The impact of a holistic energy-efficient retrofitting strategy in a vernacular residential building in Central Spain

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Abstract

HERB project (Holistic energy-efficient retrofitting of Residential Buildings) is a collaborative project within the context of the EU Seventh Framework Programme, and comprises several research studies from various European companies and institutions with the common purpose of addressing energy reduction in European residential buildings. Thus, taking HERB project premises and objectives as benchmarks, present study investigates thermal performance of an existing vernacular case-study house located in Gotarrendura (Spain) and the impact of a potential holistic energy-efficient retrofit strategy, which encompasses opaque envelope and fenestration areas upgrade, energy-efficient lighting measures, and finally, a hybrid photovoltaic-solar thermal system. In order to do so, dynamic thermal simulations have been carried out with DESIGN BUILDER programme to assess the performance of each measure individually and in a simultaneous retrofit scenario. Results showed case-study house in *as-built* state performs satisfactory in summer conditions due to earth walls thermal mass. However, the house proved to be highly energy-inefficient in winter conditions. Subsequent retrofit measures tested improved overall building thermal behaviour, yet some of them clearly worsened comfort conditions in summer. In regard to energy saving and associated CO_2 emissions reduction, the most effective retrofit measures were firstly, opaque envelope upgrade; secondly, hybrid PV-thermal system; thirdly, fenestration upgrade and lastly, energy-efficient lighting measures. The holistic energy-efficient retrofit strategy accounted for 65.9% of energy saving and 67.9% coupled CO_2 emissions reduction. All in all, present retrofit strategy fulfilled partially HERB project goals figures, such as CO_2 emissions reduction and lighting energy reduction. However, it did not reach the required 50 kWh/m2/year maximum consumption nor 80% net energy saving.

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1. Introduction

The increasing global net energy consumption coupled with the limited sources of fossil fuels leads to a future gloomy scenario with serious social, economic and political consequences. Moreover, the continuous growth of energy consumption entails the liberation of increasing amounts of CO_2 to the atmosphere, hence worsening the greenhouse effect and triggering serious environmental problems. This potential scenario can only be changed by addressing the variables involved in this complex equation. Governments and the scientific community have been made an important effort on the development of either new energy sources to reduce the reliance on fossil fuels or strategies to reduce energy consumption in every single process of the human activity.

In the European Union, countries import the majority of the energy and the demand is continuously increasing. This fact and limited reserves of fossil fuels entails a steady rise in energy price and insecurity problems associated to the reliance on external energy sources. Namely, it is estimated that the reliance on non-EU energy sources will grow from 50% to 70% by 2020 (Martínez de Alegría et al, 2009). On top of that, serious environmental problems arise due to the use of conventional energy sources, such as oil leaks, nuclear accidents and CO_2 emissions which worsens the climate change. Besides, energy distribution and usage is highly inefficient. It is calculated that roughly 20% of energy is wasted in these aspects. Therefore, the energy issue have been increasingly gaining importance in the EU concerns and the final objective of current EU energy policies is to create a highly energy efficient and low Carbon emissions economy for Europe. In order to do so, EU directives and programmes have been oriented to address two main aspects of the problem: the energy production and the energy consumption. EU energy policies aims to both develop renewable energy sources as alternative to traditional fossil fuels and address the inefficiencies due to energy distribution for final uses and energy saving measures to control the increasing energy consumption. Promoting energy saving strategies is one of the best methods to achieve a balance in the energy generation-consumption relationship.

In this scenario, the share of energy consumption in the built environment represents 40% of the total and expanding. The largest proportion of this amount lays on the residential and commercial building sector whose estimated saving potential is 27% and 30% respectively. Most energy consumed by buildings in Europe is due to heating which still presents a large potential of efficiency improvement through retrofit measures. Also, building energy consumption for lighting and appliances is quite high and its estimated saving potential represents roughly 25% (Martínez de Alegría et al, 2009).

The search of novel energy-efficient measures in the built environment has been a high priority in EU research funding programmes. The HERB project (Holistic energy-efficient retrofitting of Residential Buildings) is a collaborative project within the context of the Seventh Framework Programme for Research and Technological development, which is a European Union five-year plan for funding research and addresses Europe's employment needs, competitiveness and quality of life (CORDIS, 2011). HERB Project comprises several research studies from various European companies and institutions with the common purpose of addressing energy reduction in European residential buildings. Thus, the HERB project was created to investigate the feasibility of different state-of-the-art building retrofit strategies. Specifically, it involves the developing, implementation and assessment of innovative strategies on real case studies.

The present study was carried out within the framework of HERB programme by covering the analysis of some wide-spread retrofit strategies combined with state-of-the-art ones in a real case-study residential building in Spain, although many of the conclusions and strategies developed herein can hopefully be set as benchmark starting points for future studies in other European regions. The present study will investigate the impact of a holistic energy-efficient strategy in a vernacular existing house in central Spain region. The building analysed in this study is an example of a type of dwelling which has considerable presence in central areas of Spain and supposes a significant fraction of the Spanish building stock. Besides, construction materials and techniques used in vernacular buildings, such as adobe and rammed earth are progressively gaining interest amongst researchers, since many studies have proved to have outstanding energy-efficient properties. Therefore, investigation of retrofit strategies in earth construction buildings supposes a relevant topic within the scope of energy reduction in the built environment.

2. Background

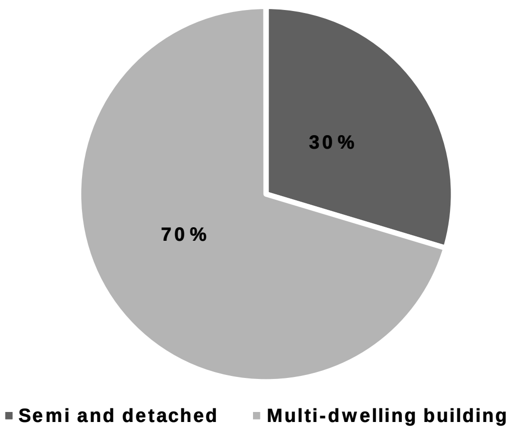
EU and Spanish energy policy and regulations

In Europe, there have been a strong believe in the direct relationship between energy demand and wealth. The more a country develops, the higher is its energy consumption. Until the Oil crisis of 1973, energy policies were oriented to guarantee the sufficient supply of energy sources to allow the development of the countries, since the axiom that production of energy was linked to wealth and economic development took priority over other assumptions. However, after 1973, the guarantee of the energy supply turned paramount and EU began to elaborate directives and programmes towards the development of renewable energy sources as alternative to traditional sources and promote energy efficiency measures. However, environmental concerns were not present in this EU energy policy change, yet those issues were already known. First programmes specify created to address environmental issues appeared in the eighties, but it was in the nineties when environmental concerns were distinctly present on the EU policies. After 1995, the main objectives in the European energy policy were the environmental protection, the competitiveness in the energy market and the security of supply (Martínez de Alegría et al, 2009). Moreover, the EU signed the Kyoto protocol in 1994 to set the limit to the greenhouse gas emissions, which it was already a serious problem.

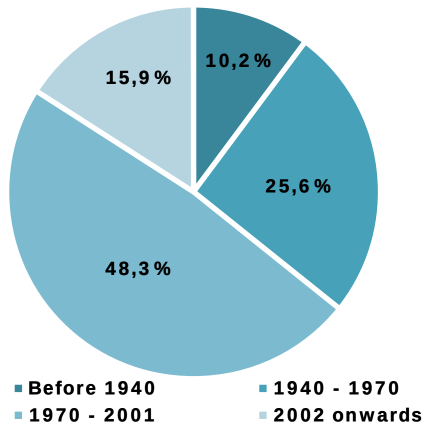
Some recent EU directives were oriented towards the development and implementation of energy efficient measures in the building sector. Namely, Directive 2002/91/EC *on the energy performance of buildings* required all EU members to set limits and benchmarks in energy performance for new buildings and large existing buildings. Also, it established a certification of energy performance for same cases in order to set a standard for energy rating in buildings. In Spain, this directive crystallised into the new Technical Building Code (CTE), which gathers the main technical construction rules for new buildings and substituted the old Basic Building Rules (NBE) valid since 1979. In contrast to the former code which set an overall heat transmission coefficient, book DB-HE of CTE deals specifically with energy efficient requirements and sets limits for thermal transmittance of individual envelope elements to minimize energy consumption within current technical building solutions. Although new building standards set by this new building code have significantly contributed to raise energy efficiency in new buildings, some studies pointed out the lack of quantitative information on energy consumption in kW/m^2 per year (Martínez de Alegría et al, 2009). Furthermore, most these new regulations and benchmark values, yet comprehensive, were designed to be applied in new and existing buildings with modern construction techniques and materials. Thus, whenever architects and engineers have to address refurbishments of traditional houses, they have to deal and fulfil requirements which worsen occasionally the building optimum thermal performance.

Spanish building Stock

Spain has roughly a housing stock of 17.2 millions of dwellings (IDAE, 2009). As shown in Graph 1, the majority of these are located in multi-dwelling residential buildings (70%). Although there is not significant distribution variation among climatic zones, the proportion of households in multi-dwelling properties is slightly higher (74%) in north coastal area. The average Spanish dwelling has 102.4 m2 floor area and 8 rooms, including kitchen and bathrooms. This surface is higher for single family houses which have 140.4 m2 of floor area and slightly higher average number of rooms.



Graph 1 - Proportion of dwellings type in Spanish building stock (IDAE, 2009)



Graph 2 - Distribution of buildings by year of construction (INE, 2011)

Regarding age of buildings, Graph 2 shows the housing stock distribution per year of construction. It can be seen that more than 35% of Spanish dwellings were built before the seventies, when there was not any energy efficient measures regulation. Also, almost half of the housing stock was built between 1970 and 2000 when the NBE building regulation was in force. Finally, dwellings under current standards and valid building regulation (CTE) are those built from year 2002 onwards and represent almost 16% over the total.

Energy Consumption in the Spanish housing Stock

Energy consumption in the housing sector in Spain represents 17% over the total of the country energy consumption and 25% of the total electricity demand, whereas EU27 average consumption represents 25% and 29% respectively (IDAE, 2009). This proportion follows an upward trend due to the increasing number of households, the higher level of comfort and the expanding use of electric appliances. The average yearly consumption of a Spanish household is 10,500 kWh, though there are significant differences among different types of dwellings according to climates and type of buildings. i.e. Dwellings in high rise building in the Mediterranean zone consume 6164 kWh per year, whilst detached houses in the Central Spain region consume around 19,655 kWh per year (IDAE, 2009).

Figure 1 - Spanish climatic areas (IDAE, 2009)

An approximate yet effective classification distinguishes among Spanish climatic zones according to average, maximum and minimum temperatures. As Figure 1 shows, there are three mayor climates in Spain; namely, North coastal climate, Continental climate and Mediterranean climate.

	North coastal area	Central Region	Mediterranean area	AVG.
Semi and detached houses	15000	19667	13250	**15972**
Multi-family buildings	7306	9806	6139	**7750**
AVG.	**11153**	**14736**	**9694**	

Table 1 - Total energy consumption in Spanish building stock [kWh] (IDAE, 2009)

Also, it can be distinguished between semi and detached houses and multi-dwelling residential building. According to these two classifications, Table 1 shows energy consumption demand in Spanish housing stock. It can be seen that single family houses consumes approximately twice as much energy than households in multi-family buildings. Besides, climatic conditions in central region are more extreme than in the rest of Spain and account for higher energy consumption. Therefore, it seems that detached houses suppose the most energy-consuming type of dwelling in Spain.

Vernacular buildings in Spanish building stock

The Vernacular architecture encompasses all constructions made with traditional techniques performed by people as a direct response to their needs and values. This type of architecture has a great respect for the existing environment and due to the limited means and technology utilised, it develops a bioclimatic approach in its designs. Furthermore, it is said to be the first known bioclimatic architecture due to the utilization of energy efficient strategies with local materials (Cañas and Martin, 2004).

At present, there is not a reliable source of information about the amount of vernacular dwellings in Spain. However, statistics show that the amount of dwellings built before 1940 within population areas smaller than 10,000 inhabitants are approximately 1.2 million distributed in both single and multi-dwelling buildings (INE, 2011). Most likely, concrete and steel construction was highly unavailable and unaffordable in those years in rural areas. Hence, it can be assumed that the majority of these houses were built with traditional construction methods and can be classified as vernacular architecture. All in all, it is reasonable to state that traditional buildings represent almost 7% of the total Spanish building stock.

There are as many types of traditional houses as climates and local conditions exist in Spain. However, the house studied the present work represents the most common typology of traditional house in rural areas of central Spain (Cañas and Martin, 2004).

3. Objectives

This chapter defines the main objectives of present study. HERB project premises and objectives have been taken as benchmarks figure to set energy and CO_2 emissions reduction goals. These are:

1. Understand the thermal behaviour of a representative vernacular Spanish house in order to find out its strengths and weaknesses from an energy-efficient retrofit point of view.

2. Assessing the performance of each retrofit measure implemented in the case-study house from an energy-efficient perspective.

3. Quantifying the energy saving that can be achieved with a holistic energy efficient retrofit action in the representative case-study house

4. Quantifying the CO2 emissions reduction achieved due to the energy saving measures in the same case study house

5. Whether the proposed holistic energy efficient retrofit strategy proposed fulfils the objectives set by the HERB project. These are:

   a. Achieving 60% CO2 reduction
   b. Achieving 80% end-use energy reduction
   c. Achieving a global energy consumption (except appliances) of 50 kWh/m^2 per year
   d. Achieving 80% energy saving for lighting

It is worth mentioning that HERB project objectives cover two other conditions to validate the feasibility of the retrofit strategy in the Spanish house. It claims an adequate user acceptability of the measures and a low payback period between 2 and 5 years. However, the present study does not analyse these subjects since that will imply a considerable amount of analyses which would be impossible to address within the scope of the present work. Therefore, the effort of the present study is made on the analysis of the efficiency of the measures in regard to their energy saving and CO_2 emissions reduction potential.

4. Literature review

This chapter deals with the analysis and review of published literature about the topics relevant for the present work. Due to the broad scope of this study, this might cover a wide range of topics related to retrofit of existing buildings; however literature review section focuses mainly in two main research topics: vernacular earth construction and holistic building retrofit.

