INTERNATIONAL
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Energy Efficiency in Urban Office Buildings

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

OCTOBER 2012

THESSALONIKI – GREECE

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Abstract

This dissertation was written as a part of the MSc in Energy Systems at the International Hellenic University. In this thesis a state of the art research protocol on urban office buildings is performed, with a focus on the parameters that influence its energy performance from the early design phase. A typical contemporary urban office building was used in order to evaluate various parameters in four different European climates; warm humid, warm dry, cold humid and cold dry. Specifically, several factors are examined, such as window to wall ratio, envelope thermal mass and internal loads to understand which results in lower energy requirements. The results are compared and discussed in terms of the building design. The various parameters are assessed using Energy Plus simulation software. The whole thesis may be used as a useful tool by engineers during design phase to assess the impact of design choices on the energy efficiency of urban office buildings.

At this point, I would like to thank my Supervisor Agis M. Papadopoulos Professor Dr. - Eng., in the Department of Mechanical Engineering of Aristotle University of Thessaloniki for his invaluable help and guidance. The completion of this thesis would not have been possible without his knowledge and supervision. Moreover, I would like to thank my valuable friend and colleague Christina Konstantinidou, Civil Engineer, MSc - PhD candidate at Aristotle University of Thessaloniki for her help and support in providing me the basic knowledge in simulation software. Finally, I would like to thank my friends and colleagues Ifigeneia Theodoridou, Katerina Christodoulou and Anna Psefteli, for their support. I cannot but thank my lifetime support team, the people who helped me begin it all; my family. The academic structure of International Hellenic University made it possible to have a consistent direction in my field of interest and develop such a great knowledge within my Master of Science in Energy Systems.

Konstantia Leonidaki

29/10/2012

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1 Introduction

1.1 Background

1.1.1 Energy and Buildings

A large growth in energy consumption appears in the building sector. It is a fact that the largest energy consumers in the world are the building services while they account for 40% -more than one third- of the world's energy consumption; therefore the building sector should be active towards energy efficiency. Specifically, the 33% of all energy in the European Union is used for transport, the 26% is used by industry and a percentage equal to 41% of all energy in the European Union is used by buildings. [1]

To this percentage a 35% is also added which is the carbon dioxide emissions that occur from the building sector. According to the International Energy Agency, [2] primary energy and carbon dioxide emissions released from building processes have increased during the last two decades; by 49% and by 43% respectively. So, from 1984 up to 2004 they had an average annual increase of 2% and 1.8%. Unfortunately, this growing trend will continue. In 2002 specifically, carbon dioxide emissions constituted the 82% of total European Union's emissions; a tremendous percentage. [3]

It is illustrated that commercial buildings and primarily office buildings are crucial contributors to demand growth. In the European Union, office buildings are among the highest energy consumption while their consumption varies from 100 up to 1.000 kWh/m^2 due to numerous factors. [4] This is intensified by the increasing demand for better office building quality, therefore leading to higher energy demand. [5]

1.2 Problem definition

As mentioned above, the commercial buildings and especially office buildings with their different trades have a crucial role towards energy demand and to that end can attain significant reductions in energy efficiency.

According to researches, [6] office buildings consume energy mainly for heating, cooling and lighting purposes, while a significant portion is devoted to the consumption of office equipment. Only the aforementioned account for about the 85% of the total energy consumption in an office building. [2] Highly glazed facades in combination with poor shading are a really common phenomenon. Deep floor plans and the wider use of false ceilings make electric lighting necessary and increase overheating. [5] In addition, because of the dense environment in the city centers higher temperatures appear. Therefore, the peak electricity for cooling of an office building in the city center can be increased even by 300% compared to the same building in the outskirts.

Therefore, reducing consumption should be a priority. There are many factors that influence building's consumption from the very early design stage; the architecture of the building, its geometric and functional characteristics, as well as its lighting, heating, ventilation and air-conditioning installations. Additionally, factors such as the office equipment, appliances, internal loads and other loads from elevators, air ducts and so on influence the energy consumption. In general, the way in which the buildings are constructed, the raw materials that are used, the pollution and the waste production from the building sector are interrelated with global warming, the heat island effect and the increase of urban temperatures. [7]

Moreover, the users' irrational energy behavior practices and their subjective judgment on whether they feel comfort in the indoor environment or not, make it even more difficult to achieve energy efficiency. Also –up until recently- there were some regulatory barriers that incommoded the development of energy efficiency in some of the EU countries. Additionally, there was lack of trusted information about energy reduction, low awareness about new technologies and lack of skills of people who apply new energy efficiency measures. [8]

From all the above, it is demonstrated that energy demand is continually increasing and especially for the buildings in the sector that we examine; the commercial office buildings.

What is needed is a rethinking of the building process and the optimization of the building's needs. The right decisions have to be taken from the early stages of design in order to have the right performance on the finished building, a statement that makes the rational design of an office building even more vital.

1.3 Aim of thesis

This thesis deals with the parameters and decisions that have to be made in order to achieve the optimal behavior of an urban office building from the early stages of its design. Consequently, the focus of this thesis is to investigate the parameters that affect a typical contemporary office building and their influence depending on the climate and the location of the building in the European region.

Based on the existing situation, there is a significant need for extensive research considering sustainable building practices and measures towards high energy efficient buildings in Europe. This research focuses on the methodological approach to the design of high energy efficiency of office buildings in a European level. Specifically, the main objective of this project is a state of the art research on the parameters that mostly influence the building energy performance from the early design phase in four different European climates; warm humid, warm dry, cold humid and cold dry. Specifically, this project investigates how several building related factors such as thermal mass, window to wall ratio and internal loads may influence the building energy performance in such climates. The result of this study could be used as a guideline for the improvement of the urban office buildings’ design in different European areas.

1.4 Scope of thesis

A typical contemporary urban office building is designed and simulated with Energy Plus simulation software in order to assess its energy performance. The building has a typical lineal geometry and composite construction. Several building related factors such as thermal mass, window to wall ratio and internal loads are investigated in order to figure out their influence on the building energy performance in the climates of Thessaloniki Greece (warm humid), Nicosia Cyprus (warm dry), London UK (cold humid) and Munich Germany (cold dry). A parametric study on these variables is followed by a deeper investigation of them depending on the respective climate. A parametric analysis is conducted with the use of simulation tools in order to evaluate the parameters that influence the typical contemporary office building. A research protocol is finally performed on the effect of such measures on each respective climate.

1.5 Structure of thesis

This thesis is organized into eight chapters. Chapter one is the introductory chapter were the aim, the scope and the structure of this thesis are described along with a brief background and description of concepts that will be used in the thesis. It is important to understand the need for energy efficiency practices in urban office buildings from the early design phase. In chapter two, concepts briefly described in chapter one are more broadly explained. Chapter three is an analytical literature review of the subject. Studies that have been carried out on urban office buildings, energy efficiency upgrades and research on the parameters that affect the building energy performance are presented and commented on. In chapter four the examined cities and their respective climate are noted as well as the legal framework of the examined countries is described in detail. Chapter five describes the methodological approach that is used for this investigation thus a brief presentation of the examined simulation variables. The results of the simulations are presented and discussed in chapter six. Chapter seven includes a brief discussion of the presented results and a comparison between the respective results in the four different climates. Finally, chapter eight describes the conclusions of the under discussion results as well as the optimal proposal for an efficient design.

2 Overview

This chapter describes concepts central to this thesis. At first it deals with the impacts of the population growth and the demographic problem on buildings energy consumption and how energy consumption affected climate change. Furthermore a brief review of the building sector evolution is given and the energy behaviour of office buildings together with the problems that they face in the urban environment are introduced and evaluated.

2.1 Energy consumption: the impact of population growth and climate change

It is widely known that energy and the way that it is utilized is an issue of great concern. One of the main reasons is that we face problems of ruthless energy consumption that has occurred with the rapid growth of the world's population and therefore it is more difficult to meet the energy demands. A percentage of about 20% of the world's population consumes approximately 80% of the available energy. [9]

This situation is intensified due to the demographic problem. It is projected that up until 2025 over 60% of the world's population will reside in cities, while in the developed countries this percentage will reach 85%. [10] Although the world's population is rising we should be concerned about the demographic problem: up until 2050, it is estimated that in industrialized countries the active population will be gradually reduced while the senile population will be more and more increased. Due to the better quality of life today, the index of life expectancy has risen. Additionally due to the uncertainty caused by the economic situation, the birth rates are reducing or staying constant –at best. Unfortunately, this has an impact at the overall energy management and energy consumption. For example it is not easy for the elder people to adapt to the intense temperature fluctuations, which are now a very common phenomenon. Furthermore, according to researches, older people are more sensitive to ambient temperatures and as a result they want warmer indoor environments which in turn lead to higher energy consumptions. [11]

Therefore, cities expand, the requirements for natural resources grow and technical infrastructure and technological equipment needs are increasing. It is a fact that the energy demand is continually increasing; it is stated that an increase of the urban population by 1%, increases energy consumption by 2.2%. [10] The thirst for energy will soon exceed the capacity of fossil fuels. As we still -at a very large proportion- count on them we have to be cautious with their use. Moreover, another factor is their repercussion to the environment. Burning fossil fuels in order to meet the increased demand inevitably increases the release of carbon dioxide into the atmosphere. Carbon dioxide is a greenhouse gas and one of the major causes of climate change.

According to researches [12], climate warming will cause a decrease in heating in central and north Europe (Finland, Netherland, Germany), while in southern Europe there will be a consequent increase in cooling and electricity demand that would outweigh the decreasing need for space heating. For instance, an increase of 3.6 - 5.5% in electricity demand is estimated in Greece, while in London CO_2 emissions are doubled due to the utilization of active cooling systems, by 2030. To understand the greatness of this percentage it is enough to mention that in 2000 in London consumed 154.400 GWh of energy which correspond to 40.972.000 tons of CO_2. [10]

The aforementioned are interrelated with each other causing environmental problems, and thus intensifying climate change. Architecture and the building sector could have a significant role in reducing greenhouse emissions and mitigating the effects of climate change.

2.2 Evolution of buildings

In order to understand the current situation of the building sector, the problems that showed up and the challenges that we can take advantage of, a brief chronology of the buildings evolution is given.

Since the early fifties’ there has been rapid and unreasonably increase in energy use. The sharp rise in industry resulted in the increase of energy consumption and eventually led to an energy crisis in the European Union; together with a boost in energy prices and a reduction in economic activities. The increase in energy costs created concerns; thus the scientists had to suggest direct solutions. From that period onwards, the reduction of operating expenses accrued and became a key economic issue. The first efforts were: the thermal protection of the building envelope, the reduction of unintentional ventilation losses and the reduction of ventilation levels to a minimum rate. The first results were satisfactory in a quantitative level, but in a qualitative level there were still several issues to be discussed. For instance, by evaluating the results of the first large-scale new construction, and interventions in existing buildings emerged that there were: inadequate natural lighting, visual problems and glaring, poor air quality, moisture problems, and so on.

It was clear that the correct use of energy was the first step for energy savings. In the 1980's focus was given on energy saving measures and seeking for solutions. Typical examples were the large-scale applications in several European countries, such as the "Milton Keynes" houses in Britain, the "Solar Village" in Greece, and the "Solar House" in Germany. In addition, it was the time that an attempt started in order to promote new combustion technologies, to achieve low temperatures, pollutant reduction and low levels of emissions.

In the 1990's there was a satisfactory reduction of heating loads. Energy design started to be more and more mature. The analysis of material properties made possible, the simulation of dynamic behavior of a component in time succeeded and the integration of a building in an urban environment with speed and accuracy was a reality. Thus, in Northern and Central Europe it was feasible to achieve lower consumption levels. However, the problem of increased cooling loads appeared. This development reminded the importance of heat capacity and thermal insulation.

From 2000 onwards an overall approach to the energy and environmental protection, thus an approach to the optimization of the building sector in order to install "intelligent" systems on "smart" buildings was initiated. The term "sustainable building design" was introduced. Every building's challenge is to ensure the quality of indoor environment conditions, to set these targets for the design and, to a great extent, to be specified by a set of standards and technical guidance. [10]

2.3 Energy behavior of office buildings in the urban environment

The situation is even more difficult for the buildings considered in this thesis. Urban environment and its crowd and dense construction create harder conditions for the energy consumption in the buildings.

The construction of the urban buildings is decoupled of its environment having as a result tremendous energy consumption. The surrounding built area influences the building; its energy conscious is not limited within the borders of the fabric. Even in the case of two identical buildings in a short distance of each other their energy performance will be completely different due to the altered climatic conditions of the region. [10]

Moreover, it is a fact that urban climate is changing, ambient temperatures are increasing, and heat waves are more frequent while hot spells have longer duration. Uncontrolled development of urban areas together with poor design, increase the heat island intensity. Especially in Southern Europe, heat island is a crucial factor that contributes to a high increase of discomfort hours, an increase of cooling loads in buildings and a very high increase of the peak electricity demand. Also, according to researches the cumulative amount of cooling and heating degree days will increase and decrease respectively in comparison to results from 1990. [13]

In a study that took place in London related to the impact of the urban heat island on the current and future energy consumption in office buildings was revealed that cooling will be a necessity for this type of buildings in the next few years. One of the repercussions will be the terrific increase of carbon dioxide emissions; between 480% and 670% in the city centre location compared to the current numbers. [14]

The mitigation of heat island, the improvement of the urban environment, and the reduction of energy needs for cooling are some of the priorities on future initiatives. The demand side management techniques to control and regulate the energy consumption thus the development of a more efficient legislative framework on the energy performance of buildings are also required. Having as a purpose to improve a building's condition all of these factors have to be ameliorated but it is still important the right decisions to be taken from the early stages of design.

3 Literature review

Various studies have been carried out so as to evaluate the energy performance in office buildings from the early design phase. Numerous parameters that influence the design of an urban office building have been studied as well as the problems that occur in office buildings by not having the correct size of these parameters. Various measures and effective ways to achieve comfort have been examined and proposed. In this chapter the concepts identified in the introductory chapter are further developed and a number of relevant studies that have been carried out will be presented, analyzed and compared.

3.1 Parameters that affect energy efficiency

Energy consumption of a building firstly depends of the building's design and that is what is studied in this dissertation. However, there are some parameters that account for about 85% of the total energy consumption; the heating, ventilation and air-conditioning systems, the lighting and the office equipment. The main reason that *this percentage is so high is the wrong and fast design of the building*. Although they are counted as "following of the design phase" it is regarded as necessary that some studies that prove they are interdependent are mentioned here.

3.1.1 Heating Ventilation and Air-Conditioning Systems

The ideology of bioclimatic design is of primary importance. Still, in an urban office building due to its location –in the city center- all of these principles cannot be applicable. As A. Avgelis and A.M. Papadopoulos [15] support heating, cooling and air-conditioning systems are the solutions to improve the building's energy efficiency. However, for the satisfaction of the user there are numerous criteria that have to be taken into account such as energy, environmental and economic. Furthermore, unsuitable use of HVAC systems may cause low environmental quality, thermal discomfort and health problems. As M. Fasiuddin and I. Budaiwi [16] have written it is feasible to attain even a 25% in commercial buildings energy saving by combining a number of HVAC operation strategies but we have to be mindful for their proper use. On the side, there is also the problem of lack of harmonization in HVAC systems in European countries. According to Luis Pérez-Lombard et.al., [17] research, in Europe each country has its own “demand-efficiency” requirements but in order to reinforce the HVAC section in buildings there have to initiate homogeneity in EU energy policies.

Moreover, a fact that should be considered is that energy consumption varies by using different HVAC systems; for instance variable air volume (VAV) systems satisfy the requirements of part-load conditions as they alter the volume of air circulated in order to achieve comfort conditions. So, it is essential to make the exact choice. For instance, Ivan Korolija et. al., [18] presented that in UK office buildings, the difference between system demand and building demand varied from over −40% to almost +30% for cooling and between −20% and +15% for heating. With a heat recovery unit in use, the difference in heating performance is even greater, rising to −70%. In the very end, they resulted that it is not possible to form a reliable judgment about building energy performance based only on building heating and cooling loads. Last but not least, the air handlers have to be taken into account thus they offer a variety of energy saving opportunities of the HVAC systems for most commercial buildings. [19]

The impact of auxiliary energy on the efficiency of the heating and cooling system has also been monitored in 11 low-energy non-residential buildings in Germany. [20] It was showed that auxiliary energy use accounts for 25–45% (3–10 kWh/(m^2_{net})) of the end and primary energy use for heating, cooling and ventilation –a percentage that it cannot be overlooked.

3.1.2 Lighting

Lighting is a part of the internal loads that we are going to investigate regarding their impact on the building. It is also one of the largest consumers, while in commercial buildings it constitutes for 20-45% of the energy demand. Marie-Claude Dubois et. al., [21] by examining previous literature reviews resulted that it is feasible -with the appropriate strategies- to reduce electric lighting in office buildings at least by 50%. There is a variety of strategies that result in this, such as: improvement in lamp technology, in ballast technology, in luminaire technology, in maintenance factor, in utilization factor, effect of latitude and orientation, effect of window characteristics, of shading devices, of ceiling height and so on. The aforementioned study emphasizes on a North European context; however the same tactics may be followed in all of the European countries.

3.1.3 Office equipment

Last but not least, a significant portion of the energy consumption is devoted to the office equipment, also a part of the internal loads. A research that took place in Greece proved that almost the 26% of the total energy consumption is because of office equipment and other electrical equipment. [22] The results of Kawamoto et. al. are also interesting. [23] They found that only by using power management in office equipment we can attain savings as much as 3.5 TWh per year. Their results were that an average desktop computer with a display, either CRT or LCD, consumes about 30% of its energy use during idling, and 40% in non-business hours. This consumption can be decreased by 60% only by enabling the power management. For copiers the results showed that 47% of energy is used in non-business hours, and about 48% of energy is used during idling in business hours. Using power management about 90% of the energy use in non-business hours can be saved. For printers, about 50% of energy is used in non-business hours and 45% of energy is used during idling in business hours. By built-in and properly functioning power management about 65% of the energy use in non-business hours can be saved. Nevertheless, the energy use of office equipment in Japanese offices with no use of power management is even lower than that in US offices with maximum use of power management. A contiguous study for US offices showed that among 1453 desktop computers the turn-off rate was 36% while only 6% of all desktop computers that were not off were in low power mode. The average turn-off rate among 1329 CRT monitors was 17% for medium offices. [24] Unfortunately, these percentages are not relevant to European countries. Nevertheless, by investigating and evaluating the impact of internal loads on an office building in this thesis, we will conclude on how the energy efficiency is differentiated and how important is to use power management in order to attain these savings.

3.2 Office buildings in the examined countries

Recently, T. Nikolaou et. al., completed an effort to create a virtual building dataset of 30,000 national office buildings built from 1960 up till 2009 in order to make information about the constructional and the operational characteristics available. Through this database, buildings simulation outputs such as the annual specific energy consumption for heating, cooling, artificial lighting, office equipment and others can be known. The results showed that the mean annual energy consumption for heating is: 38.70

kWh/m^2 for climatic zone A, 49.96 kWh/m^2 for climatic zone B, and 76.09 kWh/m^2 for climatic zone C. The mean annual energy consumption for cooling is 108.80 kWh/m^2 for climatic zone A, 110.54 kWh/m^2 for climatic zone B, and 97.91 kWh/m^2 for climatic zone C. [25] Another research that took place in Greece proved that commercial buildings and specifically the offices that represent the 2.74% of the building stock, have energy consumption equal to 339 kWh/m2 [26] that is extremely high in comparison to other European countries. This average annual total energy consumption is even higher for office buildings used as bank branches and was found to be as much as345 kWh/m2. [27] Mainly because of economic factors and the lack of information there is a problem in promoting bioclimatic design. According to C. Karkanias et. al., [28] constructors have a great profit that reaches up to 160% of the construction cost, from constructing a conventional building rather than a bioclimatic one. So, customers are forced to that direction. In addition the very dense urban space and the lack of expertise are other repulsive factors.

For Cypriot office buildings there are no published papers about their energy efficiency. All the studies concern residential buildings. However, some of the factors that will be examined in this thesis have been investigated for a residential house in the city of Nicosia. Specifically, Kefa Rabah [29] investigated the pre-design stages to utilize passive solar energy the best. The considered techniques were: passive solar control, mass effect, mass effect with night ventilation, air movement effect, evaporative cooling and indirect evaporative cooling. Simulations showed that the appropriate combination of passive solar control was 18.0%, with equatorial window covering 20% of floor area and efficiencies of 0.7 and 0.5; mass effect/mass effect with night ventilation 22.0%; air movement effect/evaporative cooling 40.2% with air velocity of 1–1.5 m/s; shading 4.5%. The remaining area covering about 33.3% requires supplementary active cooling with high mass gain. The impact of storage mass will also be studied in this dissertation and will be examined if the percentages of the office buildings are similar to the residential ones.

The above figures that referred to the European Union (37%) were proved to be the proportion of building consumption in the United Kingdom (39%). The main percentages of energy consumption in offices by end use are, in particular, 55% for HVAC, 15% for lighting and 5% for office equipment. [30] According to studies that took place there, the factors that influence an office building have an immediate impact on the occupants. Subsequently, we have to take under consideration the productivity of the employees. The link between work productivity and indoor temperature or thermal conditions, another reason that the design phase of a building is important, was investigated by Jones L., De Wilde, P. [31] Additionally, again in the UK a study was conducted to quantify how climate changes and the temperature's rise will affect heating and cooling energy use in future office environments. It was proved that UK offices –despite the warm climate- can reduce their cooling usage through management of lighting loads and equipment. Specifically only with this measure, D. Jenkins et. al., [32] proved that reductions can be from 60 to 75%. Office buildings with high internal gains will always require a more complex cooling strategy; however, according to this study cooling loads can be reduced to the point that passive cooling may be able to maintain tolerable temperatures. With that it is also proved that the previous mentioned parameters are crucial. In this dissertation, the effect of internal loads on the building's efficiency will also be studied.

Offices in Germany and other European countries examined within the "OFFICE project". It was an effort to advance energy performance and indoor working conditions in office buildings. It was demonstrated that offices in German have poor conditions with high possibilities of retrofitting. [33] Additionally, there are numerous publications about attempts of buildings' renovation.

Nevertheless, there are also literature reviews about the limitations and barriers on energy efficiency. However, in Germany at least, factors that affect the building's design have not yet examined as it is going to be done here. So, this thesis will give innovative results.

3.3 Previous relevant efforts

A first effort made by G. Kanagaraj and Ashwin Mahalingam, [34] concerns the proposal of *a comprehensive design process*, the so-called "Energy-Efficient Building Design Process". This process consists of three phases in order to identify the broad parameters that will affect the building's design, to involve the generation of design alternatives and evaluate those using predictive methods and tools for their performance across energy efficiency and occupant comfort parameters. It was used to demonstrate its applicability by designing an office building in New Delhi, India. In this thesis, a similar design will be proposed but for cities in Europe.

Design factors like *the geometry of an office building* have examined by Adnan AlAnzi et. al., [35] in a detailed parametric analysis. A number of different shapes and floor plans investigated such as Rectangular shape, L-shape, T-shape, Cross-shape, H-shape, U-shape and Cut-shape. The results of the analysis showed that mainly three factors are affected by the form of the building. Specifically, the relative compactness, the window to wall ratio and the glazing type as it is described by its solar heat gain coefficient. It was proven that -independently of the shape- the total energy use is conversely proportional to the building relative compactness when it has low window to wall ratios. Additionally, it was verified that there is a correlation between the aforementioned parameters and annual total building energy use. It was given an equation to be used by architects in the design phase to evaluate the contact of the shape on the energy efficiency of office buildings. The only disadvantage of this study is that refers only in buildings in Kuwait. Here the lineal shape will be examined in four different cities across Europe.

Bojan V. Anđelković et. al., [36] investigated *the impact of thermal mass* of a low, medium and heavy mass building. Cases such as concrete that is used only in the floors and ceilings (light weight construction), concrete that is used in the floors and exterior walls and roofs (medium weight) and also concrete that is used in combination with insulation (heavy weight) were some of the simulations done. The results proved that in all of the cases annual space heating energy requirements were reduced and in 67% of the simulated cases, annual space cooling energy requirements were reduced. In the 83% and 50% of the cases the peak space heating and cooling demand reduced respectively. The simulation program that used was Energy Plus but this study was only for an office building in Belgrade while in this dissertation these factors will be studied in four European countries.

The *window-to-wall ratio* and its effect were investigated by Farshad Nasrollahi. [37] The results showed that the best window ratio for heating, cooling and lighting is respectively 80%, 10% and 40%. In order to decrease the total energy consumption, the optimum window to wall ratio is 50%. These percentages are different if there are shading devices. Additional, Xing Su and Xu Zhang [38] approached the window-to-wall ratio by an environmental aspect resulting that the ratio of single glazing window has a huge impact on the life cycle environmental trouble and that by choosing a lower U-value window the life cycle environmental impact is reduced. Our study is an energy approach of the aforementioned factor.

The *impact of –mainly- envelope related factors on the thermal performance of office buildings in four different climatic areas* was examined by Mohammad S. Al-Homoud. [39] It was showed that by implementing optimization techniques in the early phase of the building design both lower energy use and lower peak heating and cooling loads can be attained. Furthermore, a number of suggestions on the thermal design of office buildings accrued. For example it was proved that in all climates the most desirable gazing exposure is the South and that the East and West are the most inappropriate, the external shading devices are the best option, that the roof U-value is more critical than wall U-value and so on. However, the results of this study were not quantified. In this thesis the results that will accrued will be quantified and percentages will be given in order to have a complete figure of its factor's influence.

An exemplary illustration of a "sustainable" construction design for office buildings was given by B. Lehmann et. al. [40] "Forum Chriesbach" in Switzerland has a unique combination of architectural and technical elements. The building, which reaches a very low 88 kWh/m^2 overall primary energy consumption, is heated mainly by using the sun and internal heat gains from lighting, electrical appliances and occupants, resulting in an extremely low space heating demand. Internal gains are used in order to reduce heating demand. In this thesis, the impact of different internal loads (high, medium and low) will be examined. Cooling is provided by natural night time ventilation and the earth-coupled air intake, which pre-cools supply air and provides free cooling for computer servers. Room temperatures during an extremely hot summer period are below 26 °C and 20–23 °C in the winter season. Additional costs compared to a conventionally constructed building were only 5% and the payback period is 13 years.

Natasa Djurica et. al., [41] conducted a study to *identify driving variables of energy use* in a low energy office building. Building energy management system (BEMS) and energy use data were integrated to understand what contributes the most to building energy use. BEMS are automation systems that have the ability to control and regulate at the same time a set of parameters (temperature, humidity, air quality and speed, lighting levels, etc.) by optimizing the operation of active and passive systems of a building. Variables such as occupancy level, control signals, and water and air temperatures, were used to explain heating, electricity, and fan energy use. However, this approach is only helpful if data are lost. K.J. Chua and S.K. Chou [42] *studied a variety of parameters that influence the energy performance* of commercial buildings in Singapore. It was revealed that the Envelope Thermal Transfer Value (ETTV) had a strong correlation with the annual cooling energy requirement (Ec); specifically it was demonstrated that a reduction of ETTV from 50 to 45 W/m^2 would yield around 2.5% reduction in cooling energy. In another research that was held in Jakarta, Indonesia, the heat transfer was also investigated together with air flow. Two office buildings with the same orientation and location with double skin façades but with a different building envelope were simulated. The role of wind –thermal performance and behavior of the wind- on the building design was proved to have an influence on the heat transfer and energy savings. [43]

Solutions that may be used in practice, so as *to design energy efficient office buildings* with a good thermal interior climate, were suggested by Elisabeth Gratia and André De Herde. [5] In the case where the influence of various parameters, like: insulation level, internal gains, ventilation strategies, thermal mass, etc were studied it was proved that the window area and the orientation had to be fixed. In a second case, in a very well insulated building, where the influence of orientation, solar gains, shadowing devices, ventilation strategies, etc were studied it was proved that insulation level and internal gains should be fixed. The whole study -that took place in Belgium (northern part of Europe) - is really close to the parametric analysis that will be done in this thesis; although here more than one climate will be studied.

