12.7	62.8	88,4	3.4	251	990
July	21.6	178,2	14.1	62.3	79,5	3.5	266	990
August	21.1	155,7	14.0	64.0	75,6	3.1	265	990
September	16.1	105,0	10.6	69.6	53,1	3.2	242	989
October	10.9	62,0	7.1	77.2	35,3	3.0	238	989
November	6.5	29,0	3.0	78.4	19,5	3.5	216	988
December	2.0	21,0	-1.4	78.0	14,7	3.6	205	988
Year	11.4	1196,2	5.8	69.2	601,8	3.5	2736	989

Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

1/4

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Month	Sd	N	TL	Bn	H_Ghmax	H_Gex	H_PAR	Snd
	[h]	[octas]	[ ]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[mm]
January	56	7	2.7	32,0	59	88	12,5	12.0
February	78	5	2.9	65,3	81	122	21,2	6.4
March	126	5	3.3	84,3	146	205	38,0	1.2
April	170	4	3.8	132,7	195	269	57,4	0.0
May	221	4	3.8	151,0	246	333	74,0	0.0
June	223	4	3.7	136,7	254	347	77,0	0.0
July	246	4	3.6	157,8	257	346	78,1	0.0
August	228	4	3.6	136,0	215	300	68,7	0.0
September	171	5	3.4	102,0	168	226	46,6	0.0
October	137	6	3.2	63,6	111	161	27,9	0.0
November	63	7	2.9	32,1	66	99	13,2	0.0
December	52	7	2.7	26,4	48	75	9,5	2.1
Year	1771	5	3.3	1119,9	1841	2565	522,9	1.8

Ta: Air temperature
RH: Relative humidity
Ta min: 10 y minimum (approx.)
Ta max: 10 y maximum (approx.)
Ta dmin: Mean daily minimum Ta
Ta dmax: Mean daily maximum Ta
SD: Sunshine duration
RR: Precipitation
RD: Days with precipitation
FF: Wind speed
SD astr.: Sunshine duration, astronomic
DD: Wind direction
Snd: Snow depth
H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
PAR: Photosynthetically active radiation

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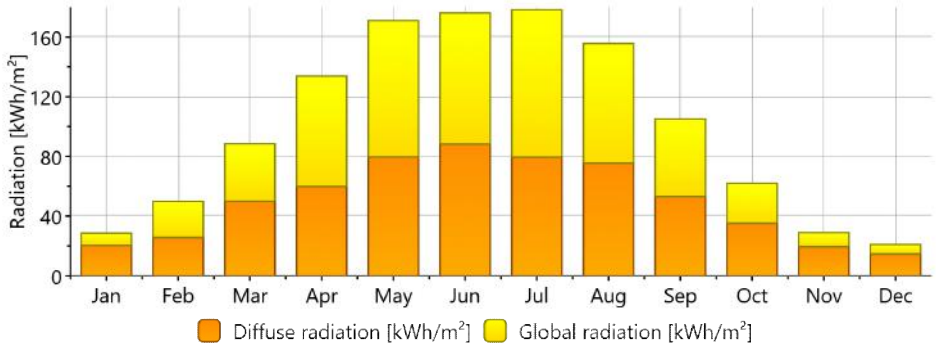
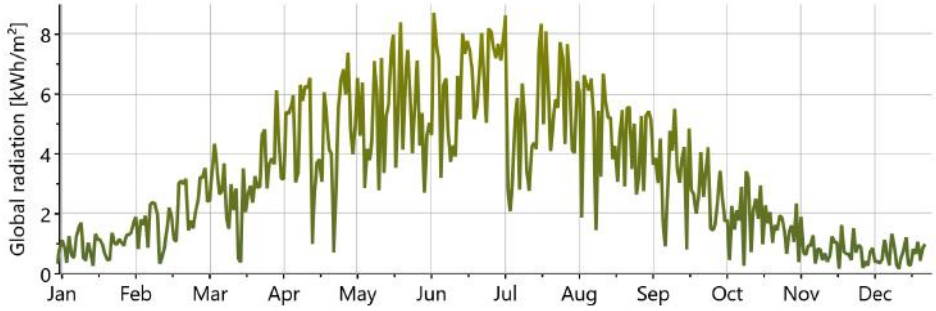
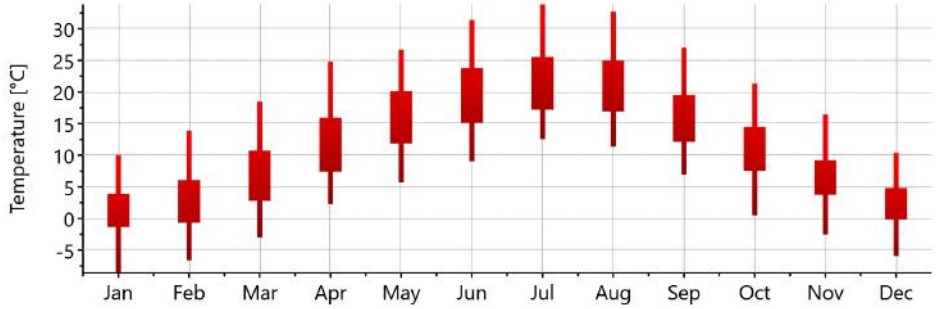
Monthly radiation



Daily global radiation



Monthly temperature



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

3/4

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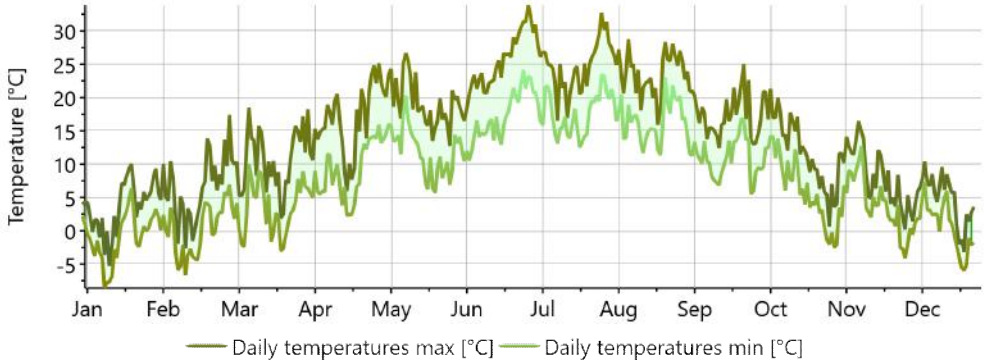
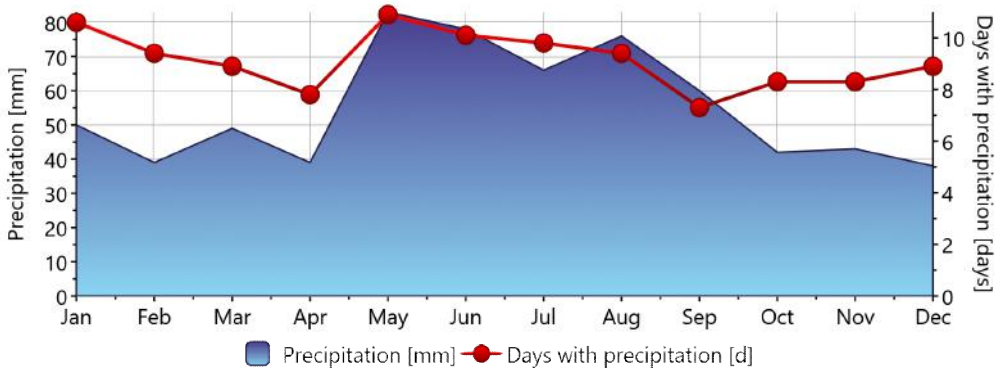
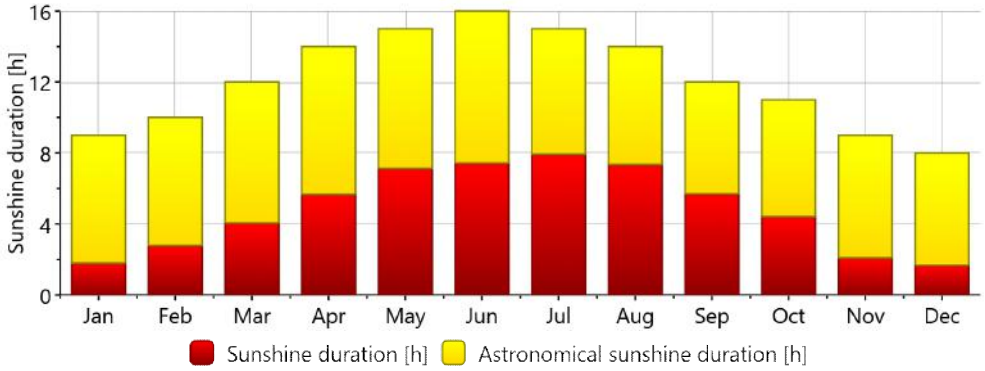
Daily temperature



Precipitation



Sunshine duration



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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Wien-Hohe Warte

Location name

48.25
Latitude [°N]

16.367
Longitude [°E]

110350
WMO

209
Altitude [m a.s.l.]

III, 3
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2030
Temperature period

2030
Radiation period

Additional information

Uncertainty of yearly values: Gh = 5%, Bn = 10%, Ta = 0,3 °C
Trend of Gh / decade: 3,2%
Variability of Gh / year: 6,0%
P90 and P10 of yearly Gh, referenced to average: 92,1%, 108,2%
Future scenario: RPC 8.5

Month	Ta	H_Gh	Td	RH	H_Dh	FF	Lin	PP
	[°C]	[kWh/m2]	[°C]	[%]	[kWh/m2]	[m/s]	[kWh/m2]	[hPa]
January	1.9	28,7	-1.8	76.2	17,7	3.8	202	988
February	3.9	49,1	-0.8	71.5	30,3	3.8	185	988
March	7.5	89,5	1.4	65.3	44,5	3.8	214	989
April	12.9	134,7	5.8	61.9	61,9	3.5	223	989
May	17.0	175,8	10.3	64.4	81,3	3.6	249	990
June	21.1	181,9	13.9	63.2	90,3	3.4	255	990
July	22.9	185,4	15.5	63.0	78,4	3.5	272	990
August	22.4	161,6	15.5	64.6	70,9	3.1	272	990
September	17.2	109,9	11.7	70.0	51,1	3.2	246	989
October	11.7	65,1	7.9	77.3	38,4	3.0	238	989
November	7.4	29,5	4.0	78.6	17,1	3.5	219	989
December	2.9	21,1	-0.4	78.9	13,9	3.6	209	988
Year	12.4	1229,2	6.9	69.6	595,9	3.5	2783	989

Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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Month	Sd	N	TL	Bn	H_Ghmax	H_Gex	H_PAR	Snd
	[h]	[octas]	[ ]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[mm]
January	56	6	2.7	42,0	59	88	12,4	18.1
February	78	6	2.9	49,8	81	122	21,0	14.1
March	126	5	3.3	97,1	146	204	38,3	0.0
April	170	4	3.8	129,8	195	269	57,9	0.0
May	221	4	3.8	153,7	246	333	76,1	0.0
June	223	4	3.7	144,9	254	347	79,4	0.0
July	246	4	3.6	167,3	257	346	81,0	0.0
August	228	4	3.6	152,4	215	300	71,1	0.0
September	171	4	3.4	118,1	168	226	48,6	0.0
October	137	5	3.2	67,9	111	161	29,2	0.0
November	63	6	2.9	41,0	66	99	13,3	0.0
December	52	7	2.7	28,6	48	75	9,5	1.7
Year	1771	5	3.3	1192,6	1841	2565	536,5	2.8

Ta: Air temperature
RH: Relative humidity
Ta min: 10 y minimum (approx.)
Ta max: 10 y maximum (approx.)
Ta dmin: Mean daily minimum Ta
Ta dmax: Mean daily maximum Ta
SD: Sunshine duration
RR: Precipitation
RD: Days with precipitation
FF: Wind speed
SD astr.: Sunshine duration, astronomic
DD: Wind direction
Snd: Snow depth
H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
PAR: Photosynthetically active radiation

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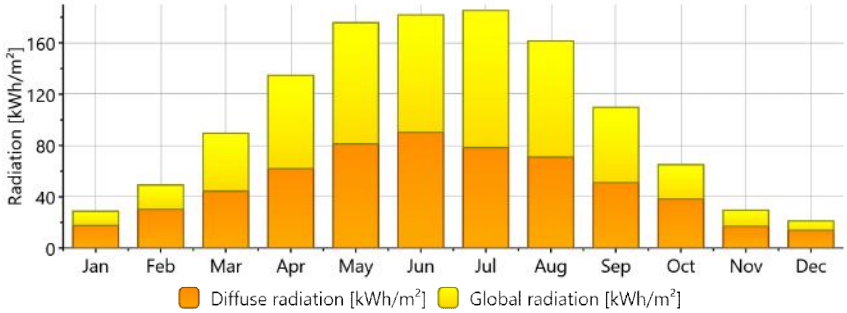
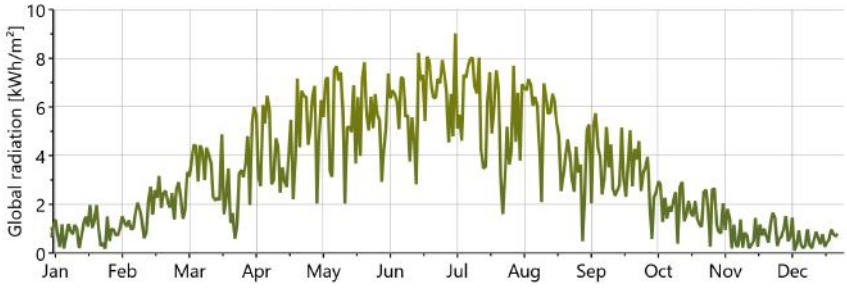
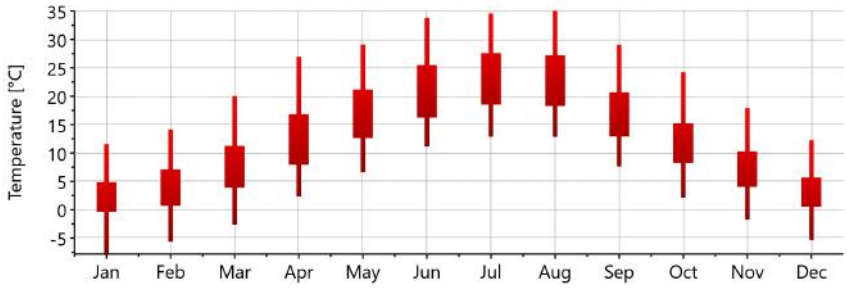
Monthly radiation



Daily global radiation



Monthly temperature



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

3/4

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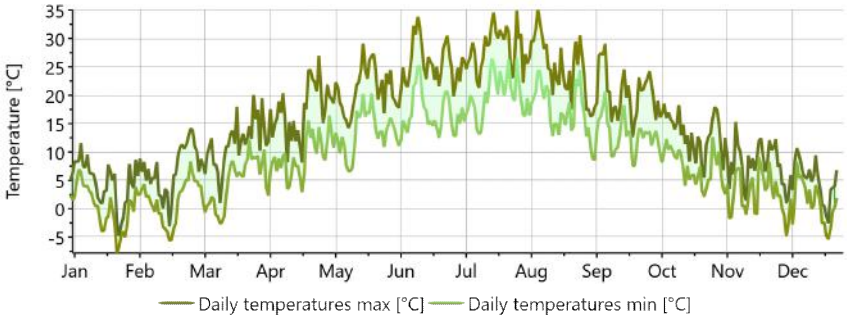
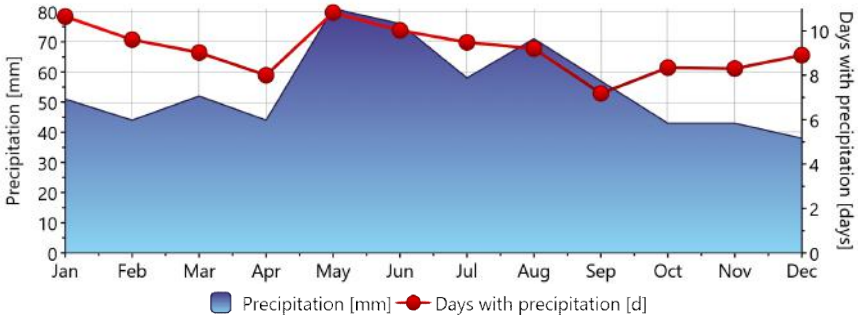
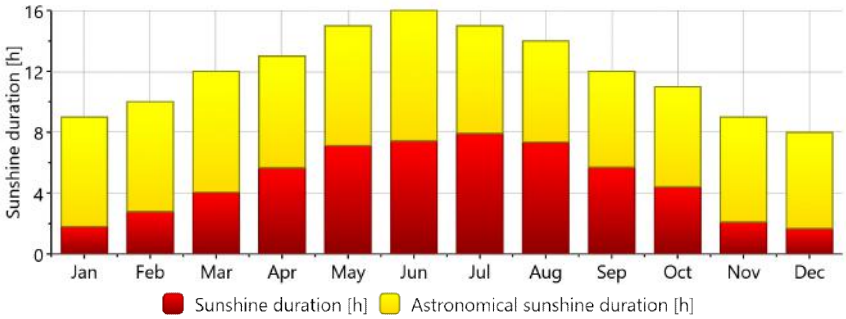
Daily temperature



Precipitation



Sunshine duration



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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Wien-Hohe Warte

Location name

48.25
Latitude [°N]

16.367
Longitude [°E]

110350
WMO

209
Altitude [m a.s.l.]

III, 3
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2070
Temperature period

2070
Radiation period

Additional information

Uncertainty of yearly values: Gh = 5%, Bn = 10%, Ta = 0,3 °C
Trend of Gh / decade: 3,1%
Variability of Gh / year: 6,0%
P90 and P10 of yearly Gh, referenced to average: 92,1%, 108,2%
Future scenario: RPC 8.5

Month	Ta	H_Gh	Td	RH	H_Dh	FF	Lin	PP
	[°C]	[kWh/m2]	[°C]	[%]	[kWh/m2]	[m/s]	[kWh/m2]	[hPa]
January	4.6	28,0	0.9	76.8	15,2	3.8	213	988
February	6.2	49,2	1.6	72.1	28,7	3.8	194	989
March	9.6	90,4	3.4	65.3	46,2	3.8	223	989
April	14.8	138,4	7.6	61.9	69,1	3.5	230	989
May	18.9	178,3	12.3	65.8	75,1	3.6	257	990
June	23.8	187,9	16.4	63.3	84,1	3.4	266	990
July	26.4	193,1	18.7	62.9	84,8	3.5	285	990
August	26.2	168,0	19.0	64.5	69,9	3.1	286	990
September	20.4	112,5	14.8	70.1	52,9	3.2	258	990
October	14.2	65,4	10.3	77.5	35,5	3.0	250	989
November	9.4	29,7	6.0	78.8	18,7	3.5	227	989
December	5.3	20,7	2.0	79.2	14,9	3.6	219	989
Year	15.0	1258,4	9.4	69.9	595,1	3.5	2905	989

Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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Month	Sd	N	TL	Bn	H_Ghmax	H_Gex	H_PAR	Snd
	[h]	[octas]	[ ]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[mm]
January	56	6	2.7	48,6	59	88	12,1	5.4
February	78	5	2.9	57,5	81	123	21,1	0.2
March	126	5	3.3	95,4	146	205	38,7	0.0
April	170	4	3.8	124,0	195	269	59,4	0.0
May	221	4	3.8	165,3	247	334	76,9	0.0
June	223	4	3.7	161,8	254	347	81,8	0.0
July	246	3	3.6	174,6	256	345	84,3	0.0
August	228	3	3.6	165,9	214	299	73,7	0.0
September	171	4	3.4	117,4	167	225	49,7	0.0
October	137	5	3.2	70,5	110	160	29,3	0.0
November	63	6	2.9	38,8	66	99	13,5	0.0
December	52	7	2.7	23,9	48	75	9,4	0.4
Year	1771	5	3.3	1243,8	1841	2565	548,5	0.5

Ta: Air temperature
RH: Relative humidity
Ta min: 10 y minimum (approx.)
Ta max: 10 y maximum (approx.)
Ta dmin: Mean daily minimum Ta
Ta dmax: Mean daily maximum Ta
SD: Sunshine duration
RR: Precipitation
RD: Days with precipitation
FF: Wind speed
SD astr.: Sunshine duration, astronomic
DD: Wind direction
Snd: Snow depth
H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
PAR: Photosynthetically active radiation

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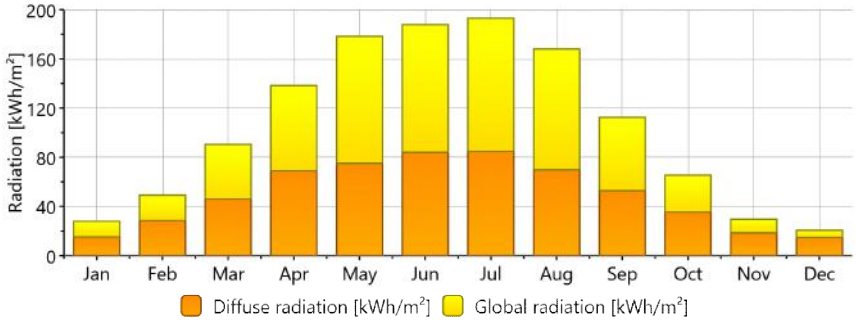
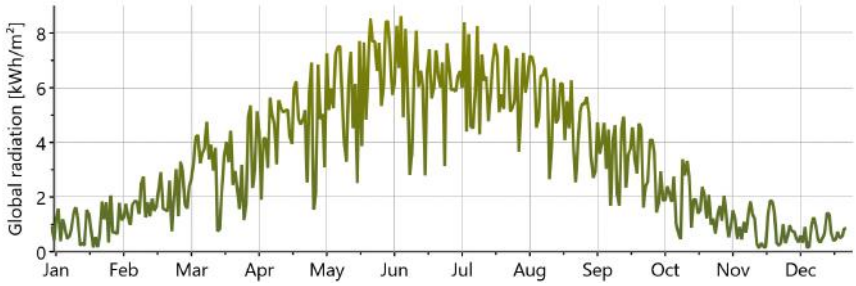
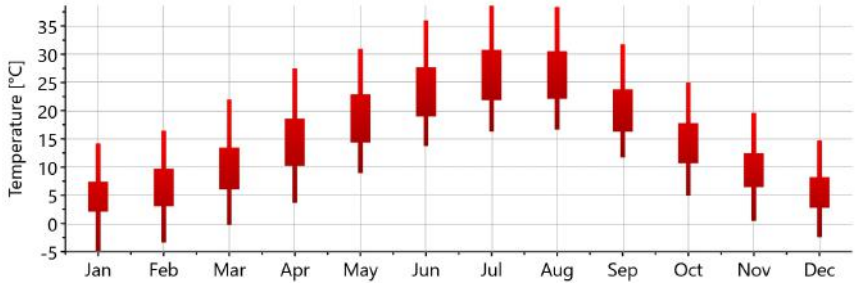
Monthly radiation



Daily global radiation



Monthly temperature



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

3/4

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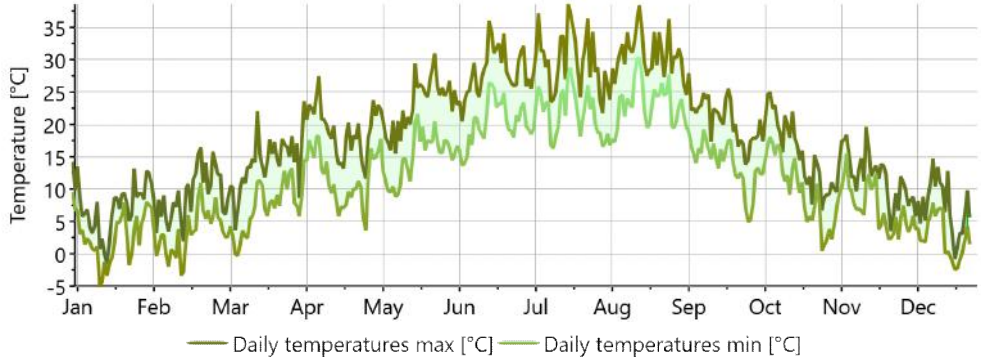
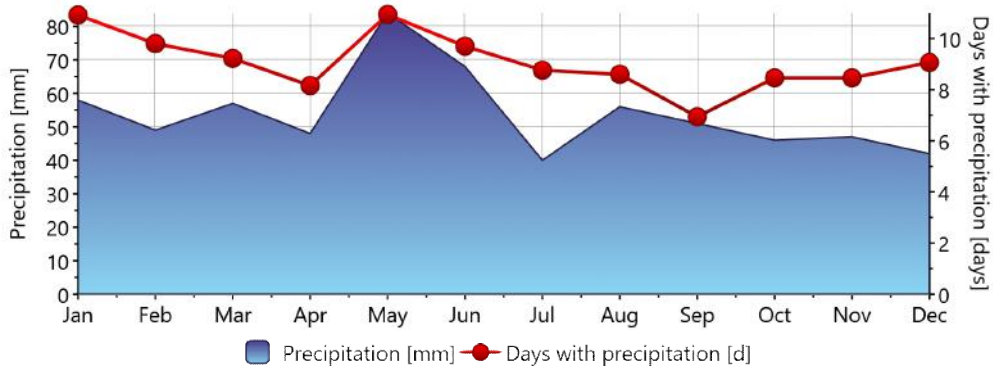
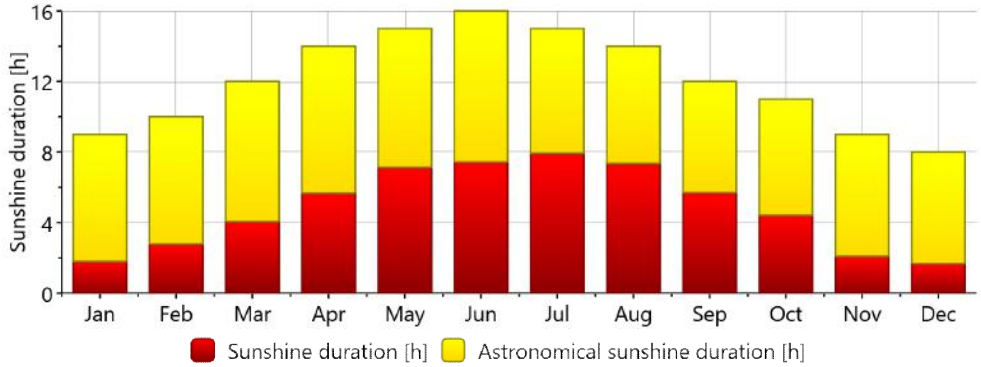
Daily temperature



Precipitation



Sunshine duration



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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Athinai/Hellenkion

Location name

37.9
Latitude [°N]

23.733
Longitude [°E]

167160
WMO

15
Altitude [m a.s.l.]

IV, 1
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2000–2019
Temperature period

Contemporary
Radiation period

Additional information

Uncertainty of yearly values: Gh = 3%, Bn = 6%, Ta = 0,3 °C
Trend of Gh / decade: -
Variability of Gh / year: 5,4%
Radiation interpolation locations: Satellite data (Share of satellite data: 100%)
P90 and P10 of yearly Gh, referenced to average: 93,3%, 107,7%

Month	Ta	H_Gh	Td	RH	H_Dh	FF	Lin	PP
	[°C]	[kWh/m2]	[°C]	[%]	[kWh/m2]	[m/s]	[kWh/m2]	[hPa]
January	10.0	67,0	4.5	68.4	33,9	2.4	225	1011
February	10.6	81,6	4.9	67.6	41,1	2.5	205	1011
March	13.1	131,7	6.4	63.6	64,2	2.4	233	1011
April	16.4	170,2	8.2	58.1	75,8	2.2	232	1011
May	20.8	217,9	11.7	56.0	74,2	2.1	253	1011
June	25.7	235,5	14.4	49.7	67,4	2.4	256	1011
July	28.6	232,1	15.7	45.4	68,6	2.7	274	1011
August	28.8	211,5	15.3	43.8	63,2	2.9	275	1011
September	24.4	153,2	14.3	53.1	47,7	2.4	259	1011
October	19.7	103,3	12.3	62.2	49,9	2.1	259	1011
November	15.5	67,7	10.0	69.6	32,8	1.9	240	1011
December	11.7	55,1	6.3	69.3	30,6	2.2	235	1011
Year	18.8	1723,2	10.3	58.9	649,3	2.4	2944	1011

Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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Month	Sd	N	TL	Bn	H_Ghmax	H_Gex	H_PAR	Snd
	[h]	[octas]	[ ]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[mm]
January	129	5	3.0	87,5	99	143	28,8	0.0
February	136	4	3.3	85,6	113	169	35,0	0.0
March	183	4	3.8	118,1	174	247	56,4	0.0
April	230	3	4.5	147,5	208	294	73,1	0.0
May	291	2	4.1	209,6	249	343	93,5	0.0
June	336	1	3.6	241,2	253	347	101,3	0.0
July	364	2	3.6	236,6	259	350	100,3	0.0
August	340	1	3.6	225,6	228	318	91,7	0.0
September	277	3	3.7	173,6	193	260	66,9	0.0
October	208	4	3.5	106,4	145	209	45,8	0.0
November	152	4	3.3	83,8	104	151	30,0	0.0
December	127	5	3.1	68,8	86	130	24,2	0.0
Year	2773	3	3.6	1784,3	2107	2957	745,4	0.0

Ta: Air temperature
RH: Relative humidity
Ta min: 10 y minimum (approx.)
Ta max: 10 y maximum (approx.)
Ta dmin: Mean daily minimum Ta
Ta dmax: Mean daily maximum Ta
SD: Sunshine duration
RR: Precipitation
RD: Days with precipitation
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SD astr.: Sunshine duration, astronomic
DD: Wind direction
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H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
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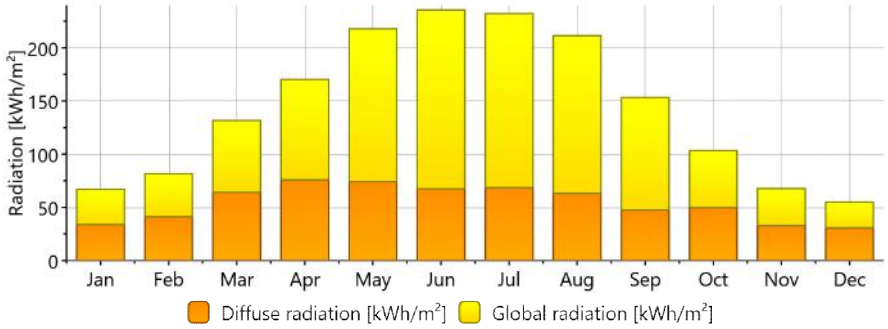
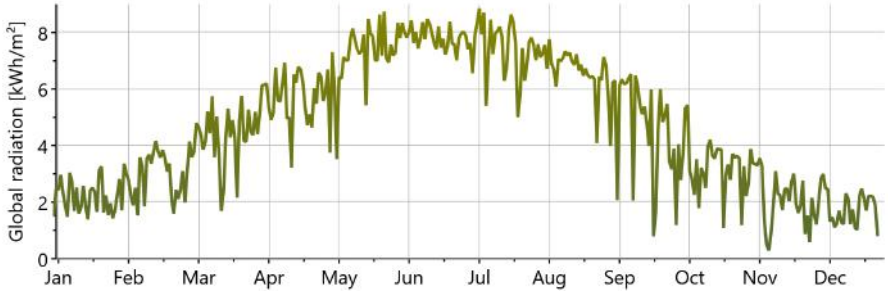
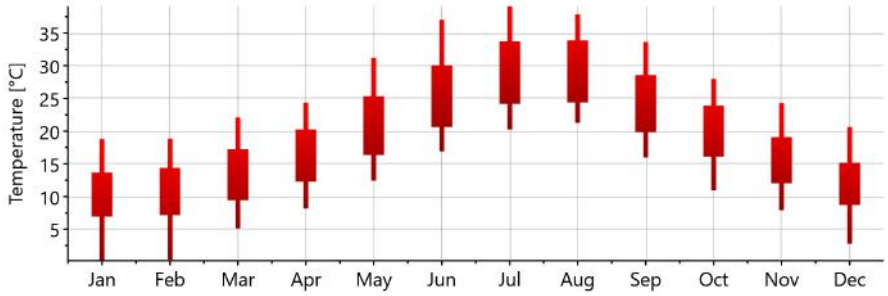
Monthly radiation



Daily global radiation



Monthly temperature



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

3/4

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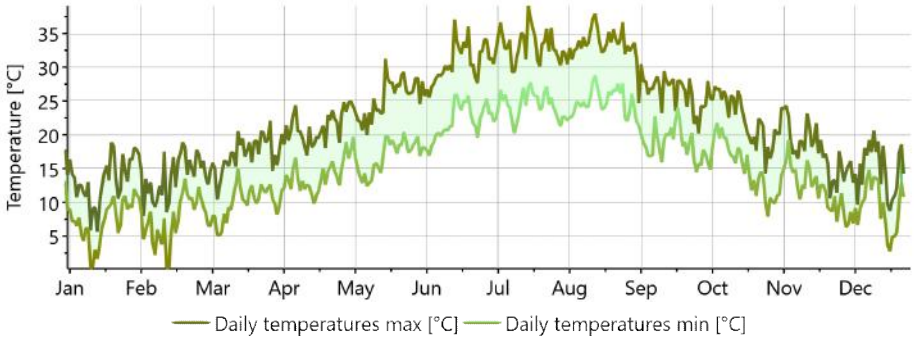
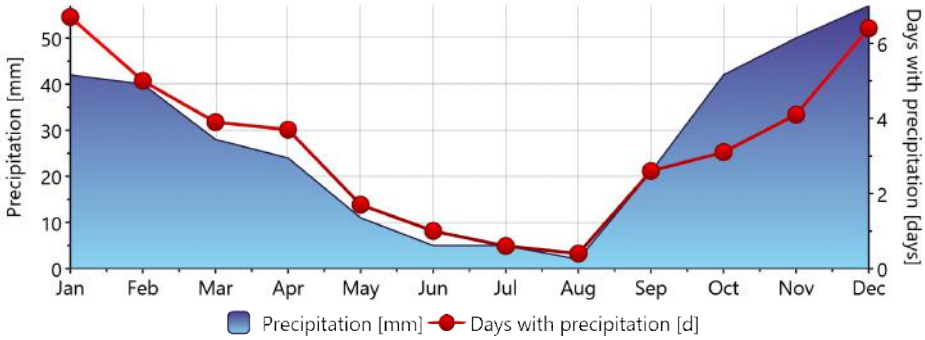
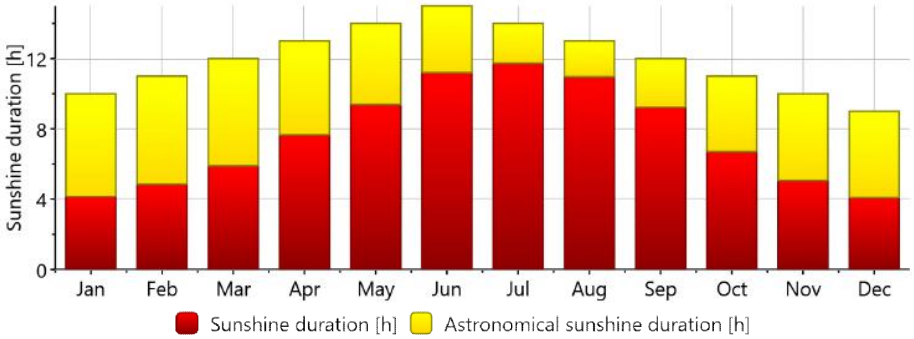
Daily temperature



Precipitation



Sunshine duration



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode 4/4

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Athinai/Hellenkion

Location name

37.9
Latitude [°N]

23.733
Longitude [°E]

167160
WMO

15
Altitude [m a.s.l.]

IV, 1
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2030
Temperature period

2030
Radiation period

Additional information

Uncertainty of yearly values: Gh = 3%, Bn = 6%, Ta = 0,3 °C
Trend of Gh / decade: -
Variability of Gh / year: 5,4%
Radiation interpolation locations: Satellite data (Share of satellite data: 100%)
P90 and P10 of yearly Gh, referenced to average: 93,3%, 107,7%
Future scenario: RPC 8.5

Month	Ta	H_Gh	Td	RH	H_Dh	FF	Lin	PP
	[°C]	[kWh/m2]	[°C]	[%]	[kWh/m2]	[m/s]	[kWh/m2]	[hPa]
January	10.9	67,9	5.4	68.5	34,5	2.4	228	1011
February	11.5	84,8	5.8	67.7	38,9	2.5	208	1011
March	13.6	135,3	6.9	63.8	57,0	2.4	234	1011
April	17.2	173,7	9.1	58.6	70,9	2.2	235	1011
May	21.7	221,5	12.7	56.5	71,7	2.1	257	1011
June	26.7	227,6	15.7	50.7	73,5	2.4	262	1011
July	29.9	233,2	17.0	46.0	67,6	2.7	280	1011
August	30.1	205,0	16.7	44.5	69,5	2.9	281	1011
September	25.5	155,5	15.5	53.6	57,9	2.4	263	1011
October	20.9	105,6	13.5	62.5	44,6	2.1	264	1011
November	16.4	69,4	10.8	69.7	32,1	1.9	243	1011
December	12.5	55,7	7.1	69.4	28,1	2.2	238	1011
Year	19.7	1732,2	11.3	59.3	646,4	2.4	2991	1011

Meteonorm 8

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Month	Sd	N	TL	Bn	H_Ghmax	H_Gex	H_PAR	Snd
	[h]	[octas]	[ ]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[mm]
January	129	4	3.0	87,3	99	143	29,2	0.0
February	136	4	3.3	94,4	113	169	36,2	0.0
March	183	4	3.8	140,7	174	247	57,7	0.0
April	230	3	4.5	158,8	208	294	74,5	0.0
May	291	2	4.1	220,3	249	343	95,0	0.0
June	336	1	3.6	220,8	253	347	98,1	0.0
July	364	1	3.6	240,5	259	350	100,7	0.0
August	340	1	3.6	208,1	228	319	89,1	0.0
September	277	3	3.7	163,9	193	260	68,0	0.0
October	208	4	3.5	116,2	145	209	46,5	0.0
November	152	4	3.3	90,9	104	151	30,6	0.0
December	127	5	3.1	76,9	86	130	24,5	0.0
Year	2773	3	3.6	1818,8	2107	2957	748,7	0.0

Ta: Air temperature
RH: Relative humidity
Ta min: 10 y minimum (approx.)
Ta max: 10 y maximum (approx.)
Ta dmin: Mean daily minimum Ta
Ta dmax: Mean daily maximum Ta
SD: Sunshine duration
RR: Precipitation
RD: Days with precipitation
FF: Wind speed
SD astr.: Sunshine duration, astronomic
DD: Wind direction
Snd: Snow depth
H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
PAR: Photosynthetically active radiation