4.1. Earth construction

Earth construction is a wide term which involves the traditional use of stabilized soil material in masonry elements for building purposes. It encompasses different types and techniques such as Wattle and daub, cob, rammed earth and adobe bricks (Pacheco-Torgal and Jalali, 2012). The beginning of this technique is unclear. However, different studies set its origin with the start of the agricultural societies. Since then, earth construction has been used in many regions across the globe. Although, it is considered as an obsolete construction technique related to non-developed countries, the truth is that this kind of buildings can be found fully occupied

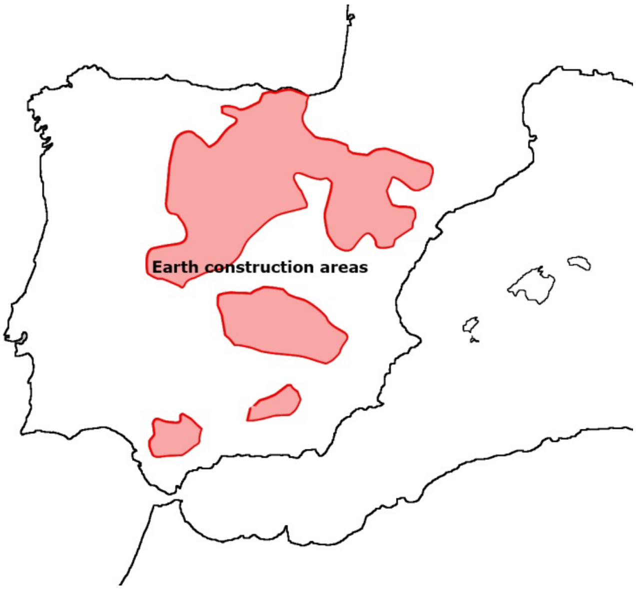


Figure 2 - Areas of influence of earth construction in Spain (Jiménez and Cañas, 2006)

and functional in many European countries. For instance, UK has around 500,000 occupied earth dwellings in its building stock (Pacheco-Torgal and Jalali, 2012). Particularly in Spain, earth construction was progressively forgotten in benefit of modern construction techniques and materials since roughly the second half of the nineteen century (Jiménez and Cañas, 2006), although this technique was still used in rural areas until barely 60 years. As shown in Figure 1, earth construction was widely used in central areas of Spain and the architectural heritage related with this technique is large and valuable. Actually, the inherent value of traditional earth construction technique in Spain has been recognised by UNESCO since it can be found not only in domestic buildings but also in the most important monuments in Spain.

Figure 3 - Two examples of earth buildings in Central Spain (Red Construtierra, 2008)

Nowadays, earth construction has been increasingly gaining interest among scientific community. Research studies on this matter have been multiplied ten times in the last decade (Pacheco-Torgal and Jalali, 2012). This is not only because of the necessity of maintaining the vernacular building heritage, but also for the significant energy efficient benefits of this construction material. Pacheco-Torgal and Jalali (2012) reviewed some of the main disadvantages related to the use of this construction material. They explain that it may generate economic issues due to the higher maintenance cost and less durability of traditional construction materials. Also, earth construction requires intensive manual labour and highly skilled workers which lead to unavailability issues and less profit for building developers. Moreover, earth construction has other limitations related to its physical properties, such as the need of higher wall thicknesses and limited structural possibilities and little suitability for seismic areas. In addition, Jiménez and Cañas (2006) identified other issues to the establishment of earth construction as a real alternative in Spain. Namely, the fact that earth construction materials are not included in current Spanish building regulations due to the limited standardization controls, and the difficulties in obtaining the 10-years compulsory insurance coverage for this type of buildings. In contrast, same authors highlight important energy benefits, such as the low embodied energy of this material and the reduction of CO_2 emissions associated to the material site transportation, since the raw material for earth construction can be obtained close to the construction site. Also, this authors point out the capacity of earth construction to improve indoor air conditions due to the absence of chemical pollutant components and the capacity of naturally control relative humidity inside the building. This non-pollutant composition and hygroscopic performance lead to lower ventilation needs in the building. The authors finally state that earth construction has important competitive advantages regarding sustainability over conventional building material.

The search for new energy-efficient construction materials and the renewed interest for earth buildings led to a exponential increase of research studies about earth hydrothermal properties. In this way, Taylor and Luther (2004) carried out an investigation to determine earth walls thermal performance in summer conditions under the statement that the heat flow lag due to internal thermal mass may result in a satisfactory overall thermal performance despite the not so low thermal transmittance. Firstly, the authors established a methodology to determine heat flux through earth walls by numerical analysis of different measured internal and external environmental data in a existing building. Secondly, Taylor and Luther analysed those recorded temperature figures over a four days period to investigate earth walls thermal performance in same conditions. Their findings were rather close to their hypothesis since they found out that earth construction performed satisfactorily. The authors concluded that earth walls thermal inertia combined with proper designed night ventilation generate a cooling effect during daytime periods in summer conditions in this climate.

Similarly, Taylor et al (2008) strives to determine the real benefits of earth construction in terms of thermal comfort and energy reduction in a building designed as "deep green". In order to do so, the authors analyze comfort and energy consumption figures in an earth office building in Australia in a hot and dry climate over a week period in summer and winter. Then, some improvements on the building were tested to assess their real impact on these parameters. Interestingly, the climatic conditions described in work by Taylor et al show significant similarities to Avila climate. This is, dry hot summers (maximum temperature of 31.8ºC) and dry cold winters (minimum temperature of 3.1ºC). Moreover, there are important daily temperature variations between night and day. In a first stage, the authors combined a qualitative and quantitative methodology to investigate comfort levels. Namely, the authors compared comfort survey results with comfort prediction models based on measured physical values. Also, they compared billing records from the case study building with a conventional but similar office building in the same location. In the second stage, the authors carried out some TRNSYS simulations to test some envelope measures retrofit and other improvements. The authors found out that environmental values were out of the comfort levels in a significant proportion of the office occupancy period, especially in wintertime, which meant that the heating system was not meeting the demand. Much more relevant for the present study is the finding that the combination of external wall insulation, glazing upgrade and reduced infiltration levels resulted suitable improvements for earth buildings since they showed an important energy demand reduction in winter. Moreover, the addition of external insulation led to a 78% reduction of heat transmission through walls at the same time that energy reduction was only one sixth of the total consumption. This fact made the authors conclude that the infiltration rate was rather high. Although, the methodology used in the paper by Taylor et al seems to be appropriate for the study, this author thinks that the analysis of the results might have been more exhaustive and the conclusions deeper.

The study by Martin, Mazarron and Cañas (2010) is probably the most interesting in this sense for the present work due to its similarities. They carried out an experimental study in Central Spain region conditions comparing two different traditional houses and a new prefabricated one. Each of them was built with different materials: adobe brick, natural stone and Wood (new one). Every building underwent minor refurbishments to accommodate some people involved in the study, yet their envelope was not modified and none of the traditional houses had neither heating nor cooling system. However, the wooden house was provided two small heaters. The authors measured on site different environmental parameters inside each house throughout a typical winter and summer week to analyse the comfort levels. Eventually, Martin, Mazarron and Cañas found out that all measured values fell out of the comfort zone in all cases in winter conditions, but the wooden house was much further from the comfort levels than the other two despite the small heaters. In contrast, in summer conditions both traditional houses presented a significant amount of values inside the comfort zone whereas the wooden house values were hotter. This work is particularly relevant for the present study since describes the thermal behaviour and analyses the relevancy of the high thermal inertia in vernacular houses in a very similar scenario to the present study.

Goodhew and Griffiths (2005) conducted an investigation to demonstrate the potential of earth construction to become a real energy-efficient alternative to common building materials. Namely, they investigate the possibilities of earth construction to meet current building standards and the upgrading possibilities of existing earth UK buildings. An experimental probe based study was carried out to determine the thermal properties of some earth building materials. Then, thermal performance of different wall configurations was compared to traditional walls. Finally, the study strived to present how earth construction might be upgraded to meet current standards. The authors highlighted that benchmark material properties required in building regulations are based on steady state thermal calculations and do not consider time-dependant properties such as thermal inertia which can be paramount in the thermal performance of a building. Nevertheless, they concluded that new earth construction can indeed satisfy current standards. Also, they concluded that existing walls can be improved with internal insulation to meet current UK building regulations.

4.2. Building energy-efficient retrofit

Building energy efficient retrofit encompasses many different strategies depending on many external and internal building variables such as the target part of the building involved in the upgrading process, the type of building or the construction material used. For the present work, review of published literature has been narrowed to those sub-topics relevant to the present study; this are, envelope retrofit, energy efficient lighting and passive solar retrofit strategies, all of them within the residential building scope.

4.2.1. Building envelope retrofit

The building envelope is a generic term which comprises the horizontal (ground floor and roof) and vertical (walls and fenestration areas) surfaces enclosing the conditioned space. Some authors also define the building envelope as what separates the indoor and outdoor environment of a building (Sadineni, Madala and Boehm, 2011). It represents one the most influential factor to determine the energy performance of the building, since it isolates the indoor environmental conditions and avoid undesired heat and humidity transmission with the external environment. Therefore, the building envelope is been studied by many researchers from the energy efficiency and savings perspective. Some authors carried out some investigations to present the impact of the building envelope as a whole in the energy balance of the building, whereas others authors conducted studies about specific parts and technologies of the building envelope. The study carried out by Sadineni, Madala and Boehm (2011) belongs to the former group. They wrote an extensive technical review of the main components of buildings envelope and their thermal performance in order to provide recommendations for improvements. Their work presents main findings of different studies about common and state-of-the-art building envelope components which can be used as baseline to plan any retrofit strategy. Although authors neither conduct any experimental study themselves nor go into details in any of the technology reviewed, they present a satisfactory overview of the main energy efficient measures to improve thermal performance of the building. Also, they found out that around 30% - 40% energy savings can be achieved with an envelope retrofit based on several experimental studies. Finally, authors conclude by giving general recommendations to address a retrofit project. Namely, they highlight the importance of the understanding of the climatic factors by the designer, since passive energy efficient strategies are climate sensitive and an appropriate choice and design can be a determinant factor for the success of the retrofit project.

Wall and roof upgrade

Walls generally represent the largest proportion of the building envelope. Their physical properties have been widely studied by researchers in regard to their impact on overall thermal performance of the building. Some authors state that increasing the thermal resistance (R-Value) is one of the best strategies to improve the thermal performance of the wall, and may studies have been published in this way. Namely, Stazi et al (2013) conducted an investigation to find out the optimal insulation strategies for traditional walls depending on how they work to prevent heat transmission. They identify 3 different walls categories: Capacity walls, with high thermal mass which storage heat and delays heat transmission; stratified walls with a multilayer structure which delay heat transfer due to different properties of layers; and Resistance walls, which comprises insulation layer with low thermal transmittance. The authors carried out a comprehensive experimental study which involved monitoring of real case studies, dynamic thermal simulation and later parametric study and finally, a dynamic thermal analysis to enhance the performance in the best case scenario. All these analyses were carried out in three case study buildings according to the three identified wall types, and in a temperate climate with significant daily temperature variations. This methodology allowed them to get accurate results about the real performance of different wall insulation retrofit. For capacity walls case (just as in Gotarrendura case study building), Stazi et al came to the conclusion that added either internal or external insulation accounted for a increase of temperature of roughly 3ºC in summer case scenario. In contrast, same insulation accounted for roughly2.5ºC degrees higher in winter scenario, though external insulation showed a slightly better performance. Also, the results showed that daily temperature variations in winter were lower with external wall insulation.

In the same way, Bojic et al (2012) wrote an article reporting their investigation about the performance of different ways of decreasing heating consumption in a dwelling through enhancing building envelope. The case study building was a single-storey house with solid brick walls located in Belgrade (Serbia), which has a continental climate with significant differences between winter and summer. They carried out dynamic thermal simulations with ENERGYPLUS in order to assess five different simple and combined envelope retrofit options. Namely, external wall insulation, roof insulation, lower ceiling, combined roof insulation - lower ceiling and finally, combined wall - roof insulation - lower ceiling were analysed. The authors also evaluated the economic aspects of every retrofit configuration to find out the best cost-performance envelope configuration. The results showed that external insulation was far the most cost-effective simple envelope upgrade measure with around a 50% of heating demand reduction, whereas the combination of wall-roof insulation and the lower ceiling accounted for roughly 65% energy saving. It was proved that overall performance of several retrofit measures is not equal to the sum their individual performances.

The effect of thermal mass is also important in thermal behaviour of buildings. Thus, it is also an important factor to take into account when addressing different mass walls retrofit options. The interaction of thermal mass with insulation has been already studied by several researchers. Namely, Al-Sanea et al (2012)conducted an extensive investigation about the impact of thermal mass on walls transmission loads, dynamic thermal resistance, time lag and decrement factor under same thermal resistance values (R-value) in a temperate climate. The authors stressed that under previous steady state analyses, insulation layers increase the total R-value of the wall whereas does not affect the thermal mass, and increasing the mass does not modify the R-value. However, dynamic state studies proved that both thermal mass and R-value interacts generating a complex model, which is also affected by HVAC operating conditions and climate. Therefore, in order to carry out their investigation, Al-Sanea et al developed a mathematical model which considers heat transfer and storage along a certain time span. Among other conclusions, the results showed that thermal mass did not alter energy loads in either winter or summer, although it reduced to almost zero in moderate months. As consequence, yearly energy consumption decreased as thermal mass was increased. Also, peak cooling and heating loads and decrement factor dropped as thermal mass increased. Finally, the authors concluded that 17% and 35% of energy saving can be achieved in cooling and heating loads respectively. Al-Sanea et al also agreed in the idea that external insulation performs better with thermal mass than internal insulation.

Fenestration retrofit

Another important part of the building envelope is represented by doors, windows and glazed surfaces in general in either walls or roofs. These elements are necessary construction elements which provide natural light and ventilation to the building. However they usually represent a weak point in the envelope when it comes to heat transmission due to their construction and glazed surface which has generally higher thermal transmittance. In addition, the continuity of the wall structure is interrupted and the mismatch of wall construction and window frame may originate air infiltration though cracks. Therefore, it is proved that fenestration areas accounts for a large proportion of building energy consumption (Grynning, et al., 2013)

Gasparella, et al (2011) stated that the most important features of a glazed area in regards to its impact of a building energy balance are solar transmittance and thermal resistance (U-Value). To prove this, they conducted a parametric study with different glazing systems, window size and orientation. Thus, they carried out computer aided simulation with TRNSYS software of a well-insulated case study building in four different climates in Southern Europe. Then, results for overall winter and summer periods and their peak values were analysed. Finally, the authors came to the conclusions that higher solar transmittance coupled with low thermal transmittance improves overall building behaviour in winter, whereas it worsens building performance in summer. Conclusions presented in this study were quite interesting, although other important issues regarding window retrofit were not considered such as lightning reduction or users' discomfort.

Similarly to the previous study, Grynning, et al (2013) conducted a parametric investigation with Energy Plus software. several types of windows were analysed in regard to their thermal transmittance (U-value) and solar transmittance in cold climate. Surprisingly, they found out that cooling loads are dominating in offices buildings rather that heating loads in the cold Oslo climate. Even more relevant than the parametric study was the review of different rating methods used to assess windows performance in published literature. Authors concluded that the three methods analysed to rate windows performance brought different energy saving outcomes.

To a lesser extent, frames also determine the overall thermal performance of windows since the proportion of area which is covered by the frame is usually small compared to the glazed area. Nevertheless, some research papers focused on the thermal properties on window frames rather than the glazed surface. Gustavsen et al (2011) noted that most highly insulated frames do not perform as well as highly insulated glazing types. Thus, they carried out some THERM software simulations to investigate the impact of different window frames configurations in heat loss and gains. The authors concluded with an extensive review of the most relevant frame properties to increase thermal performance. Although their study in terms of thermal performance was quite broad and exhaustive, some considerations about the availability of these technologies in the market were missing. Most of their solutions proposed were out of range of most common retrofit options.

Other authors propose an alternative to multi-layered glazing for windows retrofit for cases where double glazing technology is unavailable or expensive. Double window rather than double glazing is a popular retrofit solution in Spanish houses. Smith, et al (2012) conducted an investigation about internal secondary window as a potential alternative to high efficient windows in building retrofit. The authors carried out an experimental study to evaluate double windows thermal performance and they were later compared with several Windows 6 software simulation results. Results showed that double windows may raise overall R-values between 130% and 290% and therefore, became a more affordable retrofit alternative to double-glazed windows. The methodology used in this paper was quite complete since the authors compared the results obtained in their simulations with real experiment data to validate them. However, the authors stressed that other important parameters were not considered, such as water condensation and infiltration issues.

