MSc Program "Building Science & Technology"

Computational Assessment of Passive Cooling Methods in Buildings

A master's thesis submitted for the degree of
“Master of Science”

Supervisor: Univ. Prof. Dr. A. Mahdavi
Department of Building Physics and Building Ecology

Angeliki Paipai

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Student ID: 0426893

Affidavit

I, **Angeliki Paipai**, hereby declare

1. That I am the sole author of the present Master Thesis, "Computational Assessment of Passive Cooling Methods in Buildings ", 101 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Various factors have been contributing to a recent steady increase in buildings' demands for cooling energy: environmental changes, increased heat gains due to equipment and growing expectations in view of acceptable indoor thermal conditions. Given this context, it's both environmentally and economically meaningful to develop and implement passive cooling techniques toward the reduction of buildings' demand for cooling energy.

In the present study, we use parametric simulations to compute the relative impact of various passive cooling technologies toward the reduction of overheating risk in residential buildings. The cooling measures under examination are shading, natural ventilation (emphasizing on night time natural ventilation), and the application of phase change materials (PCM). The buildings that are being used for the parametric studies are an apartment and a double-storey single house, both simulated for a Mediterranean climate (Athens, Greece) and middle-European one (Vienna, Austria).

The results showed that passive cooling methods can significantly contribute the reduction of overheating in buildings. In particular shading and night time ventilation have been shown to be very effective especially if applied in combination. PCMs on the other hand, showed a limited potential in the reduction of overheating risk, at least under the specific climatic circumstances.

Keywords: Passive cooling; Parametric modeling; Thermal storage; Night ventilation; Phase Changing materials.

1. Introduction

1.1. Motivation

During the past decades the heat island effect and the consequential increase of temperature raised a high demand on cooling techniques. The problem of overheating is rather intense especially in urban areas during the summer months in warm and hot climates. The urge for a solution led to the widespread of air conditioning in residential and commercial constructions.

The global sale of air conditioning is still increasing from 39 million units in 1999 to 58 million forecasted in 2007. The European Union is about 7 % of the global market by number of units, with sales growing from about 3 million to about 5 million units. The major markets within Europe are the southern countries with Italy, Greece, and Spain accounting for about 75% of sales by number of units [EFCTC 2006].

The impact of air conditioners usage on electricity demands is a serious problem for many developed countries. Peak electricity loads oblige utilities to build power plants in order to satisfy the demand, thus increasing the average cost of electricity. The existing penetration of air condition equipment in Southern Europe and especially the Mediterranean area increased significantly the energy consumption leading to a growing weakness of the countries to satisfy their energy needs.

In the framework of achieving a more energy efficient built environment many countries worldwide have started a broad discussion about issues like: the impact of urbanization on the cooling demand of buildings, the impact of temperature increase of cities on the cooling load of urban buildings, the problem of appropriate climatic data for design, the increased peak electricity load as well as the decreased efficiency of air condition. As a result of these new phenomena a great part of research and practice in the construction area is concentrated nowadays on techniques and methods that manage to reduce or even eliminate the cooling loads of a building as well as on their energy conservation potential.

In the direction of achieving energy efficient built environment an increasing number of countries considered as an attractive approach the Energy Performance (EP) standardization and regulation. Several countries have already enacted such EP based regulations or are preparing one [Wouters 2004]. Moreover, a European Directive on the energy performance of buildings (existing and to be constructed) was adopted In November 2002 and is in force in all countries-members of European Union since the last January.

For the above mentioned reasons addressing successful solutions to counterbalance the energy and environmental effects of air conditioning is a strong requirement for the future. Possible solutions involve the use of passive cooling techniques and in particular of heat and solar protection techniques, heat amortization and heat dissipation techniques.

1.2. Background, previous research

1.2.1. Thermal comfort considerations

To achieve thermal comfort in the summer in a more sustainable way, one should use a three step design approach:

- ✓ The first step consists of *heat avoidance*. At this level the designer does everything possible to minimize heat gain in the building. Strategies at this level include the appropriate use of shading, orientation, color, vegetation, insulation, daylight and the control of internal heat sources.
- ✓ Since heat avoidance is not always sufficient to keep temperature low enough all summer, the second stage is *passive cooling*. With a range of passive cooling systems, temperatures are actually lowered and not just minimized as in heat avoidance. Passive cooling also includes the use of ventilation to shift the comfort zone to higher temperatures.
- ✓ In warm climates, the combined effort of heat avoidance and passive cooling is still not sufficient to maintain thermal comfort. For this reason the third step of *mechanical equipment* is required [Lechner 2001].

1.2.2. Passive cooling systems

Since the goal of using passive cooling systems is to create thermal comfort during the summer (the overheated period), we can either cool the building or raise the comfort zone sufficiently to include the high indoor temperature. In this second case, people feel more comfortable even though the building is not actually being cooled. Nowadays there are mainly five methods of passive cooling. Some of them are already applicable, others still experimental, but they are all very promising under the right conditions [Lechner 2001].

1.2.3. Radiant cooling

Radiant cooling is an old idea that has recently gained popularity in Europe and Canada because it offers the potential to reduce cooling energy consumption and when coupled with building thermal mass, reduce peak cooling loads. Radiant cooling refers to any system where surrounding surface temperatures are lowered so that thermal comfort can be maintained at higher air temperatures. There are two kinds of radiant systems:

- ✓ *Direct radiant cooling:* A building's roof structure cools by radiation to the night sky by circulating cool water in specialized panels, plastic bags or roof ponds.
- ✓ *Indirect radiant cooling:* Radiation to the night sky cools a heat-transfer fluid, which then cools the building structure [Lechner 2001].

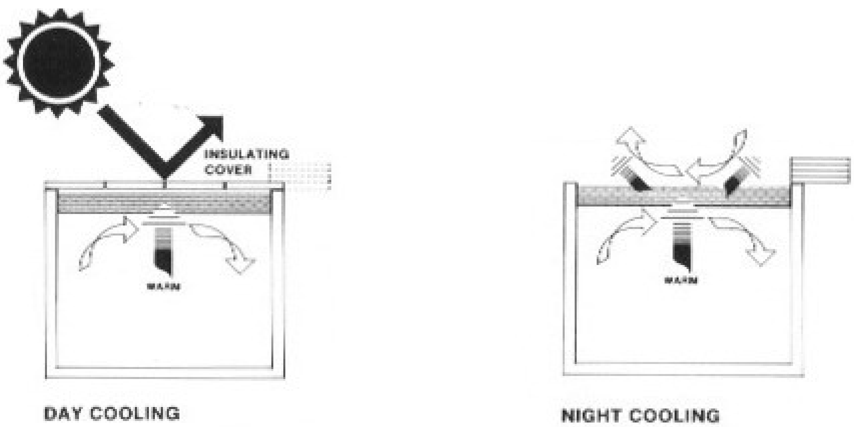


Figure 1: Roof ponds utilizing cool, clear night sky can provide total cooling. LEFT: panels are kept closed during the day; RIGHT: panels are opened after dusk to radiate out the absorbed day time interior heat.
[AZSC 2005]

The main disadvantage of radiant systems is that the surface temperature cannot be lowered below the dew point without causing condensation on interior surfaces that can lead to indoor air quality and maintenance issues. This places a limitation on the maximum cooling loads that can be safely managed by a radiant cooling system [CBE 2006].

1.2.4. Evaporative cooling

When water evaporates, it draws a large amount of sensible heat from its surroundings and converts this type of heat into latent heat in the form of water vapor. As sensible heat is converted to latent heat, the temperature drops. This phenomenon is used to cool buildings in two different ways:

- ✓ *Direct evaporation cooling:* water is sprayed into the air entering a building. This lowers the air's temperature but raises its humidity. It is accomplished with the use of evaporative coolers that are simple, inexpensive and use little energy.
- ✓ *Indirect evaporation cooling:* Evaporation cools the incoming air or the building without raising the indoor humidity [Lechner 2001].

Passive evaporative cooling design solutions include the use of pools, ponds and water features immediately outside windows or in courtyards to pre-cool air entering the house [Passive cooling 2005]. They are best suited to areas where humidity is low, as lower humidity increases the effectiveness of the unit.

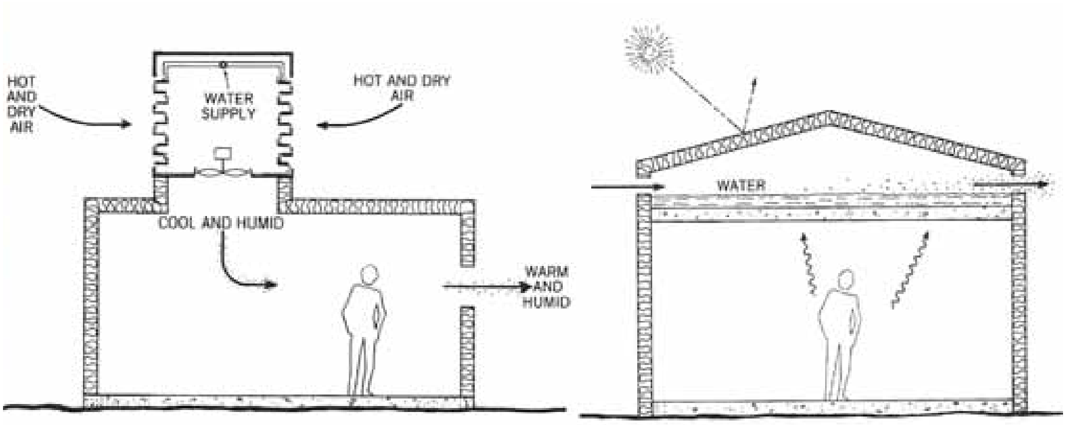


Figure 2: LEFT: Direct evaporative cooling with the use of evaporative coolers (swamp coolers); RIGHT: Indirect evaporative cooling system. Note that no humidity is added to the indoors.
[Lechner 2001]

1.2.5. Earth cooling

It is widely known that ground temperature is always below the maximum air temperature, and the difference increases with depth. Thus, the earth can always be used as a heat sink in the summer. Since the sun heats the soil, shading the surface significantly reduces the maximum earth temperature. Water evaporating directly from the surface can also cool the soil. The cooling of the earth can be useful in terms of cooling the building in two ways:

- ✓ *Direct coupling:* In this case earth-sheltered buildings have their walls in direct contact to the ground and they lose heat directly to the earth.
- ✓ *Indirect coupling:* Air enters the building by way of earth tubes. When cooling is desired, air is blown through the tubes into the building. The earth acts as a heat sink to cool the air.

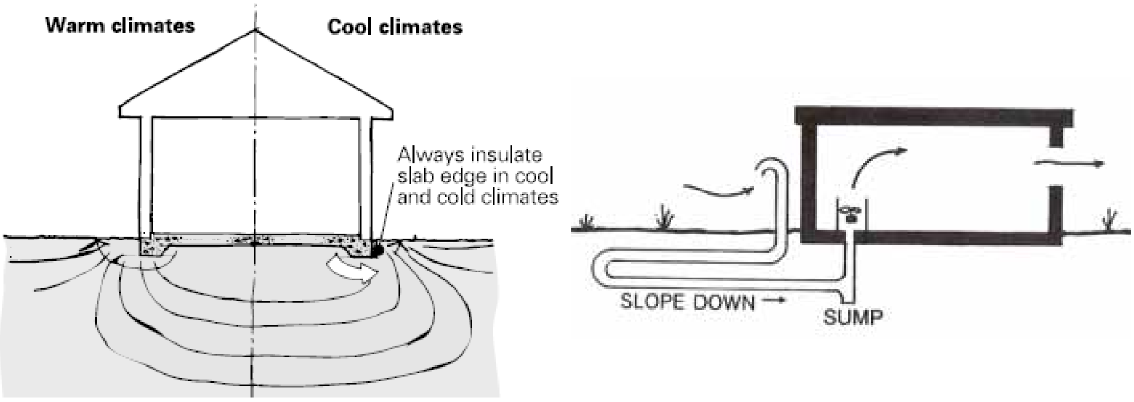


Figure 3: LEFT: Direct earth coupling; RIGHT: Indirect earth cooling is possible by means of tubes buried in the ground. An open-loop system is shown, while a closed-loop system would return the air from indoors.
[Passive cooling 2005 & Lechner 2001]

Directly coupled (underground) structures have reduced access to natural ventilation, which has top priority in hot and humid climates. Thus, earth cooling works best in dry climates and can be problematic in humid climates [Lechner 2001].

1.2.6. Cooling with ventilation, night-time ventilation

Until recently, ventilation has been the major cooling technique throughout the world. It is very important to note that not only are there two very different ventilation techniques, but also that they are mutually exclusive:

- ✓ *Comfort ventilation* brings in outdoor air, especially during the daytime when temperatures are at their highest. The air is then passed directly over people to increase evaporative cooling on the skin. Although thermal comfort might be achieved, the warm air is actually heating the building.
- ✓ *Night time* ventilation is quite different. With this technique, cool night air is introduced to flush out the heat of the building, while during the day very little outside air is brought indoors so that heat gain to the building can be minimized. Meanwhile, the mass of the relatively cool structure acts as a heat sink for the people inside [Lechner 2001].

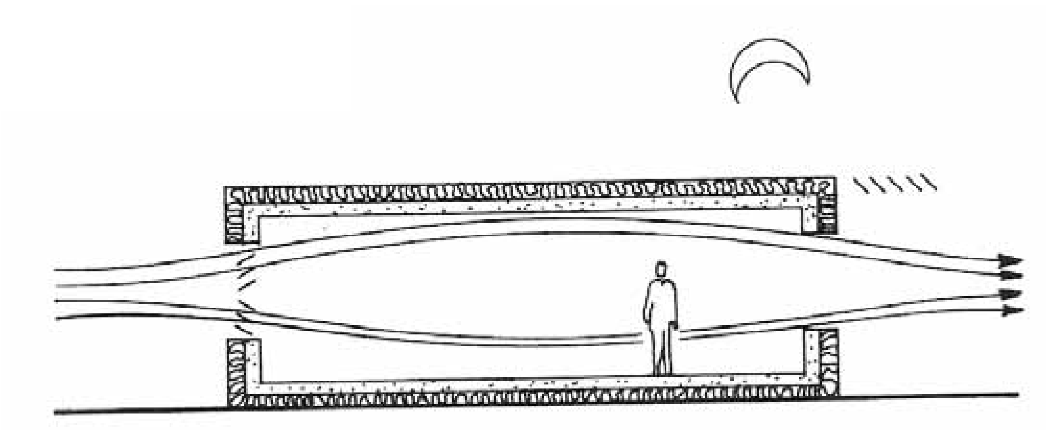


Figure 4: With night cooling, night ventilation cools the mass of the building. *[Lechner 2001]*

Night ventilation systems are classified as direct or indirect as a function of the procedure by which heat is transferred between the thermal storage mass and the conditioned space. In direct systems the cool air is circulated inside the building zones and heat is transferred in the exposed opaque elements of the building. The reduced temperature mass of the building contributes to reduce the indoor temperature of the next day through convective and radiative procedures. In indirect systems on the other hand, the cool air is circulate during night, through a thermal storage medium (usually a slab covered by a false ceiling or floor) where heat is stored and is recovered during the day period. Direct and indirect night ventilation systems are used many times in a combined way.

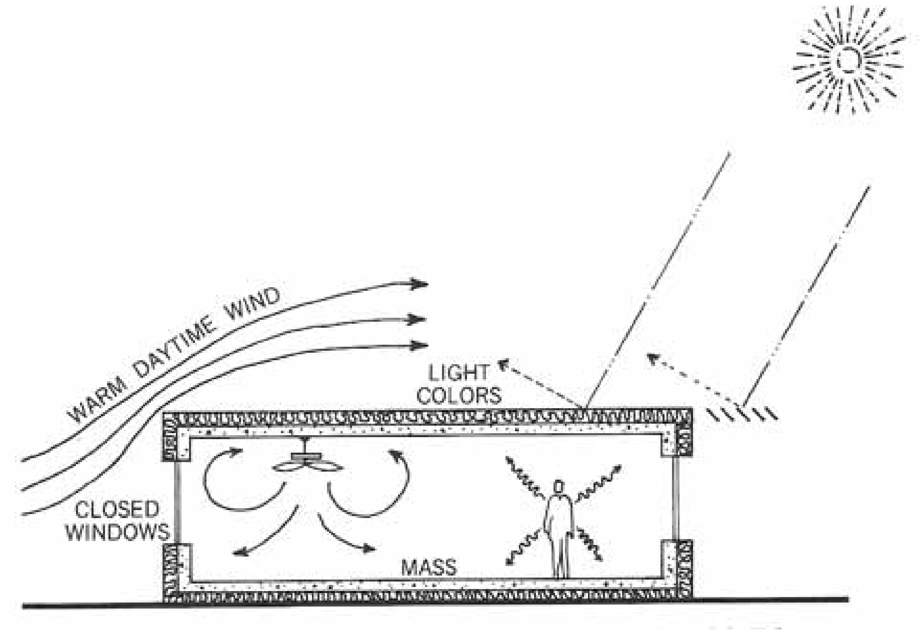


Figure 5: During the day the cooled mass acts as a heat sink. Light colors, insulation, shading and closed windows keep the heat gain to a minimum. Interior circulating fans can be used for additional comfort.
[Lechner 2001]

The performance of night cooling systems depends on three main parameters:

1. The temperature and the flux of the ambient air circulated in the building during the night period.
2. The quality of the heat transfer between the circulated air and the thermal mass.
3. The thermal capacity of the storage medium [Santamouris 2004].

Night ventilation, although a very powerful technique, presents important limitations. Moisture and condensation control is necessary in particular in humid areas. Pollution and acoustic problems as well as problems of privacy are associated with the use of natural ventilation techniques.

The state of art regarding the effectiveness of night ventilation in reducing the cooling loads of buildings, offices or residential, consists of a great variety of experiments, case studies, simulations, calculations and research. Measurements were performed in free floating and A/C night ventilated office building in Athens (Greece). It is found that under free floating conditions, the use of this technique decreases the next day peak up to 3^{o}C. In this case the reduction of overheating hours for air flow rates 10 ACH and 30 ACH varies between 39% and 96% respectively. In case of A/C conditions the temperature peak reduction is up to 2,5 ^{o}C and the overheating reduction between 48% and 94% for air flow rates of 10 ACH and 30 Ach respectively [Geros at al. 1999]. In another experimental study, that was conducted for another office building in La Rochelle (France), night ventilation succeeded in decreasing the diurnal indoor air temperatures from 1,5 to 2 ^{o}C, resulting in a significant comfort improvement for the occupants [Blondeau 1997]. Calculations aiming to study the influence of thermal mass and night ventilation on the maximum indoor temperature in summer were performed in a residential building along the Mediterranean costal plane. They showed that the combination of high thermal mass and high night ventilation rate can significantly decrease the indoor temperature up to 5 ^{o}C [Shaviv et al. 2001].

1.2.7. Phase changing materials (PCM)

The success of some passive cooling systems depends largely on the proper use of heat-storage materials. Besides water, concrete, stone or brick that have a certain degree of heat storage ability; there are potentially even more efficient materials for storing heat. These are called phase- change materials (PCM) [Lechner 2001].

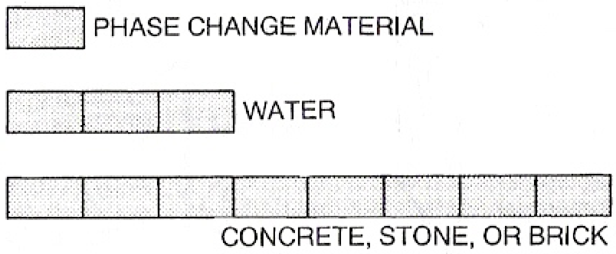


Figure 6: Relative volumes required for equal heat storage
[Lechner 2001]

They store the energy in the form of latent heat, while the previously mentioned materials store the energy as sensible heat. They use chemical bonds to store and release heat. The thermal energy transfer occurs when a material changes from a solid to liquid or from a liquid to a solid. This is called a change in state or "phase". Initially, these solid-liquid PCMs perform like conventional storage materials; their temperature rises as they absorb solar heat. Unlike conventional storage (sensible) materials, when PCMs reach the temperature at which they change phase (their melting point) they absorb large amounts of heat without getting hotter. When the ambient temperature in the space around the PCM material drops, the PCM solidifies, releasing its stored latent heat. PCMs absorb and release heat while maintaining a nearly constant temperature. Within the human comfort range of 20 to 30 ^{o}C, latent thermal storage materials are very effective. They store five to fourteen times more heat per unit volume than sensible storage materials [PCM 2005].

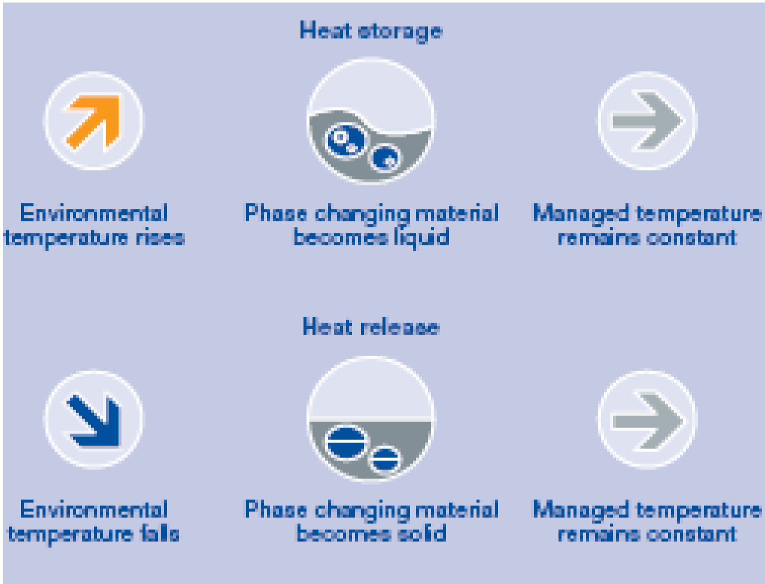


Figure 7: How phase changing materials work.
[BASF 2006]

Organic and inorganic compounds are the two most common groups of PCMs. Most organic PCMs such as paraffin waxes are chemically stable and non-corrosive, exhibit little or no supercooling properties (that is, they do not need to be cooled below their freezing point to initiate crystallization) and compatible with most building materials, have a high latent heat per unit weight and are recyclable. Their disadvantages are low thermal conductivity, high changes in volume during phase change and flammability. Inorganic compounds such as salt hydrates have much higher latent heat per unit volume, higher thermal conductivity, are non-flammable and lower in cost in comparison to organic compounds. However, they are corrosive to most metals and suffer from decomposition and supercooling, which can affect their phase change properties [Bruno 2005].

PCMs are proved to be very effective in light weight buildings, since they increase their thermal mass. They are used either in prefabricated PCM wallboards [BASF 2006], they can be also stored in aluminum bags that are installed in suspended ceilings [DOERKEN 2006] or they are impregnated into conventional porous construction materials as granulates [RUBITHERM 2006]. In those prefabricated elements it is estimated that the heat storage capacity of a 1,5 cm PCM wallboard is comparable to that of a 9 cm concrete wall or a 12 cm brick wall [BASF 2006]. By impregnation of paraffin PCM into a conventional gypsum wallboard it has been reported that the storage capacity of the wallboard has been increased at least 20 times [Metivaud et al. 2004].

An experimental investigation of gypsum board impregnated with a PCM was performed in a direct gain outdoor test-room in Montreal. The results showed a reduction of the maximum indoor temperature up to 4 ^{o}C during the daytime and a significant reduction of the heating load during the night [Athienitis et al. 1997]. In another case study of a building located in California (USA) it was estimated that the peak cooling load can be reduced up to 28% after the application of PCMs. The same research also concluded that the use of PCM in climates with night temperature above 18 ^{o}C can not be considered as an energy or peak power saving opportunity [Stetiu and Feustel 1998].

2. Research Design, Approach

2.1. Case studies_ Parametric studies

In order to study and analyze the application of various techniques as well as to evaluate their impact on the building performance in terms of cooling loads, a series of parametric studies were conducted. Considering it as a challenge to study how the same parameters influence the building performance in areas with different climate and consequently different cooling requirements, the case studies were located in Austria and Greece.

This whole comparative parametric analysis was based on two case studies-buildings. Since Greece was the basis of the research, I chose two residential buildings that are considered to be representative in terms of form, type and construction in Greece. The first one is an apartment and the second one a single family house.

Due to the fact that real-time experiments and measurements were not possible, the study relied on building simulation tools. Software tools were used in order to model the shape and the construction of the buildings as well as to locate them either in Austria or Greece. Afterwards, using a building performance simulation tool it was possible to study how the alteration of the parameters affected the cooling loads and the thermal comfort of various spaces.

The analysis process was based on the results taken by changing and controlling different parameters. The parameters that were chosen are supposed to affect the performance of the buildings in terms of cooling. They deal with decisions about the design of the envelope (floor plan, orientation, openings etc) as well as about the construction (thermal mass, materials, insulation etc).

So, these parameters are:

- ✓ Glazing.
- ✓ Shading.
- ✓ Ventilation / Night time cooling.
- ✓ Application of phase changing materials (PCM).

2.2. Selected climates: Greece-Austria

2.2.1. Athens _ Greece

As already mentioned the selected climates are Austria and Greece. Greece is a typical Mediterranean country with a temperate climate. The winters are mild and wet but summers are hot and dry [Climatic data 2006]. The buildings were located in the capital, Athens [Appendix A]. The corresponding climatic data for Athens are:

Table 1: Climatic data for Athens, Greece.
[NOA 2005]

Climatic data	Athens, Greece
Latitude	37,98 N
Longitude	23,73 E
Altitude	0
Time Zone	-2

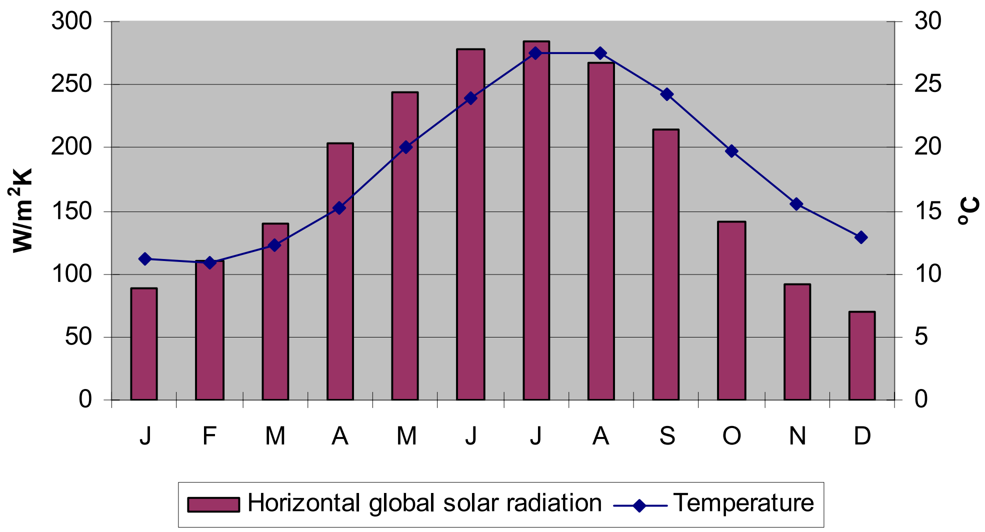


Figure 8: Mean monthly horizontal global solar radiation and average monthly temperatures for Athens, Greece.
[Climatic data from METEONORM]

Table 2: Mean monthly horizontal global solar radiation and average monthly temperatures for Athens, Greece.
[Climatic data from METEONORM]

Month	Horizontal global Solar radiation (W/m^2K)	Temperature (^oC)
January	88,3	11,2
February	110,6	10,9
March	140	12,3
April	203,1	15,3
May	243,9	20
June	277,6	24
July	284,9	27,5
August	267,2	27,5
September	214,8	24,3
October	141,8	19,8
November	91,1	15,6
December	70,6	12,9

2.2.2. Vienna _ Austria

Austria is located in the Central Europe and its climate is generally characterized as temperate continental. Winters are usually cold with frequent rain in lowland and snow in mountains and summers are cool with occasional showers [Climatic data 2006]. Again, the buildings were located in the capital city, Vienna [Appendix A]. Some of the basic climatic data for Vienna are presented in the following tables and figures:

Table 3: Climatic data for Vienna, Austria.
[ZAMG 2005]

Climate data	Vienna, Austria
Latitude	48,12 N
Longitude	16,22 E
Altitude	171
Time Zone	-1

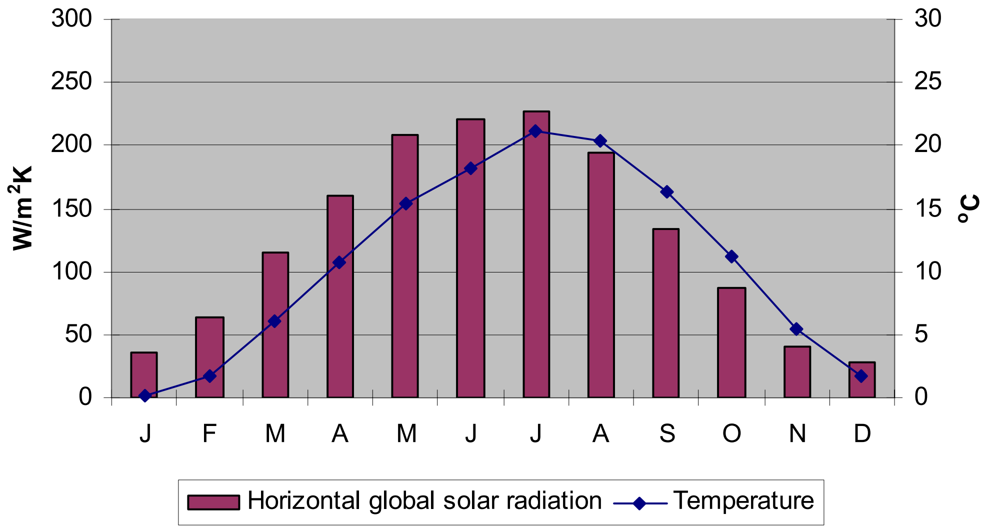


Figure 9: Mean monthly horizontal global solar radiation and average monthly temperatures for Vienna, Austria.
[Climatic data from METEONORM]

Table 4: Mean monthly horizontal global solar radiation and average monthly temperatures for Vienna, Austria.
[Climatic data from METEONORM]

Month	Horizontal global solar radiation (W/m^2K)	Temperature (^oC)
January	35,9	0,1
February	63,2	1,7
March	114,3	6,1
April	159,4	10,8
May	208,9	15,4
June	220,3	18,2
July	227	21,1
August	195	20,3
September	133,6	16,3
October	86,5	11,2
November	40,5	5,5
December	27,6	1,7

2.3. Buildings

As mentioned before the parametric studies were based on two residential buildings. They are two examples highly representative of the general housing stock characteristics. In terms of housing typology the buildings that were chosen are one apartment (multi-storey house) and one single house. According to a resent survey that was conducted between four European countries the building stock in Greece as well in Austria is dominated by single family dwellings and apartments [EPA-ED 2003].