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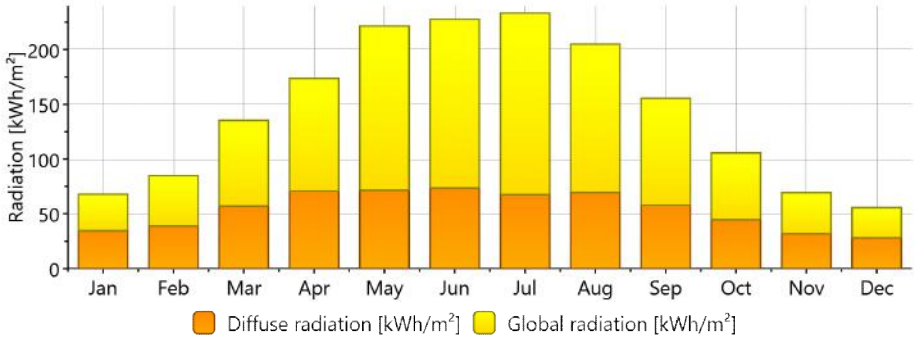
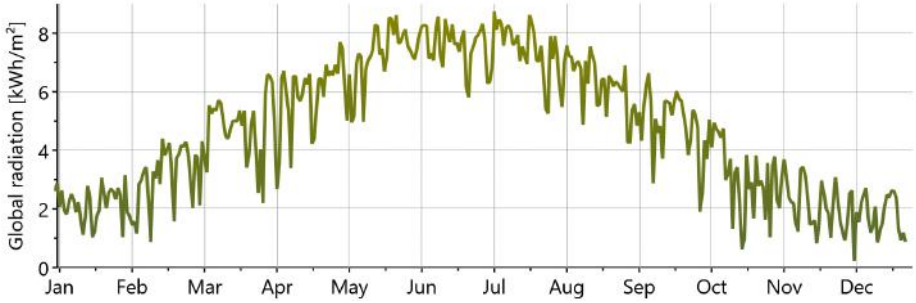
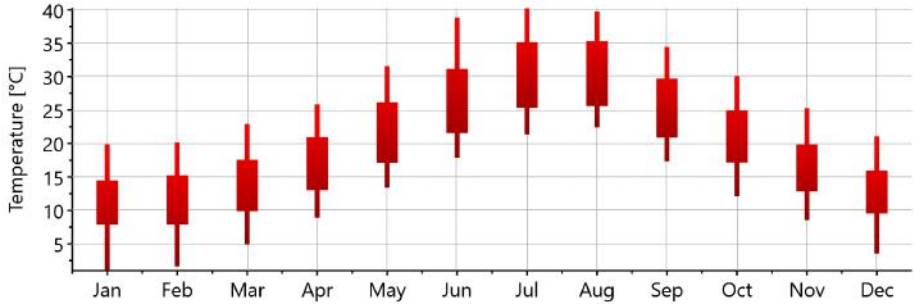
Monthly radiation



Daily global radiation



Monthly temperature



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

3/4

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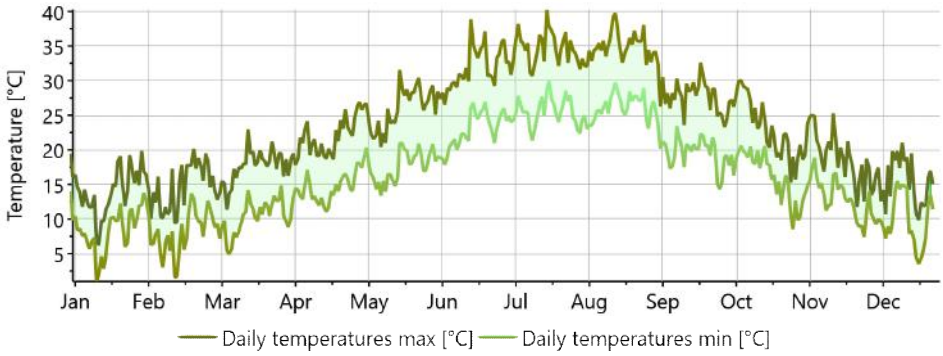
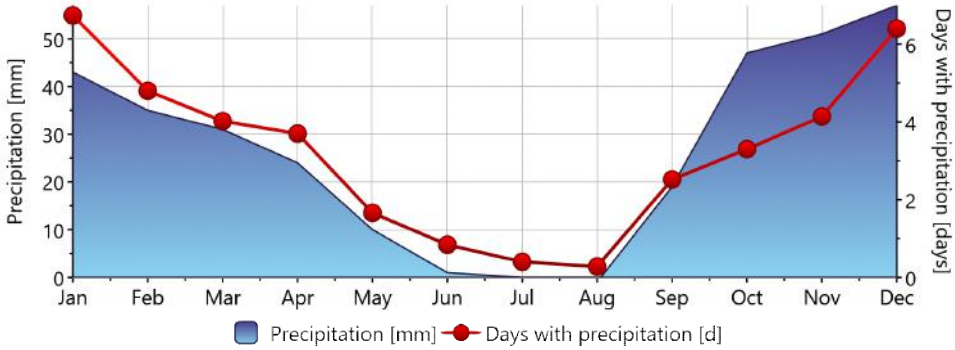
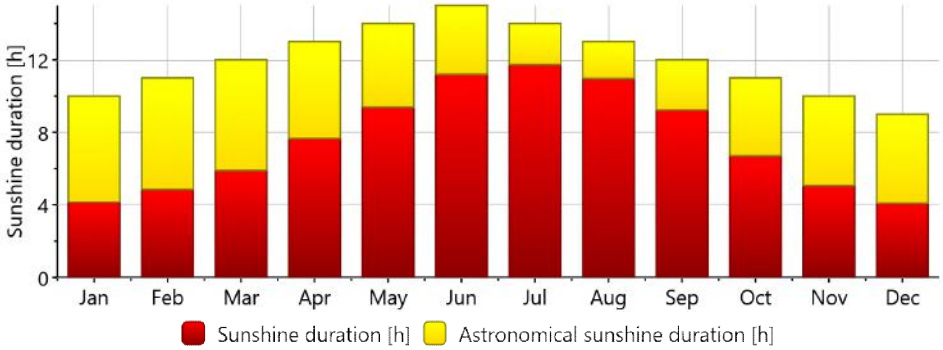


Precipitation



Sunshine duration



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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IV, 1
Climate region

Standard
Radiation model

Standard
Temperature model

Perez
Tilt radiation model

2070
Temperature period

2070
Radiation period

Additional information

Uncertainty of yearly values: Gh = 3%, Bn = 6%, Ta = 0,3 °C
Trend of Gh / decade: -
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Radiation interpolation locations: Satellite data (Share of satellite data: 100%)
P90 and P10 of yearly Gh, referenced to average: 93,3%, 107,7%
Future scenario: RPC 8.5

Month	Ta	H_Gh	Td	RH	H_Dh	FF	Lin	PP
	[°C]	[kWh/m2]	[°C]	[%]	[kWh/m2]	[m/s]	[kWh/m2]	[hPa]
January	12.8	70,5	7.2	68.5	34,4	2.4	235	1011
February	13.4	87,7	7.5	67.7	36,9	2.5	213	1011
March	15.6	139,4	8.9	64.1	60,9	2.4	242	1011
April	19.2	178,6	10.9	58.7	68,6	2.2	242	1011
May	24.1	224,1	14.9	56.5	71,2	2.1	266	1011
June	29.6	227,7	18.3	50.8	69,5	2.4	274	1011
July	33.0	233,1	19.8	46.0	70,8	2.7	293	1012
August	33.1	204,7	19.5	44.6	68,2	2.9	294	1011
September	28.2	156,2	18.0	53.7	54,8	2.4	274	1011
October	23.0	106,9	15.5	62.4	46,9	2.1	273	1011
November	18.4	70,5	12.8	69.8	37,7	1.9	251	1011
December	14.4	58,7	8.8	69.4	31,5	2.2	244	1011
Year	22.1	1754,8	13.5	59.4	651,3	2.4	3101	1011

Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

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	[h]	[octas]	[ ]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[kWh/m2]	[mm]
January	129	4	3.0	92,1	99	143	30,2	0.0
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April	230	3	4.5	170,1	208	294	76,4	0.0
May	291	2	4.1	224,2	249	343	96,1	0.0
June	336	1	3.6	226,8	253	347	98,1	0.0
July	364	1	3.6	236,9	259	350	100,7	0.0
August	340	2	3.6	209,1	227	318	88,9	0.0
September	277	3	3.7	169,2	192	259	68,2	0.0
October	208	4	3.5	116,3	145	208	47,2	0.0
November	152	5	3.3	79,4	103	151	31,2	0.0
December	127	5	3.1	75,5	86	130	25,7	0.0
Year	2773	3	3.6	1845,5	2107	2957	758,1	0.0

Ta: Air temperature
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Ta min: 10 y minimum (approx.)
Ta max: 10 y maximum (approx.)
Ta dmin: Mean daily minimum Ta
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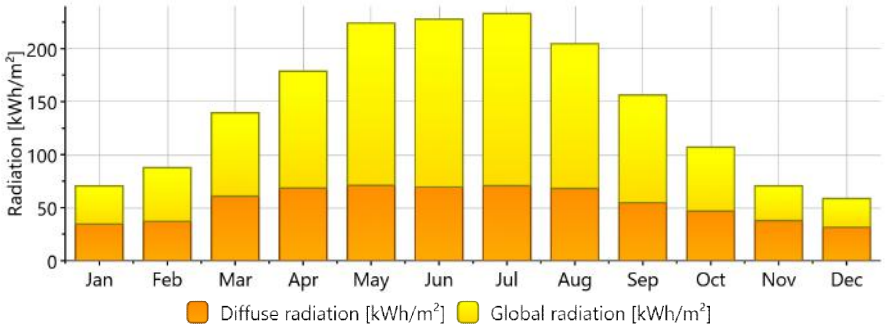
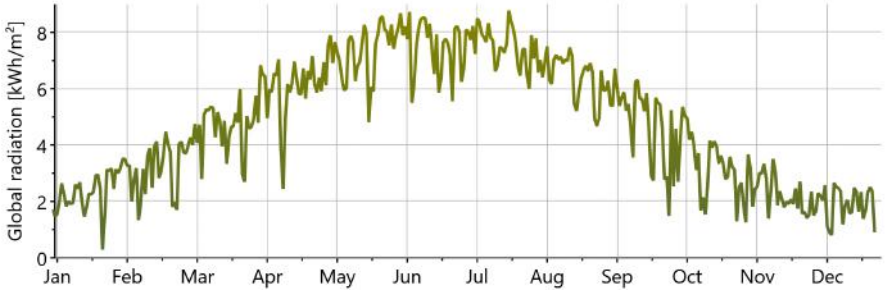
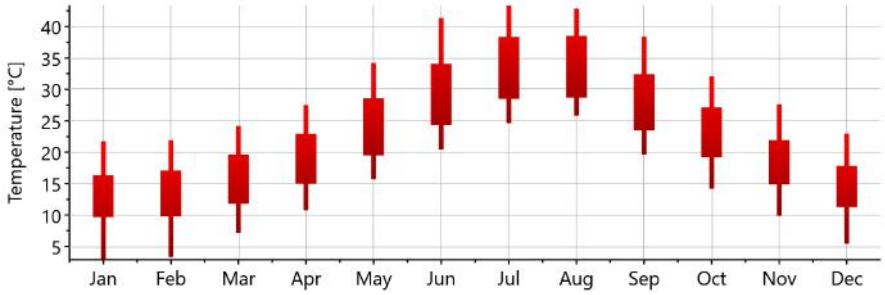
Monthly radiation



Daily global radiation



Monthly temperature



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

3/4

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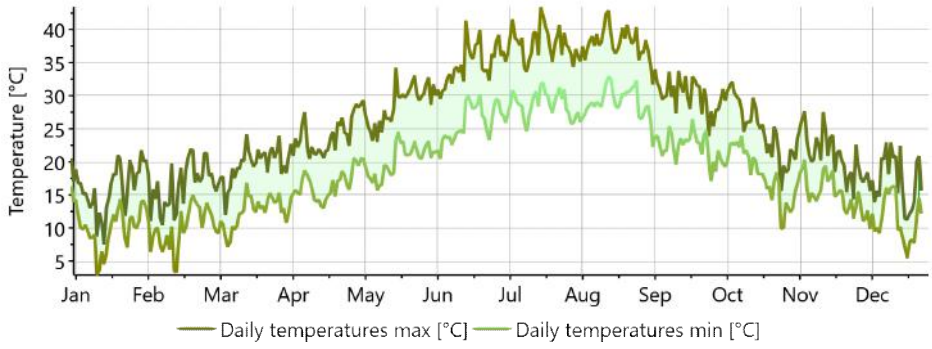
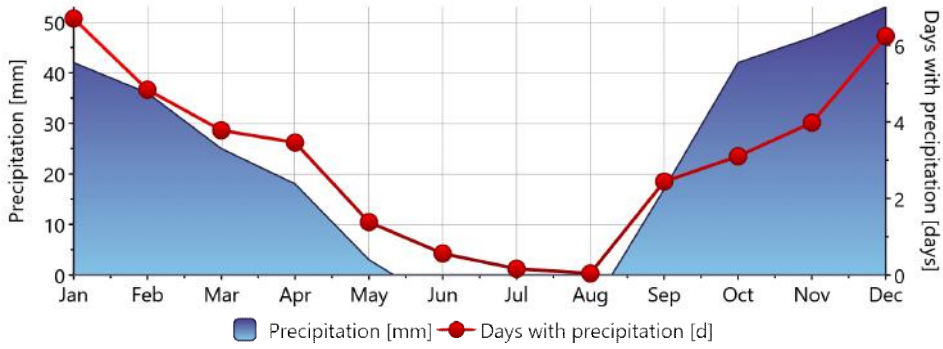
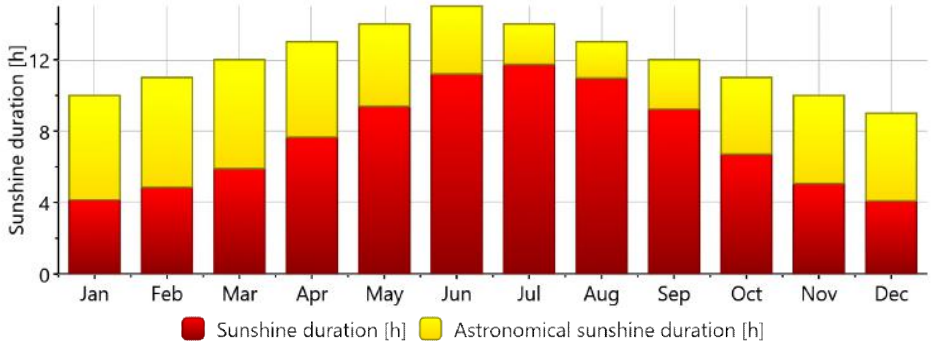
Daily temperature



Precipitation



Sunshine duration



Meteonorm 8

Meteonorm V8.0.4.21990 - Demo mode

4/4

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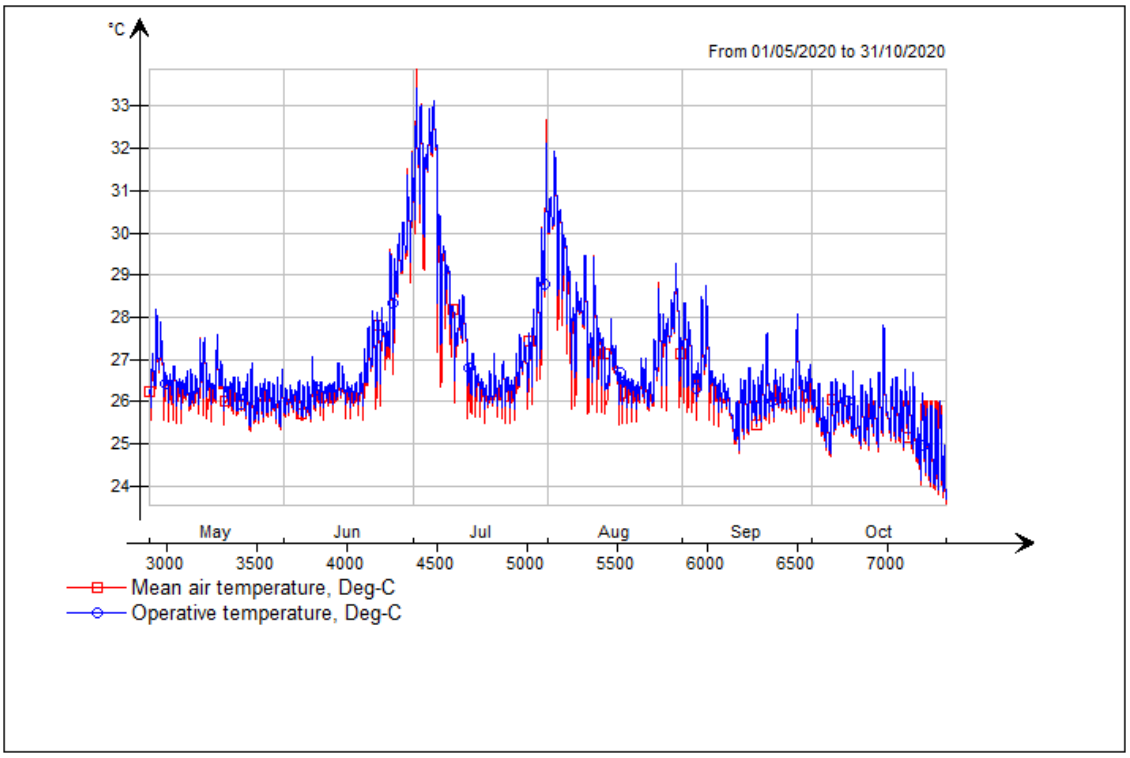
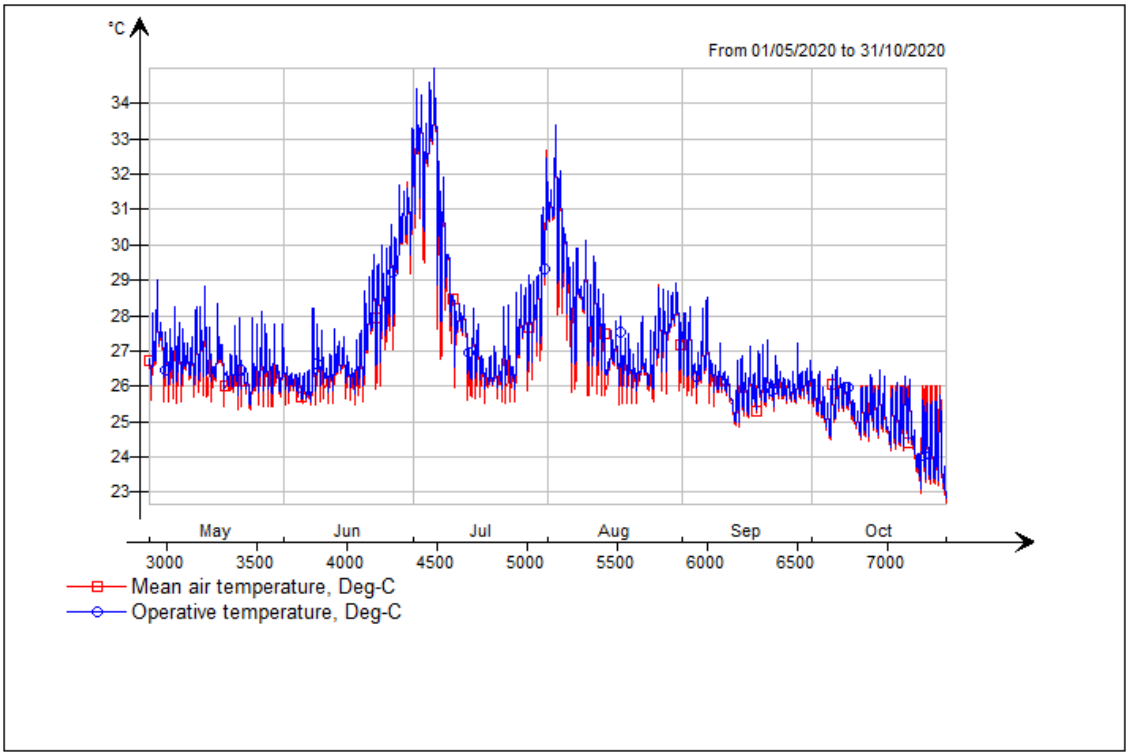
B. Graphs of mean air and operative temperatures

Basic scenario Vienna 2020

Zone 1 (South)



Zone 2 (West)



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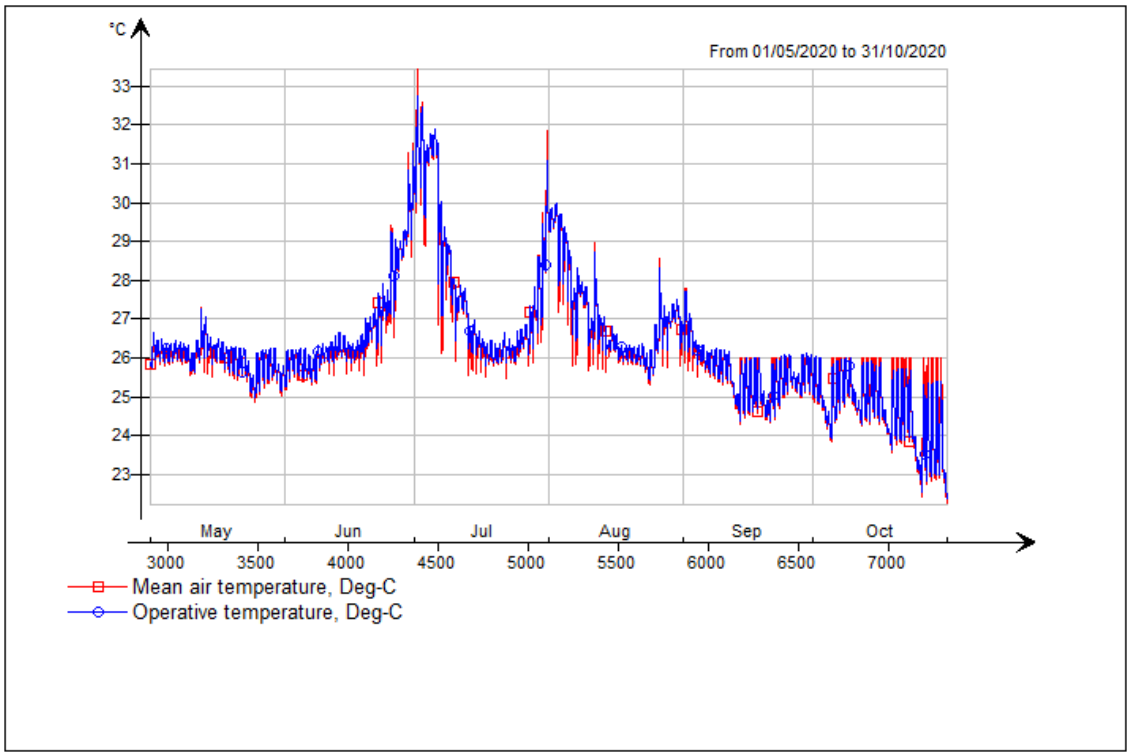
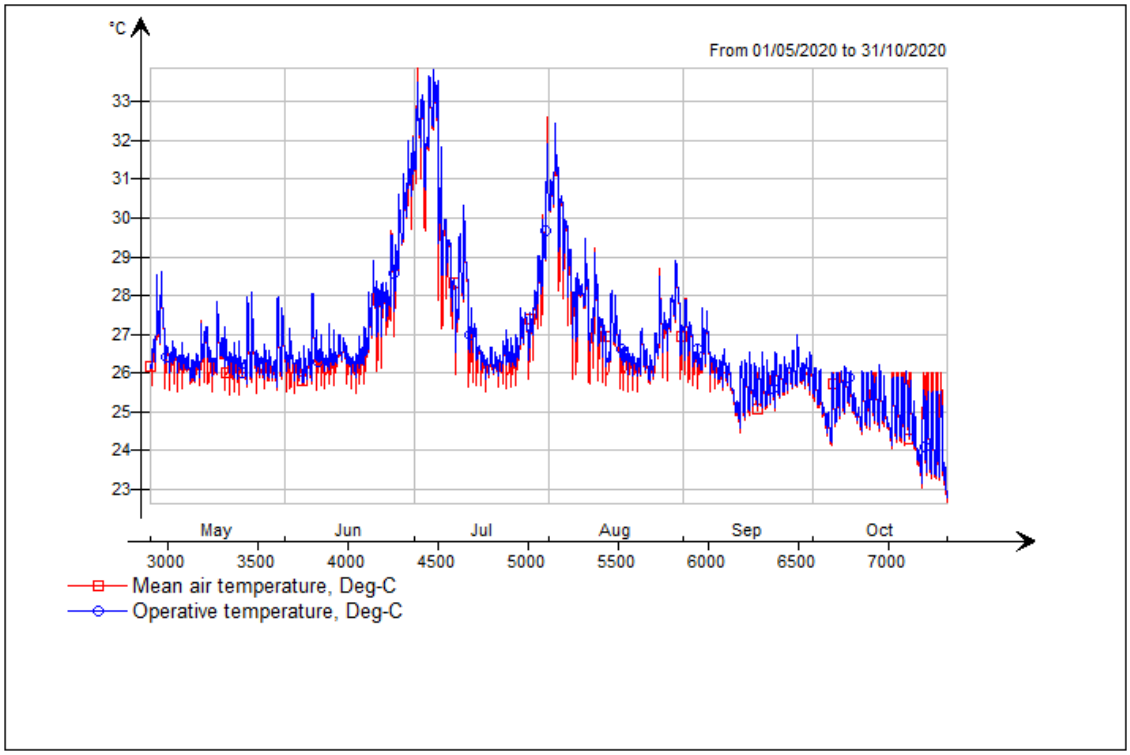
Zone 3 (North)



Zone 4 (East)



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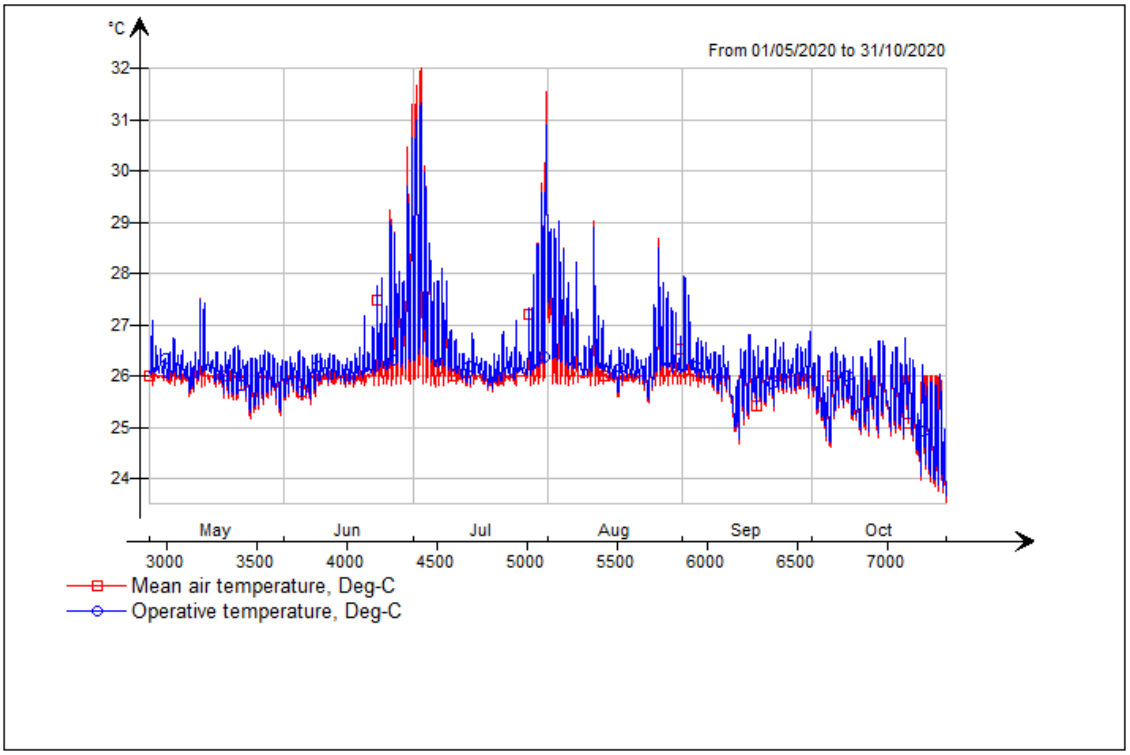
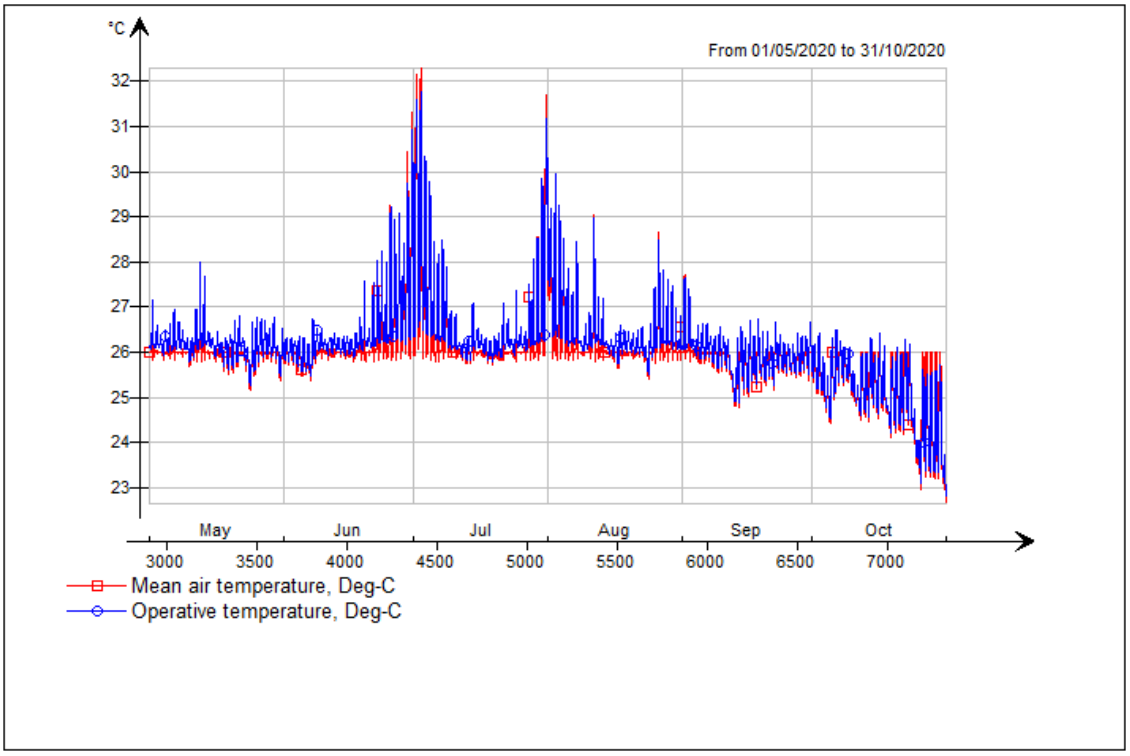
Night ventilation scenario Vienna 2020

Zone 1 (South)



Zone 2 (West)



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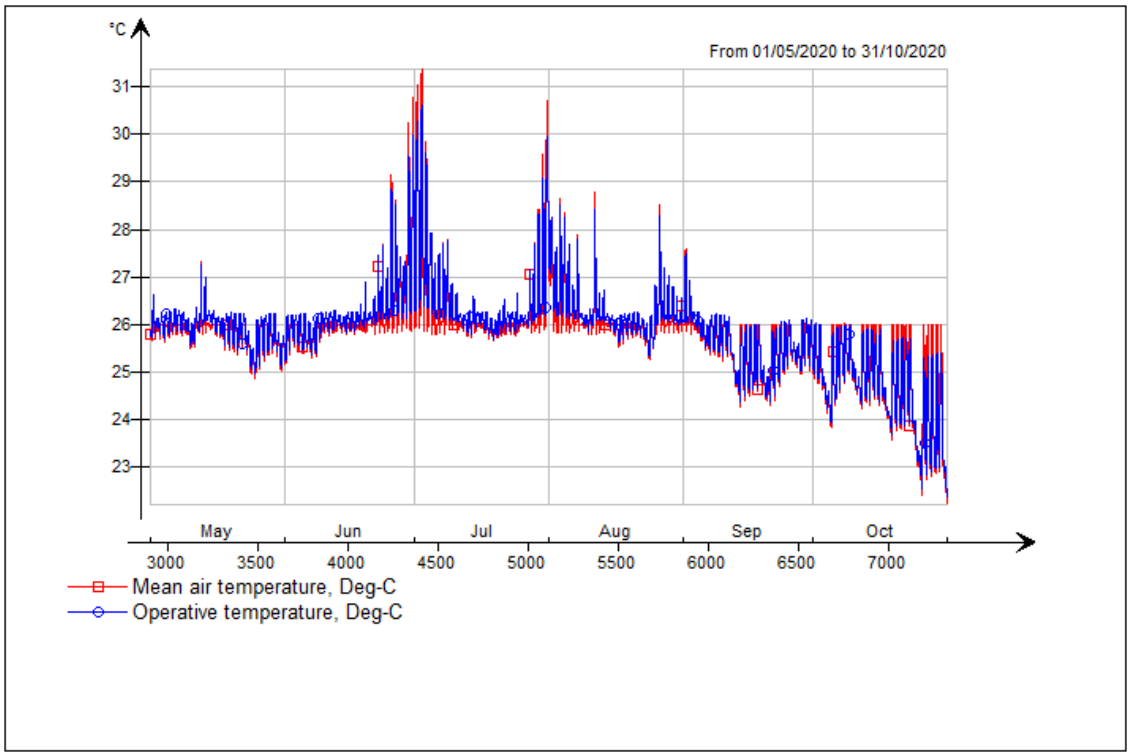
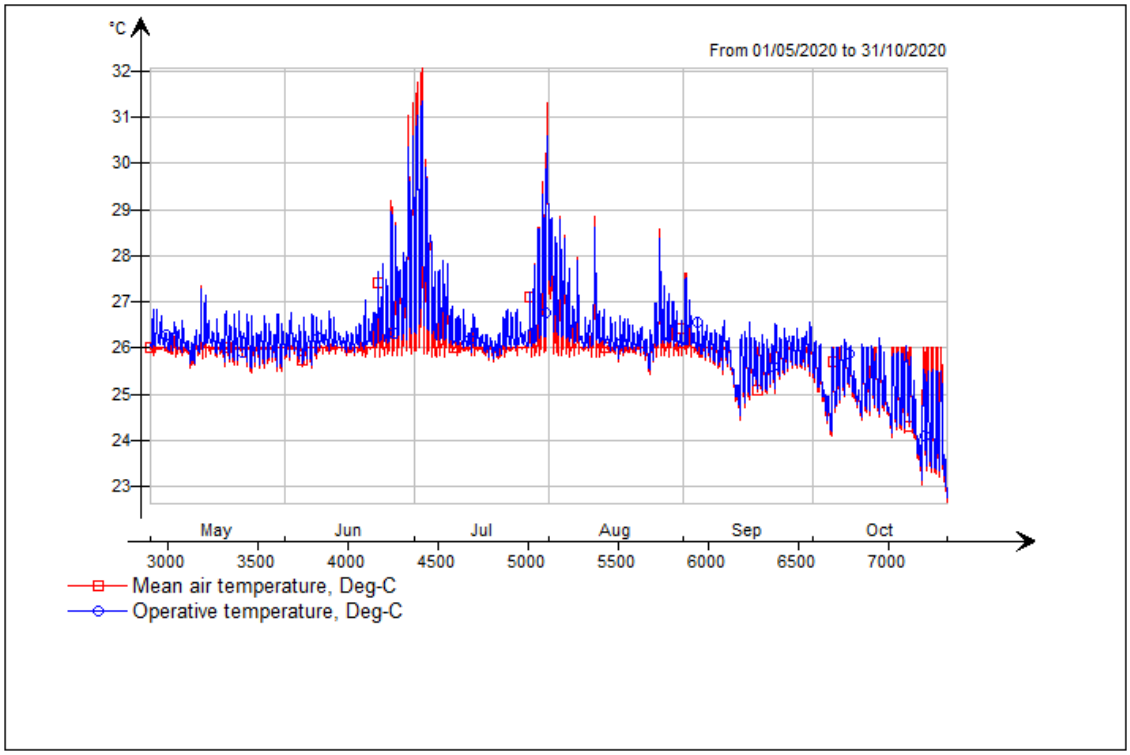
Zone 3 (North)



Zone 4 (East)



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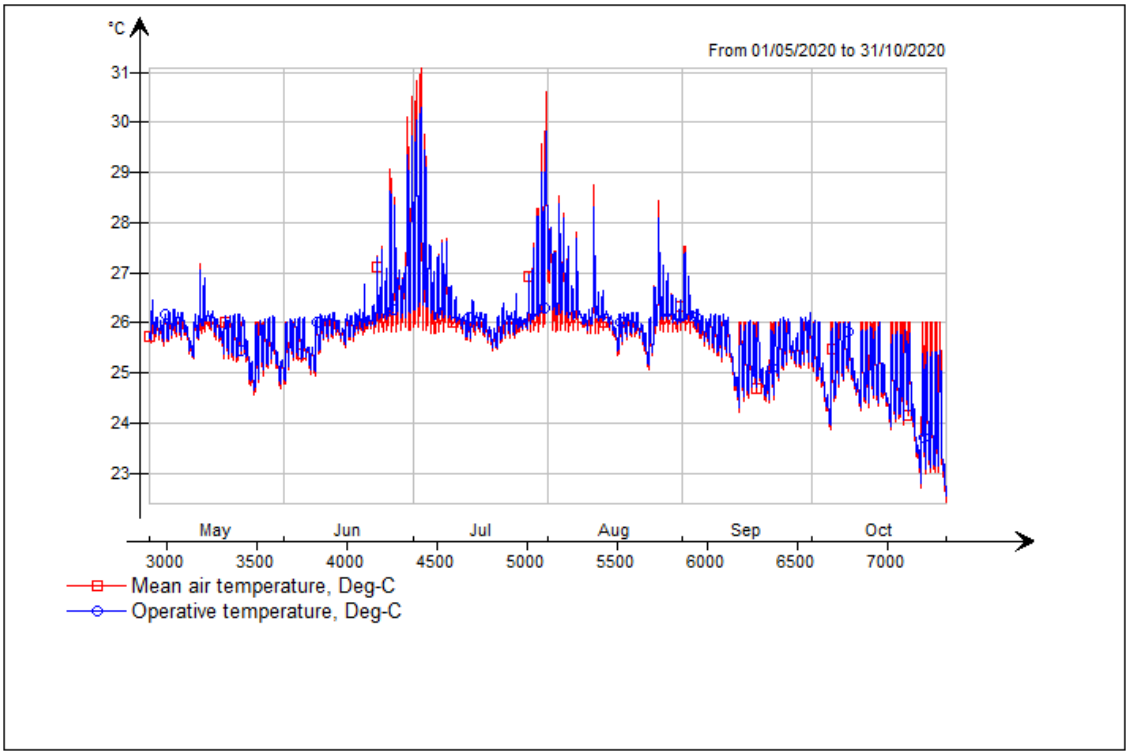
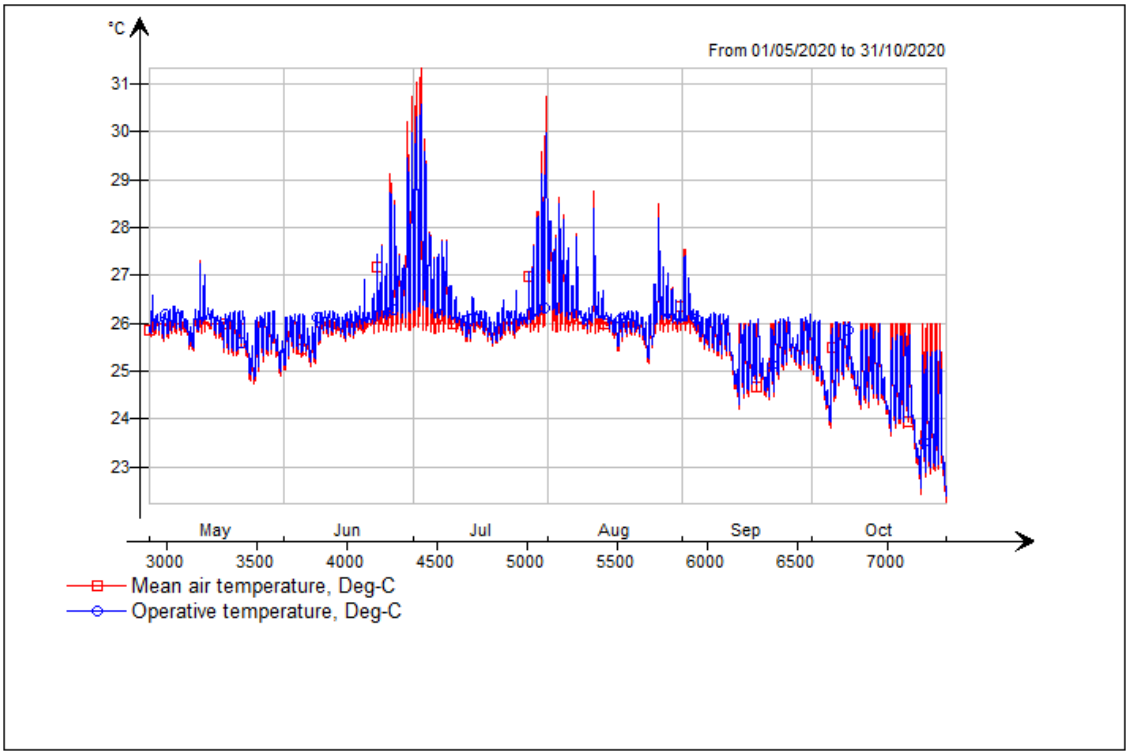
Night ventilation and shading scenario Vienna 2020