It seems that dynamic thermal simulation is the most extended method to evaluate windows performance. However, other quantitative methodologies were used in recently published papers. For instance, Manz and Menti (2012) developed a methodology to evaluate the potential of various glazing types through analysing climatic data from Madrid (Spain) and other European cities. The authors developed the Alpha value concept, which represents the coefficient of glazing solar gains to building thermal losses. Then, every glazing type were analysed in regard to this value. The authors concluded that triple glazing was the best option in all locations in wintertime, whereas double glazing was adequate just in southern European climates. Finally, the authors remarked that some overheating issues in the buildings that may arise due to south oriented glazed areas. Perhaps, further analysis of these windows in summer conditions would have been necessary.

4.2.2. Efficient lighting

According to the paper by Aman et al (2013), the lighting system of a residential building may account for a significant proportion of electricity consumption. For instance, some studies noted that in developed countries such as Sweden, lighting energy accounts for 27% of total electricity consumption in the country, whereas in other countries like USA this proportion goes to 18%. Therefore, substituting old inefficient lamps for energy efficient lamps such as compact fluorescent or LED lamps can be a relatively straightforward strategy to reduce energy consumption in the dwelling. This was demonstrated by Aman et al (2013), who conducted a study about different domestic lams and ballast available in the market to compare their performance and determine their advantages and disadvantages of each device. The authors carried out a number of computer aided simulations using DIALux lighting design software for incandescent lamps, fluorescent lamps, compact fluorescent lamps and LED lamps. The outcomes showed that compact fluorescent lamps were as much as twice efficient in terms of power consumption compared to incandescent lamps, while LED lamps appeared to be roughly four times less power consuming compared with same incandescent lamps. Moreover, the authors noted that domestic LED lamps bring additional energy saving benefit due to their longer life, which can be up to 25 times longer than incandescent lamps. Aman et al also foresee that LED lamps will be the majority of the lighting system installed in the future, based in their investigation.

Another retrofit strategy which has proved its efficacy in reducing lighting energy consumption in residential buildings is the installation of a solar duct. This device is described by De-Urrutia and Salas (1996) as:

> "(...) lighting and ventilation duct by which, through a system of reflectors, daylight reaches spaces where it does not naturally arrive and natural ventilation is also enhanced."

These authors measured the performance of a solar duct installed in a residential building in Barcelona (Spain) to provide natural light and ventilation in the kitchens of each dwelling. The results of their investigation showed that the light pipe provided up to 150 lux in worst case scenario, meeting the lighting needs in these kitchens and preventing the use of artificial lighting in these rooms. Moreover, the solar duct provided adequate natural ventilation to comply with the building regulations.

4.2.3. Building-integrated photovoltaic thermal systems

According to HERB project guidelines, the analysis of performance of a multifunctional solar system is required in the case study building. Therefore, this section deals with the review of relevant literature about hybrid solar systems able to generate electricity and thermal energy, and their integration in the building structure. An hybrid photovoltaic/solar thermal system consists of a combination of photovoltaic and solar thermal components to produce both electricity and thermal energy in a single system, to maximize the use of solar energy (Chow, 2009). A common PV cell converts roughly 4-17% on solar energy into electricity depending on the solar cell. This means that most of the energy is converted into heat causing the PV cell temperature to raise up to 50ºC over ambient temperature, which triggers two undesired effects: the drop of PV cell performance and structural damages in the support due to heat stress. The underpinning theory of a photovoltaic/solar thermal system is to take advantage of the rejected heat to convert it to thermal energy and at the same time cooling down the PV cells.

According to the extensive review of this matter by Chow (2009), a significant amount of research has been focused on this technology since the mid 70's. During the first 15 years, the studies were focused on fundamental concepts and the feasibility test of simple PV/T solar collectors. Then, the research papers over the next decade were related to design improvements, cons-performance analysis, more accurate simulations and analyses. Also, in the 90's a new interest for building integration of these technologies came up. Finally, since year 2000 onwards, the studies focused on more comprehensive analyses and serious commercial applications were further explored.

Besides the studies focused of the performance of PV/T standalone models in forms of panels or similar devices, many other research papers have studied the performance of PV thermal systems integrated in larger passive solar systems such as double facades and Trombe walls. These are called building integrated photovoltaic/thermal systems (BIPV/T). In this way, Quesada et al wrote two extensive reviews of different research studies published so far about solar façades, which they defined as "(...) special facades involved in the processes of heating, ventilation, thermal isolation, shading, electricity generation and lighting of homes." In the first article, they review the Opaque solar facades (Quesada et al, 2012) and they identified the Building-integrated photovoltaic thermal systems as active solar facades which aim to achieve the most efficient use of the solar energy. They review some of the most important research papers published so far about this technology and classified them in theoretical and experimental studies, development studies and feasibility studies. The authors noted that BIPVT systems combine the advantages of both PV and thermal systems since the heat extraction improves the overall performance of the systems and reduces the payback period. Also, they came to the conclusion that this technology is promising, yet further studies are needed to bring it to its full potential.

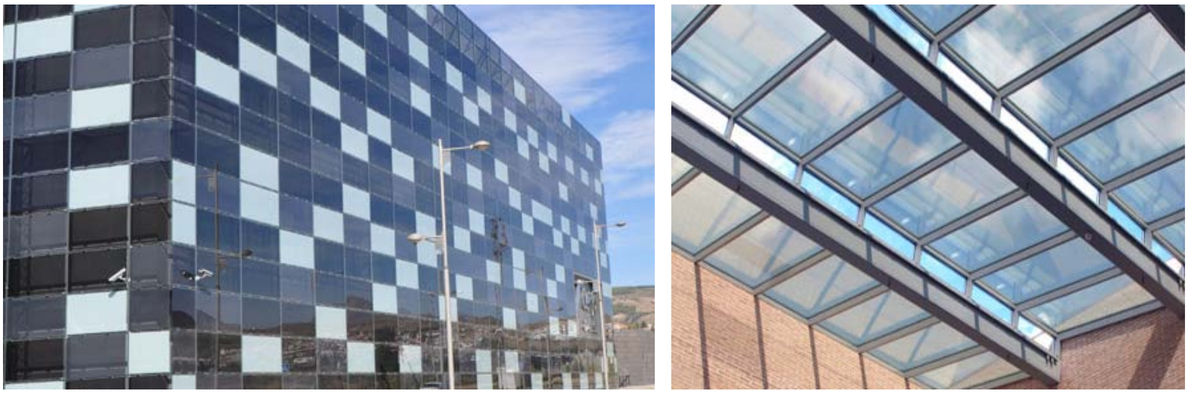


Figure 4 - Examples of integrated PV glass with thermal appliances (ONYX SOLAR, 2013)

In regard to the performance assessment of BIPV/T systems, Chow (2009) highlights the difficulty of reaching a satisfactory analysis method and predictive mathematical model. Whereas the electrical performance of these systems is quite straightforward to analyse and foresee, the situation with the thermal performance is totally different since it is integrated within a complex building heat supply system. Nevertheless, some authors have proposed models in this way, such as Jie et al (2007)who conducted a study about the performance a novel PV integrated Trombe wall attached to a room. The authors stated that the 80% of the solar energy incident on a conventional PV cell is converted into heat rather than electricity. Therefore, the integration of semi-transparent PV panel in a Trombe wall may bring an increase of efficiency in the PV cells plus heating energy and aesthetic value. Jie et al assumed the Trombe wall space and the room space as a unique thermal zone for thermal balance calculations. Then, they carried out some two dimensional computer aided simulations over three days in cold conditions for the PV Trombe wall, conventional Trombe wall and Room with no passive solar system. Finally, the authors found out that the two dimensional model is feasible and the maximum difference between the room with and without PV Trombe wall reached 12.3ºC in three days period. Besides, the authors concluded that room air temperature is higher with conventional Trombe wall. However, PV Trombe wall generates electricity while achieving an increase of 5% in PV cells efficiency.

Similarly, Kim and Kim (2012) carried out a simulation study of an air based building integrated PV-thermal system. The authors stated that an air-type BIPVT facade applied to a building modifies thermal properties of the building walls by altering the U-value and infiltration levels. Therefore, they evaluated the performance of the system itself and integrated within the overall building thermal system. Three different facades were analysed (BIPVT, BIPV and the original facade) using a dynamic thermal simulation software (TRNSYS). Finally, they concluded that a BIPVT system prevent the efficiency losses due in the electricity generation due to temperature increase when compared with a simple BIPV. It was also proved that a BIPVT enhances overall thermal performance of the building in comparison with a BIPV, despite the wall cooling effect due to the air flow through the double facade air gap.

4.3. Literature review conclusions

In this section, some conclusions drawn from the review of published literature relevant to the purposes and aims of the present work are presented as follows.

Earth construction is been recently gaining popularity among professionals and researchers as sustainable and energy-efficient material. This material has clear unavoidable limitations derived from its physical structure such as low stress resistance or seismic areas unsuitability. However, most studies highlighted their thermal mass potential and their outstanding hygrothermal properties. Retrofit projects in these types of buildings have a clear opportunity to take advantage of the inherent thermal mass for energy saving purposes. The use of computer aided dynamic thermal simulations was proved as a valid methodology for the present study. It is clear that in cases where thermal mass is involved, a dynamic mathematical model is more accurate to analyse building energy balance rather than steady state model (Al-Sanea et al, 2012). Also, the impact of different retrofit measures is different than the simple sum of effects of those same improvements assessed individually. Therefore, it is advisable to use a computer aided powerful tool which allow a comprehensive study of the building and retrofit measures performance (Bojic et al, 2012). Fenestration areas account for a significant proportion of heat gains and losses in buildings. Hence, upgrading simple glazed windows to double glazed windows or even placing secondary windows (Smith et al, 2012) can be a effective retrofit action to reduce energy consumption. However, in contrast to opaque wall or roof areas, glazed areas allows solar thermal gains, so solar transmittance should be considered just as thermal transmittance when evaluating fenestration retrofit options. Lighting system upgrade seems to be a straightforward method to reduce energy consumption in houses. Moreover, the analysis of the impact of this strategy as part of a holistic energy-efficient retrofit project is rather simple. In many retrofit cases rooms are not provided with natural light or ventilation. Thus, the inclusion of solar ducts appears as an interesting solution for refurbishment of old houses. Although the performance of this technology is difficult to predict until is installed and working, some studies proved that solar pipes can meet entirely the lighting needs of a room (De-Urrutia and Salas, 1996). It seems that a BIPVT system has clear advantages in comparison with BIT and BIPV systems. This technology performs particularly well in cold conditions where it proved to increase interior air temperature in roughly 12ºC plus enhancing PV cells efficiency in 5% (Jie et al, 2007). There is no general consensus about the best method to assess the performance of this technology, although many authors defended the use of dynamic thermal modelling for a building integrated analysis (Kim and Kim, 2012).

5. Methodology

This chapter deals with the methodology applied in present work. Firstly, main characteristics of case-study building and climate are reviewed. Then, methodology for quantitative numerical analysis is presented and finally, every energy-efficient retrofit measure configuration is explained.

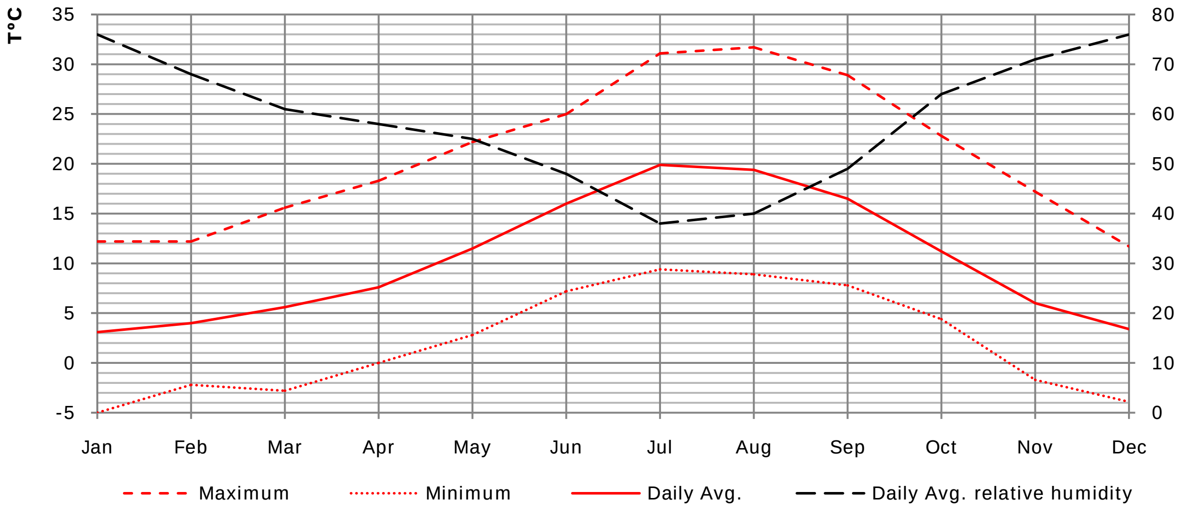
5.1. Case Study

HERB project requires investigating holistic retrofit strategies on real case-study residential buildings in different regions and climates of Europe. Thus, the building analysed in present work correspond to the Spanish sample and it is a traditional rural single family house located in Gotarrendura (Spain). Present section deal with the description of Gotarrendura climate and brief description of the house.

5.1.1. Gotarrendura Climate

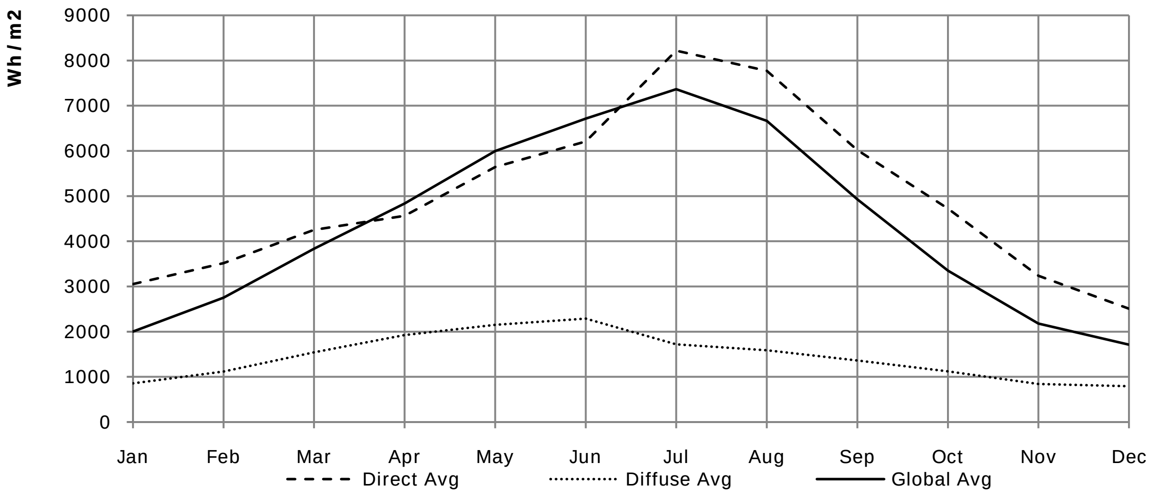
Spain has an area of 580,850 km2 and is located in the southwest part of Europe, between latitudes 36º and 43º47', and longitudes 7ºW and 5º36'. Due to its distance to the Equator, It can be roughly said that the Spanish peninsula has a temperate climate, but due its orographic and geographical characteristics, it can be found three main climates according to Köppen classification, namely, Dry climate in the south, Temperate climate approximately in the upper half of the Peninsula and Cold climate in mountainous areas (AEMET, 2011).