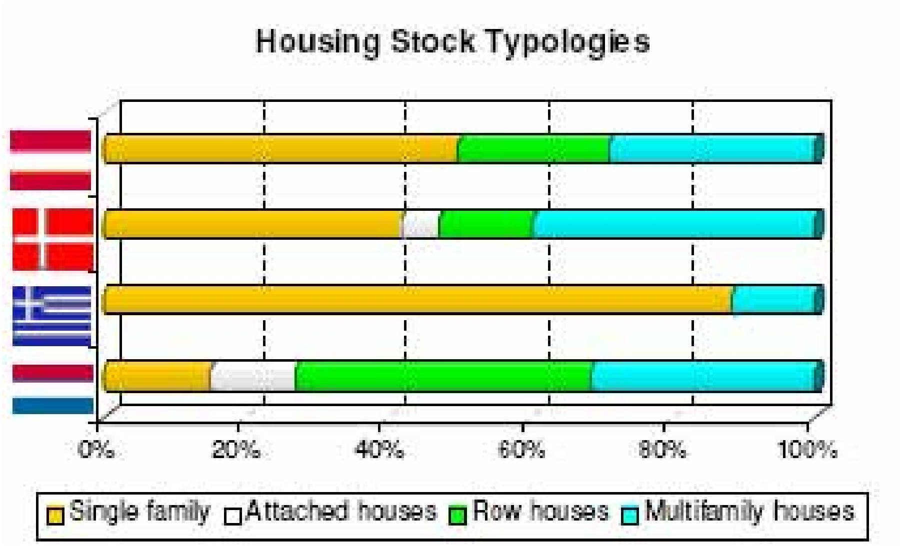


Figure 10: Housing stock typologies in four European countries: Austria, Denmark, Greece, The Netherlands.
[EPA-ED 2003]

2.3.1. Apartment

The apartment is located in the last floor of a multistory multi family building. I chose this case because apartments of that type have special needs concerning cooling mainly for two reasons. The first one is the direct exposure of the ceiling to the solar radiance. In addition to this those apartments don't get shaded by other buildings, trees or obstacles of the urban equipment because of their height. These special conditions increase the internal heating loads and consequently make the need for cooling more urgent.

The apartment covers the whole floor. Due to the fact that the building is attached by two other multistory buildings by both sides, the apartment is also attached in two sides to the apartments of the neighboring buildings. The orientation is north-south, which means that it has openings only in the northern and southern side and a small one in the western side. The roof is a typical flat roof. The layout of the apartment as well as its demarcation in zones can be seen in the following figure.

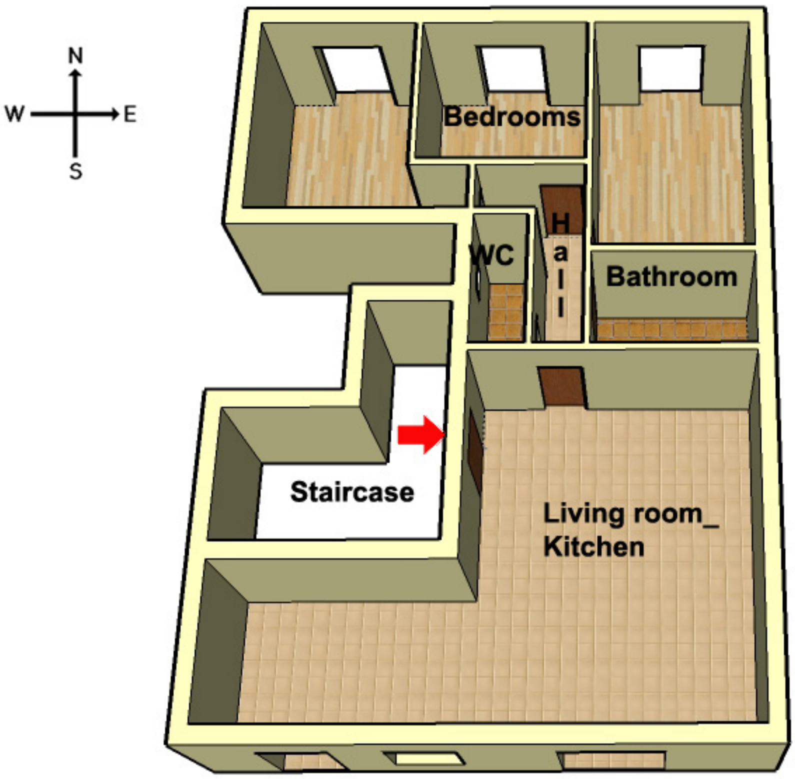


Figure 11: The apartment.

2.3.2. Double-storey single family house

The house is a typical two storey single family house. It is free from all sides, which means that it has openings in all sides. Its roof is flat. In the first floor in the southern side there is a balcony which also serves as permanent shading for the room on the ground floor. The layout of both floors is shown in the figures below.

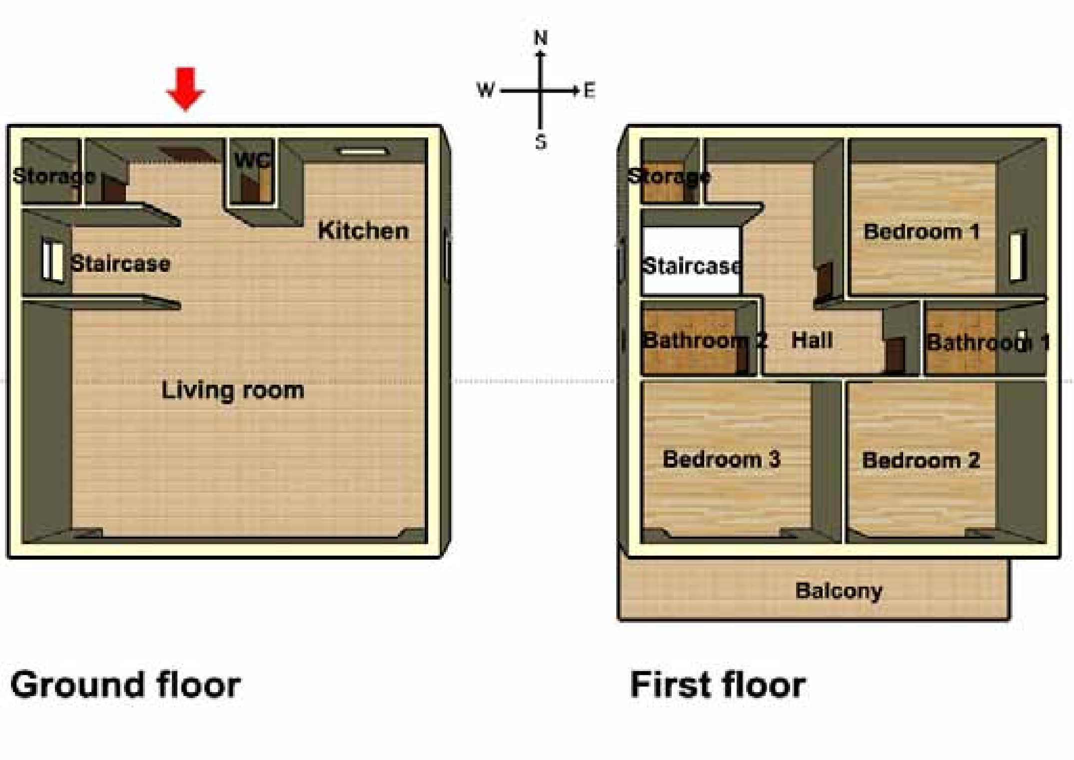


Figure 12: The Double-storey single family house.

2.3.3. Construction

In both buildings the construction of the static system and the walls is the same. Construction details of the floor, the ceiling, the windows, external and internal walls are presented in the following figures.

Table 5: Construction details of external and internal walls, ceiling, floor and windows.

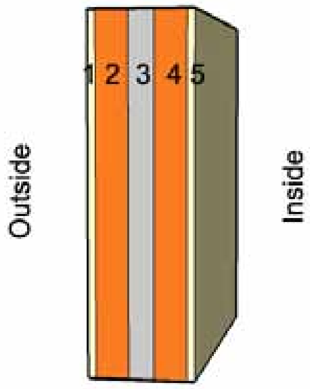
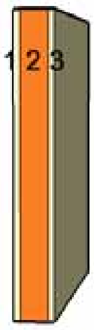
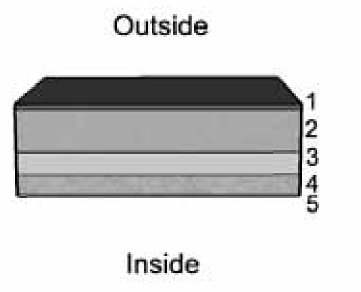
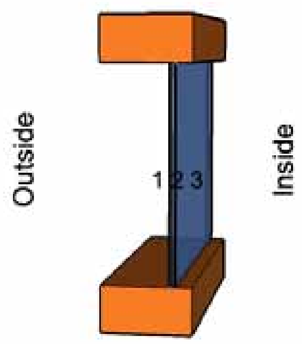
External walls	 	1. Plaster 2. Brick 3. Insulation 4. Brick 5. Plaster
Internal wall	 	1. Plaster 2. Brick 3. Plaster

Table 5 (continued): Construction details of external and internal walls, ceiling, floor and windows.

Ceiling		1. Asphalt cover 2. Concrete 3. Insulation 4. Reinforced concrete 5. Plaster
Floor		1. Timber/ Tiles 2. Cement plaster 3. Concrete screed 4. Reinforced concrete 5. Plaster
Windows		1. Glass 2. Air cavity 3. Glass

2.4. Software tools: METEONORM & CAPSOL

2.4.1. METEONORM

METEONORM is a tool designed by the company METEOTEST (located in Switzerland). It is a comprehensive climatological database for solar energy applications:

1. A *meteorological database* containing comprehensive climatological data for solar engineering applications at every location of the globe.
2. A *computer program* for climatological calculations.
3. A *data source for engineering design programs* in the passive, active and photovoltaic application of solar energy with comprehensive data interfaces.
4. A *standardization tool* permitting developers and users of engineering design programs access to a comprehensive, uniform data basis.
5. *Meteorological reference* for environmental research, agriculture, forestry and anyone else interested in meteorology and solar energy [METEONORM 2003].

METEONORM was used in order to obtain the climatological data needed for my simulations. The received data gave hourly values during a whole year for the following parameters:

- ✓ Temperature (^oC)
- ✓ Horizontal global solar radiation (W/m^2K)
- ✓ Horizontal diffuse solar radiation (W/m^2K)
- ✓ Direct beam solar radiation (W/m^2K)

The data that METEONORM created for weather stations in Vienna and Athens were edited and imported in CAPSOL as climate functions, describing the climate of the regions in study.

2.4.2 CAPSOL

CAPSOL is a software product of company PHYSIBEL (located in Belgium). It is a computer program to calculate multizonal steady-state and dynamic heat transfer, including one dimensional heat conduction, convection, view factor based infrared radiation, multizonal ventilation and solar radiation. During the dynamic calculation a system of energy balance equations is built and solved each calculation time step, using a finite difference method. The steady state calculation can be used to calculate the required heating and cooling loads.

CAPSOL basically consists of four computer programs: *input* module, *calculation* module, *function editor* module and *wall type editor* module. All these programs work seamlessly together during defining a problem, making the calculation and reporting the results. The report can consist of several user defined charts and alphanumeric results.

As already mentioned CAPSOL allows the simulation of dynamic thermal behavior of multi-zoned objects such as buildings. The simulation basics are explained in five basic schemes:

1. Interzonal heat flows by conduction, convection and infrared radiation.
2. Conduction, convection, infrared and solar radiation in wall types.
3. Solar processing through zones.
4. Boundary conditions: known temperatures, powers and mass flow rates.
5. Temperature controls for heating and cooling: powers, mass flow exchanges and solar screens [CAPSOL 2002].

2.5. Power schemes

In both projects there is a free heat dissipated in every zone. This heat is a power released by the equipment and the occupancy of every internal space. Since equipment and occupancy differs from zone to zone the value of the free heat varies in every zone. In CAPSOL this free heat was simulated as a constant function, different for every zone. Its value was estimated by the standard equipment and occupancy I assumed for each zone separately. Below, the internal load for every zone of both the apartment and the single house is presented: the first column of every case lists the maximum power that is released in hours of full use of the equipment and occupancy and in the second column the efficient average of 33%. This last value was the one used in the simulations.

Table 6: Internal loads for each zone of the apartment, released by equipment and occupancy.

Zones	Maximum power [W]	Efficient average_33%[W]
Living room & kitchen	1000	333
Bedrooms	900	300
Bathroom	300	100
WC	140	47
Hall	240	80

Table 7: Internal loads for each zone of the double-storey single family house, released by equipment and occupancy.

Zones		Maximum power [W]	Efficient average_33%[W]
Ground floor	Living room & kitchen	1200	400
	WC	140	47
	Storage room	140	47
	Staircase	300	100
First floor	Bedroom_1	300	100
	Bedroom_2	300	100
	Bedroom_3	400	133
	Bathroom_1	300	100
	Bathroom_2	300	100
	Storage room	140	47
	Hall	260	87

2.6. Glazing schemes

As already mentioned, the glazing that was used in both buildings is double glazing with air cavity. According to experts, replacing old single pane windows with double glazed units can reduce the annual heating and cooling costs an average of 25-50% [Glazing 2006].

Besides the type of the glazing there are also other properties of the material that affect the solar energy transmittance and consequently the inside temperatures, like the g-value. This factor is composed of the direct transmission of solar radiation as well as the heat transfer of the parts absorbed in the glass, like heat radiation and convection towards the interior [g-value 2006].

The glazing used in this study has a g-value of 68%, which is a common value for constructions like this. In order to realize the importance of glazing in a more tangible way, a series of “experimental” simulations and calculations were conducted using glazing with a g-value of 20%. These calculations were conducted for the standard air exchange rate of $1h^{-1}$and for different shading schemes.

2.7. Shading schemes

As mentioned before in the framework of the parametric studies, I examined the impact of different shading variations in the thermal comfort of a zone. In general I chose five different shading scenarios. I applied the first four to the apartment and all five of them to the one family house.
In CAPSOL the internal and external shading is simulated as a screen (or roller blind). In reality by internal shading I mean sun-shading devices such as roller shades, Venetian blinds, curtains and drapes etc. In case of external shading I mean operable units, such as louvers made of wood or metal, exterior Venetian blinds or shutters. Overhangs could also be considered as external shading devices. Due to the fact that they are fixed to the building envelope, they are studied separately.

Table 8: The five different variations of shading schemes.

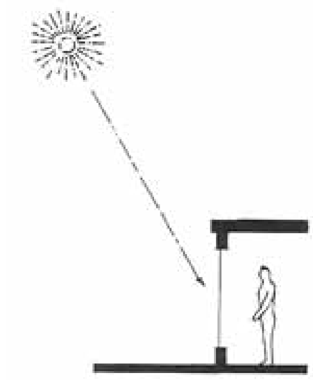
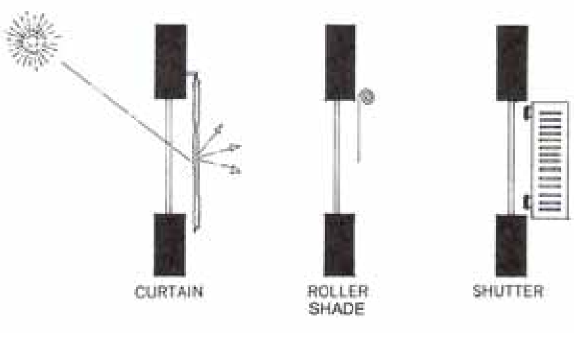
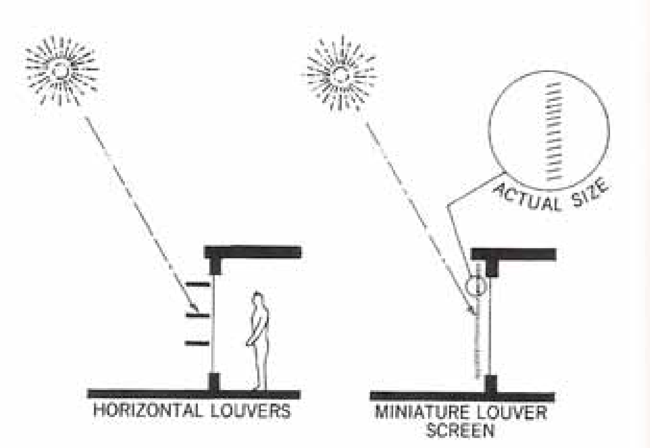
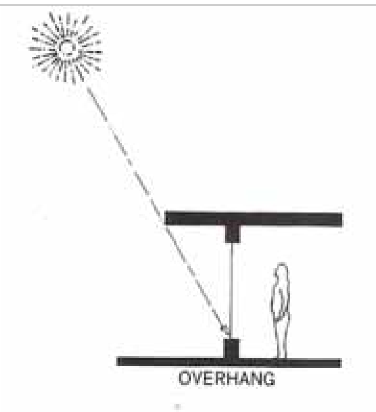
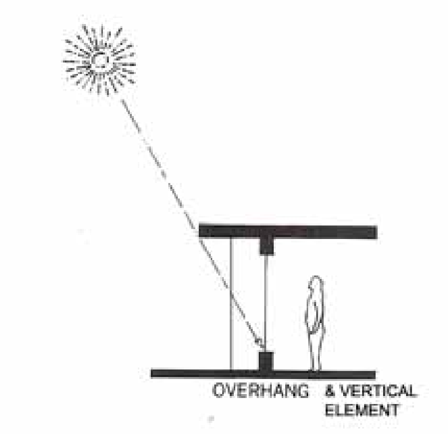
sh1		**No shading**
sh2		**Internal shading**

Table 8 (continued): The five different variations of shading schemes.

sh3		**External shading**
sh4		**Overhang**
sh5		**Overhang & Vertical elements**

2.8. Ventilation schemes

In an attempt to conduct a complete approach of different natural ventilation scenarios, at the beginning multiple possible ventilation schemes were studied. Trying to analyze the impact of ventilation, a series of simulations were carried out by changing every time the air exchange rate starting from a minimum standard value and proceeding till various night ventilation scenarios. These schemes are also determined by a hypothetical scenario that all the members of the family are at work or at school during the day (from 9:00 till 17:00 the house is supposed to have minimum occupancy).

Table 9: Different variations of ventilation scenarios.

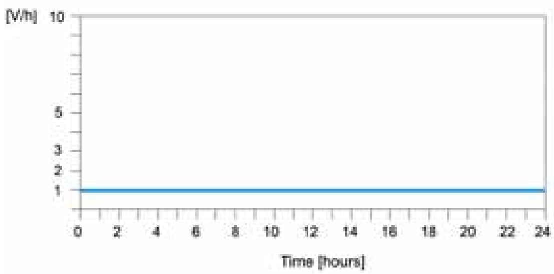
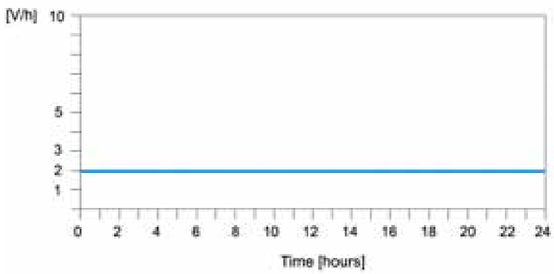
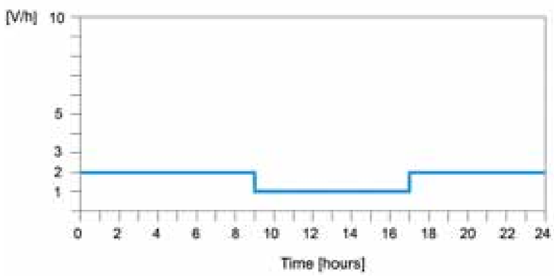
Variation name	Ventilation rate [h^{-1}]	Description
v1.1		Constant function, where air exchange rate is stable at 1 h^{-1}
v1.2		Constant function, where air exchange rate is stable at 2 h^{-1}
v2.1		Step function, where air exchange rate interchanges between 1 and 2 h^{-1}.

Table 9 (continued): Different variations of ventilation scenarios.

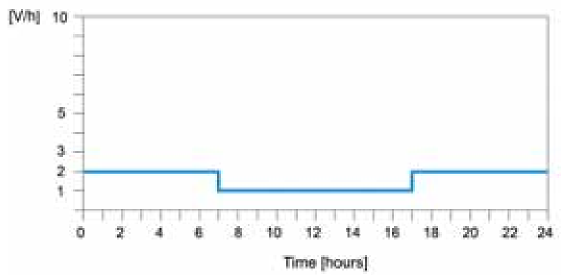
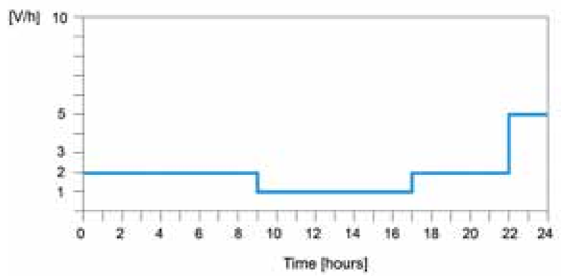
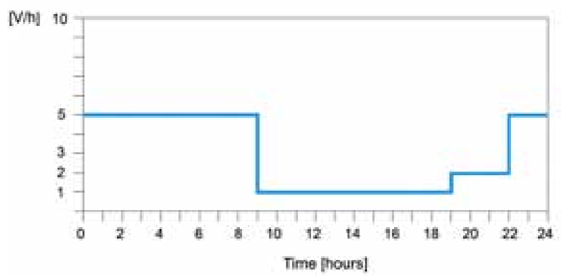
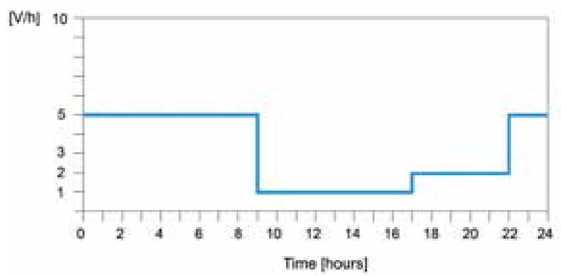
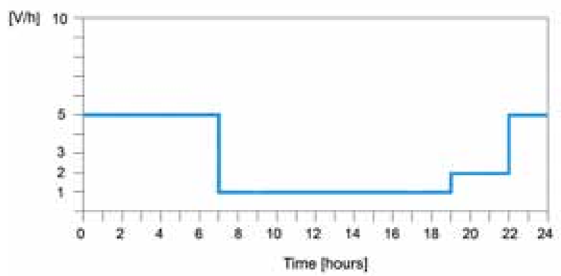
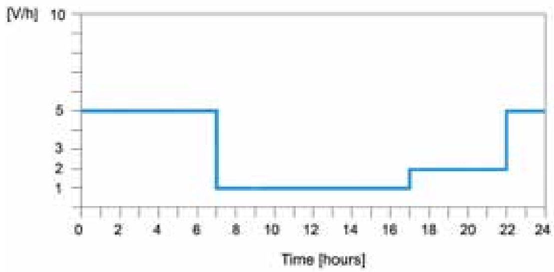
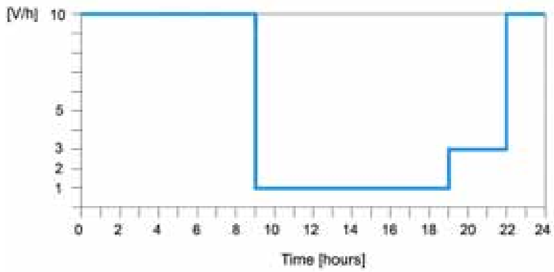
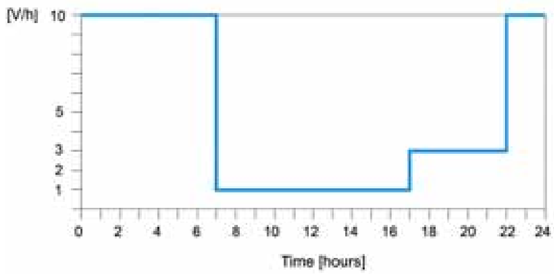
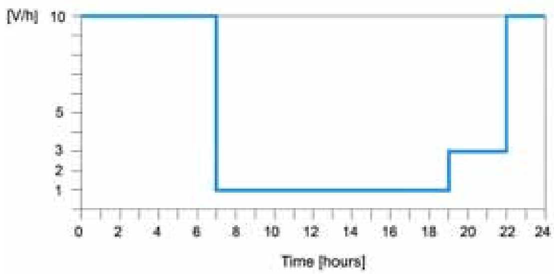
v2.2		Step function, where air exchange rate interchanges between 1 and 2 h^{-1}.
v3.1		Step function, where air exchange rate interchanges between 1, 2 and 5 h^{-1}.
v4.1		Step function, where air exchange rate interchanges between 1, 2 and 5 h^{-1}.
v4.2		Step function, where air exchange rate interchanges between 1, 2 and 5 h^{-1}.
v4.3		Step function, where air exchange rate interchanges between 1, 2 and 5 h^{-1}.

Table 9 (continued): Different variations of ventilation scenarios.

v4.4		Step function, where air exchange rate interchanges between 1, 2 and 5 h^{-1}.
v5.1		Step function, where air exchange rate interchanges between 1, 3 and 10 h^{-1}.
v5.2		Step function, where air exchange rate interchanges between 1, 3 and 10 h^{-1}.
v5.3		Step function, where air exchange rate interchanges between 1, 3 and 10 h^{-1}.

All these scenarios were tested in the apartment considering as default shading scheme the overhang [Appendix B]. By comparing the results, we concluded to the four most representative, that were used in all the parametric studies.

2.9. Phase Change Materials (PCM)

2.9.1. The choice of the material

In order to choose the PCM, that would be most suitable for the parametric studies, a range of temperatures in the inner zones was studied. Since the studies were first conducted for the Greek climate, the inner temperatures for the period April to September were at high levels (both day and night temperature), especially for the warmer months. That means that both melting and congealing point of the material should be of high value. On the other hand the aim of the application of PCM is to control the inner temperatures in terms of reducing the overheating hours. Consequently the above mentioned values could not be very high. Finally after a thorough research on the commercial PCMs that are available on the market, the most fitting one was the material RUBITHERM RT 27.

In general the products RUBITHERM RT is a series of phase change materials based on paraffins and waxes. It is a new generation of ecological heat storage materials utilizing the processes of phase change between solid and liquid to store and release large quantities of thermal energy at nearly constant temperature. They are very effective even when low operating temperature differences are applicable [RUBITHERM 2006]. The technical data for the specific material RUBITHERM RT 27 are:

Table 10: Technical data for the phase change material RUBITHERM RT 27. *[RUBITHERM 2006]*

RUBITHERM RT 27	Typical values
Melting point [^{o}C]	28
Congealing point (PCM) [^{o}C]	26
Heat storage capacity [kJ/kg]	179
Specific heat capacity [kJ/(kgK)]	1,8 / 2,4
Heat conductivity [W/(mK)]	0,2

This material as described above is paraffin in form of granulates. In practice, the PCM is incorporated into building construction materials. In this case I assumed that the material would be applied on the building envelope as wallboard, placed on the existing construction. The wallboard is loaded with 20% of RUBITHERM RT 27. The thermal characteristics of PCM-wallboard are measured to be pretty close to those of PCM alone [Metivaud et al. 2004]. So, the technical data of the material PCM-wallboard that will be finally applied are formed like the following:

Table 11: Technical data of the final product PCM-wallboard and comparison to the normal wallboard that was enriched with paraffin RUBITHERM RT 27.
[Metivaud et al. 2004]

Material	Wallboard	PCM - wallboard
Melting point [^oC]	-	28
Congealing point (PCM) [^oC]	-	26
Thickness [cm]	2,5	2,5
Weight [kg]	28,44	34,13
Heat storage capacity [kJ/m^2]	49	1110
Cooling performance [W/m^2]	-	25-40

2.9.2. Application of PCM-wallboard

For the parametric studies the PCM-wallboard was applied in one space in every project. This space was selected according to the high cooling needs of the zone. In every case the material was applied on the ceiling of the zone.

In the case of the apartment the zone that was chosen is the zone living room & kitchen. The reason was that this particular zone due to its southern orientation has higher cooling needs in comparison to the others.

In the case of the one family house, the zone that would be studied was selected based on the same criteria. Consequently it was a zone of the first floor (direct solar radiation) and more particularly zone Bedroom_2 because of its southern-eastern orientation.

2.9.3. Simulation of PCM-wallboard in CAPSOL

The challenge of using CAPSOL in the simulation of the PCM-wallboard is that it doesn't have this material in its database. This means that it was necessary to find a way of introducing the material to the program in a way that the program would simulate the special characteristics of the material and determine its performance in an acceptable and reasonable way.

This was achieved by introducing various functions that represent the free heat in the studied zone. The creation of these functions follows the following procedure:

- ✓ At first the indoor temperature of the zone on an hourly basis for the six months from April to September was calculated. The material was not applied yet.
- ✓ Considering that the PCM-wallboard was applied, I tried to figure out how the material would react according to the temperature range. It means that over 28 ^{o}C the material absorbs energy and below 26 ^{o}C it releases.
- ✓ Having the surface of the material and its technical data, the amount of energy it absorbs or releases was calculated. [Appendix C]

- ✓ From these values power functions were created. These functions represent hourly the energy interchange in the zone after the application of the material.
- ✓ The simulations run again and a new comparison was made between the resulted inner temperatures to the initial one (before application).

2.10. The Degree Hours Method

After having designed the research approach and before starting the calculations and the simulations, a way to present the results should be found. This way should be effective not only in showing the results in a "readable" way but most important to allow an easy comparison between the results of the different parametric studies. In order to evaluate the various approaches the results should be quickly recognizable.

For this reason the Degree Hours (DH) Method was used. This method requires the simulation of the pattern of internal temperature variations in a building over a specific time period in response to exposure to the weather conditions. A simulation run is carried out in which the building in question is exposed to all the thermal influences except that of a cooling system: solar radiation, outside temperature variations, occupancy and casual gains. A suitable value of internal base temperature is chosen and the degree hours are calculated from the following equation:

DH (cooling) = $\sum (t_i - t_b)$, where

t_i → the value for internal temperature
t_b → the value for the internal base temperature
[Letherman and Al-Azawi 1986]

The Degree Hours Method was used for a time period of the six warmest months from April to September with an hourly time step, which means that in every study 4392 hourly values were processed. Using the solar radiation and outside temperature functions from METEONORM and creating a function for occupancy and internal heat gains the simulations were performed. The aim was to proceed with the parametric studies by evaluating them in terms of overheating in the internal zones. Above 27^{o}C inside was considered as an overheating case. So, the base temperature was defined at 27^{o}C and according to these assumption, calculations were carried out.