Zone 1 (South)



Zone 2 (West)



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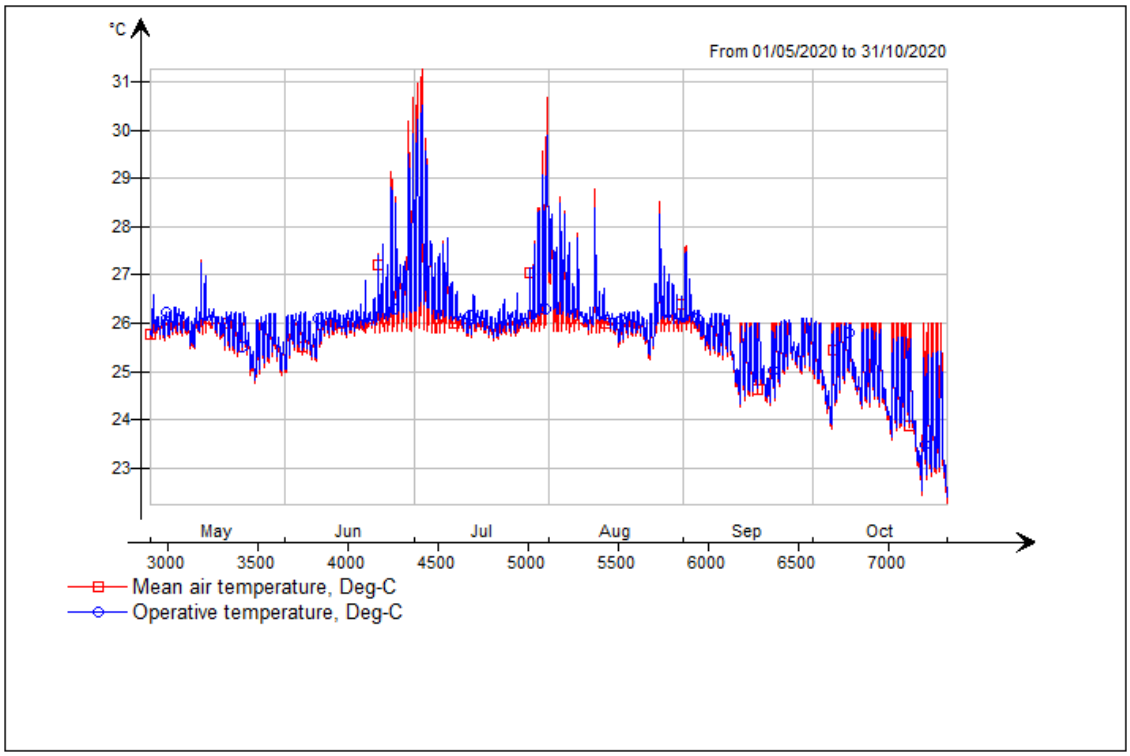
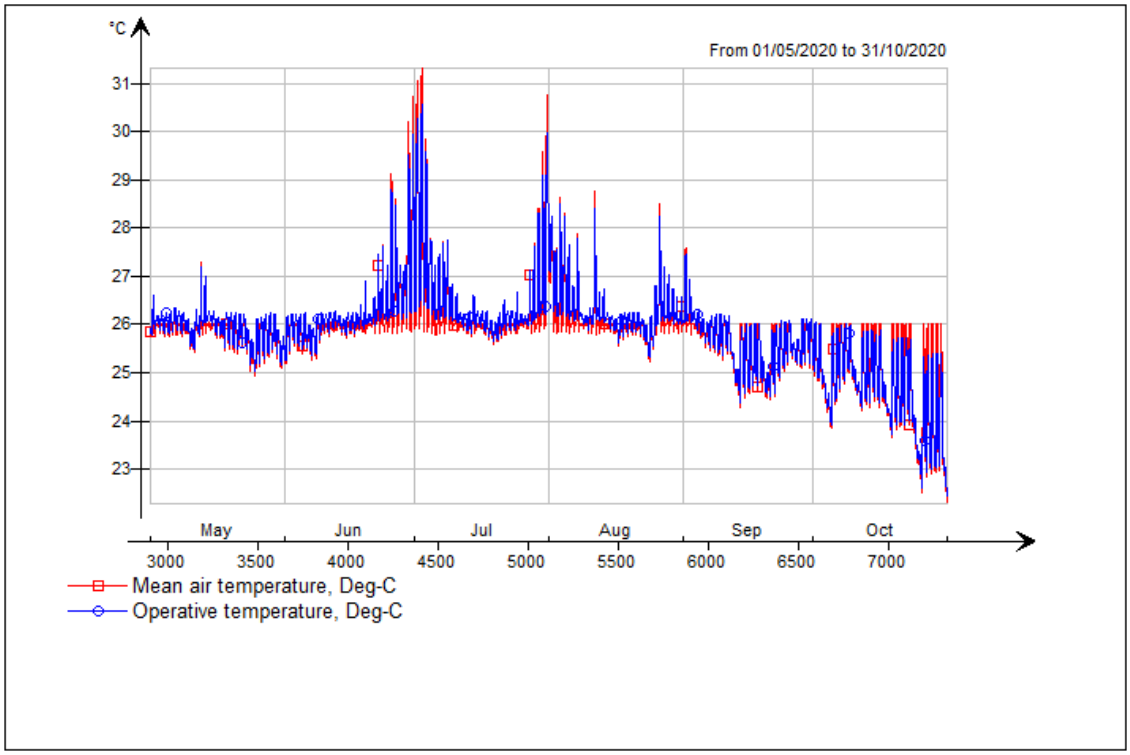


Zone 4 (East)



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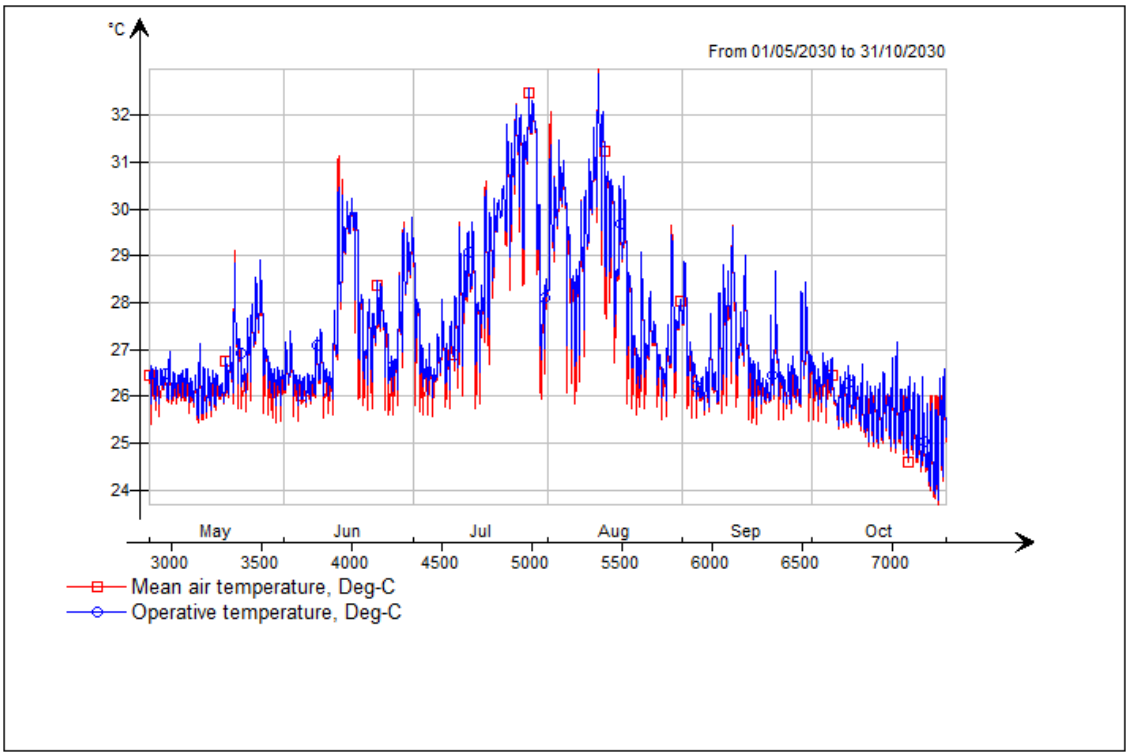
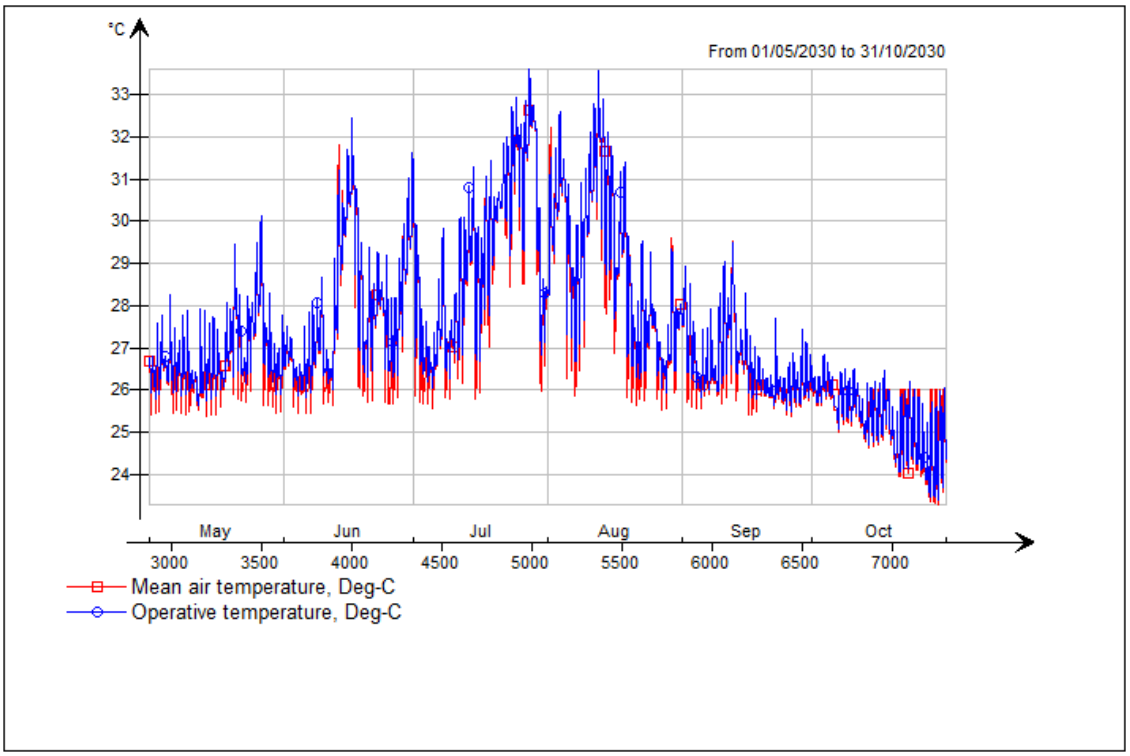
Basic scenario Vienna 2030 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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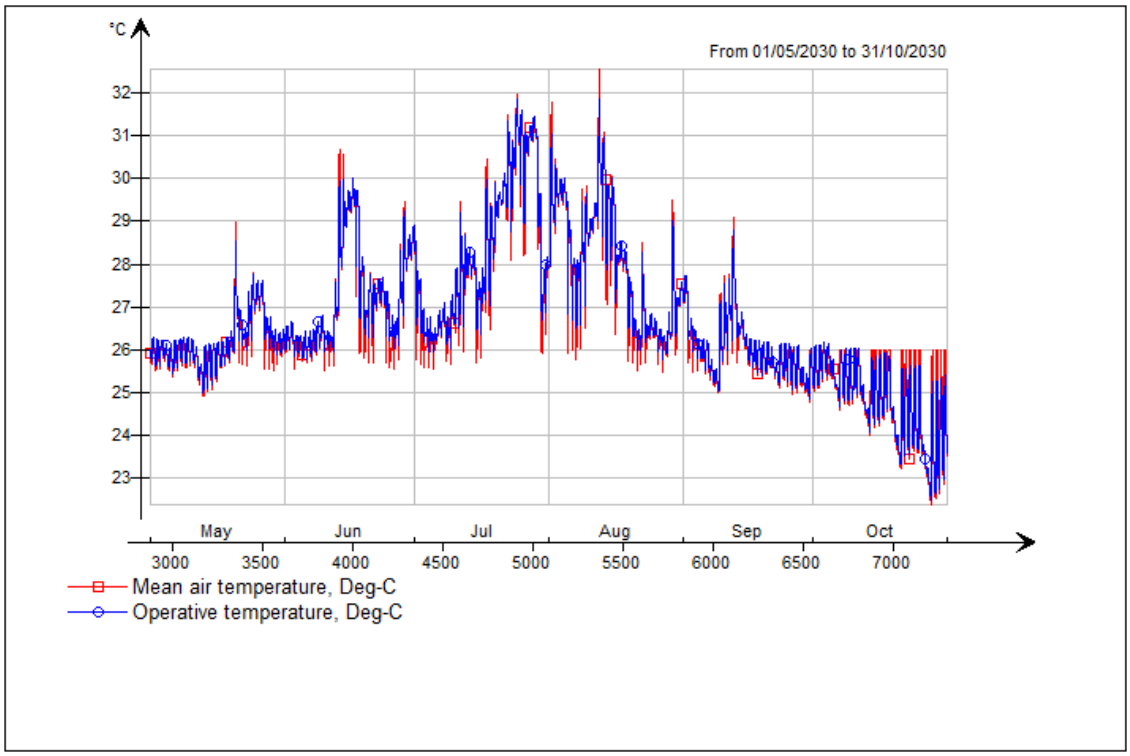
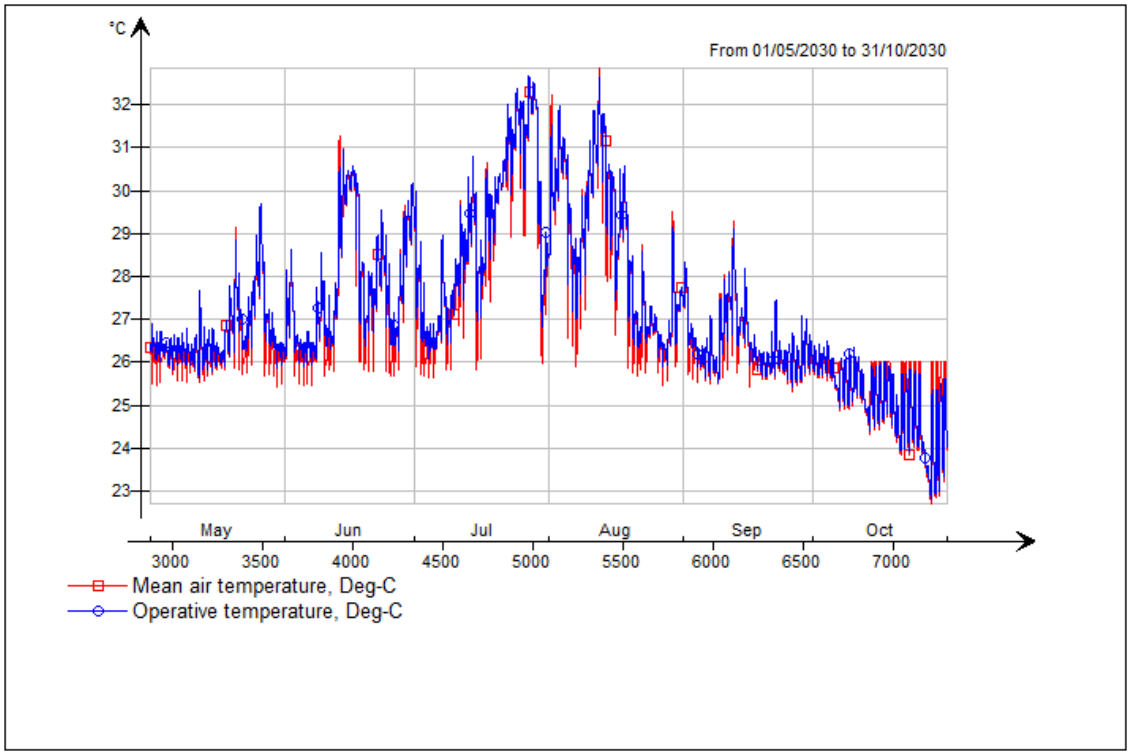
Zone 3 (North)



Zone 4 (East)



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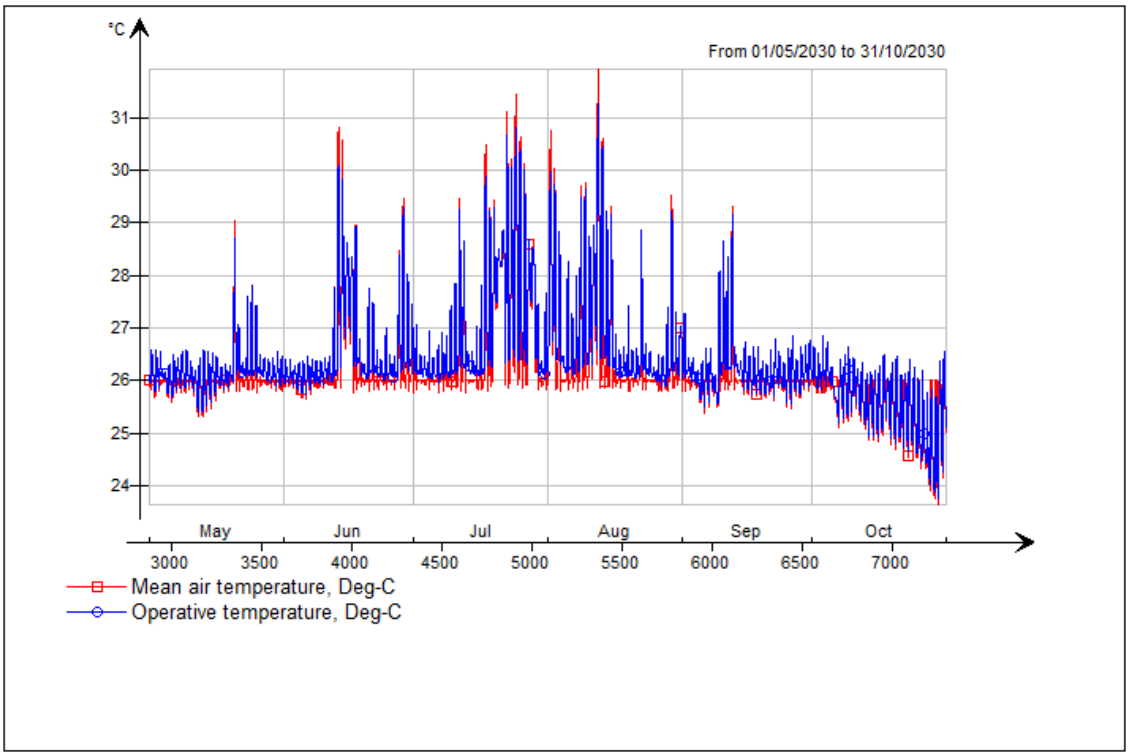
Night ventilation scenario Vienna 2030 (RCP8.5)

Zone 1 (South)



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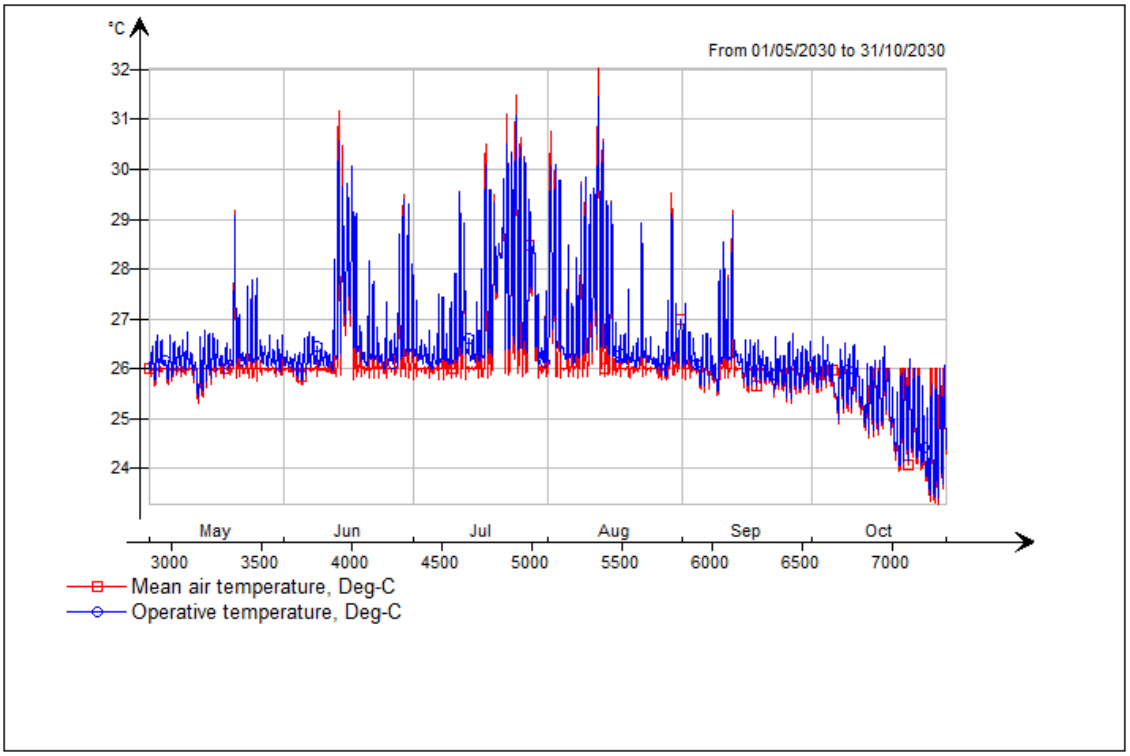

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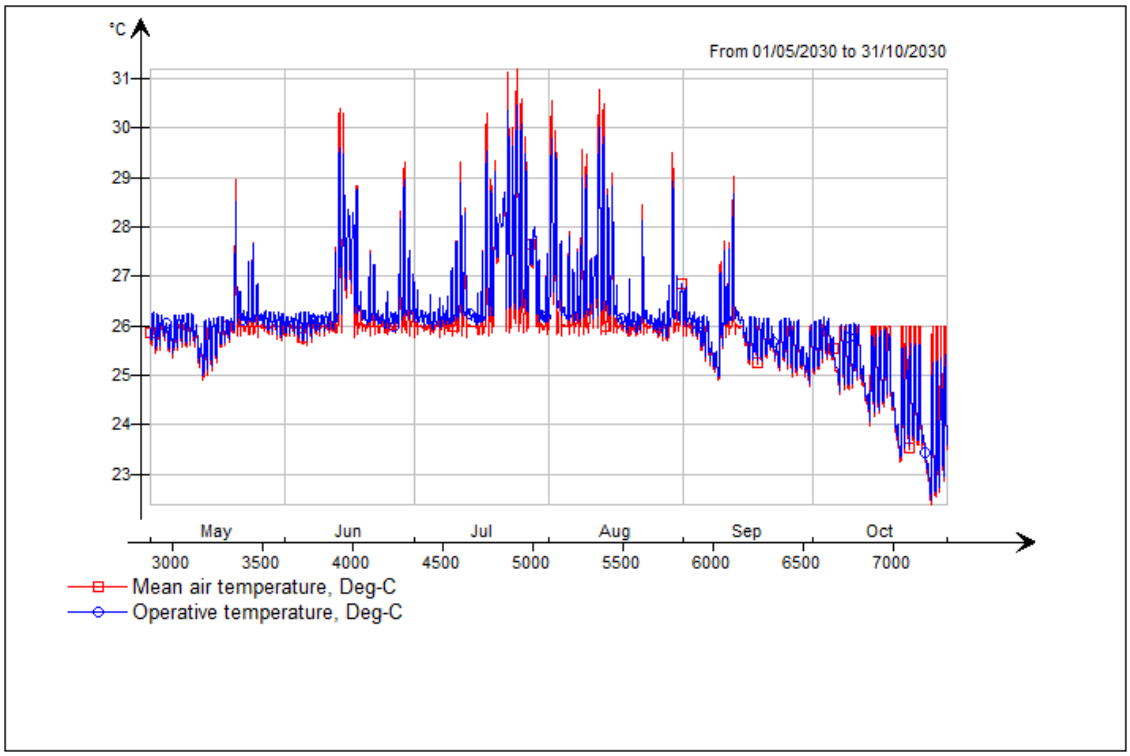
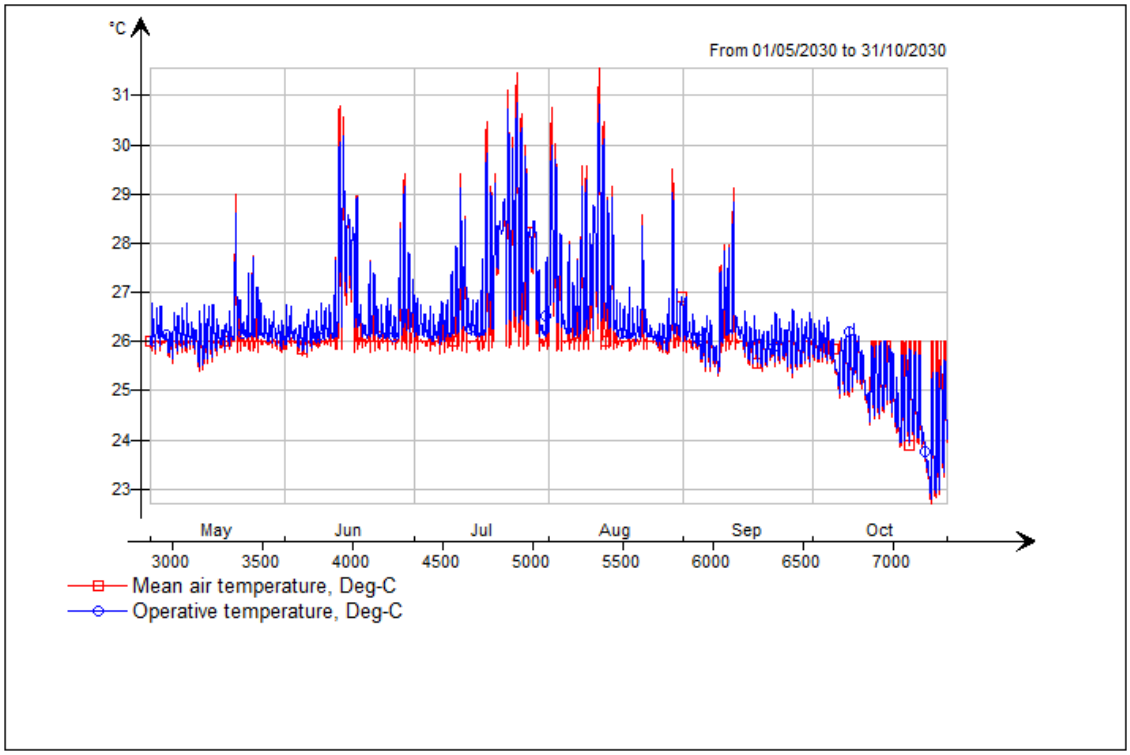
Zone 3 (North)



Zone 4 (East)



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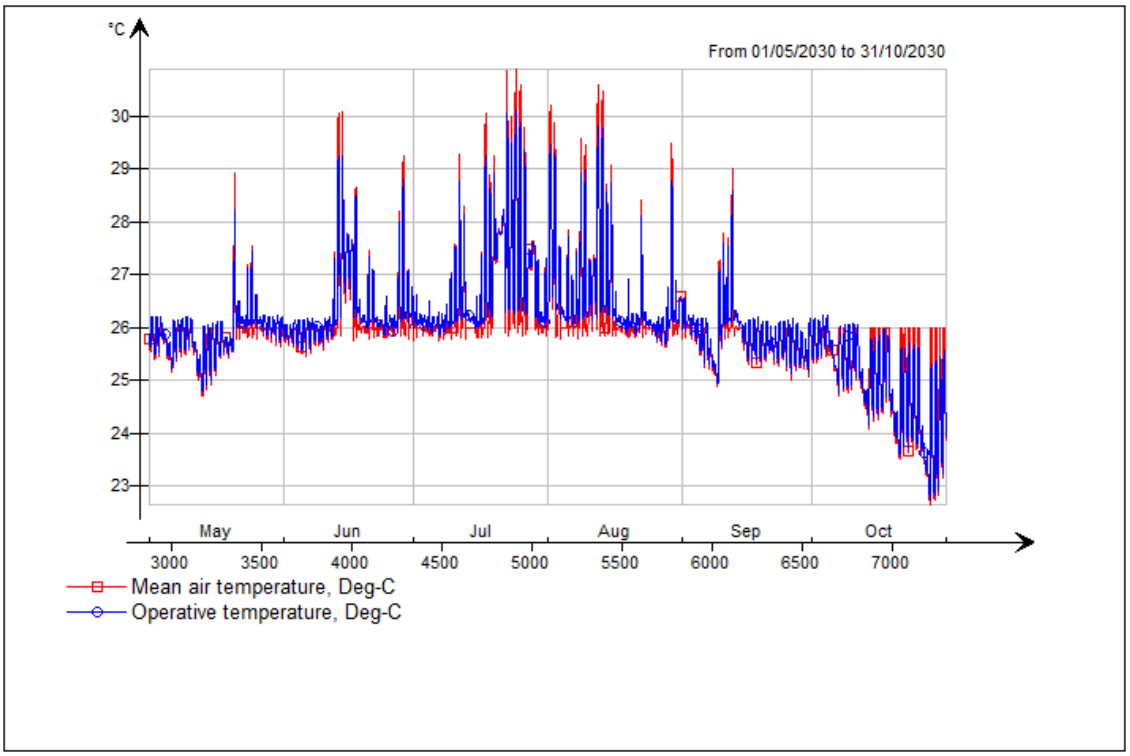
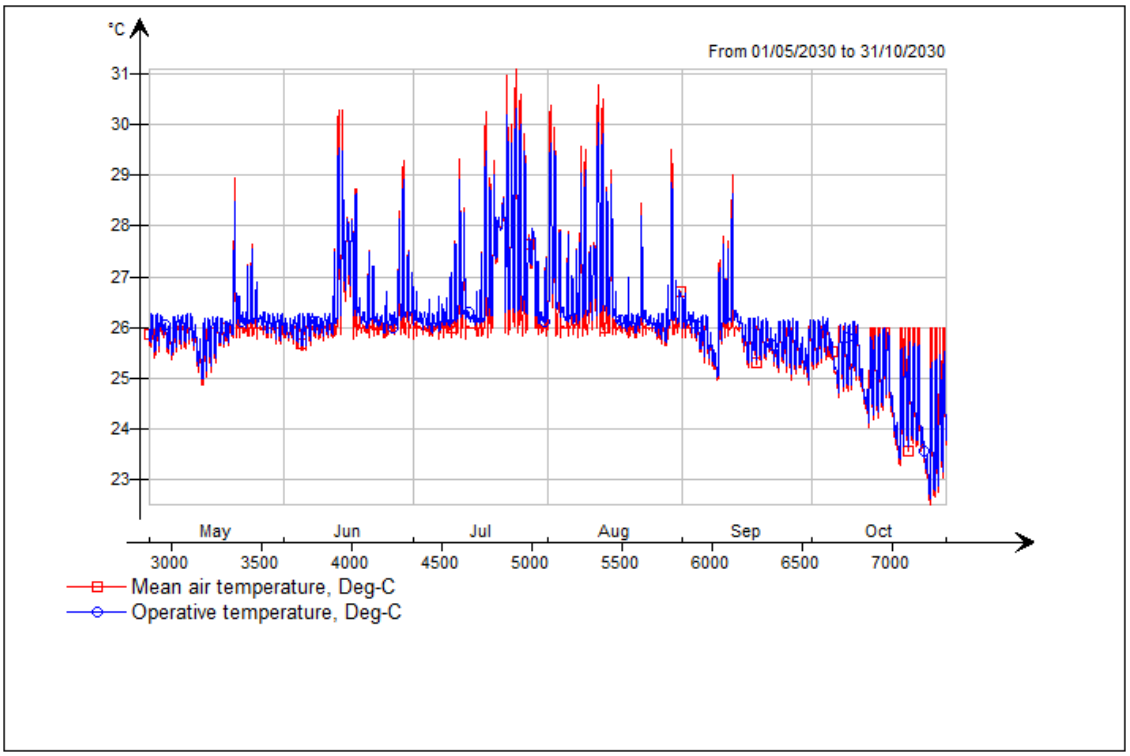
Night ventilation and shading scenario Vienna 2030 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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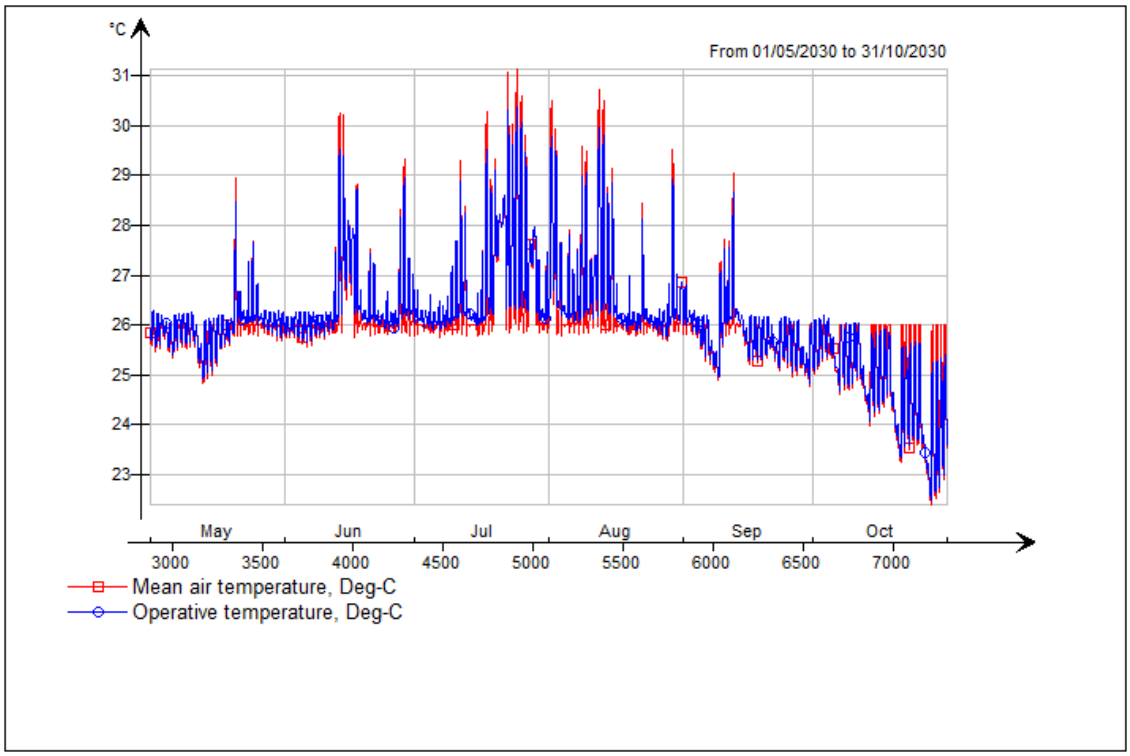
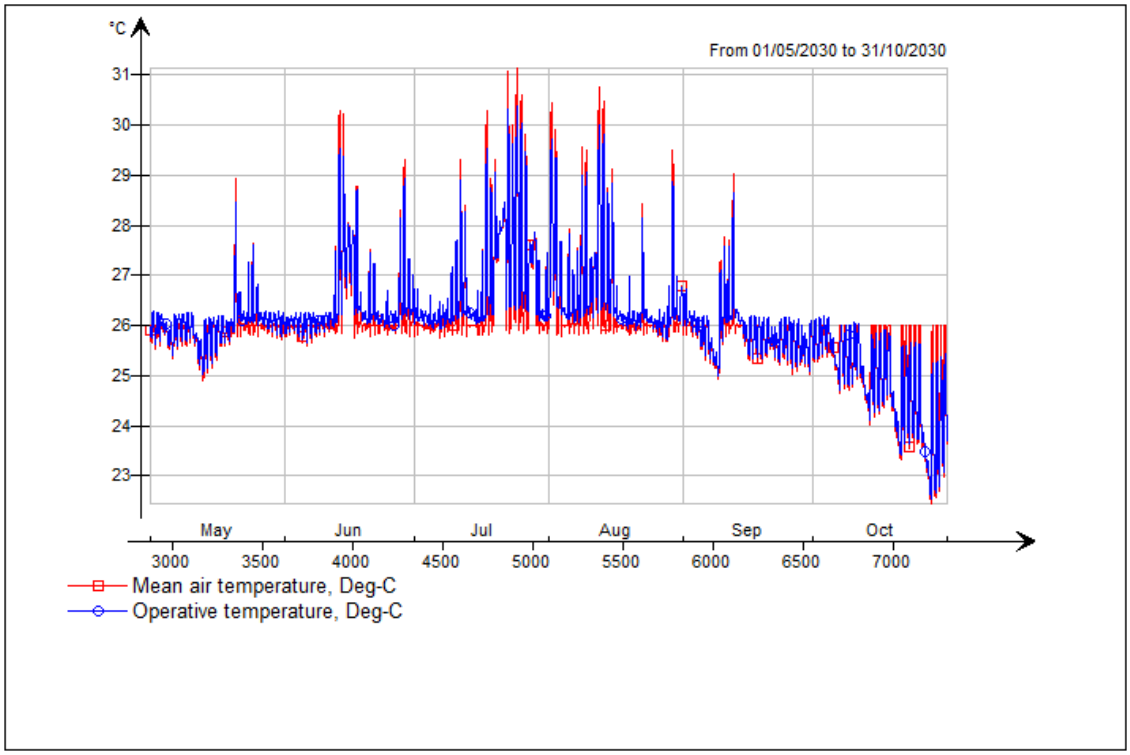
Zone 3 (North)