The case study building is situated in Gotarrendura village in Avila region, approximately in the geographical centre of Spanish Peninsula in coordinates 40°49'32.94" N / 4°44'19.60" W. Gotarrendura is located 664 meters above sea level and the climate is classified as Temperate with dry or temperate summer (Csb) according to Köppen classification, which is one of the most common climates in the Spanish Peninsula. Graph 3 present yearly maximum, minimum and average temperatures for Avila city, which is barely 18 km from Gotarrendura village. It can be seen that temperature variation over the whole year is significant, yet maximum and minimum temperatures does not reach extreme levels. Winter months (December, January and February) are rather cold with maximum temperatures of roughly 12ºC and minimum between 0 and -5ºC, whilst June, July and August present maximum temperatures over 30ºC and minimum of just below 10ºC. Regarding relative humidity, we can see that average values stay between 70% and 50% throughout the whole year excepting summer months when values drops below 50% and even 40%.



Graph 3 - Temperatures and relative humidity in Gotarrendura (DOE, 2009)

Graph 4 depicts average global, direct and diffuse solar radiation values over the whole year period. It can be seen that overall values fluctuate roughly between 2000 and 7000 Wh/m2, yet it can be distinguish between direct and diffuse radiation. Direct radiation curve follows roughly the same path than the global radiation, whereas diffuse radiation barely represents a small fraction in comparison with direct normal radiation. This means that overcast periods to clear sky periods ratio is rather low. It can be concluded from Graph 3and Graph 4 that there are four clear seasons in Gotarrendura village: cold but not very humid winters from December to February, mild and dry summer from June to August, and spring and autumn as transition seasons. Finally, it is worth stress two important features: the significant amount of sunny periods and high solar radiation values in comparison with the low temperatures and the high daily temperature variations of almost 20 degrees throughout the whole year. This study takes into account these characteristics to design the retrofit strategy for the case study house.



Graph 4 - Solar radiation levels in Gotarrendura (DOE, 2009)

5.1.2. Case study building: description and construction features

The case study building is a semi attached single family house located in Gotarrendura village in Avila region located approximately in the geographical centre of Spanish Peninsula in coordinates 40°49'32.94" N / 4°44'19.60" W. The house represents a typical two-storey rural construction with a total area of142.1 m^2 and low ceiling height. Its main façade is oriented south towards the street (Figure 3) and the north façade oriented north towards the courtyard (Figure 4). There is not data about the building construction date, although most of similar buildings in this area were built approximately at the beginning of the twentieth century. Nevertheless, the house has been refurbished and went though some minor maintenance operations, such as replacement of windows, substitution of some frame elements and external plastering repairs which could be observed in the site visit. None of the post built works seem to have direct significant impact on the thermal behaviour of the building.

Figure 5 - South façade (Author's photograph)

Figure 6 - North façade (Author's photograph)

One the most noteworthy feature is that the house was built with thick adobe solid walls, which have both supporting frame and envelope function. As previously explained, adobe is a type of earth construction technique by means of raw clay brick stabilized with lime plaster. Most windows are situated on the south façade and the wall has been reinforced with conventional hollow bricks around the fenestration holes as shown in Figure 5. All windows are single glazed with a 6 mm glass and have simple aluminium frame, yet some of them were replaced by wooden frame instead of aluminium in a latter refurbishment (Figure 6). Also, they are all provided with internal shutters and external plastic blinds. The house has three doors to access the house from the main street, from the courtyard and to access the balcony in the first floor. They are made of a simple steel sheet and a portion of their surface is glazed with a simple 6 mm glass.

Figure 7 - Reinforced adobe wall close-up (Author's photograph)

Figure 8 - Window close-up (Author's photograph)

The house is provided with old convective baseboard heaters fed with grid electricity. It seems they were conceived as auxiliary heating system to support a former traditional coal based heating system. However, nowadays it is being used as primary heating source. Baseboards are distributed of baseboards in the house. Only main living rooms, kitchen and some bedrooms are provided with heaters. For domestic hot water production (DHW) there is a butane boiler fed with individual domestic bottles which meets kitchen and bathroom needs. In the kitchen there are also four butane stoves for cooking and an electric oven. As usual on this region and type of buildings, the house is not provided with any cooling system since just few hours in summer temperature surpasses comfort levels (26ºC). Finally, the house has some few electric appliances in the living rooms, kitchen and bedrooms, although the quantity is far from the actual standards for a single family dwelling. All in all, the case-study house is fairly representative of typical old rural house in central region of Spain.

5.2. Thermal simulation of case-study building - DESIGN BUILDER

Many studies have validated the use of dynamic thermal modelling as an adequate method to analyse buildings heat balance and performance of different retrofit measures (Jie et al, 2007) (Kim and Kim, 2012), since simultaneous changes in the original building model entail complex interactions, where steady models might not be accurate. Besides, the use of computer aided simulations allows the researcher to save significant amount of time when performing complex parametric studies.

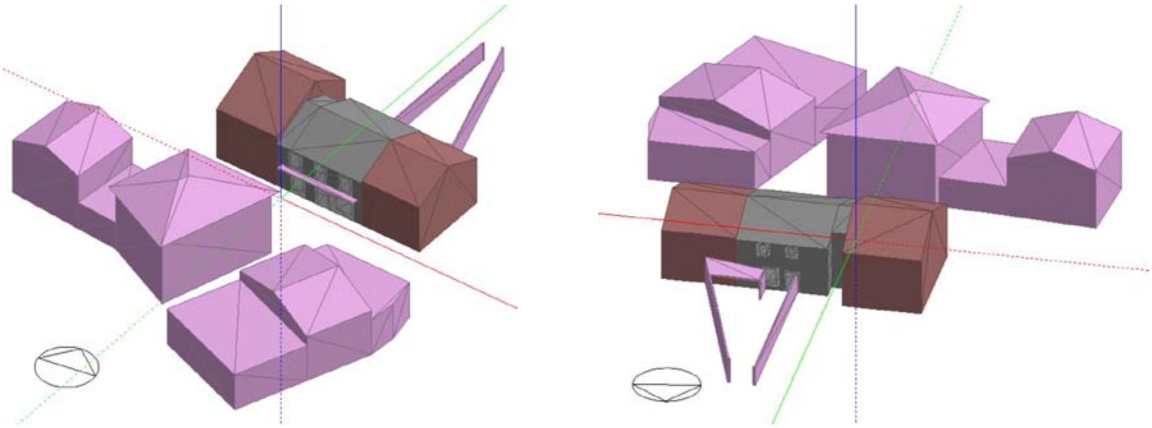


Figure 9 - Images of Design Builder modelling interface

Therefore, DESIGN BUILDER software was used to carry out dynamic thermal simulations of the "as built" and modified building models to analyse the impact of different retrofit actions. DESIGN BUILDER is a comprehensive user interface to create complex 3D models (Figure 7) and input advanced relevant data to perform building thermal simulation, which uses ENERGYPLUS engine to process the algorithms needed to calculate energy balance of buildings (Design Builder Software, 2005). ENERGYPLUS is dynamic thermal calculation software developed by the Department of Energy of the US (DOE).

In order to process calculations of complex buildings, most dynamic thermal simulation programs divide building space into simplest smaller spaces. DESIGN BUILDER considers a thermal zone as a unitary space with energy inputs and outputs which tent to equalize until it achieves an energy balance. Thus, a single building can be modelled as composed of several thermal zones or just one; depending on how detailed it is required the thermal simulation. It the case presented in this work, each room was modelled as single thermal zones. Therefore, ground floor rooms are differentiated from first floor spaces and north façade rooms are differentiated from south façade rooms. This assumption may have an impact of the final simulation results since DESIGN BUILDER software considers the interaction and heat flow through internal partitions. Nevertheless, heat gains and losses and energy loads are presented for the whole building, unless otherwise required for the analysis of a particular feature.

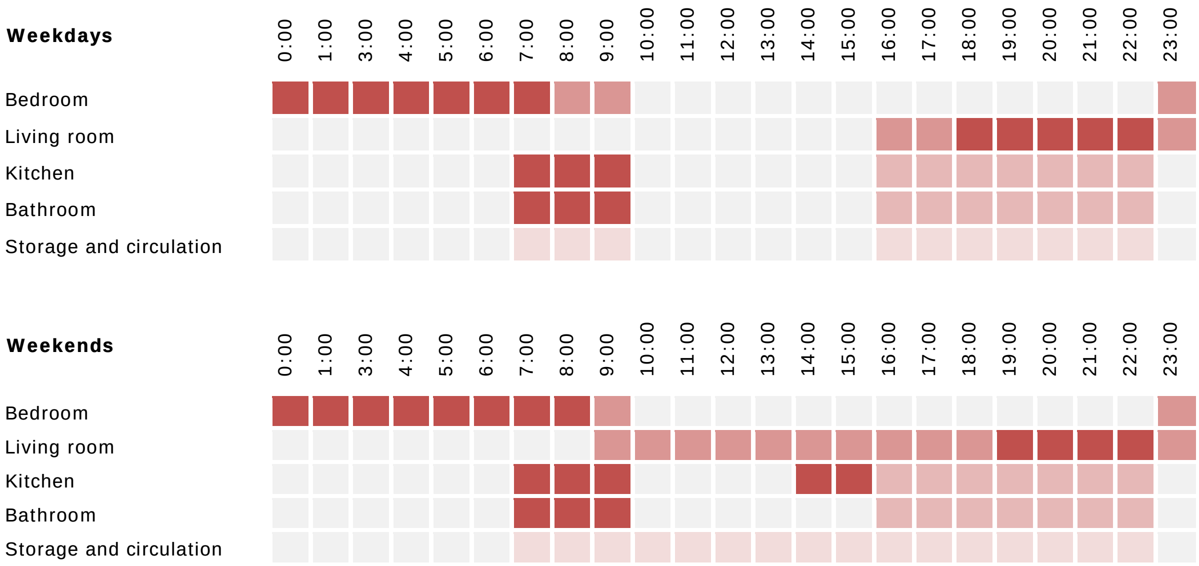


Table 2 - Occupancy schedules for building simulation

DESIGN BUILDER uses schedules to input operation patterns and parameters involved in the heat balance of the building; i.e. heating operating hours and set-points, lighting power density, occupancy rates, etc. Most of these values have been recorded from *ad hoc* site visits to the house and direct observation of those parameters, whilst others schedules are assumptions based on practical author's experience. However, heating set-point and comfort temperatures are based on Spanish building codes (RITE, 2008), which specifies 22ºC as a minimum heating design temperature. Thus, Table 1 represents schedule for occupancy periods, whereas Table 2 shows heating and natural ventilation schedule.

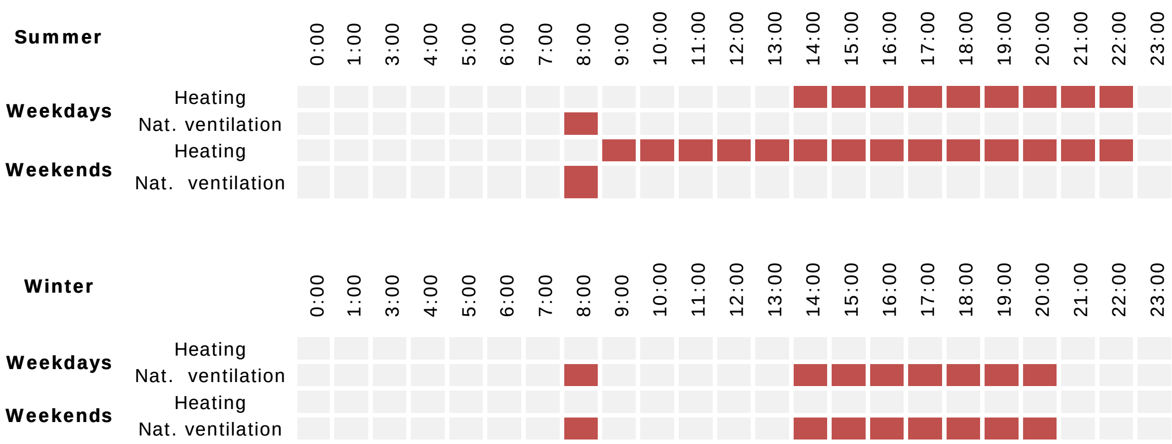


Table 3 - Heating and natural ventilation schedules

Similarly, thermo-physical properties of different building material are needed to perform simulations. Besides dimensions, the most determinant parameter is the thermal resistance (R-Value), which indicates the permeability to conduction heat flow through the material. However, in a composite wall, the thermal transmission value

(U-Value) gives the overall heat transmission rate as the interaction of all material layer R-Values. Also, there are other relevant parameters to the heat balance calculations, such as specific heat (c) and density (ρ), which accounts for thermal mass in the building. R-value, U-value, c and ρ are experimental values and their measurements are not straightforward since they vary with external conditions. Therefore, thermo-physical values that can be found in manufacturer specifications data or official building codes are approximations of real values and these are usually mean values gathered from multiple sources. Table 2shows main construction elements of the building and their thermo-physical values employed for the present study with the original source.

Envelope element	Layers	Overall thermal transmittance. U-value (W2/m2K)	Thickness (cm)
Exterior walls	Lime cement plastering + Adobe bricks + Gypsum plastering	1,06	65
Ground floor slab	Concrete slab + Supporting cement layer + Terrazzo tiles	2,17	25
Roof	Roof tiles + Asphalt + Hard wood board	1,34	15
First floor ceiling	Hard wood board	2,00	1,8
Partition walls	Gypsum plastering + Hollow brick + Gypsum plastering	1,76	12

Table 4 - Construction elements composition and main properties (CIBSE guide A, 2006) (Martín et al, 2010)

Adobe brick walls is worthy of particular mention since this material is not included in most building codes, although there are some experimental research studies which provides some approximate values (Table 2).

K Thermal transmittance (W/mK)	C Specific heat (J/kgK)	P Density (kg/m^2)
0,71	969	1772

Table 5 - Adobe thermo-physical properties (Martín et al, 2010)

Air infiltration and ventilation rates are paramount when analysing building thermal behaviour. These terms stand for the wanted or unwanted exchange of air volume between the interior and exterior of the building space. Thus, this air flow accounts for a significant fraction of heat gains and losses in the building thermal balance. The air-infiltration rate value assumed for the present study was 20 m^3/h/m^2 at 50 pa pressure differential since this building was considered as "leaky" (CIBSE Guide A, 2006) from direct site observations by the author. However, in later scenarios, air-infiltration values were changed to simulate retrofit operations.

Output results

Results are presented hourly for the coldest and the hottest week, and monthly over a whole year period. This represents a comprehensive analysis of the whole scenario since it covers the performance of the building in a long term period showing the seasonal differences and in short time period demonstrating daily environmental variations.

Results calibration

There are not billing records available for similar buildings in same conditions. However, results have been compared with national household energy consumption statistics. Results are shown in next chapter.