In order to simplify the results even more and in order to make the comparisons more efficient the notion of “Degree Days” (DD) was introduced. After having calculated the Degree Hours over the period of six months (183 days) we divided the DH by 183. The resulted value is a smaller number and therefore easier to handle.

3. Results

3.1. Presentation of the results

As mentioned before the above described series of parametric studies is applied in four different cases: an apartment and a double-storey single family house, both located in Athens (Greece) and Vienna (Austria). The results are presented separately for every case in four units. In every unit the results follow the same structure:

- ✓ At the beginning there is a concentrated table. The first four columns of every table show the glazing, ventilation, shading and PCM schemes in all possible combinations. The following columns present the resulted overheating indicator for every zone and for every scenario of the project. The number in the cells is the value for "Degree Days"
- ✓ The number in the last column of those tables represents an average value for the whole apartment or house. This average results from the zones that are considered to be of higher importance in terms of cooling needs and thermal comfort e.g the living room, kitchen, bedrooms. The formula that gives this average is:

$$DD_m = \frac{DD_{R1} \times A_{R1} + DD_{R2} \times A_{R2} + DD_{Rn} \times A_{Rn}}{A_{R1} + A_{R2} + A_{Rn}}$$

where: DD → „Degree Day“

R1 → Name of the room

A → Area of the room [m^2]

- ✓ Afterwards, some illustrations of the results are presented.
- ✓ Finally, there is a table that describes more detailed the results for the application of PCM. We can see the distribution of overheating in every month of the period April-September. The values in the cells that correspond to every month represent the Degree Hours. The values in parenthesis show the number of hours that the temperature exceeded

the comfort limit of 27°C during every month. In the sum the last number is the “Degree Day” value.

✓ Again some illustrations are cited, that show the indoor temperature and the free heat after the application of the PCM-wallboard.

In order to name and describe any possible scenario in a short and convenient way, a system of tags was introduced. Every scenario has a six-part name. Every part describes a different parameter:

Table 12: Shortcuts for naming every possible parametric study scenario.

Part	Parameter	Values	Description
1.	*Building*	**Ap** **H**	Apartment One family house
2.	*Location*	**A** **V**	Athens (Greece) Vienna (Austria)
3.	*Glazing schemes*	**g20** **g68**	g-value=20% g-value=68%
4.	*Ventilation schemes*	**v1.1** **v2.1** **v4.1** **v5.1**	Variations of different ventilation schemes [Table 8]
5.	*Shading schemes*	**sh1** **sh2** **sh3** **sh4** **sh5**	Different shading scenarios [Table 7]
6.	*PCM*	**-** **PCM**	No use of PCM PCM - wallboard

3.2. Apartment in Athens_Greece (Ap_A)

After performing all the simulations and calculations, that were described above, the results of all parametric studies for the apartment in Athens in terms of the overheating risk are presented in this chapter.

Table 13: Concentrated results in “Degree Days” of parametric studies for the apartment in Athens (Greece).

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Outside	Living room &kitchen	Bedrooms	Bathroom	WC	Hall	Mean
g20	v1.1	sh1	-	21,36	19,41	34,24	36,83	59,97	40,17	**26,10**
g20	v1.1	sh2	-	21,36	23,64	45,88	41,23	73,74	46,67	**33,68**
g20	v1.1	sh3	-	21,36	16,54	26,25	34,08	49,96	36,10	**20,92**
g20	v1.1	sh4	-	21,36	15,19	20,23	30,65	30,85	29,31	**17,47**
g68	v1.1	sh1	-	21,36	35,73	76,12	51,16	110	61,10	**53,96**
g68	v1.1	sh2	-	21,36	24,62	47,04	41,88	75,36	47,33	**34,74**
g68	v1.1	sh3	-	21,36	16,88	27	34,40	50,89	36,36	**21,45**
g68	v1.1	sh4	-	21,36	16,90	21,90	31,63	33	30,45	**19,16**
g68	v2.1	sh1	-	21,36	29,47	64,90	39,63	95,43	48,21	**45,47**
g68	v2.1	sh2	-	21,36	20,49	39,65	32,48	64,20	37,28	**29,14**
g68	v2.1	sh3	-	21,36	14,40	22,90	26,85	42,87	28,68	**18,24**
g68	v2.1	sh4	-	21,36	14,10	17,76	24,60	26,46	23,95	**15,75**
g68	v4.1	sh1	-	21,36	21,45	50,50	24,96	74,60	31,13	**34,56**
g68	v4.1	sh2	-	21,36	15,12	29,80	20,58	47,88	23,89	**21,75**
g68	v4.1	sh3	-	21,36	11,17	17,48	17,20	31,40	18,39	**14,02**
g68	v4.1	sh4	-	21,36	10,13	11,96	15,53	17,14	15,04	**10,96**
g68	v5.1	sh1	-	21,36	18,03	41,90	17,02	59,10	20,82	**28,81**
g68	v5.1	sh2	-	21,36	13,24	24,76	14,47	36,66	16,36	**18,44**
g68	v5.1	sh3	-	21,36	10,42	14,95	12,48	24	12,91	**12,47**
g68	v5.1	sh4	-	21,36	9,36	9,93	11,43	12,04	10,74	**9,62**
g68	v4.1	sh4	PCM	21,36	9,73	-	-	-	-	**9,73**
g68	v5.1	sh4	PCM	21,36	7,81	-	-	-	-	**7,81**

The illustrative presentation of the above listed results is represented in the following figures. We can observe the changes in the indoor temperature of several zones according to the different scenarios and variations of shading and ventilation schemes.

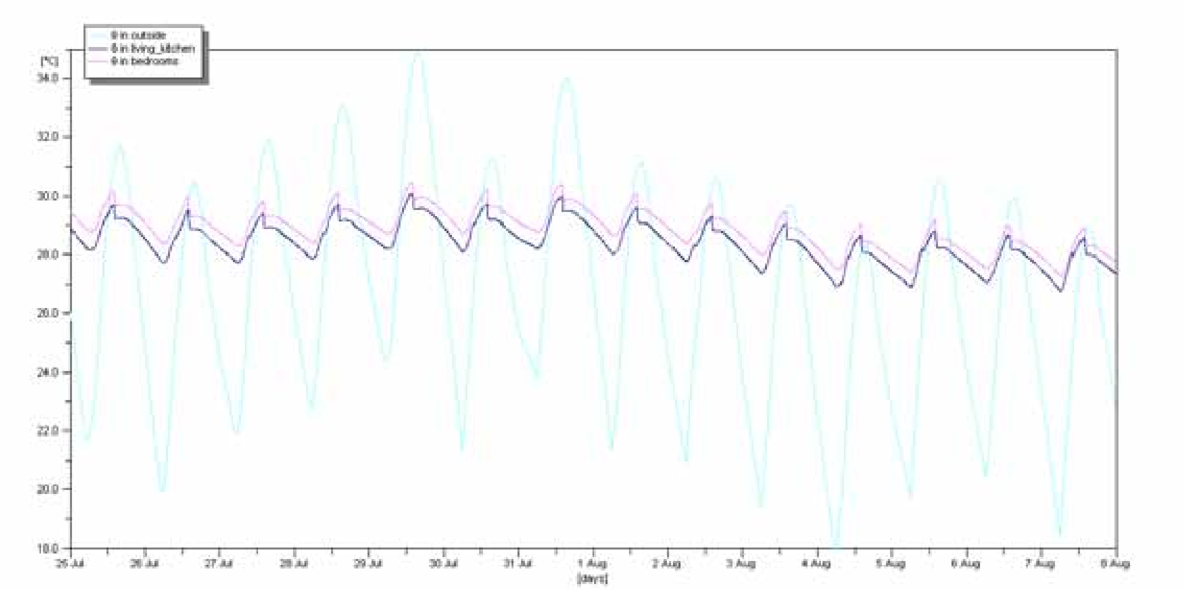


Figure 13: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_A_g68_v1.1_sh4.

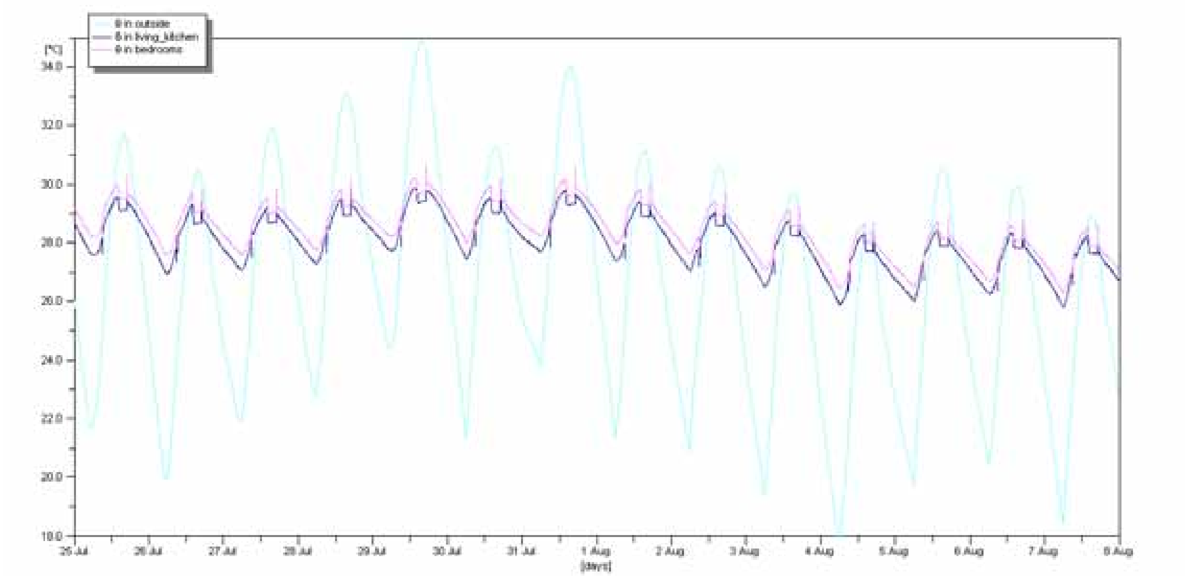


Figure 14: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_A_g68_v2.1_sh4.

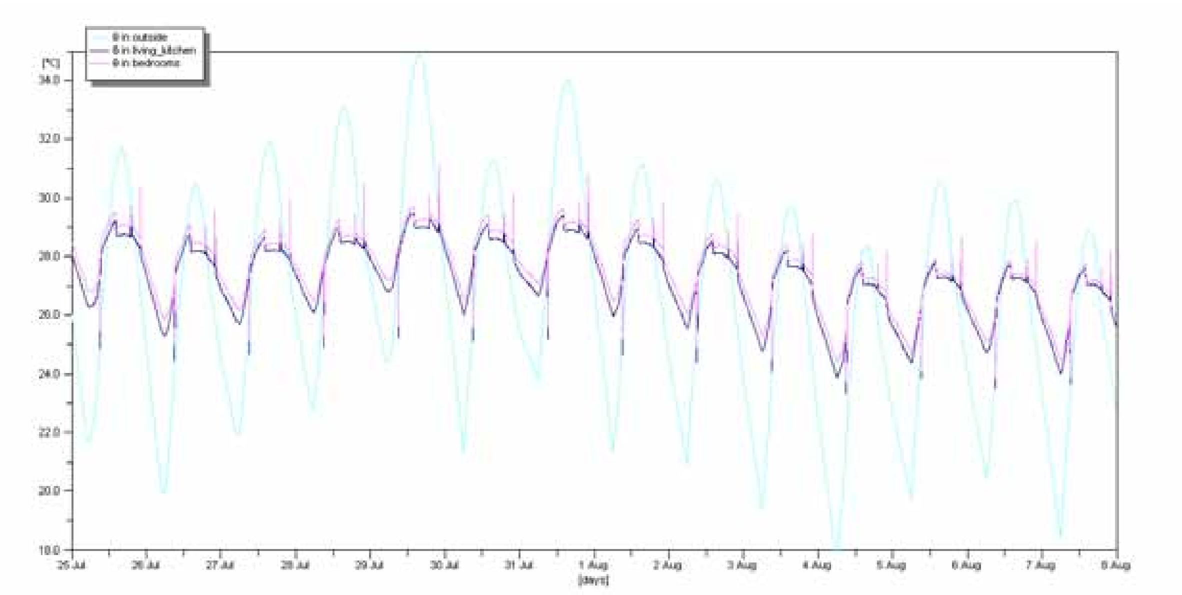


Figure 15: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_A_g68_v4.1_sh4.

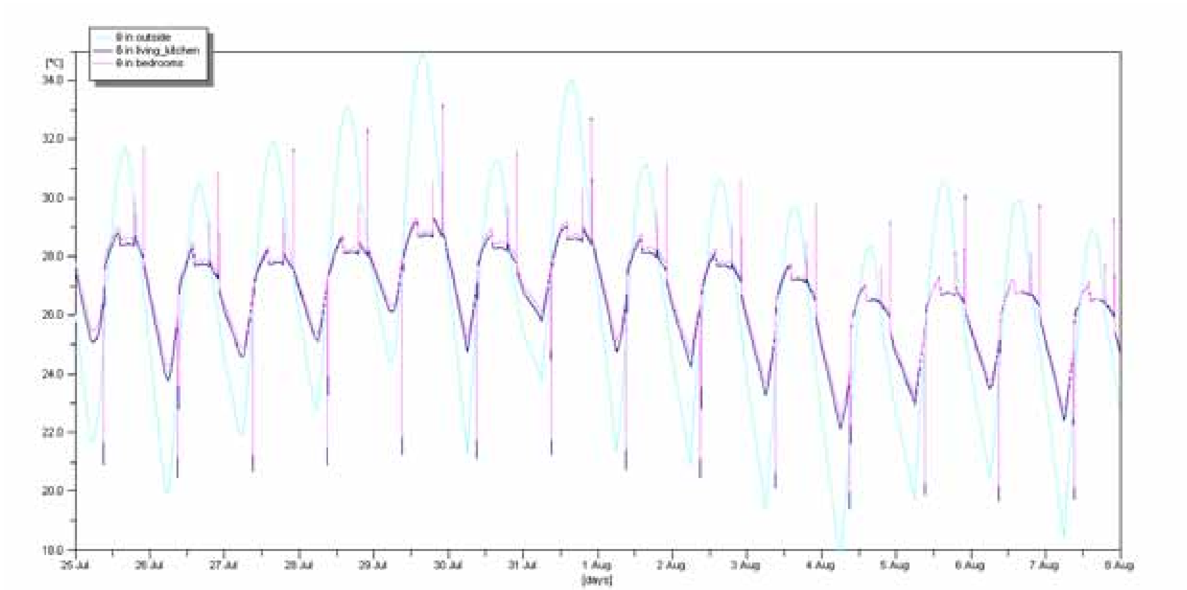


Figure 16: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_A_g68_v5.1_sh4.

Concerning the application of the PCM-wallboard, the results describe the changes in temperature for every month separately. The numerical as well as the graphical results can be observed in the following table and figures.

Table 14: Values of “Degree Days” before and after the application of PCM-wallboard for the ventilation scenarios v4.1 and v5.1.

	April	May	June	July	August	September	SUM	
g68 _ v4.1 _ sh4								
No PCM	0 (0)	0,3 (1)	139,2 (158)	742,6 (543)	813,8 (560)	157,2 (155)	1853,1 (1417)	**10,13**
PCM	0 (0)	0,3 (1)	159 (158)	666,9 (519)	777,6 (545)	176,6 (160)	1780,1 (1394)	**9,73**
g68 _ v5.1 _ sh4								
No PCM	0 (0)	6,7 (9)	137,3 (137)	671 (451)	737,5 (459)	159,6 (127)	1712,1 (1183)	**9,36**
PCM	0 (0)	6,7 (9)	84,7 (116)	524 (403)	660,8 (438)	159,2 (135)	1428,7 (1092)	**7,81**

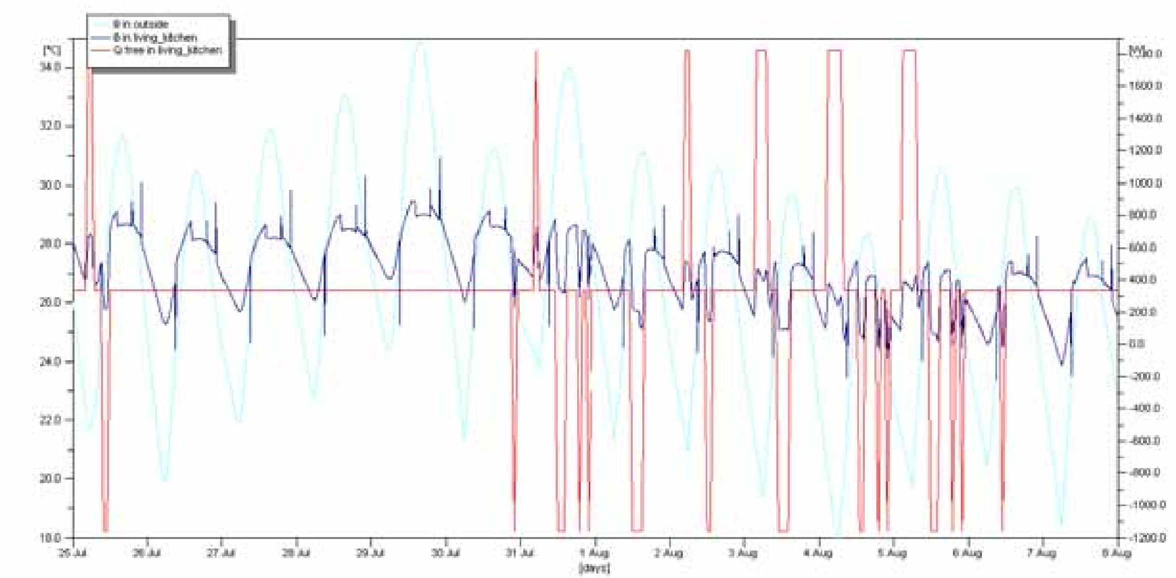


Figure 17: Temperatures in zone living room & kitchen after the application of PCM-wallboard for ventilation v4.1.

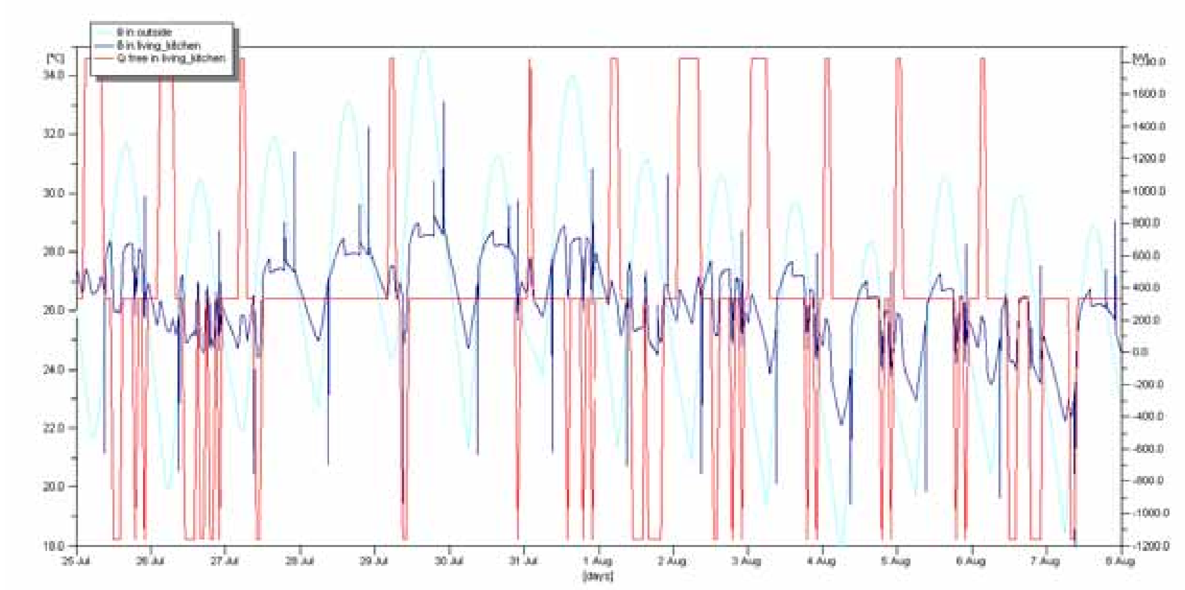


Figure 18: Temperatures in zone living room & kitchen after the application of PCM-wallboard for ventilation v5.1.

3.3. Apartment in Vienna_Austria (Ap_V)

After performing all the simulations and calculations, that were described above, the results of all parametric studies for the apartment in Vienna in terms of the overheating risk are presented in this chapter.

Table 15: Concentrated results in "Degree Days" of parametric studies for the apartment in Vienna (Austria).

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Outside	Living room &kitchen	Bedrooms	Bathroom	WC	Hall	Mean
g20	v1.1	sh1	-	1,35	2,67	1,62	5,30	6,17	4,51	**2,20**
g20	v1.1	sh2	-	1,35	4,77	2,40	6,27	8,28	5,51	**3,70**
g20	v1.1	sh3	-	1,35	1,62	1,25	4,87	5,01	4,01	**1,45**
g20	v1.1	sh4	-	1,35	0,48	0,55	2,83	1,89	2,00	**0,51**
g68	v1.1	sh1	-	1,35	26,70	13,56	14,56	20,77	14,30	**20,77**
g68	v1.1	sh2	-	1,35	8,95	5,40	8,82	11,01	8,09	**7,35**
g68	v1.1	sh3	-	1,35	4,73	2,34	5,53	5,47	4,60	**3,65**
g68	v1.1	sh4	-	1,35	2,23	0,78	3,49	2,56	2,49	**1,58**
g68	v2.1	sh1	-	1,35	18,23	6,86	5,30	10,30	5,37	**13,10**
g68	v2.1	sh2	-	1,35	6,38	3,35	3,16	5,23	2,99	**5,01**
g68	v2.1	sh3	-	1,35	4,42	1,84	2,03	2,72	1,75	**3,26**
g68	v2.1	sh4	-	1,35	1,49	0,36	1,07	0,92	0,80	**0,98**
g68	v4.1	sh1	-	1,35	11,29	2,59	1,35	3,48	1,31	**7,36**
g68	v4.1	sh2	-	1,35	3,94	1,48	0,90	2,05	0,83	**2,83**
g68	v4.1	sh3	-	1,35	3,58	1,03	0,66	1,38	0,57	**2,43**
g68	v4.1	sh4	-	1,35	0,85	0,14	0,32	0,24	0,23	**0,53**
g68	v5.1	sh1	-	1,35	7,50	1,23	0,67	1,35	0,58	**4,67**
g68	v5.1	sh2	-	1,35	2,64	0,87	0,53	0,89	0,45	**1,84**
g68	v5.1	sh3	-	1,35	3,13	0,66	0,45	0,67	0,36	**2,01**
g68	v5.1	sh4	-	1,35	0,65	0,17	0,26	0,14	0,17	**0,43**
g68	v4.1	sh4	PCM	1,35	0,89	-	-	-	-	**0,89**
g68	v5.1	sh4	PCM	1,35	0,63	-	-	-	-	**0,63**

The illustrative presentation of the above listed results is represented in the following figures. We can observe the changes in the indoor temperature of several zones according to the different scenarios and variations of shading and ventilation schemes.

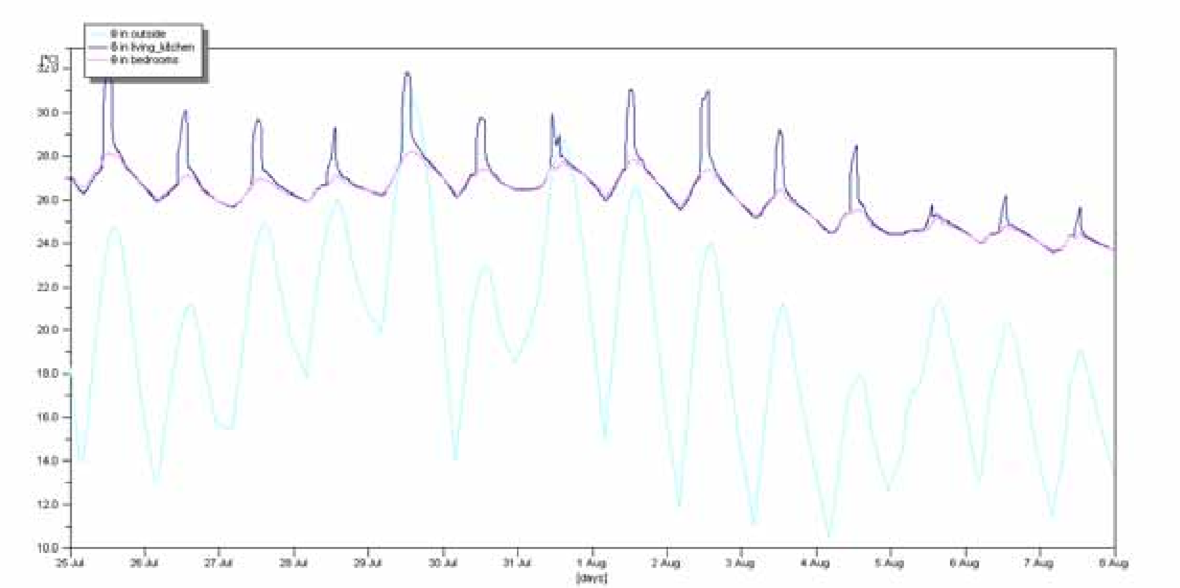


Figure 19: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_V_g68_v1.1_sh4.

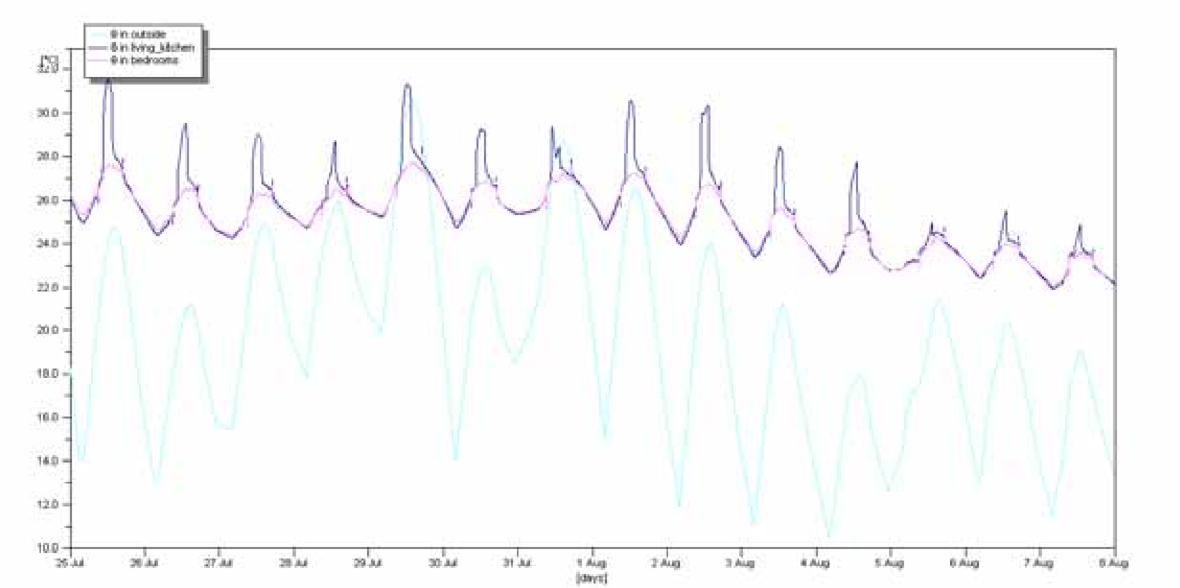


Figure 20: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_V_g68_v2.1_sh4.

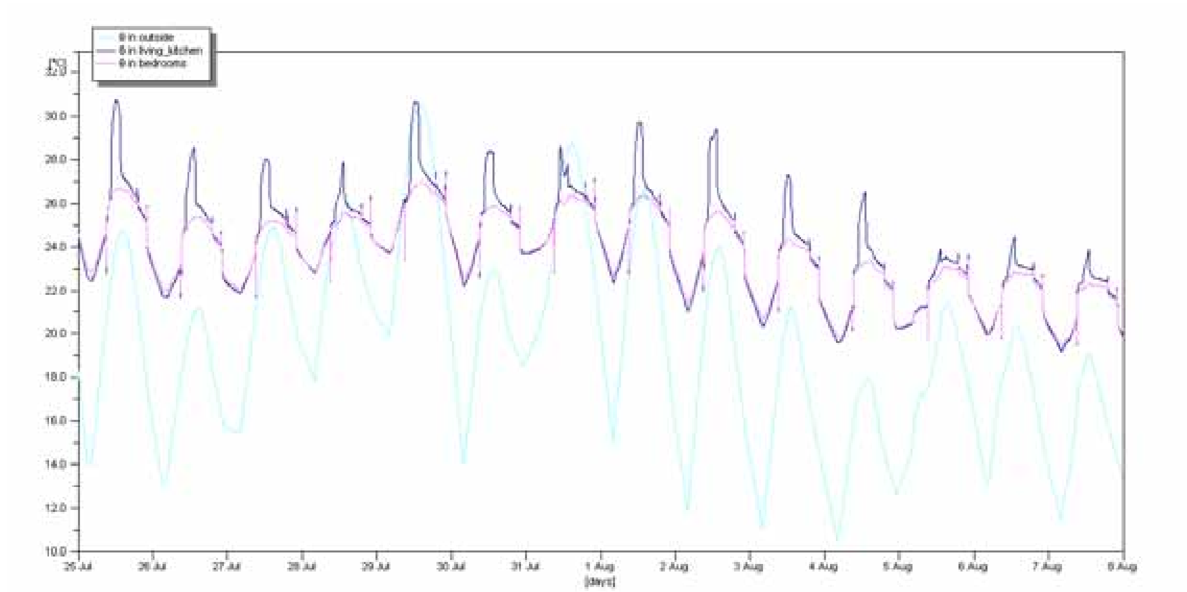


Figure 21: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_V_g68_v4.1_sh4.