What is more, within the "OFFICE" project –a coordinated by the University of Athens and institutes from eight European countries project- were given *design guidelines and methodologies for best practice office buildings*. [44] In the same project, several examples of renovated office buildings throughout Europe investigated to result in a rating methodology and classify them according their consumption, emissions and comfort.

The case of night ventilation in a *lightweight construction* –as the one that we study- office building located in cold climates was looked into by Zhaojun Wang et. al. [45] Night ventilation used cool outdoor air in order to cool the surface of the building envelope. Important factors were evaluated that could influence night ventilation performance such as ventilation rates, ventilation duration, building mass and climatic conditions. The locations outside temperatures were 24 to 30 ^{o}C maximum during the summer period and 10 to 22 ^{o}C minimum. It was concluded that even in lightweight constructions more energy can be saved in office buildings cooled by a night ventilation system. This strategy was appropriate to postpone active cooling operation and reduce cooling loads in typical air-conditioned offices but mechanical night ventilation could lead to increased energy consumption. Jens Pfafferott et. al. [46] had a slightly more advanced approach in Germany, a location with lower temperatures. It aimed *to design, monitor and evaluate a low energy office building* with passive cooling by night ventilation. The concept was to *use architectural solutions to minimize HVAC and artificial lighting from the design phase*. With the required thermal insulation and moderate window dimensions a low heating and cooling energy demand was succeeded. With the design of an atrium both a buffer zone for solar energy gains and also natural lighting was achieved. Both natural and mechanical ventilation was used in the offices. It is important to note that the building for the period from 16th July 2001 to 12th August 2001 had internal heat gains that were higher than the solar heat gains. The strategy was to optimize night ventilation and the additional mechanical ventilation to be controlled without manual involvement. The results showed that it is a great need for hybrid ventilation strategies to be implemented carefully in order to avoid disturbance of the natural ventilation by additional, mechanically driven air flows.

In warm climate regions though, thermal storage mass can be utilized as a cooling strategy to reduce the required power loads throughout the daily working period in office buildings. R. Becker and M. Paciuk [47] insisted that the most effective strategy for lowering the required power loads is night pre-cooling. However this is appropriate for office building with *large internal heat loads*. For non-loaded buildings, on the other hand, it increases total energy loads and night-time peak power loads. Nevertheless, night ventilation is suitable for both types of buildings. The impact of thermal storage mass and internal loads will be some of the parameters that will be simulated, studied and evaluated in this study. The results will give the best design choices for -commercial- office buildings.

4 Description of the selective areas

Four different climatic regions are selected for the needs of this thesis. Specifically, in order to evaluate the effect of various building related factors in a warm-humid, a warm-dry, a cold-humid and a cold-dry climate, the cities of Thessaloniki Greece, Nicosia Cyprus, London UK and Munich Germany are respectively selected. In this chapter the climatic parameters of these four (4) European cities are described and is investigated the legal framework in the chosen countries giving leadenness to its country's Energy Performance of Buildings Directive (EPBD). Furthermore, the European's Union energy targets are presented and the relationship between this dissertation and the "20-20-20" targets is commented.

4.1 Climatic characteristics

4.1.1 Thessaloniki (humid warm climate)

In order to evaluate the effect of the selected parameters on a humid warm climate the case of Thessaloniki in Greece is examined. Greece is one of the sunniest countries in Europe. It is located at the Southeast end of Europe and has a generally temperate climate. [Figure 1]

Figure 1: Greece's location in the European Union

The characteristic of its climate is the mild wet winters and hot dry summers. Thessaloniki (with north latitude 40° 31' and east longitude 22° 58') which is the examined city is the second-largest city in Greece and the capital of the region of Central Macedonia. Due to its situation –next to the sea- Thessaloniki's climate is affected directly by it. It is proved [48] that the areas along and the buildings near Thermaikos bay are influenced even more by the sea breeze. According to Köppen climate classification Cfa, the city has a humid subtropical climate that borders on a semi-arid climate. Data from the World Meteorological Organization shows that average temperatures during winter are 5.3 – 11.1 ^{o}C. Winters are relatively dry, with common morning frost. Almost every year snowfalls occur, but the snow does not stay for more than a few days. During the coldest winters, temperatures can drop to −10 °C; thus the minimum temperature that has recorder was −14 °C. On average, Thessaloniki spends 32 days a year below 0 °C. Wind is also a usual phenomenon for the city of Thessaloniki. Summers are hot and humid. The average temperatures are 22.8 – 25.1 ^{o}C however temperatures usually rise above 30°C. The maximum temperature that has been recorder was 42 °C. In Figures [2, 3] the average high and low temperature for Thessaloniki and the average rainfall are presented in order to have a complete idea of its climate.

Furthermore, Thessaloniki is used to heat waves. For such a warm and humid climate the traditionally proposed design criteria use natural cross ventilation. Air velocity and solar protection are the major design criteria for warm humid climate. [49]

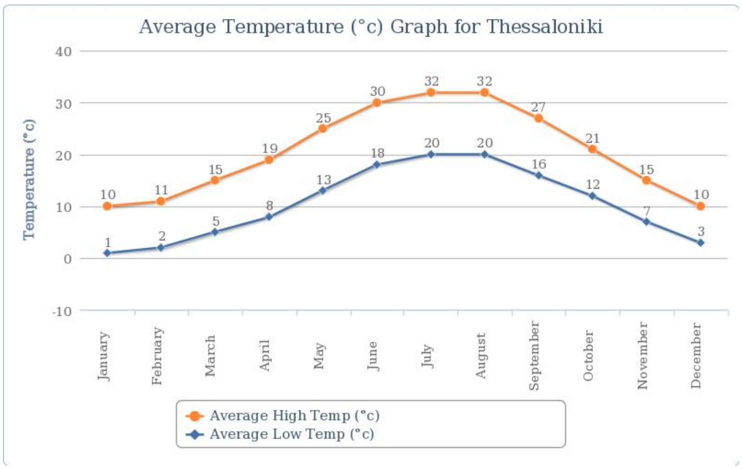


Figure 2: Average High/Low Temperature for Thessaloniki, Greece [50]

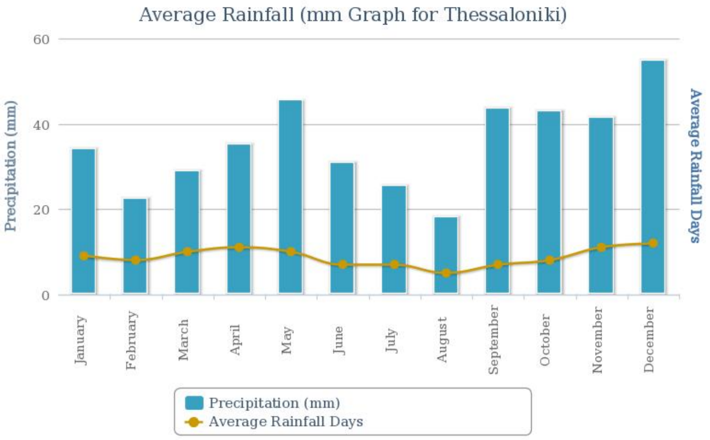


Figure 3: Average Rainfall for Thessaloniki, Greece [50]

4.1.2 Nicosia (dry hot climate)

Another location with semi-arid, Mediterranean climate is Nicosia in Cyprus. Cyprus, a recent member of the European Union, is located in Southern Europe, in the East of the Mediterranean Sea, 75 kilometers South of Turkey. With an area of 9.251 km it constitutes the third larger island after Sicily and Sardinia. [Figure 4]

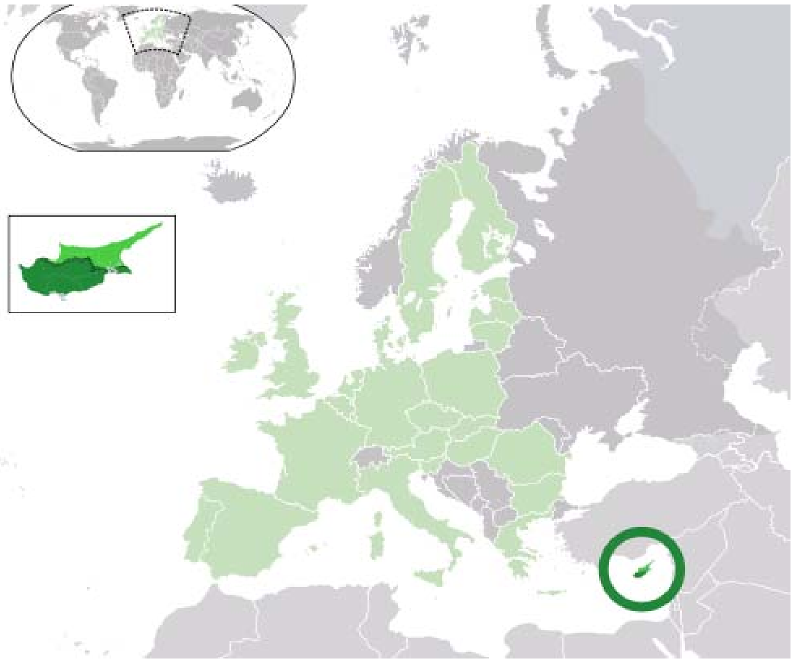


Figure 4: Cyprus' location in the European Union

Its climate is characterized as a hot subtropical semi-arid climate, according to Köppen climate classification. It has long, hot and dry summers with high temperatures however due to the sea breeze a pleasant atmosphere is created in the coastal areas. The average temperatures during summer are 32 ^{o}C. Winters are relatively wet and mild with average temperatures 12 - 15 ^{o}C. Moreover, autumn and spring seasons are short with average temperatures 21 – 28 ^{o}C. As it is clear from Figure 6, rainfall rates are relatively high only during December and January. Nicosia (with north latitude 35° 11' and east longitude 33° 23') is the capital of Cyprus and is located in the central part of the island. In Figures [5, 6] the average high and low temperature for Nicosia and the average rainfall are presented in order to have a complete view of its climate.

The focal problem with Nicosia's climate is overheating that reduces evaporative cooling effect. So, it is important to take the right design decisions respecting a building's mass, its thermal properties, sun protection, ventilation and so on. [51] It has to be stated here that as said by G. Manioglu and Z. Yılmaz [52] a dynamic model should be used to evaluate the thermal performance of areas with hot and dry climate; and heat capacity of the building envelope has to be one of the factors that has to be taken into account.

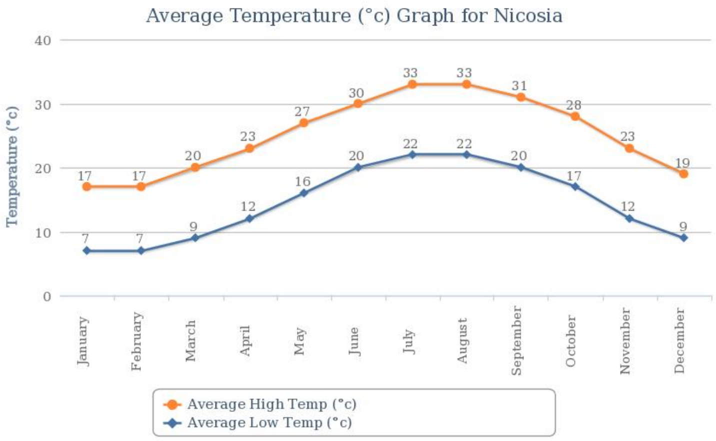


Figure 5: Average High/Low Temperature for Nicosia, Cyprus [53]

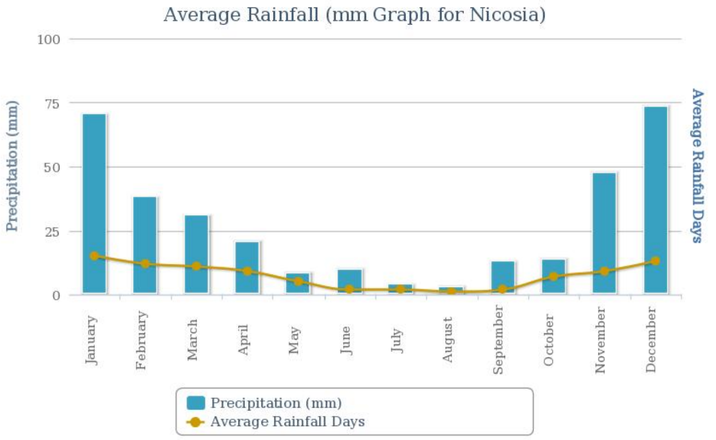


Figure 6: Average Rainfall for Nicosia, Cyprus [53]

4.1.3 London (humid cold climate)

The third location is the United Kingdom of Great Britain and Northern Ireland. The UK is surrounded by the Atlantic Ocean, the North Sea, the English Channel and the Irish Sea. [Figure 7]

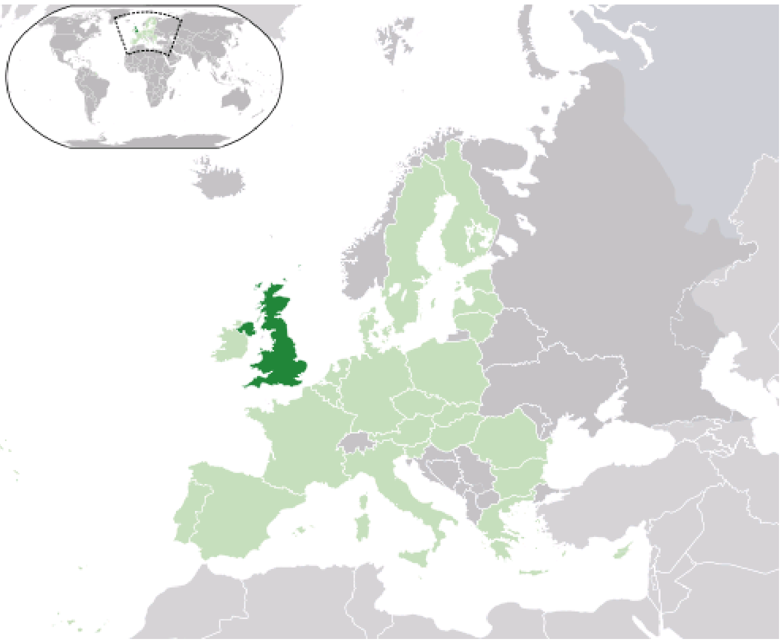


Figure 7: United Kingdom's location in the European Union

Its climate is temperate with plentiful rainfalls all year round. The Atlantic Ocean affects the climate and creates frequent spells of mild and wet weather. The prevailing wind is from the south-west, although the eastern parts are mostly sheltered from this wind. London (with north latitude 51° 30' and east longitude 0° 10') is located in the South and its climate is characterized as oceanic. According to the United Kingdom's national weather service, winters are chilly to cold with temperatures that fall below -4 °C or rise above 14 °C. Summers in London are warm. The average temperature is around 24 °C. However London is affected by the urban heat island effect, resulting in a 5 °C rise in temperature in the city center compared to the outskirts. Data reveals that during the 2003 European heat wave there were 14 consecutive days above 30 °C. In Figures [8, 9] the average high and low temperature for London and the average rainfall are presented in order to have a complete view of its climate.

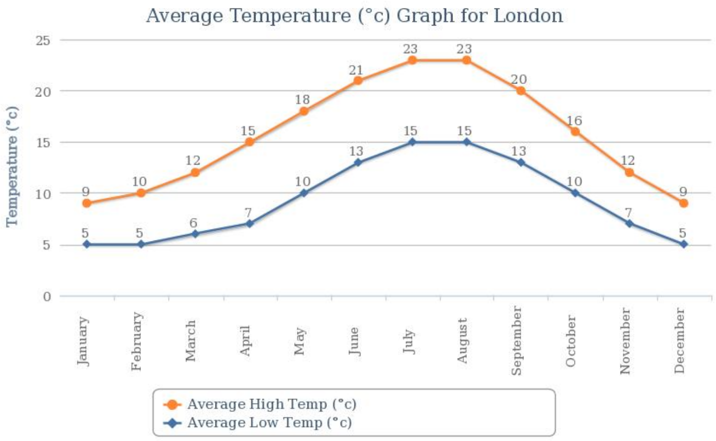


Figure 8: Average High/Low Temperature for London, United Kingdom [54]

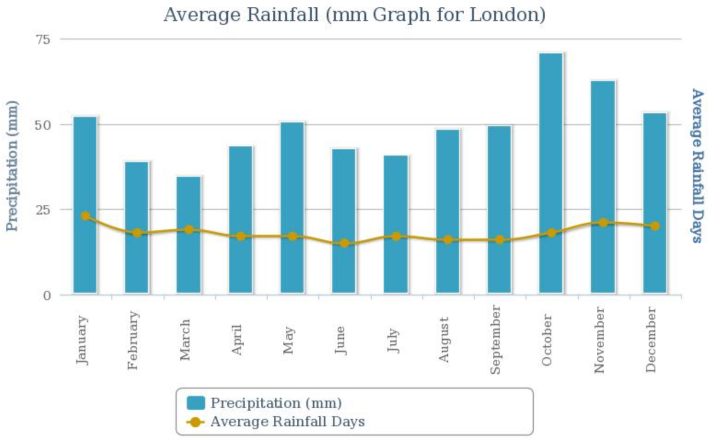


Figure 9: Average Rainfall for London, United Kingdom [54]

4.1.4 Munich (dry cold climate)

The last location is Munich (with north latitude 48° 8' and east longitude 11° 34'); the capital and largest city of Germany of Bavaria. It is located on the River Isar north of the Bavarian Alps. Germany’s climate is affected by the North Atlantic Drift, the Northern extension of the Gulf Stream. [Figure 10]

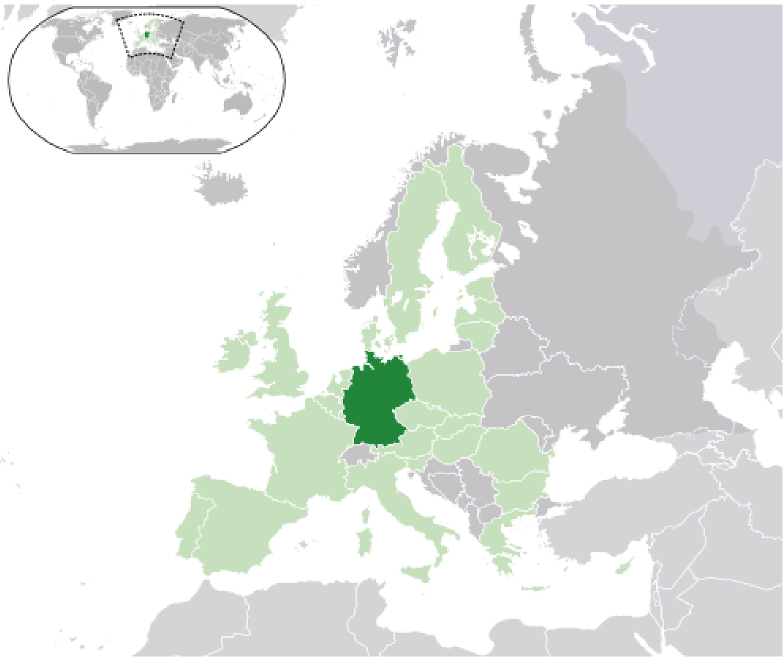


Figure 10: Germany's location in the European Union

In most areas in Germany humid westerly winds predominate. A difference of the previous two climates is that in Germany rainfall occurs especially in summer. Specifically, the wettest months are June and August, and the driest on average October and February. However, the East has a more continental climate with very cold winters and warm summers and long dry periods. Munich has a continental climate, strongly modified by the proximity of the Alps. The city's altitude and proximity to the northern edge of the Alps mean that precipitation is high. Rainstorms often come violently and unexpectedly. The range of temperature between day and night or summer and winter can be extreme. A warm downwind from the Alps can raise temperatures sharply within a few hours, even in winter.

Winters last from December to March. Munich experiences cold winters, but heavy rainfall is rarely seen in the winter. The coldest month is January with an average temperature of −2.2 °C. Snow cover is seen for at least a couple of weeks during winter. Summers in Munich city are warm with an average maximum of 24.0 °C in the hottest month of July. The summers last from May until September. Precipitation can be prodigious in the summer months from May to September.

Due to heat island and the city's urban environment, temperatures in Munich's city center can be 4 °C higher in the city than in the surrounding areas. In Figures [11, 12] the average high and low temperature for Munich and the average rainfall are presented in order to have a complete view of its climate.

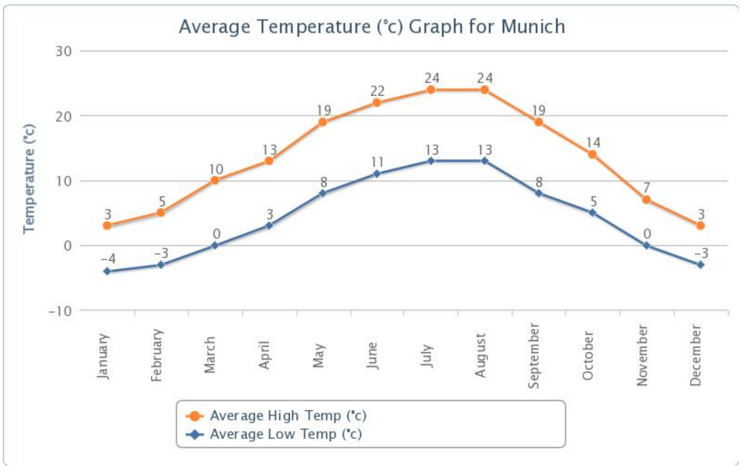


Figure 11: Average High/Low Temperature for Munich, Germany [55]

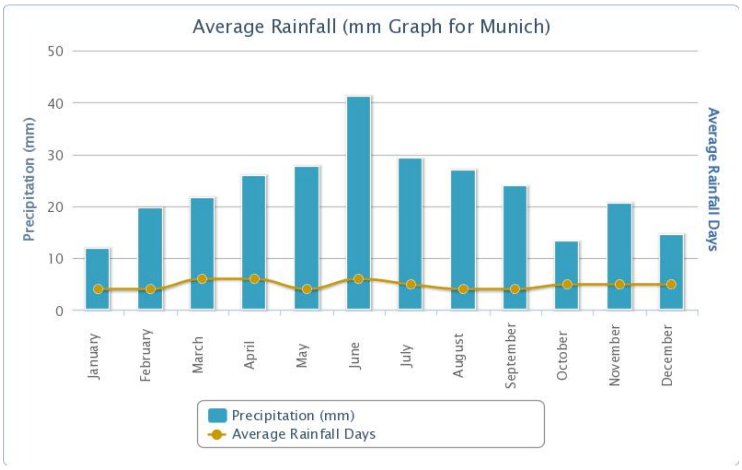


Figure 12: Average Rainfall for Munich, Germany [55]

4.2 Legal framework

As aforementioned above, a modern typology of an urban office building will be selected and studied in four different European climates. The selected countries are: Greece, Cyprus, United Kingdom and Germany.

The European Union in March 2007 set targets about climate and energy. These targets, known as the “20-20-20” targets, have three main objectives for 2020: reduction of a percentage equal to 20% in EU greenhouse gas emissions regarding the 1990 levels; increase of the renewable resources production share in EU of about 20% and the improvement of energy efficiency in the EU by 20%. While these targets are mandatory, the EU members shall comply with them. So, new buildings have to be constructed according to new regulations in order to be more efficient, release less emissions and integrate renewables. This thesis is an effort to create a way of design for efficient office buildings.

Following a comparative analysis [56] considering the Energy Performance Building Directive (Directive 2002/91/EC) implementation is given.

4.2.1 Implementation of the EPBD in Greece

In Greece, the first effort to include energy performance of buildings in the national legislation was made with the so-called "Energy 2001" project. However, the first publication of the KOXEE regulation was completed in early 2004. After four years of effort Greece managed to adapt the Energy Performance of Buildings Directive by the national law N.3661/2008. By the national laws N.3855/2010 and N.3851/2010 on RES, Greece consorted with the European Directives 2006/32/EC and 2009/28/EC respectively. The Hellenic EPBD law is essentially a translation of the European one, nevertheless with the Hellenic "Regulation on Energy Performance in the Building Sector – KENAK" the energy audits of buildings, along with heating ventilation and air-conditioning equipments are introduced. In addition, KENAK introduced lower U-values for the four Greek climate zones. Moreover, four technical guidelines (TOTEE) were published and a simulation program (TEE-KENAK) was developed for the comprehensive implementation of KENAK. [3] For the new buildings a number of requirements were initiated and for both new and existing ones a classification was introduced. So, if an existing building undergoes major renovation, it has to be classified at least as B. [57]

According to the effort done by Antonio P.F. Andaloro et. al., [56] who tried to give a comparative analysis by examining the extent to which the Directive has been implemented by the 27 EU Member States, resulted that in Greece national laws adopted in 2008. Specifically, in November of 2008 the execution orders had been assigned to Centre for Renewable Energy Sources (CRES) and published. Unfortunately, the obligation to certify new buildings and buildings to be rented or sold delayed, while issues such as professional requirements for energy certificate advisors resolved a few months ago. In addition in line with this study there is no energy certification experience gained prior to the EPBD.

For this study the characteristics of the building elements used are based on each country's existing legislation. The Greek territory is divided into four climatic zones based on heating degree days. Thessaloniki ranks the third climatic zone (C) of Greece in relation to Technical Guidelines. [[58], [59], [60], [61]] The minimum requirements for the U-values were changed with the implementation of the EPBD and according to the new regulation are given in the following Table 1:

Table 1: Minimum Requirements according to the New Greek Regulation [57]

Minimum Requirements according to the new Regulation		U-value [W/m^2.K]			
		Climatic Zone			
		A	B	C	D
Roofs	U_v_D	0.5	0.45	0.4	0.35
External Walls	U_v_W	0.6	0.5	0.45	0.4
External Floors	$U_v\_D_L$	0.5	0.45	0.4	0.35
Floor over ground	U_v_G	1.2	0.9	0.75	0.7
External walls in contact with the ground	$U_v\_W_E$	1.5	1.0	0.8	0.7
Openings	U_v_F	3.2	3.0	2.8	2.6
Glass Facades	$U_v\_G_F$	3.2	2.0	1.8	1.8

4.2.2 Implementation of the EPBD in Cyprus

In Cyprus, the EPBD Law was based on the Law for the Regulation of the Energy Performance of Buildings L. 142(I)/2006. The implementation of the EPBD Law was completed in 2009 along with the initiation of the Energy Performance Certificate (EPC). In 2009 a new Ministerial Order was enacted with more strict requirements: the average U-value of the building envelope and the EPC with a B category. The EPC, a two-phase procedure, became mandatory in 2010. At the first phase only residential buildings had to be certified but at the second one commercial, educational, office and all of the other non-residential buildings had to be certified. The methodology is described in the "Guide of Thermal Insulation of Buildings (2nd Edition" and in "Methodology for Calculating the Energy Performance of Buildings". [62]

According to the effort done by Antonio P.F. Andaloro et. al., [56] in Cyprus the National laws related to the EPBD and the harmonization of calculation methodologies with CEN standards applied early enough, in 2006. However, there was not enough information about the professional requirements for energy certificate advisors. It was stated that experts could be any Architect, Civil, Mechanical or Electrical engineer registered in the Technical Chamber of Cyprus who had 3 years experience in the related fields for residential buildings, and 6 years for non-residential buildings and have a certificate for the successful completion of the training course related to the knowledge of the methodology, software and legislation. In addition, there is no knowledge about the energy certification experience gained prior to the EPBD.