Zone 4 (East)



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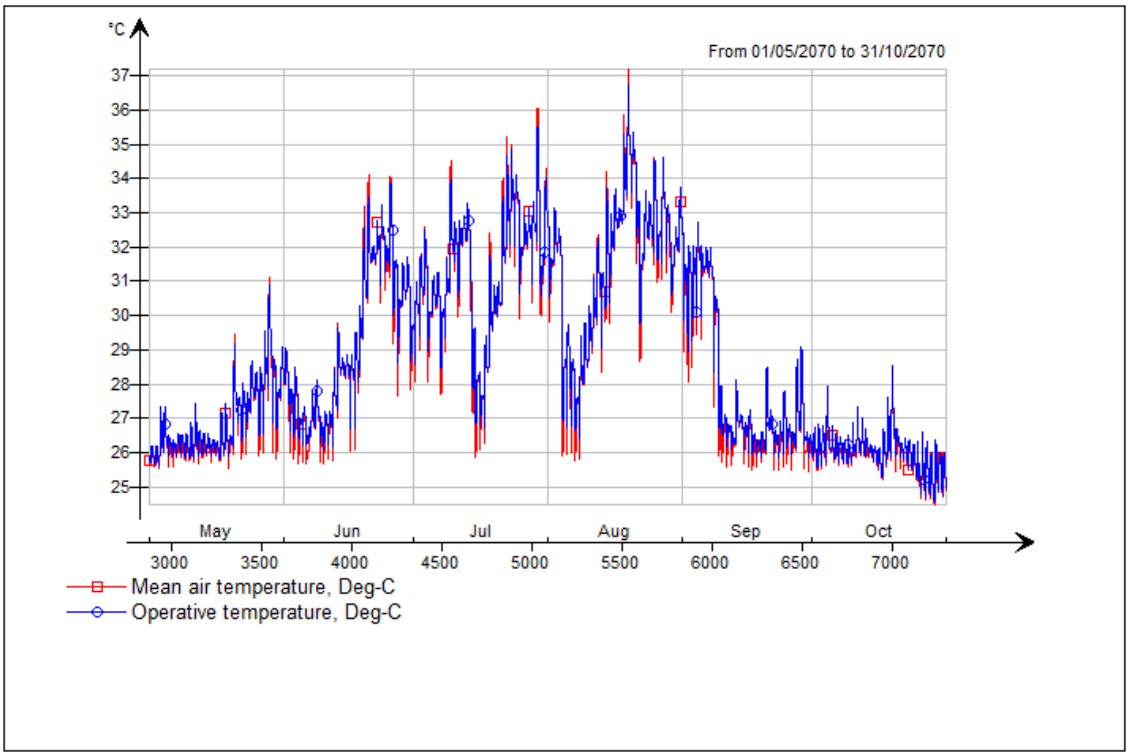
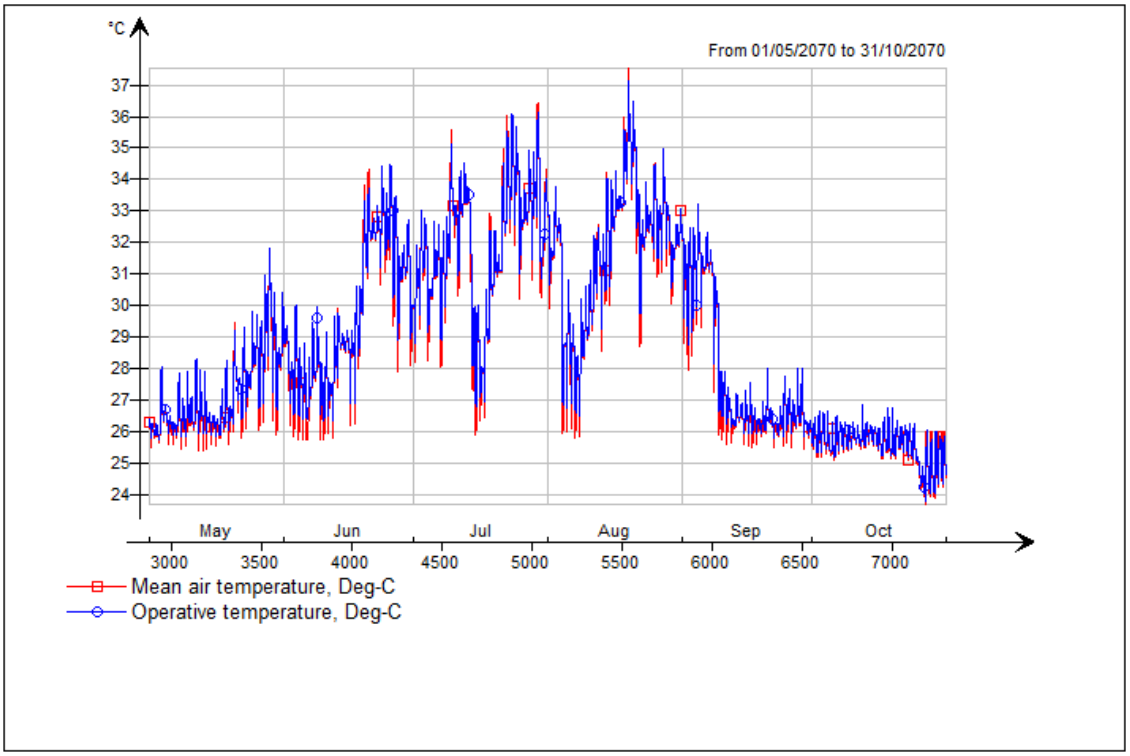
Basic scenario Vienna 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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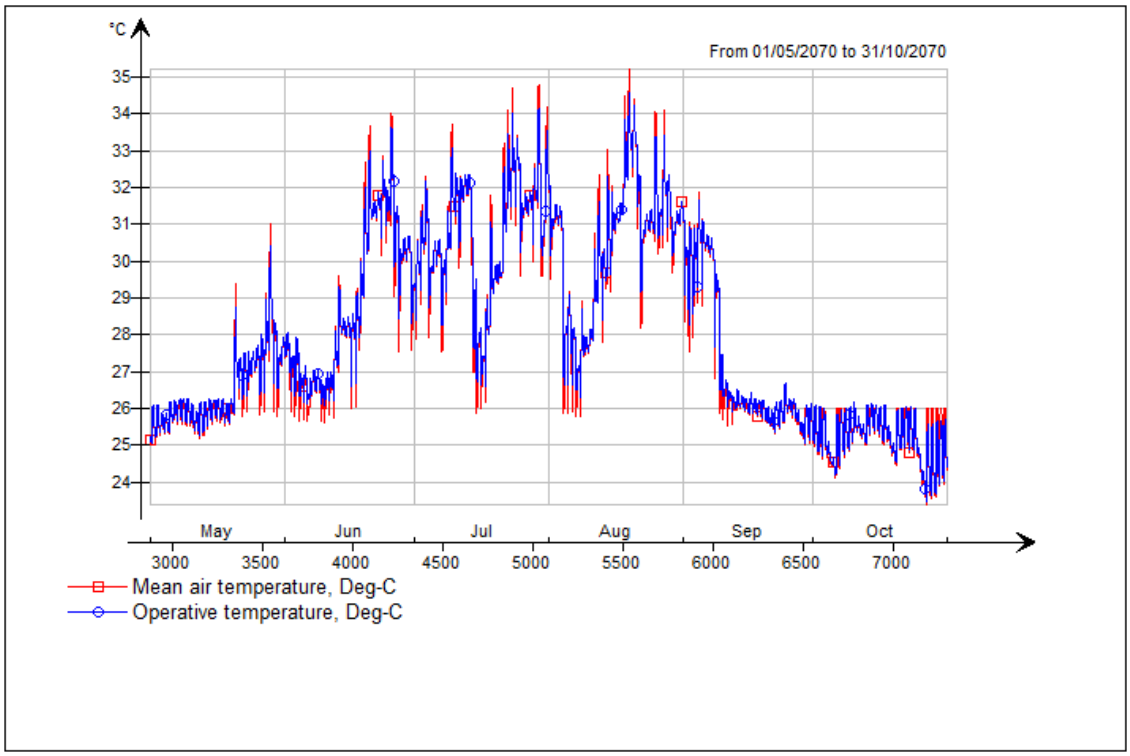
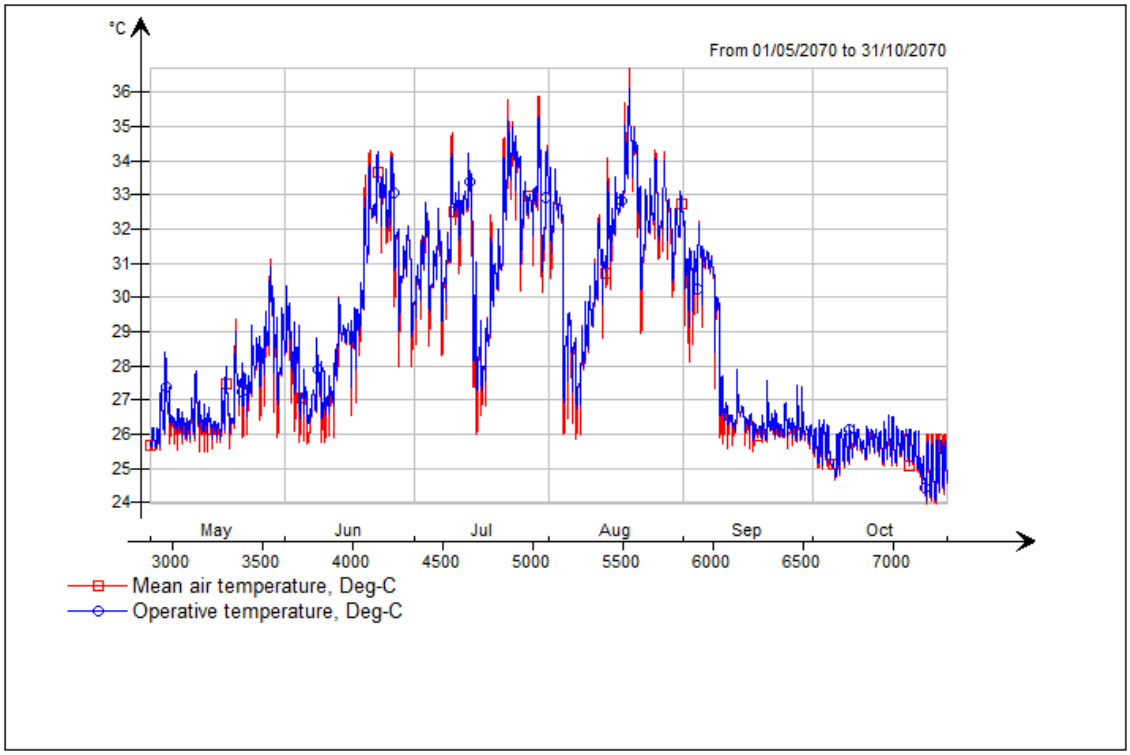
Zone 3 (North)



Zone 4 (East)



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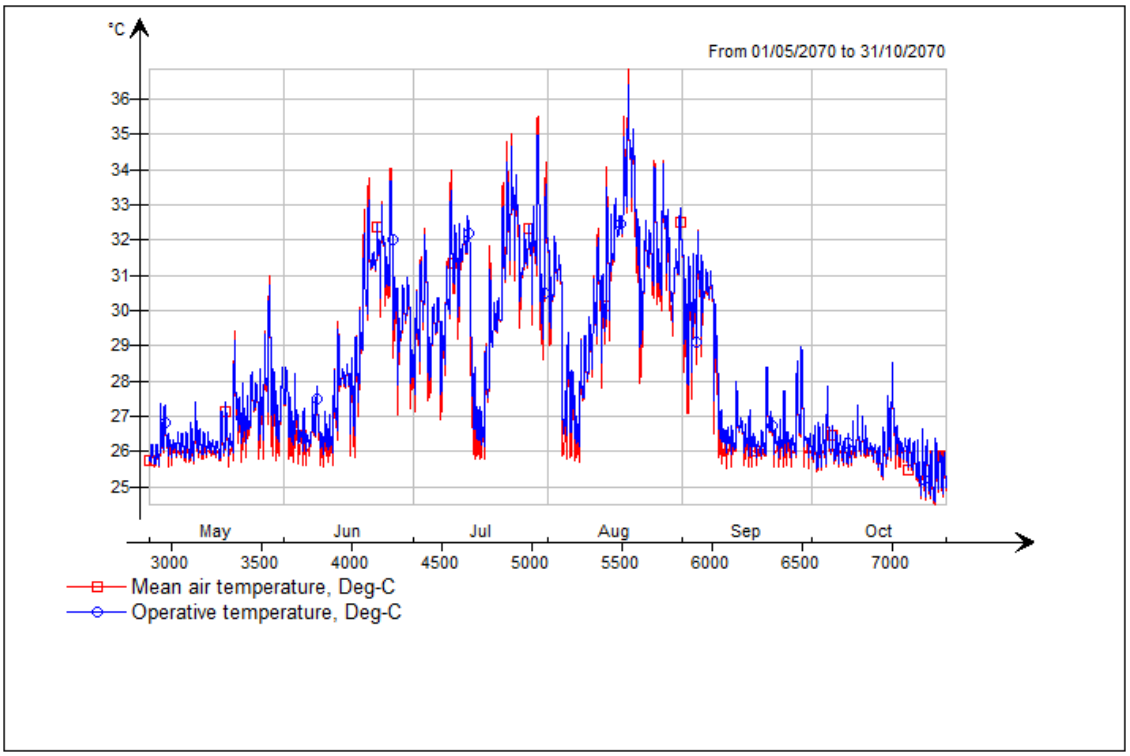
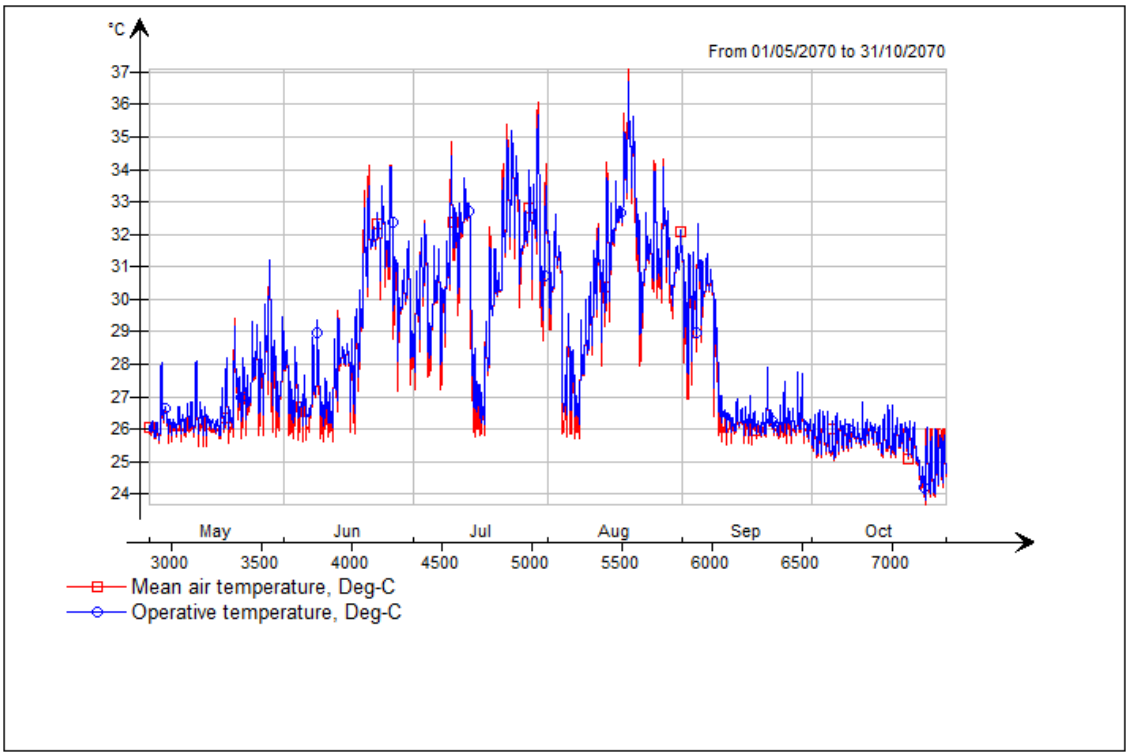
Night ventilation scenario Vienna 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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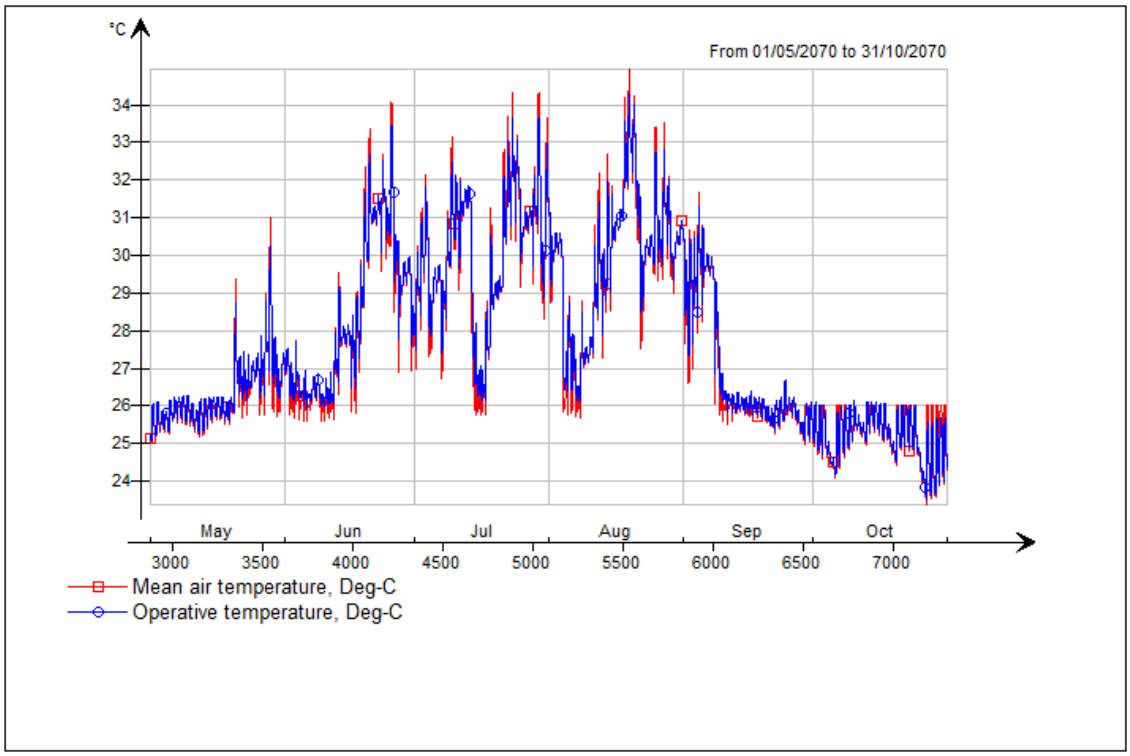
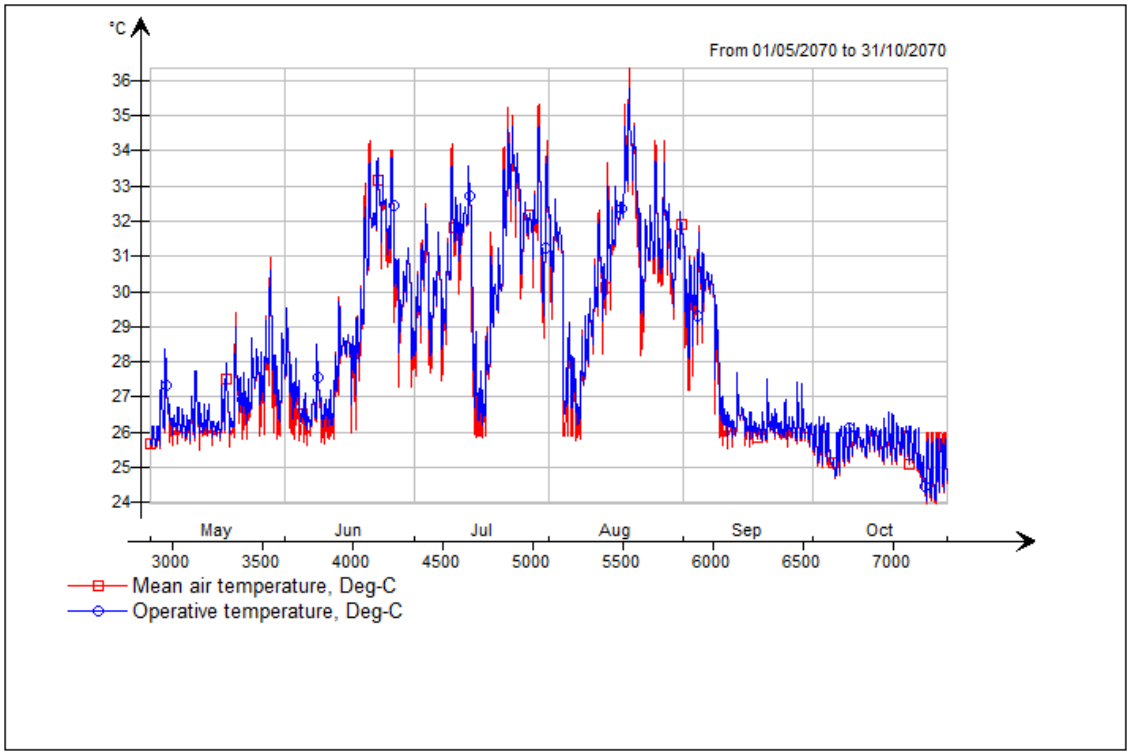
Zone 3 (North)



Zone 4 (East)



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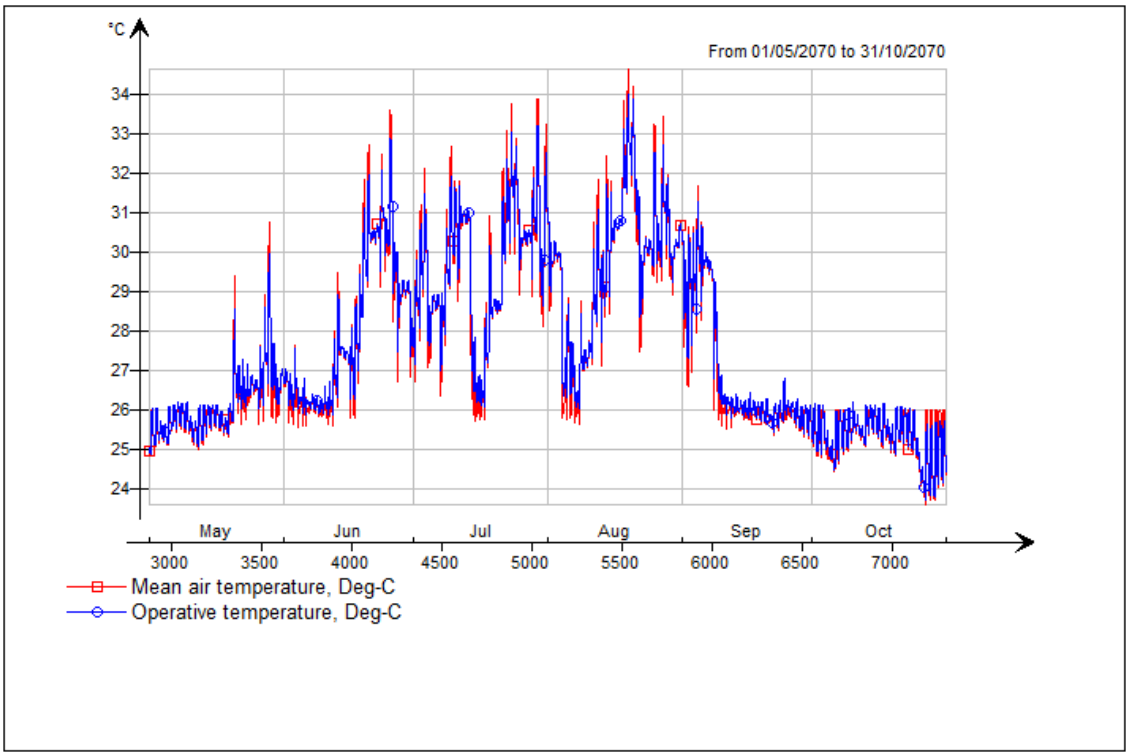
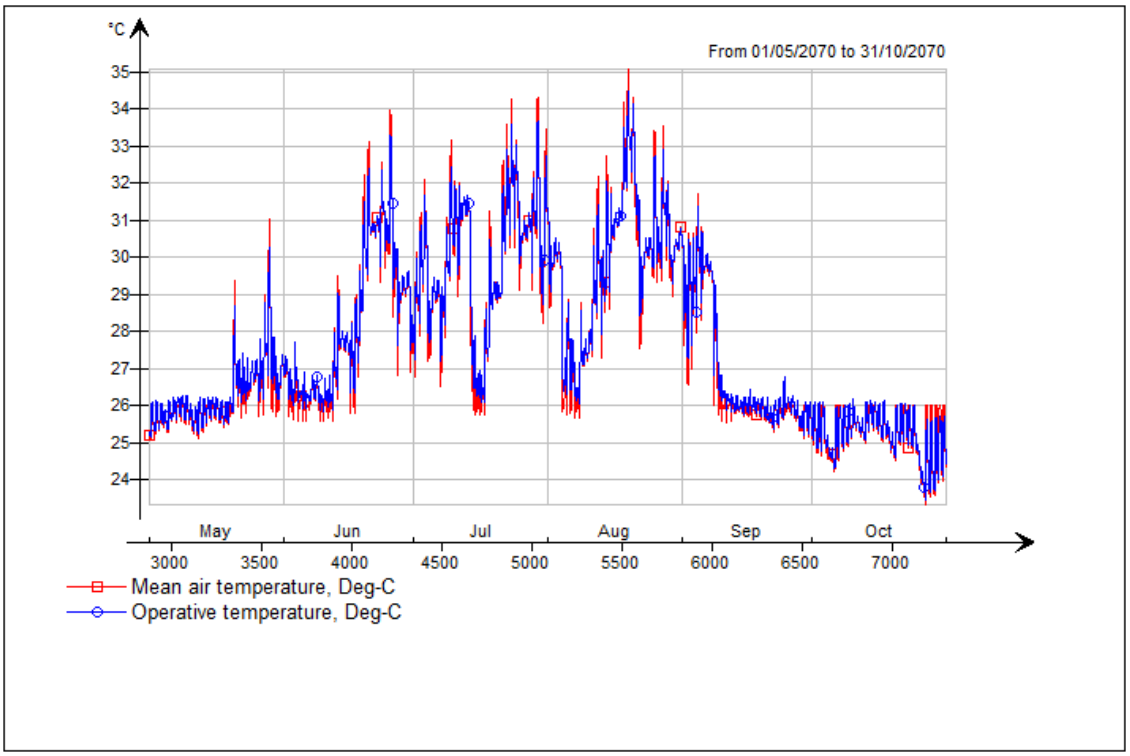
Night ventilation and shading scenario Vienna 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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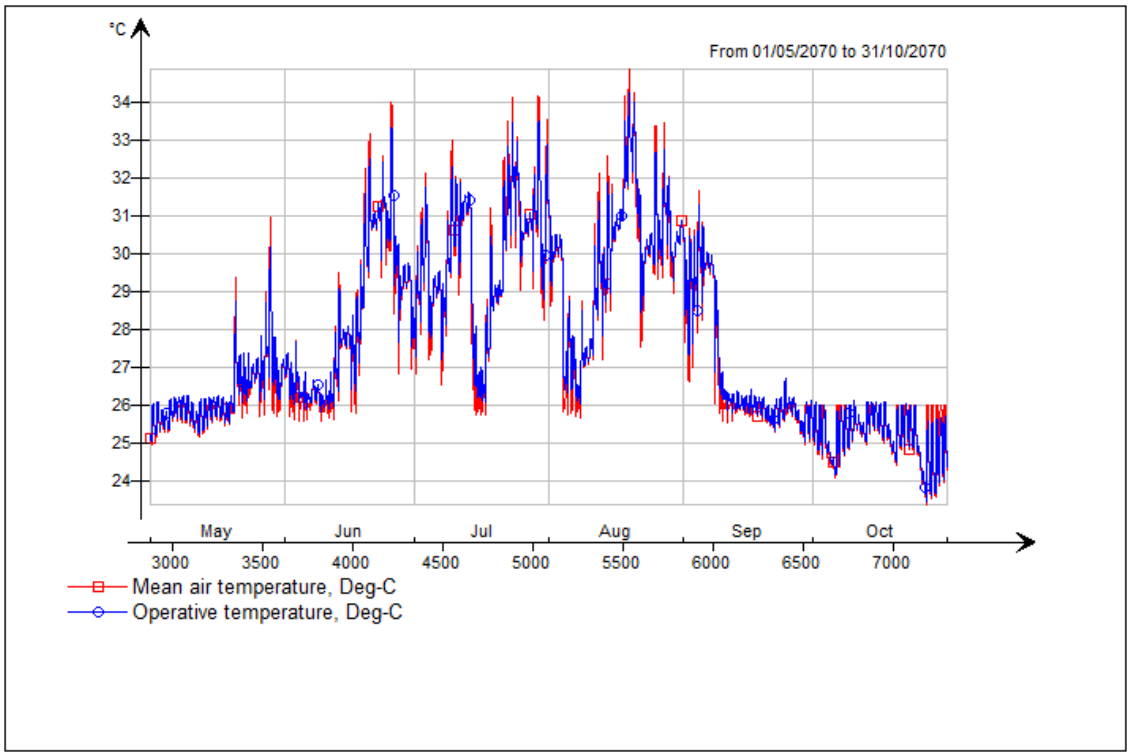
Zone 3 (North)



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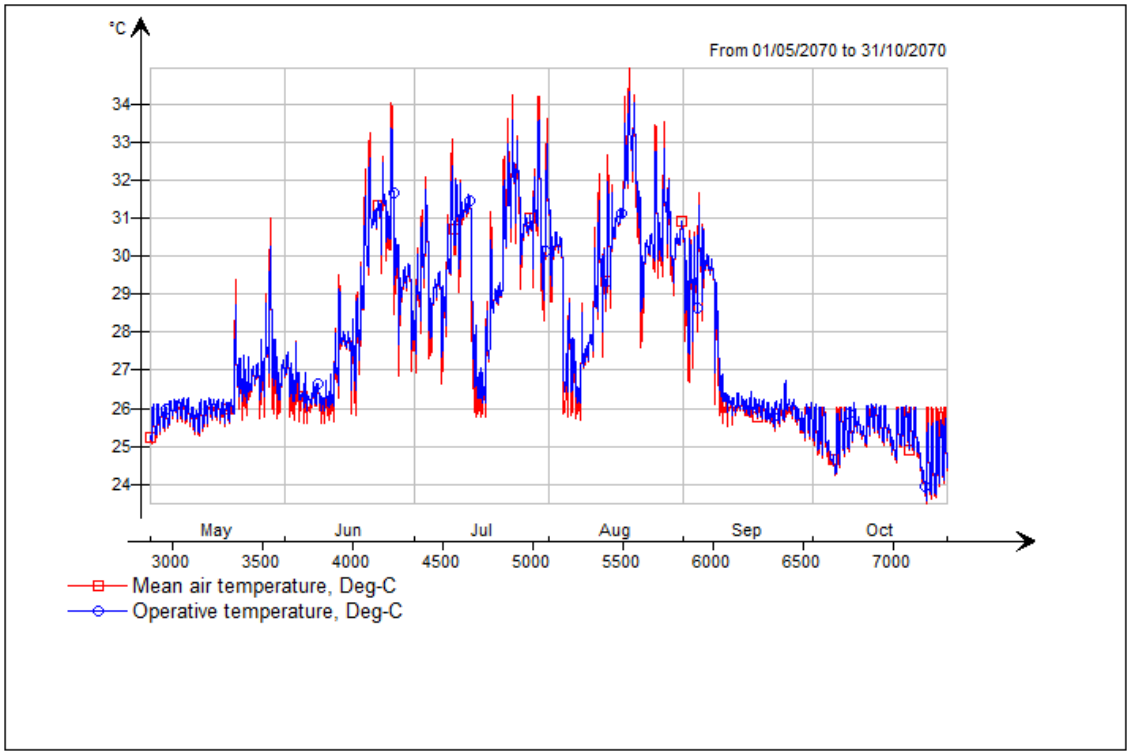

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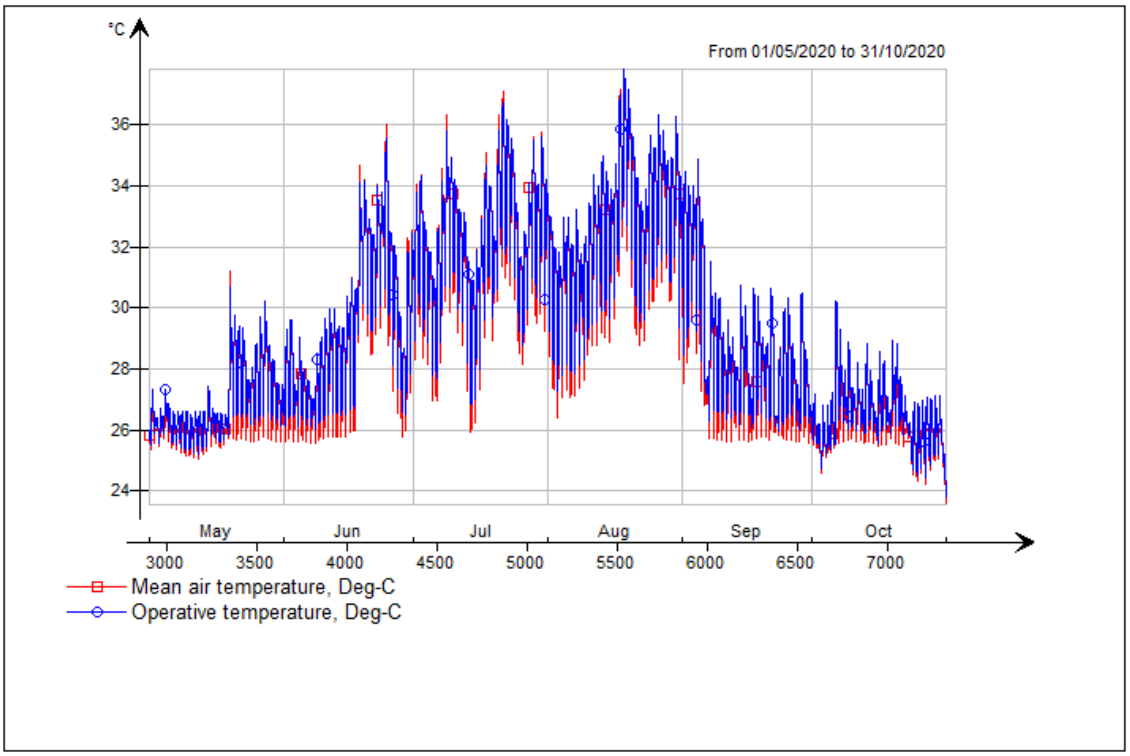
Basic scenario Athens 2020

Zone 1 (South)



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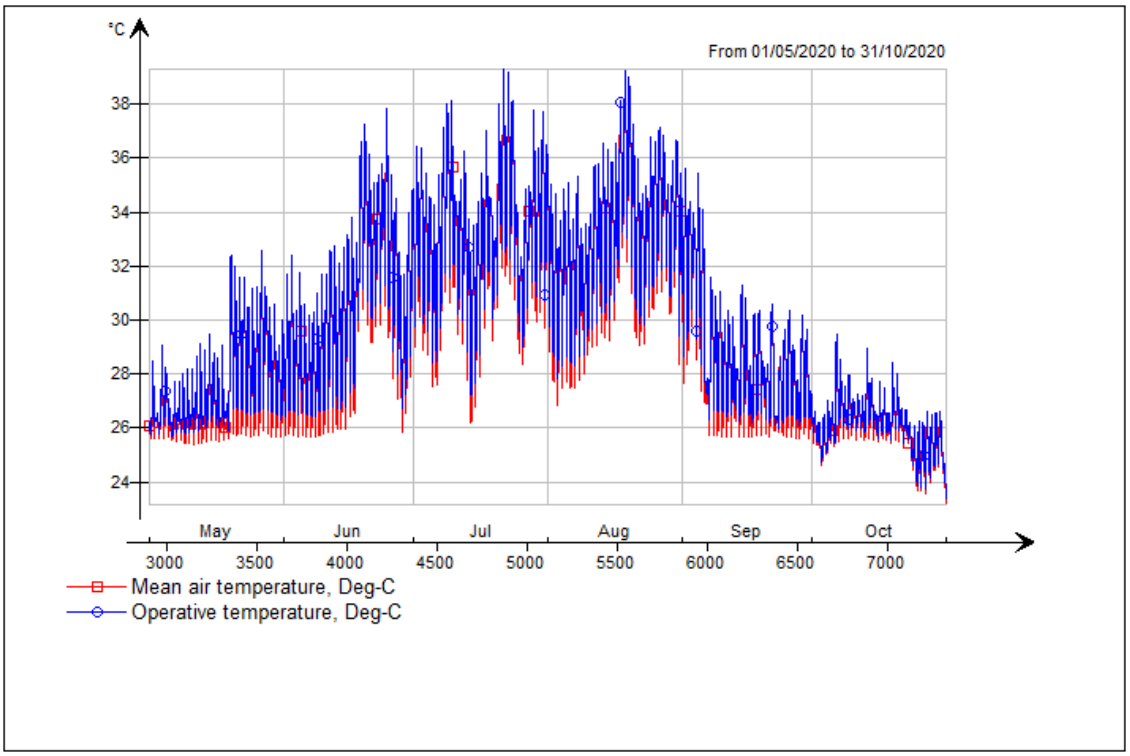