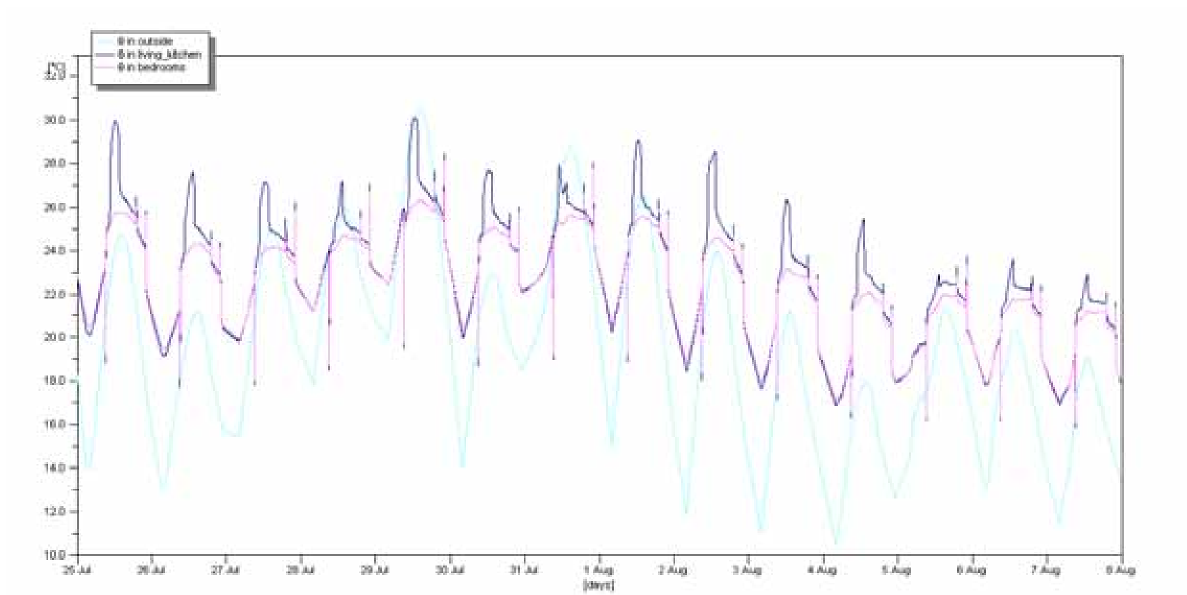


Figure 22: Temperatures in zones living room & kitchen and bedrooms for scenario Ap_V_g68_v5.1_sh4.

Concerning the application of the PCM-wallboard, the results describe the changes in temperature for every month separately. The numerical as well as the graphical results can be observed in the following table and figures.

Table 16: Values of "Degree Days" before and after the application of PCM-wallboard for the ventilation scenarios v4.1 and v5.1.

	April	May	June	July	August	September	SUM	
g68 _ v4.1 _ sh4								
No PCM	0 (0)	1,1 (4)	7,5 (14)	115,5 (91)	31,2 (36)	0 (0)	155,3 (145)	**0,85**
PCM	0 (0)	1,1 (4)	7,5 (14)	121,7 (95)	32,7 (42)	0 (0)	163 (155)	**0,89**
g68 _ v5.1 _ sh4								
No PCM	0 (0)	0 (0)	5,5 (9)	88,4 (74)	25 (23)	0,3 (1)	119,2 (107)	**0,65**
PCM	0 (0)	0 (0)	5,5 (9)	86 (70)	24,3 (23)	0,3 (1)	116,1 (103)	**0,63**

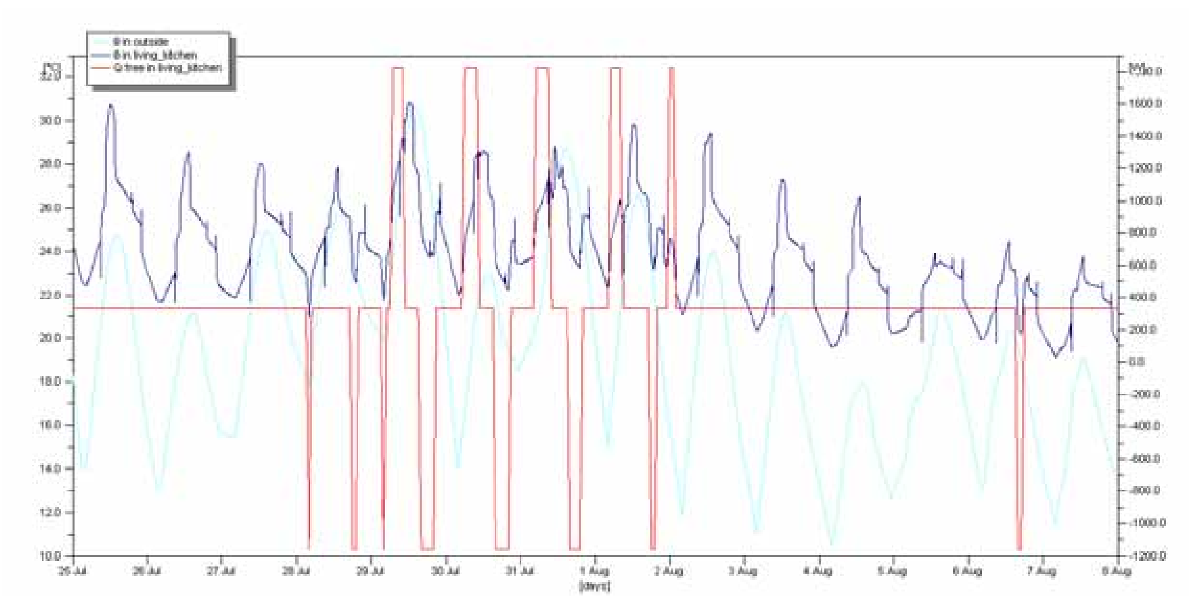


Figure 23: Temperatures in zone living room & kitchen after the application of PCM-wallboard for ventilation v4.1.

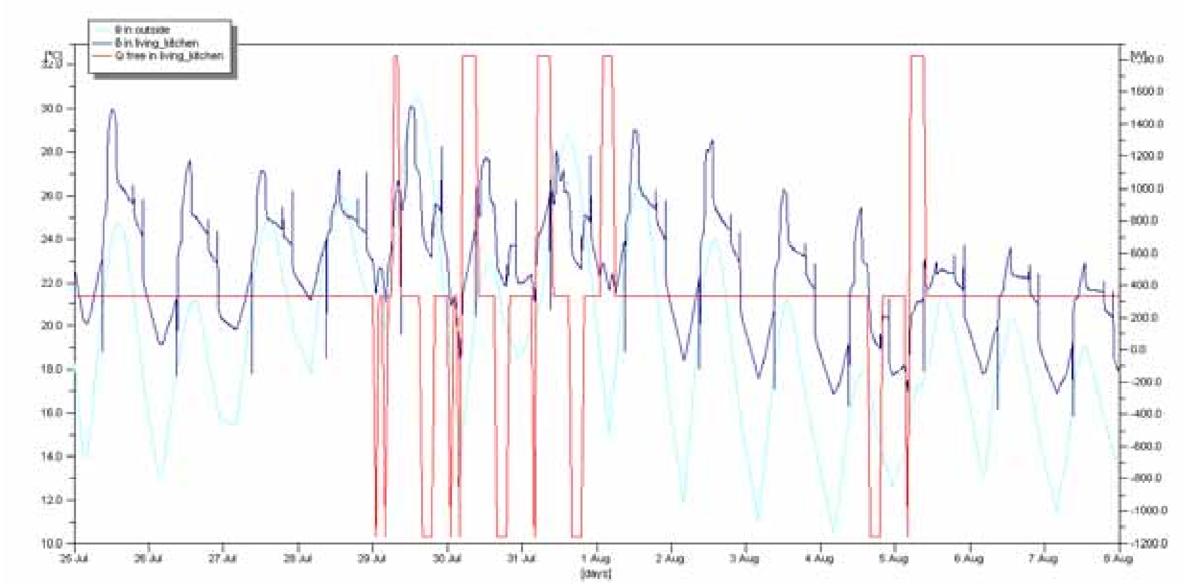


Figure 24: Temperatures in zone living room & kitchen after the application of PCM-wallboard for ventilation v5.1.

3.4. Double-storey single house in Athens_Greece (H_A)

The results of all parametric studies for the single house in Athens in terms of the overheating risk are presented in this chapter.

Table 17a: Concentrated results in “Degree Days” of parametric studies for the single house in Athens (Greece).

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Outside	*Ground floor*			Staircase	*1st floor*	
					Living room &kitchen	WC	Storage room		Bedroom_1	Bedroom_2
g20	v1.1	sh1	-	21,36	0,06	0	8,27	41,30	24,41	24,87
g20	v1.1	sh2	-	21,36	0,12	0	13,31	70,61	30,82	32,69
g20	v1.1	sh3	-	21,36	0,04	0	5,63	20,38	20,08	19,80
g20	v1.1	sh4	-	21,36	0,01	0	3,77	19,33	16,83	18,28
g20	v1.1	sh5	-	21,36	0,01	0	3,89	19,55	17,37	18,56
g68	v1.1	sh1	-	21,36	1,42	0,07	12,47	48,26	45,48	54,13
g68	v1.1	sh2	-	21,36	0,80	0,03	14,64	72,80	33,13	35,54
g68	v1.1	sh3	-	21,36	0,51	0	6,59	21,57	21,80	21,73
g68	v1.1	sh4	-	21,36	0,18	0	4,99	21,75	22,53	23,09
g68	v1.1	sh5	-	21,36	0,20	0	5,44	22,78	24,73	24,24
g68	v2.1	sh1	-	21,36	1,60	0,22	10,05	43,07	37,15	44,92
g68	v2.1	sh2	-	21,36	1,04	0,13	12,06	66,53	26,76	29,36
g68	v2.1	sh3	-	21,36	0,69	0,05	5,86	19,86	17,97	18,82
g68	v2.1	sh4	-	21,36	0,37	0,04	4,53	20	18,38	19,29
g68	v2.1	sh5	-	21,36	0,38	0,05	4,85	20,70	20,01	20,09
g68	v4.1	sh1	-	21,36	1,72	0,40	6,15	35,55	25,70	32,50
g68	v4.1	sh2	-	21,36	1,36	0,32	7,54	56,70	17,97	20,97
g68	v4.1	sh3	-	21,36	1,08	0,23	0,04	16,54	12,30	14,56
g68	v4.1	sh4	-	21,36	0,80	0,18	3,02	16,54	11,98	13,40
g68	v4.1	sh5	-	21,36	0,82	0,19	3,17	17,02	12,96	13,87
g68	v5.1	sh1	-	21,36	3,59	1,41	5,43	32,63	20,97	26,59
g68	v5.1	sh2	-	21,36	3,32	1,33	6,40	52,07	15,10	17,87
g68	v5.1	sh3	-	21,36	3,05	1,19	4,22	16,15	11,09	13,87
g68	v5.1	sh4	-	21,36	2,75	1,06	3,61	16,08	10,49	11,90
g68	v5.1	sh5	-	21,36	1,79	1,08	3,69	16,38	11,10	12,20
g68	v4.1	sh4	PCM	21,36	-	-	-	-	-	12,26
g68	v5.1	sh4	PCM	21,36	-	-	-	-	-	10,33

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Outside	1st floor					
					Bedroom_3	Bathroom_1	Bathroom_2	Storage room	Hall	Mean
g20	v1.1	sh1	-	21,36	31,58	32,90	43,13	45,36	24,33	**10,83**
g20	v1.1	sh2	-	21,36	40,74	38,39	56,25	54,70	31,44	**14**
g20	v1.1	sh3	-	21,36	25,76	29,49	34,86	39,79	19,67	**8,78**
g20	v1.1	sh4	-	21,36	24,22	27,35	35,62	34,92	16,55	**7,93**
g20	v1.1	sh5	-	21,36	25,52	27,93	36,14	35,65	18,85	**8,22**
g68	v1.1	sh1	-	21,36	63	50,17	73	55,80	43,48	**22,58**
g68	v1.1	sh2	-	21,36	43,65	40,97	60	57,27	33,60	**15,50**
g68	v1.1	sh3	-	21,36	27,54	31,16	37,28	41,57	21,30	**7,22**
g68	v1.1	sh4	-	21,36	29,96	32,53	53,88	38,04	20,46	**10,20**
g68	v1.1	sh5	-	21,36	31,12	34,76	56,15	40,86	30,30	**10,81**
g68	v2.1	sh1	-	21,36	52,52	39,79	61,11	45,87	35,11	**18,95**
g68	v2.1	sh2	-	21,36	36,16	32,95	49,92	47,52	26,93	**12,95**
g68	v2.1	sh3	-	21,36	23,51	25,86	31,79	35,51	17,39	**8,47**
g68	v2.1	sh4	-	21,36	25,03	27,01	46,76	32,36	16,32	**8,60**
g68	v2.1	sh5	-	21,36	25,87	28,78	48,51	34,66	25,14	**9**
g68	v4.1	sh1	-	21,36	38,30	25,90	44,66	32,05	23,56	**13,94**
g68	v4.1	sh2	-	21,36	25,88	21,39	35,56	33,44	17,50	**9,48**
g68	v4.1	sh3	-	21,36	18	17,22	22,56	25,37	11,46	**6,65**
g68	v4.1	sh4	-	21,36	17,57	17,63	35,14	22,57	10,08	**6,22**
g68	v4.1	sh5	-	21,36	18,11	18,79	36,40	24,32	17,24	**6,50**
g68	v5.1	sh1	-	21,36	30,94	18,57	34,90	22,94	18,62	**12,65**
g68	v5.1	sh2	-	21,36	21,58	15,82	27,36	24,19	14,09	**9,28**
g68	v5.1	sh3	-	21,36	16,48	13,41	18,26	18,83	10,08	**7,37**
g68	v5.1	sh4	-	21,36	15	13,55	28,85	16,72	8,73	**6,65**
g68	v5.1	sh5	-	21,36	15,31	14,27	29,70	17,85	14,67	**6,23**
g68	v4.1	sh4	PCM	21,36	-	-	-	-	-	**12,26**
g68	v5.1	sh4	PCM	21,36	-	-	-	-	-	**10,33**

Table 17b: Concentrated results in “Degree Days” of parametric studies for the single house in Athens (Greece).

The illustrative presentation of the above listed results is represented in the following figures. We can observe the changes in the indoor temperature of several zones according to the different scenarios and variations of shading and ventilation schemes.

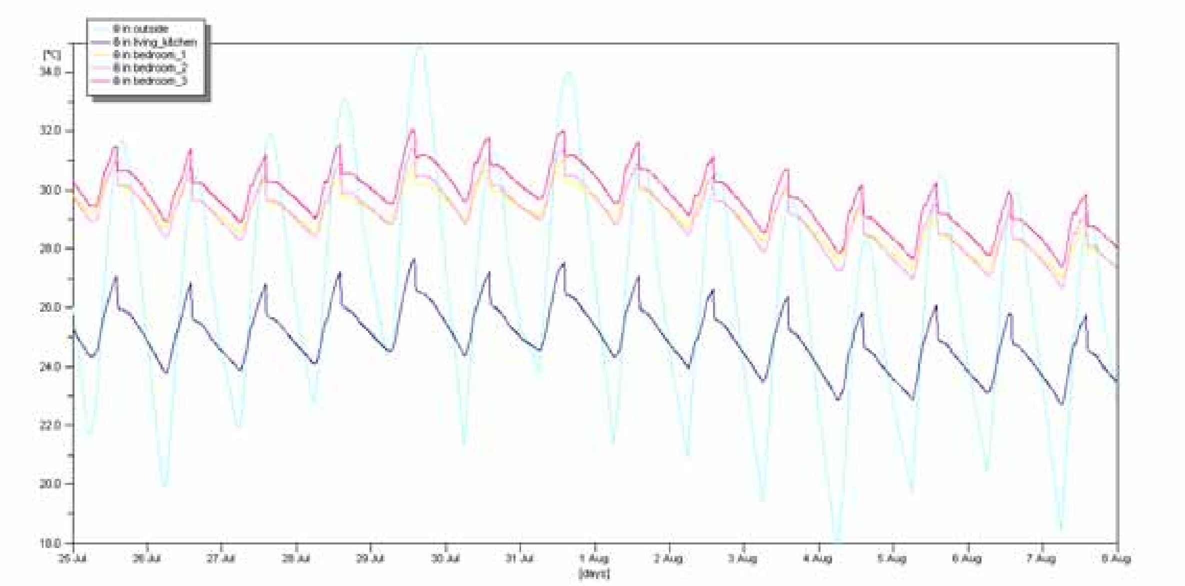


Figure 25: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_A_g68_v2.1_sh4.

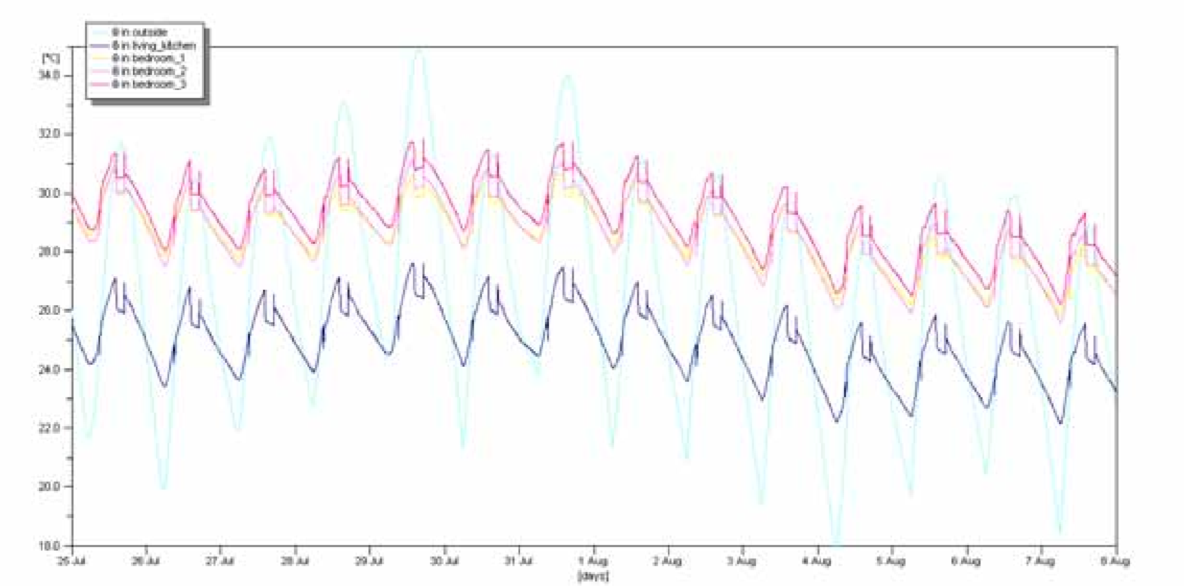


Figure 26: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_A_g68_v1.1_sh4.

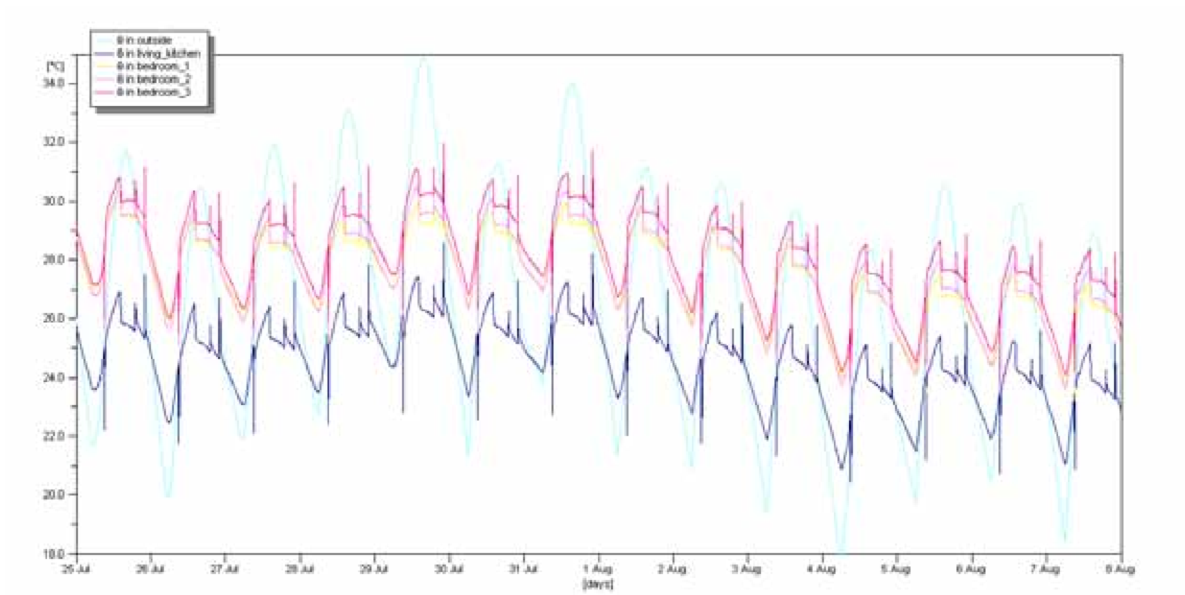


Figure 27: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_A_g68_v4.1_sh4.

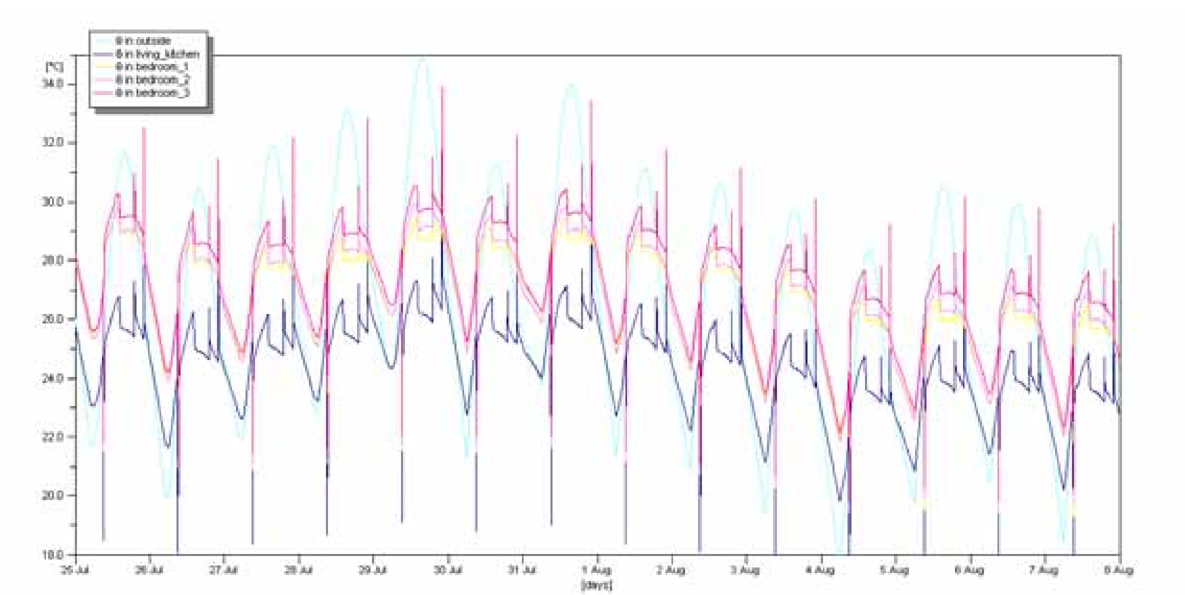
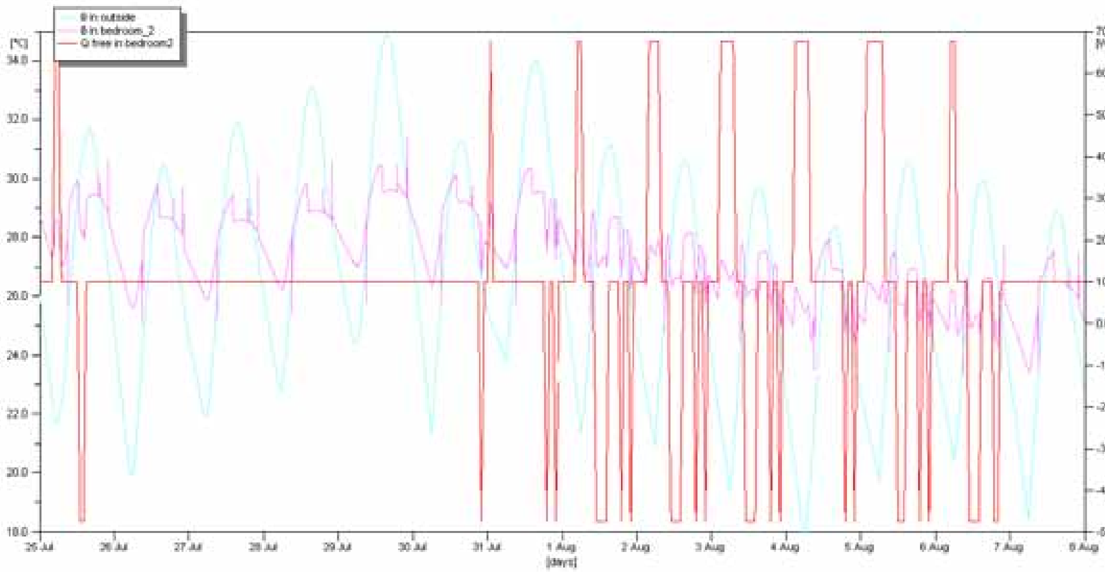


Figure 28: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_A_g68_v5.1_sh4.

Concerning the application of the PCM-wallboard, the results describe the changes in temperature for every month separately. The numerical as well as the graphical results can be observed in the following table and figures.

Table 18: Values of “Degree Days” before and after the application of PCM-wallboard for the ventilation scenarios v4.1 and v5.1.

	April	May	June	July	August	September	SUM	
g68 _ v4.1 _ sh4								
No PCM	0 (0)	0 (0)	133,6 (140)	957,7 (536)	1137,1 (556)	222,6 (153)	2451 (1385)	**13,40**
PCM	0 (0)	0 (0)	112,5 (133)	824 (486)	1089,3 (547)	218,6 (150)	2244,4 (1316)	**12,26**
g68 _ v5.1 _ sh4								
No PCM	0 (0)	4,1 (8)	138 (118)	839,5 (439)	985,1 (465)	211,5 (128)	2178,2 (1157)	**11,90**
PCM	0 (0)	4,1 (8)	100,6 (112)	661,5 (381)	923,6 (454)	204,1 (128)	1889,8 (1076)	**10,33**



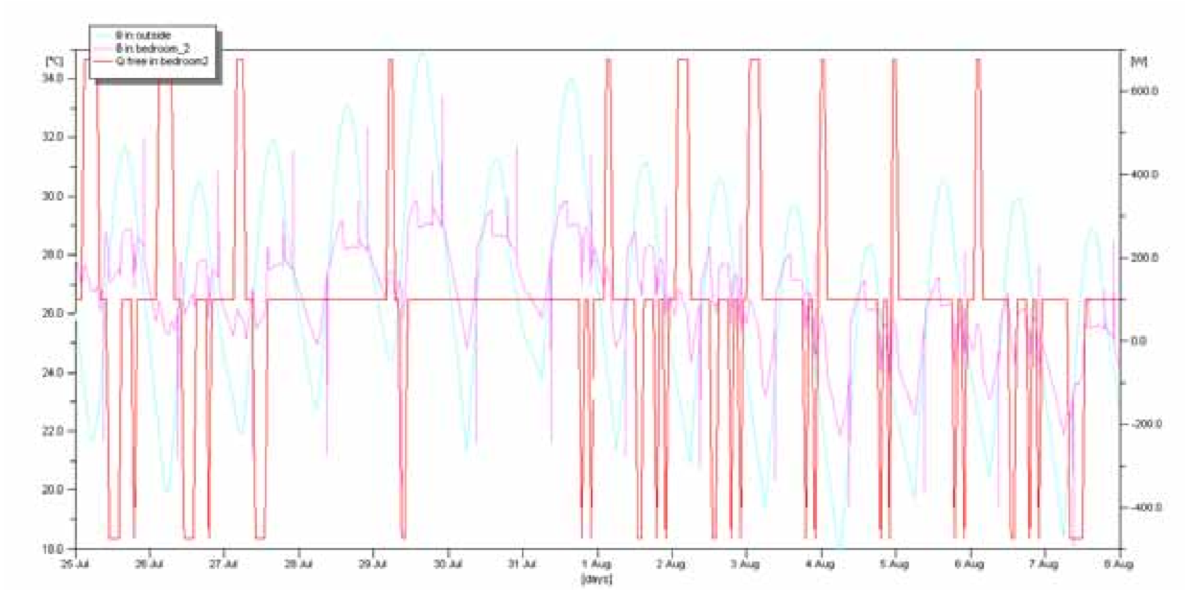


Figure 30: Temperatures in zone bedroom_2 after the application of PCM-wallboard for ventilation v5.1.

3.5. Double-storey single house in Vienna_Austria (H_A)

The results of all parametric studies for the single house in Vienna in terms of the overheating risk are presented in this chapter.

Table 19a: Concentrated results in "Degree Days" of parametric studies for the single house in Vienna(Austria).

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Outside	Ground floor			Staircase	1st floor	
					Living room &kitchen	WC	Storage room		Bedroom_1	Bedroom_2
g20	v1.1	sh1	-	1,35	0	0	0	0,04	0,04	1,69
g20	v1.1	sh2	-	1,35	0	0	0	0,04	0,06	3,93
g20	v1.1	sh3	-	1,35	0	0	0	0,03	0,04	0,67
g20	v1.1	sh4	-	1,35	0	0	0	0,01	0	0,19
g20	v1.1	sh5	-	1,35	0	0	0	0,01	0	0,15
g68	v1.1	sh1	-	1,35	1,08	0	0	0,32	6,43	42,44
g68	v1.1	sh2	-	1,35	0,38	0	0	0,24	1,62	13,36
g68	v1.1	sh3	-	1,35	0,65	0	0	0,09	0,90	11,89
g68	v1.1	sh4	-	1,35	0,61	0	0	0,09	1,44	4,64
g68	v1.1	sh5	-	1,35	0,46	0	0	0,08	1,47	3,72
g68	v2.1	sh1	-	1,35	0,78	0	0	0,19	2,64	30,66
g68	v2.1	sh2	-	1,35	0,36	0	0	0,11	0,85	10,57
g68	v2.1	sh3	-	1,35	0,53	0	0	0,10	0,69	10,30
g68	v2.1	sh4	-	1,35	0,47	0	0	0,07	0,55	3,51
g68	v2.1	sh5	-	1,35	0,36	0	0	0,06	0,57	2,80
g68	v4.1	sh1	-	1,35	0,49	0	0	0,05	0,72	20,58
g68	v4.1	sh2	-	1,35	0,28	0	0	0,03	0,35	7,81
g68	v4.1	sh3	-	1,35	0,38	0	0	0,03	0,27	7,97
g68	v4.1	sh4	-	1,35	0,32	0	0	0,01	0,14	2,36
g68	v4.1	sh5	-	1,35	0,23	0	0	0,01	0,15	1,82
g68	v5.1	sh1	-	1,35	0,46	0,01	0,02	0,15	0,50	14,84
g68	v5.1	sh2	-	1,35	0,33	0,01	0,01	0,14	0,34	6,17
g68	v5.1	sh3	-	1,35	0,37	0,01	0,01	0,13	0,35	7,94
g68	v5.1	sh4	-	1,35	0,32	0	0,01	0,11	0,21	1,83
g68	v5.1	sh5	-	1,35	0,25	0	0,01	0,11	0,22	1,42
g68	v4.1	sh4	PCM	1,35	-	-	-	-	-	2,41
g68	v5.1	sh4	PCM	1,35	-	-	-	-	-	2

Table 19b: Concentrated results in "Degree Days" of parametric studies for the single house in Vienna (Austria).