For this study the characteristics of the building elements used are based on each country's existing legislation. According to the new Ministry Energy Performance Requirements that issued the U-values were kept the same for the building envelope with the 2007 regulations, but the requirements made more stringent as now the building is regulated as one entity. The 2007 U-values are given in Table 2 below:

Table 2: Minimum energy performance requirements for new buildings in Cyprus [62]

Minimum energy performance requirements for new buildings and all buildings above 1000 m^2 that undergo a major renovation (2007 regulations)	
Description	U-value [$W/m^2.K$]
Horizontal structure elements of the shell	≤ 0.75
Wall and structural elements of the shell	≤ 0.85
Windows and external doors	≤ 3.8
Floor n contact with unheated spaces	≤ 2.0

4.2.3 Implementation of the EPBD in United Kingdom

In England and Wales it was in 2010 when some revisions to the Building Regulations and the Approved Inspectors were initiated. In Scotland "The Building Amendment Regulations 2010" initiated also in 2010. However, in Northern Ireland the same legislation was introduced in 2006 while the "Energy Performance of Buildings Regulations" in 2008. In England the certification were implemented and completed in 2008 were Energy Performance Certificates became mandatory. As in the previous mentioned European countries, EPC shows the energy performance of a building and has a rating scale.

In the United Kingdom the energy used in buildings accounts for almost 50 per cent of all UK carbon emissions, thus it is of a great importance to rapidly improve the energy efficiency of the existing building stock. The UK strongly supports efforts to tackle climate change and reduce carbon emissions. Specifically, the government has recently set a binding target to reduce carbon emissions by 80 per cent by 2050. [63]

According to the comparative analysis [56] the EPC became compulsory in England and Wales since the first month of 2008 for new residential buildings while for commercial buildings since the middle of 2008. The methods to calculate energy performance, currently in use or being perfected and the professional requirements for energy certificate advisors had already been arranged since 2006. In England and Wales the energy assessors have to hold a current qualification in Energy Inspection. An energy assessor must be a member of a specialist accreditation scheme approved by the Government. Each accreditation scheme is responsible for ensuring that energy assessors are suitably qualified to conduct energy assessments and for ensuring the quality of the assessments and any certificates or reports produced. However, the harmonization of calculation methodologies with CEN standards was done in 2009.

For this study the characteristics of the building elements used are based on each country's existing legislation. In London the requirements are divided into two categories: for dwellings and non-dwellings. For non-domestic buildings the limiting U-values are shown in the Table 3. It is essential to note that there is an obligation; a 25% reduction in CO_2 emissions across the new build-mix.

Table 3: Limiting requirements for new buildings in United Kingdom [63]

Non Dwellings: Limiting U-values (new build)	
Element	Limiting U-Value [W/m^2.K]
Wall	0.35
Floor	0.25
Roof	0.25
Windows, roof windows, roof lights and curtain walling	2.2
Pedestrian doors	2.2
Vehicle access and similar large doors	1.5

High usage entrance doors	3.5
Roof ventilators (including smoke vents)	3.5

4.2.4 Implementation of the EPBD in Germany

In Germany it was in October 2009 when the “Energy Saving Ordinance” was initiated and its requirements along with the obligation to use renewable energies for heating in new buildings. The latter made mandatory according to the “Renewable Energies Heat Act. The EPBD has its bases on the “Energy Saving Act” (1976) which included requirements such as: thermal insulation of buildings, heating, ventilation and hot water systems and billing on an individual consumption basis. Since 2002 an “Energy Performance Certificate” has been obligatory for new or renovated buildings which in order to be certified standard forms are filled in. The calculation method for the certification is described in the standard DIN V 18599. [64]

According to Antonio P.F. Andaloro et. al., [56] and their comparative analysis related to the Directive 2002/91/EC is clear that German was prepared regarding its national laws, obligation to certify arising from the EPBD, methods to calculate energy performance since 2006 or even earlier. Before the EPBD was arranged a voluntary certification system; the first regulation was developed in 1982. Since 1995 the Energy performance of new buildings is object of a document fixed by law.

For this study the characteristics of the building elements used are based on each country’s existing legislation. The requirements methodology for the non-residential buildings in Germany has already been the reference building method. However, for the energy efficiency of the building envelope a minimum requirement was also set. The limiting U-values for Germany are as follows:

Table 4: Limiting requirements for buildings in Germany [64]

Component	Reference design /U-Value [W/m^2.K]	2nd requirement
External walls, Floors	0.28	Small detached residential building H'_T=0.40 W/m^2.K Large detached residential build-
Floor, basement structural element	0.35	
Roof, upper ceiling	0.2	

Windows incl. French windows	1.3 (skylight U=1.4)	ings: H'_T=0.50 W/m^2.K Residential semi-detached building: H'_T=0.45 W/m^2.K All others: H'_T=0.65 W/m^2.K
Entrance doors	1.8	
Boilers	Condensing boilers	Requirements for pipe insulation and control systems
Hot water	Central, with solar system	
Cooling	None	Thermal protection in summer
Ventilation	Central exhaust fan, demand-controlled	None

5 Methodology

The methodology of this study is of multidisciplinary character. Its main objective is to understand how a typical contemporary office building is affected by various parameters and to study the importance of these parameters in four different climates - warm humid, warm dry, cold humid and cold dry - across Europe. Having a typical lineal geometry and using specific architectural features the building is studied in Greece, Cyprus, United Kingdom and Germany respectively. The study is approached in a quantitative method through simulation.

With the numerical simulation the aim is firstly to determine the impact of independent variables, such as window to wall ratio, envelope thermal mass and internal loads in order to evaluate their influence on the building energy performance in each respective climate. Subsequently, an effort to prioritize their effect and figure out the combination that leads to the optimization of the building behavior is made. The significance of this thesis is trying to quantify the impact of each parameter in each respective climate.

In terms of energy analysis, a detailed energy calculation is performed for the needs of this thesis in order to achieve an in depth assessment of the examined factors. Comparing the two basic levels of energy analysis tools - simplified and detailed energy calculations -the degree-day method is used for simplified while hour-by-hour energy simulations are used for detailed calculations. Therefore, this dynamic simulation model has the ability to provide detailed information of the building and perform detailed calculation of the building performance. [39]

There is a great number of commercially available building performance simulation tools which deliver different results. For the evaluation of the examined building-related factors and the optimization of the building design Energy Plus simulation software is used.

Energy Plus has its roots in both BLAST and DOE–2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE–2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools. Their intended audience is a design engineer or architect that wishes to size appropriate

HVAC equipment, develop retrofit studies for life cycling cost analyses, optimize energy performance, etc. Born out of concerns driven by the energy crisis of the early 1970s and recognition that building energy consumption is a major component of the American energy usage statistics, the two programs attempted to solve the same problem from two slightly different perspectives. Both programs had their merits and shortcomings, their supporters and detractors, and solid user bases both nationally and internationally.

Like its parent programs, Energy Plus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., Energy Plus calculates the heating and cooling loads necessary to maintain thermal control set points, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would. Many of the simulation characteristics have been inherited from the legacy programs of BLAST and DOE–2. [65]

5.1 Description of the building

For the purpose of this study, a typical office model with a fixed geometry has been designed and a set of construction characteristics are given in accordance with each country's legislation. The aim is to quantify the effect of the various factors that influence the building behaviour depending on the climate and building construction. The main complexity is to find the appropriate combination of factors that achieve an optimised design solution for an office building in four different climates.

5.1.1 Office model – Fixed simulation parameters

It was complex to define a typology appropriate for office buildings throughout Europe, so we decided on the *lineal typology* as the most representative. The building model is based on a typical five-storey lineal office building with dimensions 28 m width, 12 m depth and 3.50 m floor-to-ceiling height. The total floor area is 336 m^2 with a height of 16 m. The building has a typical *composite construction* which has a number of advantages such as high building standards, freedom of architectural design, earthquake proofing, and lower foundation costs. It is assumed that the baseline scenario has 25%

window to wall ratio. In the figure below, the model of the office building is shown in the OpenStudio plug-in environment in used Google SketchUp.

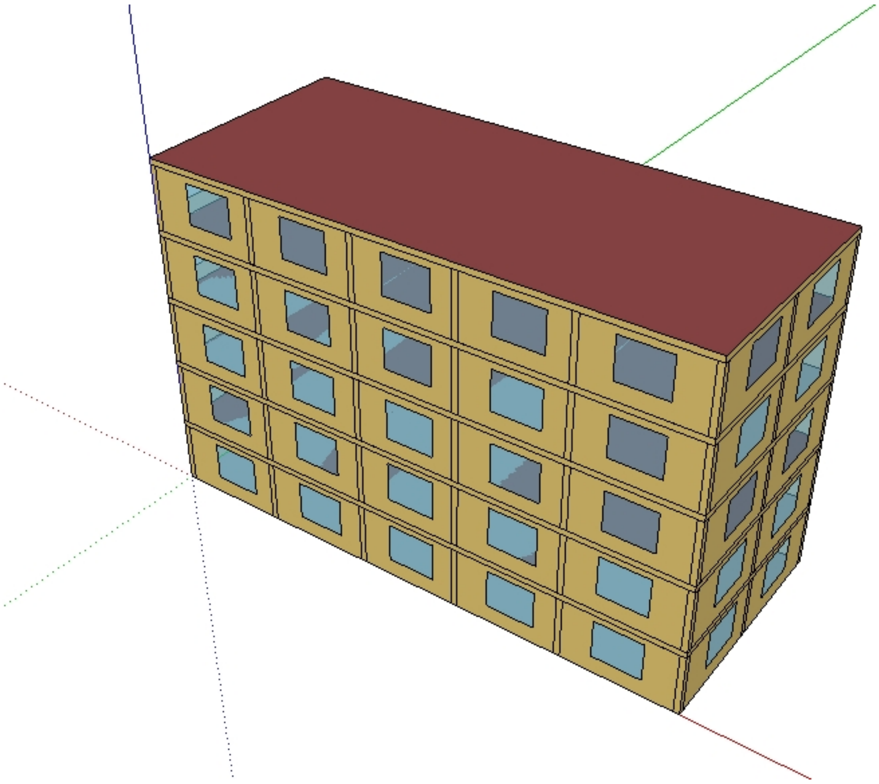


Figure 13: The building office model

The wide face of the building is south oriented which is thought to be the best orientation so as to gain solar heat in winter and airflow rate in summer. The building is divided in five thermal zones, one for each level.

For the needs of the simulations various basic assumptions have been made. Initially, the indoor design temperatures are 20 °C in winter and 26 °C in summer, the relative humidity is 40% during winter and 60% during summer. The lighting level is 500 lux. The office working hours are Monday to Friday 9:00 am to 18:00 pm based on ASHRAE standards and the office occupancy schedule is also based on ASHRAE standards. The metabolic rate of the building users is 80 W/person for office work based on ASHRAE standards.

5.1.2 Office model – Variable simulation parameters

Climatic data

The meteorological data used for the simulation are given from the Energy Plus simulation program. Weather data is available for over 2.000 locations in a file format that can be read by Energy Plus. The weather data provided in EnergyPlus weather format are derived from 20 sources and are arranged by World Meteorological Organization region and Country.

The climatic data that are used for the buildings' simulation in EnergyPlus cover a typical year for the energy consumption calculations. The typical climate year used is the IWEC (International Weather for Energy Calculations) form and is the result of ASHRAE Research Project 1015 implemented by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Technical Committee 4.2.

Building elements

As already mentioned, the proposed model is a contemporary office building with a compact construction. The characteristics of the building elements are based on each country's existing legislation, the requirements of which are presented in detail in Chapter 4.2. The U-values within the limiting requirements that were used for each city are given in Table 5:

Table 5: U-values that used for each city according to each country's existing legislation

Building Element U-Value [W/m^2.K]	Thessaloniki / Greece	Nicosia / Cyprus	London / United Kingdom	Munich / Germany
External walls	0.39	0.55	0.33	0.27
Beams / Props	0.41	0.54	0.33	0.28
Floor on the ground	0.65	0.57	0.25	0.28
Flat roof external	0.65	0.57	0.25	0.28

The selected openings are chosen according to each country's required U-values. The type of the frame is horizontal sliding frame having as an advantage that the open area can be adjusted in order to canalize the drift to a specific area.

5.2 Simulation variables of urban office building

A number of building-related factors are investigated and simulated in order to evaluate which of the cases are the most critical. The aforementioned basic parameters are kept the same according to each country's regulations. The examined factors are briefly described in the following sections.

5.2.1 Window to wall ratio

An important factor for an office building's heating and air-conditioning energy consumption is the window to wall ratio (WWR). Direct solar radiation produces huge variability in loads making window design optimization vital in increasing the building energy efficiency. Solar heat gains are increased as the WWR increases; on the other hand, the heat exchange is also increased as the heat transfer coefficient of window is usually larger than wall. WWR of office building is limited strictly according to the design standard for energy-efficiency of buildings on various climates, for it is the dominant influencing factor of the air conditioning and heating energy consumption in building use phase. [38] Additionally, the proportion of windows in conjunction with the building thermal mass are interrelated influencing the building energy performance in separate ways. Nevertheless, WWR has a direct effect in lighting consumption while maximizing natural lighting is a way for reducing lighting.

In this thesis the building and therefore the window orientation is the same in all the examined cases; thus low, medium and high window to wall ratios are being tested in order to find the optimal case for offices' design. The glazed area ranges according to Table 6. Furthermore, the U-values of the components of thermal envelope are the same according to each country's limiting requirements.

Table 6: Examined building related factors– window to wall ratio

Building-related factors	
Window to wall ratio	25% windows
	50% windows
	75% windows (glazed façade)

In Table 7 the dimensions of the windows are presented, while in the figures below are demonstrated the different building models for the respective window to wall ratio.

Table 7: Window dimensions that used

Window to wall ratio	Window dimensions (Length – Width) [m]
WWR equal to 25%	2.45 – 2.00
WWR equal to 50%	3.25 – 3.00
WWR equal to 75%	5.00 – 3.00

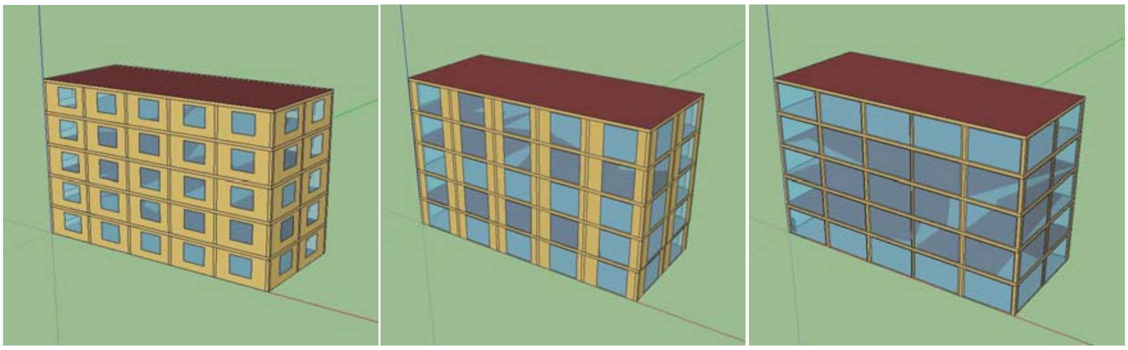


Figure 14: Building models for the respective window to wall ratio: 25%, 50% and 75% WWR respectively

5.2.2 Thermal mass

The ability of building materials to store heat is called thermal mass. Thermal mass is one of the powerful tools designers can use in order to control diurnal temperature changes and achieve thermal comfort. In buildings where solar gain is used as a heating strategy, diurnal effects can be managed by absorbing the heat of the winter sun during the day, while keeping the air temperature moderate, and releasing the heat at night to prevent the air temperature from plummeting. On the other hand, in buildings where forced or natural ventilation is used as a cooling strategy, diurnal effects can be managed by mass which absorbs the heat of internal building loads during the summer's day and the day's accumulated heat is flushed by cool air each night. High thermal mass is generally useful in climates with immense differences in the maximum day and minimum night temperatures.

In this thesis, three different cases of storage mass are simulated and evaluated as an effort to quantify the effect of thermal mass on the building energy performance. [66] A variation of the most typical cases of lightweight, medium-weight and heavyweight buildings is presented in Table 8.

Table 8: Examined building related factors– storage mass

Building-related factors	
Storage mass	Low < 130 kJ/m^{2}K
	Medium 130 – 260 (165 kJ/m^{2}K)
	High > 260 kJ/m^{2}K

The building model is simulated with different constructions for the building elements for each examined thermal mass case. Specifically, the thermal mass values that are used are presented in Table 9. The constructions used in each different climate have thermal mass values as close as possible to the ones presented in Table 9. Constructions for beams and props do not vary for lightweight, medium-weight and heavyweight constructions and are kept the same in all cases for static purposes. However because of the fact that beams and props constitute only the 10-15% of the total building's area have a negligible effect in the calculations.

Table 9: Low thermal mass values for each building element in each examined country

Building Element	Low Thermal Mass [kJ/m^{2}K]	Medium Thermal Mass [kJ/m^{2}K]	High Thermal Mass [kJ/m^{2}K]
External walls	120	190	290
Beams / Props	320	320	320
Floor on the ground	130	196	295
Flat roof external	130	196	295

5.2.3 Internal loads

The internal loads are caused by people, lighting and equipment. Internal loads are dependent on the number of the occupants, the type of their activity and the time of operation of all the appliances. During the design phase all the internal loads must be taken into account. The more increased the internal loads are, the more high the cooling and ventilation needs are and the less the heating needs. [67] Based on past researches on office buildings [[68], [69], [70], [71]] there is a variation on the values for internal heat gains. Three different cases are examined: light loads, medium loads and high loads as showed in Table 10.

Table 10: Building related factors that will be examined – Variation of internal heat gains

Internal heat gains	Light use - Light loads	Medium use - Medium loads	Intense use - High loads
Lighting [W/m^2]	5	10	15
People [m^2/person]	8	10	12
Equipment [W/m^2]	3	9	15

6 Results

In this chapter the results from the parametric analysis performed are presented and analyzed. The results for each climate are demonstrated separately evaluating the effect of each examined parameter.

6.1 Window to wall ratio (WWR)

Direct solar radiation produces huge variability in loads making window design optimization vital in increasing the building energy efficiency. The window to wall ratio of the building in conjunction with the envelope thermal mass is a factor that significantly affects the energy performance of an office building in terms of heating, cooling and lighting consumption. In this study the model office building is simulated for a window to wall ratio ranging from 25% to 75%. A comparison of the energy consumption for heating and cooling for all the examined cases is performed in the following sections for each of the examined cities.

6.1.1 Thessaloniki (humid warm climate)

In this section, the results of the parametric analysis are compared in order to evaluate the effect of the envelope window to wall ratio on an office building in the humid warm climate of Thessaloniki. Situated next to the sea, the city's climate is directly affected by it. As already mentioned, the city has a humid subtropical climate that borders on a semi-arid climate with characteristics of continental and Mediterranean climates. On average, Thessaloniki spends 32 days a year below 0 °C, which is also the average number of days the temperature is above 32 °C, therefore, it is a city where both heating and cooling are almost of equal importance.

In Figure 14 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The examined cases with 25% window to wall ratio appear to have high heating energy consumption and quite low needs for cooling. This is explained by the low incoming solar radiation and the enclosed building envelope of this type of buildings. Additionally, buildings with 50% window to wall ratio seem to have a wide variation in the heating and cooling energy consumption when changing other parameters such as thermal mass and internal loads. Specifically, cases with low thermal mass appear to have the lowest heating energy consumption and at the same time quite increased cooling energy consumption, while the examined scenarios with medium and high thermal mass have significantly larger heating energy consumption per area and quite lower cooling energy consumption. Finally, the cooling energy consumption is significantly increased in the simulated cases with 75% window to wall ratio compared to the rest of the examined cases, while the heating energy consumption is lower. This explains the high increase in the total primary energy consumption in buildings with 75% window to wall ratio (Figures 15 and 16).

Figure 15 shows a comparative graph of the total primary energy consumption of all the examined cases grouped depending on the window to wall ratio. Specifically, as expected, the cases with 25% window to wall ratio seem to have lower total primary energy consumption per area compared to the cases with 50% and 75% window to wall ratio respectively. It is observed in Figure 16 that increasing the window to wall ratio to 50% results to an increase of about 17-19% while changing the window to wall ratio to 75% increases the total primary energy consumption around 30%. In the case of a building with low thermal mass increasing the window to wall ratio to 75% leads to a somewhat larger change in the total primary energy consumption compared to the other scenarios; specifically an increase of around 34% is observed. This can be explained by the fact that a building with high WWR does not have enough thermal mass to absorb the high incoming solar radiation from the windows. This situation in conjunction with the high thermal losses from the window area leads to a weakness of the building envelope to mitigate the diurnal internal temperature changes, increasing the cooling needs of the building (Figure 14).

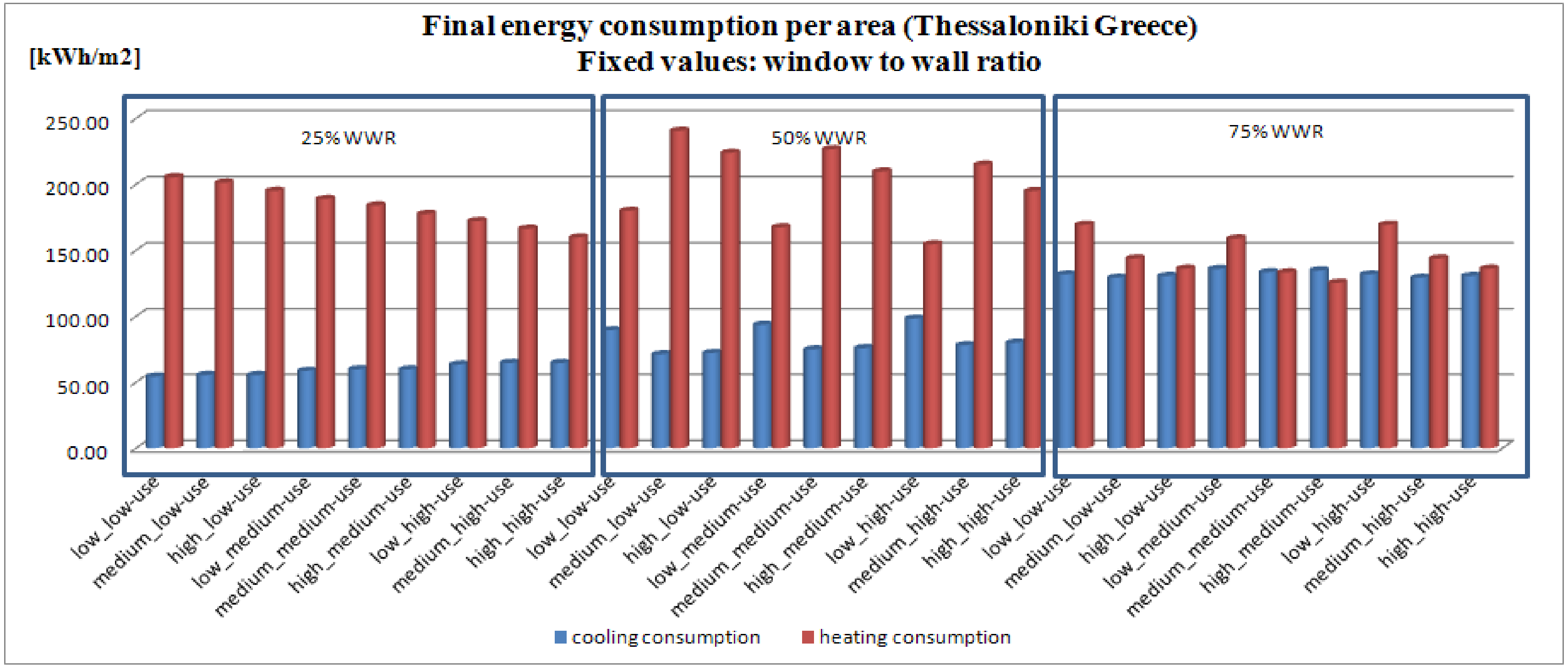


Figure 15: End use energy consumption per area for Thessaloniki Greece

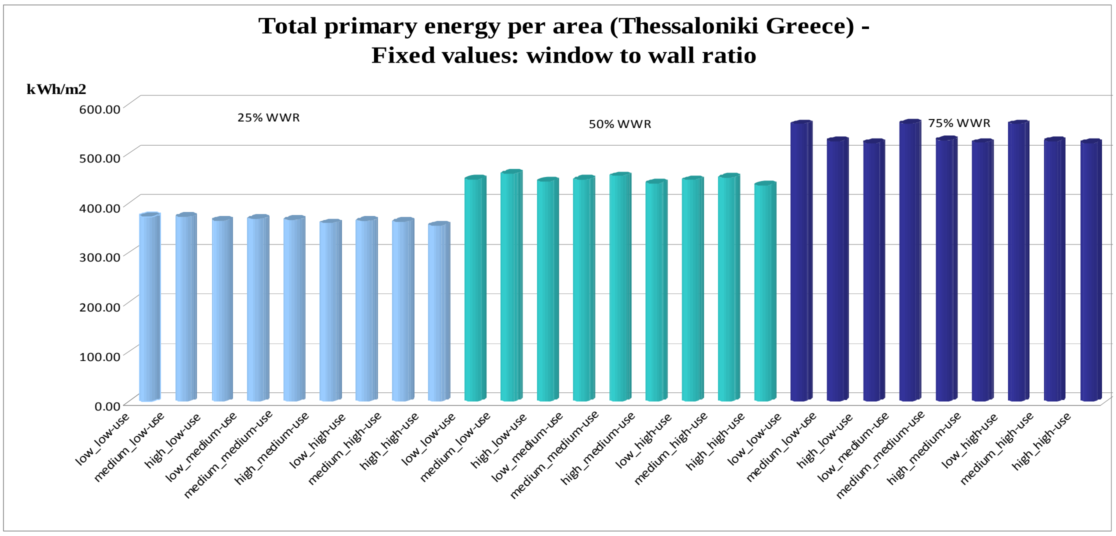
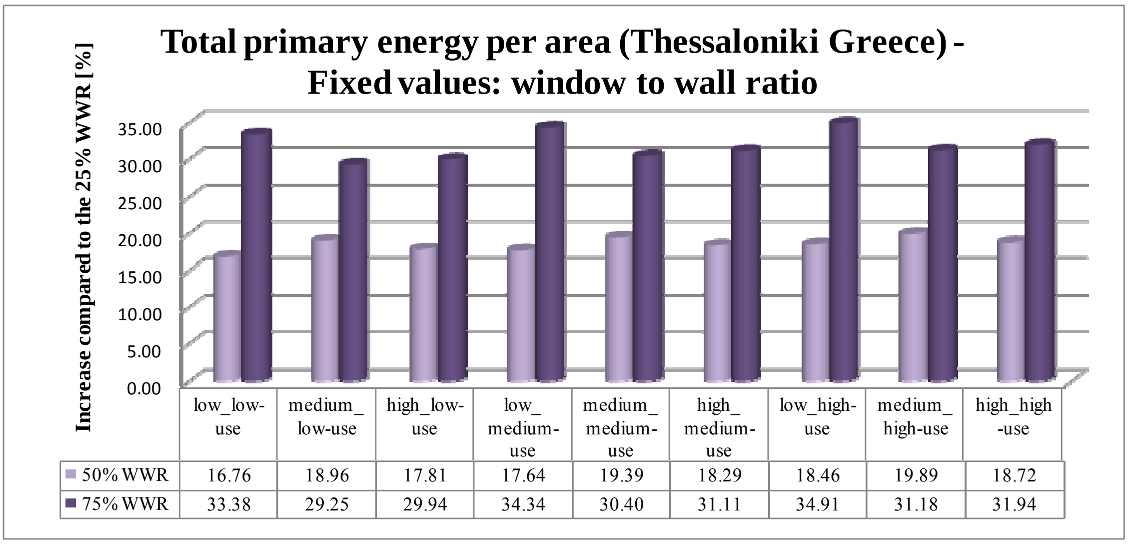


Figure 16: Total primary energy consumption per area for all examined cases with fixed window to wall ratio values for Thessaloniki Greece



	low_low-use	medium_low-use	high_low-use	low_medium-use	medium_medium-use	high_medium-use	low_high-use	medium_high-use	high_high-use
■ 50% WWR	16.76	18.96	17.81	17.64	19.39	18.29	18.46	19.89	18.72
■ 75% WWR	33.38	29.25	29.94	34.34	30.40	31.11	34.91	31.18	31.94

Figure 17: Percentage of increase of the total primary energy per area for the examined cases for Thessaloniki Greece when changing the window to wall ratio.

