

Modeling and Simulation of Energy Efficiency Measures Related to Passive Solar Building Design

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Abstract

Sustainability in the construction field must respect the environment, the human health, and the ecology of the area, decreasing the impact and the pollution to the environment. Thus, the use of solar spaces, also called atriums, have been studied for many years. In this thesis, four configurations (Cases 1-4) will be defined and studied by using an energy system model to quantify the reduction of heating and cooling, the availability of the atrium in different climates and to explain how to prevent the overheating. The results showed that the atrium and the insulation save a lot of energy in any climate, but in high radiation countries the atrium is a better option than the insulation, and the opposite for low radiation countries.

Language: English

Key words: energy models, solar passive systems, simulations, energy efficiency, european prespective, overheating.

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1. INTRODUCTION

According to the United Nations Conference on Environment and Development ^[1], different issues came up to light and a common objective for the human future was lay out: *“Work to provide the needs of the present without compromising the ability of future generations to meet their own needs”*.

The sustainability in the construction field must respect the environment, the health, and the ecology of the area, building where the less impact is done. It has to reduce residues, save resources and also energy, because the energy expense of the buildings is up to 40% ^[2] of the total world energy consumed. Sustainability not only cares about the process itself, but also about all the previous and after stages of the materials and activities have been done.

The sustainable architecture has as the main objective, guarantee a thermal comfort level seeking to minimize the negative environmental impact of buildings by efficiency and moderation in the use of materials, energy, and development space and the ecosystem at large. This adaptation to the landscape can cause a huge inversion in the beginning, but it is supposed to gain an energetic save in a long term.

The use of solar spaces, also called atrium, is an issue that for many years has been investigated and that there are numerous scientific articles that refer to the energetic benefits that provides. At the Concepción University in Chile, Jean-Michel Mottard Adelqui Fissore ^[3], in 2006 studied the energy demand that could be reduced by using solar spaces. The atrium caused a rise in temperature in the contact rooms of 2.4°C, and the energy reductions were slightly above 10%.

At the University of Athens, G. Mihalakakou ^{[4][5]}, tried to quantify the impact, in solar areas, of parameters such as the orientation, different types of climates or the materials of the glazed surfaces to maximize the benefit of those. However, he mainly focuses on combating the problem of glazed areas in summer, the overheating. She uses techniques such as ventilation, solar protection and use of pipes buried underground that helped lower the temperature inside the atrium.

The energy demand for a building can be nowadays simulated by many software that predict the behavior of the energy system according to different parameter set up before. Those parameters can be the weather, the period of the year the study is focused, the

equipment providing energy to the house or even the schedules the people will be using the equipment inside the system defined.

Three different software are used: SketchUp ^[6], which is the structure and the main software is used to define the model and the dimensions of it; OpenStudio ^[7] which defines the thermal zones, the weather, the comfort temperature and all the requirements need for the study; and finally, EnergyPlus ^[8], which performs all the calculation and gives the data needed to reproduce graphs which are more intuitive and easy to compare.

The main objective of this project is to quantify, by using the software, the reduction of energy caused by the use of insulation and an atrium in the residential building, determine the temperature profile through the wall and verify whether the use of the atrium is beneficial in different locations. Finally, attest the importance of using blinds during the summer to prevent overheating due to the solar energy captured and stored in the atrium.

2. THEORY

The development of energy models raised from the need to predict the future energy demand and supply of a country or a region. They are mostly used in an exploratory manner assuming certain boundary conditions such as the development of economic activities, demographic development, or energy prices on world markets.

Every modelling approach abstracts to a certain degree from reality using stylized facts, statistical average Figures, past trends as well as other assumptions. Consequently, energy models represent a more or less simplified picture of the real energy system and the real economy; at best they provide a good approximation of today's reality^[9].

Nowadays two types of energy models are mainly used to represent the real energy system. Those types are: the bottom-up models, which are generally constructed and used by engineers, natural scientists, and energy supply companies; whereas top-down models tend to be developed and used by economists and public administrations.

2.1. Top-Down energy models

Top-down energy models try to represent the economy as a whole on a national or regional level and to assess the aggregated effects of energy and/or climate change policies in monetary units. Driven by economic growth, inter-industrial structural change, demographic development, and price trends, macroeconomic models try to equilibrate markets by maximizing consumer welfare using various production factors (labour, capital, etc.) and applying feedback loops between welfare, employment, and economic growth.

Currently, macroeconomic energy models are often being used to evaluate the economic costs and environmental effects of general energy or climate policy instruments, such as energy or CO₂ taxes or surcharges, emission trading schemes (ETS), feed-in tariffs of renewable energies, etc. ^{[10][11]}

2.2. Bottom-Up energy models

The main characteristic of a conventional bottom-up energy model is its relatively high degree of technological detail (compared to top-down energy models) used to assess future energy demand and supply. Regarding the mathematical form, bottom-up energy models have been developed in the form of simulation or optimisation models. Bottom-up modellers try to identify the best technologies by assessing policies, their effects, investment, costs, and benefits, by calculating external benefits (e.g. environmental, etc.)

of energy efficiency measures, by identifying synergy-effects between sectors, and sectoral costs and surpluses.

Recent or current projections and studies of energy demand and supply using energy models ^[12] are not just made for routine decisions; they also increasingly serve as a scientifically derived information basis for societal debate among governments, energy companies, trade associations, and NGOs. The recent discussions about greenhouse gas emission, phasing out nuclear energy, and the speed of introducing renewable energies have been increasingly influenced by the results taken from various energy demand and supply models developed during the last two decades.

In the near future, energy models on both levels (bottom-up and top-down) should intensify the interaction between them. Moreover, new variables have to be developed, for example: the different impacts on material substitution or material efficiency should be modelled in more detail based on numeric factors and relationships. In this context, export/import ratios and detailed recycling data of the different basic products should also be taken into account.

3. METHODOLOGY

To run the model in EnergyPlus, numerous of assumptions had to be taken and different steps had been followed before getting the results.

First of all, the methodology for the modelling and the simulation has been defined. The use of the three software has an order that must be followed. First, SketchUp provides the model structure; OpenStudio defines the spaces and the weather and thermal conditions; and finally the EnergyPuls does the calculations and provides the results.

Four cases have been defined and named as Case 1, 2, 3 and 4 which will provide the data to verify the objectives.

Finally, the most important part, there are many assumptions that have been taken, as the materials used for the model, the dimensions of it, the heat transfer involved, etc.

In the next chapter all this methodology is explained in detail.

3.1. Modelling & Simulating

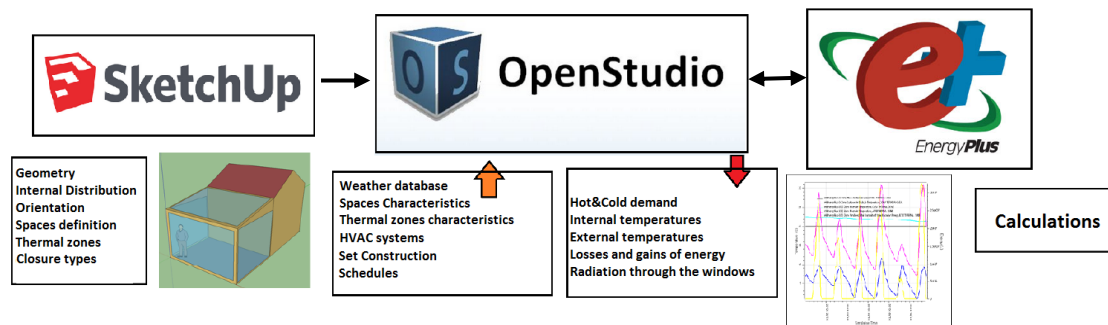


Figure 1. – Representation of the methodology and steps of each software.