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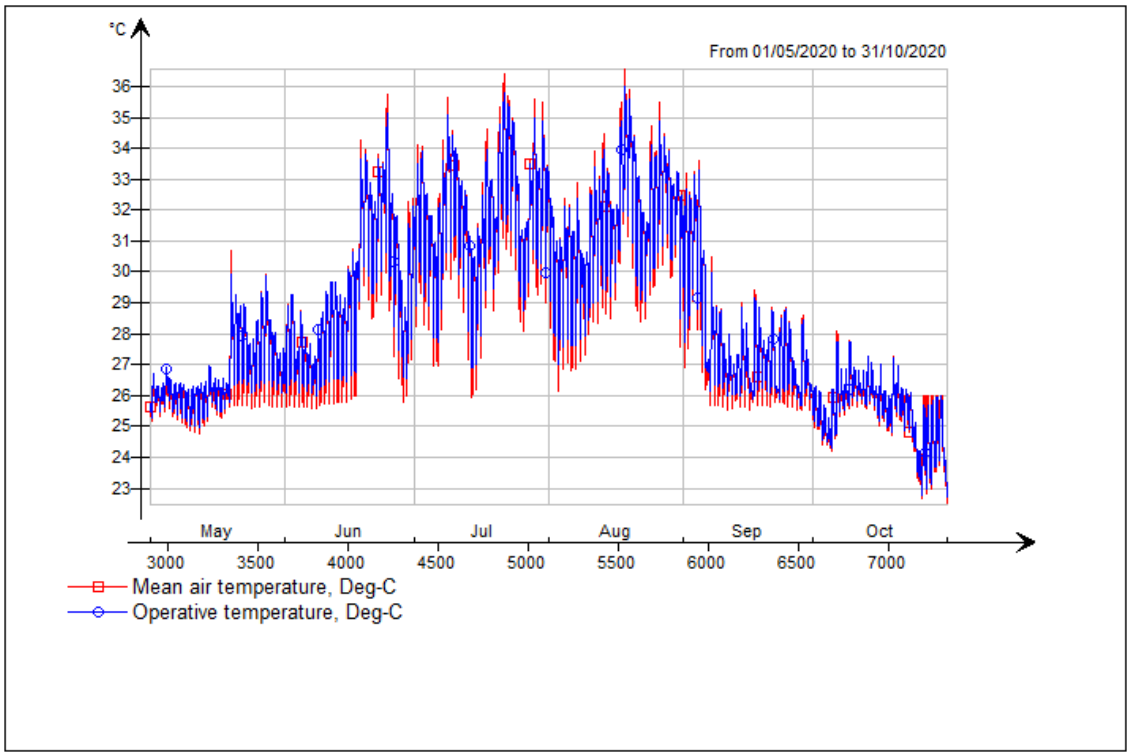
Zone 3 (North)



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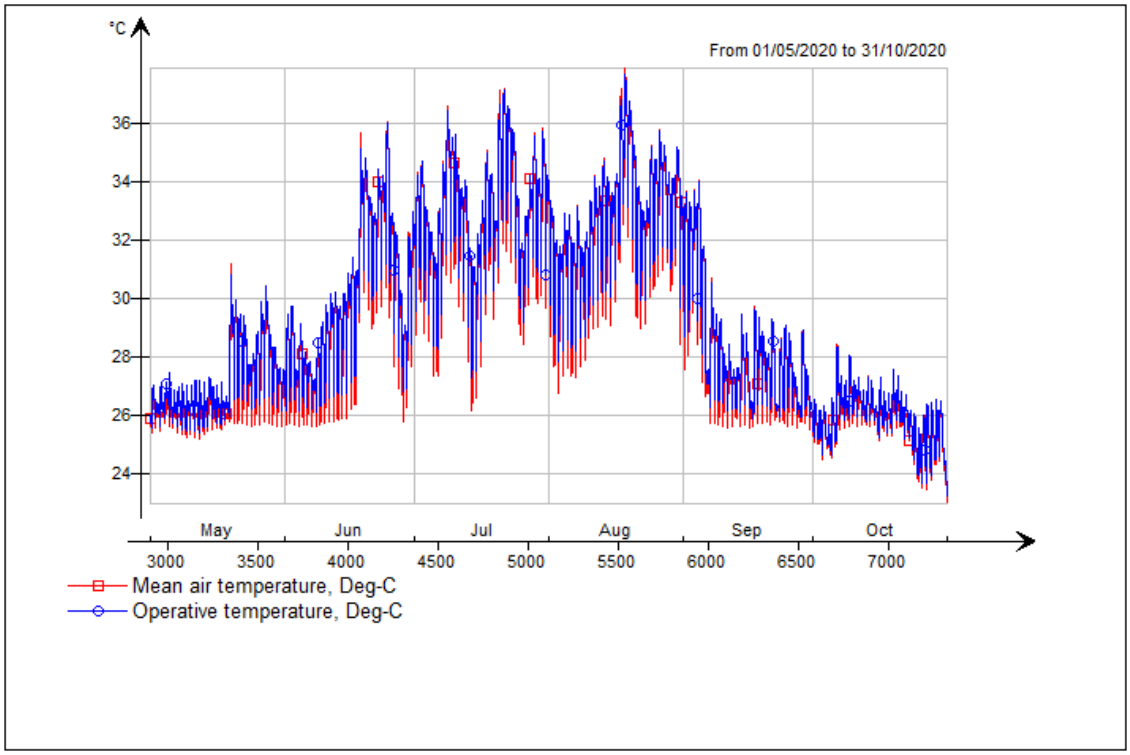

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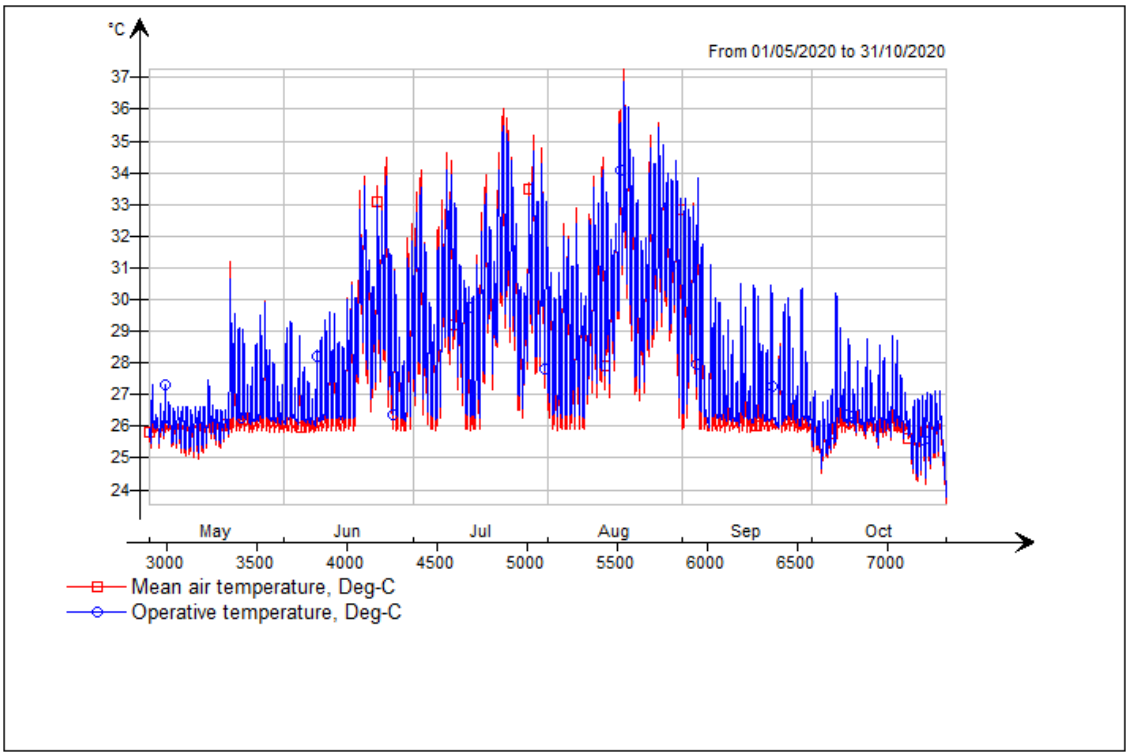
Night ventilation scenario Athens 2020

Zone 1 (South)



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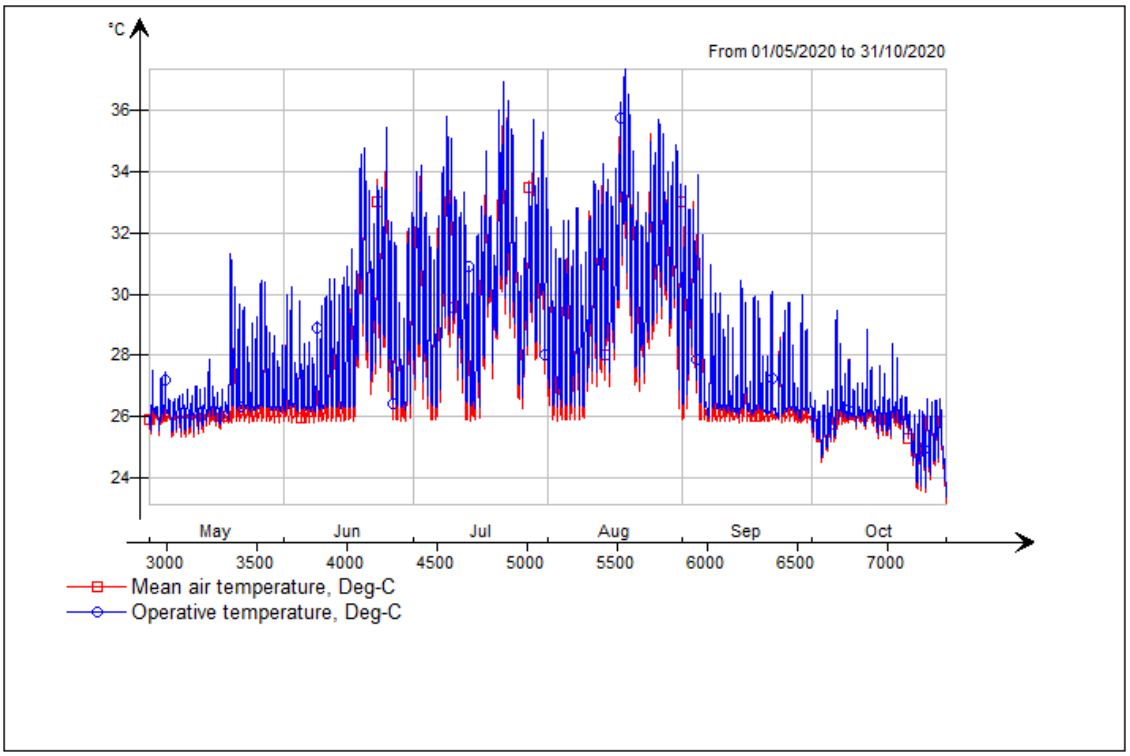

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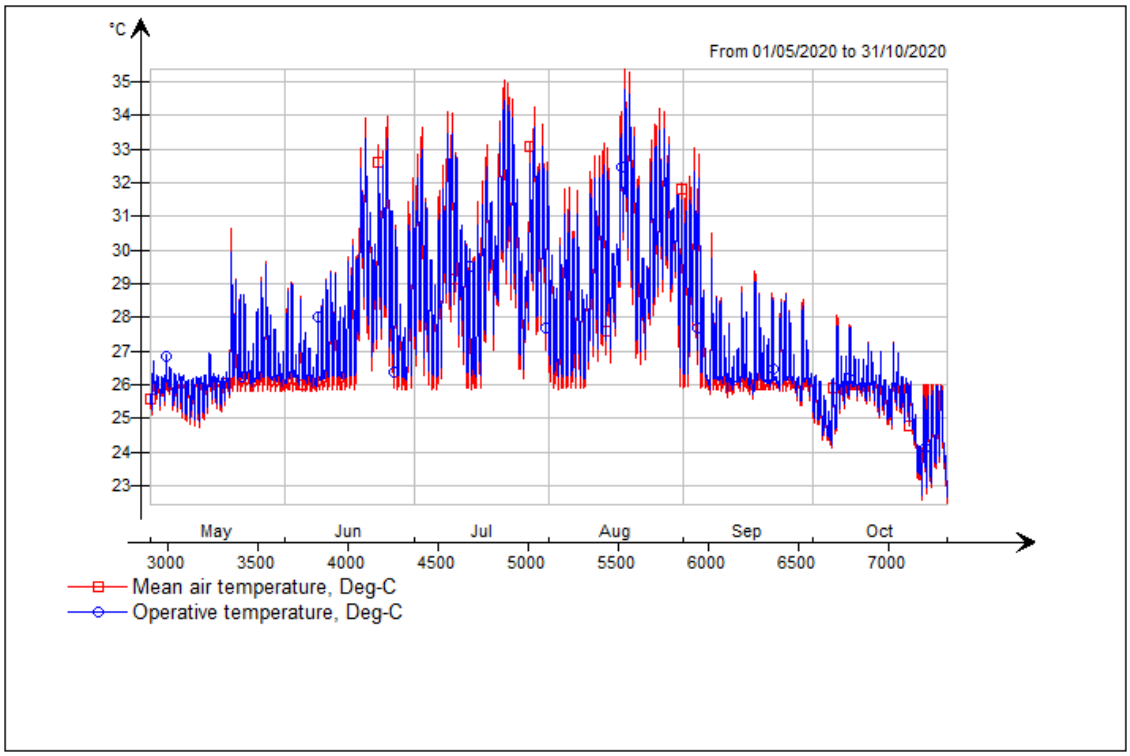
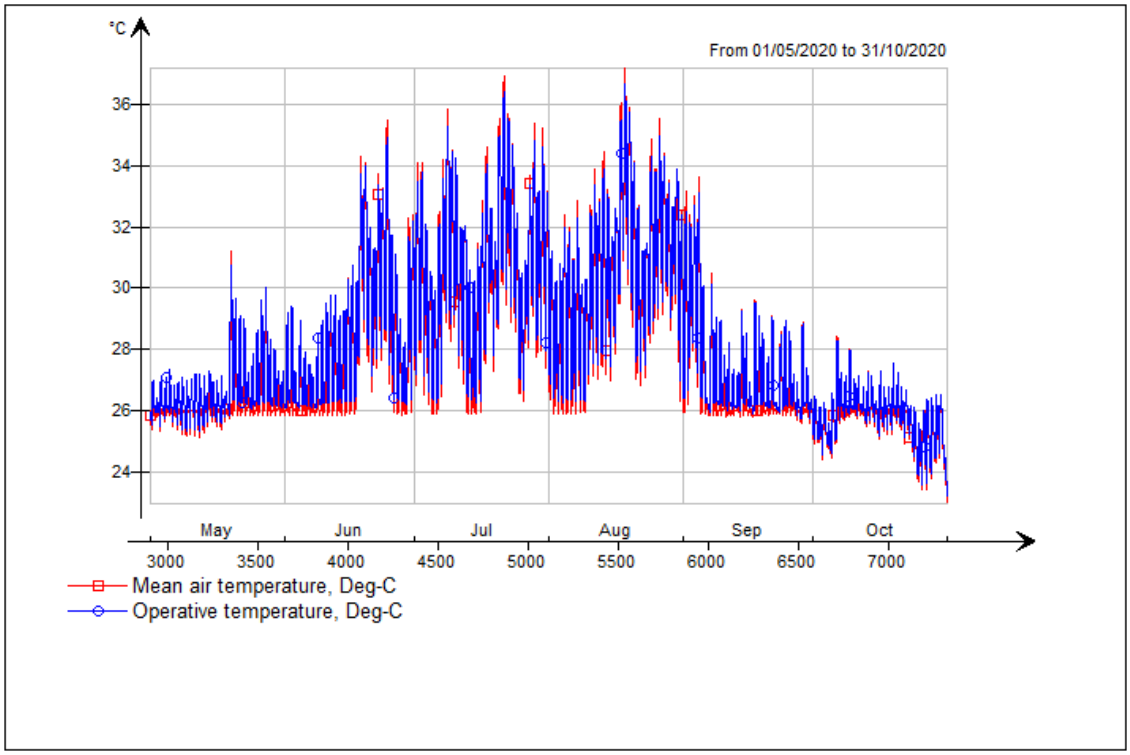
Zone 3 (North)



Zone 4 (East)



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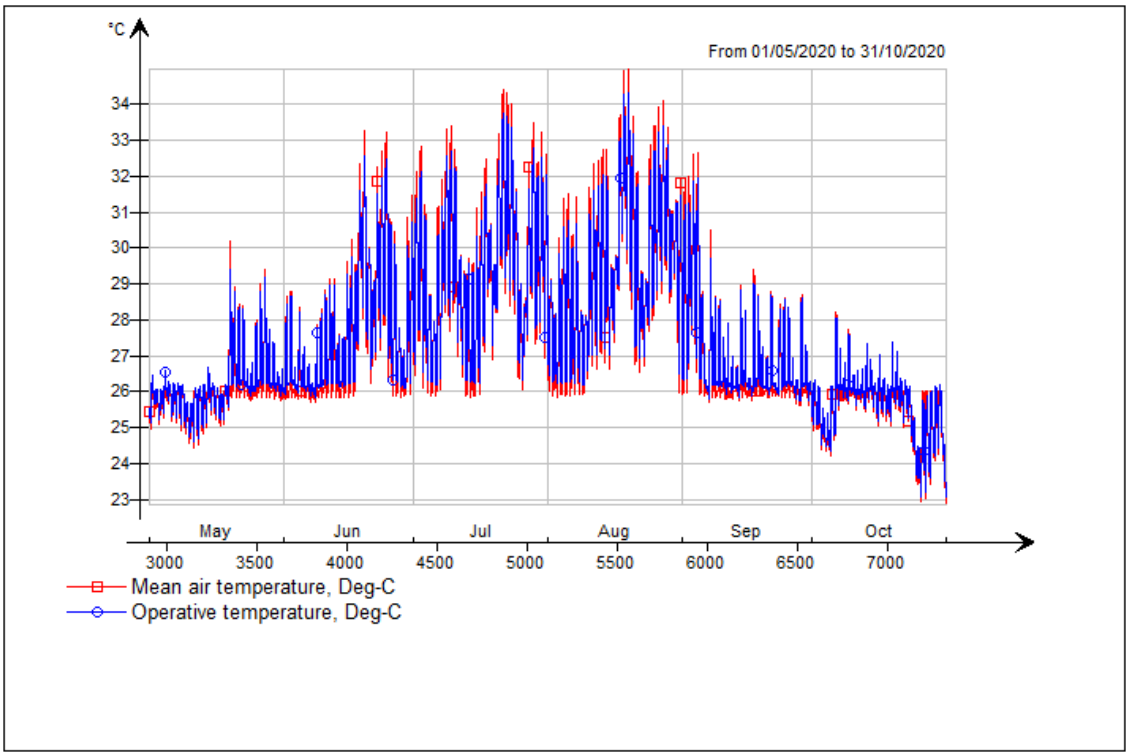
Night ventilation and shading scenario Athens 2020

Zone 1 (South)



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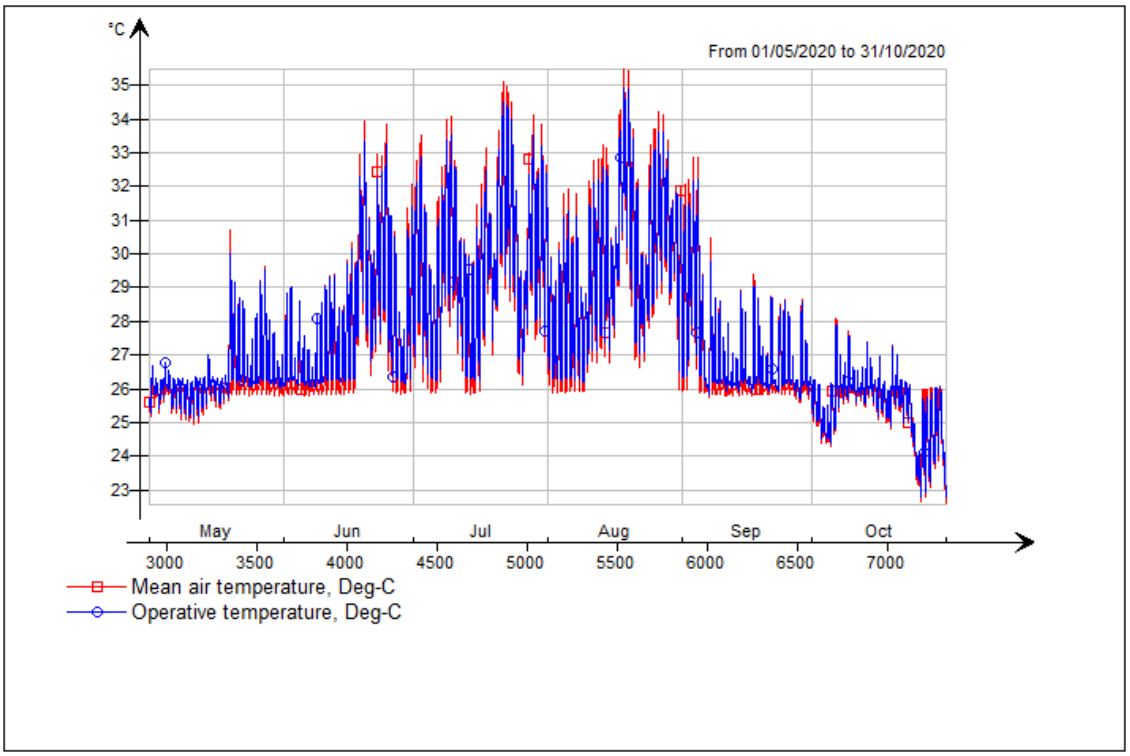

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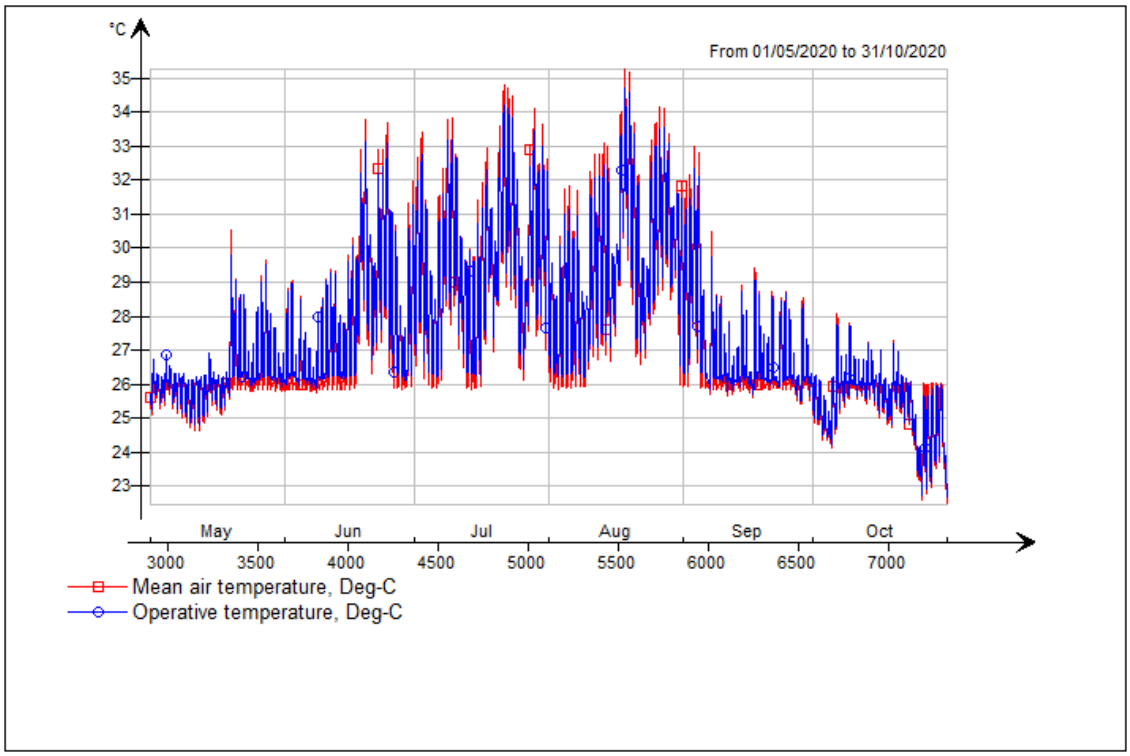
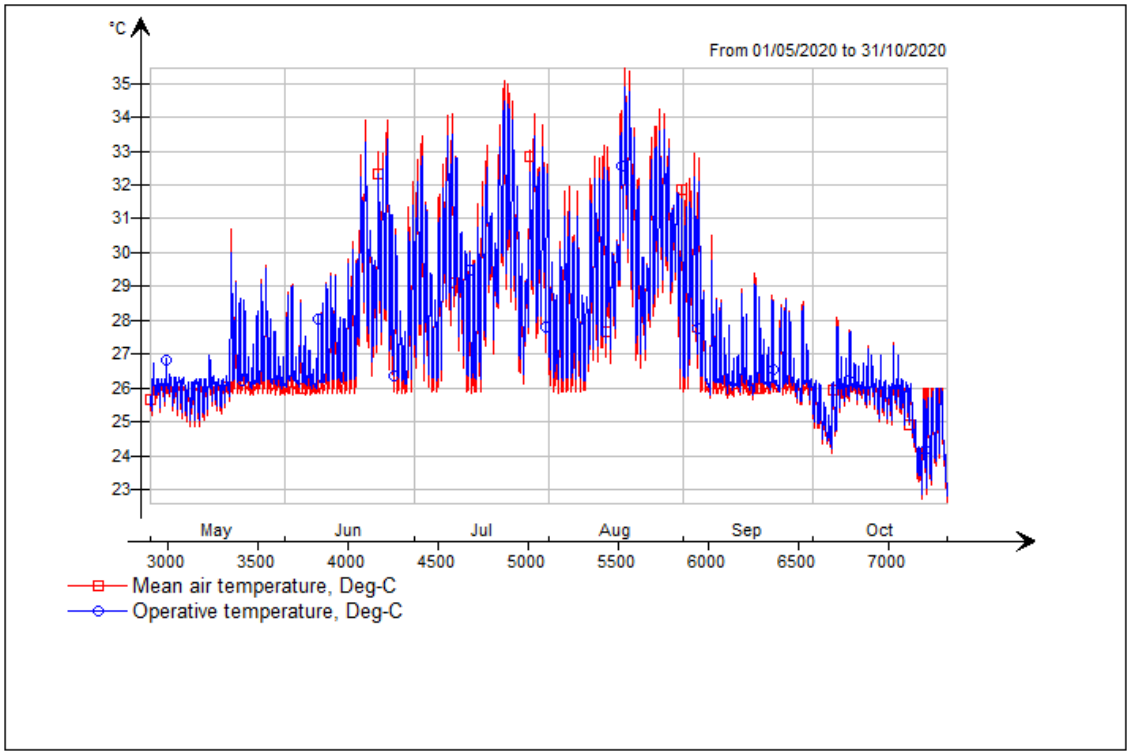
Zone 3 (North)



Zone 4 (East)



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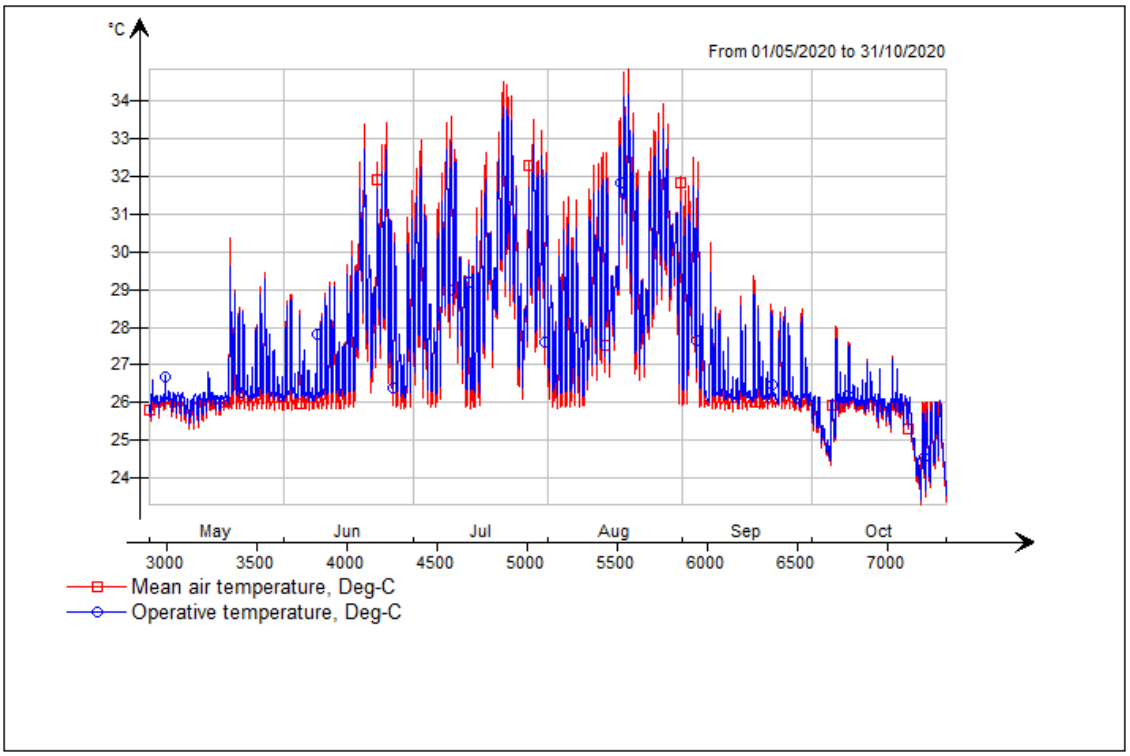
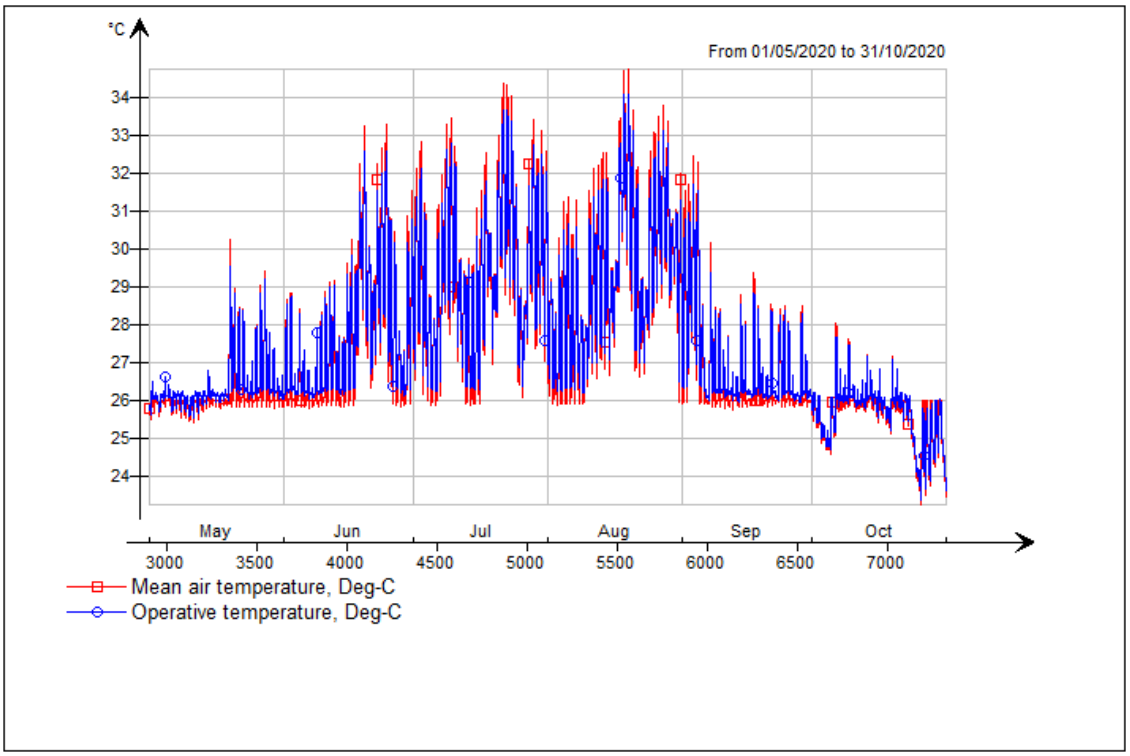
Night ventilation, shading and glazing scenario Athens 2020

Zone 1 (South)



Zone 2 (West)



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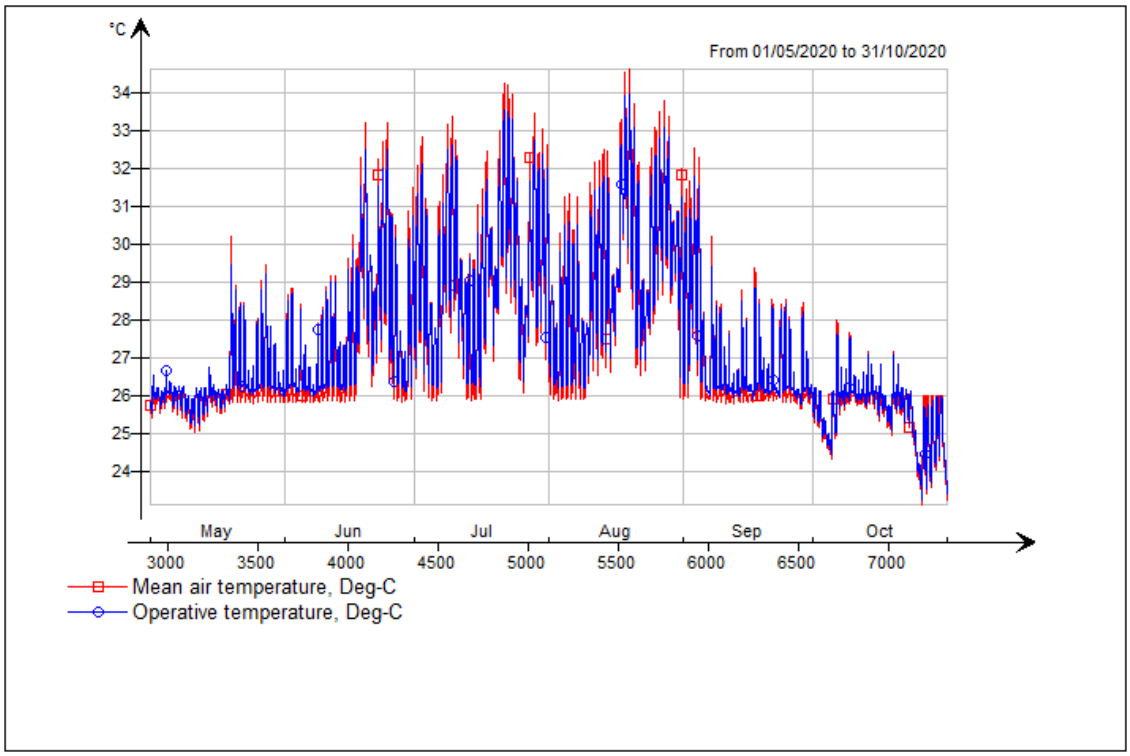
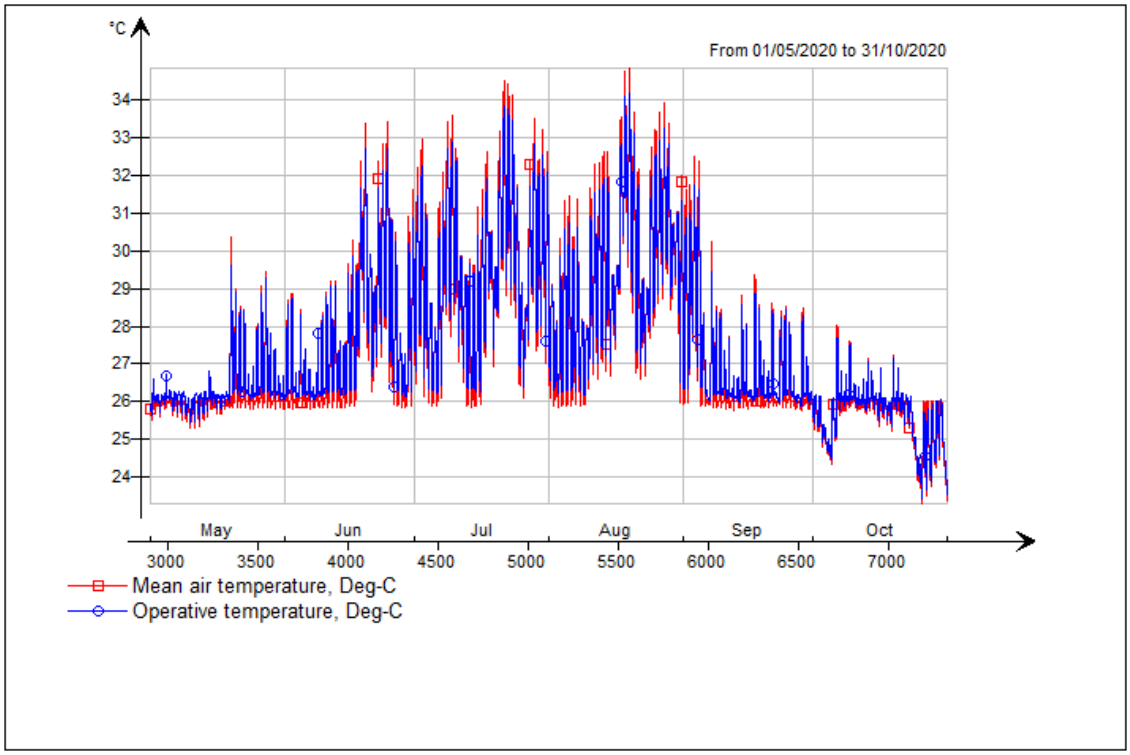
Zone 3 (North)



Zone 4 (East)