6.1.2 Cyprus (dry warm climate)

The results of the parametric analysis are compared in order to evaluate the effect of the window to wall ratio on an office building in the dry warm climate of Nicosia Cyprus. Nicosia has a hot subtropical semi-arid climate with long, hot and dry summers and relatively wet and mild winters. Therefore, Nicosia is a city where cooling needs are the most critical in buildings.

In Figure 17 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The examined cases with 25% window to wall ratio have cooling energy consumption ranging from 75kWh/m^2 to 90kWh/m^2, while the respective heating consumption ranges from 20kWh/m^2 to 40kWh/m^2. Changing the various parameters in this case, such as thermal mass and internal loads, has only minor effect on the building energy performance given the low incoming solar radiation and the enclosed building envelope of this type of buildings. Similarly to the climate of Thessaloniki, the examined scenarios with 50% window to wall ratio seem to have a wide variation in the heating and cooling energy consumption when changing other parameters such as thermal mass and internal loads. As mentioned above, in Cyprus cooling consumption is the most critical as observed in the graph. Specifically, cases with low thermal mass appear to have the highest cooling energy consumption and at the same time the lowest heating energy consumption when 50%WWR. Finally, 75% window to wall ratio leads to significantly high cooling energy consumption, almost twice as high as in the scenarios with 25% WWR. At the same time the requirements for heating are minimized. This can be explained by the large proportion of glazing in the building envelope and the lack of thermal mass. This increase on cooling energy consumption also explains the large increase in the total primary energy consumption (Figures 18 and 19). It is evident from the above that in a dry warm climate like Cyprus there is a considerable risk of overheating especially during the summer months when there is a high percentage of glazing on the building envelope.

Figure 18 shows a comparative graph of the total primary energy consumption of all the examined cases grouped depending on the window to wall ratio (WWR). Specifically, as expected, the cases with 25% window to wall ratio seem to have lower total primary energy consumption per area compared to the cases with 50% and 75% window to wall ratio respectively. It is observed in Figure 19 that increasing the window to wall ratio to 50% results to an increase of about 22-26% while changing the window to wall ratio to 75% increases the total primary energy consumption around 41-44%. The effect of the window to wall ratio on the building energy performance is higher in the dry warm climate of Nicosia Cyprus compared to the one of Thessaloniki and it can be judged as a critical factor when designing an office building in Cyprus.

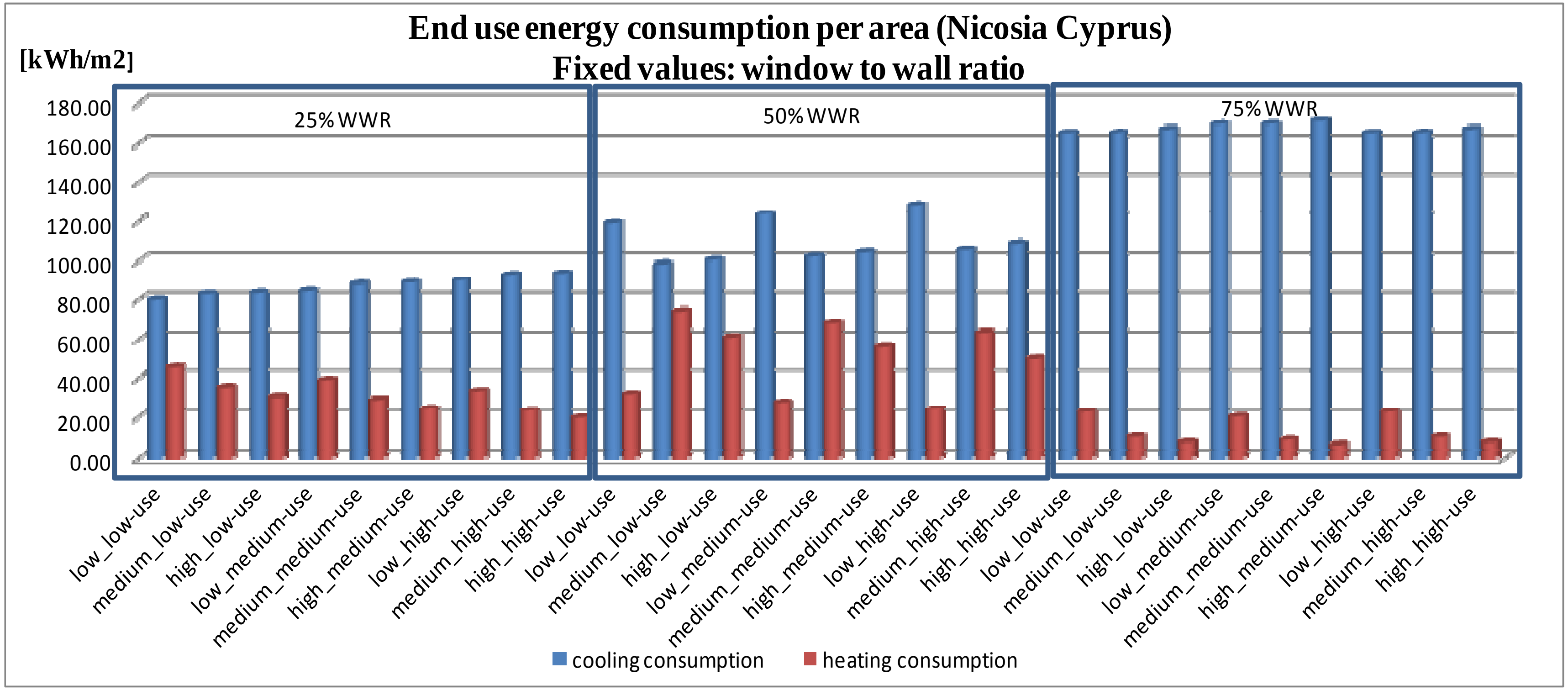


Figure 18: End use energy consumption per area for Nicosia Cyprus

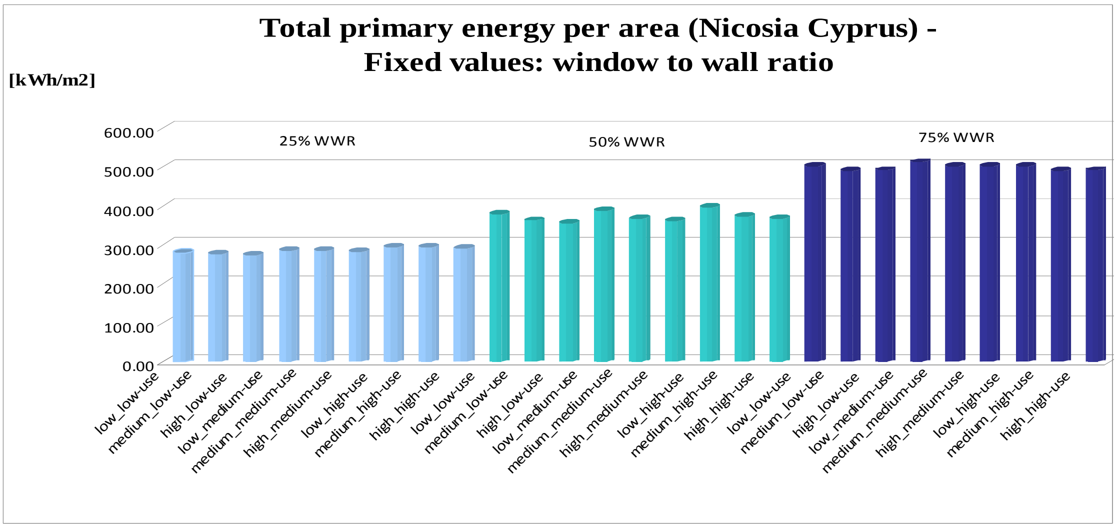
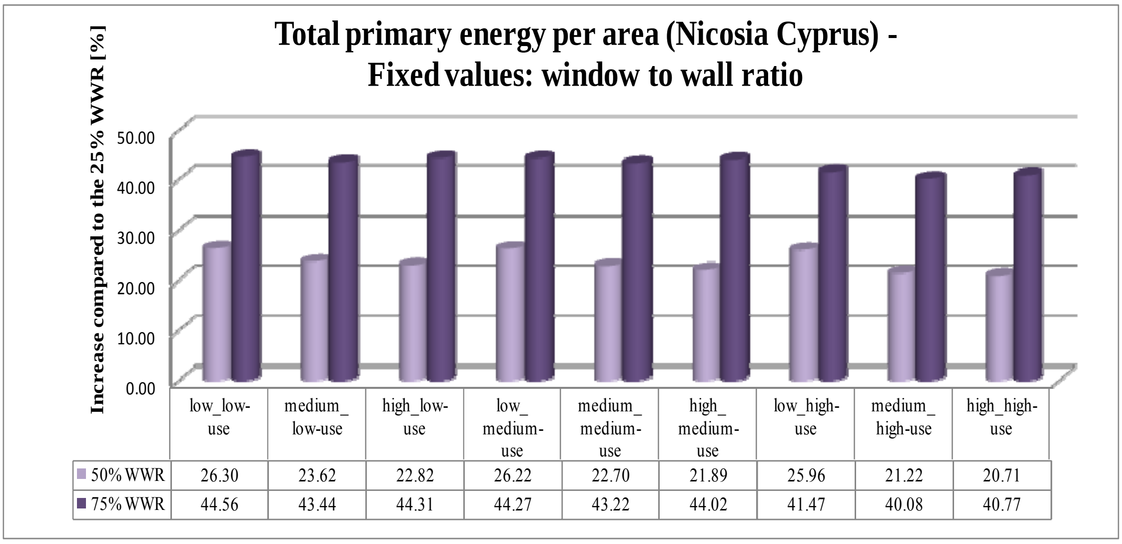


Figure 19: Total primary energy consumption per area for all examined cases with fixed window to wall ratio values for Nicosia Cyprus



	low_low-use	medium_low-use	high_low-use	low_medium-use	medium_medium-use	high_medium-use	low_high-use	medium_high-use	high_high-use
▨ 50% WWR	26.30	23.62	22.82	26.22	22.70	21.89	25.96	21.22	20.71
■ 75% WWR	44.56	43.44	44.31	44.27	43.22	44.02	41.47	40.08	40.77

Figure 20: Percentage of increase of the total primary energy per area for the examined cases for Nicosia Cyprus when changing the window to wall ratio

6.1.3 London (humid cold climate)

The results of the parametric analysis are compared in order to evaluate the effect of the window to wall ratio on an office building in the humid cold climate of London UK. London has a temperate oceanic climate, similar to much of southern Britain. Winters are generally chilly to cold with frost usually occurring in the suburbs on average twice a week from November to March. Summers are generally warm and sometimes hot, the heat being boosted by the urban heat island effect making the centre of London at times 5 °C warmer than the suburbs and outskirts. London in general is considered a city where heating is the most critical consumer in buildings, while cooling is not negligible.

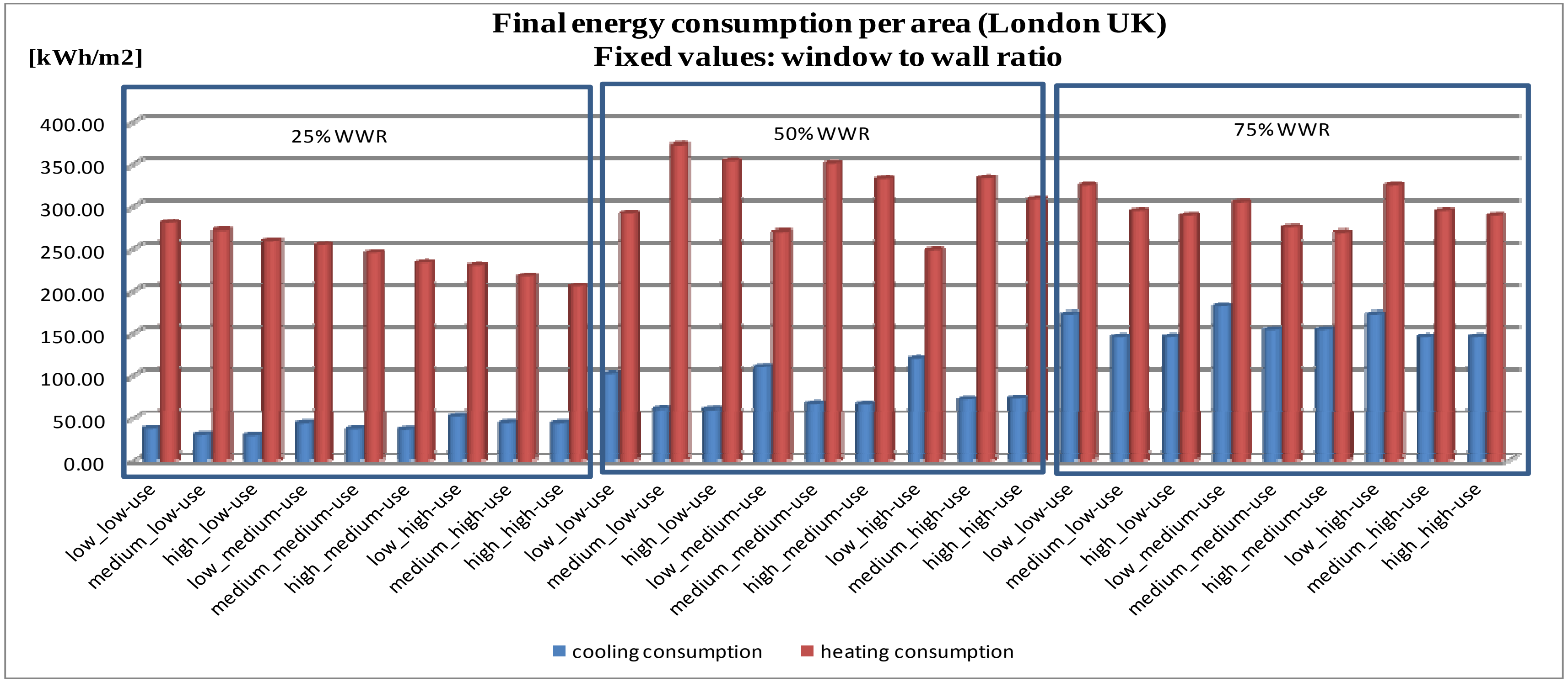


Figure 21: End use energy consumption per area for London United Kingdom

In Figure 20 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The examined cases with 25% window to wall ratio appear to have high heating energy consumption and quite low needs for cooling. This is explained by the low incoming solar radiation and the enclosed building envelope of this type of buildings given the cool climate of London. Additionally, buildings with 50% window to wall ratio seem to have a wide variation in the heating and cooling energy consumption when changing other parameters such as thermal mass and internal loads. Specifically, cases with low thermal mass appear to have the lowest heating energy consumption and at the same time quite increased cooling energy consumption. Increasing the building thermal mass significantly increases the heating energy consumption, while decreasing the required cooling energy about 50kWh/m^2 in cases with 50%WWR. Finally, the cooling energy consumption is somewhat increased in the simulated cases with 75% window to wall ratio compared to the rest of the examined cases, while the heating energy consumption is somewhat lower. Specifically, the cooling energy consumption is almost doubled compared to the 50%WWR cases. This explains the high increase in the total primary energy consumption in buildings with 75% window to wall ratio (Figures 21 and 22).

Figure 21 shows a comparative graph of the total primary energy consumption of all the examined cases grouped depending on the window to wall ratio. Specifically, as expected, the cases with 25% window to wall ratio seem to have lower total primary energy consumption per area, ranging from 240kWh/m^2 to 300kWh/m^2. The respective energy consumption for the 50% and 75% WWR cases range from 260kWh/m^2 to 360kWh/m^2. It is observed in Figure 22 that increasing the window to wall ratio to 50% results to an increase of about 19.4-35.41% with lower increase observed in low thermal mass scenarios and higher increase in medium thermal mass scenarios respectively. Moreover, changing the window to wall ratio to 75% increases the total primary energy consumption around 31.63% to 43.36% with lower increase observed in medium thermal mass scenarios and higher increase in low thermal mass scenarios respectively. This can be explained by the fact that a building with high WWR does not have enough thermal mass to absorb the high incoming solar radiation from the windows. This situation in conjunction with the high thermal losses from the window area leads to a weakness of the building envelope to mitigate the diurnal internal temperature changes, increasing mostly the cooling needs of the building (Figure 20).

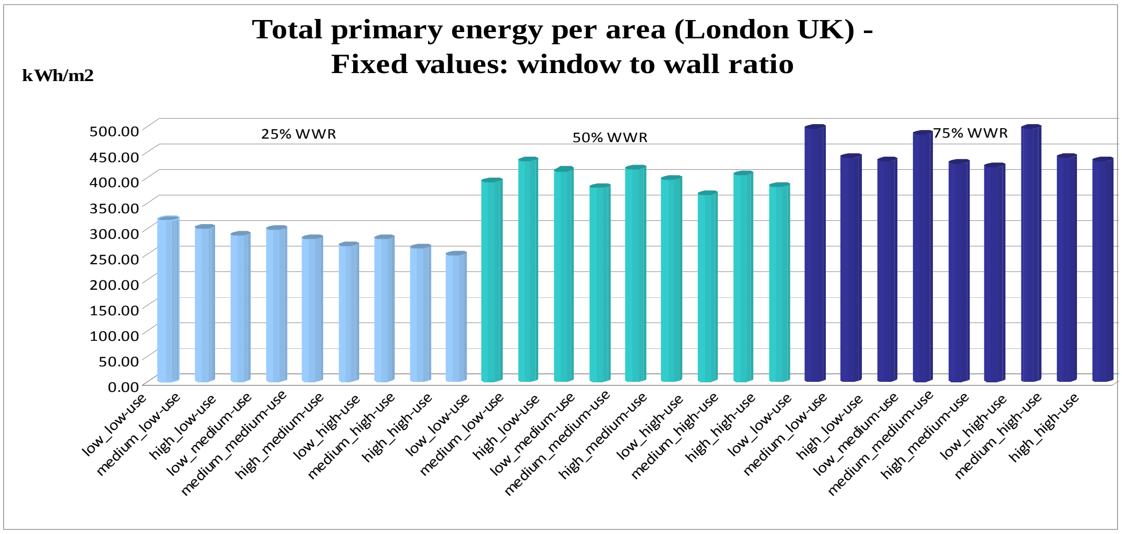
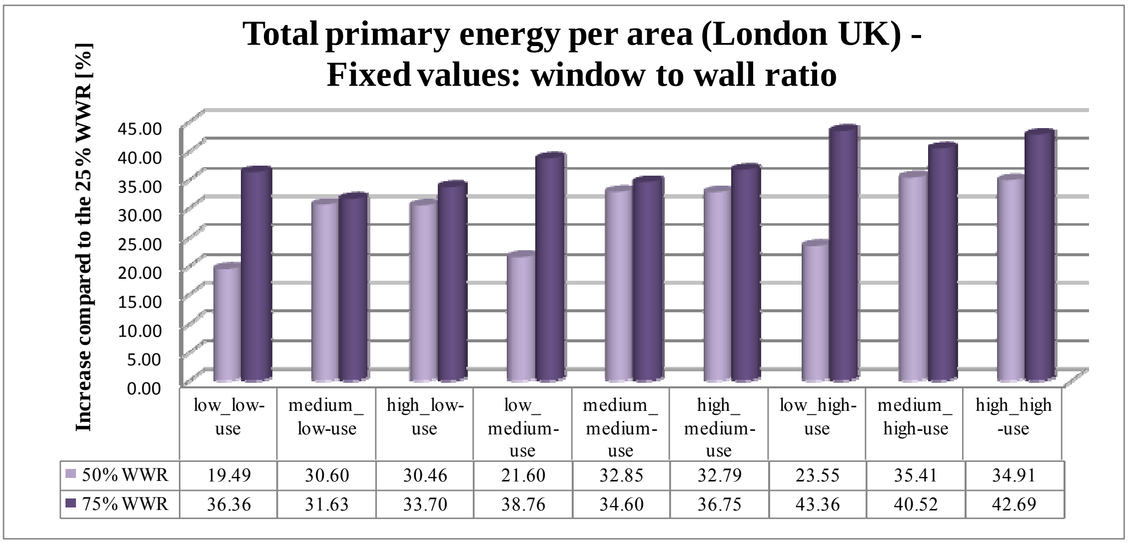


Figure 22: Total primary energy consumption per area for all examined cases with fixed window to wall ratio values for London UK



	low_low-use	medium_ low-use	high_low-use	low_ medium-use	medium_ medium-use	high_ medium-use	low_high-use	medium_ high-use	high_high -use
■ 50% WWR	19.49	30.60	30.46	21.60	32.85	32.79	23.55	35.41	34.91
■ 75% WWR	36.36	31.63	33.70	38.76	34.60	36.75	43.36	40.52	42.69

Figure 23: Percentage of increase of the total primary energy per area for the examined cases for London UK when changing the window to wall ratio

6.1.4 Munich (dry cold climate)

The results of the parametric analysis are compared in order to evaluate the effect of the window to wall ratio on an office building in the humid cold climate of Munich Germany. Munich has a continental climate, strongly modified by the proximity of the Alps. Munich experiences cold winters, but heavy rainfall is rarely seen in the winter. Summers in Munich are warm with an average maximum of 24.0 C in the hottest month of July. Minimizing heating energy consumption is therefore critical when designing an office building in Munich.

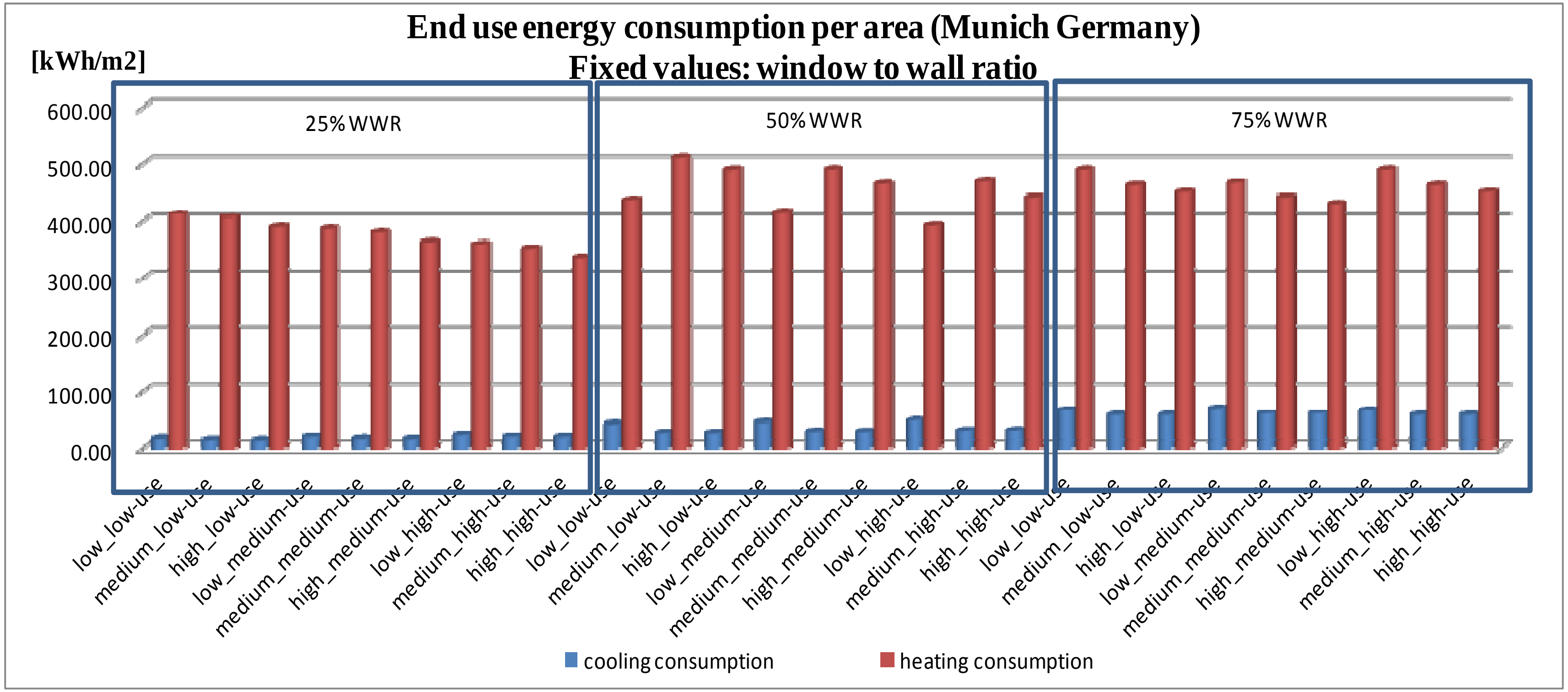


Figure 24: End use energy consumption per area for Munich Germany

In Figure 23 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The examined cases with 25% window to wall ratio appear to have high heating energy consumption and negligible cooling energy consumption as expected. Increasing the window to wall ratio to 50% and to 75% respectively leads to an increase in both heating and cooling energy consumption. Specifically, for 50% WWR, medium and high thermal mass scenarios present a larger increase in heating energy consumption compared to low thermal mass scenarios. Moreover, buildings with 50% window to wall ratio seem to have a wide variation in the heating energy consumption when changing other parameters such as thermal mass and internal loads. Finally, the cooling energy consumption is somewhat increased in the simulated cases with 75% window to wall ratio compared to the rest of the examined cases, while the heating energy consumption is somewhat lower. Specifically, the cooling energy consumption is almost doubled compared to the 50%WWR cases. This explains the high increase in the total primary energy consumption in buildings with 75% window to wall ratio (Figures 24 and 25).