As it is shown in this Fig. 1, there are three software used. The first and the main one is SketchUp, this is the structure of the whole software system, and the other two are extensions added as an extra-tools to this main software. In this main software the basic tool are set up, as the dimensions of the building and the definition the spaced. The OpenStudio is inside SketchUp as a window providing specific information for the study, such as the weather, the space characteristics or the comfort temperature. All this information allows the user to run the EnergyPlus and obtain the energy demand, the temperature profile, the radiation through the window, etc. Below it is explained in detail the function of each one, as well as the connection between them.

3.1.1. SketchUp

It is a software of graphic design and three-dimensional modeling used in architecture, engineering, industrial design, video games, etc. It is characterized by simplicity when using it and offers extensive possibilities when designing. In the thesis it has been used as the base of the project, to define the geometry of the model, the composition and definition of the interior spaces, the orientation and the type of closures.

3.1.2. OpenStudio

It is a software with a set of tools that are used for modeling the energy demand in buildings using Energy Plus. Inside the SketchUp, there is a window called OpenStudio, where it is possible to enter all the information of the building and decide the data we want to extract. It is possible to define the type and the composition of the closures, equipment schedules or types of spaces and thermal zones, HVAC systems, select the climate, etc. From all these data it is possible to extract plenty of information such as the temperatures of the spaces, losses and gains power through the closures, levels of radiation through the windows or the heat and cold demand setting a comfortable temperature, among others.

3.1.3. EnergyPlus

This is the energy simulation program founded by the US Department of Energy, for modelling and calculating the heating, cooling, lighting, ventilation and other energy flows. This software is installed in the SketchUp domain, and it produced all the graphs and calculations from the data introduced in the previous software, the OpenStudio.

Apart from this three software, matlab^[14] and excel are also used to create the proper figures and tables to show the data in a proper and easy way.

3.2. Definition of the Cases

Four different cases, described below, will be studied in order to satisfy the objectives announced before.

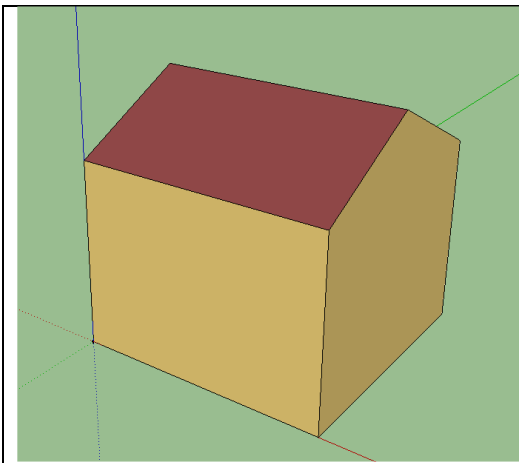


Figure 2. – Case (1)

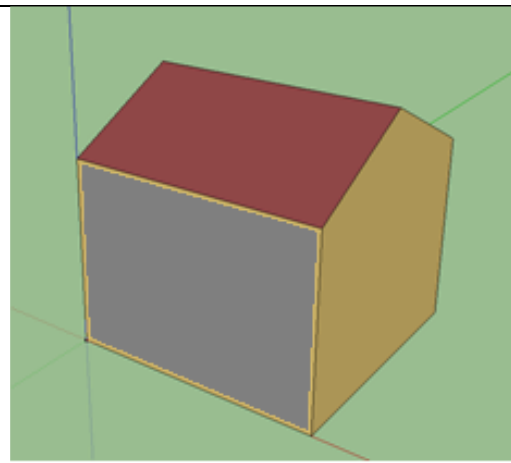


Figure 3. – Case (2)

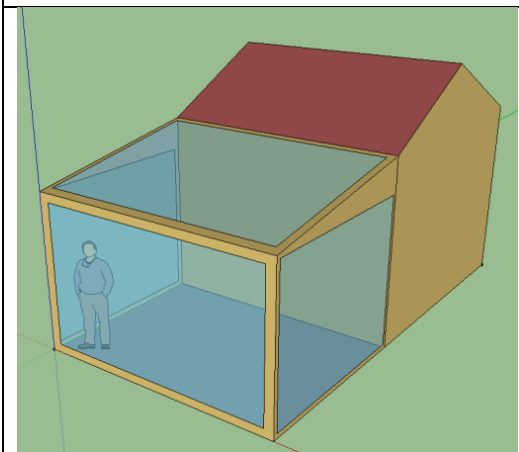


Figure 4. – Case (3):

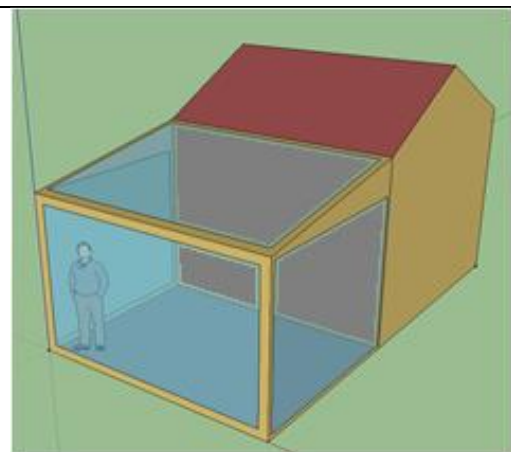


Figure 5. – Case (4)

Case (1) -House without atrium and without insulation – the most basic model, where the wall of the study is the external and it is not insulated.

Case (2) - House without atrium, but with insulation - Identical to the model of the case (1), but the study wall is insulated.

Case (3) - House with atrium, but without insulation - Identical as the model in case (1), but with the glass structure called atrium.

Case (4) - House with atrium and insulation - Identical as the model in case (2), but with the glass structure called the atrium.

3.3. Assumptions

To satisfy the objective of the thesis, it is possible to simplify a home or a building by creating a model, which contains the most basic infrastructure for being habitable but all the necessary information to make comparisons that the study requires. This simplification will cause changes on the levels of the real demand, but doesn't affect the comparisons between the different cases.

This first simplification, as it is seen in the Figure 6 includes the omission of the evaporation, convection and internal loads terms on the thermal balance of the model. This means that the influence of the air change rate on the energy balance was not included, which certainly is a parameter to consider if accurate and absolute energy performance indicators are required. The omission of internal loads might also have large implications on final energy balance. However, both of these parameters were omitted from simulations to simplify the modeling work and focus on the relative comparisons between the four different cases.