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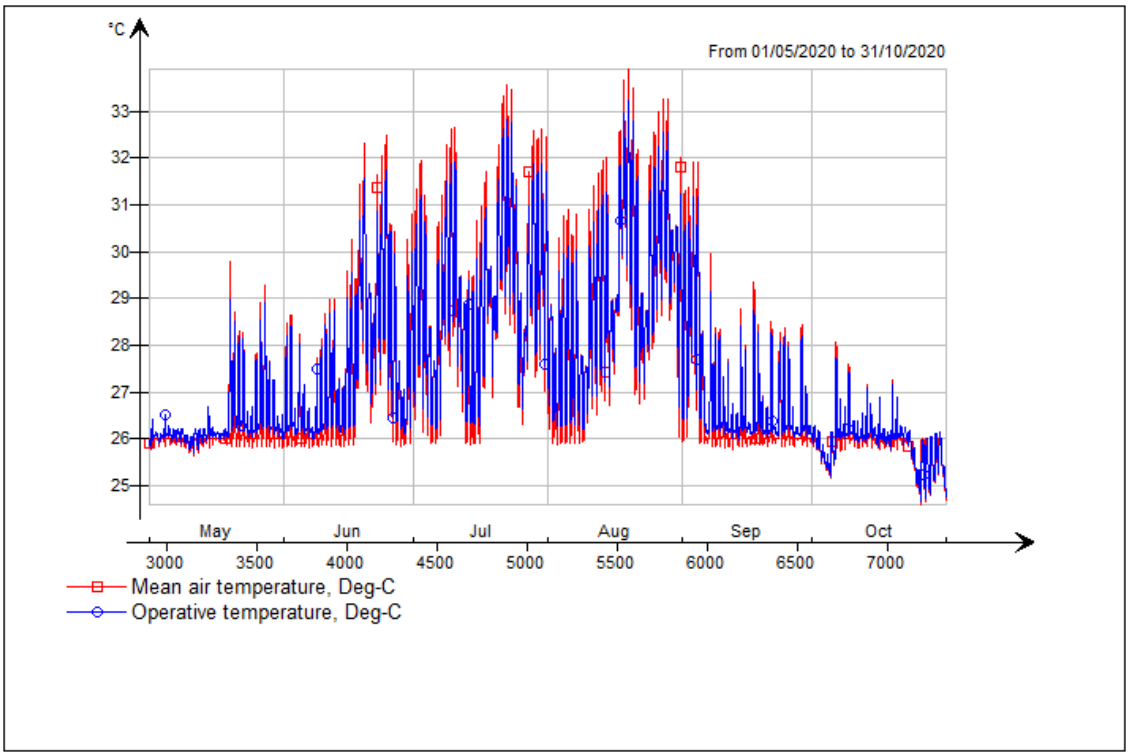
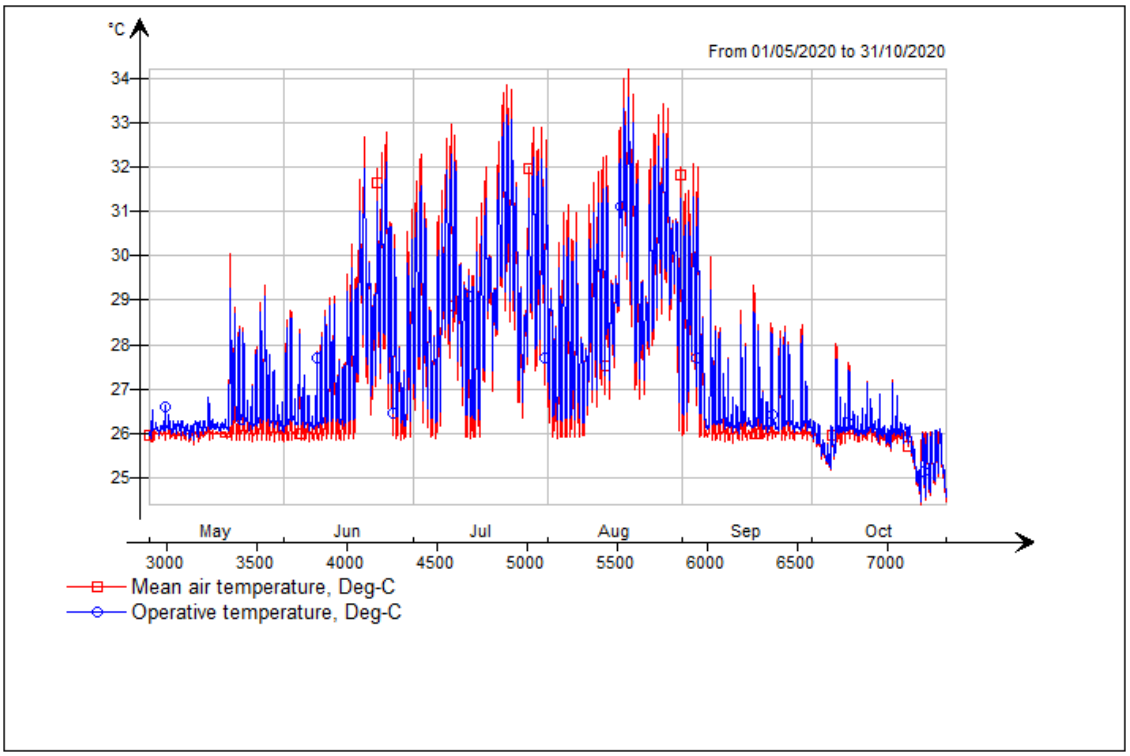
Night ventilation, shading, glazing and thermal mass scenario Athens 2020

Zone 1 (South)



Zone 2 (West)



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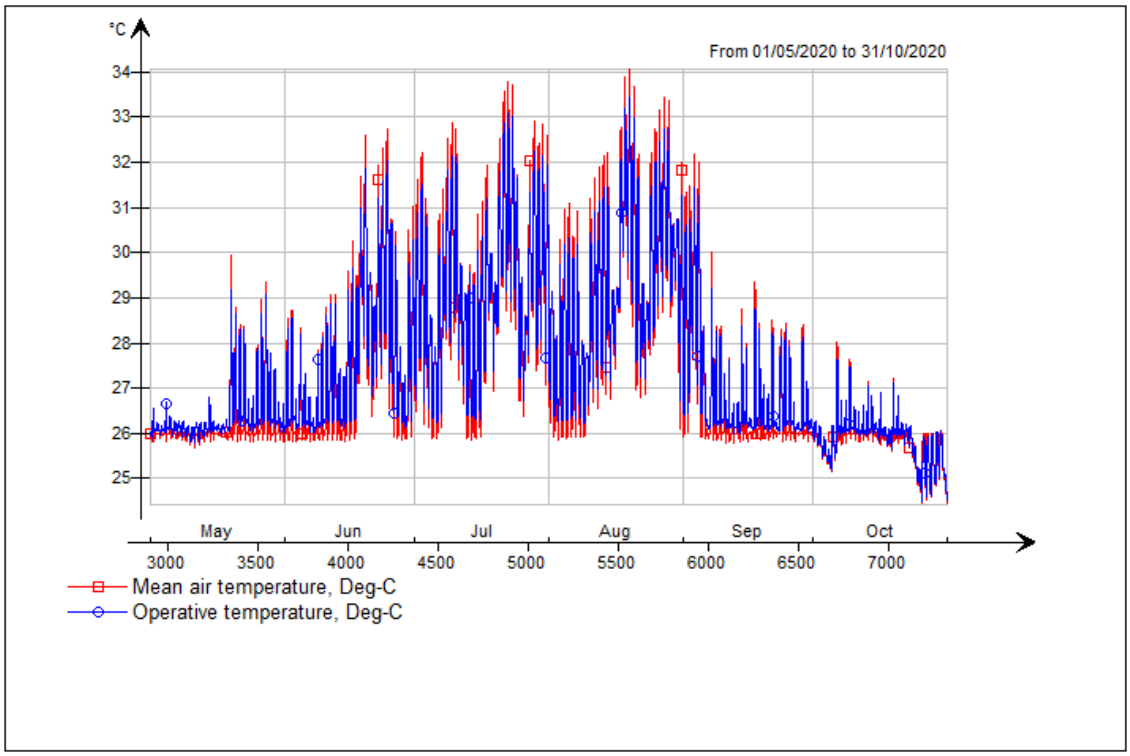
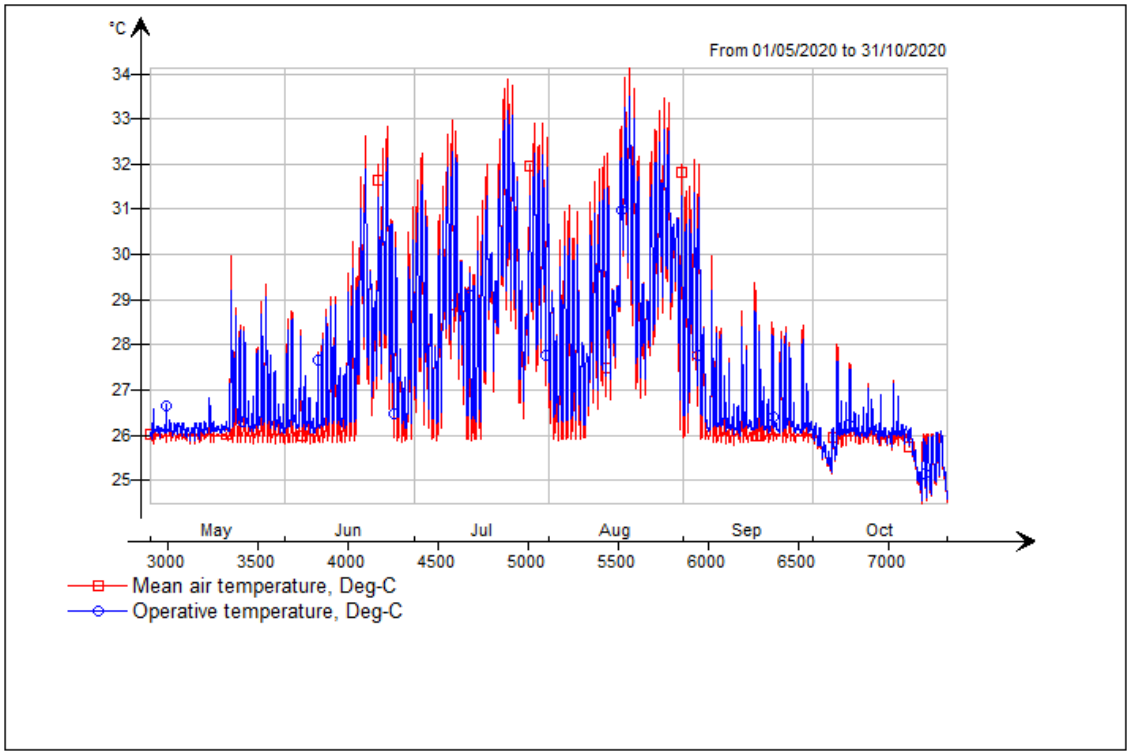
Zone 3 (North)



Zone 4 (East)



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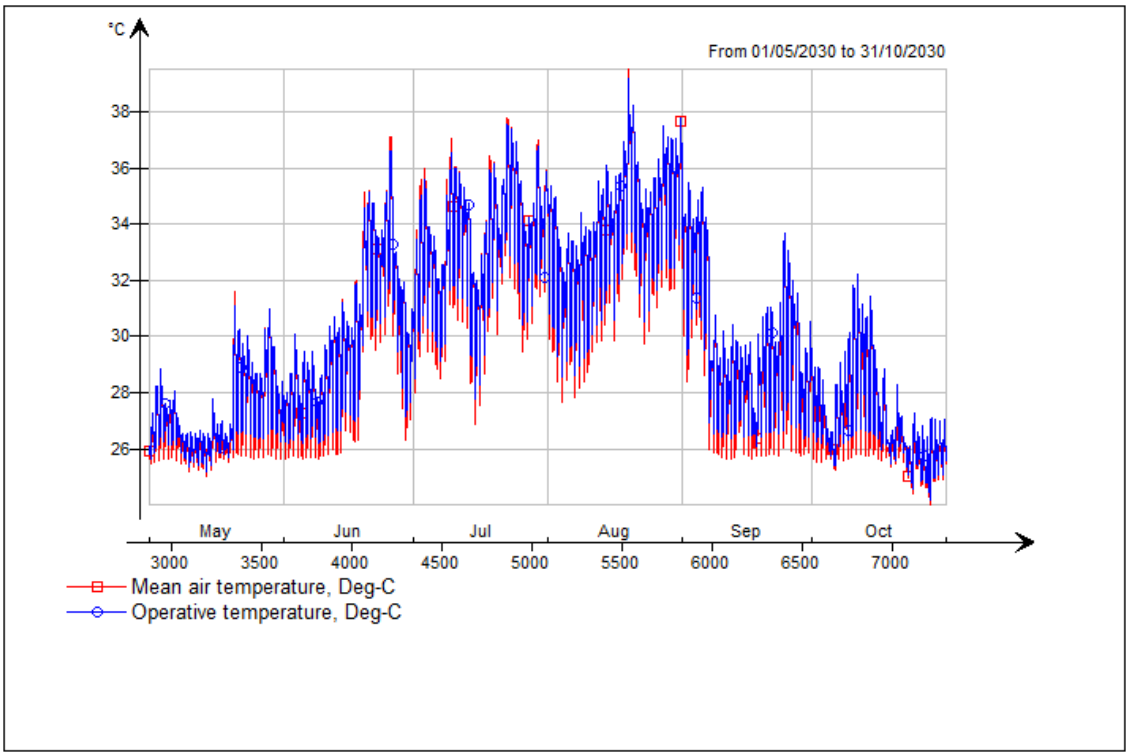
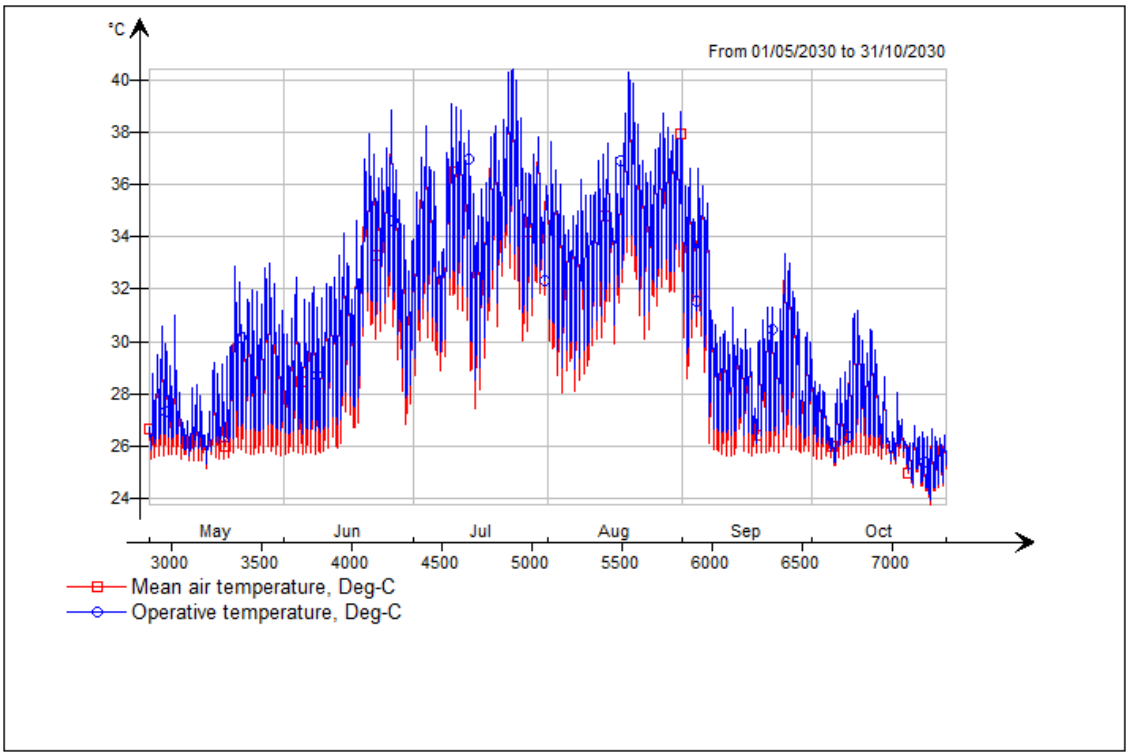
Basic scenario Athens 2030 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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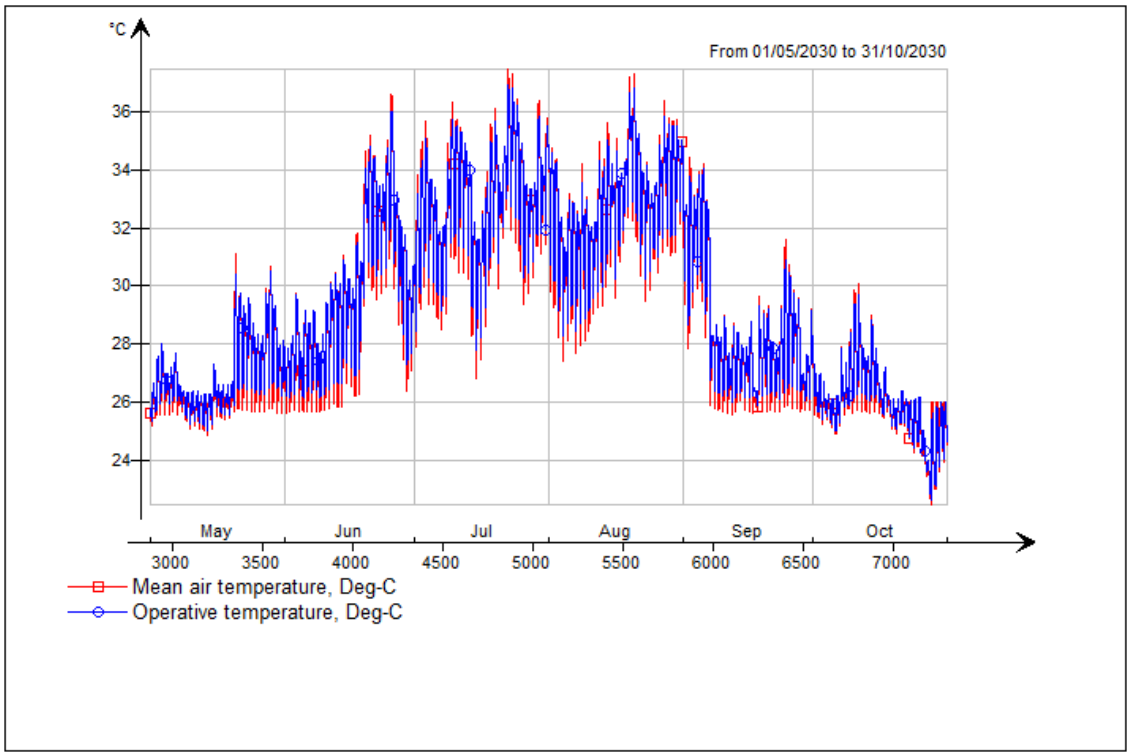
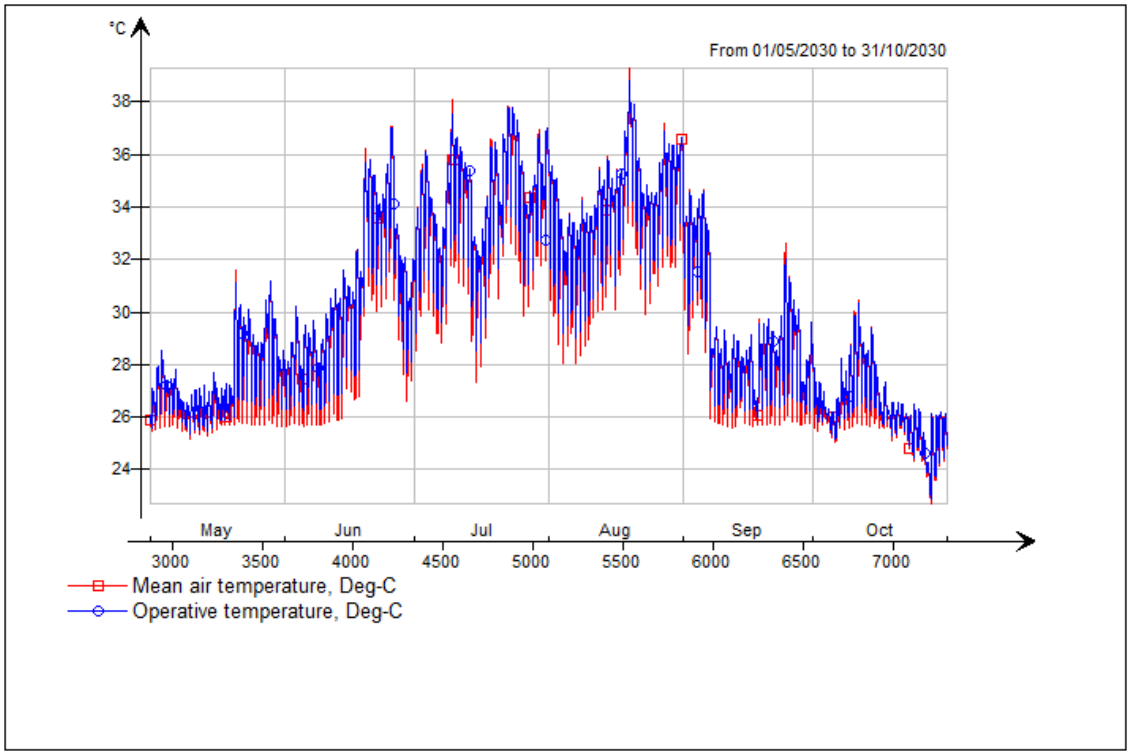
Zone 3 (North)



Zone 4 (East)



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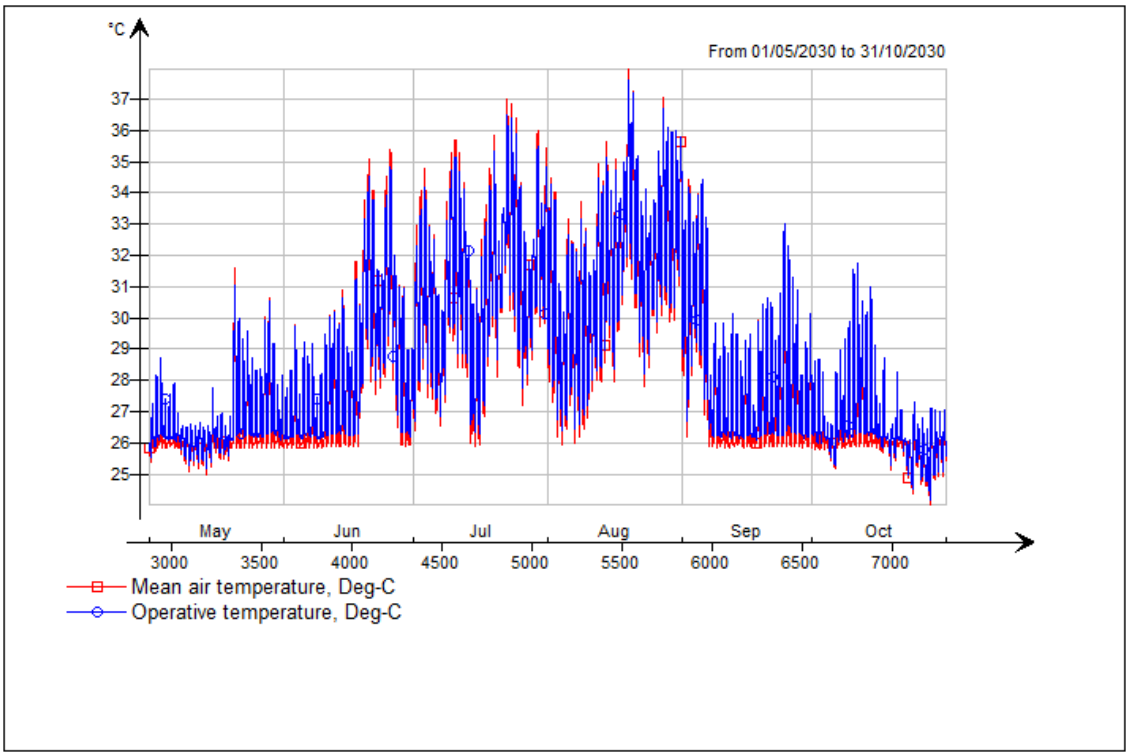
Night ventilation scenario Athens 2030 (RCP8.5)

Zone 1 (South)



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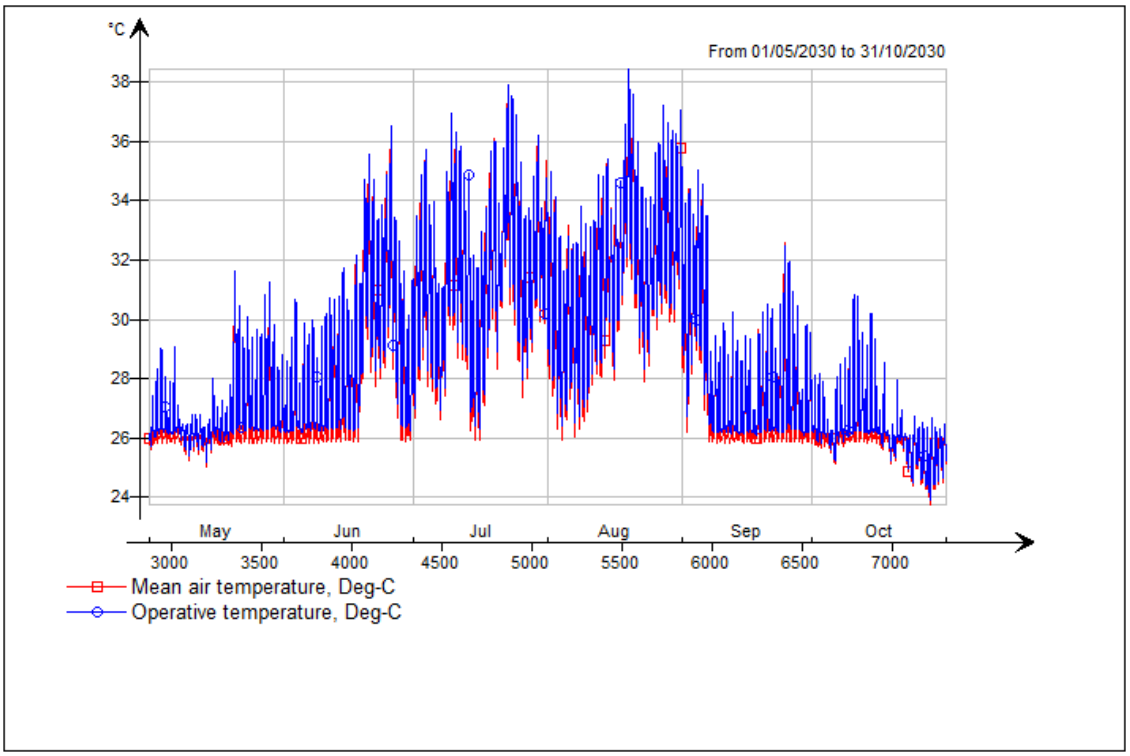

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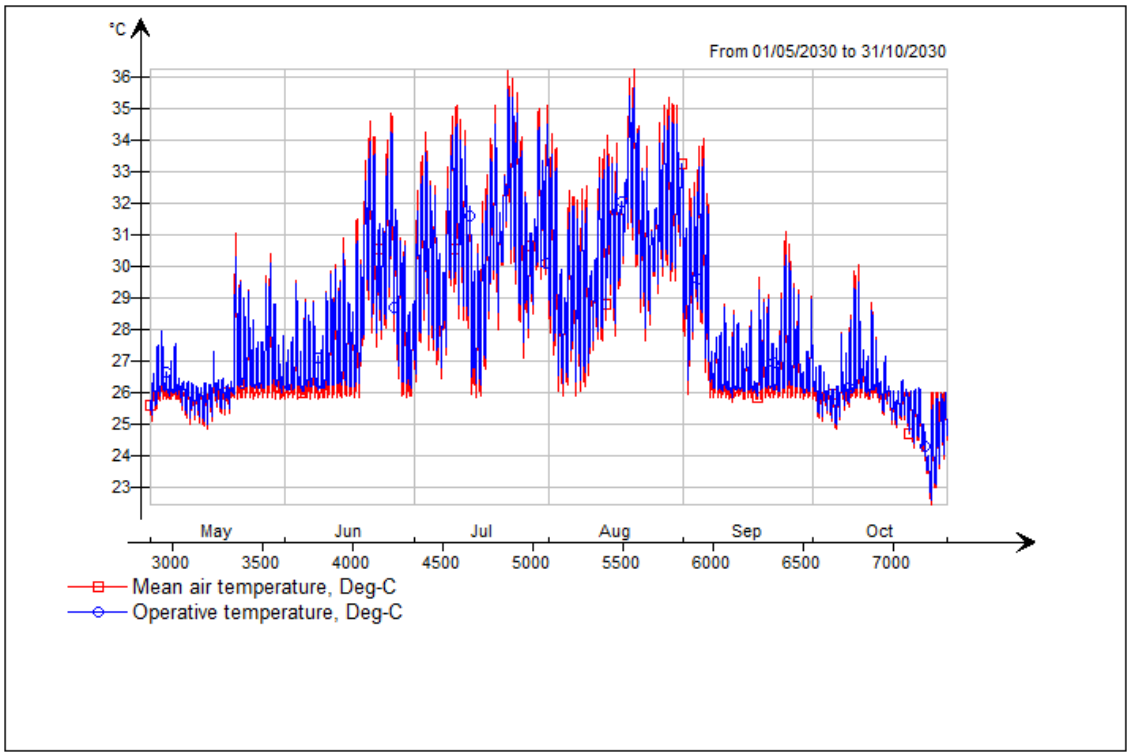
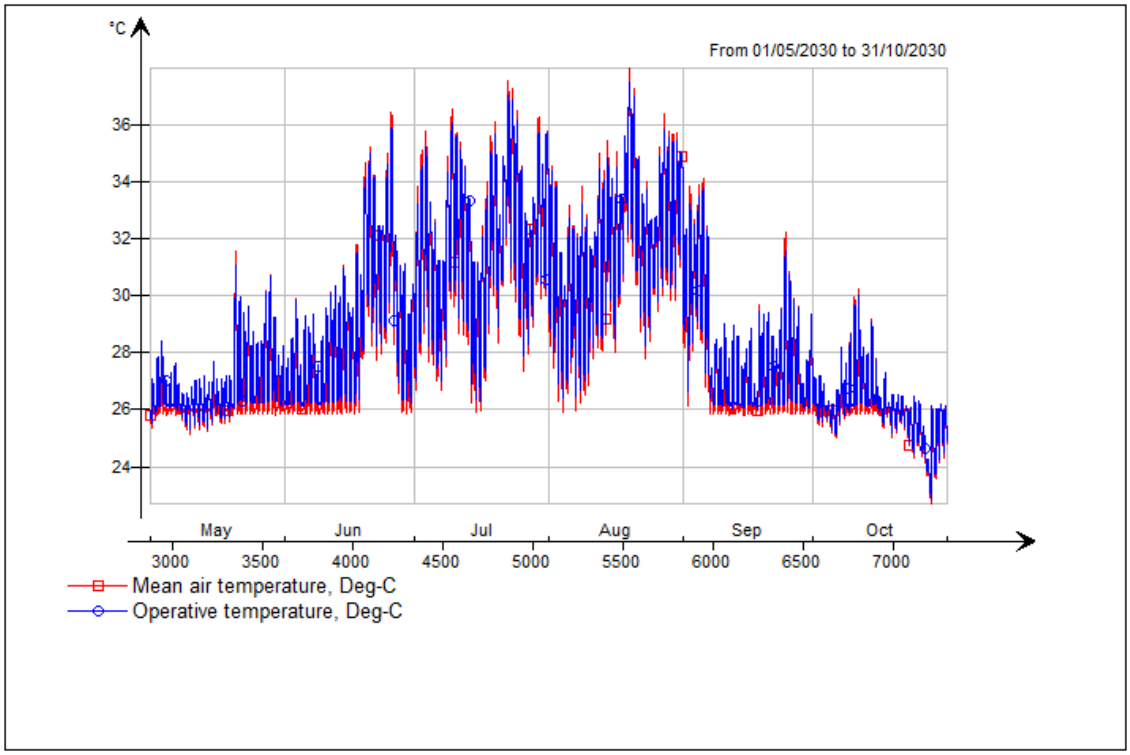
Zone 3 (North)



Zone 4 (East)



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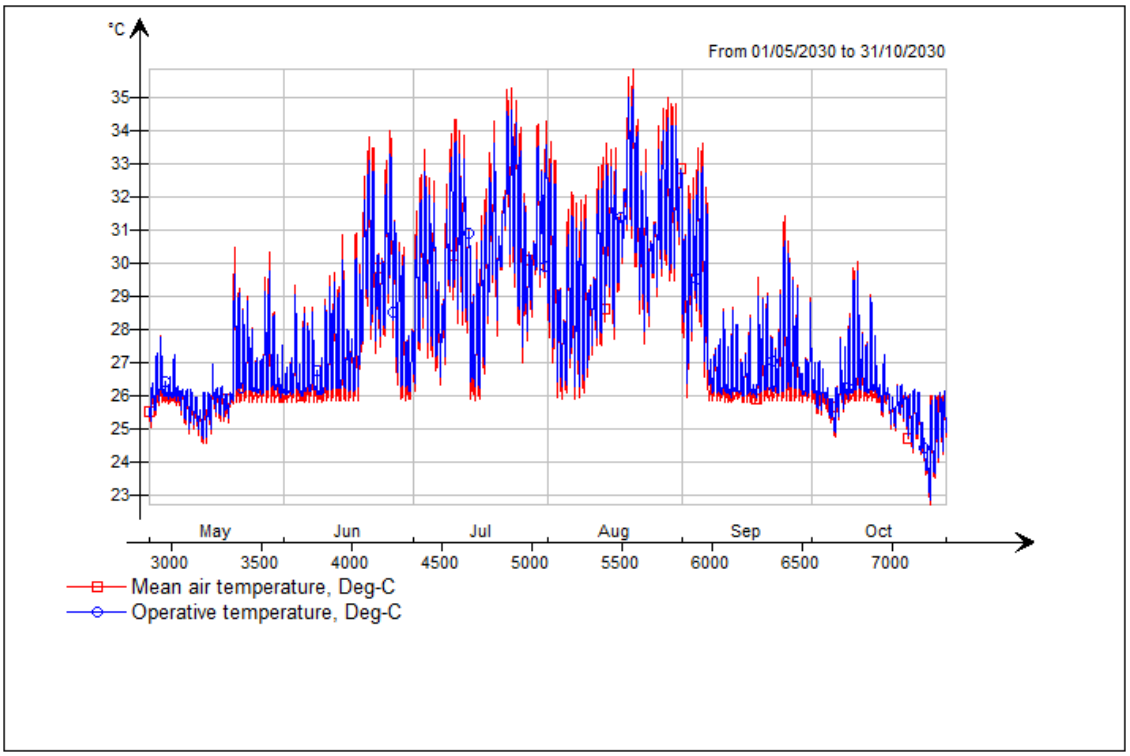
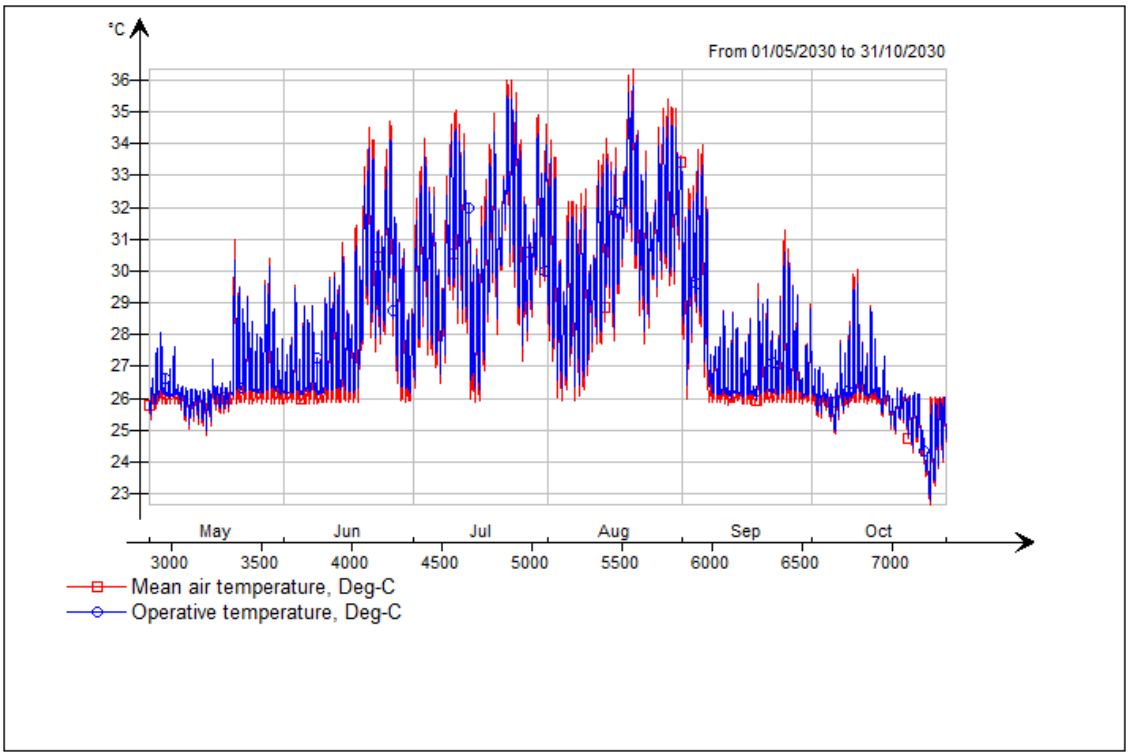
Night ventilation and shading scenario Athens 2030 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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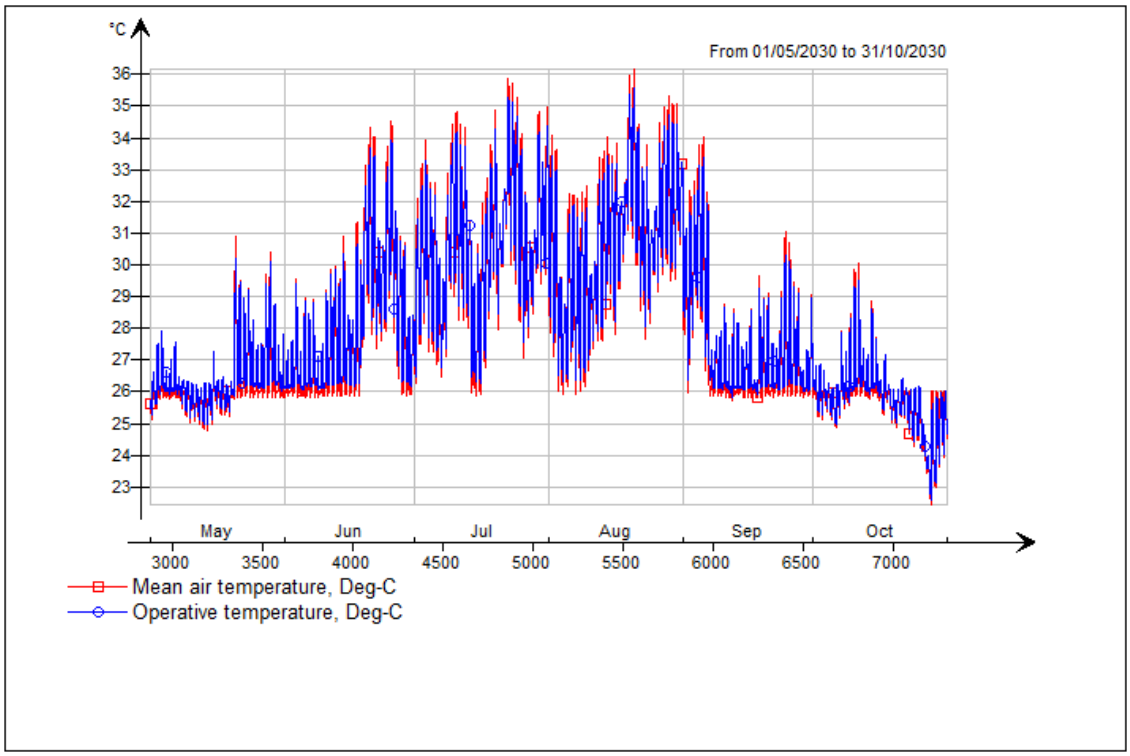
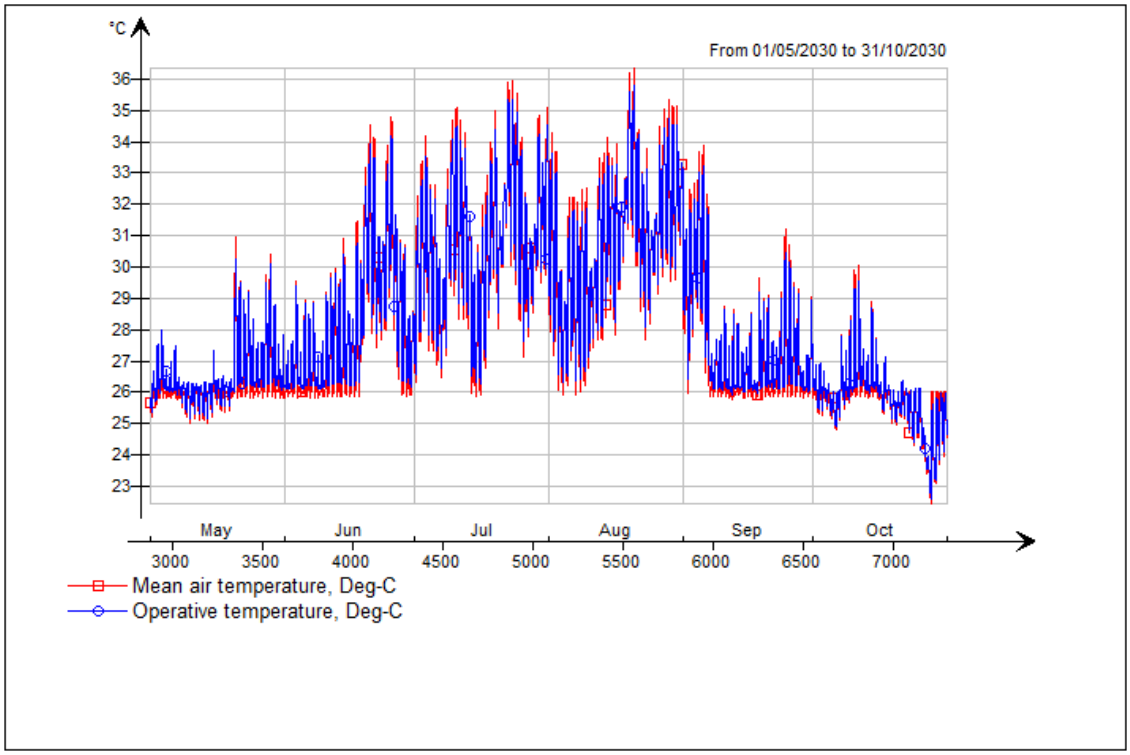
Zone 3 (North)