Figure 24 shows a comparative graph of the total primary energy consumption of all the examined cases grouped depending on the window to wall ratio. Specifically, as expected, the cases with 25% window to wall ratio seem to have lower total primary energy consumption per area, ranging from 390kWh/m^2 to 480kWh/m^2. The respective energy consumption for the 50% and 75% WWR cases range from 520kWh/m^2 to 600kWh/m^2. It is observed in Figure 25 that increasing the window to wall ratio to 50% results to an increase of about 16.96-26.82% with lower increase observed in low thermal mass scenarios and higher increase in medium thermal mass scenarios respectively. Moreover, changing the window to wall ratio to 75% increases the total primary energy consumption around 28.76% to 37.58% with lower increase observed in medium thermal mass scenarios and higher increase in low thermal mass scenarios respectively. This situation is similar to the other examined cities and can be explained by the fact that the building does not have enough thermal mass to absorb the high incoming solar radiation from the windows. Additionally, the lack of thermal mass in conjunction with the high thermal losses from the window area leads to a weakness of the building envelope to mitigate the diurnal internal temperature changes, increasing the heating and cooling needs of the building (Figure 23).

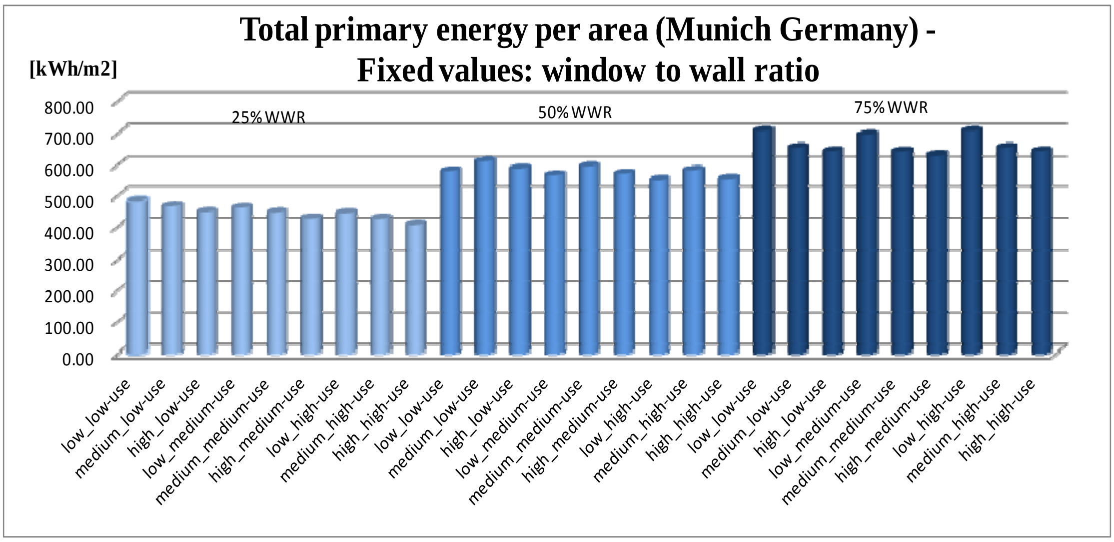
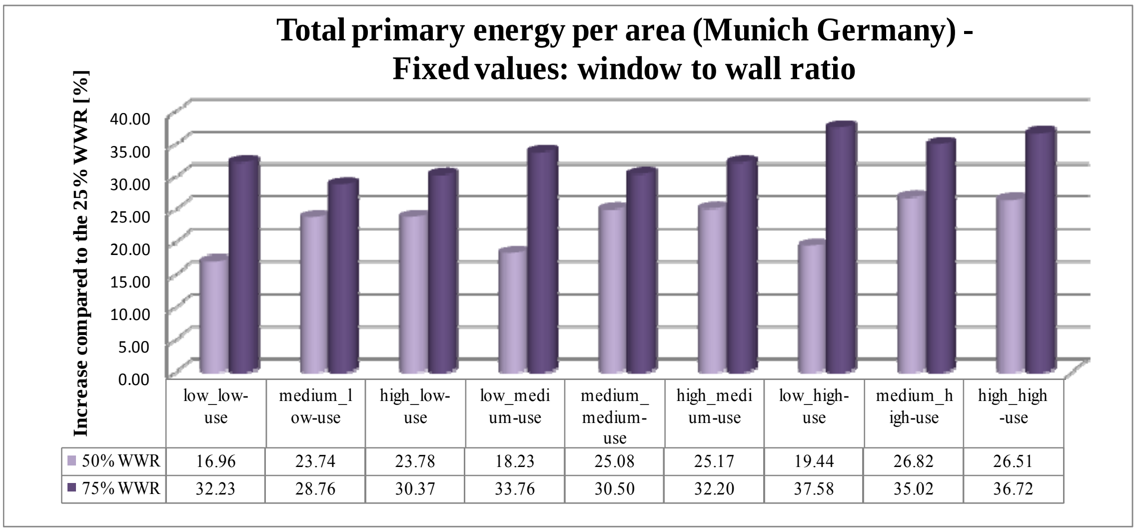


Figure 25: Total primary energy consumption per area for all examined cases with fixed window to wall ratio values for Munich Germany



	low_low-use	medium_low-use	high_low-use	low_medium-use	medium_medium-use	high_medium-use	low_high-use	medium_high-use	high_high-use
■ 50% WWR	16.96	23.74	23.78	18.23	25.08	25.17	19.44	26.82	26.51
■ 75% WWR	32.23	28.76	30.37	33.76	30.50	32.20	37.58	35.02	36.72

Figure 26: Percentage of increase of the total primary energy per area for the examined cases for Munich Germany when changing the window to wall ratio

6.2 Thermal mass

Thermal mass is considered one of the powerful tools designers can use in order to control diurnal temperature changes and achieve thermal comfort. In buildings where solar gain is used as a heating strategy, diurnal effects can be managed by absorbing the heat of the winter sun during the day, while keeping the air temperature moderate, and releasing the heat at night to prevent the air temperature from plummeting. On the other hand, in buildings where forced or natural ventilation is used as a cooling strategy, diurnal effects can be managed by mass which absorbs the heat of internal building loads during the summer's day and the day's accumulated heat is flushed by cool air each night. In this section, the results of the model office building simulated for various thermal mass levels, ranging from 110 kJ/m^{2}K to 290 kJ/m^{2}K, are presented. A comparison of all the examined cases is performed for each of the examined cities.

6.2.1 Thessaloniki (humid warm climate)

In this section, the results of the parametric analysis are compared in order to evaluate the effect of the building thermal mass on an office building in the humid warm climate of Thessaloniki. As already mentioned, Thessaloniki is a city where both heating and cooling are almost of equal importance. In Figure 26 the energy consumption for heating and cooling is respectively compared for the examined scenarios that are respectively grouped by the amount of the envelope thermal mass. The simulation of the model building with low thermal mass reveals that the energy consumption for heating ranges from 160 kWh/m^2 to 200 kWh/m^2, while the respective energy for cooling ranges from 50 kWh/m^2 in cases with low WWR to 130 kWh/m^2 in cases with high WWR. The variation of cooling energy consumption can be explained by the fact that in lightweight buildings with high WWR there is a small proportion of wall area with very little thermal mass which is not enough to absorb the excess heat keeping the air temperature moderate and releasing the heat during the night. Cases with medium and high thermal mass reveal that simply increasing the building thermal mass not combining it with natural or mechanical ventilation does not affect the building cooling energy consumption. On the other hand increasing the building thermal mass leads to an increase in the building energy consumption in cases with low and medium window to wall ratio and a significant decrease in heating energy consumption in buildings with high WWR.

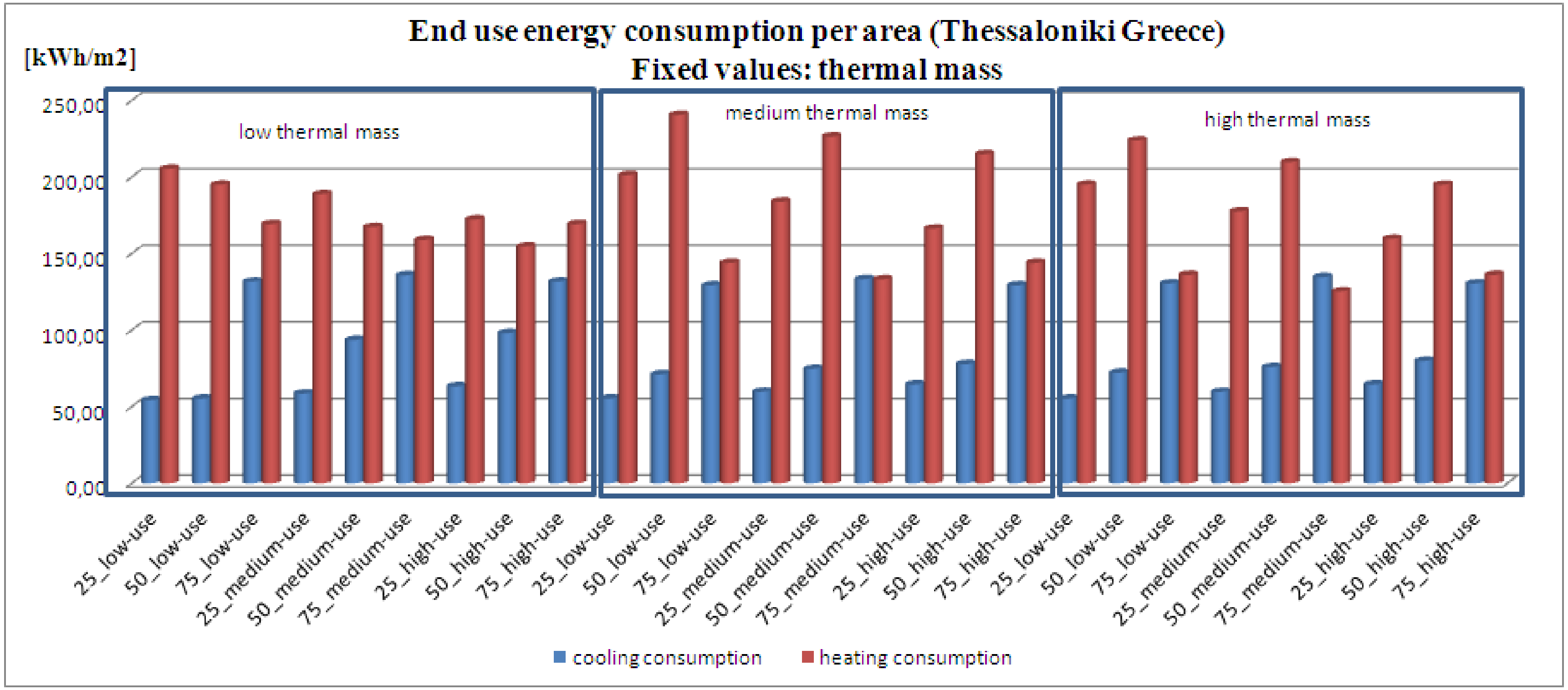
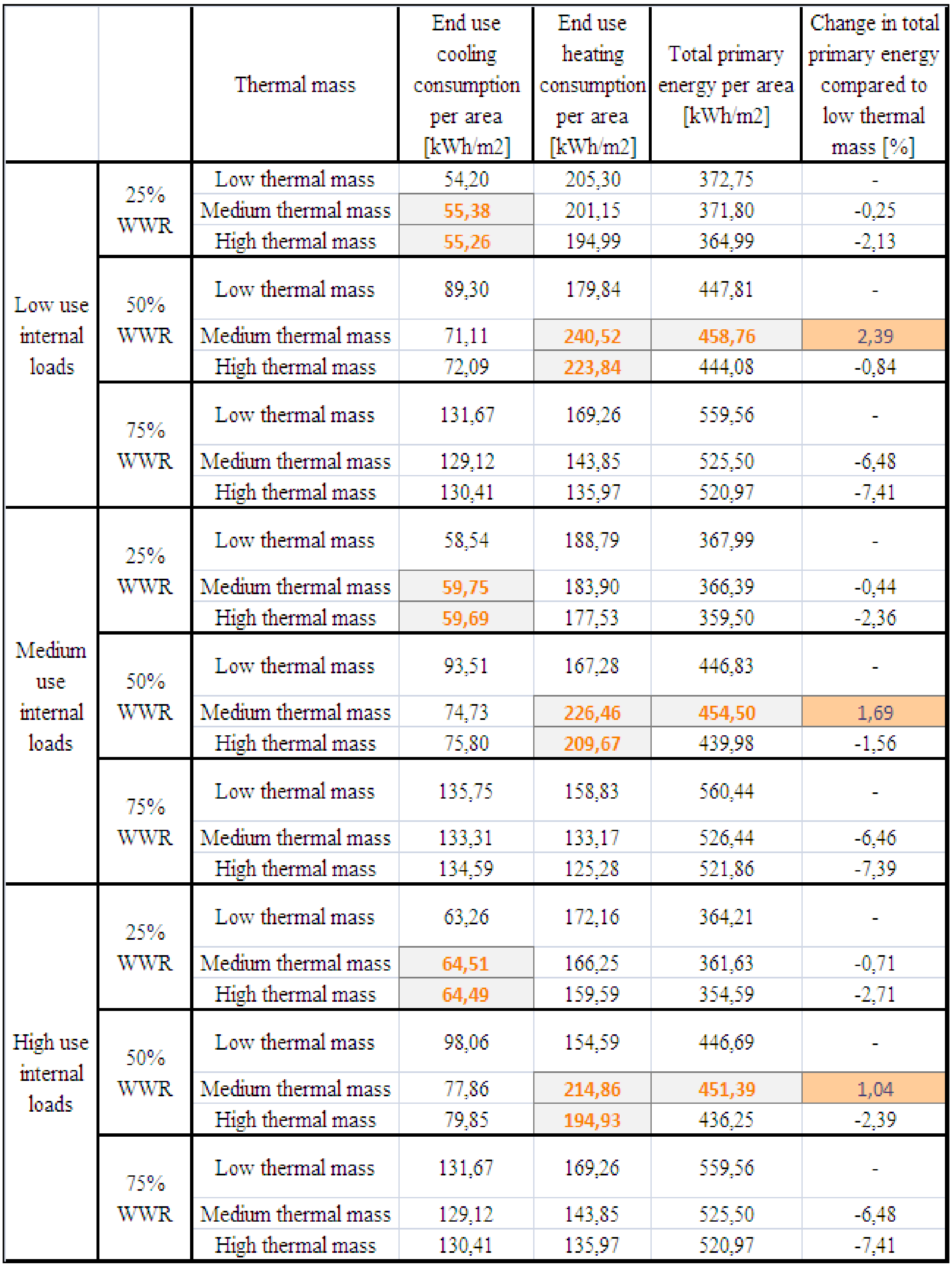


Figure 27: End use energy consumption per area for Thessaloniki Greece

Table 11: Heating and cooling energy consumption, total primary consumption and change in total primary energy consumption for various scenarios depending on the envelope thermal mass for Thessaloniki Greece



		Thermal mass	End use cooling consumption per area [kWh/m2]	End use heating consumption per area [kWh/m2]	Total primary energy per area [kWh/m2]	Change in total primary energy compared to low thermal mass [%]
Low use internal loads	25% WWR	Low thermal mass	54,20	205,30	372,75	-
		Medium thermal mass	55,38	201,15	371,80	-0,25
		High thermal mass	55,26	194,99	364,99	-2,13
	50% WWR	Low thermal mass	89,30	179,84	447,81	-
		Medium thermal mass	71,11	240,52	458,76	2,39
		High thermal mass	72,09	223,84	444,08	-0,84
	75% WWR	Low thermal mass	131,67	169,26	559,56	-
		Medium thermal mass	129,12	143,85	525,50	-6,48
		High thermal mass	130,41	135,97	520,97	-7,41
Medium use internal loads	25% WWR	Low thermal mass	58,54	188,79	367,99	-
		Medium thermal mass	59,75	183,90	366,39	-0,44
		High thermal mass	59,69	177,53	359,50	-2,36
	50% WWR	Low thermal mass	93,51	167,28	446,83	-
		Medium thermal mass	74,73	226,46	454,50	1,69
		High thermal mass	75,80	209,67	439,98	-1,56
	75% WWR	Low thermal mass	135,75	158,83	560,44	-
		Medium thermal mass	133,31	133,17	526,44	-6,46
		High thermal mass	134,59	125,28	521,86	-7,39
High use internal loads	25% WWR	Low thermal mass	63,26	172,16	364,21	-
		Medium thermal mass	64,51	166,25	361,63	-0,71
		High thermal mass	64,49	159,59	354,59	-2,71
	50% WWR	Low thermal mass	98,06	154,59	446,69	-
		Medium thermal mass	77,86	214,86	451,39	1,04
		High thermal mass	79,85	194,93	436,25	-2,39
	75% WWR	Low thermal mass	131,67	169,26	559,56	-
		Medium thermal mass	129,12	143,85	525,50	-6,48
		High thermal mass	130,41	135,97	520,97	-7,41

These changes of the heating and cooling energy consumption as well as the total primary consumption in the various examined scenarios are shown in Table 11. Increasing the envelope thermal mass in most cases leads to a decrease in heating and cooling energy consumption. Specifically, the required cooling energy is slightly increased only in the examined scenarios with 25% window to wall ratio, while the required heating energy is considerably increased when the model building has 50% window to wall ratio. This increase of the building heating energy consumption leads to an increase of the total primary energy consumption in the examined scenarios with 50% window to wall ratio and medium thermal mass. In all the other cases increasing the building thermal mass leads to a decrease of the total primary energy consumption ranging from 0.25% to 7.41% depending on the examined scenario.

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building thermal mass is presented in Figure 27. It is evident from the graph that increasing the envelope thermal mass leads to a considerable decrease in the total primary consumption in the examined cases with 75% window to wall ratio. Specifically, medium and high thermal mass envelope with 75% WWR show a decrease in the total primary energy consumption ranging from 6.4% to7.41%, while the respective decrease is buildings with 25% WWR ranges from 0.25% to 2.71%. Considering the building with 50% WWR, the situation is slightly different, as already mentioned. Specifically, medium thermal mass envelope shows an increase in the total primary energy consumption, ranging from 1.04% to 2.39%, while high thermal mass envelope leads to a decrease of the total primary energy consumption ranging from 0.84% to 2.39%.

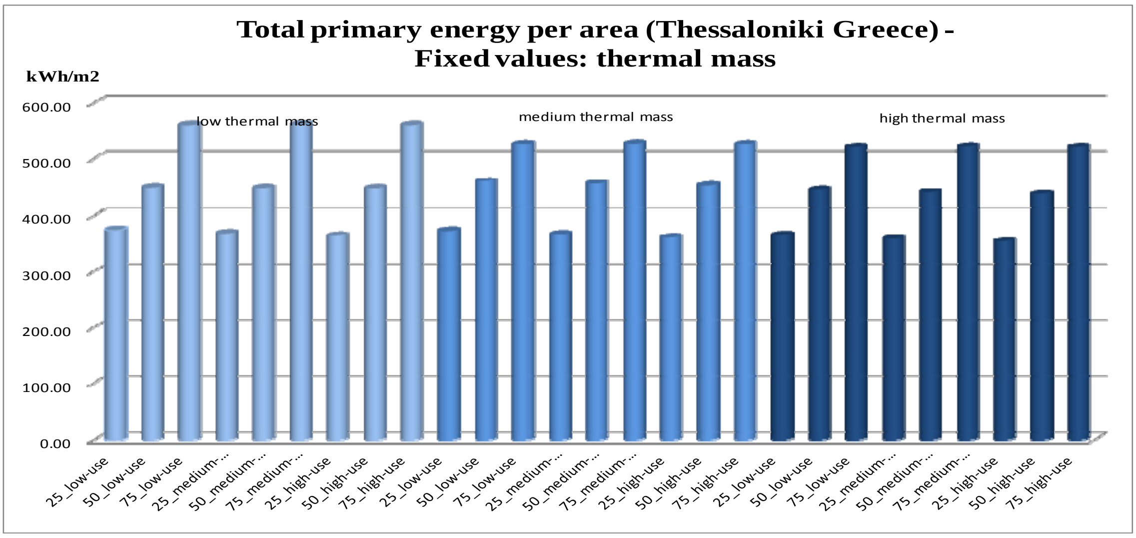


Figure 28: Total primary energy consumption per area for all examined cases with fixed thermal mass values for Thessaloniki Greece

6.2.2 Cyprus (dry warm climate)

In this section, the results of the parametric analysis are compared in order to evaluate the effect of the building thermal mass on an office building in the dry warm climate of Nicosia. As already mentioned, Nicosia is a city where cooling needs are the most critical in buildings. In Figure 28 the energy consumption for heating and cooling is respectively compared for the examined scenarios that are grouped by the amount of the envelope mass. The simulation of the model building with low thermal mass reveals that the energy consumption for heating ranges from 20 kWh/m^2 in cases with high WWR to 40 kWh/m^2 in cases with low WWR, while the respective energy for cooling ranges from 80 kWh/m^2 in cases with low WWR to 165 kWh/m^2 in cases with high WWR. Increasing the envelope thermal mass to medium and high does not affect the heating and cooling requirements in cases with 25% and 75% WWR respectively, as observed in Figure 28, while it significantly changes the performance in the examined scenarios with 50% WWR. Specifically, in medium thermal mass scenarios the heating energy consumption is increased almost by 46%, while the respective cooling energy consumption is decreased by 37.5%. The same effect occurs in high thermal mass scenarios with 50% WWR; the heating energy consumption is increased almost by 42%, while the respective cooling energy consumption is decreased by 37%. The variation of cooling energy consumption can be explained by the fact that buildings with high WWR there is a small proportion of wall area with very little thermal mass which is not enough to absorb the excess heat keeping the air temperature moderate and releasing the heat during the night. It is evident from this graph that the question of thermal mass is directly affected by the proportion of glazing and consequently the insulation of a building envelope and therefore the amount of incoming solar radiation.

These changes of the heating and cooling energy consumption as well as the total primary consumption in the various examined scenarios are shown in Table 11. Increasing the building thermal mass leads to a decrease in heating and cooling energy consumption and consequently a decrease of the total primary energy consumption ranging from 0.25% to 8.20% depending from the examined scenario. Furthermore, a comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building thermal mass is presented in Figure 29. It is evident from the graph that increasing the envelope thermal mass leads to a small decrease in the total primary consumption in the examined cases with 50% and 75% window to wall ratio.

Specifically, medium and high thermal mass envelope with 25% WWR show a decrease in the total primary energy consumption ranging from 0.25% to1.77%, while in buildings with 75% WWR the respective decrease ranges from 1.88% to 2.62%. Finally, scenarios with 50% WWR seem to be affected the most by the increase of thermal mass showing a respective decrease in the total primary energy consumption ranging from 4.24% to 8.20%.