5.3. CO2 emissions calculations

Calculation of CO_2 emissions due to energy consumption in a building is calculated in a straightforward way. Each source of energy has associated a CO_2 emission factor depending on the consumption of fossil fuels associated. In case of fossil fuel consumption on site, this factor depends on the efficiency of the boiler which is given in the specifications. In case of energy collected from the grid, the CO_2 emission factor depends on the Country energy generation share. Spanish Government provides that information according to yearly energy generation figures. Therefore, CO2 emission was calculated as follows:

$$E_{CO2} = Eeu \times Ef$$

Where,

E_{CO2} is CO_2 emissions

Eeu is end use energy consumed

Ef is emission factor of the energy source

Table 1presents current CO_2 emission factors for each source of energy available in Spain during year 2011.

Energy source	Emission factors (Kg CO_2 / kWh)
Coal	0.378
Biomass	Neutral
Photovoltaic	0.0
Natural Gas	0.201
LPG	0.234
Butane	0.234
Propane	0.230
Grid Electricity	0.334

Table 6 - CO2 emission factors for different energy sources in Spain (IDAE, 2012)

5.4. Simulation of different energy saving strategies

After the analysis of the building thermal performance in its "as built" state, retrofit actions were implemented in the model for further study. These retrofit actions were based on a holistic retrofit strategy according to the diagnosis of the original house thermal behaviour and previous literature reviewed. In a first stage, insulation material layers were added progressively to the building envelope. The criterion was upgrading the original envelope thermal transmittance to minimum current standards set by the compulsory Spanish building code (CTE, 2009). Similarly, fenestration areas were upgraded to minimum compulsory national and air infiltration values were reduced accordingly since it was assumed that the replacement of window and door frames would increase the air-tightness in the wall. Lighting upgrade was also considered in present retrofit strategy since it is one of the most straightforward and cost-effective methods to reduce energy loads. Finally, a photovoltaic / thermal buffer was installed in the building to provide electricity and passive solar heating. All systems were simulated individually and then compared with a fully retrofit scenario to analyse the hypothetical interaction amongst them.

5.4.1. Roof, wall and floor thermal insulation improvement

Several studies have validated walls and roof upgrade as the most energy-efficient refurbishment strategy for non-insulated buildings (Bojic et al, 2012). In present study, layers of common insulation materials was added to the original composition of external walls, ceiling and ground slab in the computer model, which was latter analysed. The objective was to increase building envelope U-value until the minimum compulsory building code standards (CTE, 2009) were reached. Table 6 presents "al built" values and upgraded values for every envelope element.

	Pre-retrofit		Improved opaque envelope		
Envelope element	Layers	U-value (W2/m2K)	Layers	U-value (W2/m2K)	Maximum U-values required by Spanish building code (CTE, 2009)
Exterior walls	Lime cement plastering + Adobe bricks + Gypsum plastering	1,06	Lime cement plastering + 40 mm rock wool + Adobe bricks + Gypsum plastering	0,47	0,57
Ground floor slab	Concrete slab + Supporting cement layer + Terrazzo tiles	2,17	Concrete slab + 60 mm Exp. polystyrene + Supporting cement layer + Terrazzo tiles	0,46	0,48
First floor ceiling	Hard wood board	2,00	40 mm rock wool + 40 mm rock wool + Hard wood board	0,35	0,35

Table 7 - Envelope features

5.4.2. Fenestration upgrade

Fenestration is worthy of separate section since it is a singular component of the building envelope. Existing windows were replaced for energy-efficient windows in the as-built simulation model. Similarly to envelope upgrade, fenestration areas were upgraded to the minimum building standards. Table 7summarizes main properties of double glazed windows with thermal-break aluminium frame used in the retrofit scenario. Also, air-infiltration values were changed in post-retrofit simulation to try to simulate air-tightness enhancement due to the improved fitting of window frames into the walls. Thus, original infiltration value of 20 $m^3/h/m^2$ was changed to 10 $m^3/h/m^2$ to simulate a scenario which complies with current common standards (CIBSE Guide A, 2006). Finally, a fully envelope retrofit scenario including fenestration areas was simulated and it results presented in next chapter.

Windows	Glazing	Frame	Overall thermal transmittance. U-value (W2/m2K)	Glazing solar transmittance. g-value (%)	Solar heat gain coefficient (SHGC)
Base-case	6 mm clear glass	Aluminium / Wooden	6,12	78%	81%
Energy-efficient windows	6 mm clear glass + 13 mm air gap + 6 mm clear glass	Aluminium with thermal break	2,71 (3,1)[1]	60%	70%

(1)Maximum U-value required by Spanish building code (CTE, 2009)

Table 8 - Windows main characteristics and values (EnergyPlus dataset, 2009)

5.4.3. Energy efficient lighting

Literature review proved that upgrading lighting system is one of the best methods to reduce energy loads in a building (Aman et al, 2013).

In this case, lighting power installed in the house has been upgraded to an energy-efficient lighting system by swapping old incandescent lamps for equivalent market available LED lamps. Table 8shows main features of old incandescent and new LED lamps.

	Type of lamp	Wattage (W)	Illuminance (Lumens)	Lighting power density (W/m2 - 100 lux)
Lighting lamps installed	Incandescent	60	710	22
Energy efficient lamps	LED	10	806	3,3

Table 9 - Lighting systems features (Aman et al, 2013) (OSRAM, 2013)

5.4.4. Multi-functional solar system (BIPV/T)

The holistic retrofit strategy studied in the present work includes the installation of a glazed buffer zone/sunspace on the south façade of the case study building, which aims to provide both electricity and thermal energy for space heating for better use of solar energy. This hybrid system consists of a semi-transparent PV technology system integrated within a passive solar heating system. This solution is singular due to the limited retrofit options which lead us to adapt its dimensions to existing conditions. However, this system shares same background physical principles than other studied building integrated photovoltaic thermal systems. Urban building regulations and aesthetic reasons limit the installation of the passive solar system to the upper floor. A glazed buffer of 70 cm wide was projected in the south façade of the first floor plan, fully covering external walls and windows of three bedrooms.

As Figure 10 depicts, theoretical operation of thermal system differs depending on the season. In winter conditions lower and upper vents are closed to allow air heating due to solar gains. Thus, when buffer internal temperature surpasses bedrooms air temperature heat will flow towards the house. In contrast, buffer vents are always open in hot conditions to induct ventilation by the stack effect generated on account of space solar gains. In addition to heat generation, PV glass produces electricity at the same time and its performance might be enhanced by thermal system operation. Namely, PV cell efficiencies grows at low temperatures, hence constant air flow in summer conditions due to stack effect potentially increases PV performance.

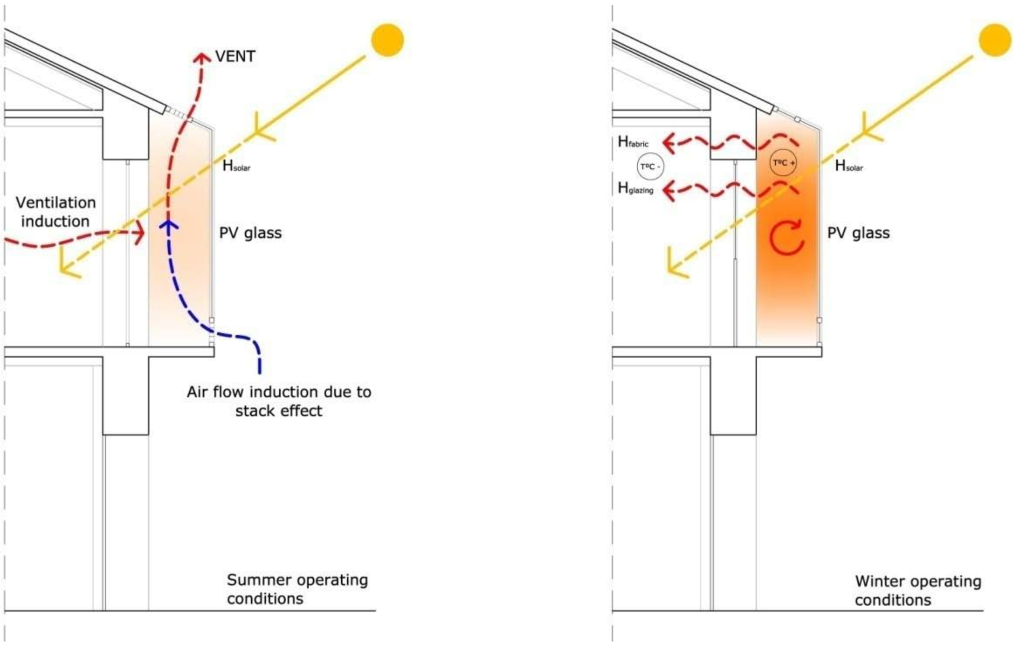


Figure 10 - PV/T solar system operating diagrams (author's drawing)

Electricity production

PV glass is state-of-the-art technology which integrates PV cells for energy production in a semi-transparent glazed structure. In this way, it multiplies PV applications and ease building integration. In this case, PV electricity production is been prioritized over thermal energy saving potential, so semi-opaque glass was selected. Besides, PV system needs at least 1 kWh power installed to start operating properly. Therefore, glass type selected for present solar system is an amorphous silicon PV glass with 10% transparency developed by a Spanish manufacturer (ONYX Solar), which properties are sorted in Table 9.

PV cell type	Layers	U-value (W / m2K)	Peak power (W / m2)	Temperature coefficient at Pmax (% / °C)	SHGC	Direct solar transmission (g)	Light transmission
Amorphous silicon	6 mm + 3 mm + 6 mm	5,2	49,4	-0,19	0,486	0,291	0,101

Table 10 - Photovoltaic glass properties (ONYX)

Instantaneous electricity generation is calculated as the product of incident solar radiation and instantaneous PV glass efficiency, which varies with PV cell temperature. Hence:

$$E_{PV} = I \times \eta_i \times A$$

$$\eta_i = \eta \times \left(1 - \left(T_{coeff} \times (T_{cell} - 25)\right)\right)$$

Where,

E_{PV} is instantaneous electricity produced

I is instantaneous incident solar radiation

η_i is instantaneous PV glass efficiency

A is active area of PC glass

T_{coeff} is temperature coefficient at STC

T_{cell} temperature of PV glass

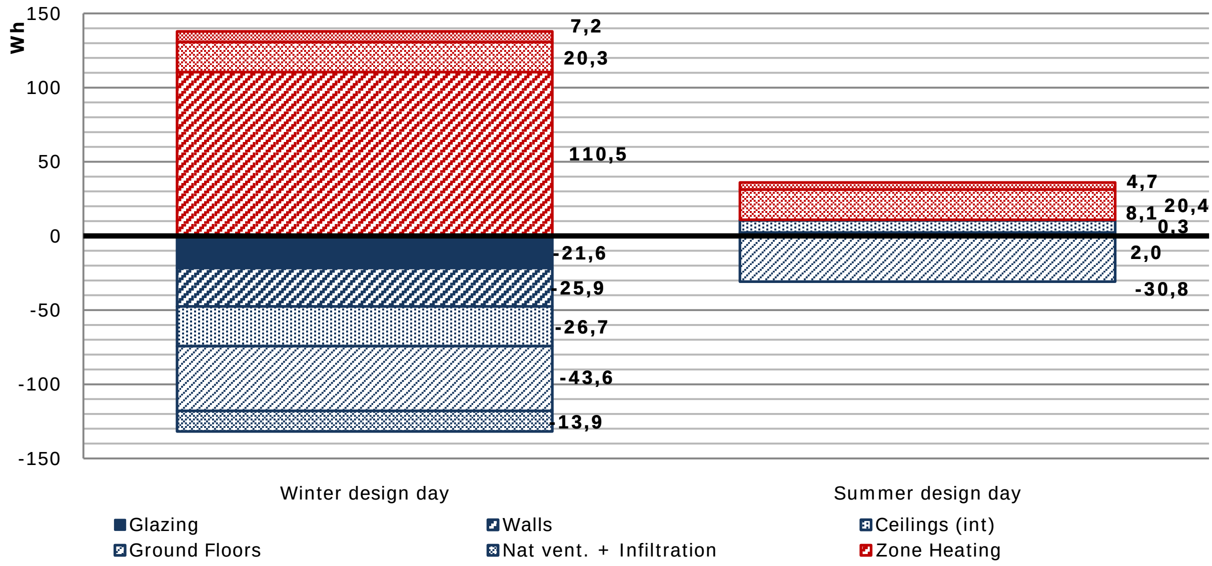
η is PV glass efficiency at STC (25ºC)

Eventually, total monthly electricity production is calculated as the sum of every instant energy production.

6. Results and discussion.

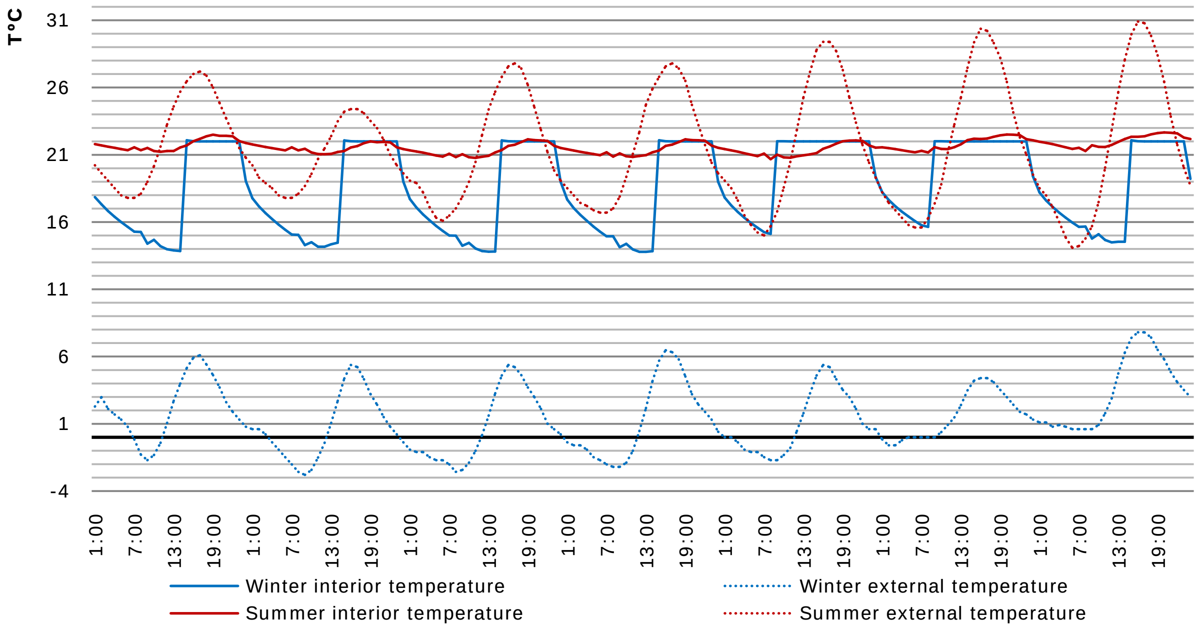
In present chapter, results from different DESIGN BUILDER simulation and calculations are presented and discussed. Firstly, performance simulation outcomes of the "as built" case are analysed. Then, performance of each individual retrofit measure is assessed to investigate individually its impact on building thermal balance and eventually, a fully post retrofit scenario was simulated and its results are presented and discussed to investigate its impact on building energy consumption and CO2 emissions.