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Outside	*1st floor*					
					Bedroom_3	Bathroom_1	Bathroom_2	Storage room	Hall	Mean
g20	v1.1	sh1	-	1,35	2	0,68	0,33	0,07	0	**0,51**
g20	v1.1	sh2	-	1,35	4,55	1,40	0,79	0,10	0,01	**1,16**
g20	v1.1	sh3	-	1,35	0,82	0,43	0,21	0,06	0	**0,21**
g20	v1.1	sh4	-	1,35	0,25	0,11	0,05	0	0	**0,06**
g20	v1.1	sh5	-	1,35	0,20	0,11	0,05	0	0	**0,05**
g68	v1.1	sh1	-	1,35	44,25	12,38	7,19	1,74	2,85	**13,23**
g68	v1.1	sh2	-	1,35	14,14	4,28	0,83	0,72	0,56	**4,16**
g68	v1.1	sh3	-	1,35	11,69	1,70	0,85	0,39	0,20	**3,70**
g68	v1.1	sh4	-	1,35	4,95	2,62	1,42	0,10	0,06	**1,85**
g68	v1.1	sh5	-	1,35	3,98	2,47	1,27	0,14	0,20	**1,51**
g68	v2.1	sh1	-	1,35	32,08	4,62	2,82	0,38	0,89	**9,31**
g68	v2.1	sh2	-	1,35	10,85	1,68	0,99	0,17	0,25	**3,23**
g68	v2.1	sh3	-	1,35	10,49	0,84	0,48	0,13	0,14	**3,23**
g68	v2.1	sh4	-	1,35	3,75	0,96	0,53	0,01	0,03	**1,34**
g68	v2.1	sh5	-	1,35	3	0,89	0,48	0,02	0,07	**1,08**
g68	v4.1	sh1	-	1,35	21,71	1,21	0,85	0,06	0,22	**6,12**
g68	v4.1	sh2	-	1,35	8,29	0,56	0,39	0,04	0,10	**2,40**
g68	v4.1	sh3	-	1,35	9,75	0,36	0,25	0,04	0,06	**2,67**
g68	v4.1	sh4	-	1,35	2,56	0,23	0,18	0,01	0,02	**0,88**
g68	v4.1	sh5	-	1,35	1,98	0,22	0,17	0,01	0,03	**0,67**
g68	v5.1	sh1	-	1,35	15,77	0,68	0,55	0,12	0,24	**4,50**
g68	v5.1	sh2	-	1,35	6,34	0,45	0,38	0,11	0,20	**1,94**
g68	v5.1	sh3	-	1,35	8,40	0,36	0,31	0,10	0,19	**2,48**
g68	v5.1	sh4	-	1,35	2	0,23	0,22	0,07	0,14	**0,73**
g68	v5.1	sh5	-	1,35	1,56	0,23	0,21	0,07	0,15	**0,58**
g68	v4.1	sh4	PCM	1,35	-	-	-	-	-	**2,41**
g68	v5.1	sh4	PCM	1,35	-	-	-	-	-	**2**

The illustrative presentation of the above listed results is represented in the following figures. We can observe the changes in the indoor temperature of several zones according to the different scenarios and variations of shading and ventilation schemes.

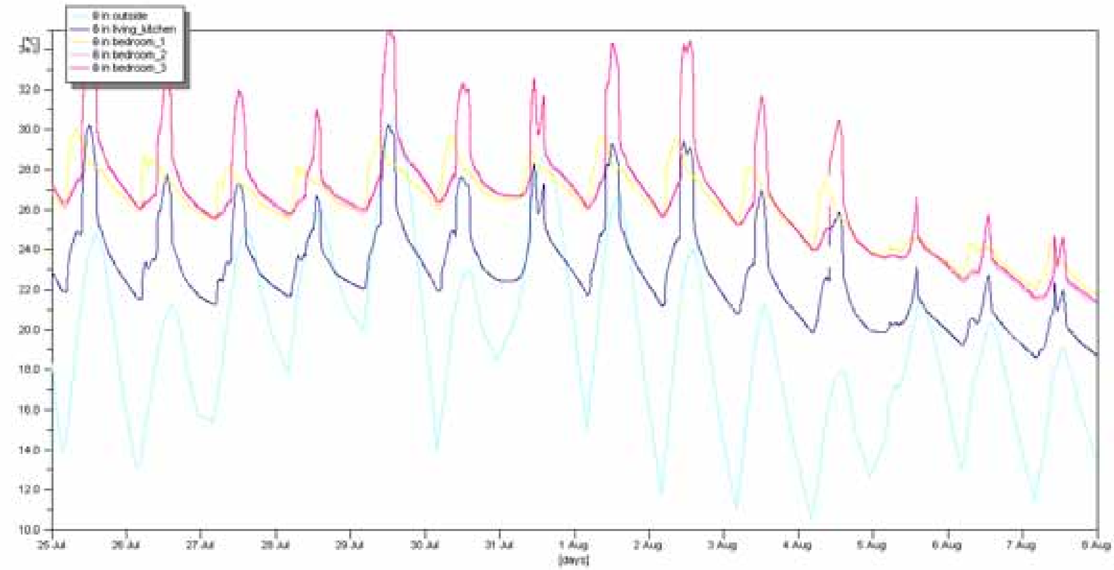


Figure 31: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_V_g68_v1.1_sh4.

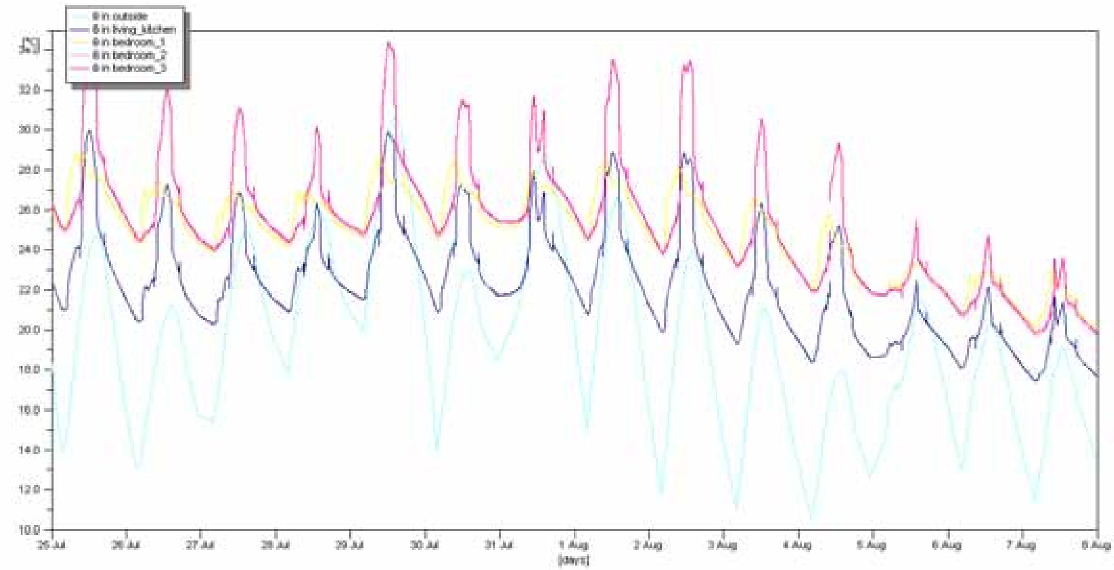


Figure 32: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_V_g68_v2.1_sh4.

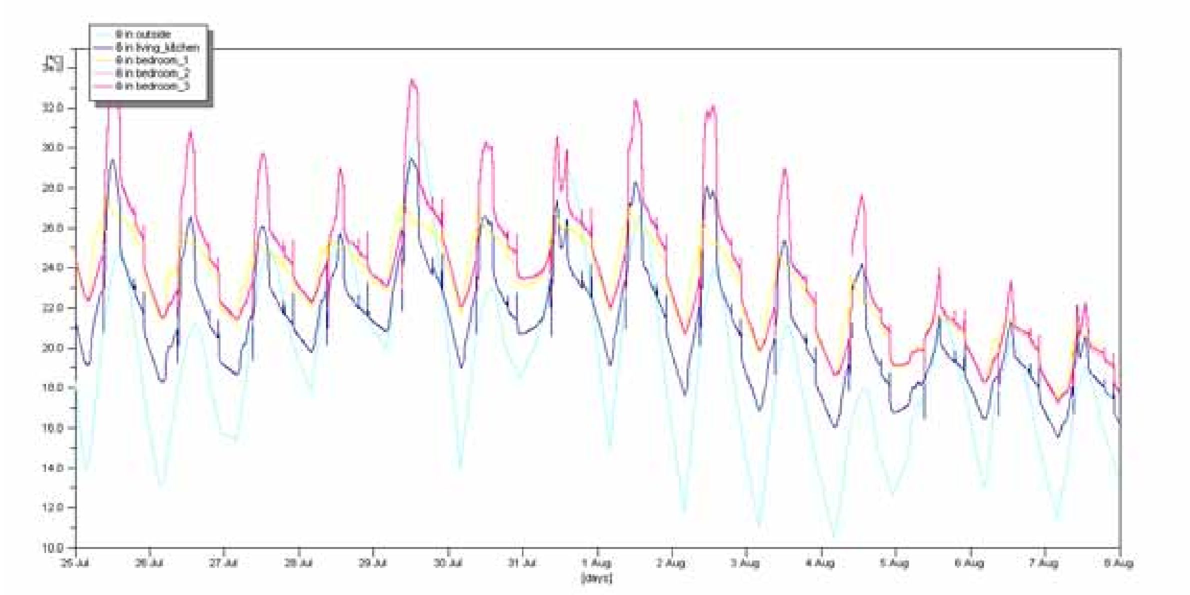


Figure 33: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_V_g68_v4.1_sh4.

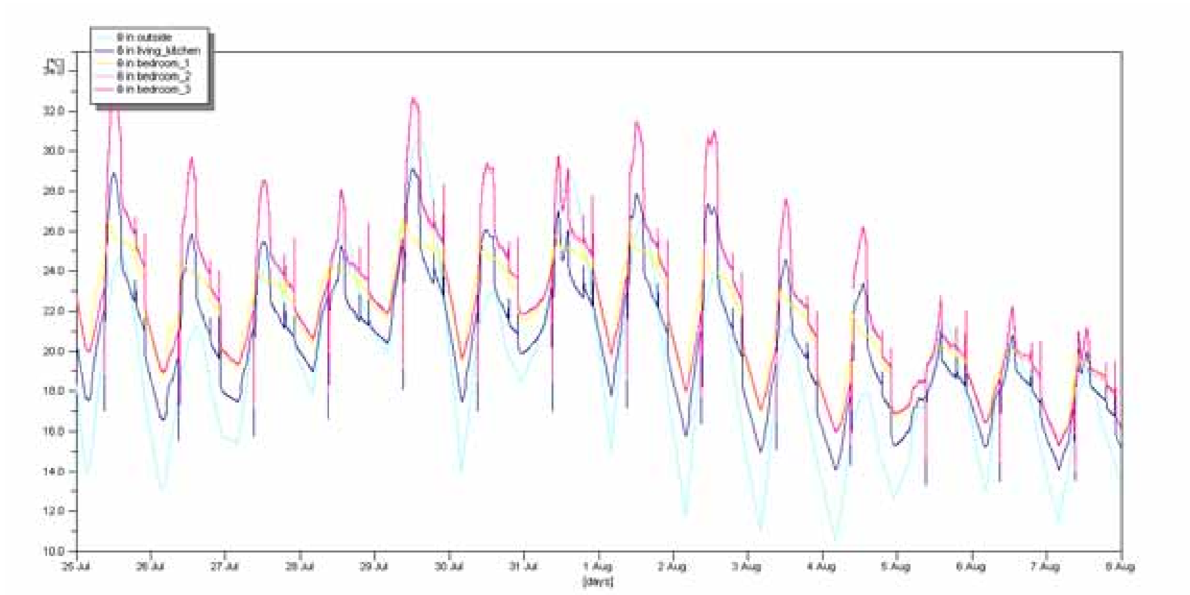


Figure 34: Temperatures in zones living room & kitchen, bedrooms 1,2 and 3 for scenario H_V_g68_v5.1_sh4.

Concerning the application of the PCM-wallboard, the results describe the changes in temperature for every month separately. The numerical as well as the graphical results can be observed in the following table and figures.

Table 20: Values of "Degree Days" before and after the application of PCM-wallboard for the ventilation scenarios v4.1 and v5.1.

	April	May	June	July	August	September	SUM	
g68 _ v4.1 _ sh4								
No PCM	0 (0)	1,7 (4)	15,6 (19)	244,2 (101)	170,4 (75)	0 (0)	431,9 (199)	**2,36**
PCM	0 (0)	1,7 (4)	15,6 (19)	249,7 (96)	173,9 (72)	0 (0)	440,9 (191)	**2,41**
g68 _ v5.1 _ sh4								
No PCM	0 (0)	0 (0)	8,5 (11)	194,5 (92)	131,9 (61)	0 (0)	334,9 (164)	**1,83**
PCM	0 (0)	0 (0)	8,5 (11)	212,8 (86)	145,2 (63)	0 (0)	366,5 (160)	**2**

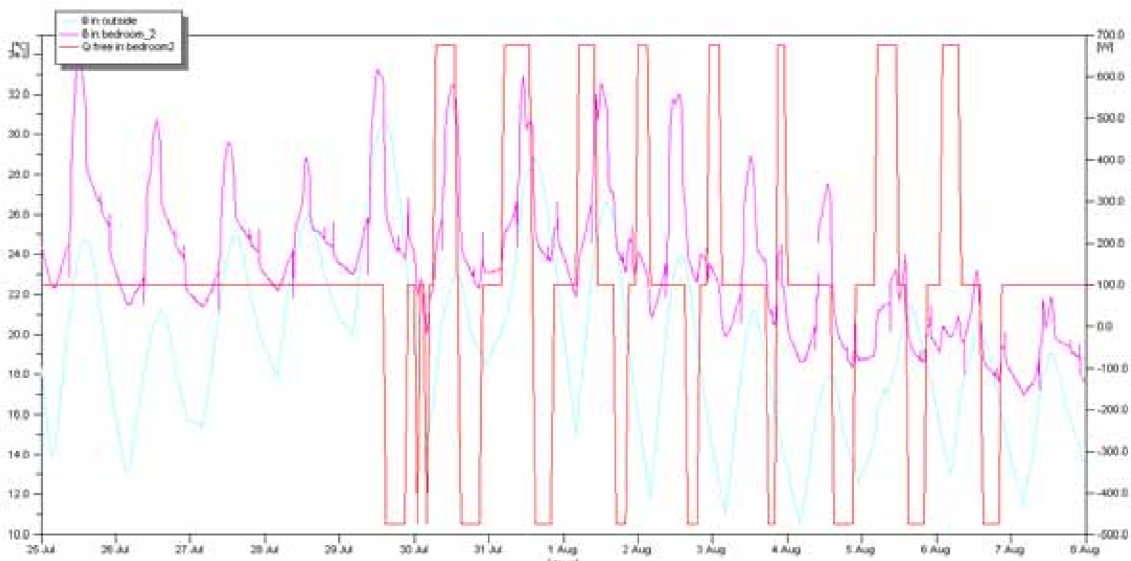


Figure 35: Temperatures in zone bedroom_2 after the application of PCM-wallboard for ventilation v4.1.

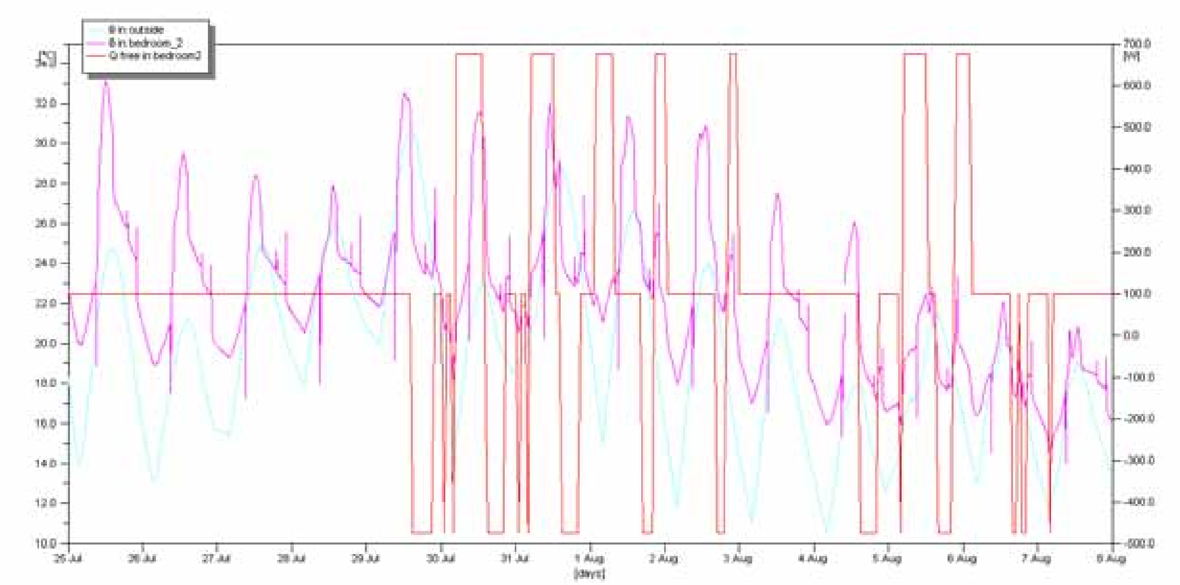


Figure 36: Temperatures in zone bedroom_2 after the application of PCM-wallboard for ventilation v5.1.

3.5. Concentrated results for all four cases

Table 21: Concentrated results for all parametric studies in terms of the average value of overheating for every project.

Glazing scenarios	Ventilation scenarios	Shading scenarios	PCM	Ap_A	Ap_V	H_A	H_V
g20	v1.1	sh1	-	26,10	2,20	10,83	0,51
g20	v1.1	sh2	-	33,68	3,70	14	1,16
g20	v1.1	sh3	-	20,92	1,45	8,78	0,21
g20	v1.1	sh4	-	17,47	0,51	7,93	0,06
g20	v1.1	sh5	-	-	-	8,22	0,05
g68	v1.1	sh1	-	53,96	20,77	22,58	13,23
g68	v1.1	sh2	-	34,74	7,35	15,50	4,16
g68	v1.1	sh3	-	21,45	3,65	7,22	3,70
g68	v1.1	sh4	-	19,16	1,58	10,20	1,85
g68	v1.1	sh5		-	-	10,81	1,51
g68	v2.1	sh1	-	45,47	13,10	18,95	9,31
g68	v2.1	sh2	-	29,14	5,01	12,95	3,23
g68	v2.1	sh3	-	18,24	3,26	8,47	3,23
g68	v2.1	sh4	-	15,75	0,98	8,60	1,34
g68	v2.1	sh5	-	-	-	9	1,08
g68	v4.1	sh1	-	34,56	7,36	13,94	6,12
g68	v4.1	sh2	-	21,75	2,83	9,48	2,40
g68	v4.1	sh3	-	14,02	2,43	6,65	2,67
g68	v4.1	sh4	-	10,96	0,53	6,22	0,88
g68	v4.1	sh5		-	-	6,50	0,67
g68	v5.1	sh1	-	28,81	4,67	12,65	4,50
g68	v5.1	sh2	-	18,44	1,84	9,28	1,94
g68	v5.1	sh3	-	12,47	2,01	7,37	2,48
g68	v5.1	sh4	-	9,62	0,43	6,65	0,73
g68	v5.1	sh5	-	-	-	6,23	0,58
g68	v4.1	sh4	PCM	9,73	0,89	12,26	2,41
g68	v5.1	sh4	PCM	7,81	0,63	10,33	2

4. Discussion

4.1 Glazing

As already mentioned the glazing study was conducted only for the standard air exchange rate of 1 h^{-1} and for all shading schemes. Focusing on the living room, the kitchen and the bedrooms (spaces with openings) the overheating risk in the two glazing scenarios is formed as follow:

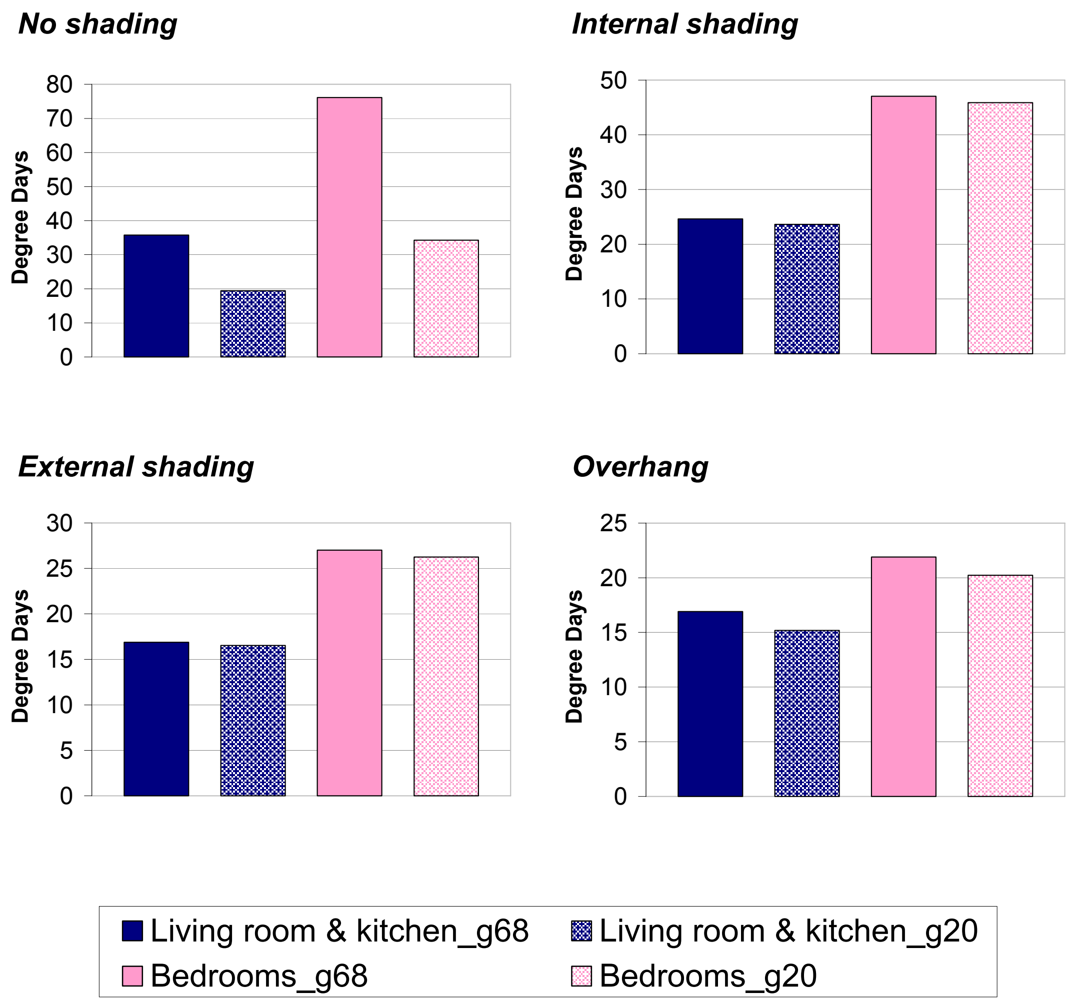


Figure 37: Apartment in Athens: Comparison between the glazing scenarios for different shading schemes. Air exchange rate: 1 h^{-1}.

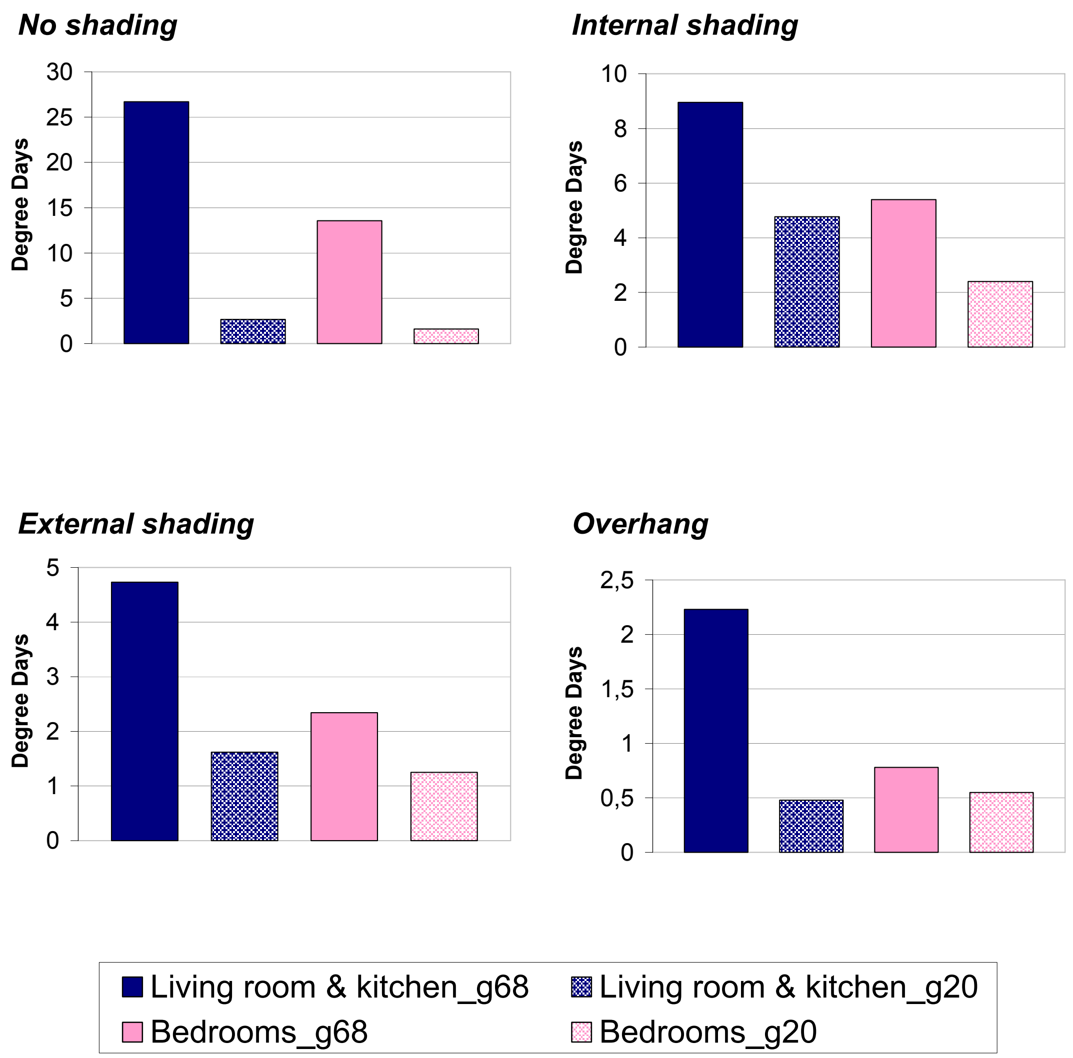


Figure 38: Apartment in Vienna: Comparison between the glazing scenarios for different shading schemes. Air exchange rate: 1 h-1.

It is implied that glazing with a g-value of 20% reduces the overheating risk in all the above cases in comparison to the standard glazing (g-value 68%). By comparing the results between Athens and Vienna, one can notice that the reduction of overheating due to different glazing is very limited in

Athens. Besides the scenario of no shading at all, where the reduction is about the half of the initial values, in all other shading scenarios the overheating risk remains almost the same. On the other hand in Vienna, low g-value leads to a spectacular reduction of overheating for all shadings. These observations between Athens and Vienna are confirmed by the single house project too.

Since the simulations were carried out for the period April till September it was expected that lower g-value would protect from solar heat impact. The question raised is if the use of such a material is advantageous even during winter. A low g-value can reduce the passive using of solar energy in winter. However if it is a combined with a low U-value (value for energy transfer) it could be useful even during the winter.

4.2. Shading

The shading schemes that were studied are: i) no shading, ii) internal shading, iii) fixed external shading, iv) overhang and in the case of the single house the possibility of v) overhangs in combination with vertical external elements.

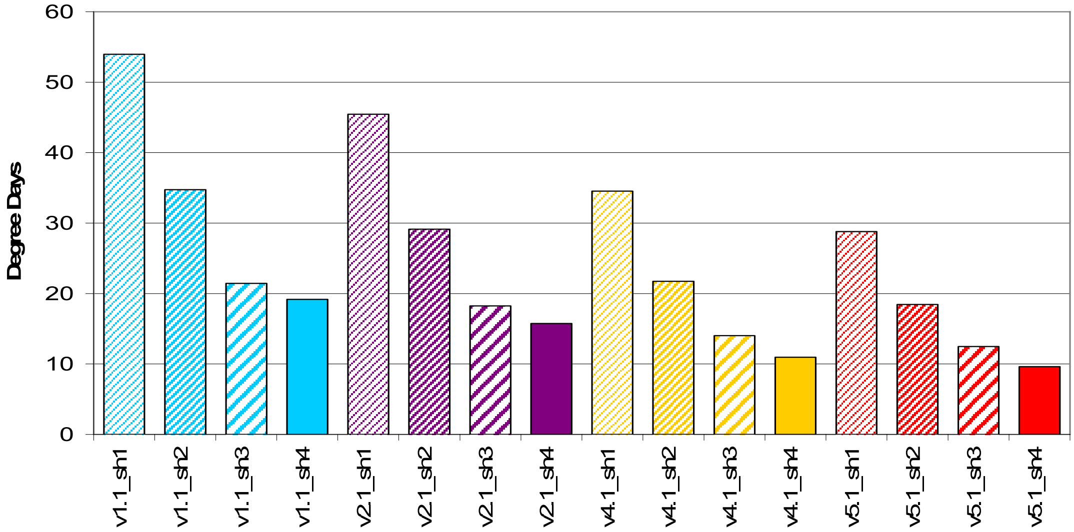


Figure 39: Effectiveness of various shading schemes in different ventilation scenarios: Apartment in Athens (Greece).