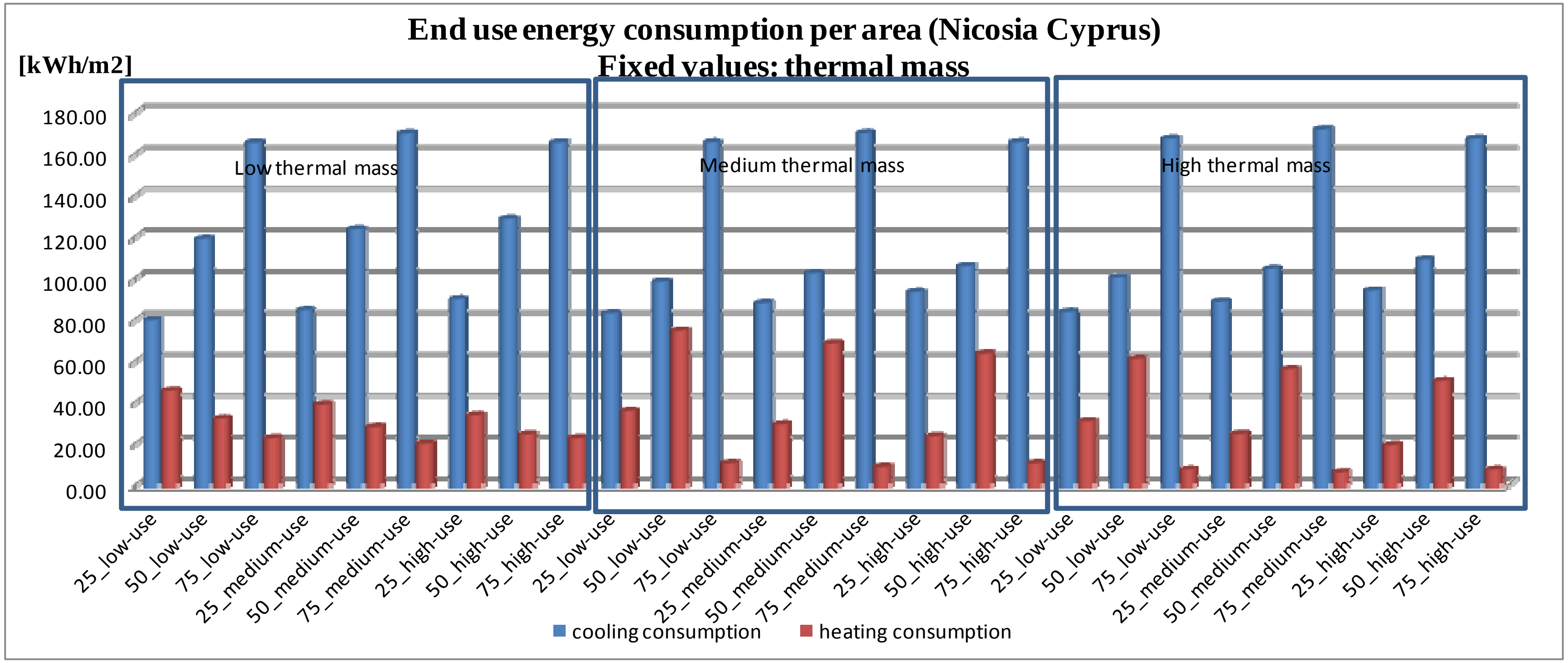


Figure 29: End use energy consumption per area for Nicosia Cyprus

Table 12: Heating and cooling energy consumption, total primary consumption and change in total primary energy consumption for various scenarios depending on the envelope thermal mass for Nicosia Cyprus

		Thermal mass	End use cooling consumption per area [kWh/m2]	End use heating consumption per area [kWh/m2]	Total primary energy per area [kWh/m2]	Change in total primary energy compared to low thermal mass [%]
Low use internal loads	25% WWR	Low thermal mass	79,66	45,38	278,66	-
		Medium thermal mass	82,80	35,16	277,05	-0,58
		High thermal mass	83,42	30,38	273,81	-1,77
	50% WWR	Low thermal mass	118,95	31,58	378,11	-
		Medium thermal mass	98,29	74,00	362,73	-4,24
		High thermal mass	100,27	60,93	354,75	-6,58
	75% WWR	Low thermal mass	165,14	22,62	502,67	-
		Medium thermal mass	165,27	10,06	489,85	-2,62
		High thermal mass	166,95	7,19	491,70	-2,23
Medium use internal loads	25% WWR	Low thermal mass	84,34	38,96	285,48	-
		Medium thermal mass	87,54	28,96	284,27	-0,43
		High thermal mass	88,21	24,47	281,49	-1,42
	50% WWR	Low thermal mass	123,38	27,76	386,96	-
		Medium thermal mass	102,17	68,06	367,74	-5,23
		High thermal mass	104,23	55,34	360,37	-7,38
	75% WWR	Low thermal mass	169,39	20,06	512,28	-
		Medium thermal mass	169,55	8,52	500,63	-2,33
		High thermal mass	171,24	5,93	502,84	-1,88
High use internal loads	25% WWR	Low thermal mass	89,45	33,18	294,23	-
		Medium thermal mass	92,70	23,49	293,50	-0,25
		High thermal mass	93,41	19,37	291,22	-1,03
	50% WWR	Low thermal mass	128,23	24,30	397,38	-
		Medium thermal mass	105,54	63,35	372,58	-6,66
		High thermal mass	108,57	49,92	367,27	-8,20
	75% WWR	Low thermal mass	165,14	22,62	502,67	-
		Medium thermal mass	165,27	10,06	489,85	-2,62
		High thermal mass	166,95	7,19	491,70	-2,23

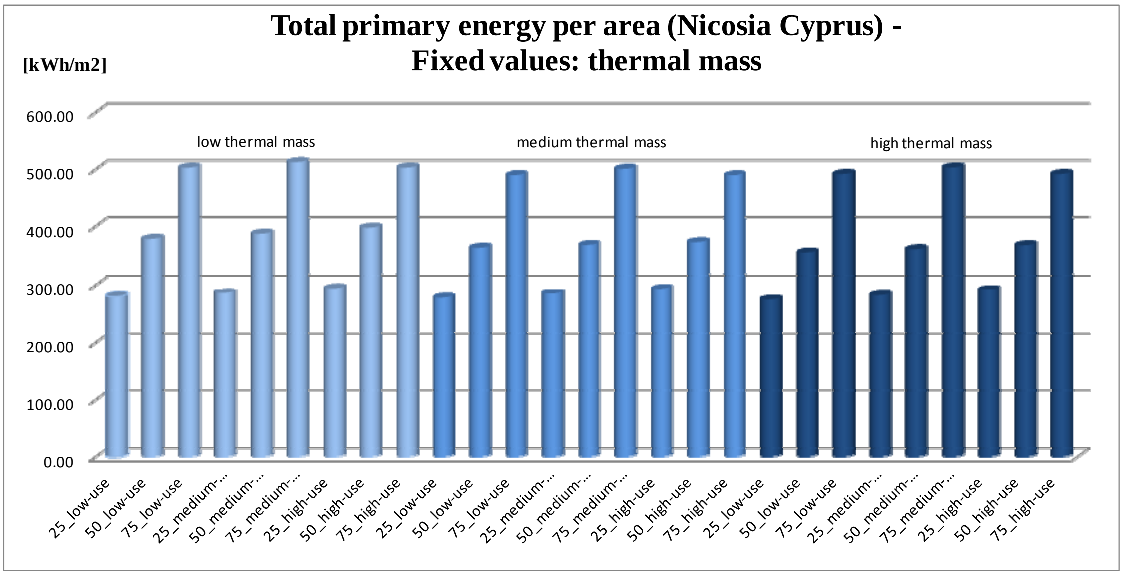


Figure 30: Total primary energy consumption per area for all examined cases with fixed thermal mass values for Nicosia Cyprus

6.2.3 London (humid cold climate)

In this section, the results of the parametric analysis are compared in order to evaluate the effect of the building thermal mass on an office building in the humid cold climate of London. As already mentioned, London in general is considered a city where heating is the most critical consumer in buildings, while cooling is not negligible. In Figure 30 the energy consumption for heating and cooling is respectively compared for the examined scenarios that are grouped by the amount of the envelope thermal mass. The simulation of the model building with low thermal mass reveals that the energy consumption for heating ranges from 260 kWh/m^2 in cases with low WWR to 320 kWh/m^2 in cases with high WWR, while the respective energy for cooling ranges from 40 kWh/m^2 in cases with low WWR to 160 kWh/m^2 in cases with high WWR respectively. The variation of cooling energy consumption can be explained by the fact that in buildings with high WWR there is a small proportion of wall area with very little thermal mass which is not enough to absorb the excess heat keeping the air temperature moderate and releasing the heat during the night. Figure 30 demonstrates that increasing the envelope thermal mass leads to a minimal decrease in the building cooling energy consumption in all cases, while decreasing the heating consumption in scenarios with 25% and 75% window to wall ratio. Medium and high thermal mass scenarios with 50% window to wall ratio present a considerable increase in the building heating energy consumption compared to low thermal mass buildings and a respective increase in the total primary energy consumption.

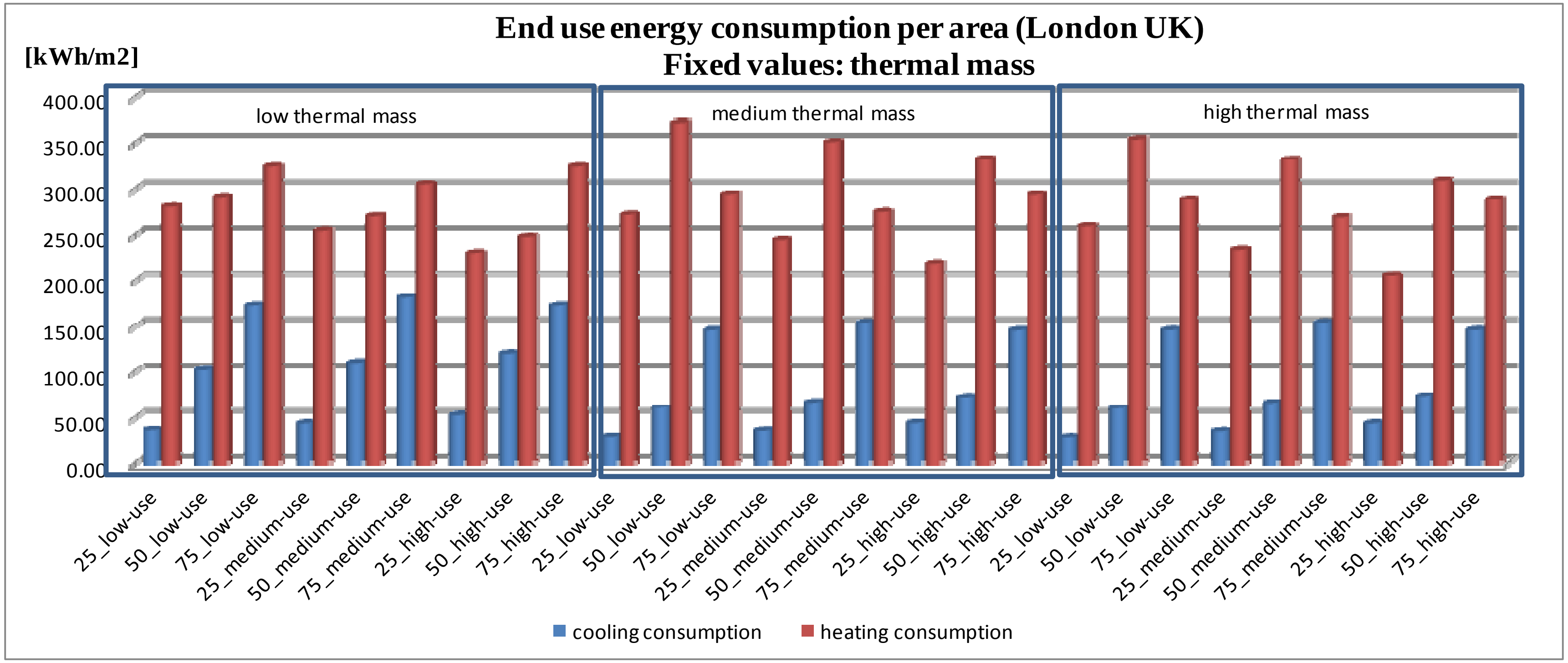


Figure 31: End use energy consumption per area for London UK

Table 13: Heating and cooling energy consumption, total primary consumption and change in total primary energy consumption for various scenarios depending on the envelope thermal mass for London UK

		Thermal mass	End use cooling consumption per area [kWh/m2]	End use heating consumption per area [kWh/m2]	Total primary energy per area [kWh/m2]	Change in total primary energy compared to low thermal mass [%]
Low use internal loads	25% WWR	Low thermal mass	35,81	279,09	314,90	-
		Medium thermal mass	28,75	270,67	299,41	-5,17
		High thermal mass	28,12	258,52	286,64	-9,86
	50% WWR	Low thermal mass	100,82	290,33	391,15	-
		Medium thermal mass	59,95	371,50	431,45	9,34
		High thermal mass	59,33	352,87	412,21	5,11
	75% WWR	Low thermal mass	171,66	323,18	494,83	-
		Medium thermal mass	144,40	293,51	437,91	-13,00
		High thermal mass	144,52	287,80	432,32	-14,46
Medium use internal loads	25% WWR	Low thermal mass	42,94	253,72	296,66	-
		Medium thermal mass	35,06	244,05	279,11	-6,29
		High thermal mass	34,54	231,81	266,35	-11,38
	50% WWR	Low thermal mass	109,40	268,99	378,39	-
		Medium thermal mass	65,90	349,77	415,67	8,97
		High thermal mass	65,40	330,91	396,31	4,52
	75% WWR	Low thermal mass	180,45	304,01	484,46	-
		Medium thermal mass	153,09	273,67	426,76	-13,52
		High thermal mass	153,21	267,92	421,13	-15,04
High use internal loads	25% WWR	Low thermal mass	51,96	228,29	280,25	-
		Medium thermal mass	43,33	217,12	260,45	-7,60
		High thermal mass	42,97	204,81	247,78	-13,11
	50% WWR	Low thermal mass	119,41	247,19	366,60	-
		Medium thermal mass	71,50	331,75	403,25	9,09
		High thermal mass	72,70	308,00	380,69	3,70
	75% WWR	Low thermal mass	171,66	323,18	494,83	-
		Medium thermal mass	144,40	293,51	437,91	-13,00
		High thermal mass	144,52	287,80	432,32	-14,46

These changes of the heating and cooling energy consumption as well as the total primary consumption in the various examined scenarios are shown in Table 13. Increasing the envelope thermal mass in most cases leads to a decrease in heating and cooling energy consumption. Specifically, the required heating energy is considerably increased when the model building has 50% window to wall ratio leading to an increase of the total primary energy consumption ranging from 3.7% to 9.34% depending on the examined scenario. In all the other cases increasing the building thermal mass leads to a decrease of the total primary energy consumption ranging from 5.17% to 15.04%.

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building thermal mass is presented in Figure 31. It is evident from the graph that increasing the envelope thermal mass leads to a considerable decrease in the total primary consumption in the examined cases with 75% window to wall ratio. Specifically, medium and high thermal mass scenarios with 75% WWR show a decrease in the total primary energy consumption ranging from 13% to 15.04%, while the respective decrease in buildings with 25% WWR ranges from 5.17% to 13.11%, as observed in Table 13. Considering the building with 50% WWR, the situation is slightly different, as already mentioned. Specifically, medium thermal mass envelope shows an increase in the total primary energy consumption, ranging from 8.97% to 9.34%, while high thermal mass envelope leads to an increase of the total primary energy consumption ranging from 3.7% to 5.11%.

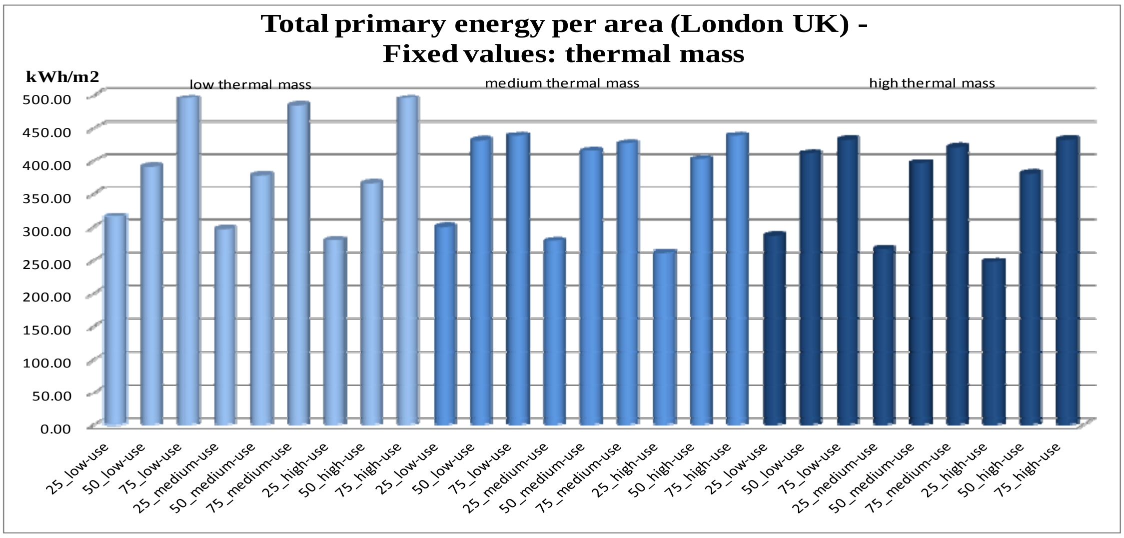


Figure 32: Total primary energy consumption per area for all examined cases with fixed thermal mass values for London UK

6.2.4 Munich (dry cold climate)

In this section, the results of the parametric analysis are compared in order to evaluate the effect of the building thermal mass on an office building in the dry cold climate of Munich. As already mentioned, in Munich heating requirements are the most critical in buildings, while cooling is negligible. In Figure 32 the energy consumption for heating and cooling is respectively compared for the examined scenarios that are respectively grouped by the amount of the envelope thermal mass. The simulation of the model building with low thermal mass reveals that the energy consumption for heating ranges from 350 kWh/m^2 in cases with low WWR to 490 kWh/m^2 in cases with high WWR, while the respective energy for cooling ranges from 10 kWh/m^2 in cases with low WWR to 90 kWh/m^2 in cases with high WWR respectively. Heating loads are higher in cases with high WWR given that in those cases there is a small proportion of wall area minimizing the existing thermal mass area and maximizing the thermal losses. Figure 32 demonstrates that increasing the envelope thermal mass leads to a minimal or even zero change in the building cooling energy consumption in all cases, while decreasing the heating consumption in scenarios with 25% and 75% window to wall ratio. Medium and high thermal mass scenarios with 50% window to wall ratio present a considerable increase in the building heating energy consumption compared to low thermal mass buildings and a respective increase in the total primary energy consumption.

These changes of the heating and cooling energy consumption as well as the total primary consumption in the various examined scenarios are shown in Table 14. Increasing the envelope thermal mass in most cases leads to a decrease in heating and cooling energy consumption. Specifically, increasing the building thermal mass leads to a decrease of the total primary energy consumption ranging from 3.07% to 10.7% in most cases, while the required heating energy is considerably increased when the model building has 50% window to wall ratio leading to an increase of the total primary energy consumption ranging from 0.64% to 5.46% depending on the examined scenario.

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building thermal mass is presented in Figure 33. It is evident from the graph that increasing the envelope thermal mass leads to a decrease in the total primary consumption in the examined cases with 75% window to wall ratio. Specifically, medium and high thermal mass scenarios with 75% WWR show a decrease in the total primary energy consumption ranging from 8.35% to 10.43%, while

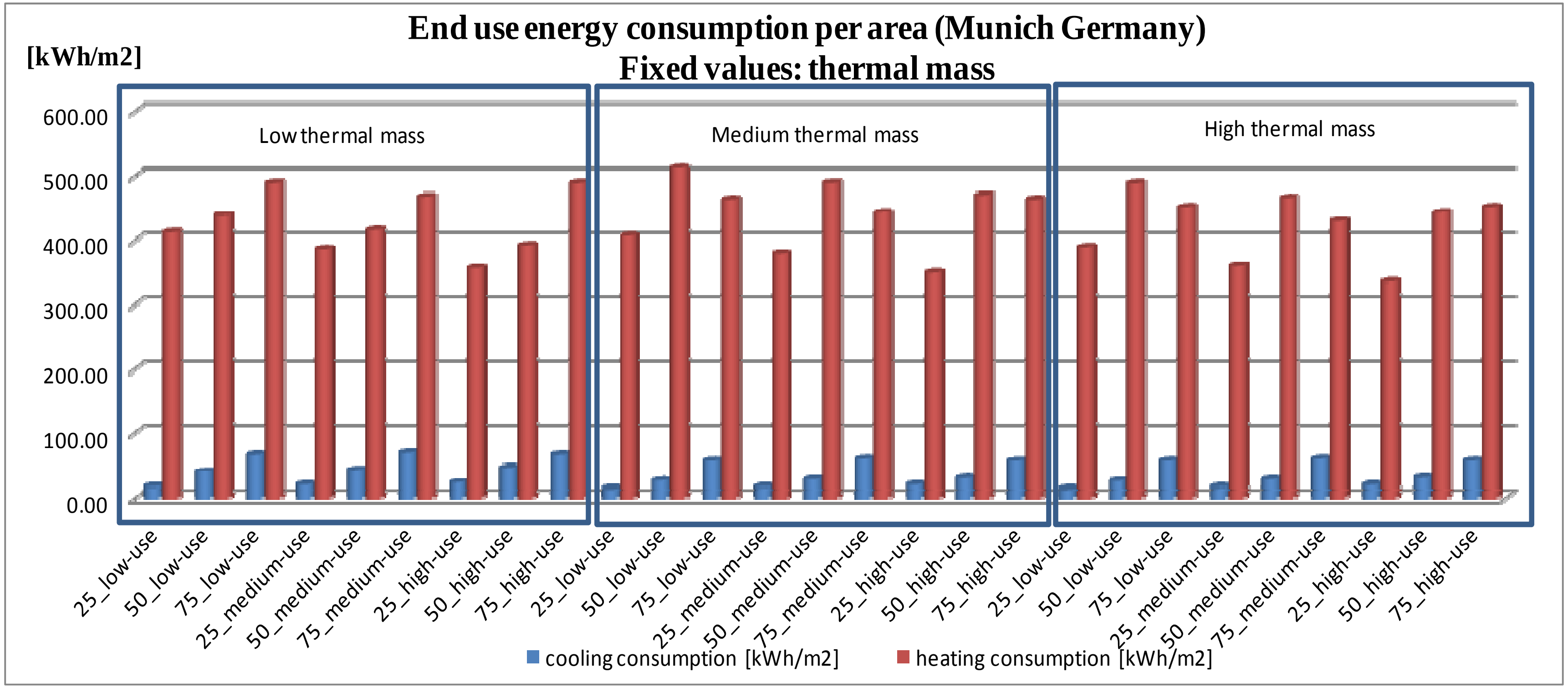


Figure 33: End use energy consumption per area for Munich Germany

Table 14: Heating and cooling energy consumption, total primary consumption and change in total primary energy consumption for various scenarios depending on the envelope thermal mass for Munich Germany

		Thermal mass	End use cooling consumption per area [kWh/m2]	End use heating consumption per area [kWh/m2]	Total primary energy per area [kWh/m2]	Change in total primary energy compared to low thermal mass [%]
Low use internal loads	25% WWR	Low thermal mass	16,50	411,90	480,34	-
		Medium thermal mass	13,65	406,14	466,02	-3,07
		High thermal mass	13,20	389,11	446,86	-7,49
	50% WWR	Low thermal mass	40,89	437,99	578,46	-
		Medium thermal mass	25,52	511,47	611,06	5,34
		High thermal mass	25,20	488,78	586,30	1,34
	75% WWR	Low thermal mass	67,32	489,08	708,75	-
		Medium thermal mass	57,64	463,81	654,14	-8,35
		High thermal mass	57,80	451,58	641,79	-10,43
Medium use internal loads	25% WWR	Low thermal mass	19,26	385,87	461,02	-
		Medium thermal mass	16,23	379,31	445,33	-3,52
		High thermal mass	15,85	362,19	426,26	-8,16
	50% WWR	Low thermal mass	43,99	415,45	563,80	-
		Medium thermal mass	27,83	489,21	594,39	5,15
		High thermal mass	27,57	466,40	569,66	1,03
	75% WWR	Low thermal mass	70,37	468,47	695,97	-
		Medium thermal mass	60,72	442,60	640,81	-8,61
		High thermal mass	60,94	430,47	628,71	-10,70
High use internal loads	25% WWR	Low thermal mass	22,60	358,92	442,40	-
		Medium thermal mass	19,37	351,32	425,06	-4,08
		High thermal mass	19,05	334,19	406,14	-8,93
	50% WWR	Low thermal mass	47,49	391,81	549,12	-
		Medium thermal mass	29,93	470,50	580,83	5,46
		High thermal mass	30,32	442,58	552,64	0,64
	75% WWR	Low thermal mass	67,32	489,08	708,75	-
		Medium thermal mass	57,64	463,81	654,14	-8,35
		High thermal mass	57,80	451,58	641,79	-10,43

the respective decrease in buildings with 25% WWR ranges from 3.07% to 8.93%, as observed in Table 14. Considering the building with 50% WWR, the situation is slightly different, as already mentioned. Specifically, medium thermal mass envelope shows an increase in the total primary energy consumption, ranging from 5.15% to 5.46%, while high thermal mass envelope leads again to an increase of the total primary energy consumption ranging from 0.64% to 1.34%.

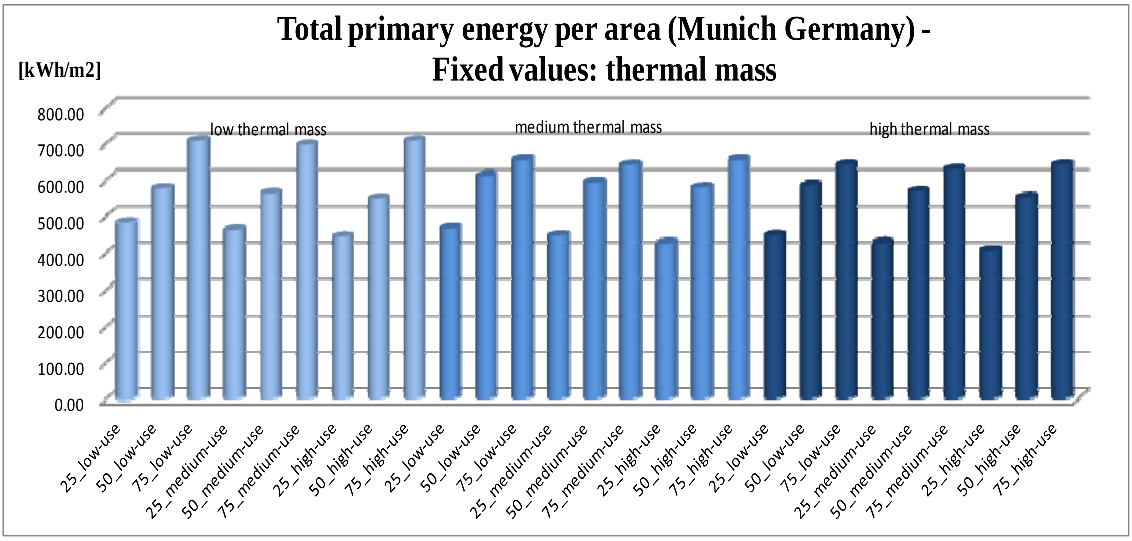


Figure 34: Total primary energy consumption per area for all examined cases with fixed thermal mass values for Munich Germany

6.3 Internal loads

Internal loads are dependent on lighting and especially the desired lighting levels and the utilization of natural lighting in the office building, the number of the occupants, the type of their activity and the time of operation of all the appliances. During the design phase all the internal loads must be taken into account. The more increased the internal loads are, the more high the cooling and ventilation needs are and the less the heating needs. [67] Based on past researches on office buildings [[68], [69], [70], [71]] there is a variation on the values for internal heat gains. In this section, the results of the model office building simulated for various internal loads, ranging from 5 W/m^2 up to 15 W/m^2 for lighting, 8 W/m^2 up to 12 W/m^2 for people and 3 W/m^2 up to 15 W/m^2 for office equipment are presented. A comparison of all the examined cases is performed for each of the examined cities.

6.3.1 Thessaloniki (humid warm climate)

In this section, the results of the parametric analysis are compared in order to evaluate the effect of the building internal loads on an office building in the city of Thessaloniki, a humid warm area as mentioned above.

In Figure 34 the energy consumption for heating and cooling is respectively compared for the examined scenarios that are grouped by the amount of internal loads. The simulation of the model building demonstrates that in all cases – low, medium and intense use scenarios - the distribution of the heating and cooling energy consumption in the respective cases does not have considerable changes.