6.1. As-built scenario



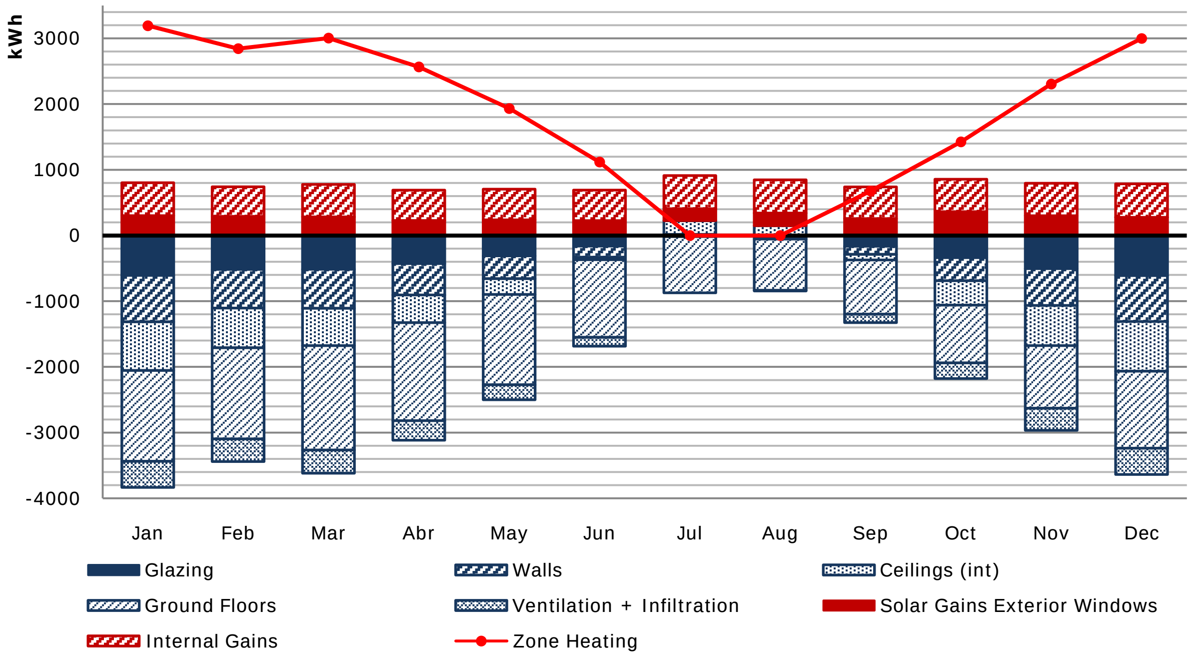
Graph 5 – Winter and summer design day. Heat gains and losses

Graph 5 depicts the heat balance of the case study house in a pre-retrofit stage during the winter and summer design days. It can be seen that heat flux is much higher in cold than in hot conditions. During winter design day, the house receives around 20 Wh of heat due to occupancy, lighting and appliances heat generation and roughly 7 Wh of heat gains through windows. In addition, a heating input of approximately 110 Wh is needed to maintain comfort levels during the scheduled hours. In the flip side, most of the heat is lost through conduction by the ground slab with roughly 43 Wh. Then, walls, roof and glazing accounts for approximately 20-26 Wh of conduction heat losses. Finally, natural ventilation and infiltration accounts for around 14 Wh of heat losses. In summer design day, there is no active system to meet cooling demand. Lighting, occupancy and appliances heat release account for the same amount of heat input than in winter (20 Wh), whereas conduction heat gain through the roof reaches roughly 8 Wh. Interestingly, solar gains through windows are lower in summer (4.7 Wh) than in winter (7.2 Wh). This might be due to the incident solar angle variation which leaves window shaded an important fraction of summer day. Conduction heat loss through ground slab is 30 Wh, whilst there is barely heat flow through walls or due to air infiltration. To sum up, it seems that ground slab is the leakiest element in the building, although wall, roof and glazing heat losses are also significant in cold conditions.



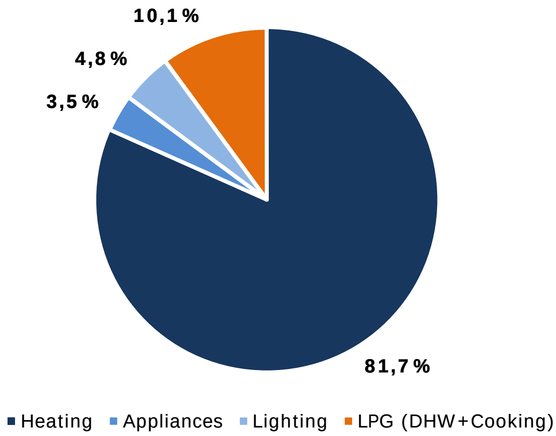
Graph 6 - Winter and summer design day. Internal temperatures

Graph 6 depicts internal and external temperatures for both winter and summer design weeks. During winter design week, ambient temperature fluctuates between roughly -2ºC at 8 am and 6ºC at 17 pm, whereas internal temperature remains flat in the heating set-point (22ºC) between 2 pm and 11 pm in week days and between 9 am and 11 pm during weekends. then it drops dramatically until it stabilizes in 14ºC at 1 pm in week days and 15ºC at 8 am during weekends. External temperature in summer week varies from approximately 17ºC at 8 am to 29ºC at 17 pm, whilst internal temperature curve remains almost flat in 21-22 degrees over the whole week period. We can conclude that thermal mass affects strongly the building thermal behaviour. In winter conditions, the heat stored in adobe walls delays temperature lag during the night so internal temperature never drops below 15ºC. In summer conditions, adobe thermal mass keeps internal temperature below 23ºC even when external temperature surpasses 30ºC. This results match with other studies (Martin, Mazarron and Cañas, 2010) which demonstrated that earth construction thermal mass reduces significantly the heating loads while may provide naturally internal comfort levels in summer conditions.

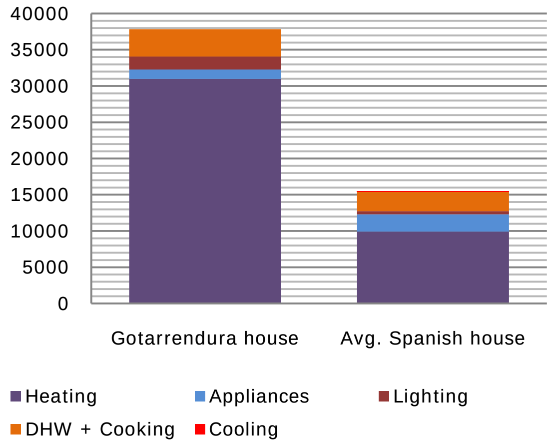


Graph 7 - Base-case. Monthly heat gains and losses

Graph 7 presents monthly total conduction and infiltration heat fluxes and heating demand. It can be seen that there is a significant amount of heat losses in winter months which is balanced though an equivalent heating energy input. Ground floor slab heat losses are roughly 1500 kWh per month during winter and spring months and 1000 kWh in summer and autumn months. Walls, roof and glazing conduction heat losses are approximately 700 kWh each in winter months, then they drops steadily to zero as they approach to summer months. Actually, roof conduction heat flux turns positive during July and August with 200 kWh energy input. Ventilation and infiltration accounts for roughly 400 kWh heat losses from November to March, then this figure decreases proportionally until is neutral in summer months. Interestingly, proportion of heat losses due to ventilation and infiltration is relatively small considering that Gotarrendura house has a leaky envelope. Finally, we can see that solar gains remain stable in 150 kWh throughout the whole period. We can conclude that ground floor slab accounts for the largest fraction of heat losses, yet other envelope elements should also be considered when addressing energy-efficient measures. Finally, we can state that building envelope is poorly energy-efficient and passive heat gains contribution to total heat balance is very small in cold months in comparison with heating input. Consequently, retrofit strategy should be oriented towards reversing those behaviour patterns.



Graph 8 - Base-case house. Total fuel consumption breakdown



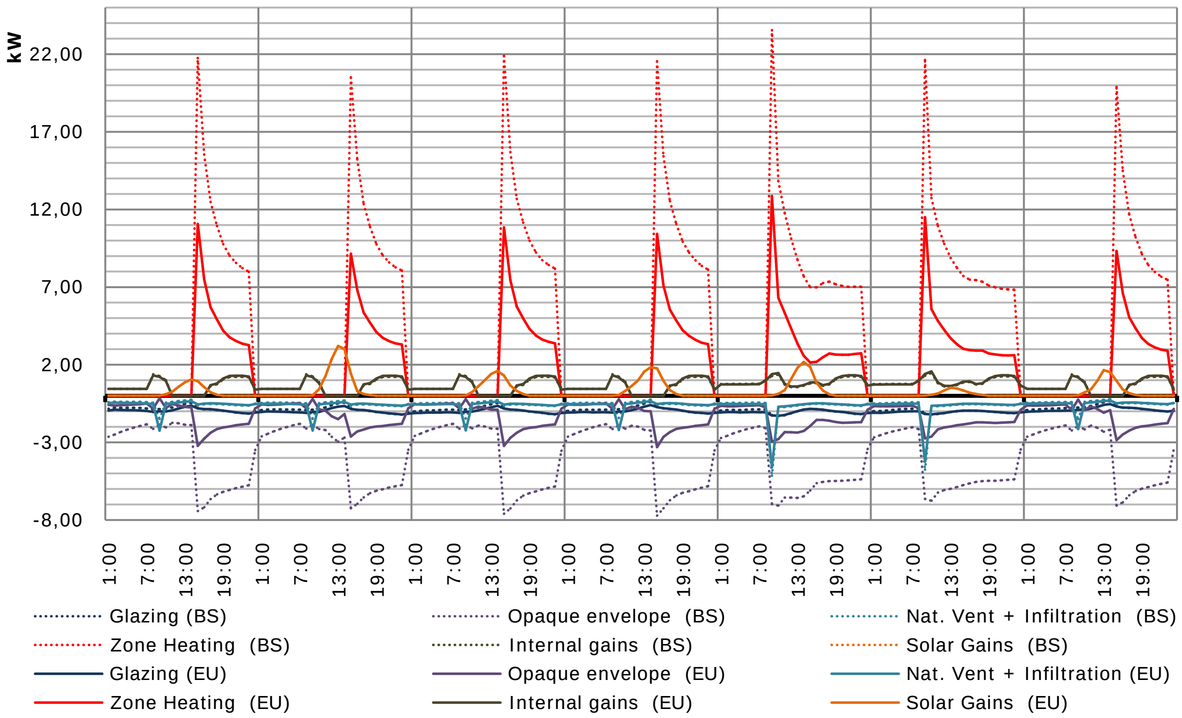
Graph 9 - Total fuel consumption in the house and Spanish standards

Graph 8 shows annual energy consumption share in the Gotarrendura case study house. We can see that grid electricity is the primary energy source in the building. Heating represents the largest fraction of annual energy consumption with roughly 82% of the total. Appliances and lighting consumes 3.5% and 4.8% of the total respectively. Finally, bottled liquefied petroleum derived gases (LPG) is the energy source for approximately 10% of energy consumption allocated to the production of domestic hot water (DHW) and cooking stoves.

Graph 9 presents total annual energy consumption figures in case-study house in comparison with average consumption in Spanish house of same characteristics. Gotarrendura house consumes around 31,000 kWh of heating per year, whilst most usual heating consumption figure in Spanish houses is around 10,000 kWh. Appliances in case-study house consume approximately 1,800 kWh of annual electricity, whereas the Spanish average is 2,600 kWh. Lighting and DHW in case-study house is approximately 1,800 kWh and 3,800 kWh respectively, whilst average Spanish consumption in same cases is 440 kWh and 2,700 kWh. Overall, we can see that Gotarrendura house is quite poorly energy-efficient in almost all aspects in comparison with current Spanish standards. The most striking feature is that heating consumption in case-study house represents the triple than the average. In contrast, electricity consumption due to appliances is lower in case-study house, which accords with author's observations about services in the house.

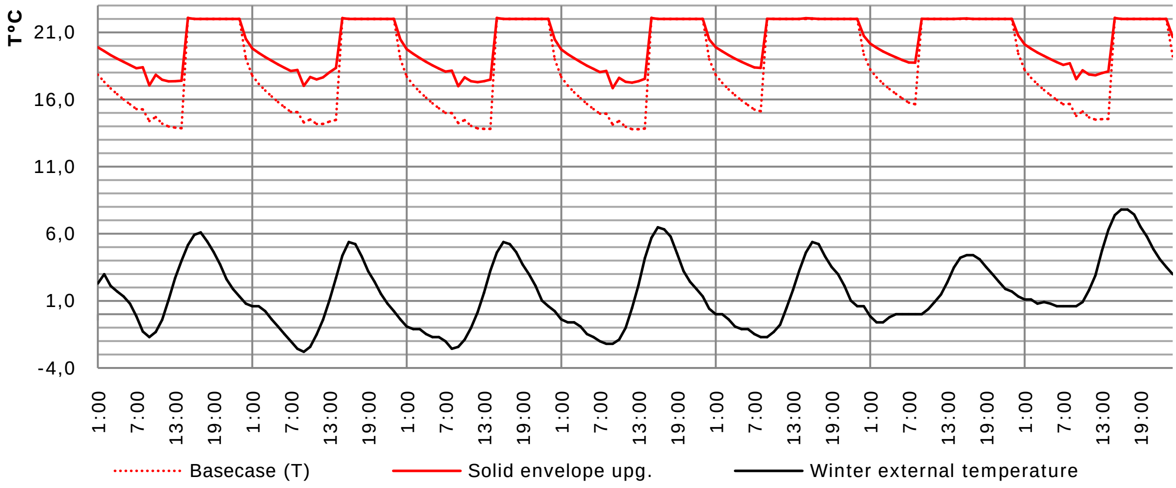
6.2. Solid envelope upgrade

In this section, effects of adding insulation layers to main opaque envelope areas of the building are presented and discussed.