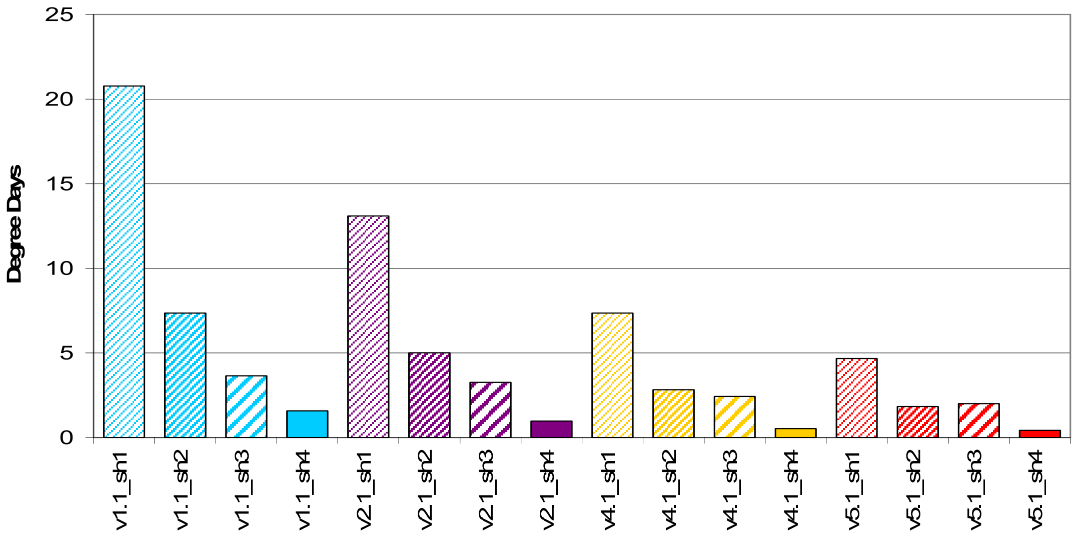


Figure 40: Effectiveness of various shading schemes in different ventilation scenarios: Apartment in Vienna (Austria).

Studying the results for the apartment in both locations, one could safely say that the use of overhangs is the most effective shading scenario. It is also worth mentioning that the scale from the least to the most effective shading solution follows exactly the same order in all cases:

No shading → Internal shading → External shading → Overhang

Even if the conclusions regarding different shading methods are qualitative equal in Athens and Vienna, there is a quantitative difference. The percentage of overheating reduction during the transition from one method to the next is much higher in Vienna. In Athens the initial overheating value was reduced by 36% in case of internal shading and by 65% in case of overhang. In Vienna on the other hand the same reduction rates were 65% and 92% respectively.

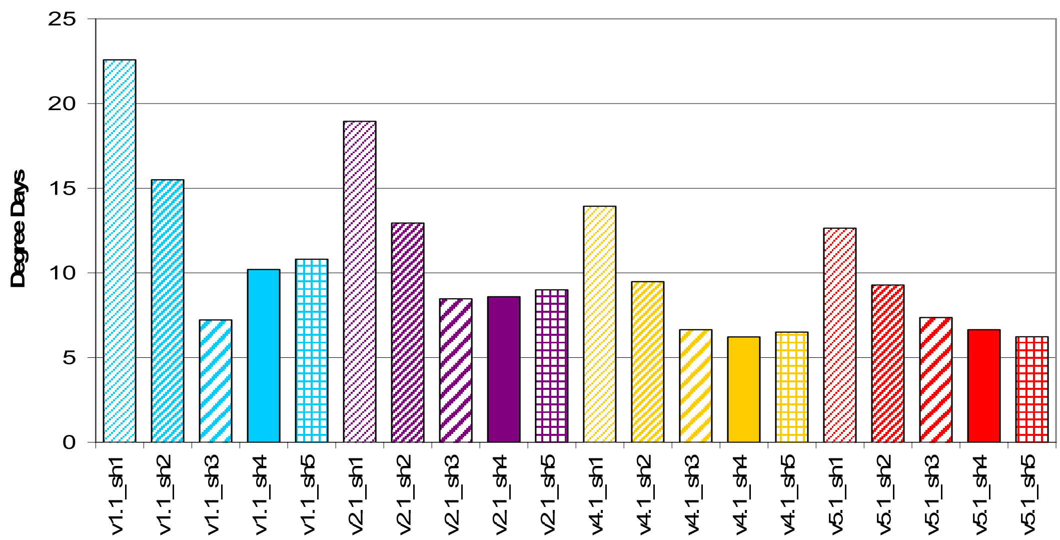


Figure 41: Effectiveness of various shading schemes in different ventilation scenarios: Double-storey single house in Athens (Greece).

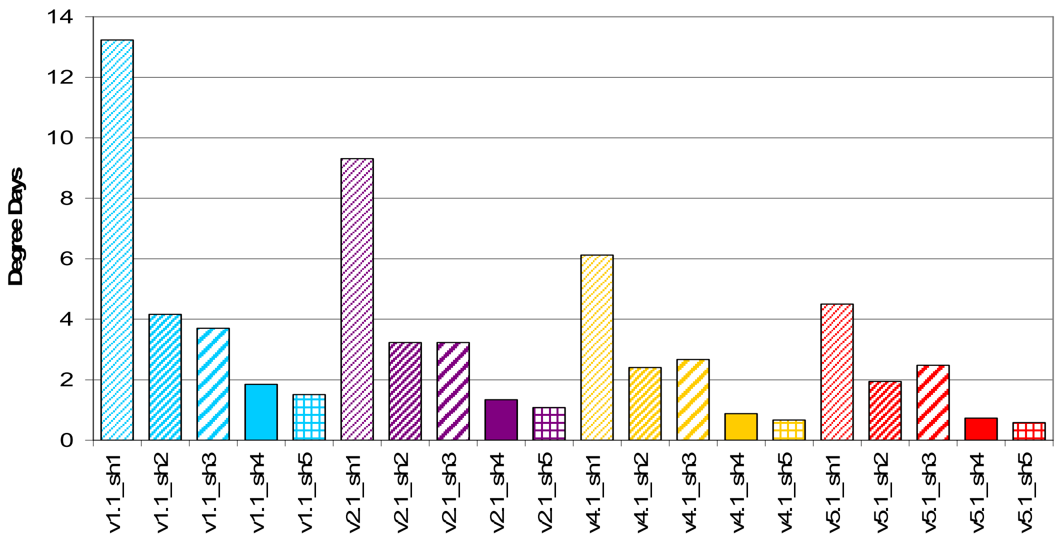


Figure 42: Effectiveness of various shading schemes in different ventilation scenarios: Double-storey single house in Vienna (Austria).

In case of the single house, the results are more complicated. When the house is located in Athens the most effective shading option is the external for low air exchange rates (scenarios v1.1 and v2.1) and the overhangs for the higher ones. In Vienna the most effective is always the combination of overhangs and vertical elements. Again the reduction rates are higher in Vienna in comparison to Athens.

To sum up, one could say that the application of overhangs is the most effective solution in order to achieve a significant reduction of overheating risk. On the other hand external and internal shading devices are easier installed and more adjustable.

From an energy-rejection point of view, the external shading devices are by far the most effective. But for a number of practical reasons, the internal devices, such as curtains, roller shades, Venetian blinds and shutters are also very important. They are often less expensive and also very adjustable and movable, which enables them to easily respond to changing requirements. Besides shading, these devices provide numerous other benefits, such as privacy, glare control, insulation and interior aesthetics.

The main drawback of internal devices is that they are not always discerning. They cannot block the sun admitting the view, something that can be effectively done with an external overhang. Since they block the solar radiation on the inside of glazing, much of the heat remains indoors [Lechner 2001].

4.2. Natural ventilation – Night cooling

The parametric studies were mainly based on four different ventilation scenarios. Starting from an air exchange rate with a constant value of 1 h^{-1}, it was gradually increased. Using overhangs as the most effective shading scheme the average overheating values for every building are formed as following:

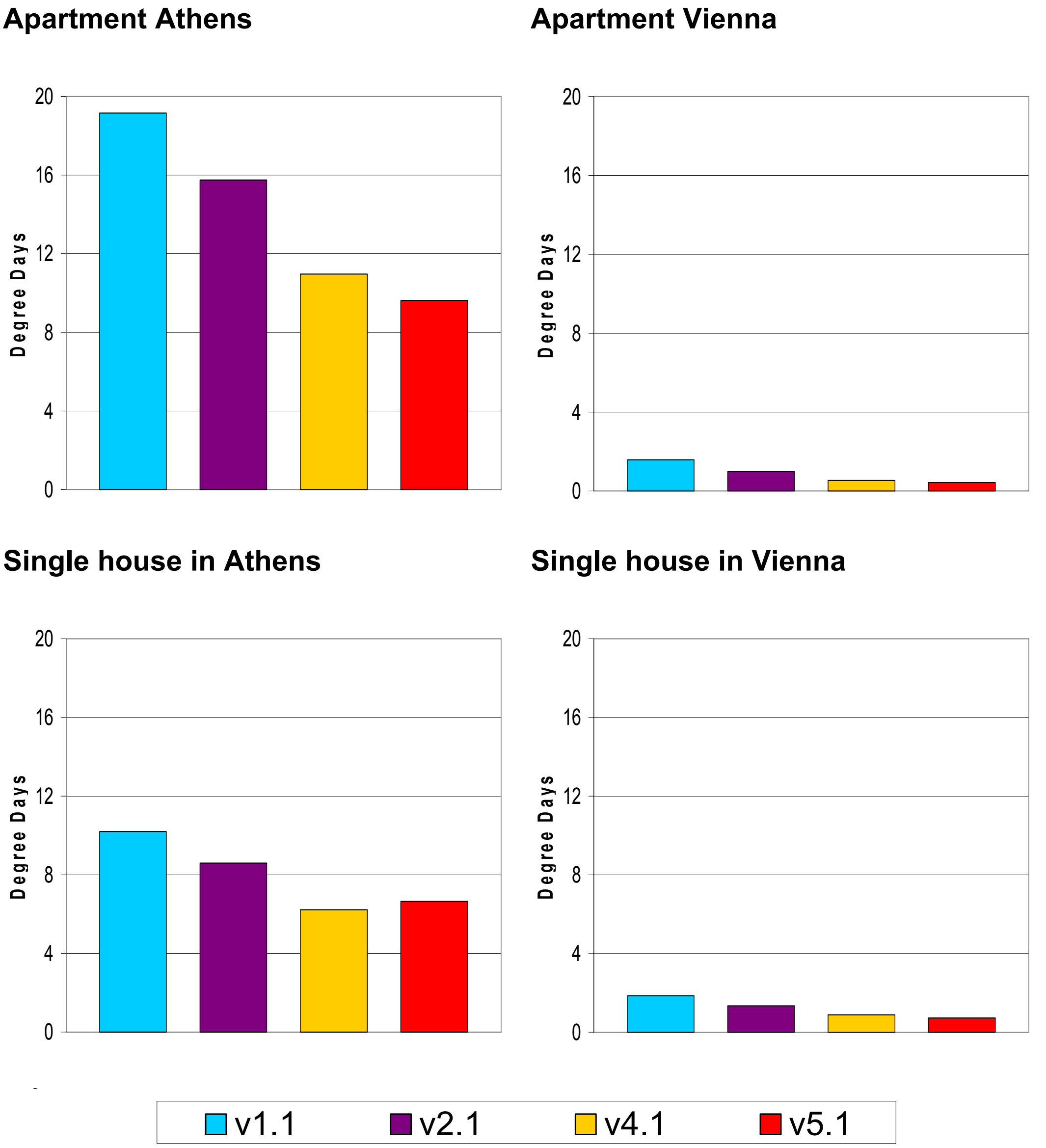


Figure 43: Overheating risk for all ventilation scenarios according to the average overheating value of every building in Athens and Vienna.

Ventilation scenarios v4.1 and v5.1 seem to be the most effective regardless the building or the climate. These schemes suggest passive cooling by night time ventilation [Table 9]. During the night the building is naturally ventilated at a maximum rate in order to remove the heat and cool the internal side of the walls. During the day, heat gains are limited to a minimum level because the ventilation openings are just slightly opened to keep warm air outside and external shading devices or the overhang protect from solar radiation.

According to the climatic data of Athens, July and August are the warmest months of the year. During these months temperatures reach very high values. Using the zone living room & kitchen of the apartment in Athens as a test space, the inside temperature for the period from 18 to 24 July reacts in different ventilation scenarios in the following way:

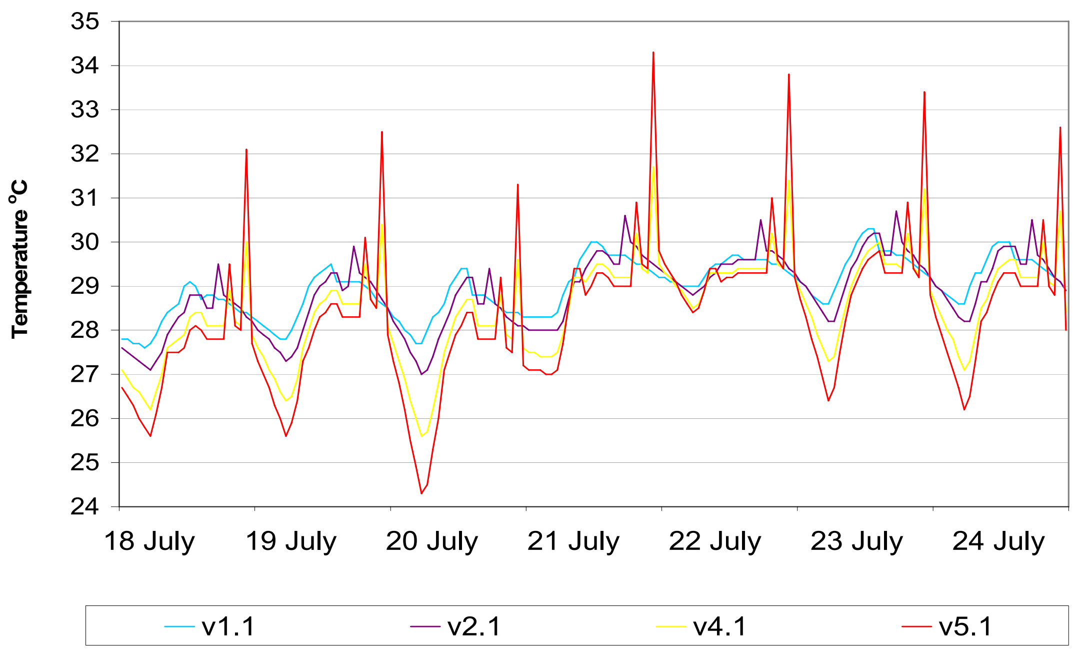


Figure 44: Inside temperature in living room & kitchen (Apartment Athens) for four ventilation scenarios. Shading scheme: Overhang.

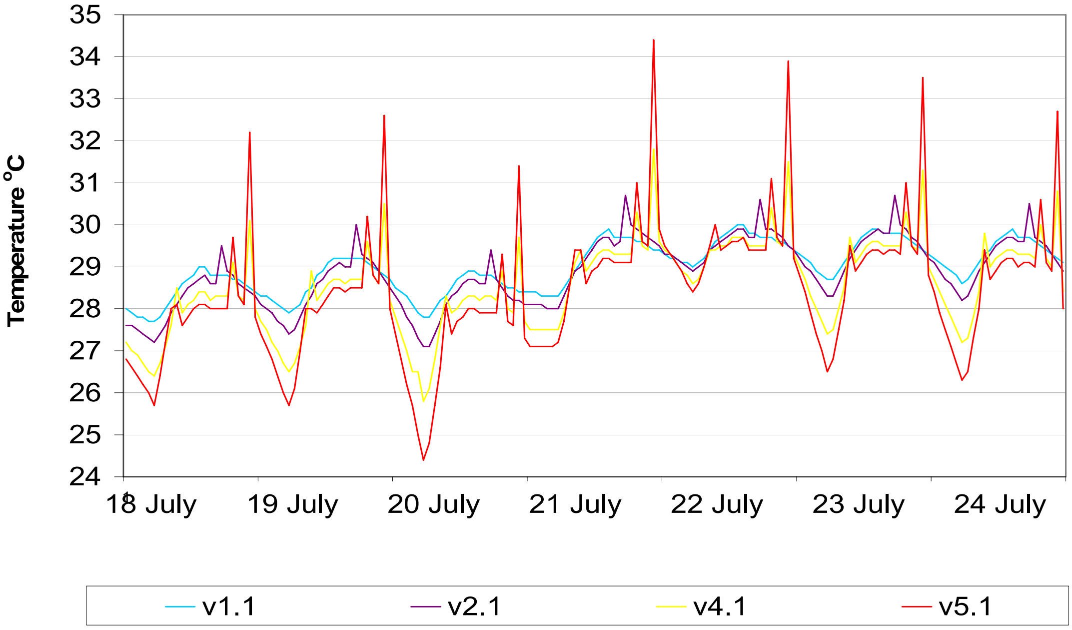


Figure 45: Inside temperature in living room & kitchen (Apartment Athens) for four ventilation scenarios. Shading scheme: External shading device.

From the climatic data of Vienna it seems that the week from 18 to 24 July is also on of the warmest. The responding inside temperature in the apartment in Vienna for the same zone is:

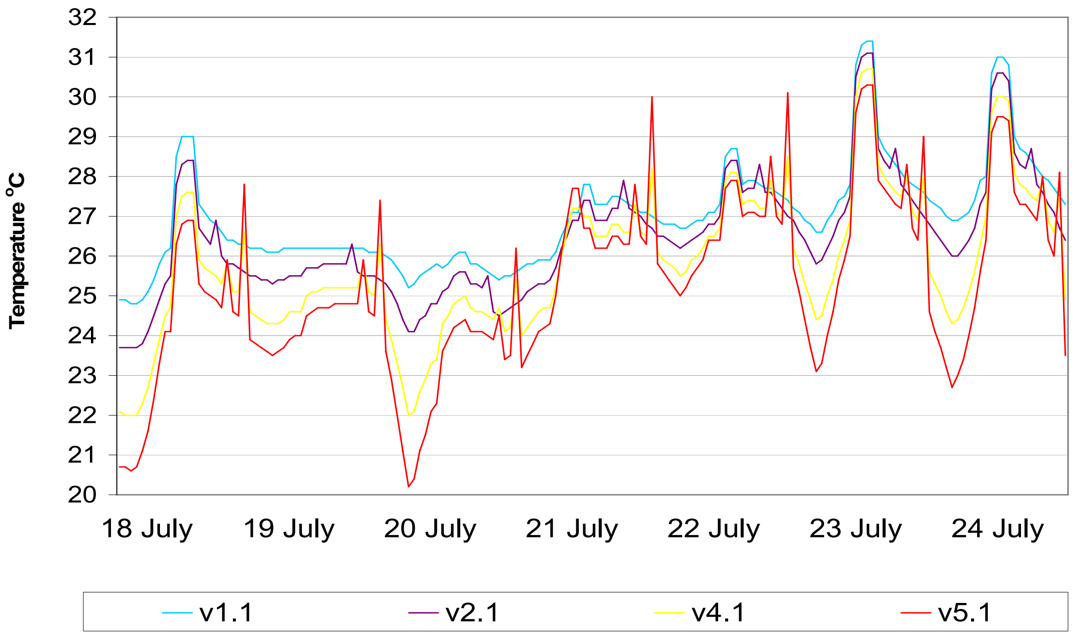


Figure 46: Inside temperature in living room & kitchen (Apartment Vienna) for four ventilation scenarios. Shading scheme: Overhang.

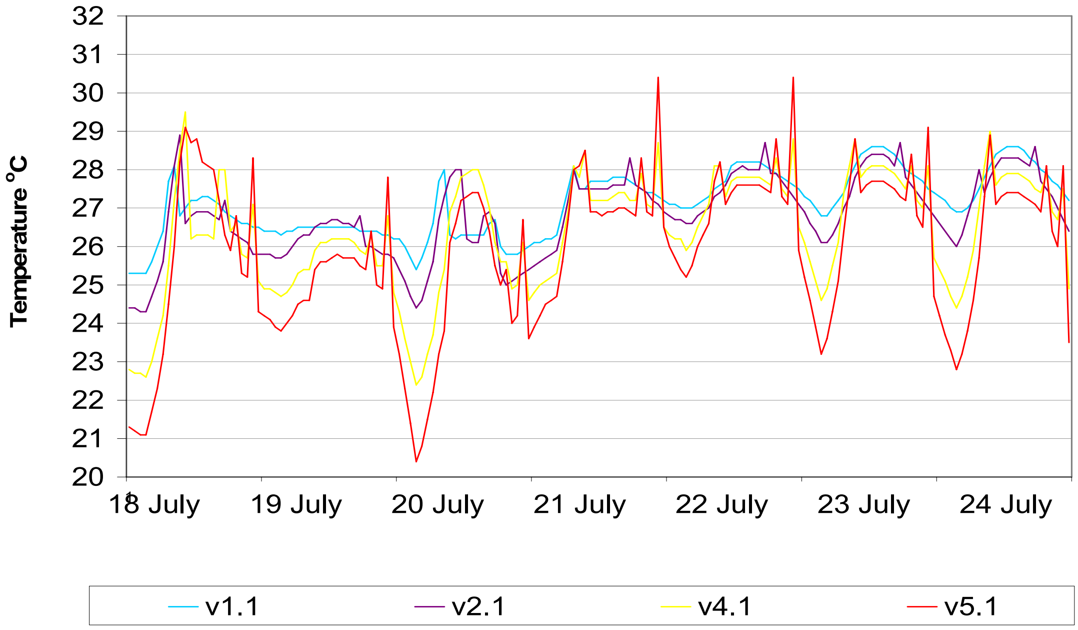


Figure 47: Inside temperature in living room & kitchen (Apartment Vienna) for four ventilation scenarios. Shading scheme: External shading device.

In both cases the inside temperature drops by the transition from v1.1 to v2.1, v4.1 and v5.1 in the same order. The conclusion drawn from the comparison of the average overheating values in figure is verified here. The ventilation scenario with the highest air exchange rate (10 h^{-1}) during the night has proved to be the most effective one in both middle and Mediterranean climates.

In the figures above the high or low peaks of temperature occur during the change of ventilation rate: when the natural air exchange rate drops from a high night-time value to the minimum 1 h^{-1} the inside temperatures drops suddenly and rapid for a moment and in the same way when the night-time ventilation is activated we notice a rapid increase in the temperature for a short time.

4.3. Phase Changing Materials (PCM)

It is known that PCM's perform better in combination with night cooling. Therefore, the study of PCM performance was limited in the two night ventilation scenarios: v4.1 and v5.1. A comparison of the overheating risk before and after the application of the material was conducted in the following figures, for both apartment and single house and for both climates. The test spaces that were selected are the zone living room & kitchen for the apartment and zone bedroom_2 for the single house.

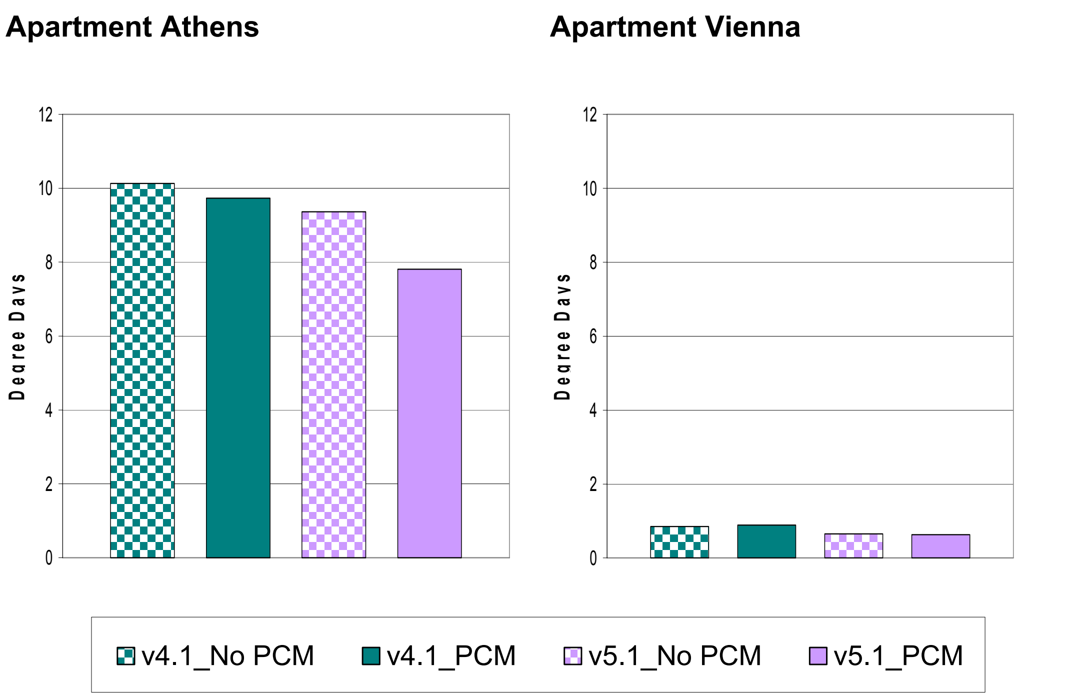


Figure 48: Apartment in Athens and Vienna: overheating risk for ventilation scenarios v4.1 and v5.1 before and after the application of the PCM-wallboard.

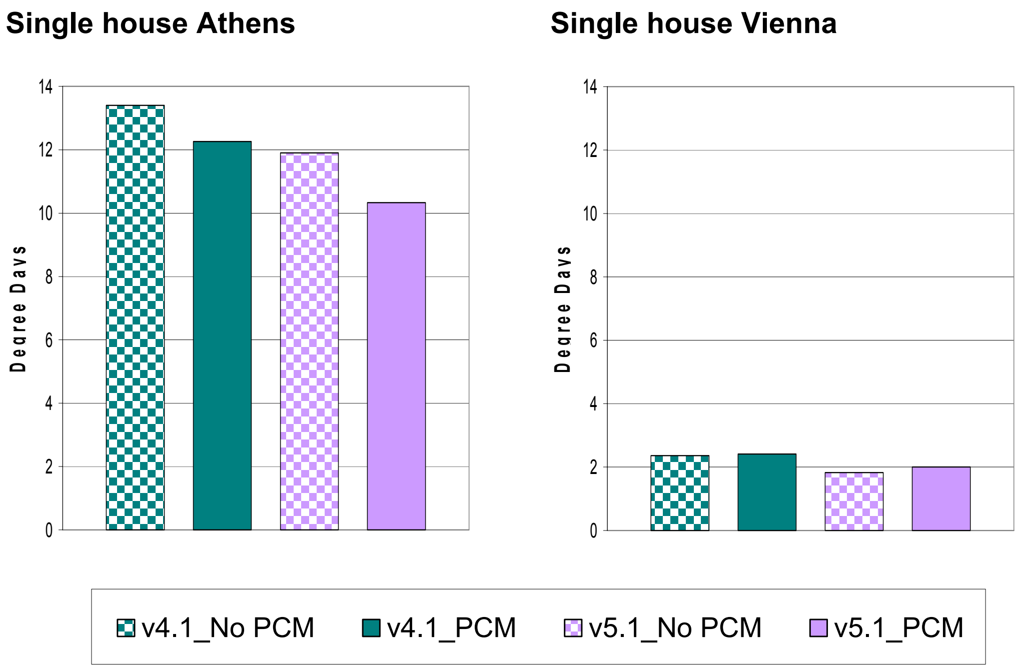


Figure 49: Single house in Athens and Vienna: overheating risk for ventilation scenarios v4.1 and v5.1 before and after the application of the PCM-wallboard.

By examining the above figures as well as tables 13, 15, 17 and 19 one could draw the conclusion that the application of PCMs is effective in Athens since the overheating risk is reduced for both ventilation scenarios. In Vienna on the other hand, the overheating is slightly increased after the application of the new material. This happens in cases where the initial overheating value is small. In tables 13, 15, 17 and 19, where we can see the overheating degree hours as they are distributed in every month from April to September, if the value is small (e.g smaller than 150 DH) the application of PCM’s results to a same value or in the worst scenario to a higher one. An explanation for this could be the fact that low overheating value during a month means that temperature seldom rises above 27^{o}C and even in the case it does, it is slightly above the limit. Sometimes if night temperature is high (e.g. above 25 ^{o}C), the release of energy during the reloading of the material, creates a short overheating, so the sum gets higher.

The calculation and comparison of the Degree hours for every case give an accurate overall impression about the effectiveness of PCM application. In addition to this, the monitoring of the indoor temperature makes the understanding of the situation more concrete. The changes in the indoor temperature for the apartment during the week 18-24 July are shown in the next figures.

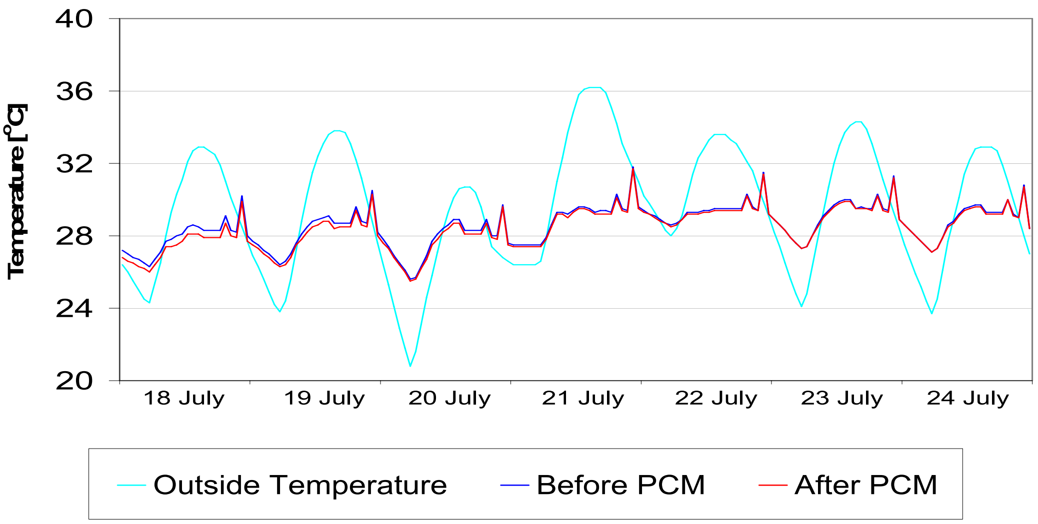


Figure 50: Indoor temperature for zone living room & kitchen of the apartment for the ventilation scenario v4.1.Location: Athens (Greece).