Zone 4 (East)



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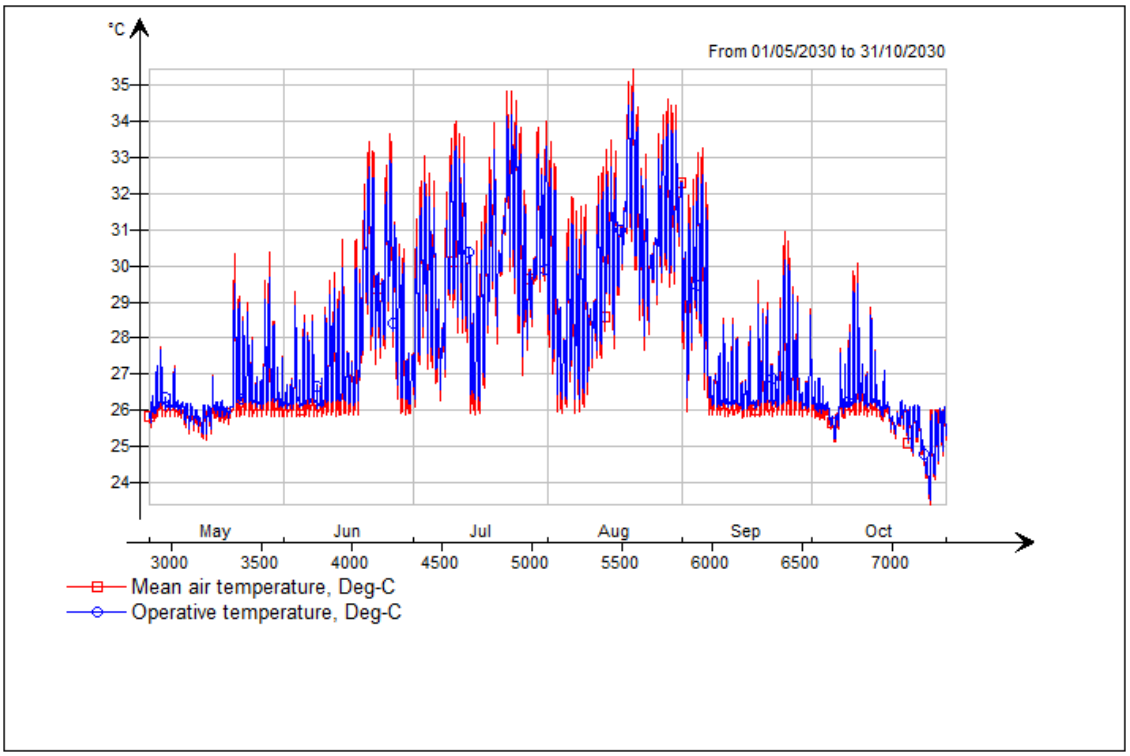
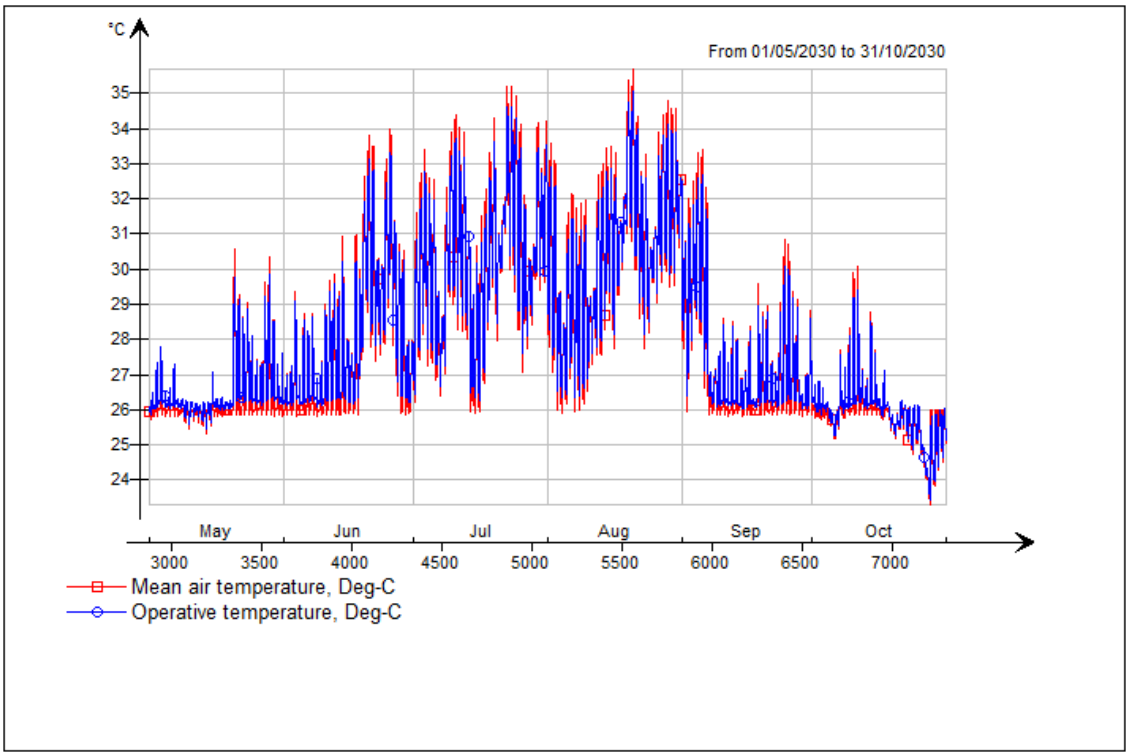
Night ventilation, shading and glazing scenario Athens 2030 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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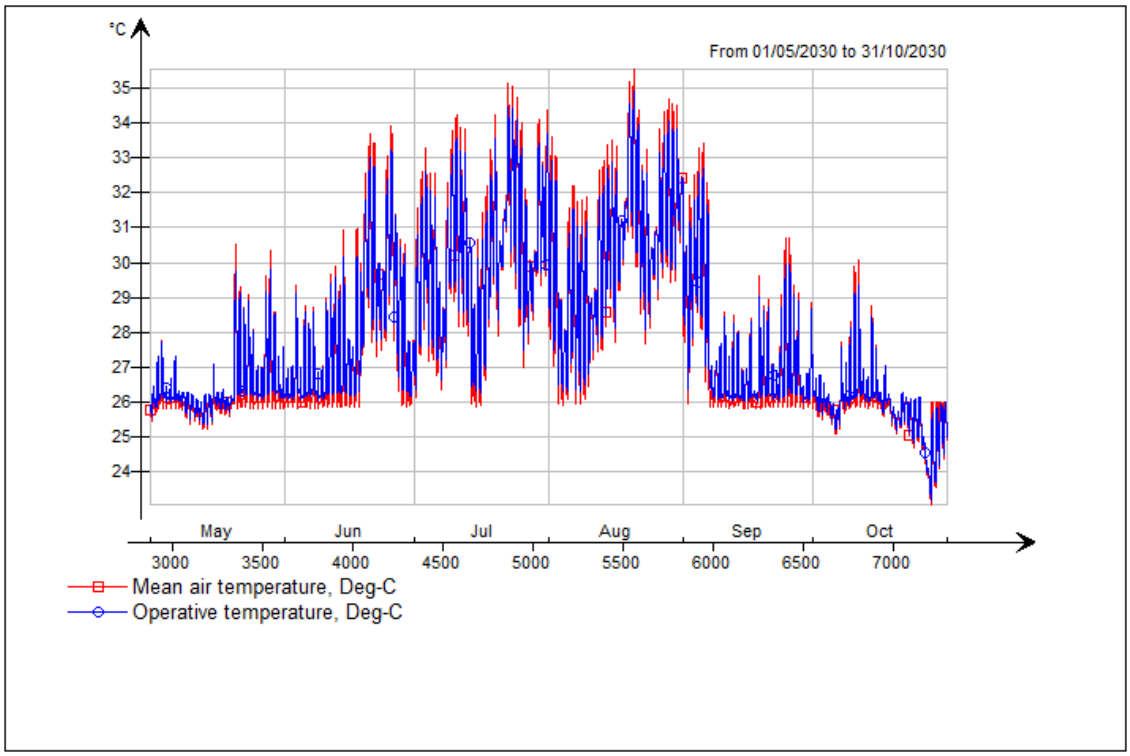
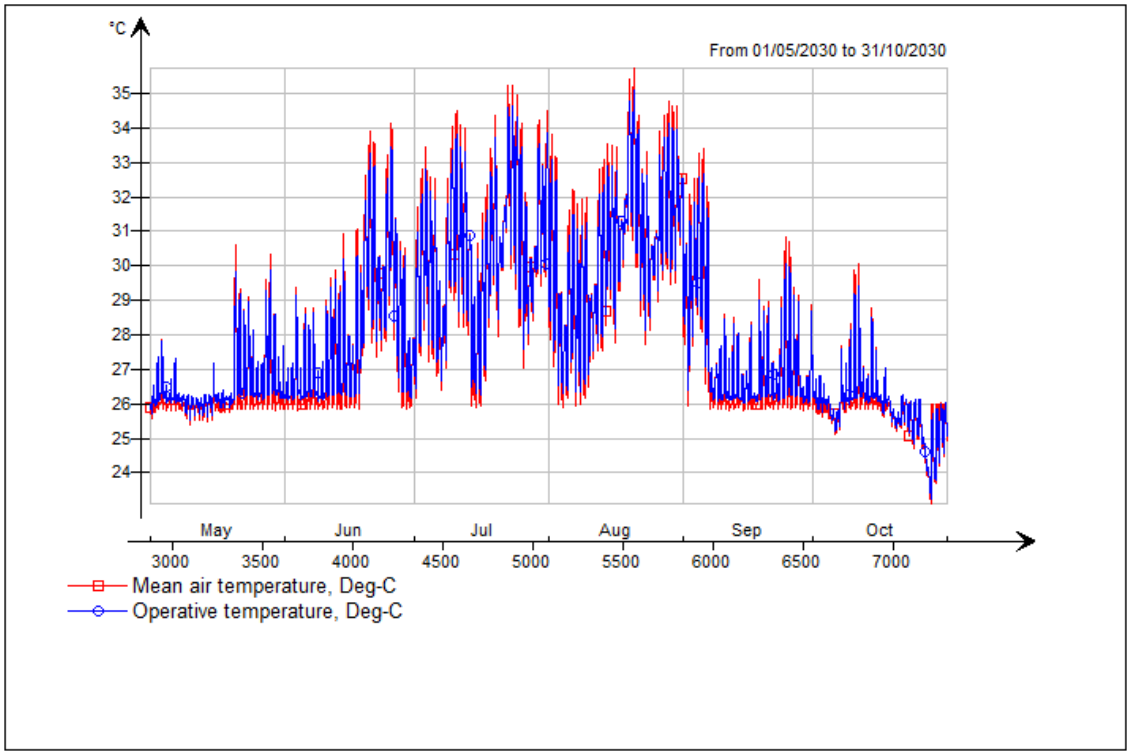
Zone 3 (North)



Zone 4 (East)



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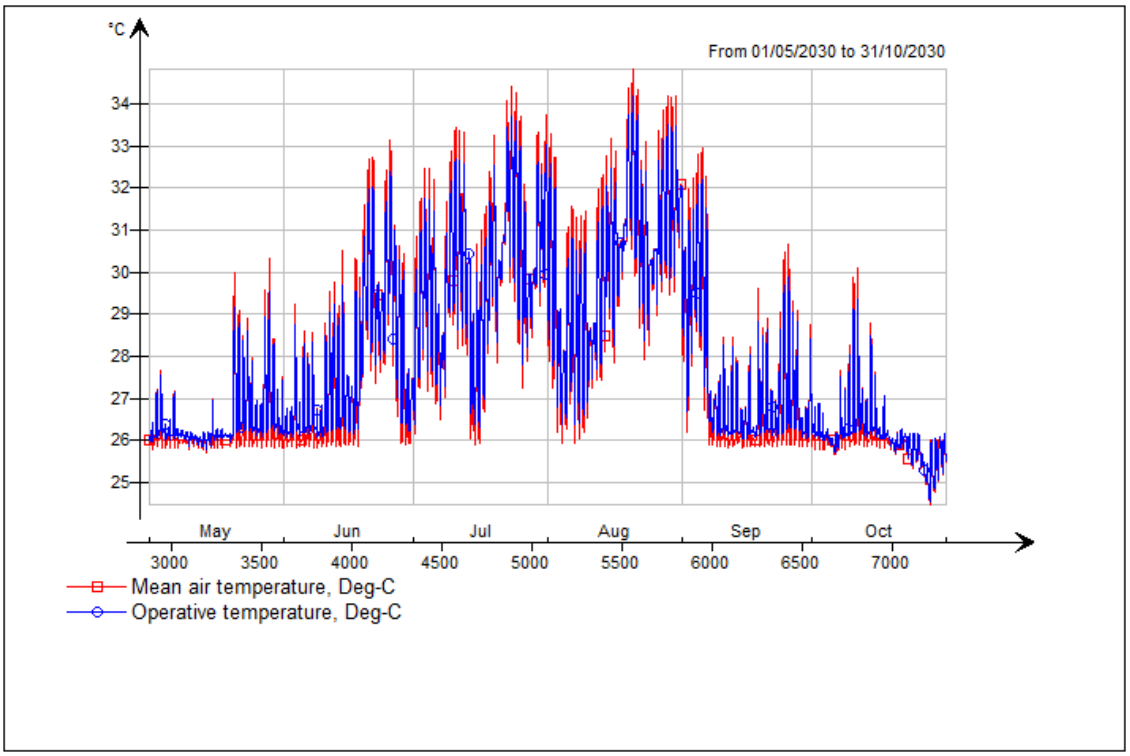
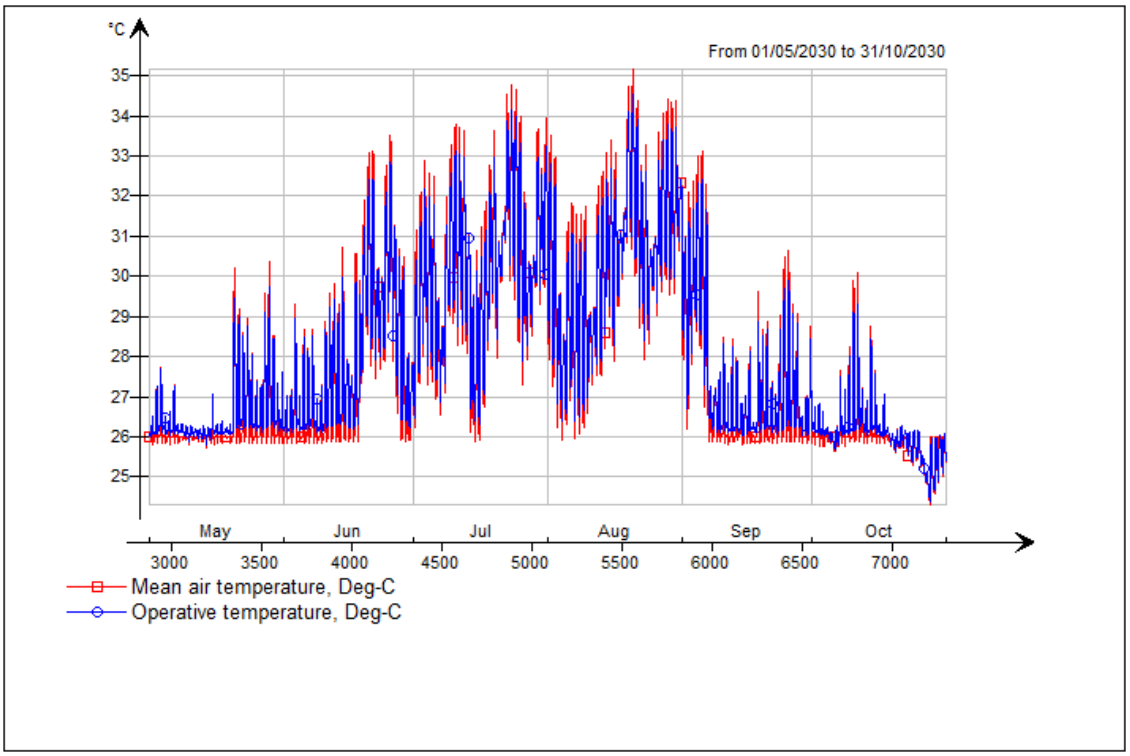
Night ventilation, shading, glazing and thermal mass scenario Athens 2030 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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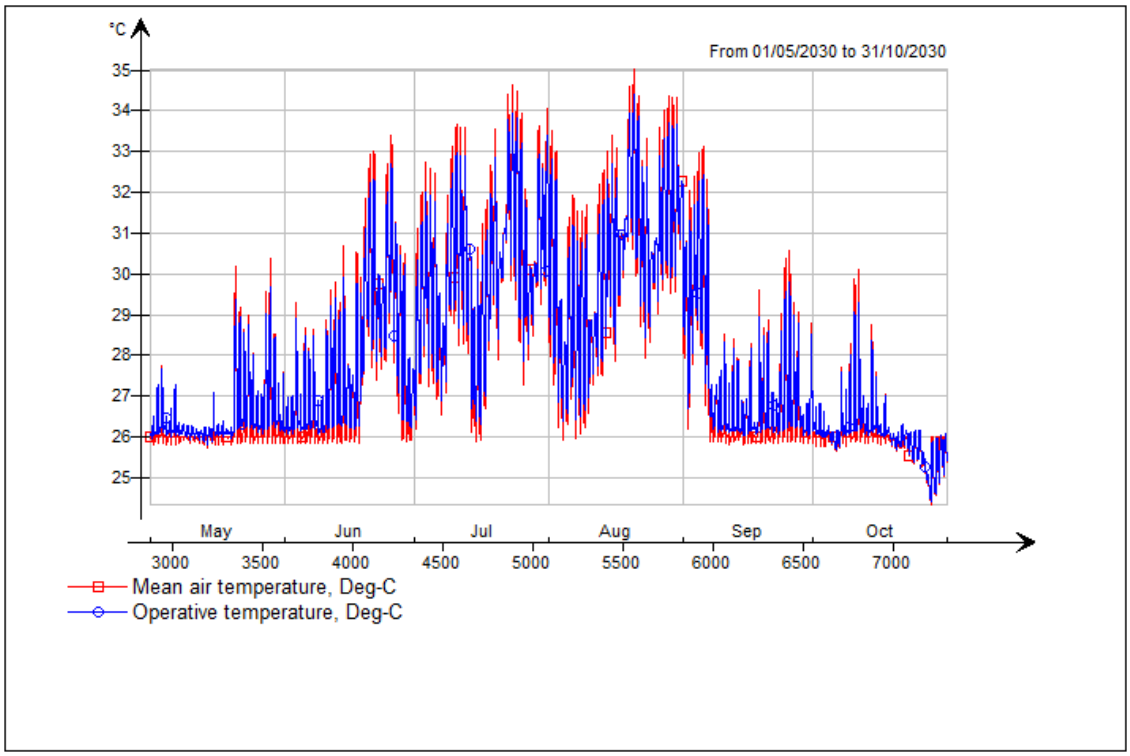
Zone 3 (North)



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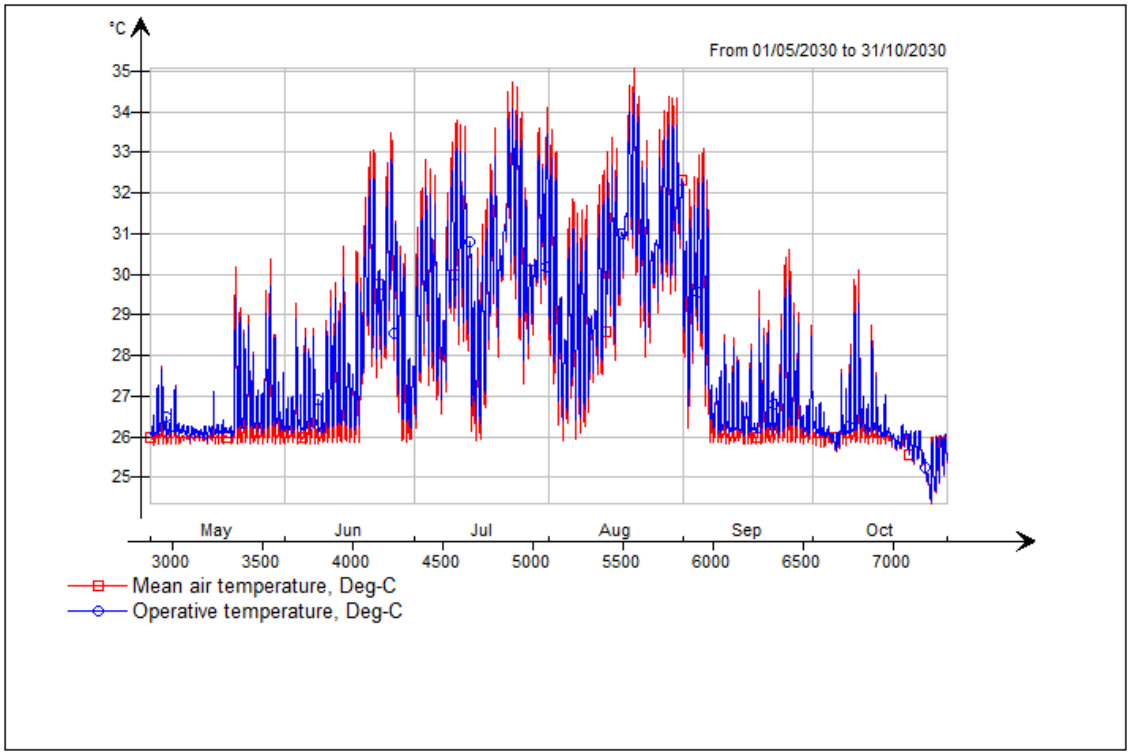

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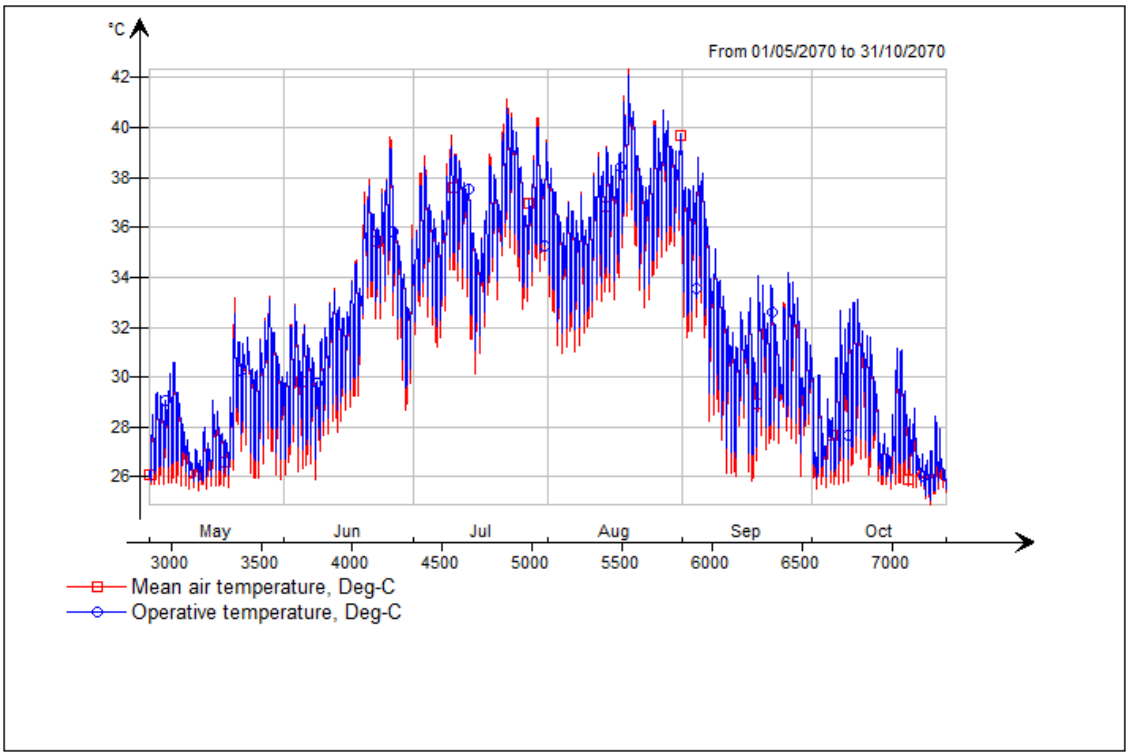
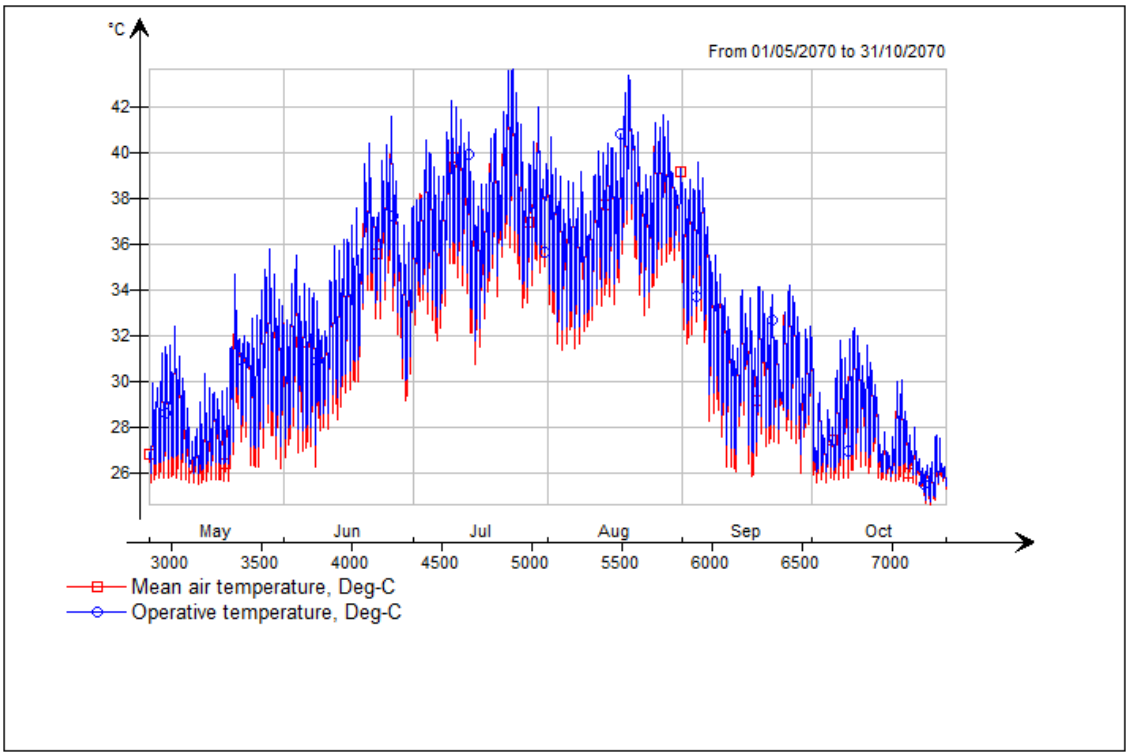
Basic scenario Athens 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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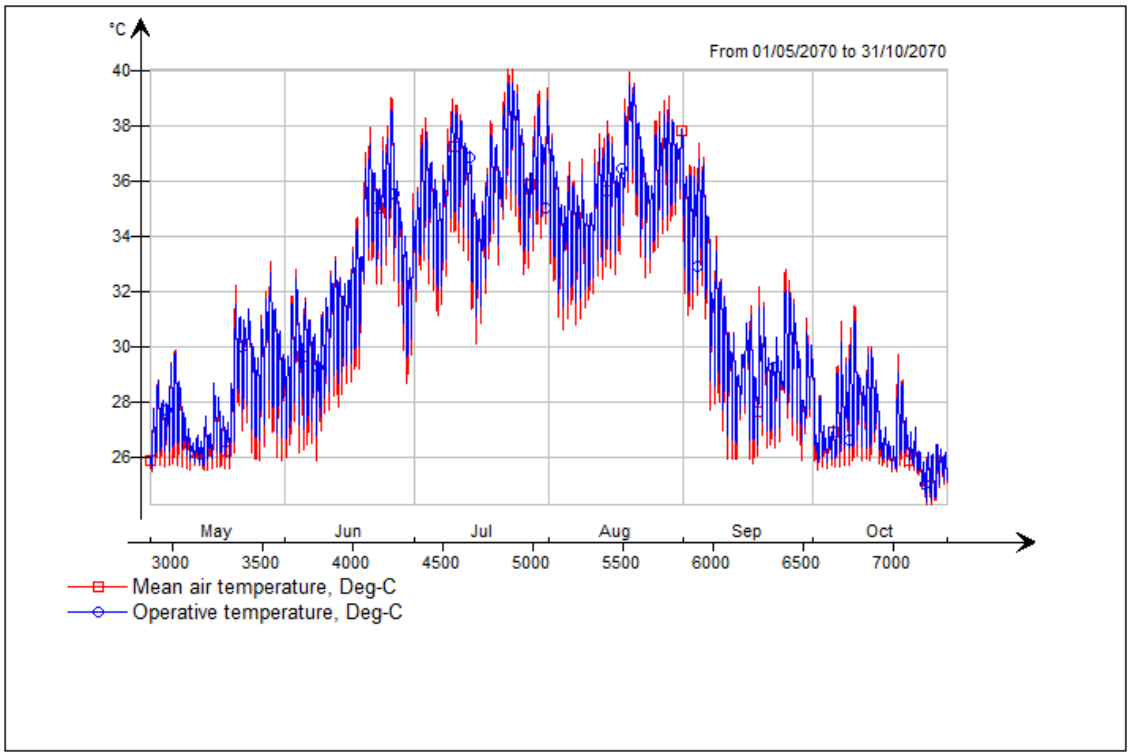
Zone 3 (North)



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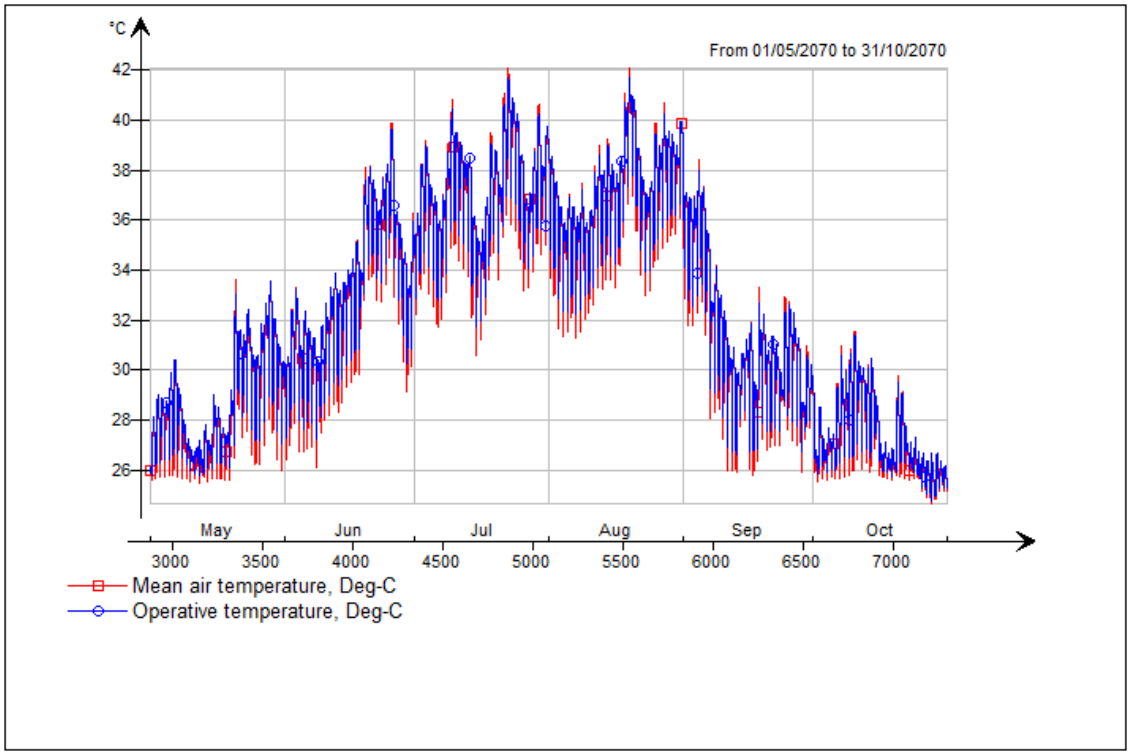

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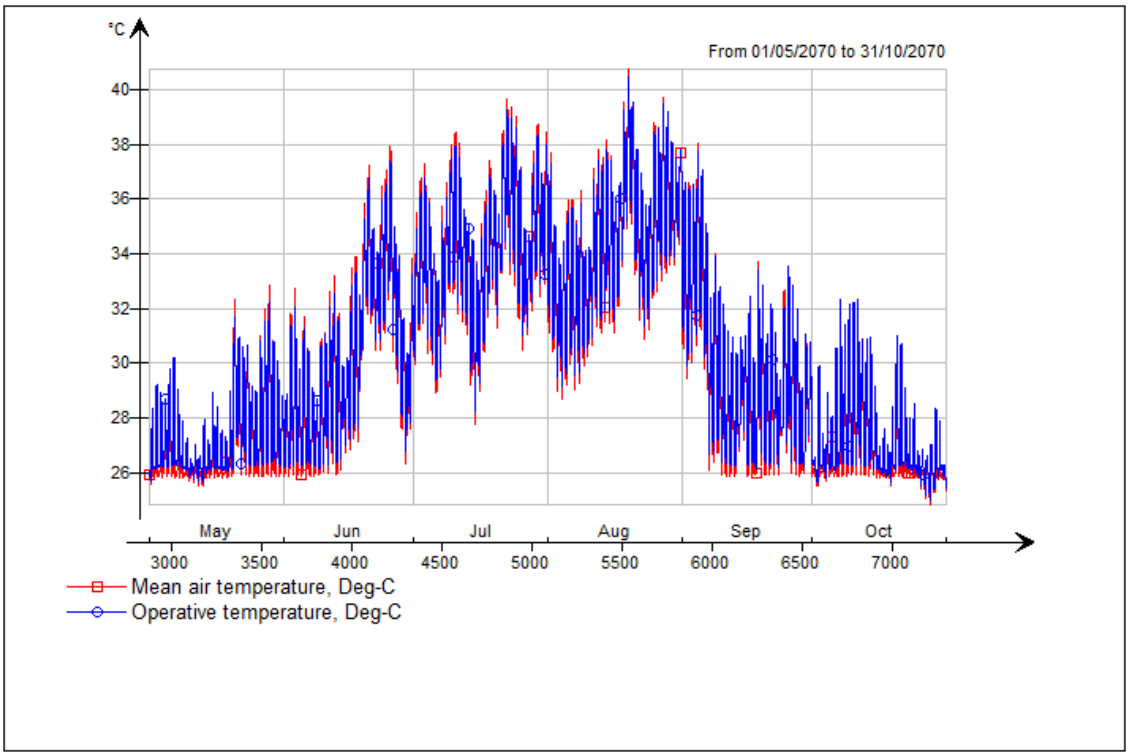
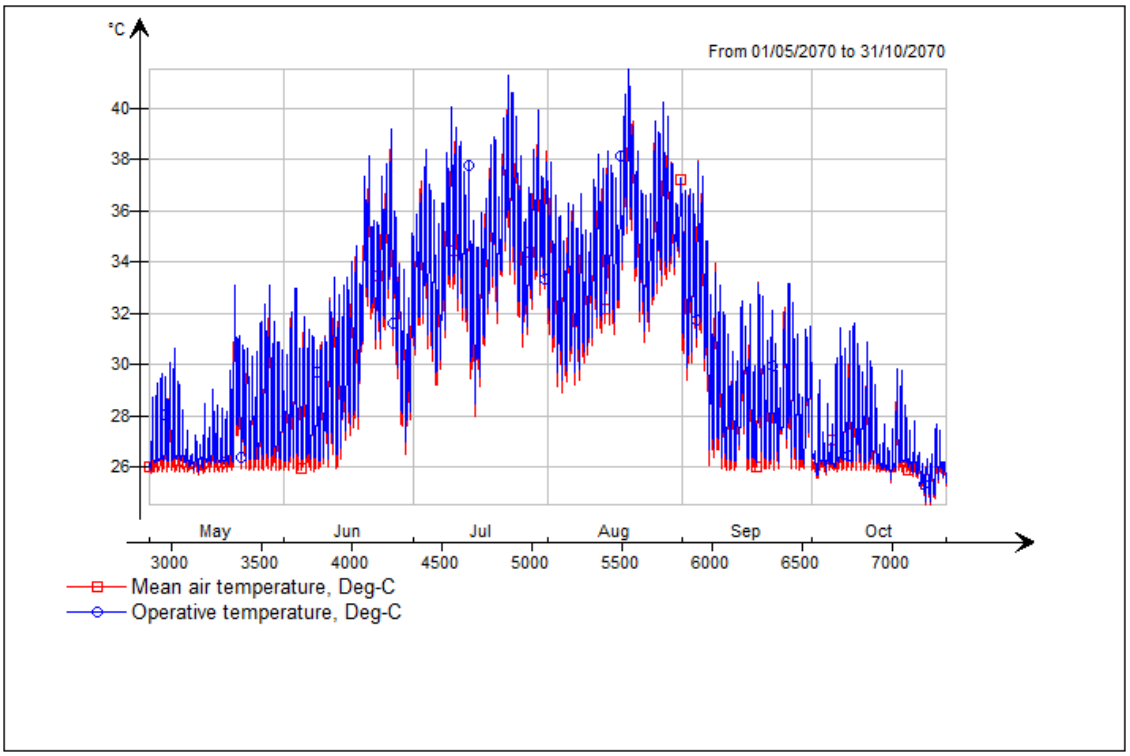
Night ventilation scenario Athens 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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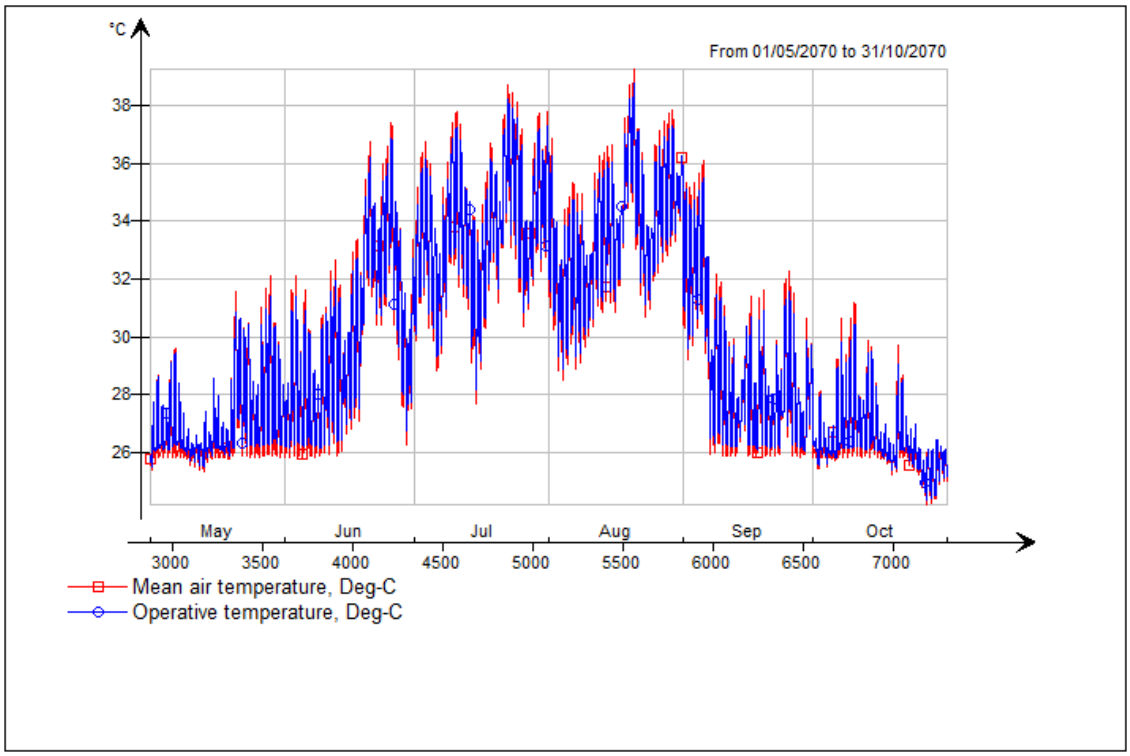
Zone 3 (North)