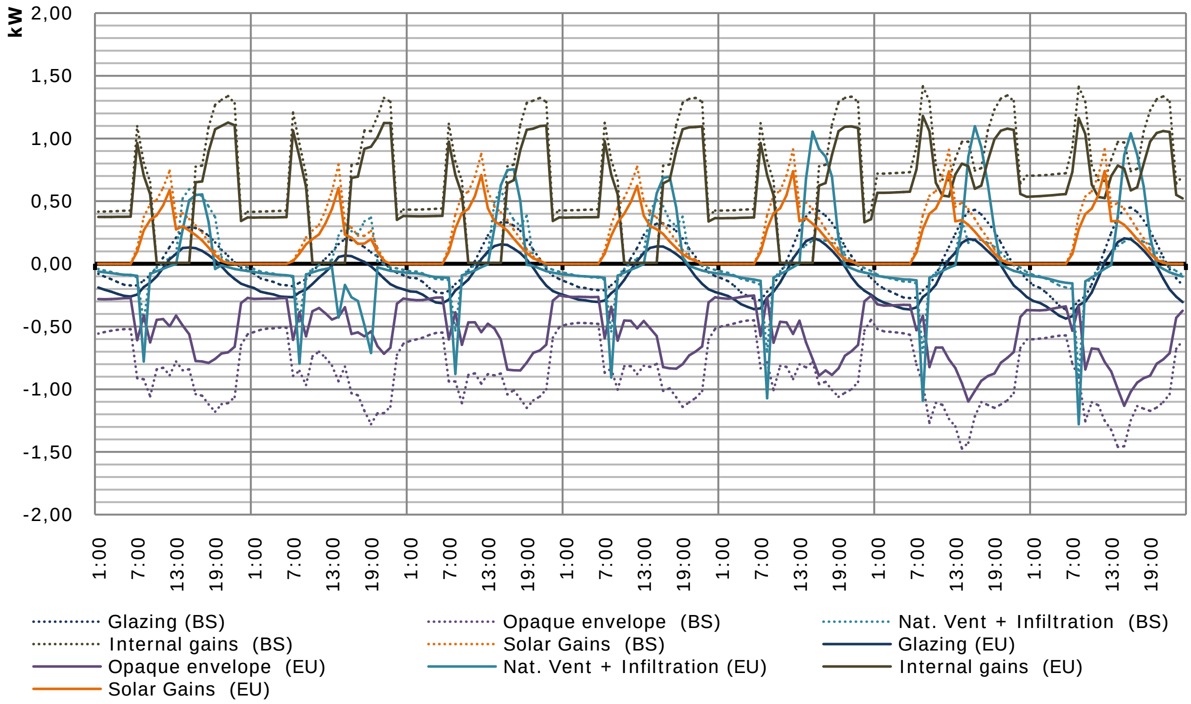
Graph 10 - Upgraded envelope. Winter week. Heat gains and losses

Graph 10 depicts case study heat gains and losses during winter design week in "as built" stage (BS) and in upgraded opaque envelope scenario (EU). It can be seen that energy demand is linked closely to envelope conduction heat losses. Peak heating demand decreases from roughly 21 kW to 11 kW in weekdays and from 23 kW to 13 kW in weekends due to envelope thermal resistance improvement. Then, heating load curve drops dramatically the first heating system operation hours, just to stabilize in 8 kW and 3 kW in as-built scenario and upgraded envelope scenario respectively. In weekend days, this fall is even larger to 7 kW and 2 Wh. As expected, opaque conduction losses change due to the impact of envelope enhancement. Envelope conduction losses keep flat until heating system operating hours, when losses increase from -1 kW to its lowest value (-3 kW). Them, it decreases slightly to 2 kW until 11 pm, when it decreases again to its original value. These figures are roughly 4 kW less than in as-built scenario. Rest of heat losses and gains values seem not vary significantly due to envelope enhancement. In conclusion, we can see that the overall decrease of envelope thermal transmittance led not only to an important fall of heating peak consumption value but also an overall decrease of heating needs at every hour. It does not seem to produce significant changes in other values.



Graph 11 - Upgraded envelope. Winter week. Internal temperatures

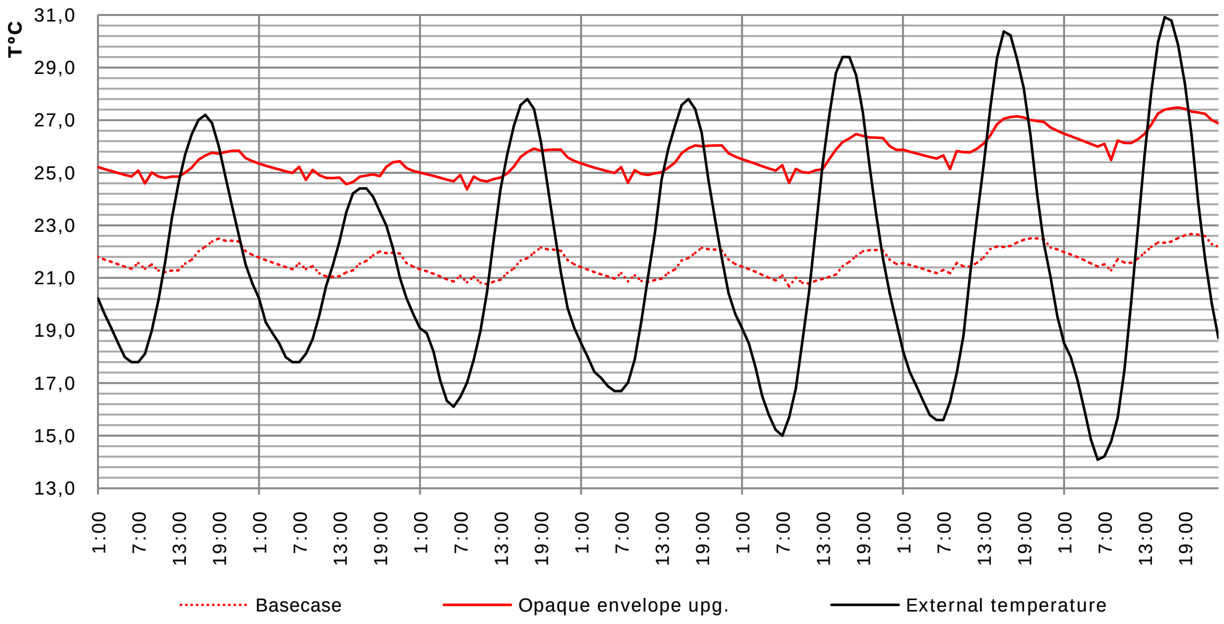
Graph 11 presents internal operative temperature profiles of upgraded envelope scenario in comparison with base-case scenario and external temperatures. We can see that during heating system operating hours temperature remains flat in 22ºC. When the system is switched off at 11 pm, internal temperature drops less sharply due to envelope enhancement. Then, it seems that temperature keeps falling but less steeply than in as-built scenario, until it stabilizes at 17ºC and 19ºC in weekdays and weekend days respectively. Also, the isolated temperature drop due to morning ventilation is slightly higher in insulated envelope case than in base-case. All in all, it can be seen that reducing envelope thermal transmittance enhances building thermal mass effect by slowing down temperature drop during night time.



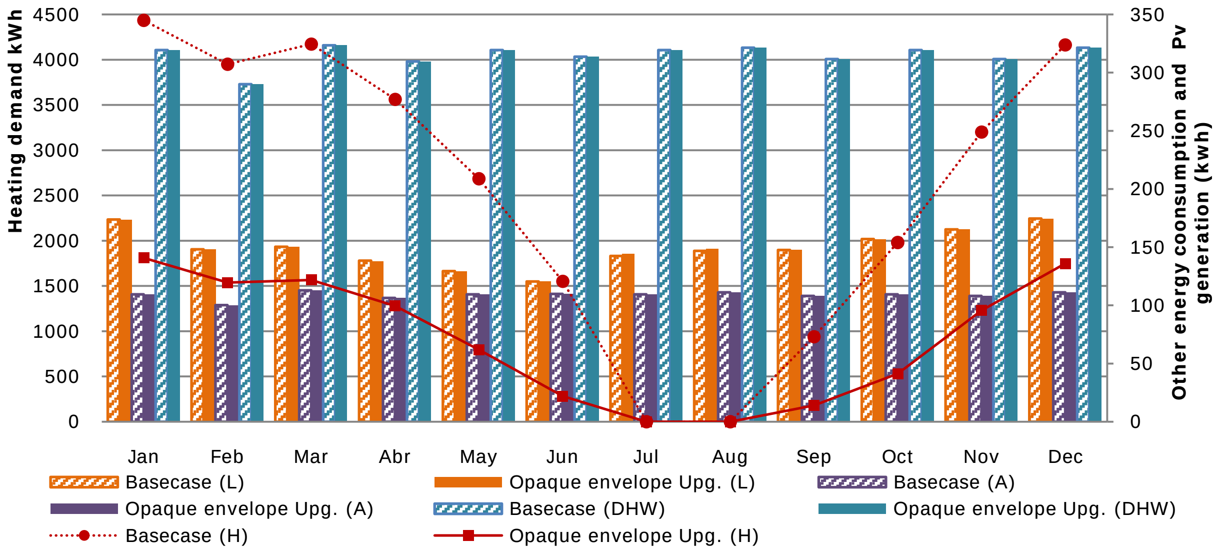
Graph 12 - Upgraded envelope. Summer week. Heat gains and losses

Graph 12 shows heat gains and losses in insulated envelope conditions (EU) in comparison with as-built scenario (BS) over a whole summer design week. Upgraded envelope conduction losses are roughly 0.3 kW lower than in base-case scenario. It can also be seen that solar gains and internal gains decrease slightly in comparison with as-built case. Glazing conduction heat flux is roughly 0.1 kW lower when is positive and same amount higher when the heat flow is negative. Finally, air infiltration heat gains are 0.3-0.5 kW higher in new scenario especially in central hours of the day. It seems that lower envelope thermal transmittance values leads to lower envelope conduction losses as expected, but also to lower internal heat gains and solar gains. Equally surprisingly is the increase of ventilation and infiltration gains in mid hours of the day. These results cannot be explained with present study and further parameters should be analysed, such as temperature curve profiles.

Graph 13 depicts external and internal operative temperature in both base-case and insulated envelope scenario during a summer design week. Internal temperature curve in upgraded envelope case depicts same profile than base-case temperature curve, but is 4 degrees average higher. Also, isolated temperature drop due to morning ventilation is slightly more noticeable in new scenario than in base-case. It can be seen that generally temperatures are over comfort conditions (25ºC) over the whole day period. It seems that insulation boost thermal mass effect; however, in contrast to winter conditions, case study house has better thermal performance in as-built state than in insulated envelope state.



Graph 13 - Upgraded envelope. Winter week. Internal temperatures



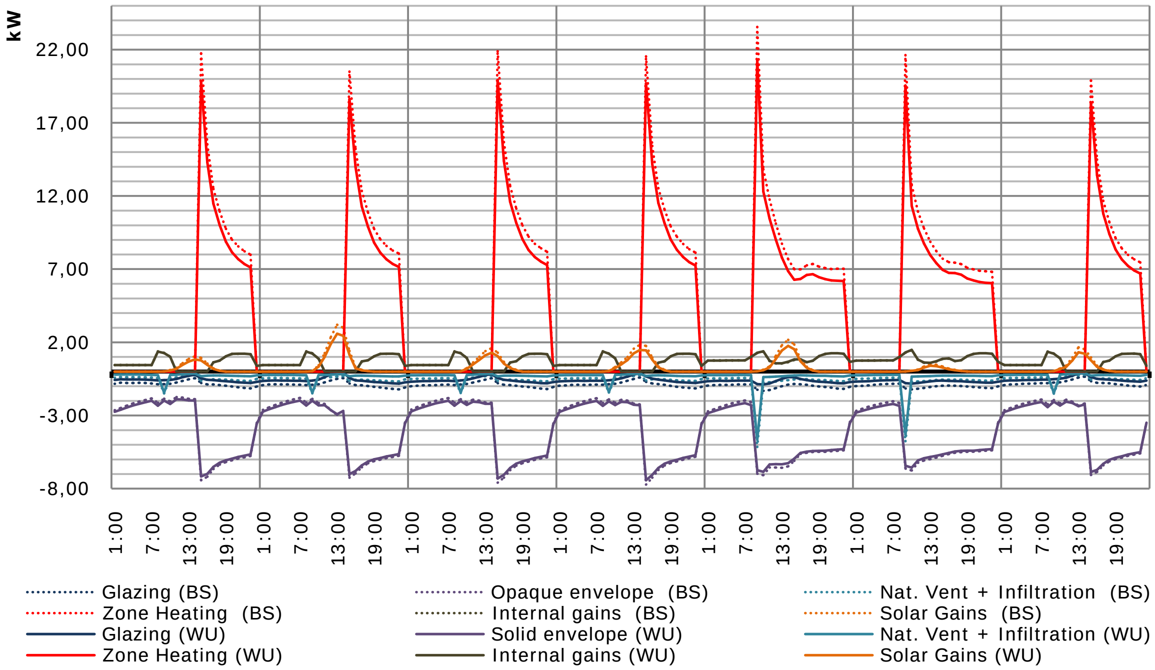
Graph 14 - Opaque envelope. Monthly energy consumption

Graph 14 presents monthly energy consumption of lighting (L), heating (H), room electricity (A) and domestic hot water and cooking (DHW) for both upgraded envelope scenario and as-built scenario. Heating consumption decreases dramatically from roughly 4000 kWh to approximately 1600 kWh due to envelope enhancement in winter months. Envelope insulation accounts for heating saving in rest of months proportionally to their consumption. Namely, heating consumption reduces from roughly 3500 kWh to 1200 kWh in April and November, from 2700 kWh to 700 kWh in May, from1500 kWh to 250 kWh in June, from 1000 kWh to 150 kWh in September, and finally, from 2000 kWh to 500 kWh in October. There are almost no changes in other energy consumption figures due to envelope insulation in comparison with base-case scenario. In conclusion, it can be stated that improving envelope thermal insulation is an effective energy-efficient retrofit strategy to reduce heating loads in all months, yet it seems more effective in milder conditions.

6.3. Fenestration upgrade

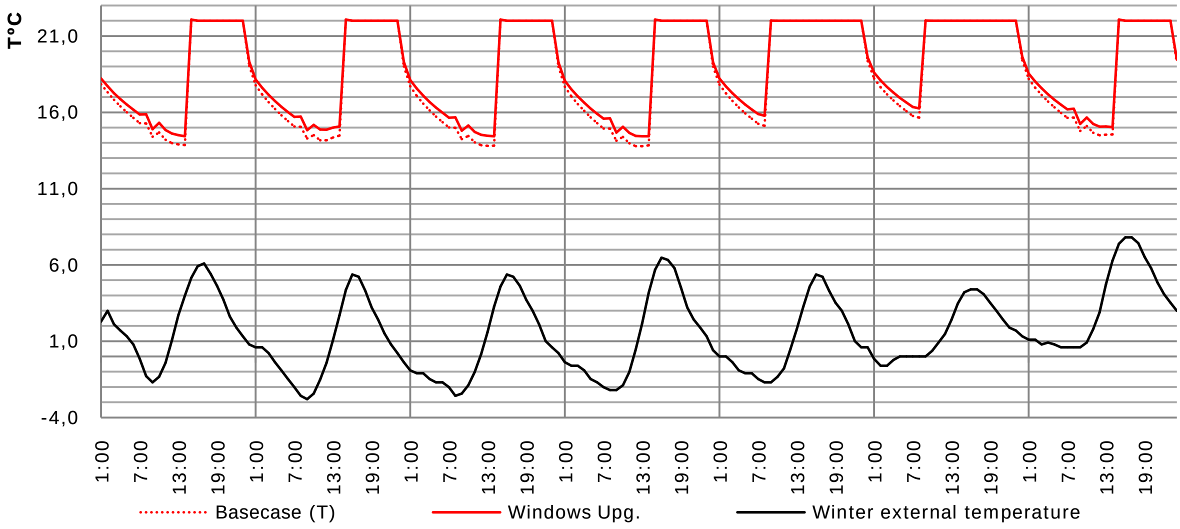
In this section, results of DESIGN BUILDER simulation for case-study with upgraded fenestration areas are presented and discussed.