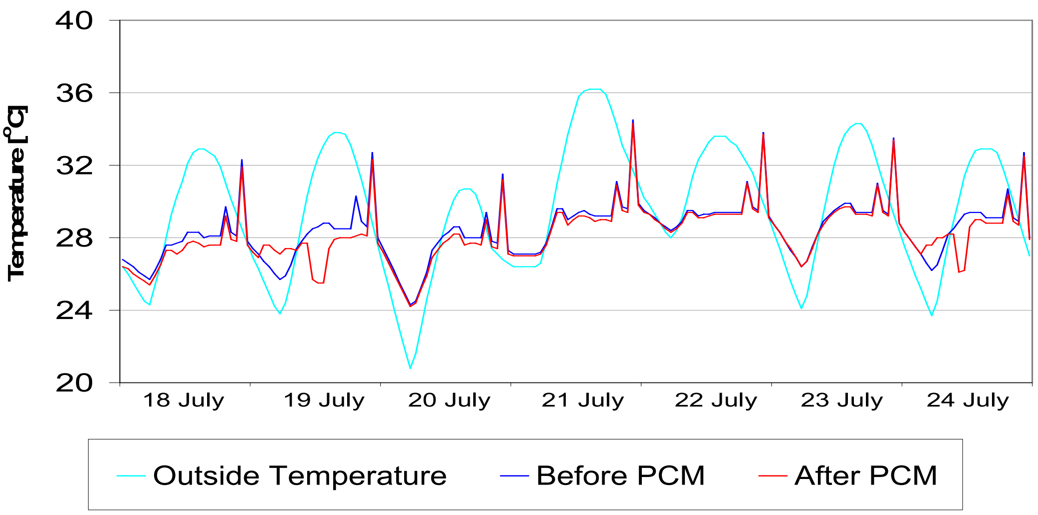


Figure 51: Indoor temperature for zone living room & kitchen of the apartment for the ventilation scenario v5.1. Location: Athens (Greece).

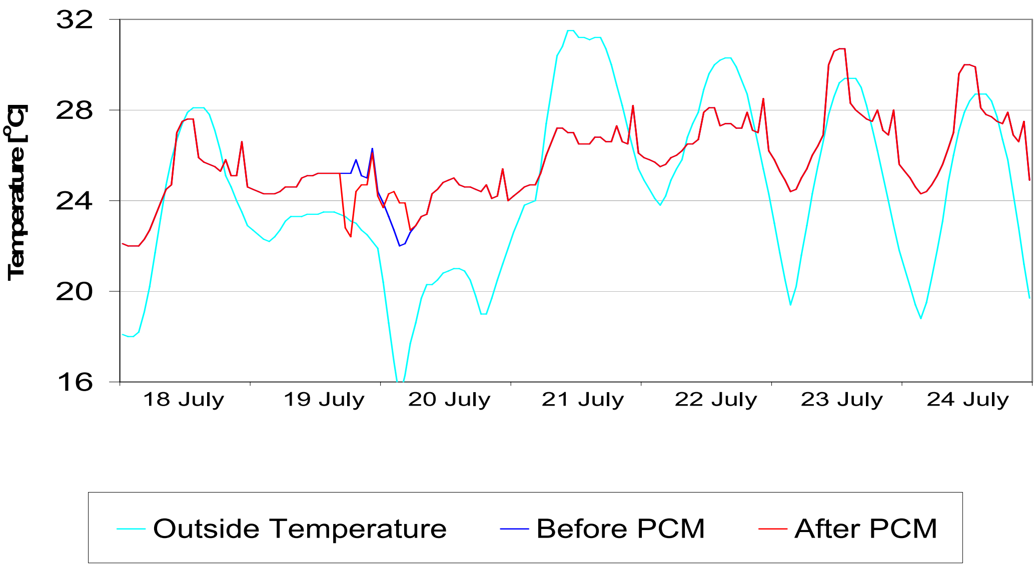


Figure 52: Indoor temperature for zone living room & kitchen of the apartment for the ventilation scenario v4.1. Location: Vienna (Austria).

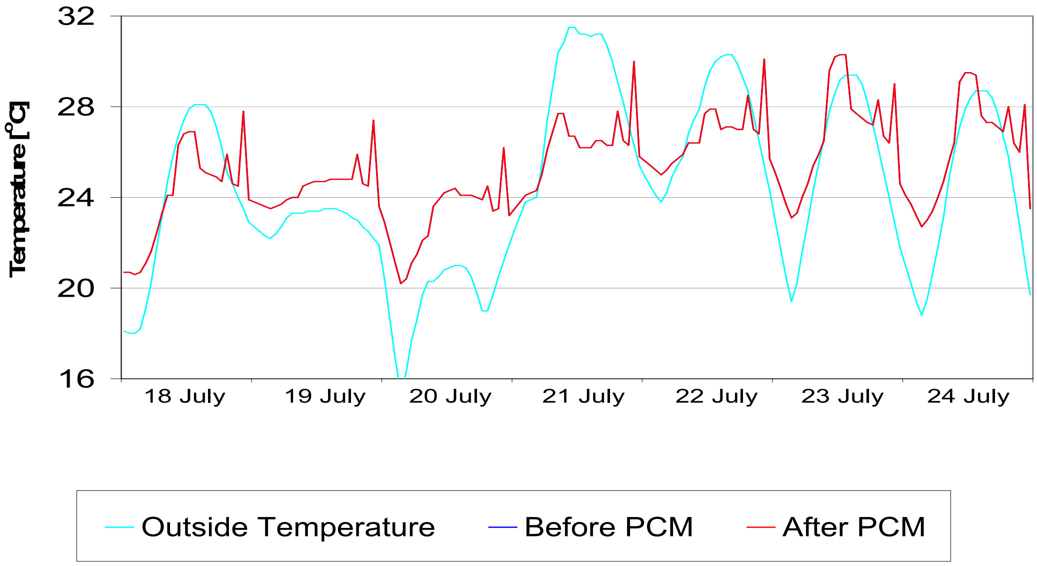


Figure 53: Indoor temperature for zone living room & kitchen of the apartment for the ventilation scenario v5.1. Location: Vienna (Austria).

In the case of the double-story single house, bedroom_2 was the test space. The changes of the indoor temperature during the same week in July for different ventilation scenarios are illustrated in the following figures.

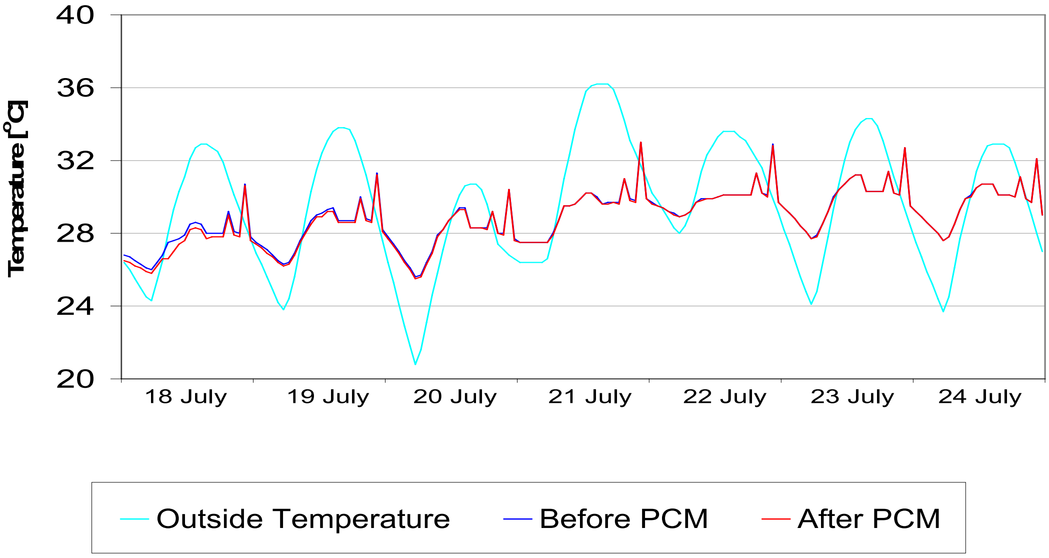


Figure 54: Indoor temperature for zone Bedroom_2 of the single house for the ventilation scenario v4.1. Location: Athens (Greece).

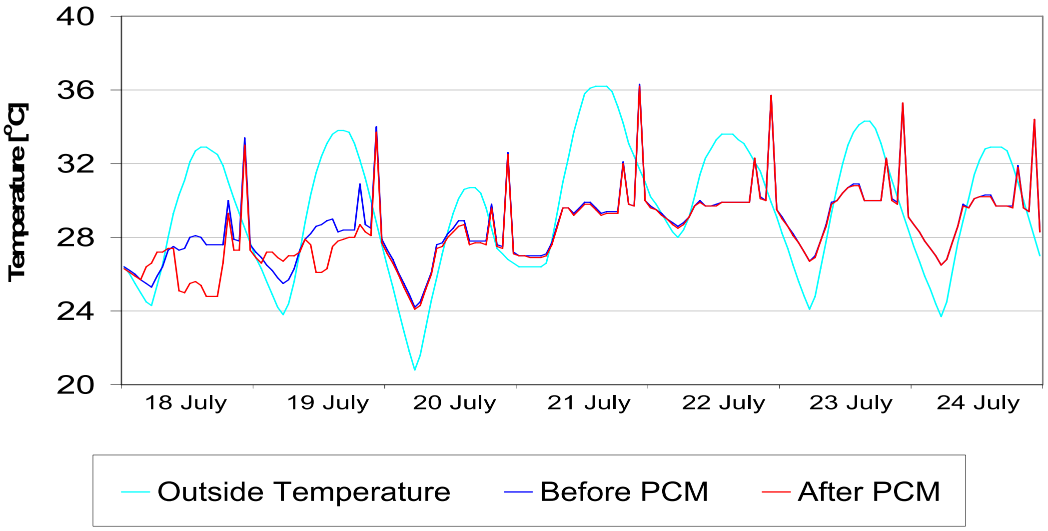


Figure 55: Indoor temperature for zone Bedroom_2 of the single house for the ventilation scenario v5.1. Location: Athens (Greece).

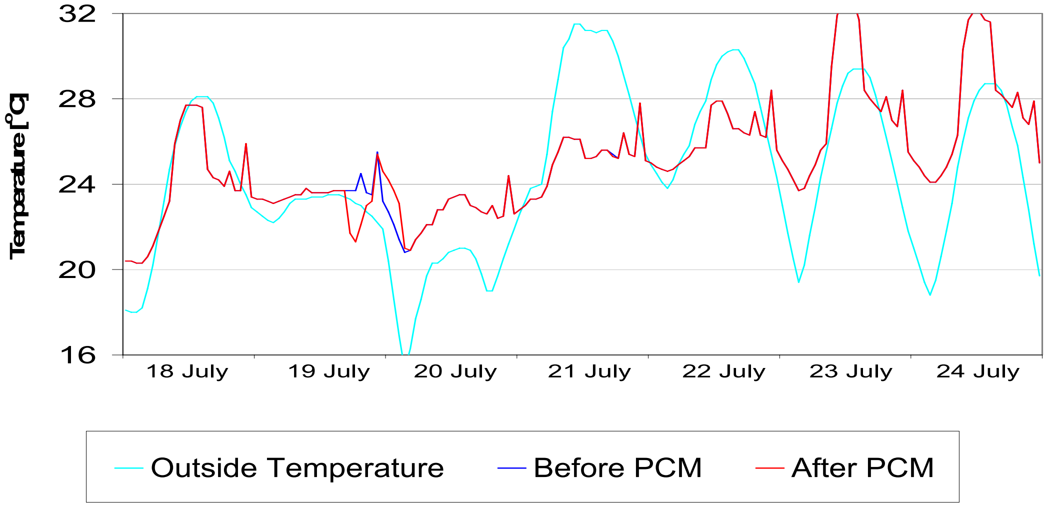


Figure 56: Indoor temperature for zone Bedroom_2 of the single house for the ventilation scenario v4.1. Location: Vienna (Austria).

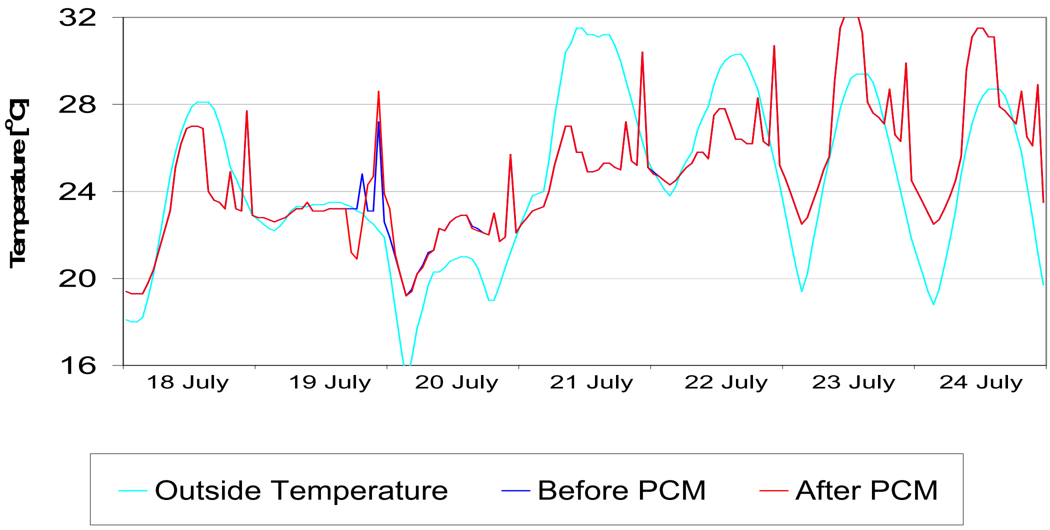


Figure 57: Indoor temperature for zone Bedroom_2 of the single house for the ventilation scenario v5.1. Location: Vienna (Austria).

To sum up we could say that the application of PCM proved to be effective in Athens, but not in Vienna. But even in case of Athens they didn’t turn out to be as advantageous as expected. First of all the reduction of the overall overheating risk during the period April to September is very moderate. Secondarily, they prove to be effective only during the warmest months, causing sometimes more overheating during the least warm ones. The explanation of these results could be summed up in three main reasons:

- ✓ PCM’s are efficient mostly in light weight buildings. The main disadvantage of building like these is their low thermal mass, which leads to high temperature fluctuations. In those cases PCM’s can smooth out the temperature variations. In the parametric studies that where conducted here, both apartment and single house have a high thermal mass.

- ✓ Another parameter that makes the use of PCM very effective is the climate and especially the temperature fluctuations. According to the state of art the performance of PCM’s is very high in climates with high diurnal differences in temperature. Neither Athens nor Vienna has a climate like this.

- ✓ The commercial PCM’s that can be applicable in the domain of constructions are still very limited. The most broadly used, have usually a low congealing point (22 ^{o}C), it means they could not be applicable in the Greek climate.

4.4. Concentrated results for all parametric studies

In chapter 3.5. table 21 showed the concentrated results for all parametric studies of the two building projects both in Athens and Vienna in terms of the overheating risk. The comparison was based on the average value of "Degree Days" as it was calculated for the apartment or the single house in every case.

The spaces that were studied more in detail and for all possible scenarios are the two test spaces: the zone living room & kitchen in the apartment and zone bedroom_2 in the single house. The changes of the overheating risk due to the application of different scenario for these specific zones are presented in the following figures.

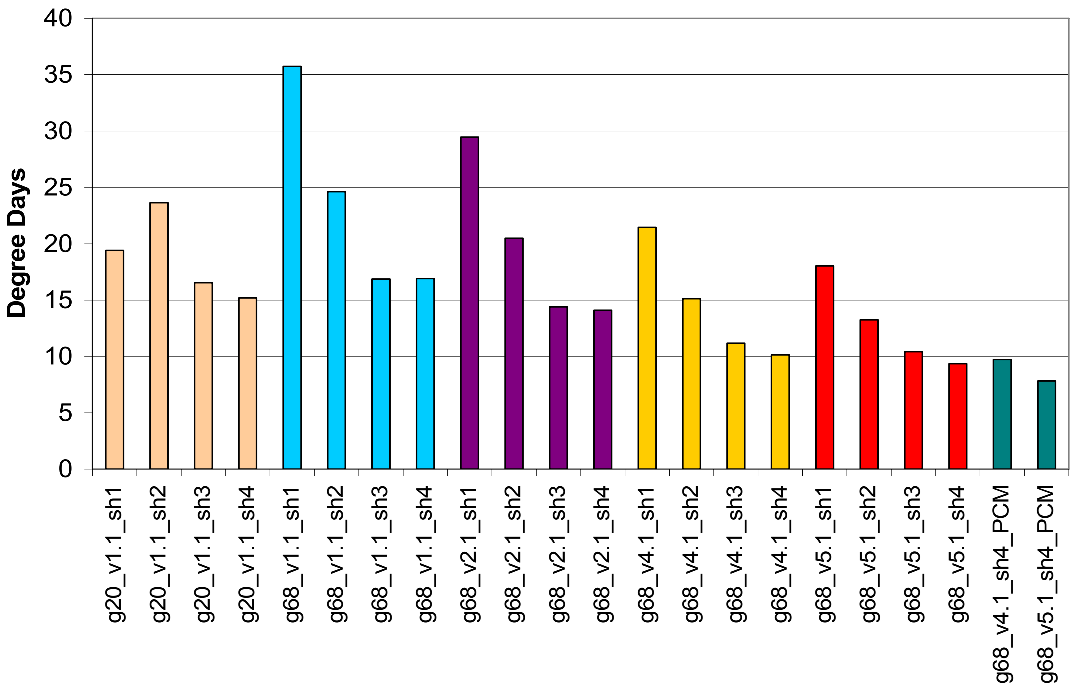


Figure 58: Concentrated results for all parametric studies for the apartment in Athens: Test room: Living room & kitchen zone

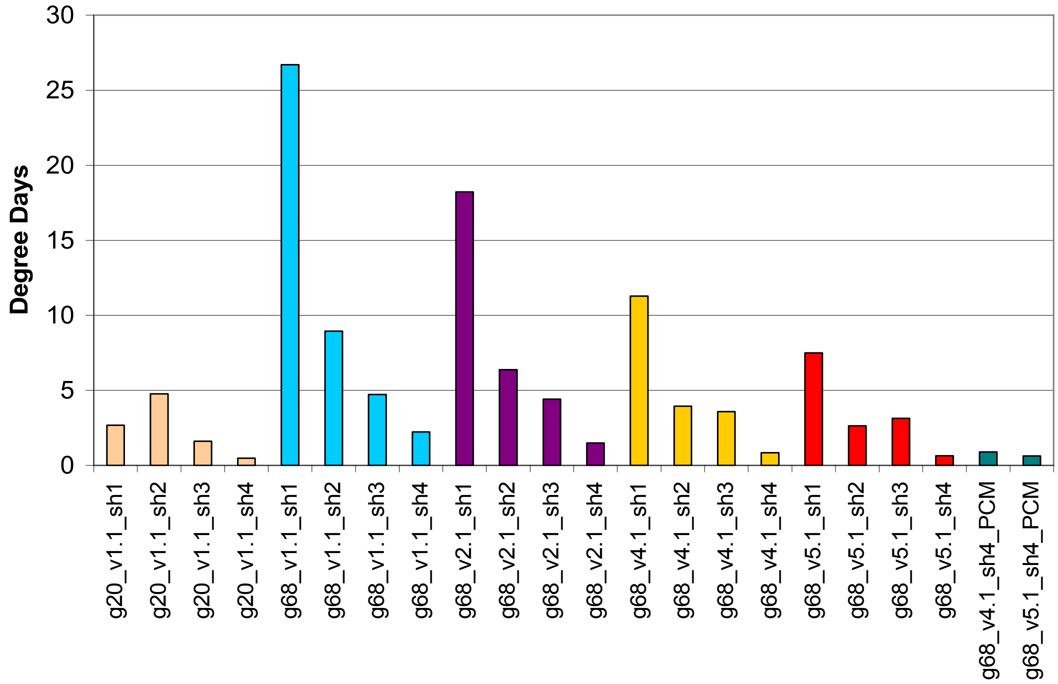


Figure 59: Concentrated results for all parametric studies for the apartment in Vienna: Test room: Living room & kitchen zone.

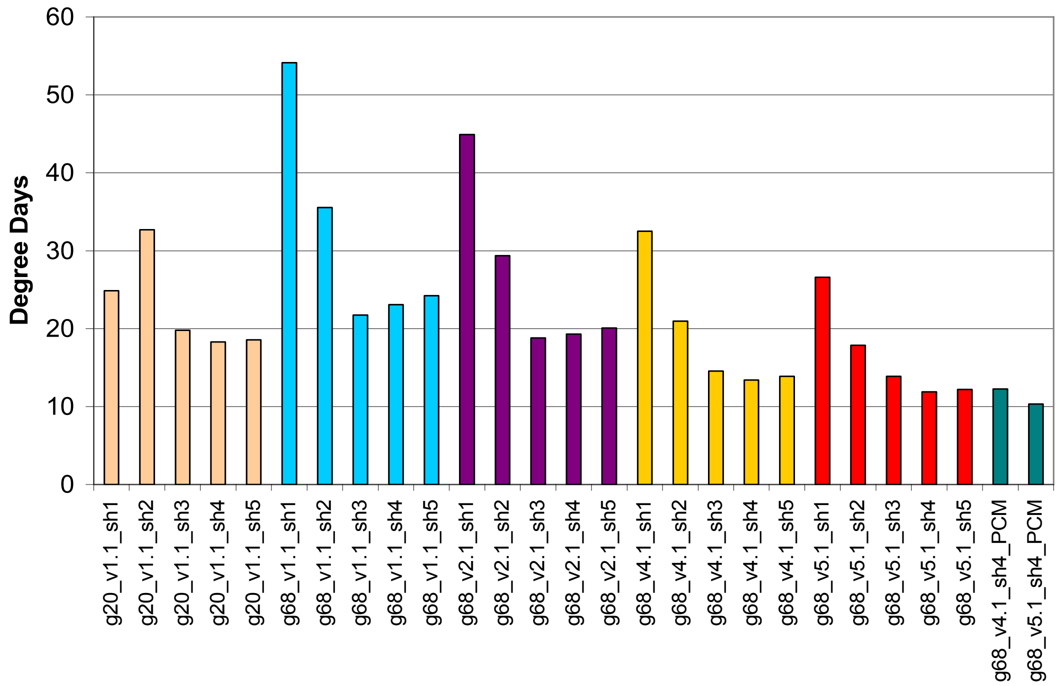


Figure 60: Concentrated results for all parametric studies for the single house in Athens: Test room: Bedroom_2.

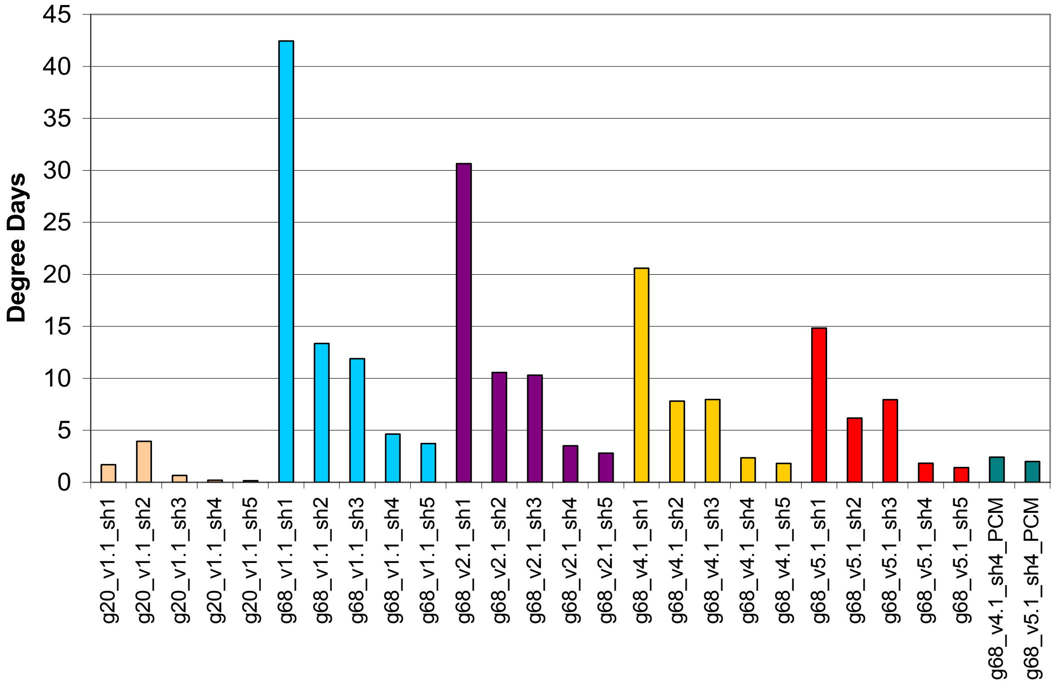


Figure 61: Concentrated results for all parametric studies for the single house in Vienna: Test room: Bedroom_2.

5. Conclusions

5.1 Contribution

Passive cooling methods can significantly contribute the reduction of overheating in buildings during the summer. In particular the combination of shading with night time ventilation has proved to be very successful. According to the parametric studies conducted in the present research, the most advantageous shading schemes have proved to be external shading devices and fixed overhangs. Considering also the other benefits of external shading (practical, easy installable, aesthetic reasons etc) it could be suggested as a very effective design solution against overheating. Only the application of external shades reduces the overheating up to 60% in Athens and up to 82% in Vienna.

Natural ventilation and especially night–time ventilation has also proved to perform very well. Moreover in the case that night ventilation is combined with external shadings, the results are significantly satisfying. In this case night cooling with an air exchange rate of 5 h^{-1} can achieve reduction in overheating up to 73% in Athens and 87% in Vienna. The reduction percentage for a higher air exchange rate e.g 10 h^{-1} is 74% and 88% respectively. The difference between the 5 ACH and 10 ACH is negligible. In addition to this high ventilation rates may not be feasible practically due to draught risk and issues pertaining to storm safety and can further reduce overheating only in climatic contexts where the external air temperature sinks over night well below the comfort temperature threshold (27 ^{o}C in this study).

In comparison to the above mentioned techniques the application of phase change materials (PCM) appears to have a rather limited effectiveness in terms of overheating reduction. A combination of shading, night-time ventilation and PCMs has been estimated to reduce the overheating risk up to 17% in Athens and 5% in Vienna. In some cases the application of PCMs increases slightly the overheating. The contribution of PCMs seems to be much less that the expected mostly because of the climatic characteristics of the locations and the limited range of available PCMs.

5.2 Future research

The parametric studies that were described above were conducted in two specific climatic contexts: Athens (Greece) and Vienna (Austria); and for a specific type of construction: high thermal mass construction. Consequently the results and the conclusions refer only to these specific conditions.

There is still room to test the effectiveness of passive cooling methods in different climates and with different constructions (light weight). In particular for PCMs the climate plays a very significant role. The potential use of PCM in building construction could be very effective if tested in climates with a good match between the comfort temperature requirements, material properties (e.g. melting and congealing point) and prevailing outdoor air temperatures during the night phase in cooling period.

The present research was based on models of existing buildings that were analyzed in performance simulation software. It could be also very interesting to have the opportunity to conduct real time experiments and calculations in existing buildings or in test –rooms in laboratories, where we could play with all kinds of material properties and create the desirable conditions.

6. References

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Appendix A

As already mentioned, METEONORM was used to obtain the climatological data needed for the simulations [see chapter 2.4.1]. The hourly values for the temperature during the whole year are presented in the following figures.

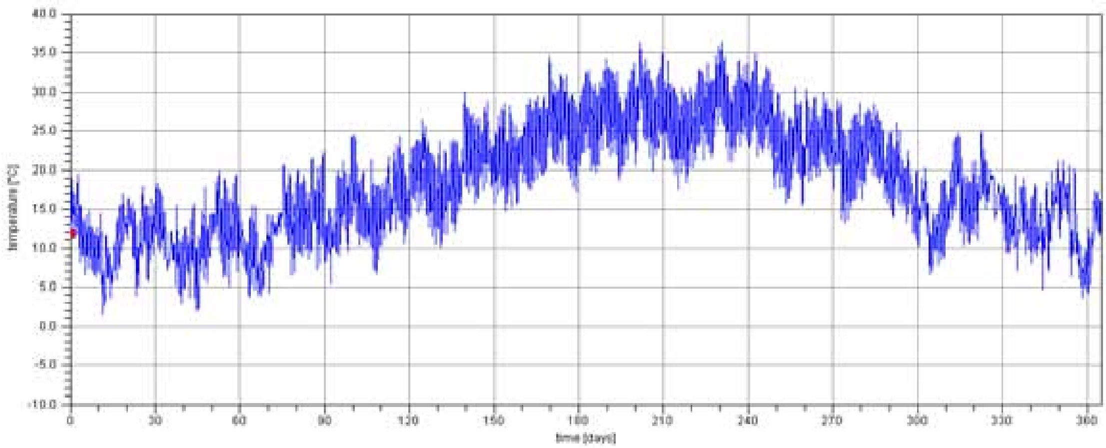

Figure A1: Hourly temperature values during the whole year for Athens (Greece). [*Climatic data from METEONORM*]

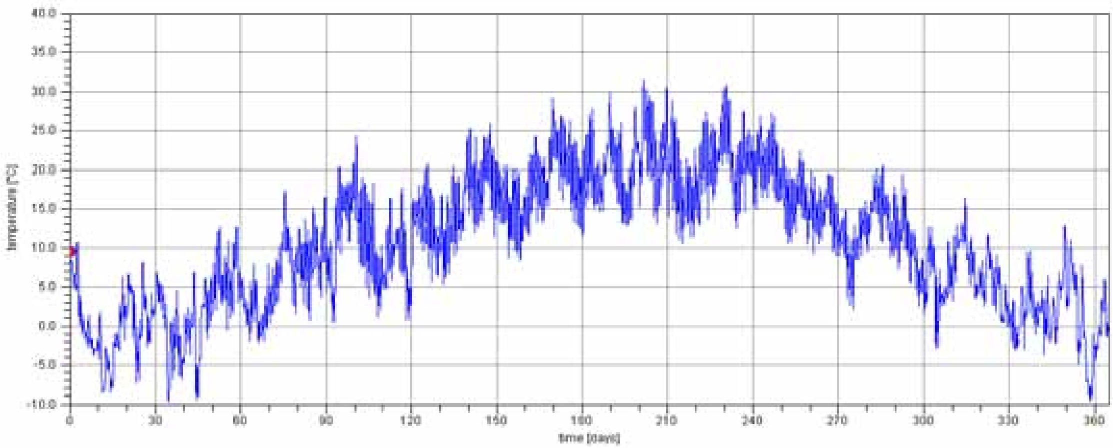

Figure A2: Hourly temperature values during the whole year for Vienna (Austria). [*Climatic data from METEONORM*]

Appendix B

All the ventilation schemes that are presented in table 8 (chapter 2.7.), were tested in the apartment in Athens considering as default shading scheme the overhang. The results are presented in the following table: the value in the first column for every zone represents the Degree Hours for the period April to September; the value in parenthesis the number of hours that the temperature exceeded the comfort limit (27^{o}C) and the second column represents the "Degree Day" value.

Table B1a: Results for all variations of ventilation scenarios: Apartment in Athens (Greece).