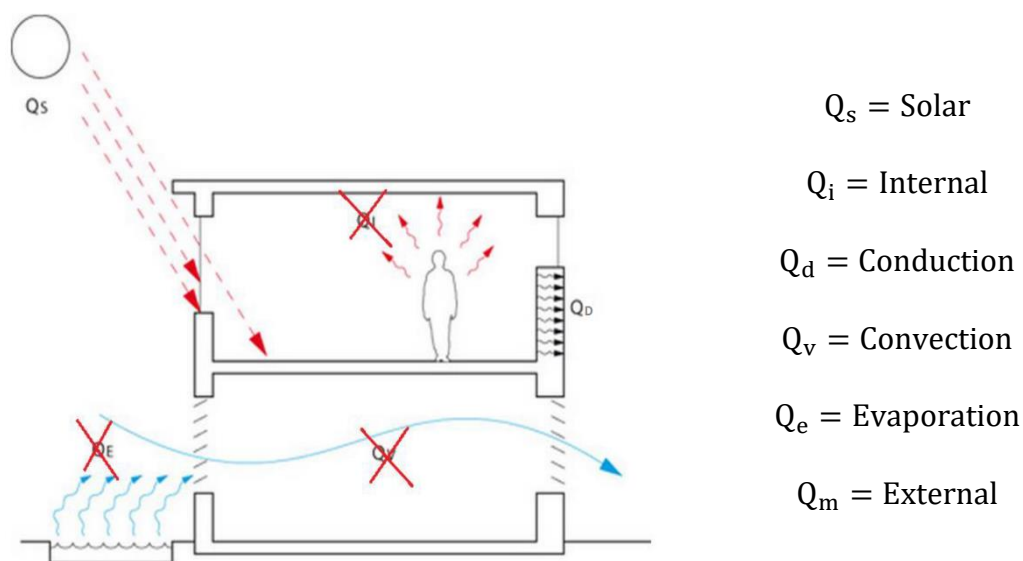


Figure 6. – Thermal gains/loses for the model

ENERGY BALANCE OF A BUILDING

$$Q_s + Q_i + Q_d + Q_v + Q_e + Q_m = 0$$

ENERGY BALANCE OF THE MODEL

$$Q_s + Q_d = 0$$

3.3.1. Geometry and element definition

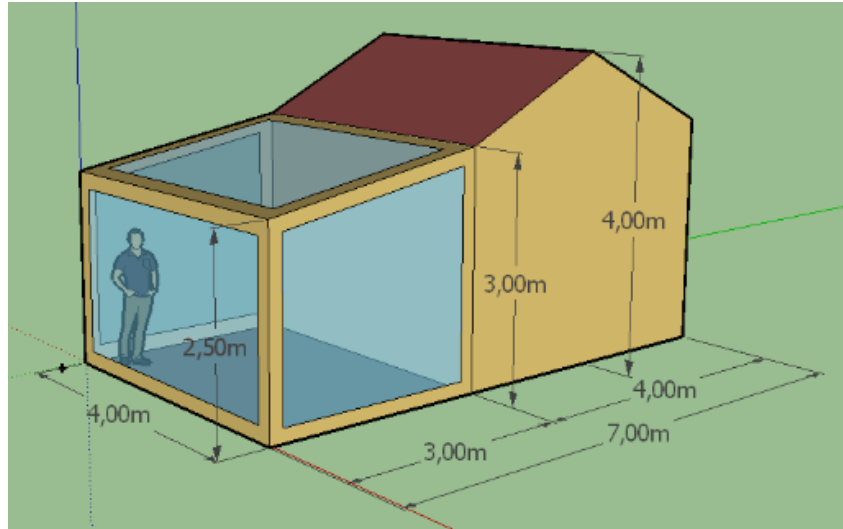


Figure 7. – Representation of the dimensions of the model. SketchUp view.

The model design follows the dimensions shown in the Figure 7, which could perfectly simulate a cottage. The front side of the atrium faced the south, to obtain the most solar radiation possible. It is needed to define two spaces and two separate thermal zones that will be in contact through the wall of study, and thus can extract the required data from both, the home and the atrium space.

Each room has been associated to a construction system. Two different construction systems have been defined, one for the atrium and one for the house, which include walls, roofs, interior walls, doors and windows. Just the wall in contact between the atrium and the house will have energy exchange, the other walls in the house are defined as adiabatic imposing there's no heat exchange with the outside. Logically, the atrium will have energy transfer from the outside.

3.3.2. Weather and thermal conditions

These are files that can be downloaded from the EnergyPlus webpage ^[13] (funded by the U.S. Department of Energy's), where there are climates from all around the world. This contains the information needed to simulate the energy demands depending on the climatic conditions of each location: the level of radiation, temperatures, wind speeds or the percentage of days that there is no sun. The simulations on the model have been conducted in different cities, but the place on which the majority of casuistry has been performed is in the city of Lleida, therefore, when there is not any specification, the results are referenced to this climate.

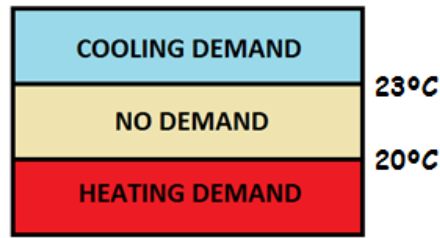


Figure 8. – Comfortable range temperature set for the house.

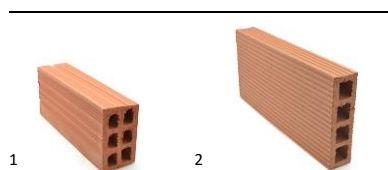
A thermal zone is an area with temperature conditions, radiation transmitted or levels of infiltration different than the surrounding areas. It has been set a comfortable temperature range between 20 °C and 23 °C, as it is shown in the Figure 8. When the external conditions change the temperature inside the house outside this range, there is an energy demand in order to maintain the temperature within the comfort range.

3.3.3. Description of the closures

The closures are surfaces that surround and protect the interior volume of a building. The main roles are the waterproofing and the thermal and acoustic insulation. The materials and the proportion of these closures are extracted from a project on a subject of sustainable construction, which validate the CTE (Technical Code of Edification) for the city of Lleida.

Table 1. – Description of the external wall with insulation.

Material	Group	Resistance (m ² K/W)	Thickness (m)	λ (W/mK)	ρ (W/m ³)	Cp (J/kgK)
1.5m. Simple LP ¹	Bricks	0.172	0.115	0.667	1140	1000
Light air chamber	Air Chamber	0.085	0.03	-	-	-
Mineral Wool	Insulation	1.235	0.05	0.0405	40	1000
Simple LH ² partition	Bricks	0.157	0.07	0.445	1000	1000



The Figure 9 is a representation of the outer wall which consists of two layers of bricks, separated by an air chamber and five centimeters of mineral wool as insulation. The total conduction resistance is $1.65 \text{ m}^2\text{K/W}$.

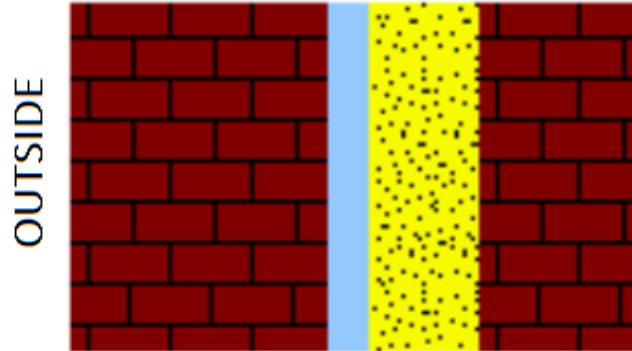


Figure 9. – Representation of the outer wall with insulation.

For cases 1 and 3, the wall is the same but excluding the woolen insulation. The total thermal resistance for the wall without insulation is $0.41 \text{ m}^2\text{K/W}$.

Table 2. – Description of the atrium

Width (m)	3.75	Framework	15%
High (m)	3	Type of framework	Aluminum
Surface (m²)	11.25	Type of Glass	Double, air chamber of 13mm
U framework (W/ m²K)	5.7	U glass (W/ m²K)	3.3
Emissivity framework	0.7	Solar factor	0.75

The atrium structure is made of aluminum and the glazed surface is a double glazing layer with an air chamber of 13mm. The solar factor of 0.75 is related with the radiation going through the building. To simulate it in the OpenStudio it is considered as a window in an enclosure all made of aluminum.