Specifically, considering the building cooling consumption scenarios with 25% window to wall ratio and medium internal loads has about 7.4% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 14.3% higher than with low loads. Having a 50% window to wall ratio office building and medium internal loads has about 4.5% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 9.7% higher than with low loads. Last but not least with a 75% window to wall ratio and medium internal loads has about 3.2% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

Considering the building heating consumption scenarios by increasing the internal loads the heating consumption decreases. Specifically, with 25% window to wall ratio and medium internal loads needs about 8.7% lower heating consumption than the one with low loads whilst with intense internal loads needs 19.2% lower. Having a 50% window to wall ratio office building and medium or high internal loads needs about 6.7% lower heating consumption than with low loads while with intense internal loads needs 14.8% lower. Furthermore, with a 75% window to wall ratio and medium internal loads needs about 8.5% lower heating consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

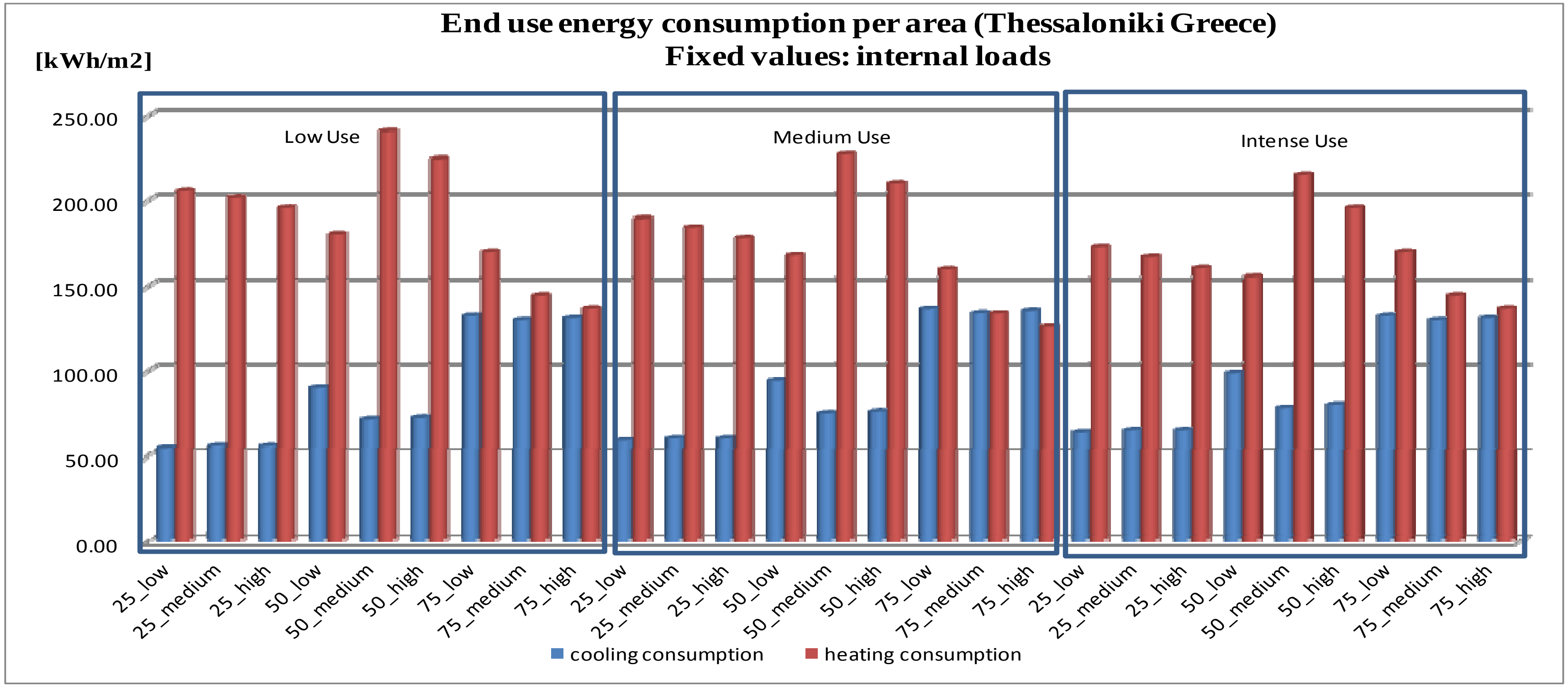


Figure 35: End use energy consumption per area for Thessaloniki Greece

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building internal loads is presented in Figure 35. It is evident from the graph that increasing the building internal loads has a minimal if not zero effect in the total primary energy consumption. Specifically, medium use scenarios require total primary energy about 0.65% lower than low use scenarios, while intense use scenarios require total primary energy about 1.31% lower than low use scenarios.

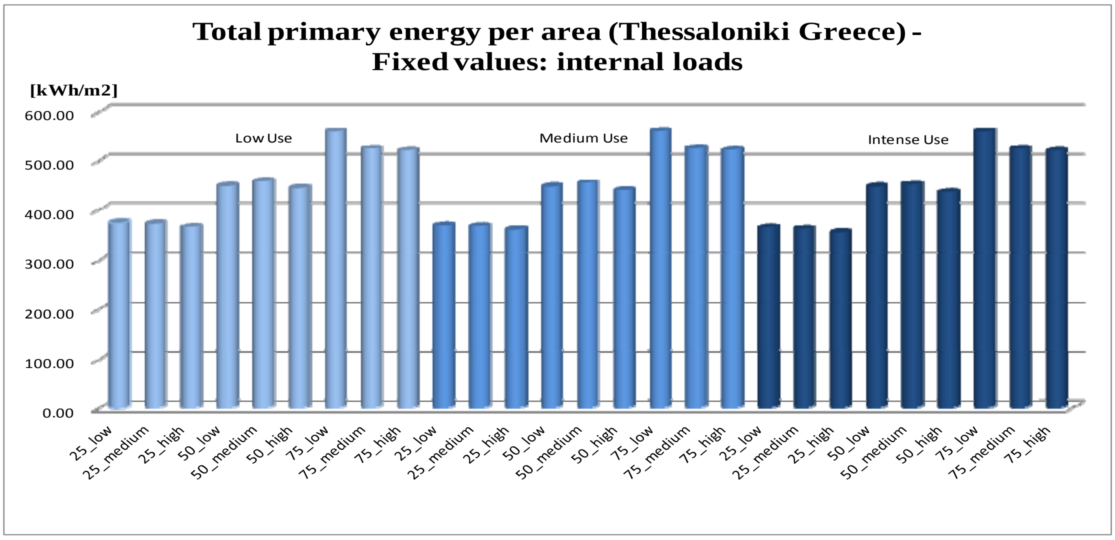


Figure 36: Total primary energy consumption per area for all examined cases with fixed internal loads for Thessaloniki Greece

6.3.2 Cyprus (dry warm climate)

The results of the parametric analysis are compared in order to evaluate the effect of internal loads on an office building in the dry warm climate of Nicosia Cyprus. In Figure 36 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The simulation of the model building demonstrates that in all cases – low, medium and intense use scenarios - the distribution of the heating and cooling energy consumption in the respective cases has diminutive changes. Additionally, it is observed that cooling is the most critical factor while the consumptions reach the 170kWh/m^2 whereas the maximum heating consumptions are only 74kWh/m^2. In Figure 36 the energy consumption for heating and cooling is respectively compared for the examined scenarios that are grouped by the amount of internal loads. The simulation of the model building demonstrates that in all cases – low, medium and intense use scenarios - the distribution of the heating and cooling energy consumption in the respective cases does not have considerable changes.

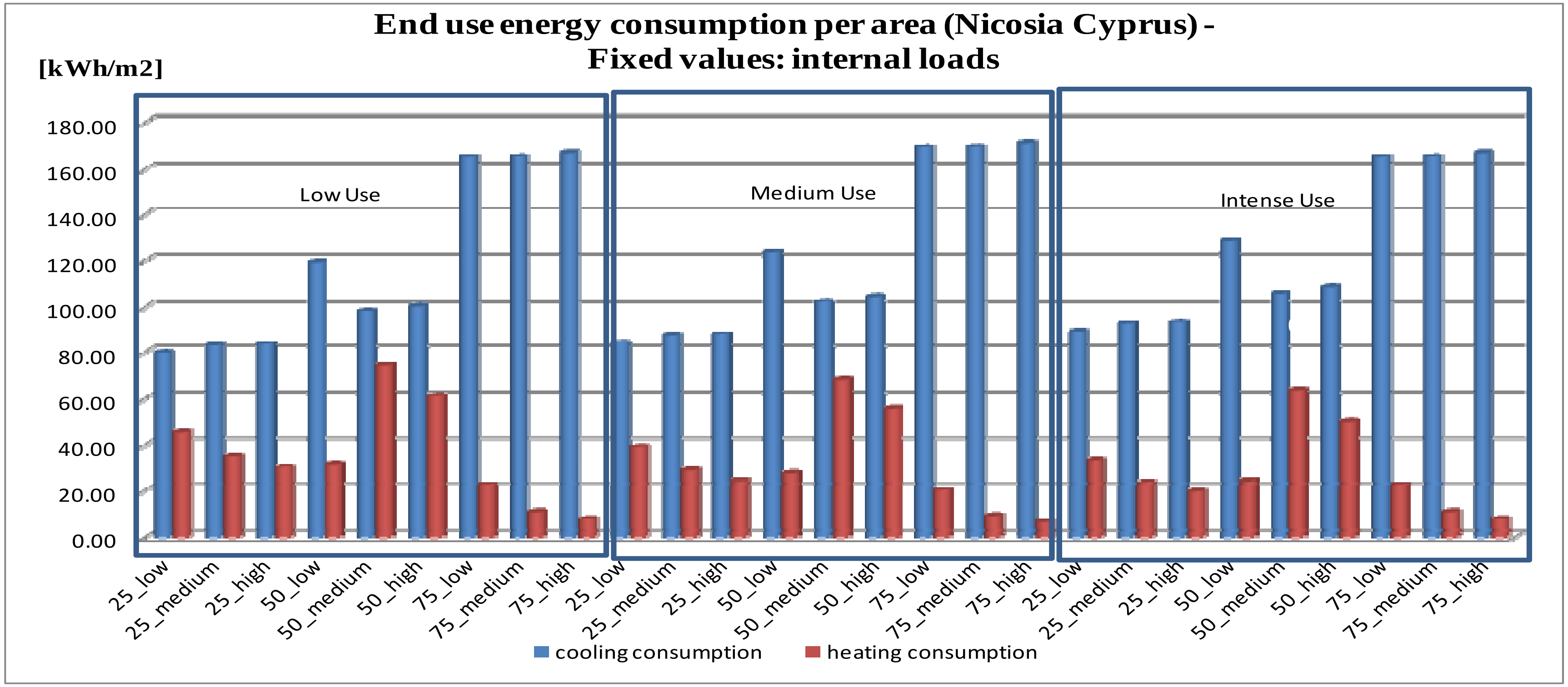


Figure 37: End use energy consumption per area for Nicosia Cyprus

Specifically, considering the building cooling consumption scenarios with 25% window to wall ratio and medium internal loads has about 5.5% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 10.9% higher than with low loads. Having a 50% window to wall ratio office building and medium internal loads has about 3.6% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 7.2% higher than with low loads. Last but not least with a 75% window to wall ratio and medium internal loads has about 2.5% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

Considering the building heating consumption scenarios by increasing the internal loads the heating consumption decreases. Specifically, with 25% window to wall ratio and medium internal loads needs about 16.5% lower heating consumption than the one with low loads whilst with intense internal loads needs 35.7% lower. Having a 50% window to wall ratio office building and medium internal loads needs about 8.7% lower heating consumption than with low loads and with intense internal loads needs 16.8% lower. Moreover with a 75% window to wall ratio and medium internal loads needs about 18% lower heating consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building internal loads is presented in Figure 37. It is evident from the graph that increasing the building internal loads in all cases the total primary energy increases. Specifically, medium use scenarios require total primary energy about 2.12% higher than low use scenarios, while intense use scenarios require total primary energy about up to 3.9% higher than low use scenarios. It is interesting to mention that total primary energy per m^2 in an office building with 75% window to wall ratio and high internal loads has zero increase compared to the one that uses low use loads whilst the most intense differences in total primary energy are presented when having 25% window to wall.

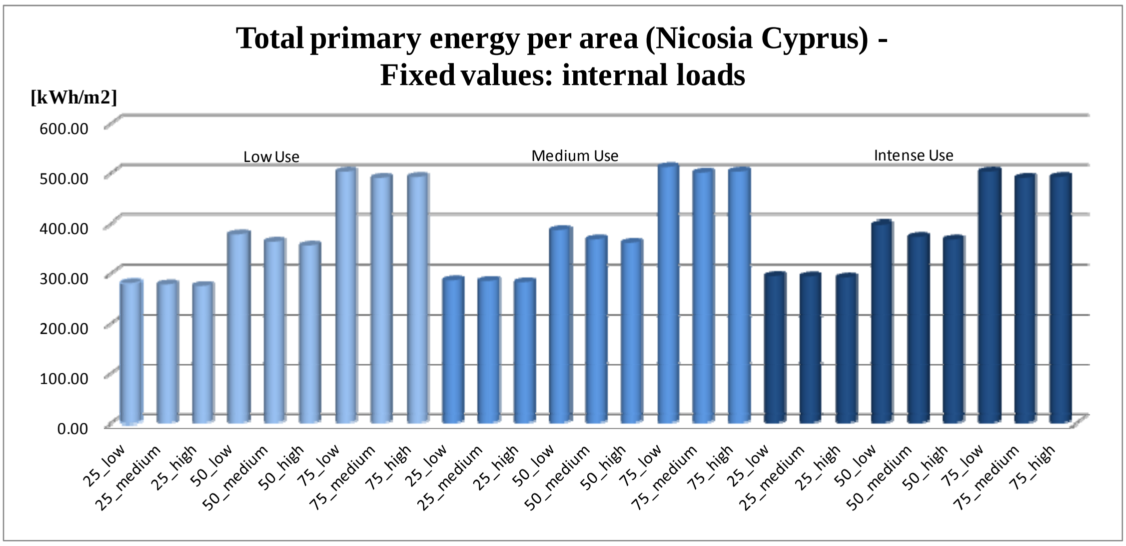


Figure 38: Total primary energy consumption per area for all examined cases with fixed internal loads for Nicosia Cyprus

6.3.3 London (humid cold climate)

The results of the parametric analysis are compared in order to evaluate the effect of internal loads on an office building in the humid cold climate of London UK. In Figure 38 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The simulation of the model building demonstrates that in average it is needed a percentage equal to 10.6% more cooling consumption when having intense internal loads relative to low internal loads and a percentage equal to 12% more heating consumption when having low internal loads. Additionally, it is observed that heating is the most critical factor while the consumptions reach the 370kWh/m^2 whereas the maximum cooling consumptions are 180kWh/m^2.

Specifically, considering the building cooling consumption scenarios with 25% window to wall ratio and medium internal loads has about 17.7% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 33% higher than with low loads. Having a 50% window to wall ratio office building and medium internal loads has about 8.6% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 16% higher than with low loads. Last but not least with a 75% window to wall ratio and medium internal loads has about 5% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

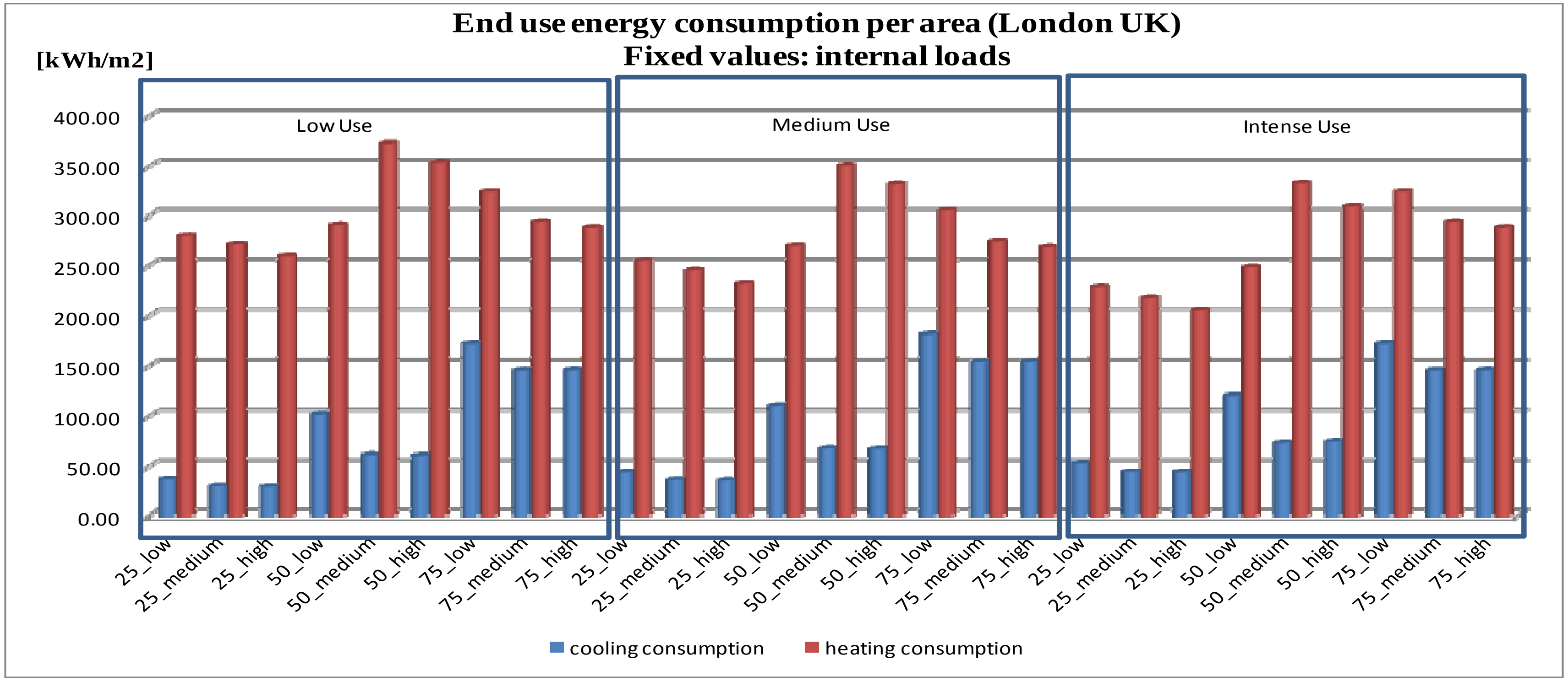


Figure 39: End use energy consumption per area for London UK

Considering the building heating consumption scenarios by increasing the internal loads the heating consumption decreases. Specifically, with 25% window to wall ratio and medium internal loads needs about 11% lower heating consumption than the one with low loads whilst with intense internal loads needs 12% lower. Having a 50% window to wall ratio office building and medium or high internal loads needs about 7% lower heating consumption than with low loads while with a 75% window to wall ratio and medium internal loads needs about 6% lower heating consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building internal loads is presented in Figure 39. The graph proves that increasing the building internal loads has a minimal if not zero effect in the total primary energy consumption. Specifically, medium use scenarios require total primary energy about 4% lower than low use scenarios, while intense use scenarios require total primary energy about 7.5% lower than low use scenarios. It is interesting to mention that total primary energy per m^2 in an office building with 75% window to wall ratio and high internal loads has zero increase compared to the one that uses low use loads whilst the most intense differences in total primary energy are presented when having 25% window to wall.

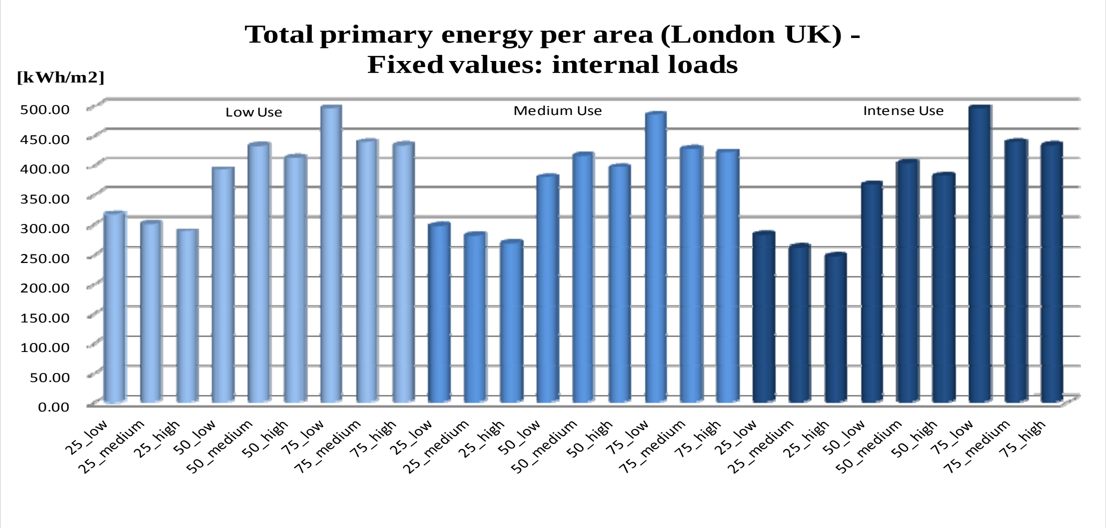


Figure 40: Total primary energy consumption per area for all examined cases with fixed internal loads for London UK

6.3.4 Munich (dry cold climate)

The results of the parametric analysis are compared in order to evaluate the effect of the internal loads on an office building in the humid cold climate of Munich Germany. Due to its climate, heating is the most crucial factor so minimizing heating energy consumption is needed when designing an office building in Munich.

In Figure 40 the energy consumption for heating and cooling is respectively compared for the examined scenarios. The simulation of the model building demonstrates that it is needed a percentage equal to 9.6% more cooling consumption when having intense internal loads relative to low internal loads and a percentage equal to 7% more heating consumption when having low internal loads. Additionally, it is observed that heating is the most critical factor while the consumptions reach the 510kWh/m^2 whereas the maximum cooling consumptions are only 71kWh/m^2.

Specifically, considering the building cooling consumption scenarios with 25% window to wall ratio and medium internal loads has about 14.3% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 27% higher than with low loads. Having a 50% window to wall ratio office building and medium internal loads has about 16% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is about 13% higher than with low loads. Last but not least with a 75% window to wall ratio and medium internal loads has about 5% higher cooling consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

Considering the building heating consumption scenarios by increasing the internal loads the heating consumption decreases. Specifically, with 25% window to wall ratio and medium internal loads needs about 6.7% lower heating consumption than the one with low loads whilst with intense internal loads needs 14.7% lower. Having a 50% window to wall ratio office building and medium or high internal loads needs about 6.5% lower heating consumption than with low loads while with a 75% window to wall ratio and medium internal loads needs about 4.8% lower heating consumption than the one with low loads whilst with intense internal loads the cooling consumption is the same with low loads.

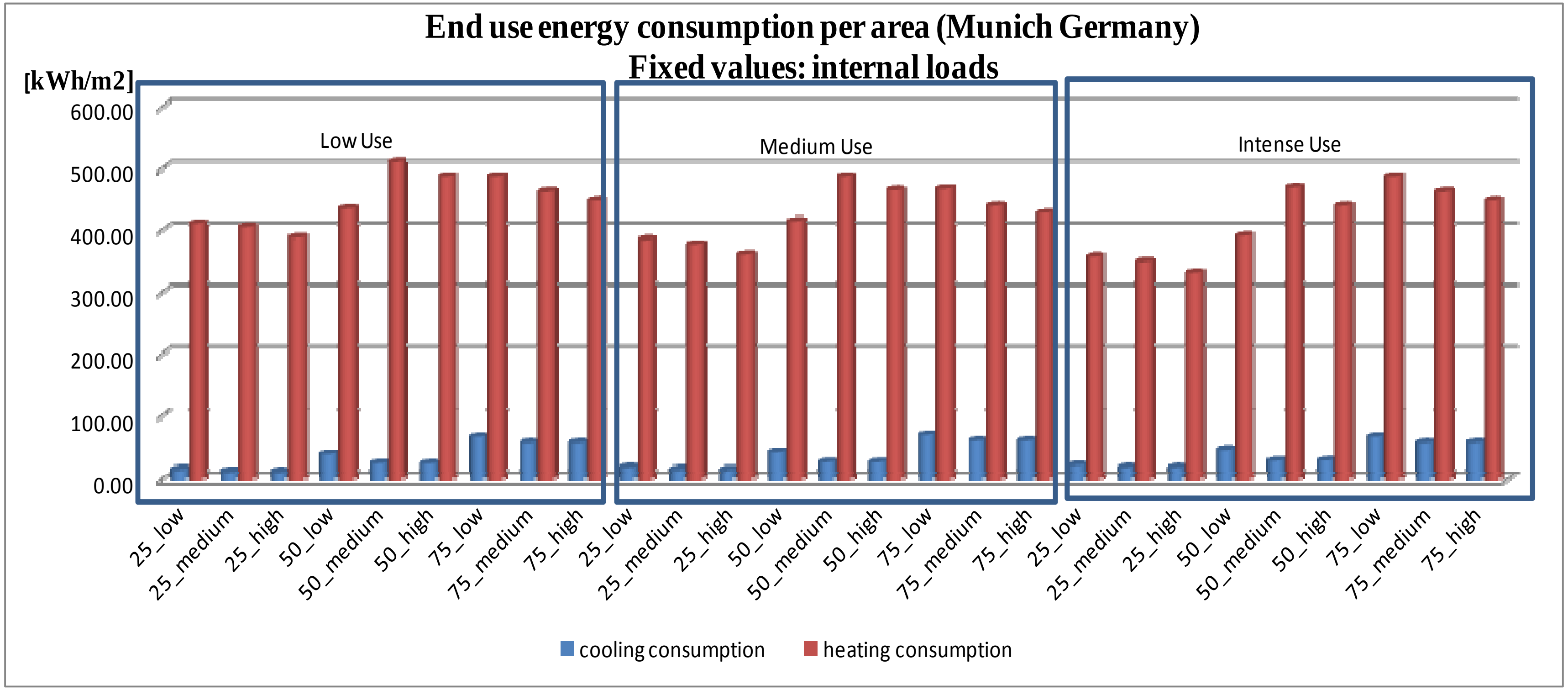


Figure 41: End use energy consumption per area for Munich Germany

A comparative graph of the total primary energy consumption of all the examined cases grouped depending on the building internal loads is presented in Figure 41. It is evident from the graph that increasing the building internal loads in all cases the total primary energy decreases. Specifically, medium use scenarios require total primary energy about 3.1% lower than low use scenarios, while intense use scenarios require total primary energy about 5% lower than low use scenarios. However it is interesting to mention that total primary energy per m^2 in an office building with 75% window to wall ratio and high internal loads has zero increase compared to the one that uses low use loads.