Air exchange rate (h^{-1})	Outside		Living room & kitchen		Bedrooms	
v1.1	3909,2 (1306)	**21,36**	3093,8 (2236)	**16,90**	4010,4 (2397)	**21,90**
v1.2	3909,2 (1306)	**21,36**	2717,5 (1865)	**14,85**	3315,4 (2021)	**18,17**
v2.1	3909,2 (1306)	**21,36**	2579,9 (1863)	**14,10**	3250,3 (2041)	**17,76**
v2.2	3909,2 (1306)	**21,36**	2679,4 (1927)	**14,64**	3372,5 (2090)	**18,43**
v3.1	3909,2 (1306)	**21,36**	2650,3 (1845)	**14,48**	3257 (2002)	**17,80**
v4.1	3909,2 (1306)	**21,36**	1853,1 (1417)	**10,13**	2189,5 (1539)	**11,96**
v4.2	3909,2 (1306)	**21,36**	1924,7 (1428)	**10,52**	2247,5 (1545)	**12,28**
v4.3	3909,2 (1306)	**21,36**	2015,9 (1512)	**11**	2408,8 (1634)	**13,16**
v4.4	3909,2 (1306)	**21,36**	2090,2 (1523)	**11,42**	2471,6 (1648)	**13,50**
v5.1	3909,2 (1306)	**21,36**	1712,1 (1183)	**9,36**	1817,9 (1216)	**9,93**
v5.2	3909,2 (1306)	**21,36**	1993,9 (1320)	**10,90**	2132,1 (1368)	**11,65**
v5.3	3909,2 (1306)	**21,36**	1868,8 (1294)	**10,21**	2026,3 (1333)	**11,07**

Table B1b: Results for all variations of ventilation scenarios: Apartment in Athens (Greece).

Air exchange rate (h^{-1})	Bathroom		WC		Hall	
v1.1	5788,7 (3139)	**31,63**	6040,1 (3031)	**33**	5573,8 (3026)	**30,45**
v1.2	4539,2 (2501)	**24,80**	4860,7 (2489)	**26,56**	4438,7 (2434)	**24,25**
v2.1	4500,8 (2569)	**24,60**	4842,2 (2541)	**26,46**	4383,2 (2487)	**23,95**
v2.2	4683,8 (2648)	**25,60**	5019,4 (2606)	**27,43**	4553,5 (2551)	**24,88**
v3.1	4423 (2486)	**24,17**	4751,7 (2479)	**26**	4303,6 (2422)	**23,52**
v4.1	2842,1 (1908)	**15,53**	3137,2 (1934)	**17,14**	2752 (1864)	**15,04**
v4.2	2901,7 (1909)	**15,86**	3190,6 (1942)	**17,43**	2805,9 (1868)	**15,33**
v4.3	3166,5 (2049)	**17,30**	3473,2 (2059)	**18,98**	3059,6 (1980)	**16,72**
v4.4	3219,9 (2051)	**17,60**	3523,9 (2058)	**19,26**	3112,2 (1981)	**17**
v5.1	2091,4 (11,43)	**11,43**	2204,2 (1486)	**12,04**	1965,4 (1400)	**10,74**
v5.2	2490,8 (1605)	**13,61**	2649,4 (1670)	**14,48**	2349,1 (1571)	**12,84**
v5.3	2388,2 (1585)	**13,05**	2553,7 (1655)	**13,95**	2249,3 (1556)	**12,29**

Appendix C

In order to simulate the PCM-wallboard in CAPSOL the amount of energy that the material absorbs or releases (depending on its phase) had to be calculated [see chapter 2.8.3.]. These calculations were based on the technical data of the wallboard [Table 10].

The heat storage capacity of the PCM-wallboard is 1110 KJ/m$^{2.}$ It can absorb or release energy with a rate of 25-40% (cooling performance). For our calculations we consider this rate to be 33%, which is its average value. In order to have the same measurement unit we transform the cooling performance into KJ:

33 W/m2 = 33 x 3600 = 118800 J ≈ 119 KJ

Consequently, the material can perform a maximum of:

$\frac{1110}{119} \approx 9{,}33 \approx 9$ h of continuous cooling.

C.1. Apartment

In the case of the apartment the application of the PCM-wallboard was limited in the zone living room & kitchen. The material covered a surface equal to the ceiling of the zone. This means that we used 45,1827 m^2 of PCM-wallboard. The total amount of energy that the material could absorb and release was:

45,1827 m^2 x 33 W/m^2 = 1491 W

Since the internal loads for this zone were assumed to be 333 W, the internal loads during the phase change were alternated in the following way:

- ✓ When the material melts, it absorbs 1491 W from the environment. So, the internal loads during this period are 333 – 1491 = -1158 W.
- ✓ When the material solidifies, it releases this same amount of energy. So, the internal loads are 333 + 1491 = 1824 W.

C.2. Double-storey single family house

In the case of the single house the PCM-wallboard was applied in the ceiling of the zone Bedroom_2. The surface of this zone was 17,4 m^2. Consequently the material could absorb or release:

17,4 m^2 x 33 W/m^2 = 574,2 W

The initial internal loads of the zone were set to be 100 W. After the application of the PCM-wallboard this value was changed according to the phase of the material in the following way:

- ✓ When the PCM melts, it absorbs 574,2 W from the surrounded environment. So, the new value for the internal loads during this transition is 100 – 574,2 = -474,2 W.
- ✓ Respectively, when it solidifies it releases 574,2 W. Consequently the internal loads for this period are 100 + 574,2 = 674,2.

Appendix D

The following figures show the indoor temperature of all zones in the apartment or the single house for the whole duration of the measurements: April to September.

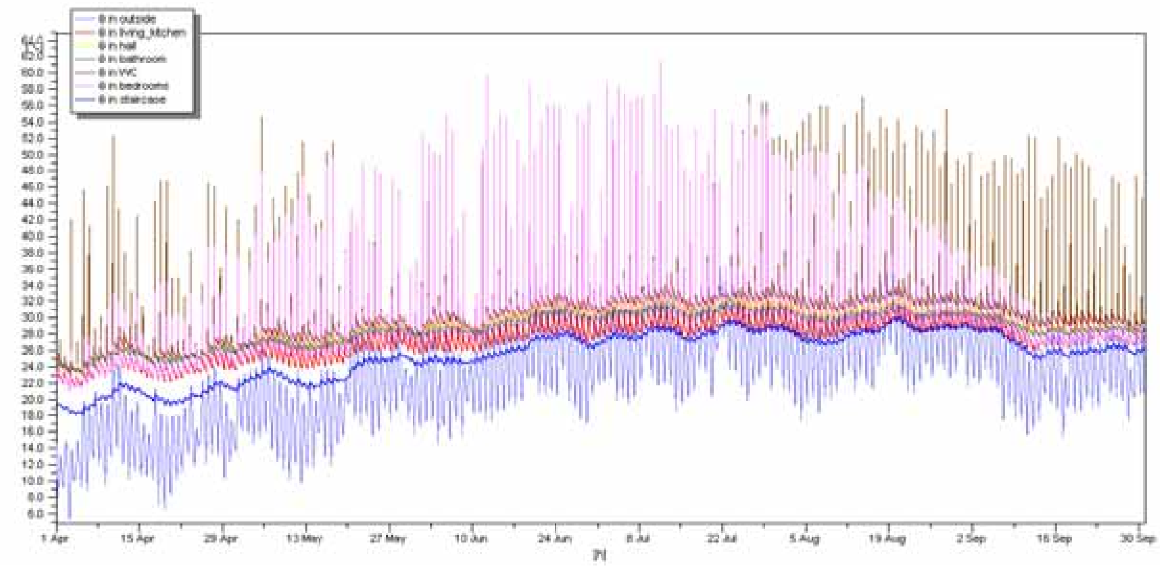

Figure D1: Apartment in Athens (Greece): Indoor temperature for all zones in the scenario sh1_v1.1.

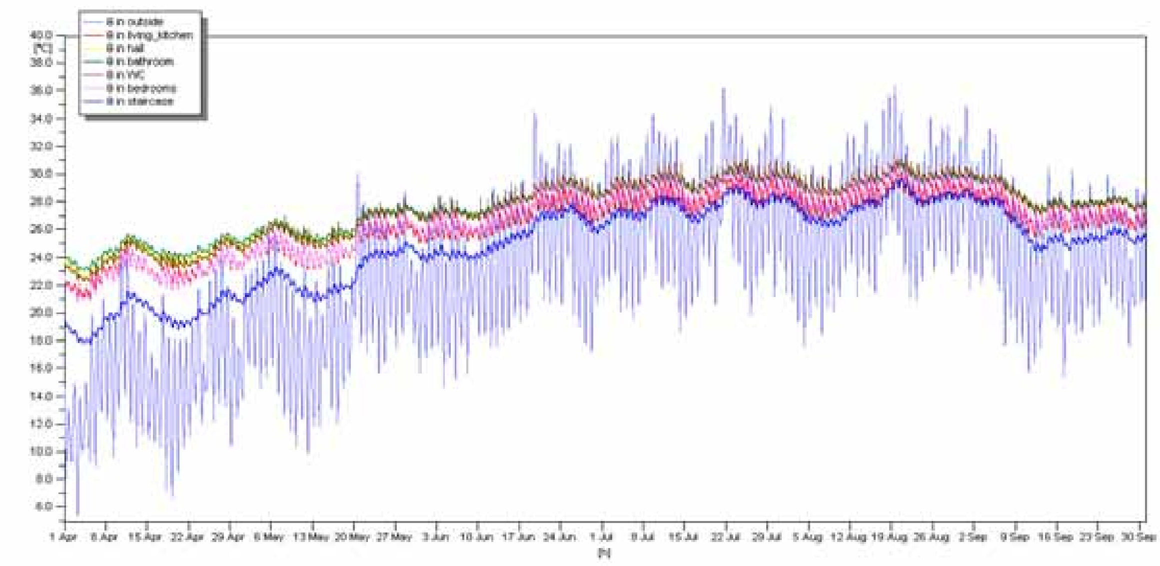

Figure D2: Apartment in Athens (Greece): Indoor temperature for all zones in the scenario sh4_v1.1.

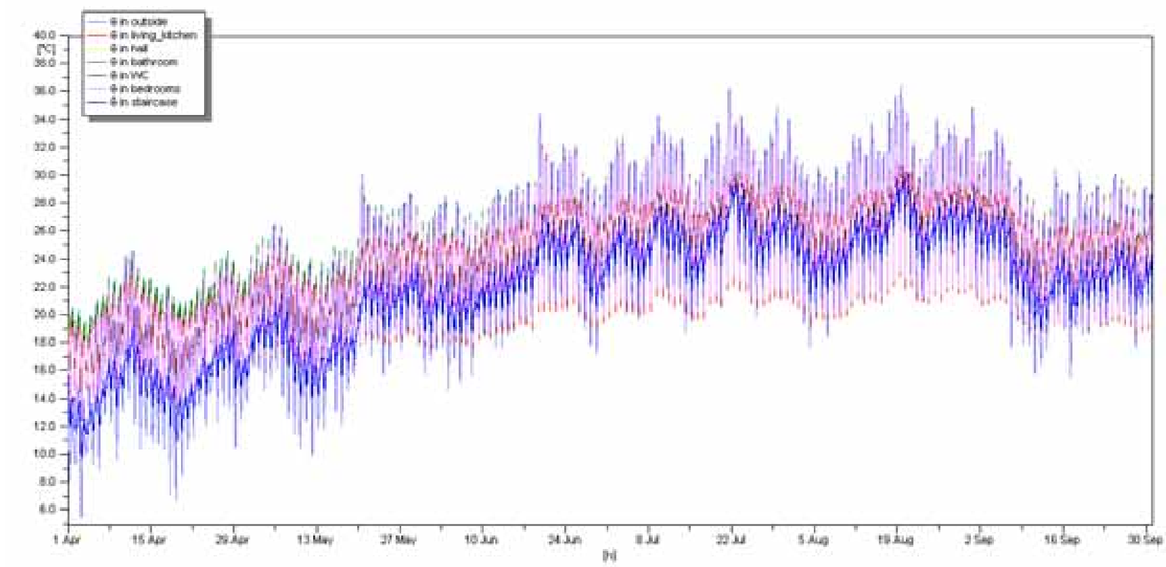

Figure D3: Apartment in Athens (Greece): Indoor temperature for all zones in the scenario sh4_v5.1.

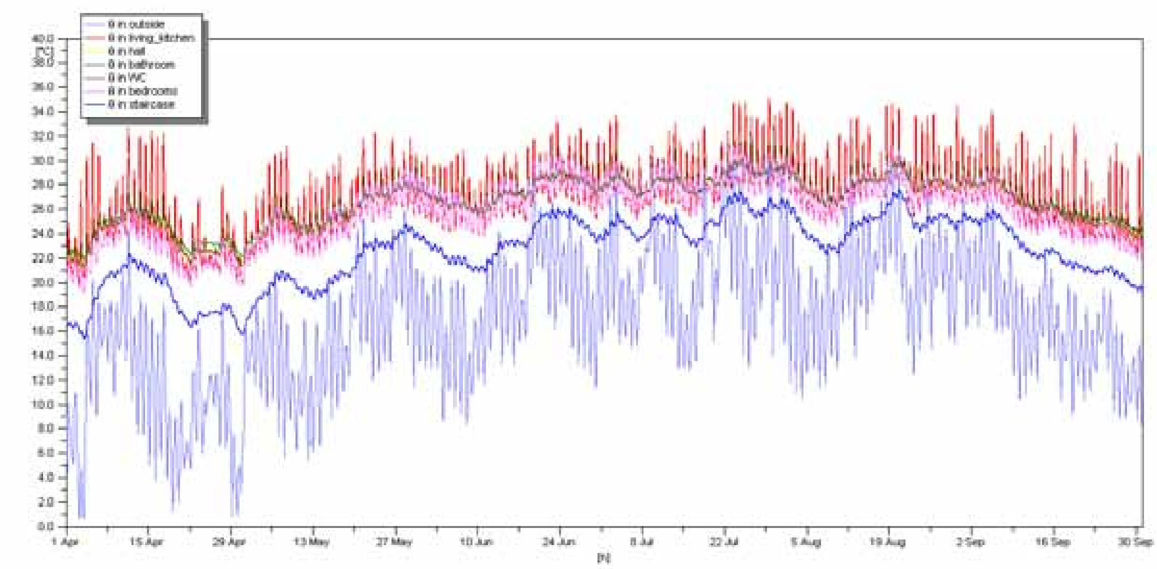

Figure D4: Apartment in Vienna (Austria): Indoor temperature for all zones in the scenario sh1_v1.1.

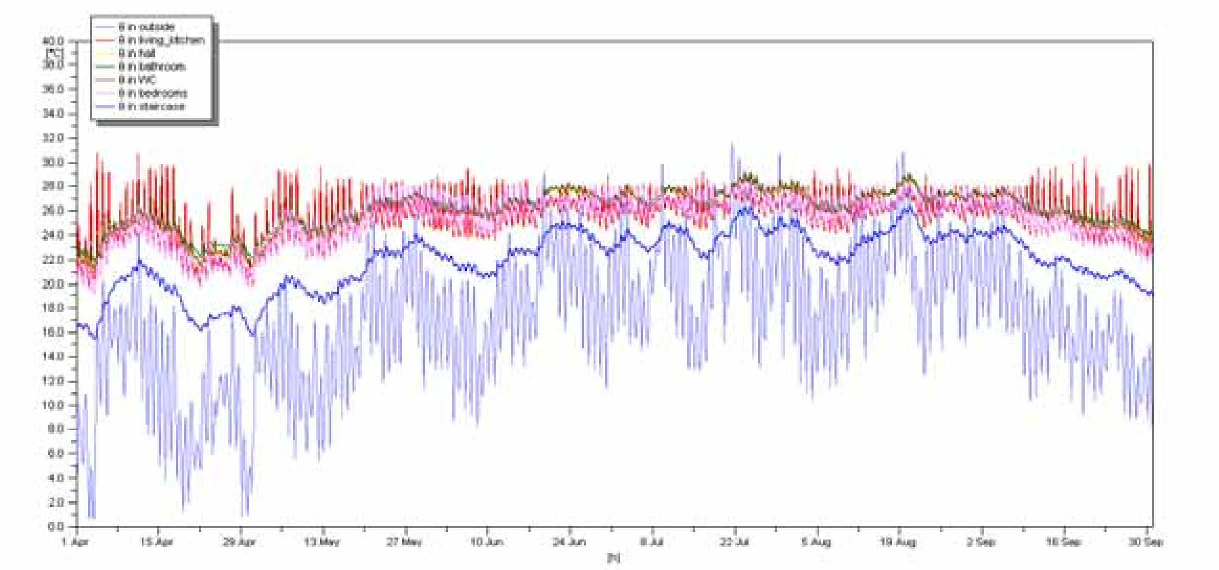

Figure D5: Apartment in Vienna (Austria): Indoor temperature for all zones in the scenario sh3_v1.1.

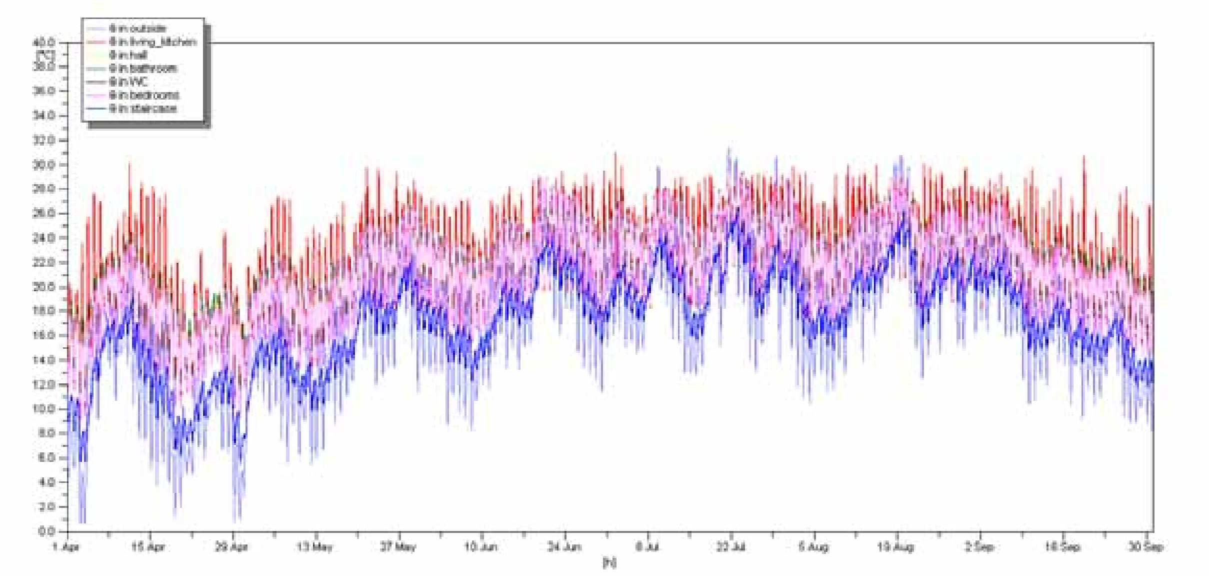

Figure D6: Apartment in Vienna (Austria): Indoor temperature for all zones in the scenario sh3_v5.1.

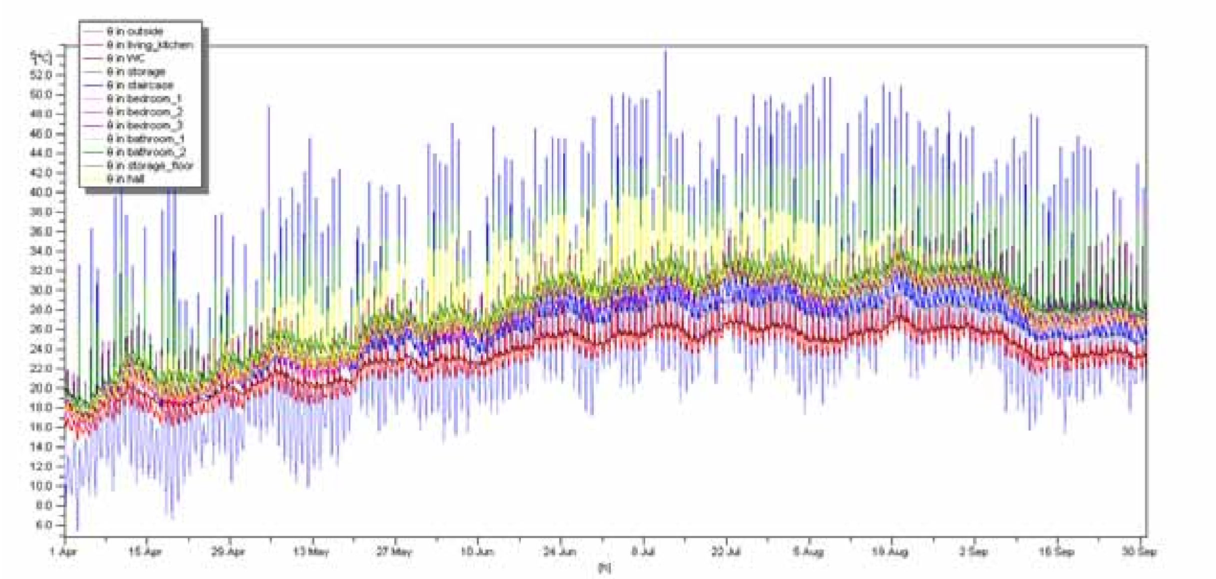

Figure D7: Double-storey single house in Athens (Greece): Indoor temperature for all zones in the scenario sh1_v1.1.

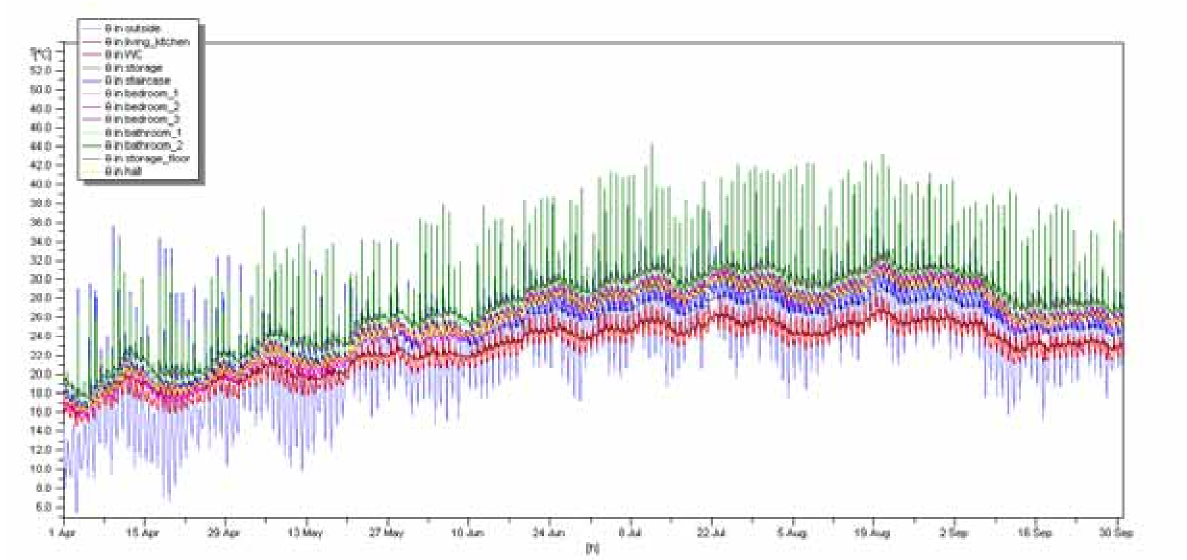

Figure D8: Double-storey single house in Athens (Greece): Indoor temperature for all zones in the scenario sh4_v1.1.

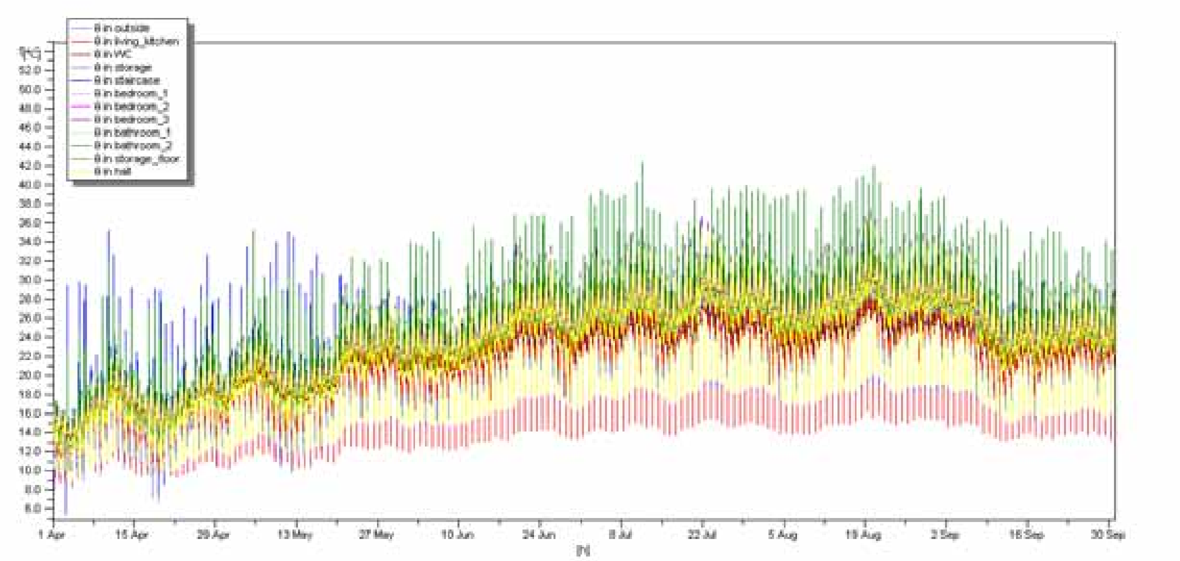

Figure D9: Double-storey single house in Athens (Greece): Indoor temperature for all zones in the scenario sh4_v5.1.

Figure D10: Double-storey single house in Vienna (Austria): Indoor temperature for all zones in the scenario sh1_v1.1.

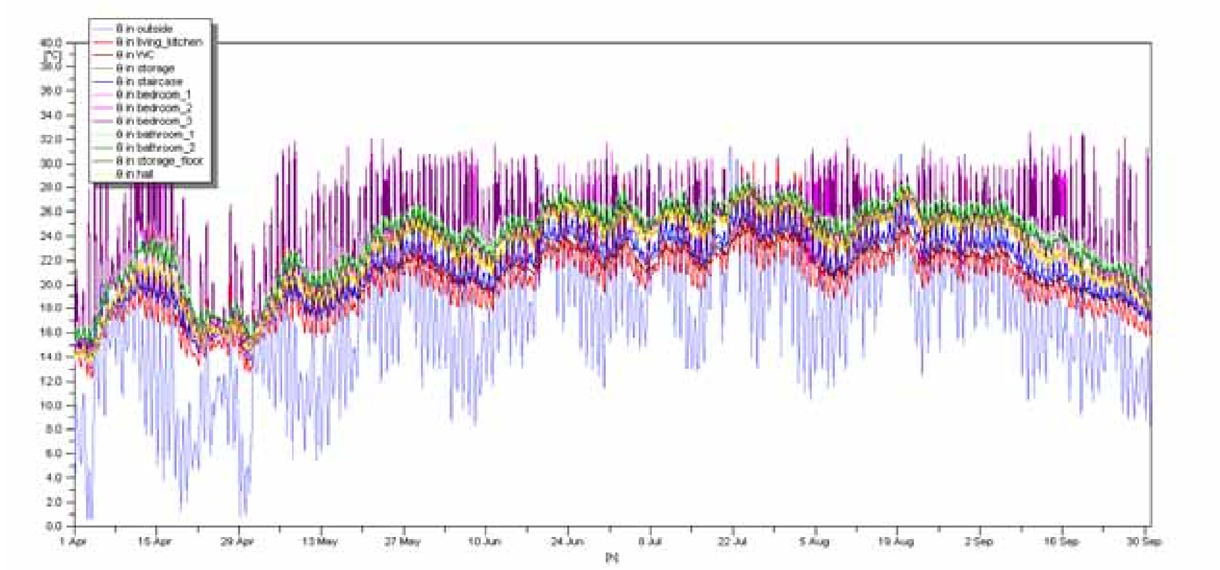

Figure D11: Double-storey single house in Vienna (Austria): Indoor temperature for all zones in the scenario sh3_v1.1.

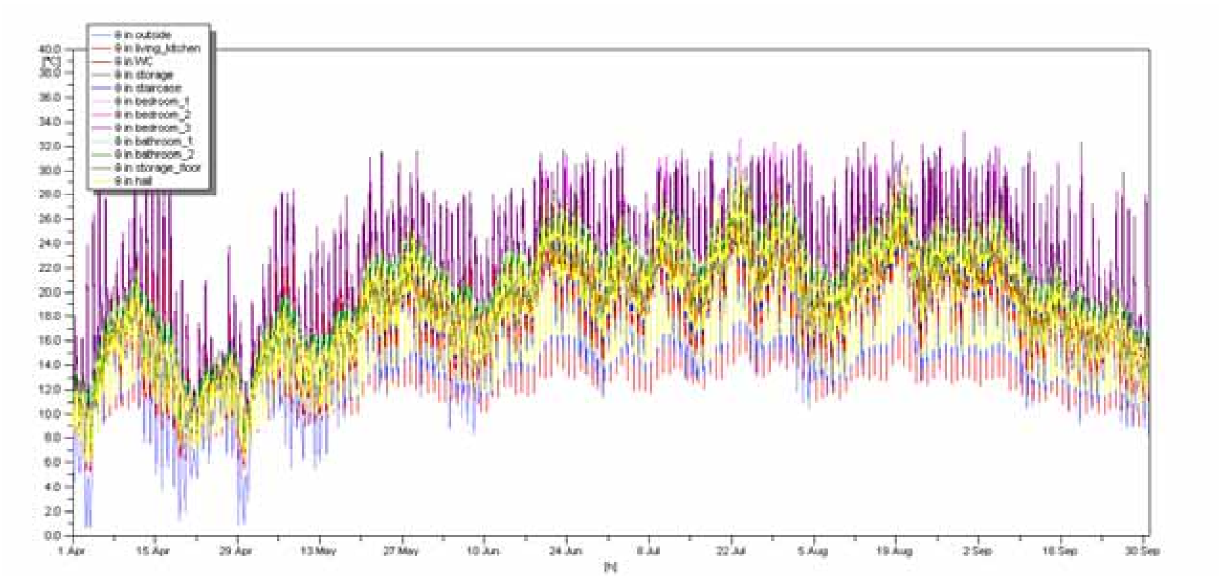

Figure D12: Double-storey single house in Vienna (Austria): Indoor temperature for all zones in the scenario sh3_v5.1.