4. RESULTS

Figures 10 and 11, shows the energy demand regarding heating and cooling, respectively, throughout the year. It is divided the heat and the cold demand so it is possible to see the influence of the atrium and the insulation, separately.

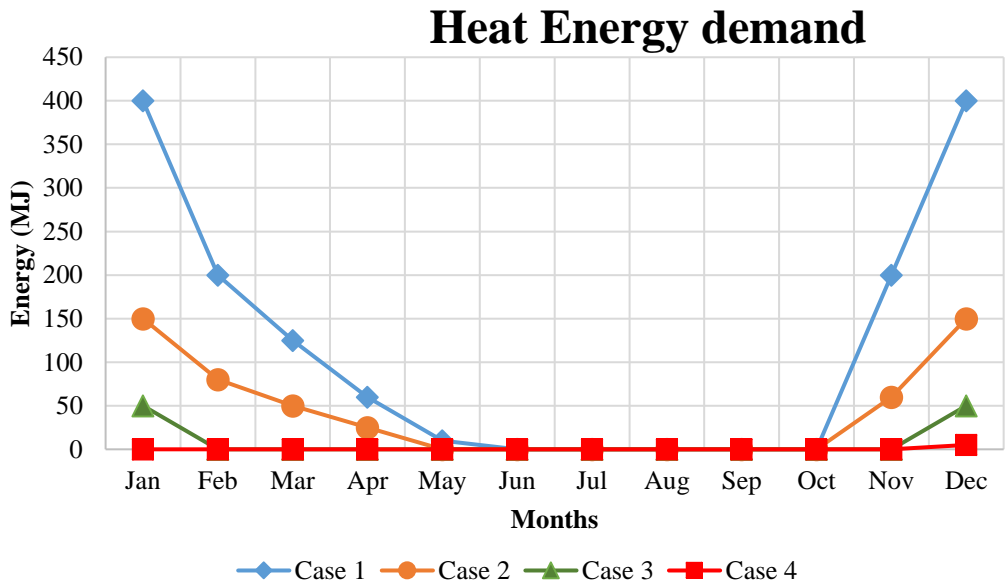


Figure 10. – Annual heat demand according to the four different cases.

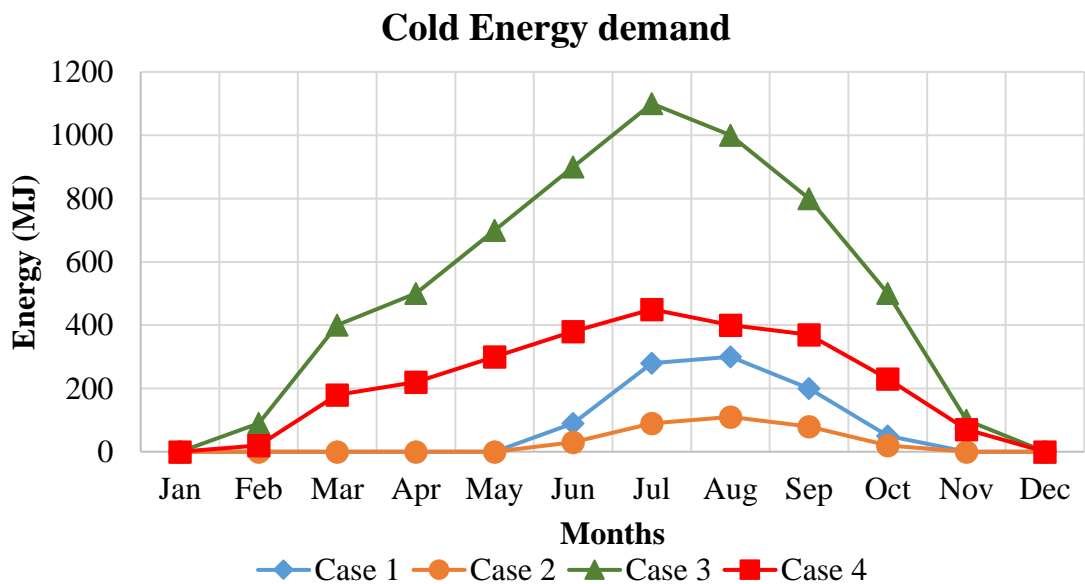


Figure 11. – Annual cold demand according to the four different cases.

On one hand, Case 1 is the one with more heat demand because of the lack of insulation, whereas the Case 4 the heat demand is nearly 6 MJ/year. On the other, the Case 3 needs more cooling because the atrium stores a lot of energy which is easily transferred to the house because of the lack of insulation, and the Case 2 has the minimum demand of cooling because the insulation prevents the transmission of the heat from the outside. Those results are simplified in the following table.

Table 3. – Annual energy demand for the 4 cases

	Atrium	Insulation	Annual Heat Demand (MJ)	Annual Cold Demand (MJ)
Case 1	NO	NO	1354,58	907,35
Case 2	NO	YES	481,11	327,07
Case 3	YES	NO	92,84	6271,25
Case 4	YES	YES	6,33	2468,83

In the Figures 12 and 13, it is shown the profile temperature for the wall. The data are taken every 30 min from 7am until 24.

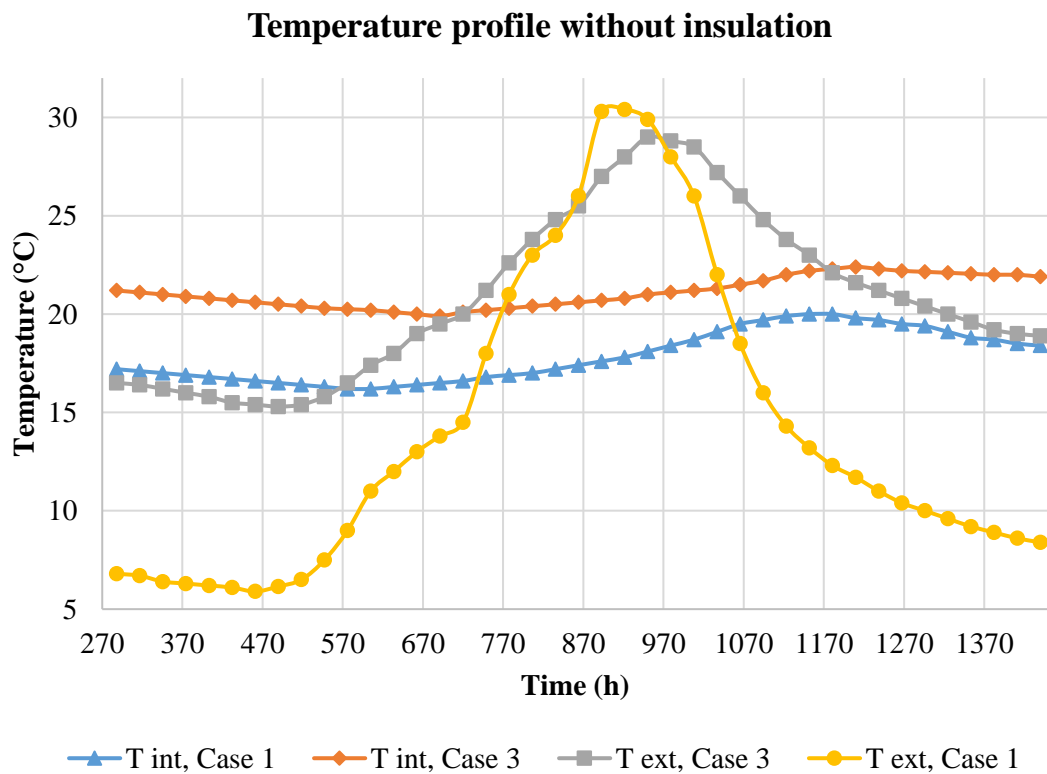


Figure 12. – Temperature profile of the study wall for the cases 1 and 3. Data from the 1st of January.