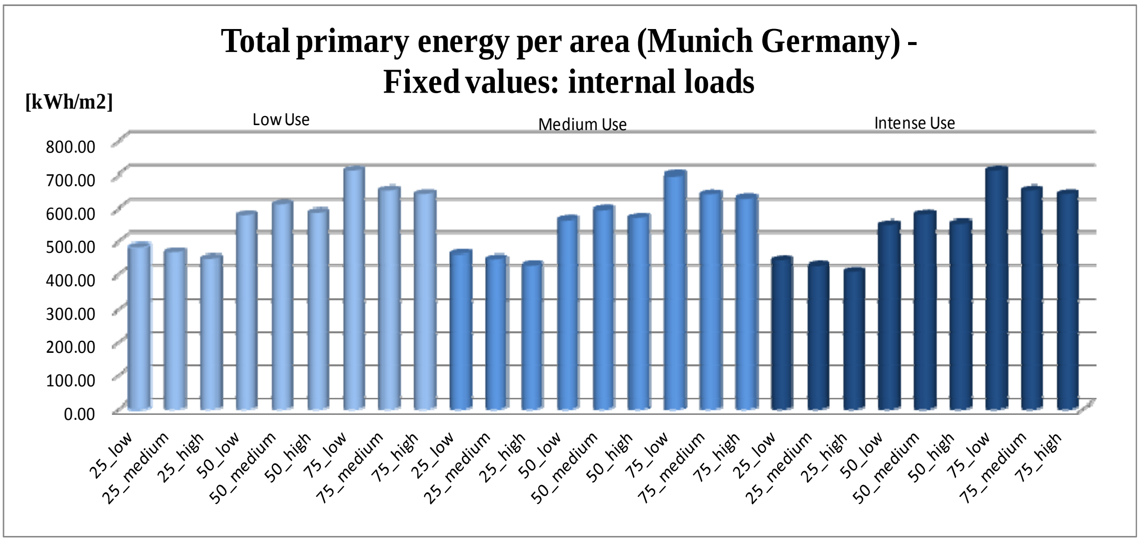


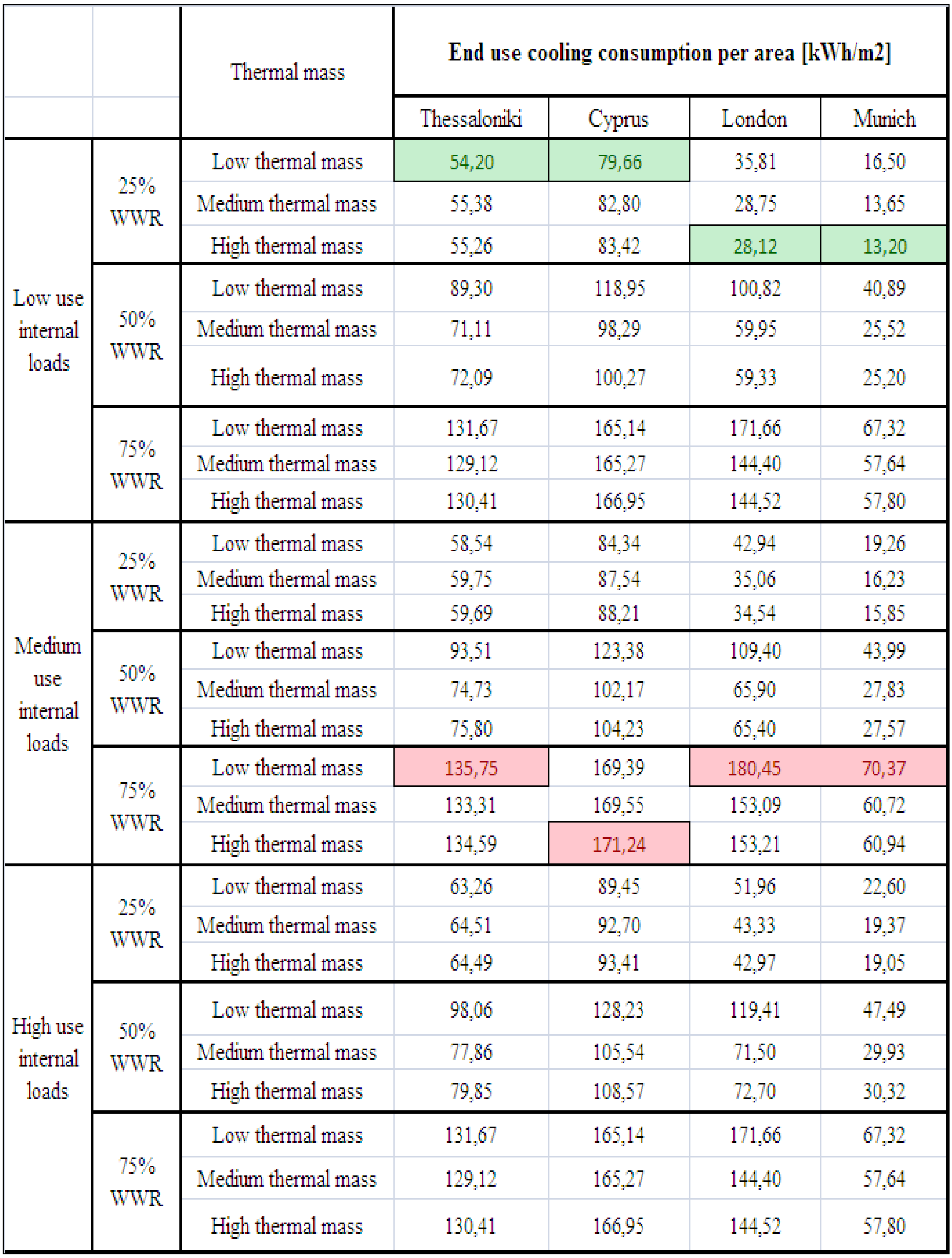
Figure 42: Total primary energy consumption per area for all examined cases with fixed internal loads for Munich German

7 Discussion

In this section a comparison of the demonstrated results for the various climates is performed. Specifically, the results of the heating and cooling energy consumption as well as the total primary energy consumption are presented in Tables 15, 16 and 17 respectively for all the simulated scenarios for the four examined climates; humid warm, dry warm, humid cold and dry cold in the cities of Thessaloniki Greece, Nicosia Cyprus, London UK and Munich Germany respectively. Additionally, the best case scenario for each climate is noted in green in the respective table, while the worst case scenario is illustrated in red.

Considering the cooling energy consumption (Table 15) the optimal scenario for each separate climate occurs in the building model with 25% window to wall ratio as expected given the low incoming solar radiation. In Thessaloniki and Cyprus – humid warm and dry warm climates respectively – the best performance is observed in lightweight buildings showing that in warm climates where cooling needs are critical increasing the envelope thermal mass does not necessarily have a positive effect. The installation of natural or forced ventilation in such climates would probable decrease the cooling energy consumption and it is a solution that should be examined in more detail in cases with high thermal mass. On the other hand, in London and Germany – humid cold and dry cold climate- the best performance is observed in heavyweight buildings showing that in cold climates where heating needs are critical increasing the envelope thermal mass leads to considerably lower cooling energy consumption. This situation can be easily explained given that the storage mass of the building is used to mitigate the indoor air temperature releasing the stored heat during the night. In all climates, the best results are observed for low use buildings since increasing the building internal loads leads to an increase on the building cooling loads as expected. On the other hand worst case scenarios considering the building cooling energy consumption occur for cases with 75% WWR and medium internal loads (Table 15). Specifically, for Thessaloniki, London and Germany the worst cases are observed in low weight constructions, while in Cyprus the worst case occurs in a high thermal mass building.

Table 15: End use cooling energy consumption in kWh/m^2 for all the examined cases in all the respective climates

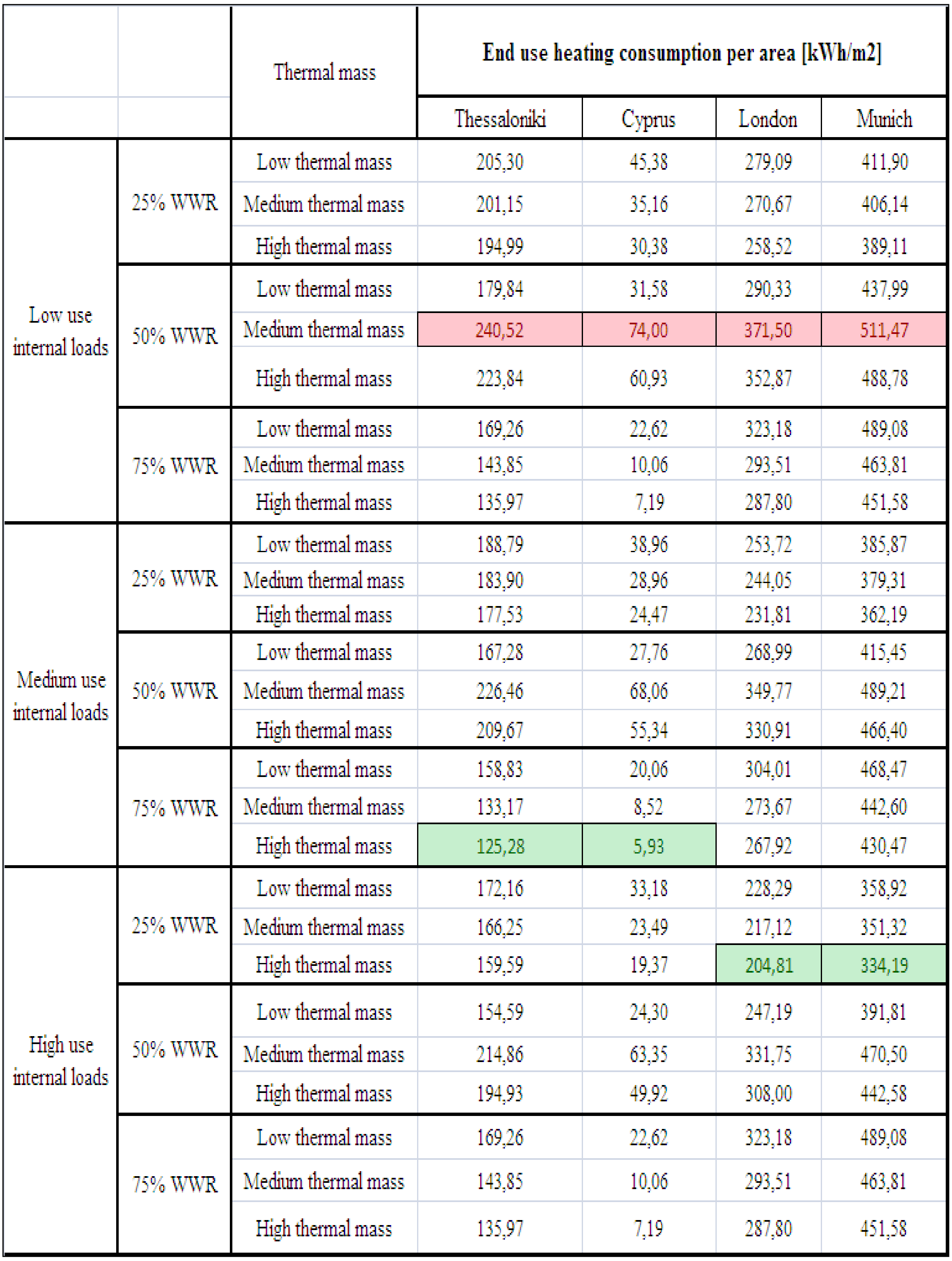


		Thermal mass	End use cooling consumption per area [kWh/m2]			
			Thessaloniki	Cyprus	London	Munich
Low use internal loads	25% WWR	Low thermal mass	54,20	79,66	35,81	16,50
		Medium thermal mass	55,38	82,80	28,75	13,65
		High thermal mass	55,26	83,42	28,12	13,20
	50% WWR	Low thermal mass	89,30	118,95	100,82	40,89
		Medium thermal mass	71,11	98,29	59,95	25,52
		High thermal mass	72,09	100,27	59,33	25,20
	75% WWR	Low thermal mass	131,67	165,14	171,66	67,32
		Medium thermal mass	129,12	165,27	144,40	57,64
		High thermal mass	130,41	166,95	144,52	57,80
Medium use internal loads	25% WWR	Low thermal mass	58,54	84,34	42,94	19,26
		Medium thermal mass	59,75	87,54	35,06	16,23
		High thermal mass	59,69	88,21	34,54	15,85
	50% WWR	Low thermal mass	93,51	123,38	109,40	43,99
		Medium thermal mass	74,73	102,17	65,90	27,83
		High thermal mass	75,80	104,23	65,40	27,57
	75% WWR	Low thermal mass	135,75	169,39	180,45	70,37
		Medium thermal mass	133,31	169,55	153,09	60,72
		High thermal mass	134,59	171,24	153,21	60,94
High use internal loads	25% WWR	Low thermal mass	63,26	89,45	51,96	22,60
		Medium thermal mass	64,51	92,70	43,33	19,37
		High thermal mass	64,49	93,41	42,97	19,05
	50% WWR	Low thermal mass	98,06	128,23	119,41	47,49
		Medium thermal mass	77,86	105,54	71,50	29,93
		High thermal mass	79,85	108,57	72,70	30,32
	75% WWR	Low thermal mass	131,67	165,14	171,66	67,32
		Medium thermal mass	129,12	165,27	144,40	57,64
		High thermal mass	130,41	166,95	144,52	57,80

Considering the building heating energy consumption, it is observed in Table 16 that the worst case scenario is the same for each separate climate and it occurs in buildings with 50% WWR, medium internal loads and low internal loads. On the other hand, the best case scenario is different for each respective climate. Specifically, for Thessaloniki and

Cyprus the best case is observed in 75% WWR, high thermal mass and medium internal loads, while for London and Munich it occurs in buildings with 25% WWR, high thermal mass and intense use internal loads.

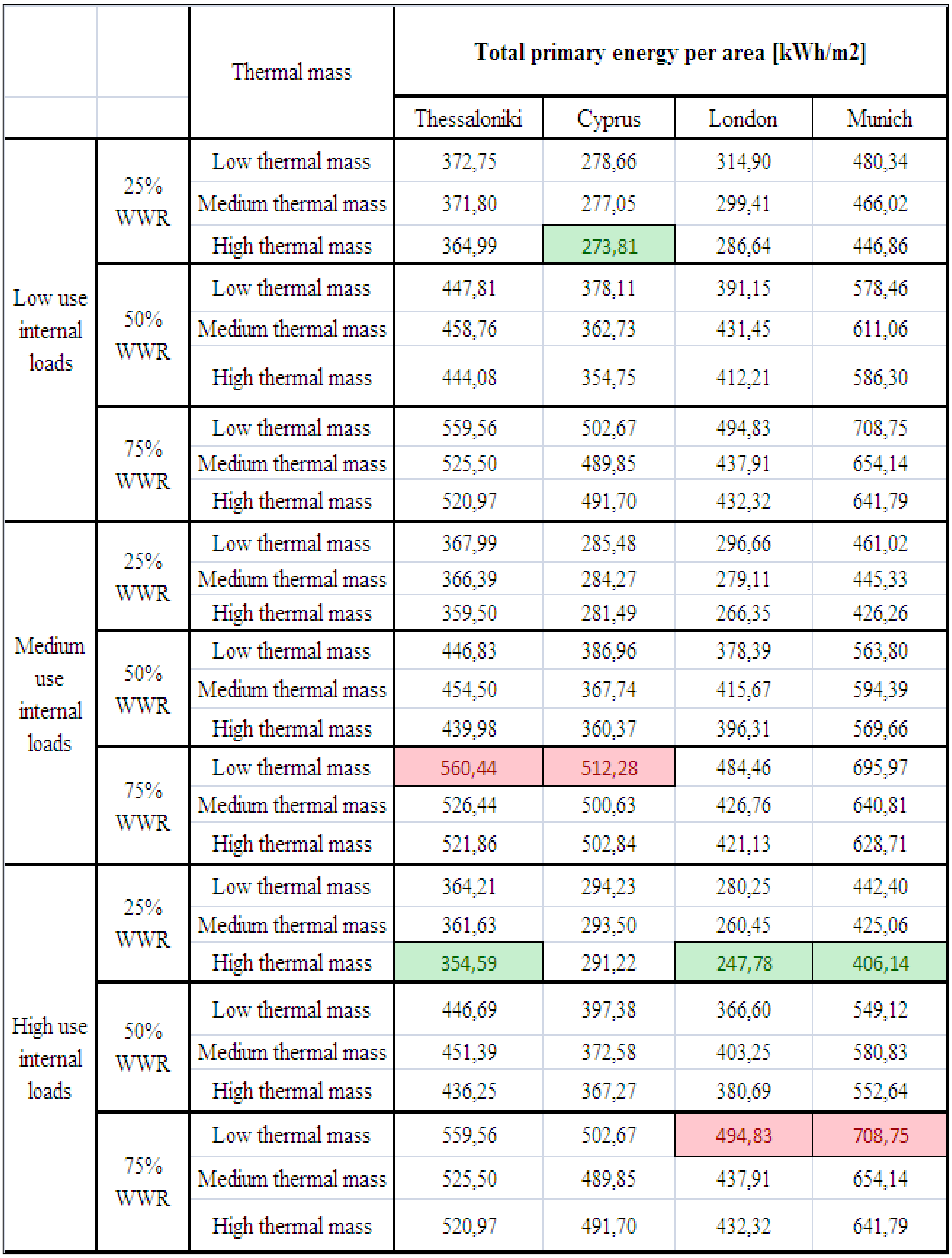
Table 16: End use heating energy consumption in kWh/m^2 for all the examined cases in all the respective climates



		Thermal mass	**End use heating consumption per area [kWh/m2]**			
			Thessaloniki	Cyprus	London	Munich
Low use internal loads	25% WWR	Low thermal mass	205,30	45,38	279,09	411,90
		Medium thermal mass	201,15	35,16	270,67	406,14
		High thermal mass	194,99	30,38	258,52	389,11
	50% WWR	Low thermal mass	179,84	31,58	290,33	437,99
		Medium thermal mass	240,52	74,00	371,50	511,47
		High thermal mass	223,84	60,93	352,87	488,78
	75% WWR	Low thermal mass	169,26	22,62	323,18	489,08
		Medium thermal mass	143,85	10,06	293,51	463,81
		High thermal mass	135,97	7,19	287,80	451,58
Medium use internal loads	25% WWR	Low thermal mass	188,79	38,96	253,72	385,87
		Medium thermal mass	183,90	28,96	244,05	379,31
		High thermal mass	177,53	24,47	231,81	362,19
	50% WWR	Low thermal mass	167,28	27,76	268,99	415,45
		Medium thermal mass	226,46	68,06	349,77	489,21
		High thermal mass	209,67	55,34	330,91	466,40
	75% WWR	Low thermal mass	158,83	20,06	304,01	468,47
		Medium thermal mass	133,17	8,52	273,67	442,60
		High thermal mass	125,28	5,93	267,92	430,47
High use internal loads	25% WWR	Low thermal mass	172,16	33,18	228,29	358,92
		Medium thermal mass	166,25	23,49	217,12	351,32
		High thermal mass	159,59	19,37	204,81	334,19
	50% WWR	Low thermal mass	154,59	24,30	247,19	391,81
		Medium thermal mass	214,86	63,35	331,75	470,50
		High thermal mass	194,93	49,92	308,00	442,58
	75% WWR	Low thermal mass	169,26	22,62	323,18	489,08
		Medium thermal mass	143,85	10,06	293,51	463,81
		High thermal mass	135,97	7,19	287,80	451,58

The results of the total primary consumption are presented in Table 17 showing a wide variation in the optimal and worst cases for each climate. Specifically, the best performance in observed in the examined scenario with 25% WWR, high thermal mass and low internal loads for the dry warm climate of Nicosia, while it is observed in the examined scenario with 25% WWR, high thermal mass and high internal loads for the humid warm, humid cold and dry cold climates respectively. It should be noted that in London and Munich the best performance in terms of total primary energy performance occurs when the heating energy consumption is minimum, given the cold climate in both cities. On the other hand, for the climates of Thessaloniki and Cyprus the situation appears to be more complicated since the minimum total primary energy performance does not coincide with the best scenarios for heating and cooling energy consumption. In terms of total primary energy consumption the best performance occurs for scenarios with low window to wall ratio and high thermal mass showing the importance to mitigate the internal air temperature using high thermal mass in buildings while keeping the window to wall ratio as small as possible minimizing the thermal losses regardless the climate.

Table 17: Total primary energy consumption in kWh/m^2 for all the examined cases in all the respective climates



		Thermal mass	**Total primary energy per area [kWh/m2]**			
			Thessaloniki	Cyprus	London	Munich
Low use internal loads	25% WWR	Low thermal mass	372,75	278,66	314,90	480,34
		Medium thermal mass	371,80	277,05	299,41	466,02
		High thermal mass	364,99	273,81	286,64	446,86
	50% WWR	Low thermal mass	447,81	378,11	391,15	578,46
		Medium thermal mass	458,76	362,73	431,45	611,06
		High thermal mass	444,08	354,75	412,21	586,30
	75% WWR	Low thermal mass	559,56	502,67	494,83	708,75
		Medium thermal mass	525,50	489,85	437,91	654,14
		High thermal mass	520,97	491,70	432,32	641,79
Medium use internal loads	25% WWR	Low thermal mass	367,99	285,48	296,66	461,02
		Medium thermal mass	366,39	284,27	279,11	445,33
		High thermal mass	359,50	281,49	266,35	426,26
	50% WWR	Low thermal mass	446,83	386,96	378,39	563,80
		Medium thermal mass	454,50	367,74	415,67	594,39
		High thermal mass	439,98	360,37	396,31	569,66
	75% WWR	Low thermal mass	560,44	512,28	484,46	695,97
		Medium thermal mass	526,44	500,63	426,76	640,81
		High thermal mass	521,86	502,84	421,13	628,71
High use internal loads	25% WWR	Low thermal mass	364,21	294,23	280,25	442,40
		Medium thermal mass	361,63	293,50	260,45	425,06
		High thermal mass	354,59	291,22	247,78	406,14
	50% WWR	Low thermal mass	446,69	397,38	366,60	549,12
		Medium thermal mass	451,39	372,58	403,25	580,83
		High thermal mass	436,25	367,27	380,69	552,64
	75% WWR	Low thermal mass	559,56	502,67	494,83	708,75
		Medium thermal mass	525,50	489,85	437,91	654,14
		High thermal mass	520,97	491,70	432,32	641,79

8 Conclusions

In this thesis a state of the art research protocol on urban office buildings in a European level is performed, with a focus on the parameters that influence its energy performance from the early design phase. For that purpose a typical office model with a lineal geometry and composite construction has been designed in order to evaluate various parameters in four different European climates; warm humid, warm dry, cold humid and cold dry. The cities that has been chosen are Thessaloniki Greece, Nicosia Cyprus, London UK and Munich Germany with the aforementioned climate characteristics accordingly. The building construction characteristics are given in accordance with each country's legislation. Several factors are examined to quantify their influence on the building behaviour depending on the climate, location and building construction. Specifically, factors such as window to wall ratio, envelope thermal mass and internal loads are investigated to understand which results in lower energy requirements. The results are compared and discussed in terms of the building design. It is interesting to mention that the main complexity is to find the appropriate combination of factors that achieve an optimised design solution for an office building in different climates. The various parameters are assessed using Energy Plus simulation software.

The results for each climate presented separately at first evaluating the effect of each examined parameter. The first factor that examined is the window to wall ratio of the building envelope; a factor that significantly affects the energy performance of office buildings in terms of heating, cooling and lighting consumption. The office building model simulated for a window to wall ratio ranging from 25% to 75%. A comparison of the energy consumption for heating and cooling for all the examined cases is performed. It is demonstrated that for Thessaloniki the examined cases with 25% window to wall ratio appear to have high heating energy consumption and quite low needs for cooling; explained easily by the low incoming solar radiation and the enclosed building envelope of this type of buildings whilst the cooling energy consumption is significantly increased in the simulated cases with 75% window to wall ratio compared to the rest of the examined cases, while the heating energy consumption is lower. This explains the high increase in the total primary energy consumption in buildings with 75% window to wall ratio. The effect of the window to wall ratio on the building energy performance is higher in the dry warm climate of Nicosia Cyprus compared to the one of Thessaloniki and it can be judged as a critical factor when designing an office building in Cyprus. Minimizing heating energy consumption is critical when designing an office building in Munich and that may be achieved with small openings in order not to have thermal losses. In conclusion, in all of the cases it is observed that changing the window to wall ratio to 75% increases the total primary energy consumption while the optimal WWR seems to be the 25%.

Another factor that examined is thermal mass; ways to control diurnal temperature changes and achieve thermal comfort. For Thessaloniki it reveals that increasing the building thermal mass leads to an increase in the building energy consumption in cases with low and medium window to wall ratio and a significant decrease in heating energy consumption in buildings with high WWR. For Cyprus though increasing the building thermal mass leads to a decrease in heating and cooling energy consumption and consequently a decrease of the total primary energy consumption; especially in cases with 50% and 75% window to wall ratio. In London increasing thermal mass with 50% window to wall ratio it is presented a considerable increase in the building heating energy, while in Munich increasing the envelope thermal mass leads to a decrease in heating consumption in scenarios with 25% and 75% window to wall ratio. Moreover due to Germany's climate a differentiation in thermal mass leads to a minimal or even zero change in the building cooling energy consumption in all cases.

The results for the internal loads evidence that in all cases – low, medium and intense use scenarios - the distribution of the heating and cooling energy consumption in the respective cases does not have considerable changes; increasing the building internal loads has a minimal if not zero effect in the total primary energy consumption. In Thessaloniki and in Cyprus medium and intense use internal loads scenarios require total primary energy higher than low use scenarios while in London and Munich the opposite is observed; medium and intense use scenarios require lower total primary energy.

Considering the optimal scenario for cooling energy consumption for each separate climate accrued to be the building model with 25% window to wall ratio as expected given the low incoming solar radiation. Specifically in Thessaloniki and Cyprus – humid warm and dry warm climates respectively – the best performance is observed in lightweight buildings, while in London and Germany – humid cold and dry cold climate- the best performance is observed in heavyweight buildings. Considering the building heating energy consumption, the worst case scenario is the same for each separate climate.

Specifically, buildings with 50% WWR, medium internal loads and low internal loads result to have the worst efficiency. On the other hand, the best case scenario is different for each respective climate. Specifically, for Thessaloniki and Cyprus the best case is observed in 75% WWR, high thermal mass and medium internal loads, while for London and Munich it occurs in buildings with 25% WWR, high thermal mass and intense use internal loads.

A wide variation in the optimal and worst cases for each climate is accrued according to the results of the total primary consumption. Specifically, the best performance is observed in the examined scenario with 25% WWR, high thermal mass and low internal loads for the dry warm climate of Nicosia, while the examined scenario with 25% WWR, high thermal mass and high internal loads for the humid warm, humid cold and dry cold climates respectively. In London and Munich the best performance in terms of total primary energy performance occurs when the heating energy consumption is minimum, given the cold climate in both cities. On the other hand, for the climates of Thessaloniki and Cyprus the situation appears to be more complicated since the minimum total primary energy performance does not coincide with the best scenarios for heating and cooling energy consumption. In terms of total primary energy consumption the best performance occurs for scenarios with low window to wall ratio and high thermal mass showing the importance to mitigate the internal air temperature using high thermal mass in buildings while keeping the window to wall ratio as small as possible minimizing the thermal losses regardless the climate.

Based on the existing situation, there is a significant need for extensive research considering sustainable building practices and measures towards high energy efficient buildings in Europe. Completing the whole thesis may be used as a guideline and a useful tool by engineers during design phase to assess the impact of design choices on the energy efficiency of urban office buildings.

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Appendix

Simulated Scenarios / Lineal typology / Composite construction	
Abbreviation	**Explanation**
25_low_low-use	25% window to wall ratio_low thermal mass_low use internal loads
25_medium_low-use	25% window to wall ratio_medium thermal mass_low use internal loads
25_high_low-use	25% window to wall ratio_high thermal mass_low use internal loads
50_low_low-use	50% window to wall ratio_low thermal mass_low use internal loads
50_medium_low-use	50% window to wall ratio_medium thermal mass_low use internal loads
50_high_low-use	50% window to wall ratio_high thermal mass_low use internal loads
75_low_low-use	75% window to wall ratio_low thermal mass_low use internal loads
75_medium_low-use	75% window to wall ratio_medium thermal mass_low use internal loads
75_high_low-use	75% window to wall ratio_high thermal mass_low use internal loads
25_low_medium-use	25% window to wall ratio_low thermal mass_medium use internal loads
25_medium_medium-use	25% window to wall ratio_medium thermal mass_medium use internal loads
25_high_medium-use	25% window to wall ratio_high thermal mass_medium use internal loads
50_low_medium-use	50% window to wall ratio_low thermal mass_medium use internal loads
50_medium_medium-use	50% window to wall ratio_medium thermal mass_medium use internal loads
50_high_medium-use	50% window to wall ratio_high thermal mass_medium use internal loads
75_low_medium-use	75% window to wall ratio_low thermal mass_medium use internal loads
75_medium_medium-use	75% window to wall ratio_medium thermal mass_medium use internal loads
75_high_medium-use	75% window to wall ratio_high thermal mass_medium use internal loads
25_low_high-use	25% window to wall ratio_low thermal mass_intense use internal loads
25_medium_high-use	25% window to wall ratio_medium thermal mass_intense use internal loads
25_high_high-use	25% window to wall ratio_high thermal mass_intense use internal loads
50_low_high-use	50% window to wall ratio_low thermal mass_intense use internal loads
50_medium_high-use	50% window to wall ratio_medium thermal mass_intense use internal loads
50_high_high-use	50% window to wall ratio_high thermal mass_intense use internal loads
75_low_high-use	75% window to wall ratio_low thermal mass_intense use internal loads
75_medium_high-use	75% window to wall ratio_medium thermal mass_intense use internal loads
75_high_high-use	75% window to wall ratio_high thermal mass_intense use internal loads