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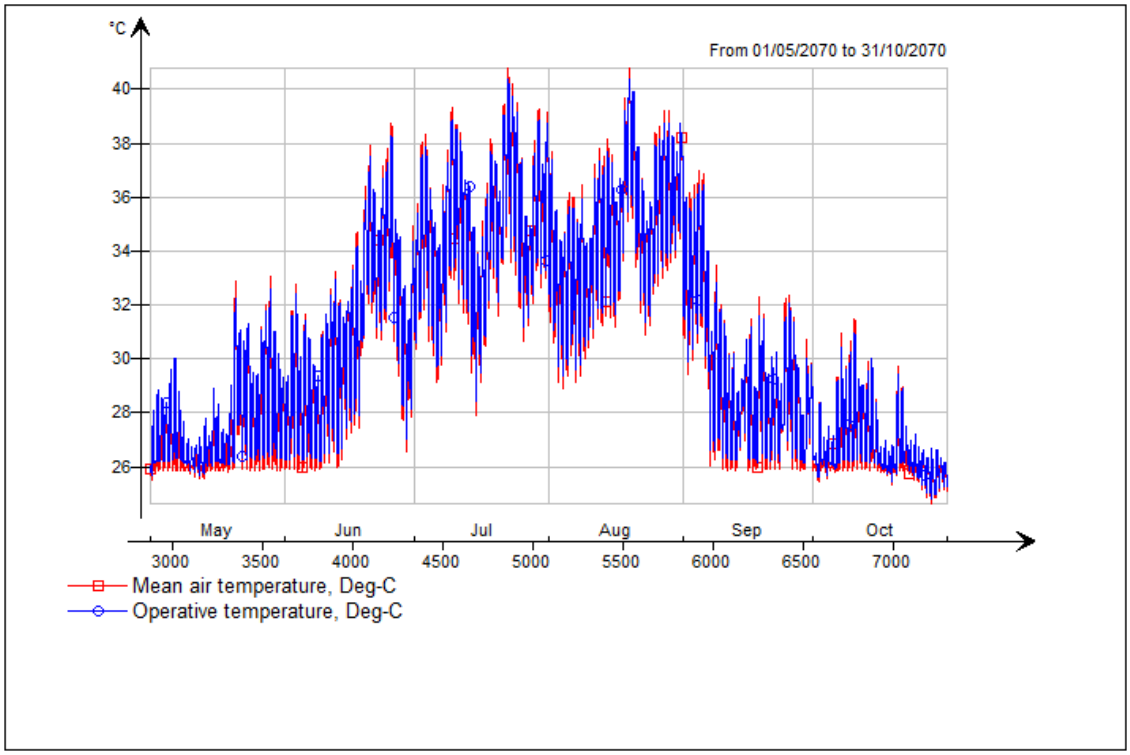

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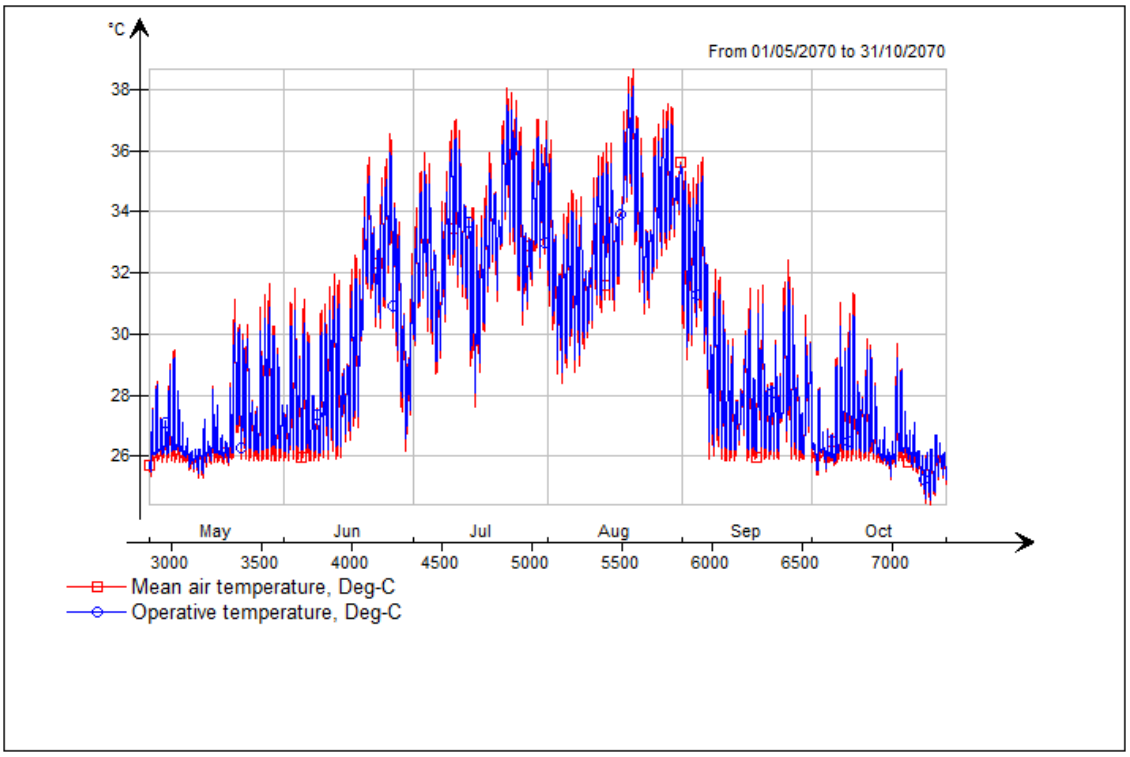
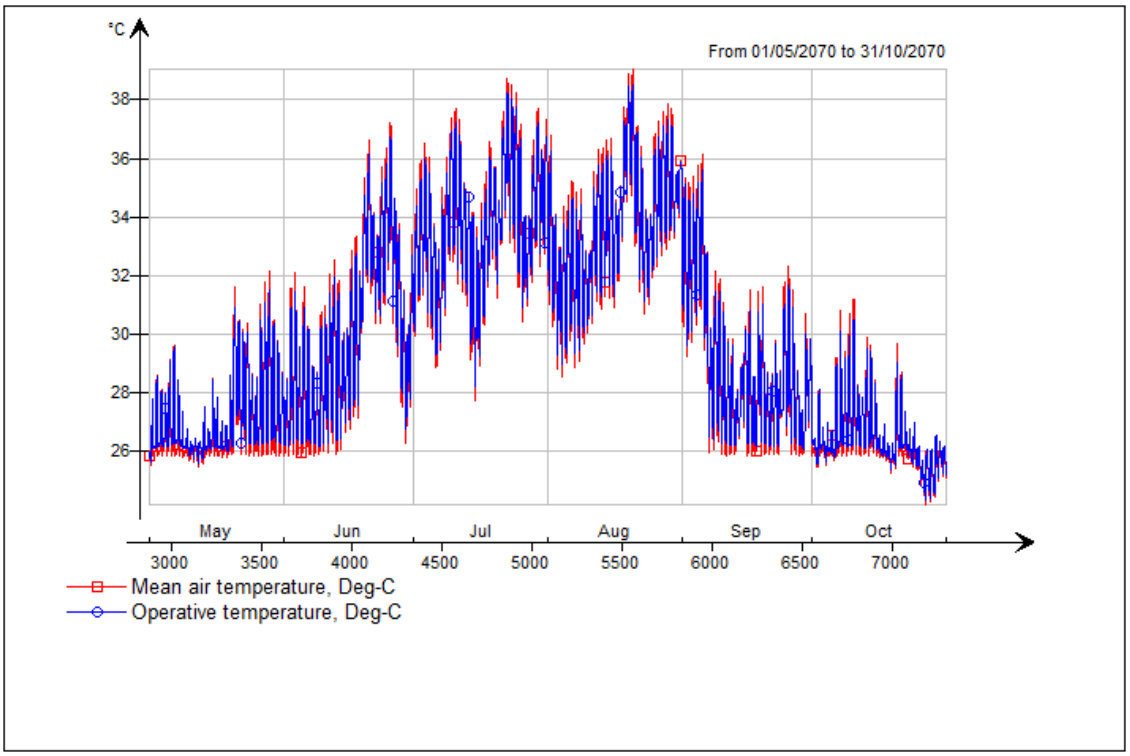
Night ventilation and shading scenario Athens 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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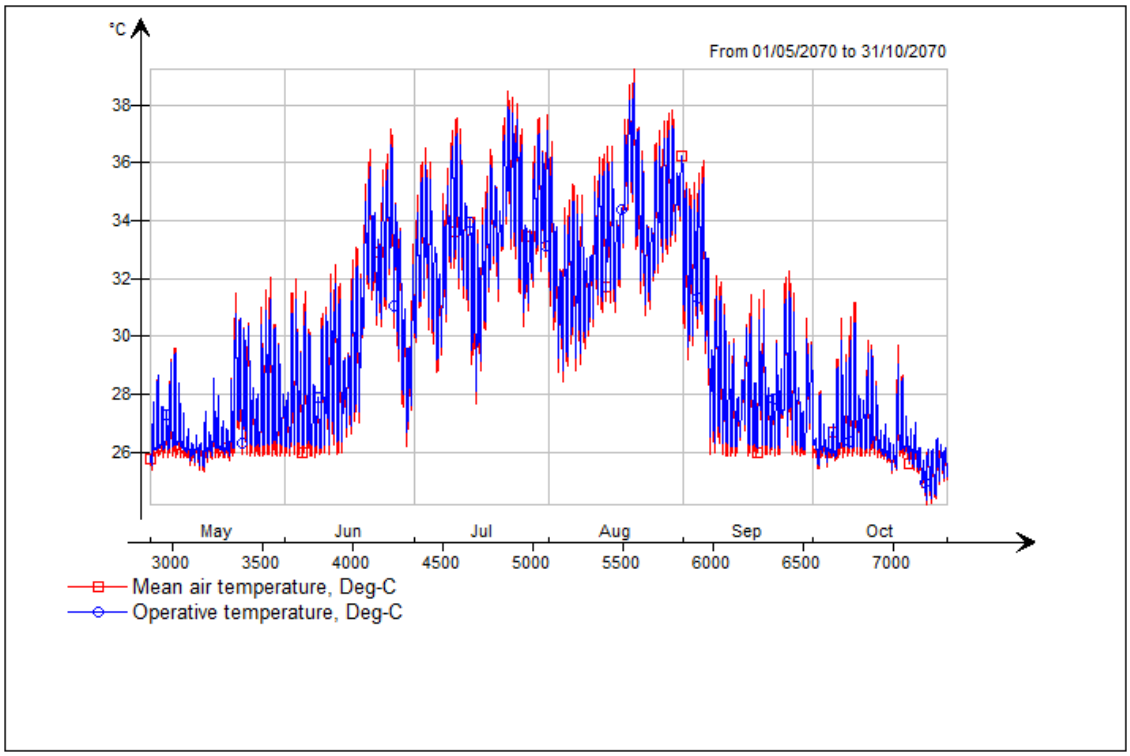
Zone 3 (North)



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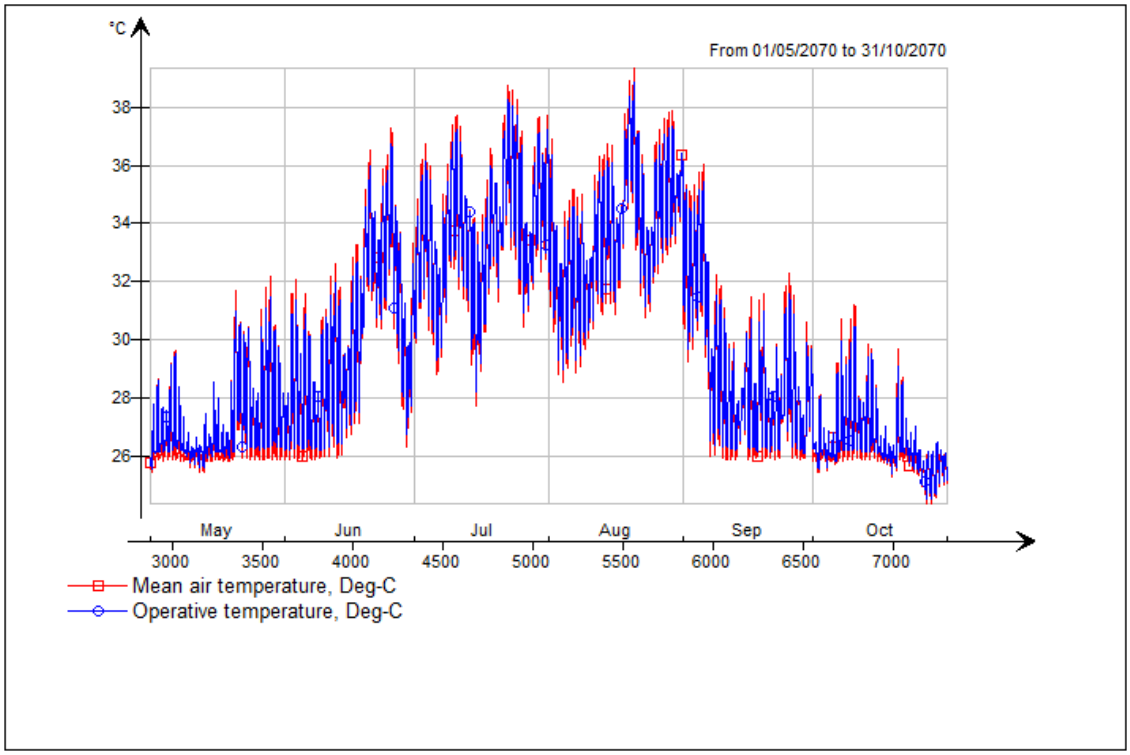

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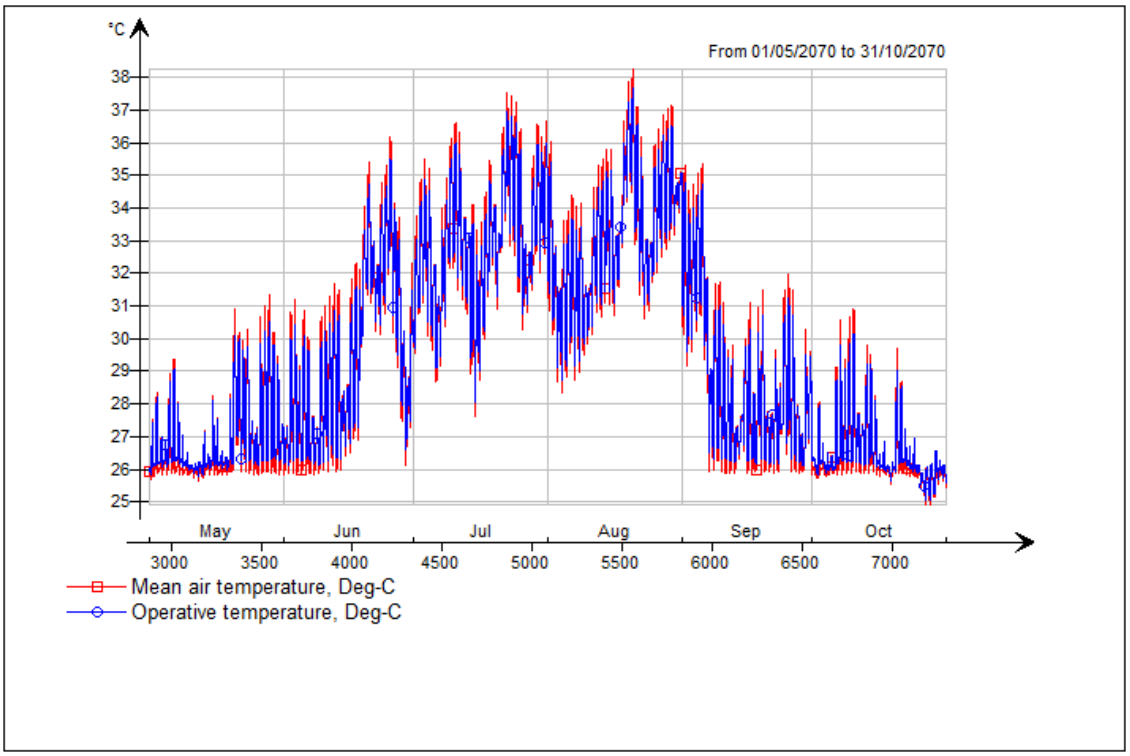
Night ventilation, shading and glazing scenario Athens 2070 (RCP8.5)

Zone 1 (South)



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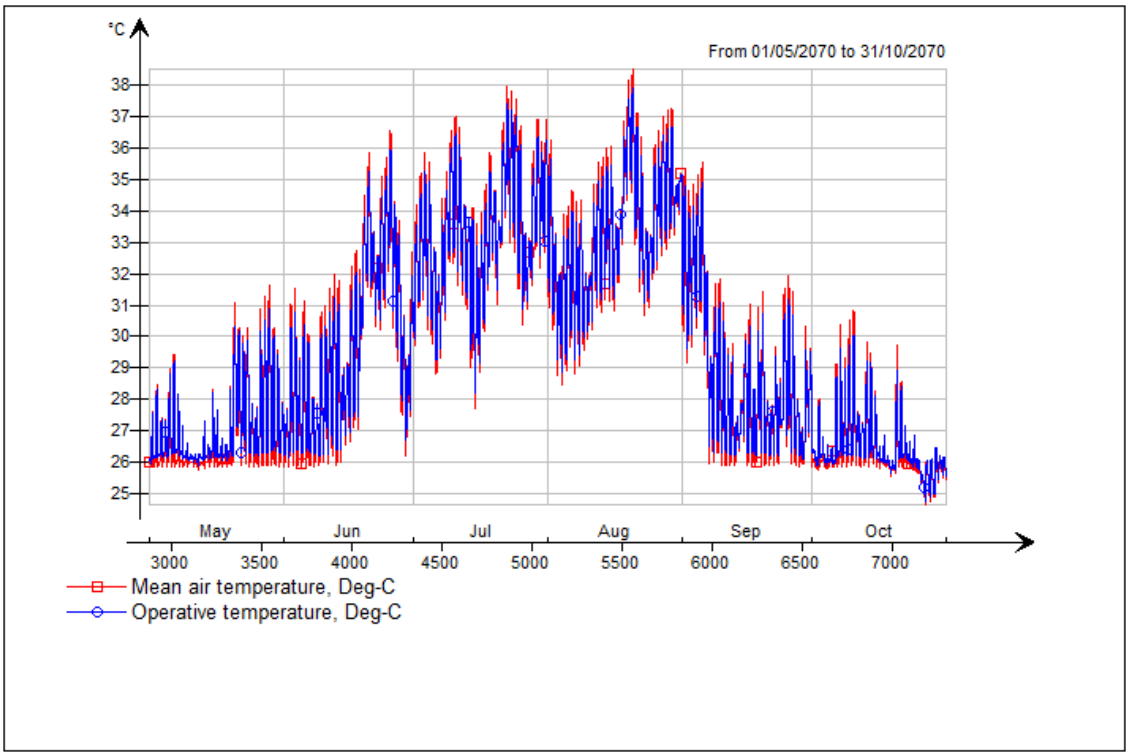

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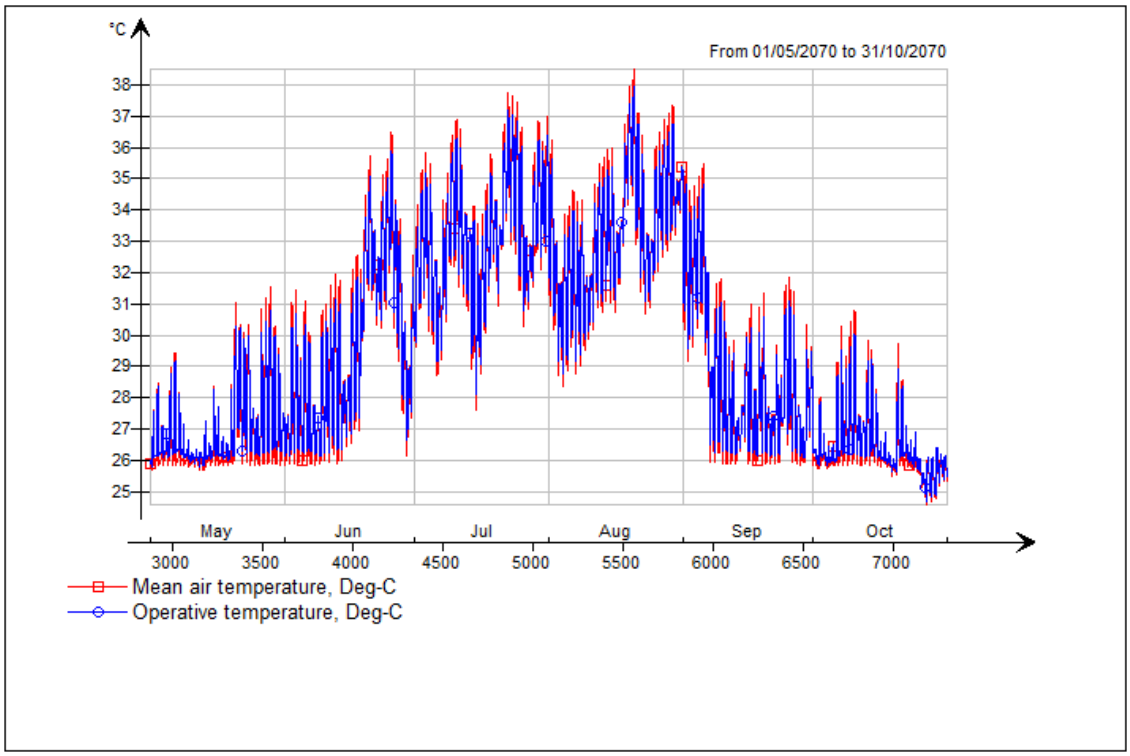
Zone 3 (North)



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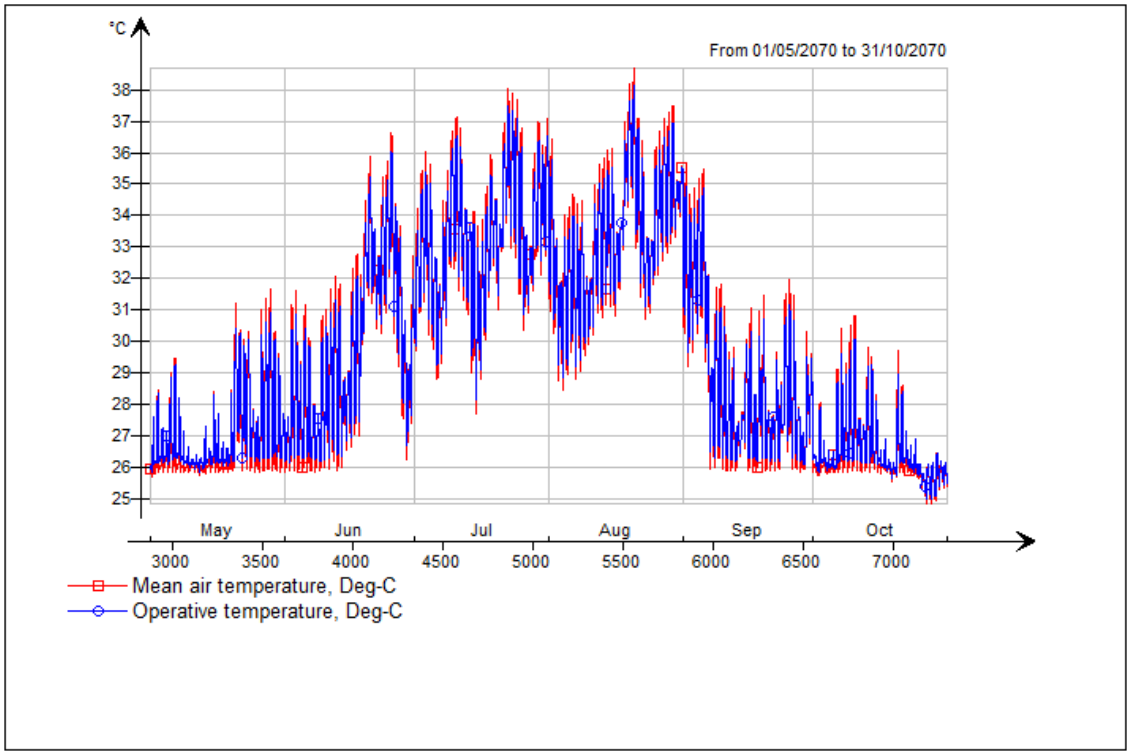

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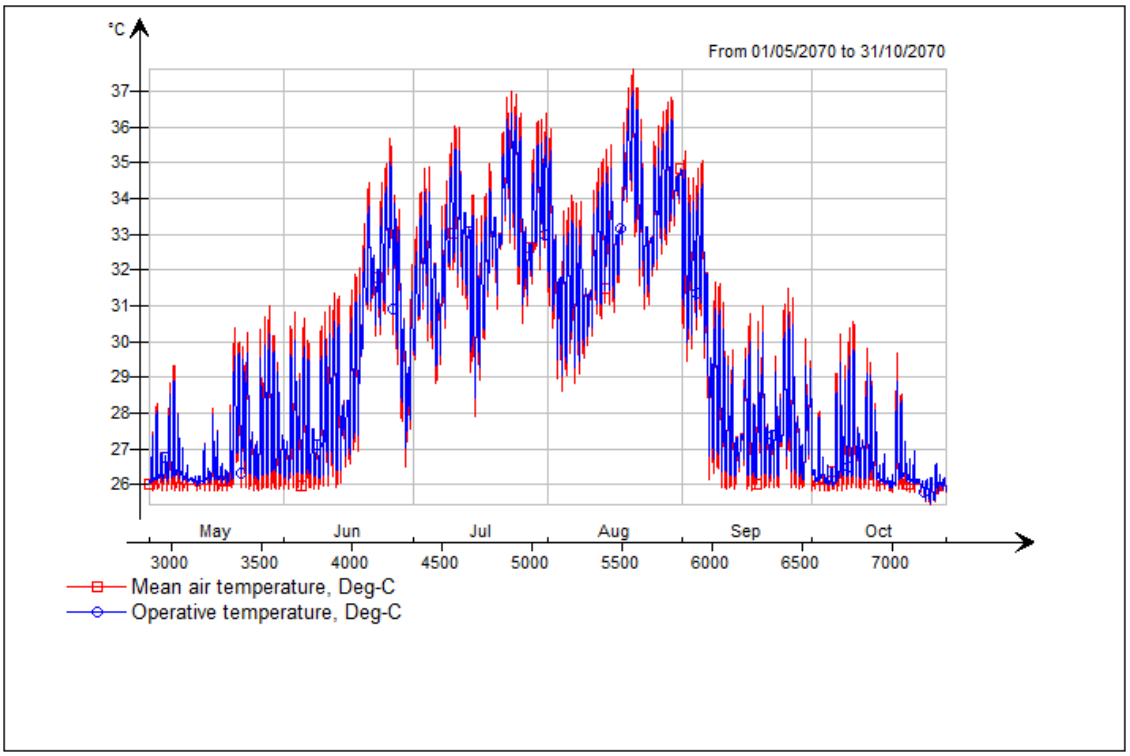
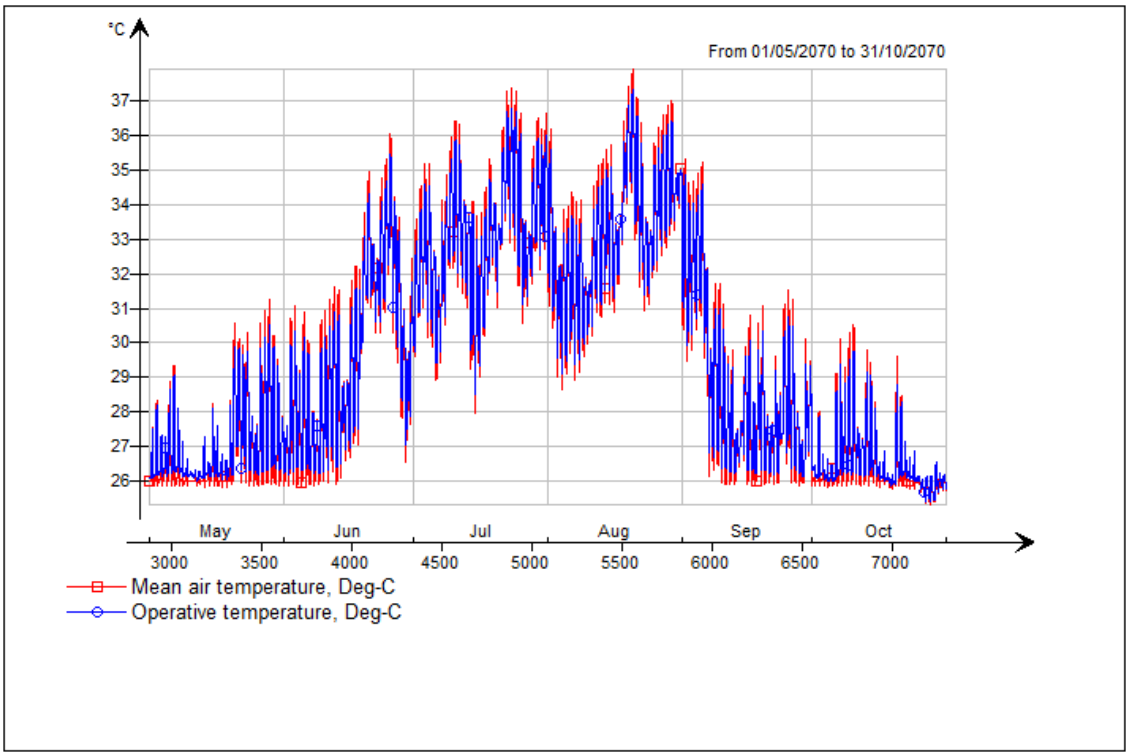
Night ventilation, shading, glazing and thermal mass scenario Athens 2070 (RCP8.5)

Zone 1 (South)



Zone 2 (West)



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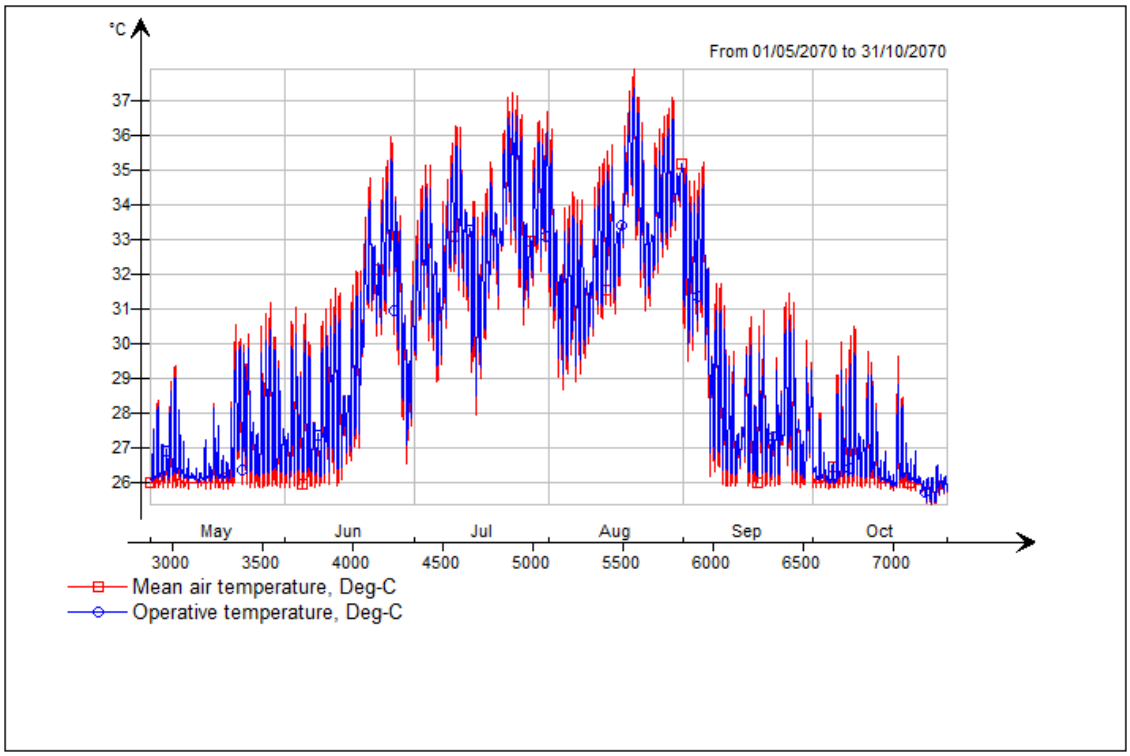
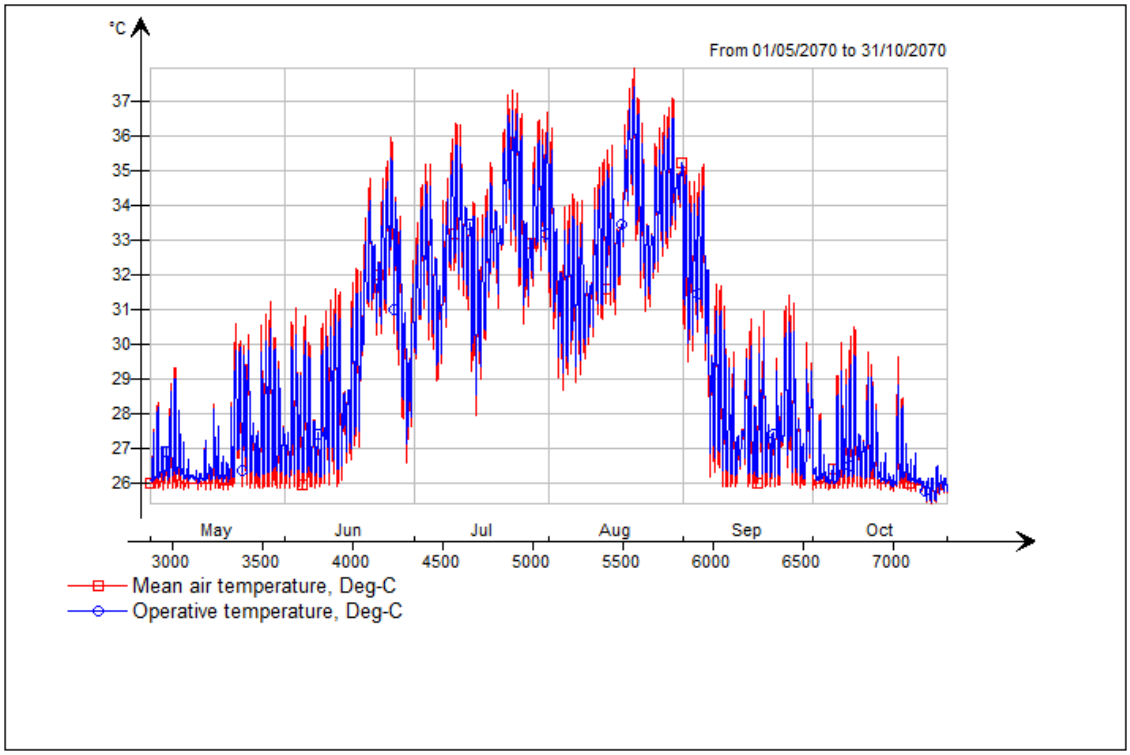
Zone 3 (North)



Zone 4 (East)



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