The temperature range for the interior side of the wall (T_{int}) is less than 5°C in both cases. For the Case 1, it is about 2°C lower because of the lack of insulation, the heat inside the room is transmitted to the outside easily. Contrary, the temperature range of the external (T_{ext}) side of the wall is quite wide big, especially for the Case 1, where the lack of insulation changes the temperature completely depending if the sun is heating the side or not.

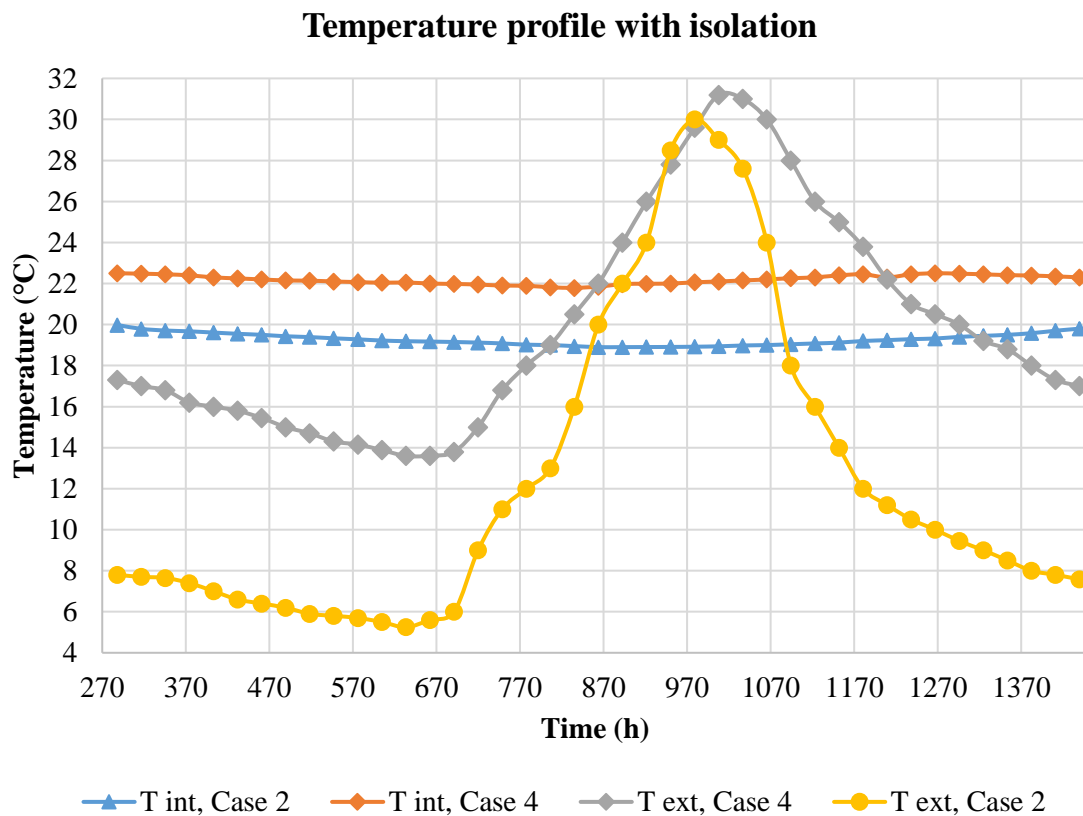


Figure 13. – Temperature profile of the study wall for the cases 2 and 4. Data from the 1st of January.

In this case, the temperature profile for the cases 2 and 4 is very similar to the profile shown in the Figure 12. In this case, the temperature for the interior side of the wall in both cases remains almost constant, higher in case 4 because of the atrium. But the big range temperature for the external side wall is still visible.

The following table summarizes the results shown in the previous Figures.

Table 4. – Maximum and minimum temperatures of the study wall for each case.

	Without Insulation			With Insulation		
	Min	Max	Dif	Min	Max	Dif
T^a outside wall, no atrium	6,0	30,5	24,5	6,0	29,9	23,9
T^a outside wall, with atrium	15,3	28,7	13,4	13,5	31,3	17,8
T^a inside wall, no atrium	16,8	19,9	3,1	18,7	19,5	0,8
T^a inside wall, with atrium	20,5	22,4	1,9	22,0	22,5	0,2

In the following two Figures 14 and 15 it is shown the temperature of the air inside the house for each case, the temperature of the air in the atrium, the temperature of the outside and the heat demand to provide the comfort temperature in case it is needed. The data have been taken every 150 min (2'5 hours), during the first 3 days of the year.

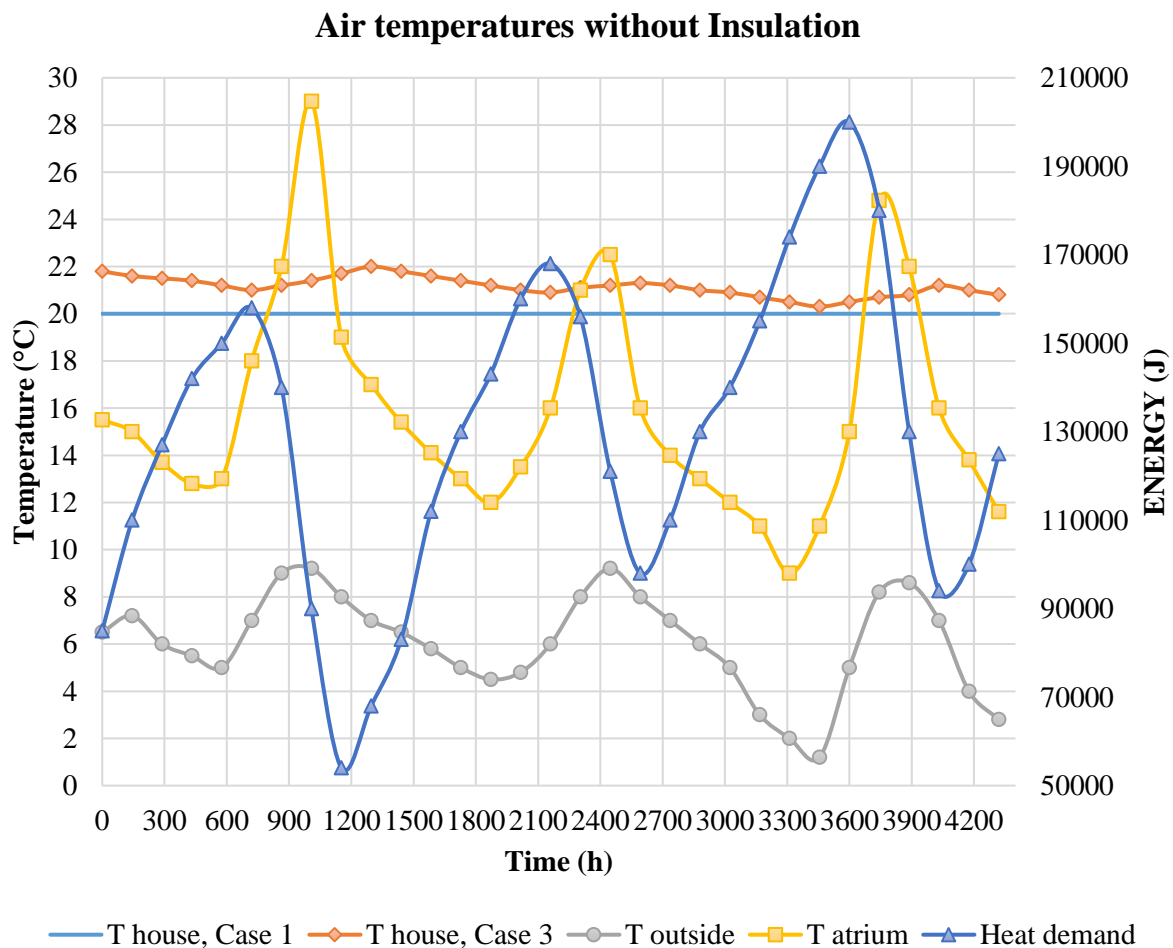


Figure 14. – Temperature profile for the air inside the house for the cases 1 and 3. Energy demand and temperature inside and outside the atrium. Data from the 1st - 3rd of January.

The temperature inside the house for the Case 1 is constant at 20 degree because there is a heat source providing heat to the room. This heat is varying depending on the amount of energy needed to reach the comfortable temperature, in this case not higher than 20° C. In the Case 3, the temperature inside the room is inside the comfortable range, so there is no need of a heat system. The profile of the temperature for the atrium and the outside is similar but with a difference of 8-14° C.

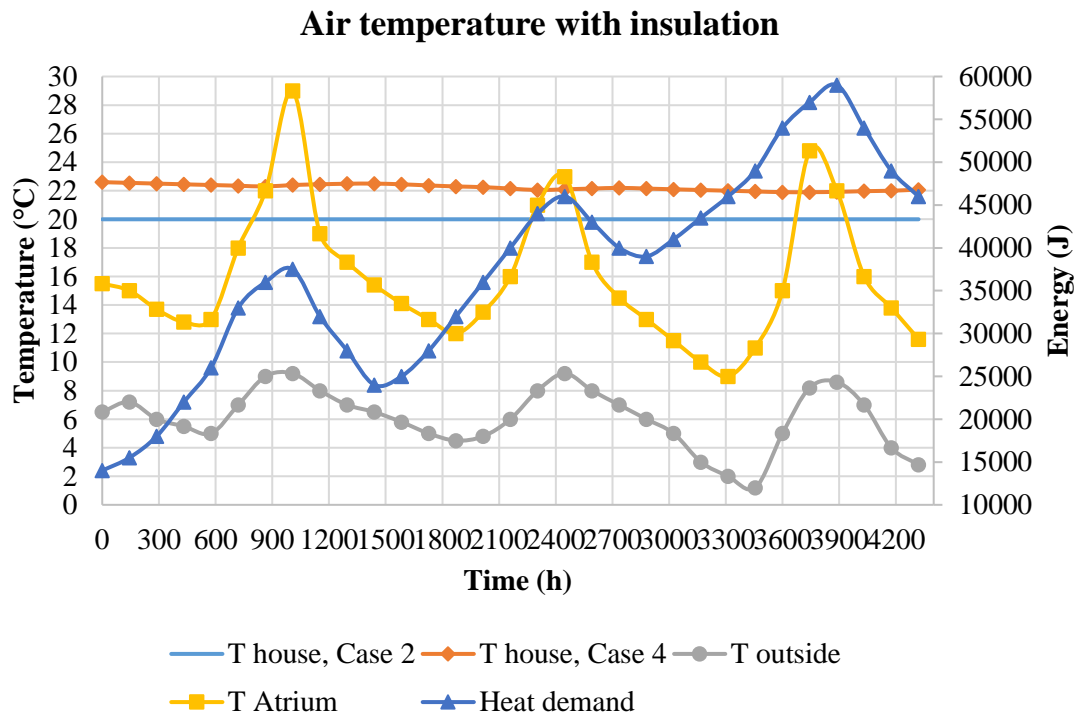
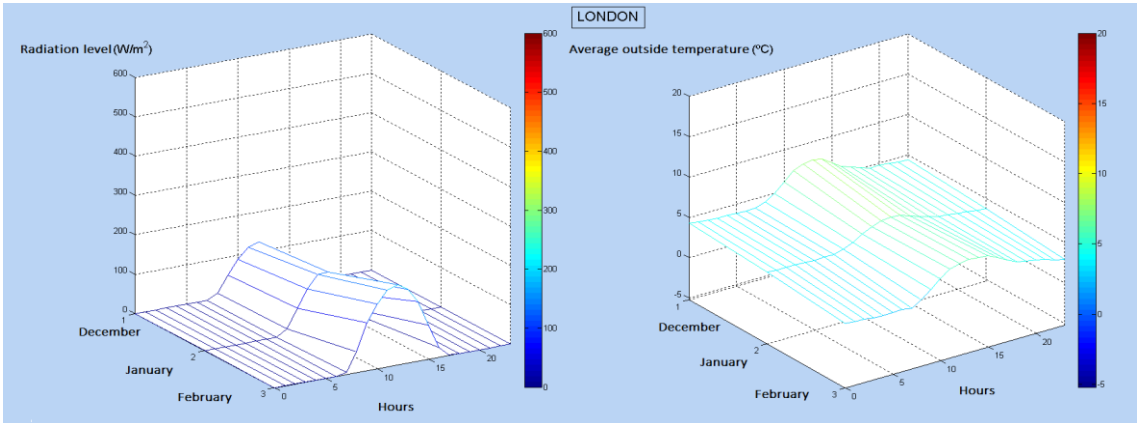
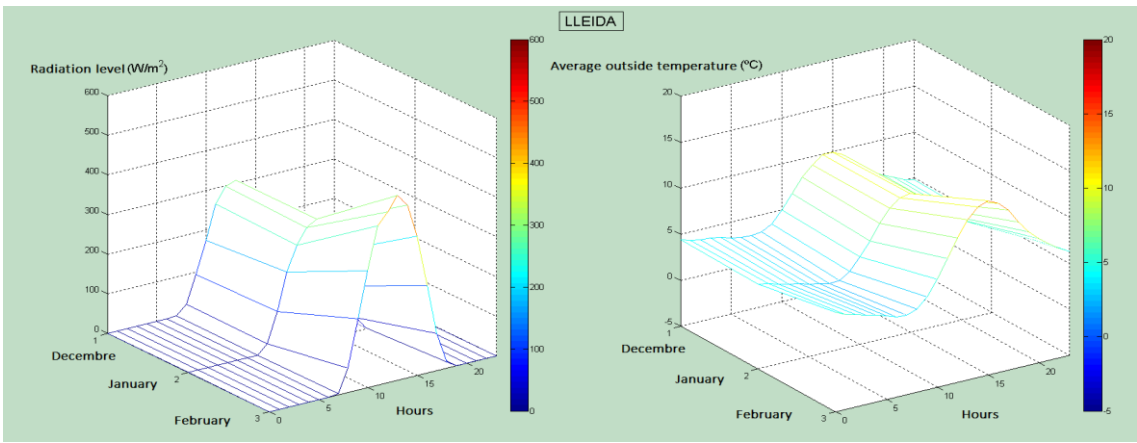
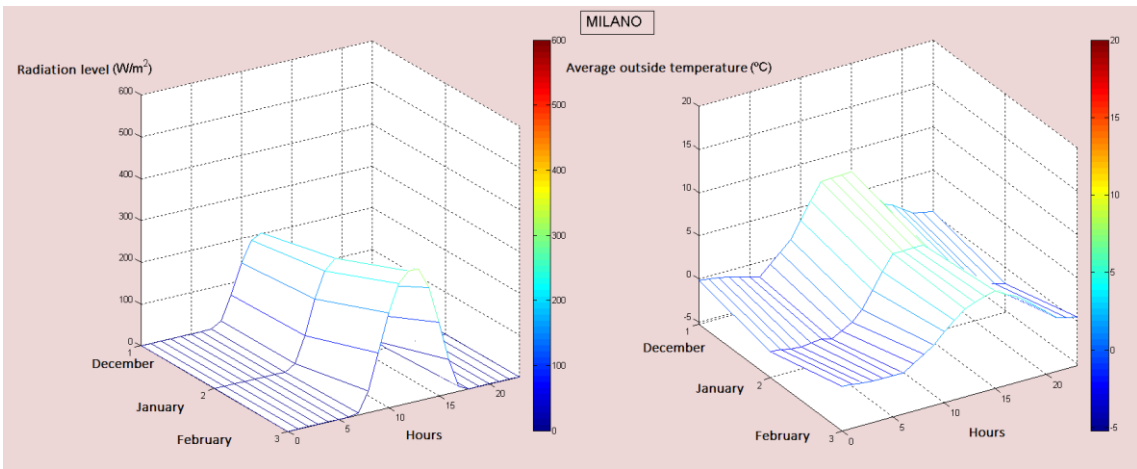
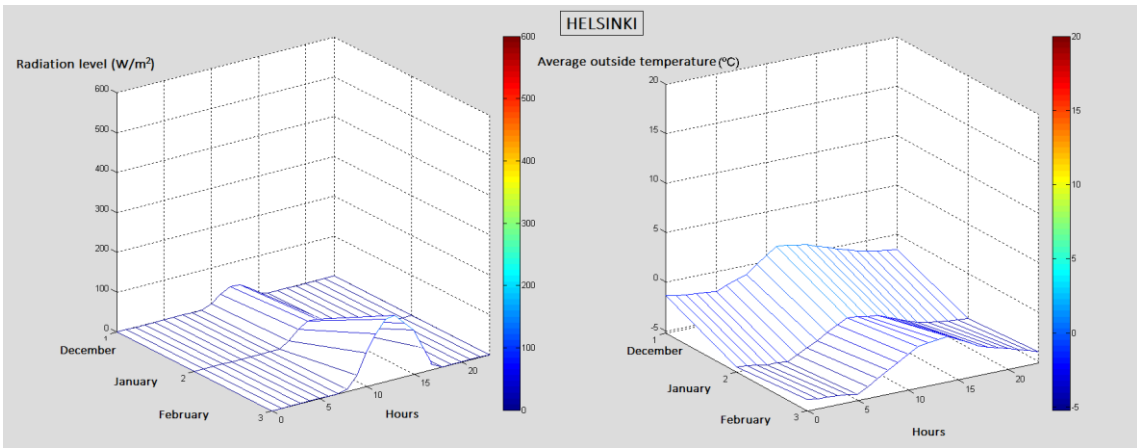


Figure 15. – Temperature profile for the air inside the house for the cases 2 and 4. Energy demand and temperature inside and outside the atrium. Data: 1st-3rd of January.

In this case, the Figure 16 shows a similar profile for the temperatures, and also the need of a heat source to provide the comfort temperature set for the Case 1. Although the temperature profile are quite similar, the total energy demand is 4 times bigger when there is no insulation.

The previous results are according to the weather database from Lleida, Spain, but to verify if the impact of the insulation and the atrium is the same in different climates. Thus, five different cities have been selected according to the location and the weather, and using another software called Matlab, a surface graphs has been done of the radiation level and the average temperature have been done. The results are shown in the Figure 16.



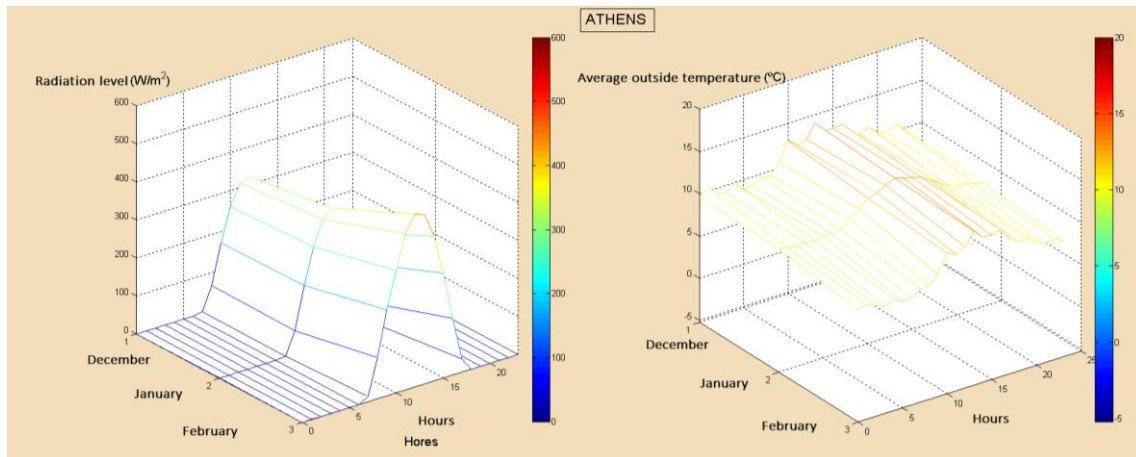


Figure 16. – Radiation level and average outside temperature contour graphic, during the winter time, for 5 different cities (Helsinki, Milano, Lleida, London and Athens).

In the previous Figure, it is possible to compare and see the differences according to the climate of each city. To quantify this difference, the Cases 2, 3 and 4 were run to obtain the energy demand. Those results are shown in the following tables.

Table 5. – Heat energy demand using 5 cm of mineral wool as insulation.

	December	January	February	Total (MJ)
HELSINKI	379,82	406,20	310,19	1096,21
LONDON	214,18	208,90	123,44	546,52
MILANO	222,62	227,89	182,52	633,03
ATHENS	66,47	50,64	69,63	186,74
LLEIDA	141,38	143,49	79,13	364,00

Table 6. – Heat energy demand using the atrium without insulation.

	December	January	February	Total (MJ)
HELSINKI	777,58	824,00	539,13	2140,71
LONDON	390,37	337,62	254,27	982,26
MILANO	375,60	349,22	123,44	848,26
ATHENS	0,00	22,16	0,00	22,16
LLEIDA	46,42	44,31	2,11	92,84

Table 7. – Heat energy demand using the atrium with insulation.

	December	January	February	Total (MJ)
HELSINKI	329,18	349,22	228,95	907,35
LONDON	164,59	135,05	109,73	409,37
MILANO	159,31	129,77	79,13	368,21
ATHENS	0,00	0,00	0,00	0,00
LLEIDA	4,22	2,11	0,00	6,33

As expected, when using the atrium and the insulation together the energy demand is lower in all the locations. But in the cities of Lleida and Athens, when the sun radiation is higher (observed in the Figure 16), it's more convenient to use an atrium than mineral wool as an insulation. The sun energy stored in the atrium keeps the house heated and less energy is needed to provide the comfortable temperature. In locations with cold weather and radiation such us Helsinki, London or even Milano, insulation saves more energy than an atrium.

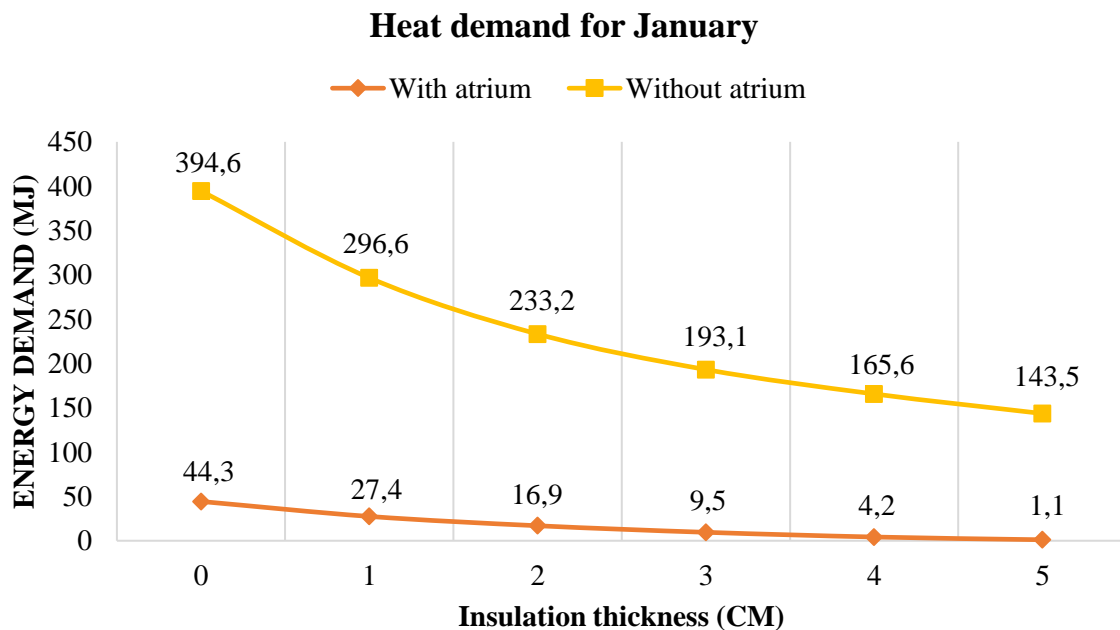


Figure 17. – Heat demand during January, according to the insulation thickness.

In this case, the Figure 17 refers to the impact of the thickness of the insulation. As it is shown this energy demand is reduced by the increase of the insulation thickness. When there is an atrium, the reduction of the energy demand is much bigger than when there is not, this is because the atrium already saves a big part of the energy.

Finally the impact of the blinds use is studied for the Case 2. Two different configurations were set: blinds active from May to September and from March to November. The results are shown in the following table.

Table 8. – Cooling demand through the year according to the use of blinds.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (MJ)
Without blinds	0,00	17,94	145,60	219,45	295,42	365,05	451,56	411,47	338,67	199,41	3,58	0,00	2448,15
Active blinds (May-Sept)	0,00	16,32	144,52	218,34	11,36	69,71	69,15	44,76	154,60	198,29	3,54	0,00	930,59
Active blinds (Mar-Nov)	0,00	16,32	7,34	0,00	0,00	0,41	67,71	44,76	16,86	0,00	0,00	0,00	153,40

The cooling is reduced considerable only using blinds the sunniest months, but is reduced up to 16 times when the blinds are used from March until November.

5. DISCUSSION

The preliminary data according to the overview energy demand study proves that the Case 1 loses a lot of heat during winter time making the use of a heat energy mandatory source to provide the comfort temperature set of 20°C. In summer time, the results are completely different. Lleida is a place where the sun heats any space most part of the time, so in Case 3 all the heat stored in the atrium is transmitted to the room because there is not any insulation that prevents it. In this case a lot of cooling energy will be needed to reduce the temperature to the maximum comfortable temperature of 23°C.

According to these results, it is clear that in a place with Lleida's climate, the use of an atrium is very useful in winter to save energy, because comparing to the Case 1, the annual heating demand is reduced by 65% in Case 2, 93% in Case 3 and 99% in Case 4; but it is detrimental in summer time because of the overheating issue. The annual cooling demand is reduced 64% in case 2, but increased 590% in case 3 and 170% in case 4. In both winter and summer seasons, the use of insulation helps to save energy.

According to the wall temperature profile, the atrium increases the temperature of the external wall with approximately 10°C during the night; while during the day this difference is reduced, even overtaken during midday as the sun is directly in contact with the wall without the atrium. Referring to the internal wall side, the insulation maintains the temperature more stable, almost constant, and the atrium keeps the temperature about 2-3°C above.

Extrapolating these results, and taking into account that the night temperature of Lleida is about 10° C, it can be said that in all the cities with a low outside radiation levels, the use of an atrium helps to keep the house warm.

In relation with the previous discussion, the study of the 5 different cities proves the advantages and disadvantages of the atrium. The combination of insulation and the atrium is the most efficient in any climate in terms of energy efficiency; but for warm weather, such as Lleida or Athens, the use of an atrium is better than the use of insulation since it keeps the sun heat and works as a natural and better insulation. Otherwise, in Helsinki, London or Milano, where there is no sun to heat the atrium, the use of insulation prevents better the heat losses through the wall.

As it was expected, the insulation has a bigger impact when there is no atrium. Increasing the thickness of the insulation, the energy demand goes from 400 MJ to 150MJ in Case 3, saving up to 250 MJ; while in Case 4 the saving is less than 50 MJ. Nevertheless, the use of the atrium itself saves eight times more energy.

Finally, regarding to those cities with warm weather, a solution to prevent the overheating during summer time may be the use of blinds. The energy saved for the cooling by using blinds from May until September is about 60%. Not to mention the use of blinds between March and November which reduces the energy demand up to 95%. This is the simplest and easiest solution to fight the overheating problem.

6. CONCLUSIONS

According to the simulations performed with EnergyPlus, and the results obtained after the energy study of the residential building with an atrium and the insulation, the following conclusions can be presented. *(All results refer to the Lleida's climate unless is specified).*

- I. The annual heat energy demand is reduced by 65% in Case 2, 93% in Case 3 and 99% in Case 4. The annual cooling energy demand is reduced by 64% in case 2, but increased 590% in case 3 and 170% in case 4.
- II. In cold weather cities, the atrium increases the temperature of the outside wall about 10° C, while the insulation keeps the inside wall temperature stable. However a heat energy source is needed to provide the residential building the comfortable temperature of 20° C.
- III. In places with high radiation levels, such as Athens or Lleida, the atrium saves more energy than the insulation, whereas the opposite holds for low radiation level cities like Helsinki or London.
- IV. The combination of the insulation and the atrium reduces the energy demand in all of the studied cities. This reduction is proportional to the radiation level: for warm weathers (Athens) the saving goes up to 99%, while in cold weathers (Helsinki, London) it is less than 25%.
- V. The use of blinds is a great solution to prevent the overheating in summer time. The results indicated that the cooling demand was reduced 60-95% depending on the active time period for the blinds.
- VI. Local bottom-up models are needed to optimize energy efficiency measures for solar passive building designs..

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