Graph 15 shows heat fluxes in case-study house with upgraded fenestration (WU) in comparison with as-build case (BS) during a winter design week. At first glance we can see that conduction heat losses through glazing decreases around 0.5 kW in new configuration scenario throughout the whole week period. Similar ventilation and infiltration heat loss reduction can be observed due to windows improvement. In contrast, solar gains decrease around 1 kW in all days, though the lower is the solar radiation, the smaller seems glazing heat gain fall. There is also a significant peak heating demand drop of 2 kW and 1 kW of overall heating demand saving due to fenestration retrofit. Finally, no significant changes can be observed in internal heat gains, although slight reduction in envelope conduction heat losses can be seen during heating system operation hours. In conclusion, we can state that double glazed windows, higher insulating window frames and better windows fitting account for roughly 50% glazing conduction heat flow reduction and 50% decrease of infiltration heat losses. However, upgraded windows also bring solar gains reduction, probably due to the lower glass solar transmittance value (g-value) of double glazing windows. Overall, all these heat flow modifications accounts for a 10% heating saving during winter design week.



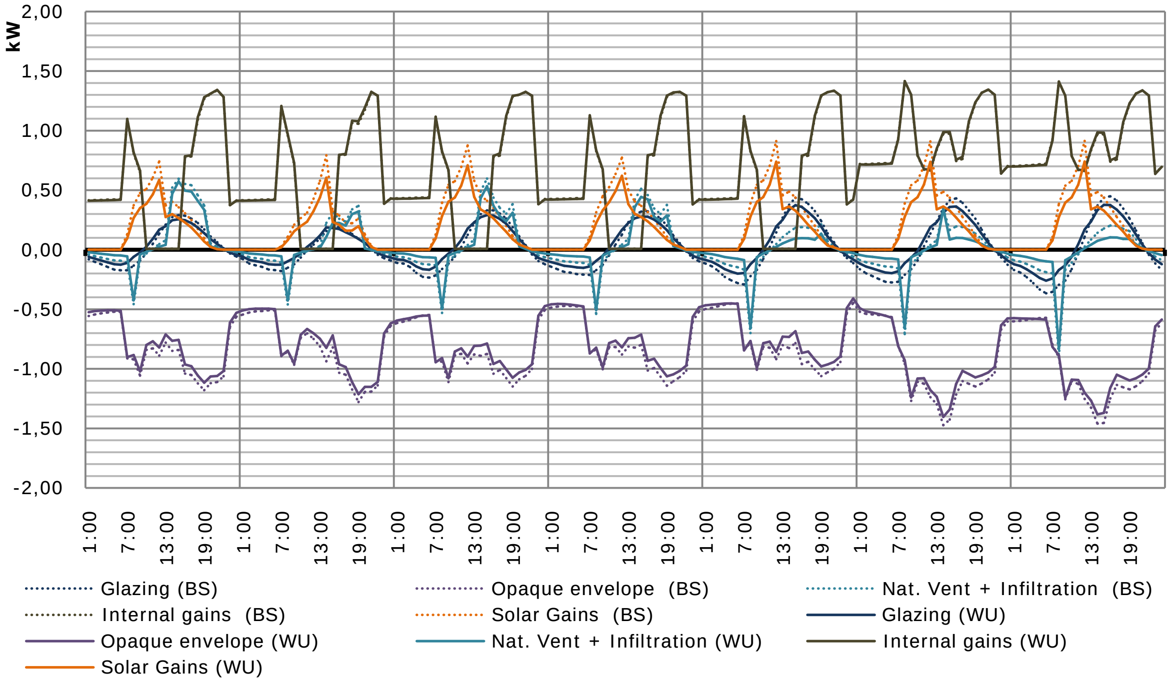
Graph 15 - Fenestration upgrade. Winter week. Heat gains and losses

Graph 16 shows internal and external temperature curve profile in fenestration retrofit scenario and base-case scenario. Temperature curve shows that internal conditions during heating system operation hours remain in 22ºC. After 11 pm, temperature value drops steeply until 14 pm when it reaches approximately 15ºC, which is 1 degree higher than in as-built scenario. This temperature difference between upgraded windows case and base-case is roughly the same throughout the whole period the heating system is off. Overall, we can state that windows upgrade accounts lower negative heat flow rate in the building. Despite temperature difference between both scenarios, temperature curves follow same trend, which might means that higher energy-efficient fenestration does not modifies building thermal mass.

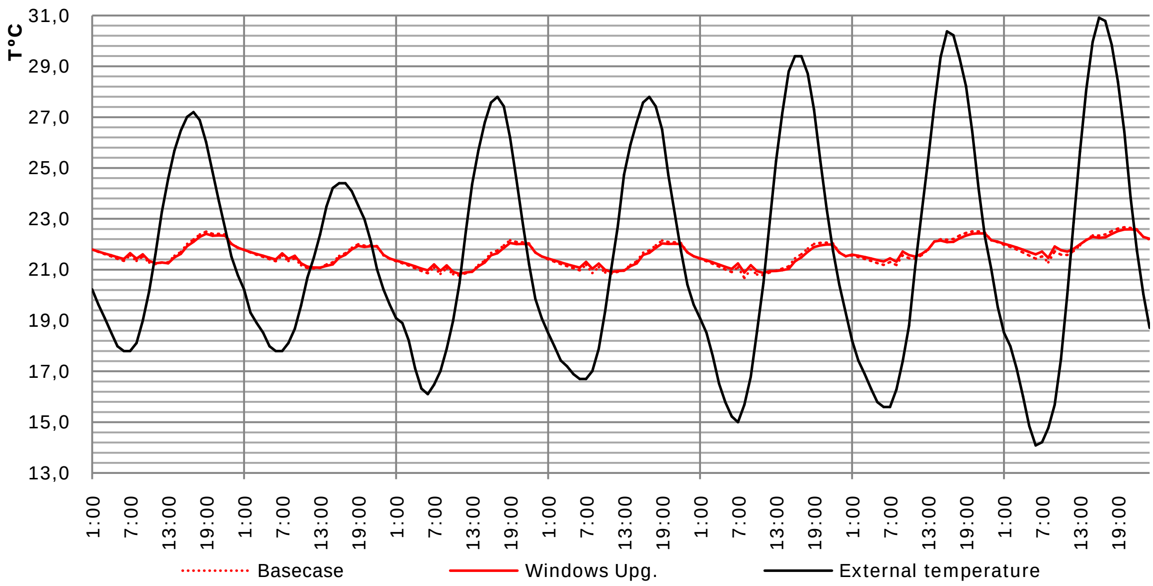


Graph 16 - Fenestration upgrade. Winter week.Internal temperatures

Graph 17 depicts heat fluxes in case-study building with upgraded windows (WU) and in its as-built state (BS) during summer design week. Conduction heat flow through glazing fluctuates according to external temperature, yet it is roughly 0.1 kW lower in upgraded windows scenario than in original base-case. Also, it can be seen that heat gains and losses due to infiltration are lower whenever the flux is positive or negative. Glazing solar gains are lower with double glazed windows that with single glazed pane. This might be caused by the lower solar transmittance of composite windows in comparison simple windows. Interestingly, there is also some opaque envelope heat flow reduction of approximately 0.1 kW during daylight hours. Probably, lower heat gains generate lower heat losses to achieve energy balance in the building.



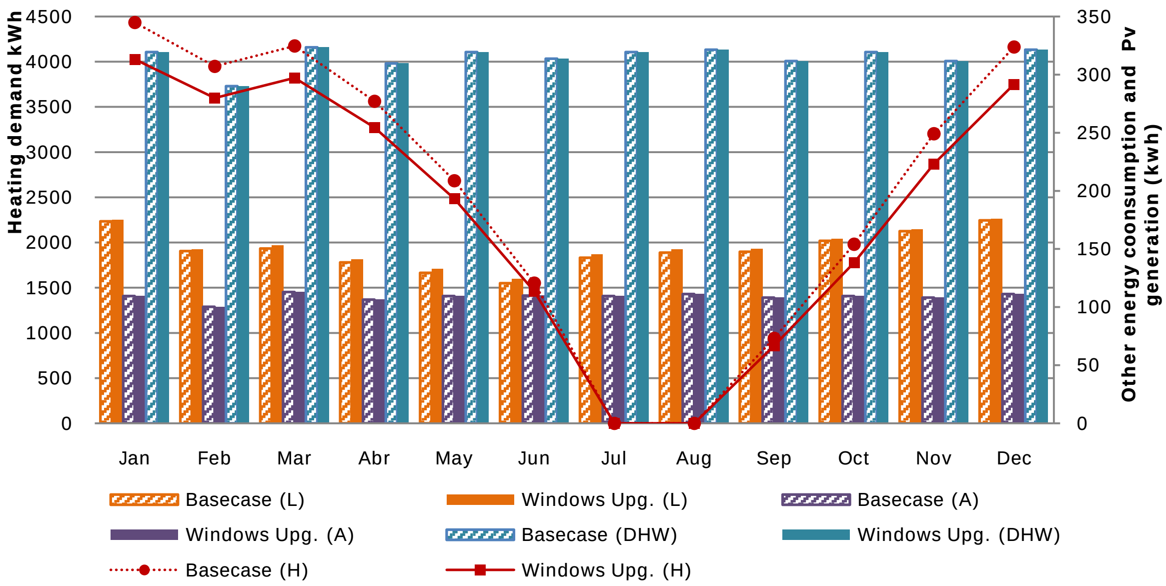
Graph 17 - Fenestration upgrade. Summer week. Heat gains and losses



Graph 18 - Fenestration upgrade. Summer week.Internal temperatures

Graph 18 shows internal and external temperature curves in case-study in as-built state and in windows retrofit scenario during a summer design week scenario. At first glance, we can see there are not significant changes in internal temperature curves profile between both scenarios. Internal temperature in both cases fluctuates between 21ºC and 23ºC, yet upgraded windows case present slightly less variation between lowest and higher values. In general terms, we may say higher energy-efficient windows do not substantially modify internal temperature conditions in summer.

Graph 19 depicts total monthly energy consumption in case-study house with fenestration improvement in comparison with base-case scenario. In a windows port-retrofit scenario heating represents by far the highest energy consumption in the building, though higher energy efficient windows account for around 500 kWh saving in winter months, approximately 300 kWh in March, April and November; and finally, about 100 kWh in rest of heating months. Lighting consumption is slightly higher with double glazed windows from March to November, whilst energy consumption due to electric appliances, DHW production and cooking does not change as expected. In conclusion, energy efficient windows accounts for roughly 11% of total heating consumption saving.

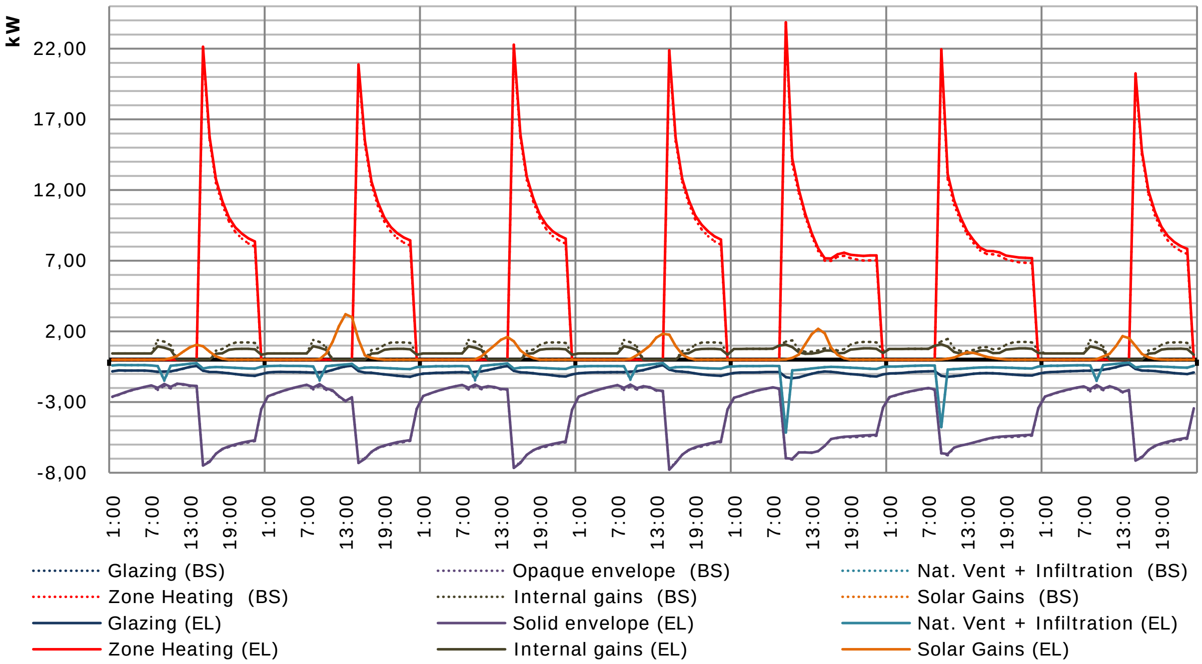


Graph 19 - Fenestration upgrade. Monthly energy consumption

6.4. Energy efficient lighting

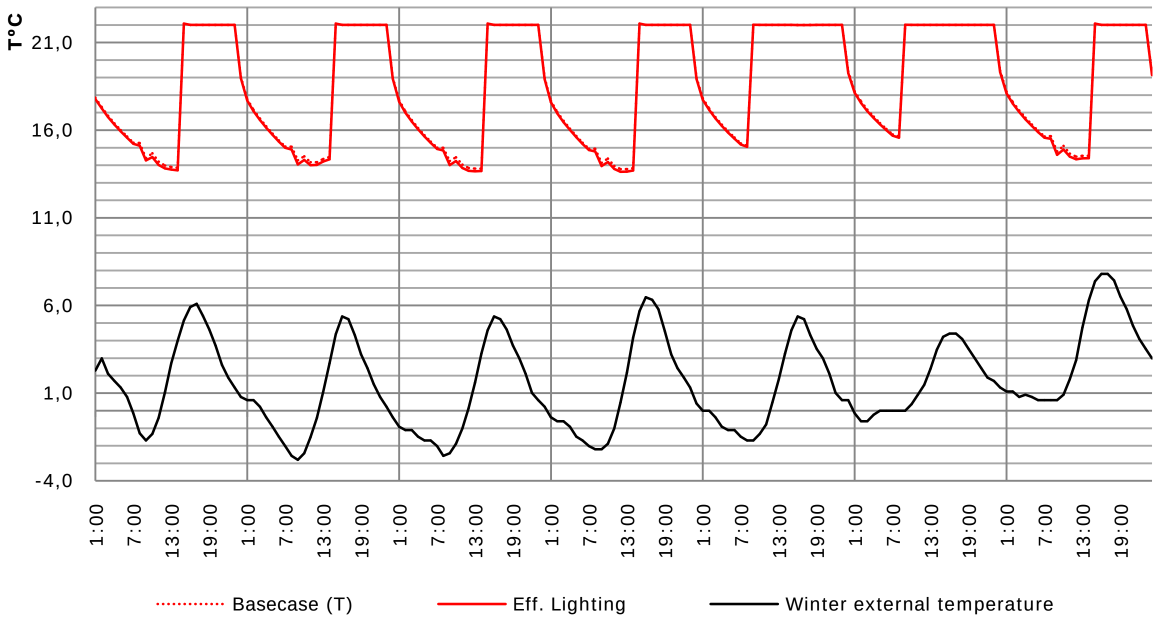
This section deals with thermal simulation results of case-study house with energy-efficient lighting system. Heat fluxes, internal temperatures and final energy consumption are presented and further discussed.

Graph 20 present heat fluxes in case-study house with energy-efficient lighting (EL) and in original condition during winter design week. It can be observed that internal heat gains are approximately 0.2 kWh lower in energy-efficient scenario than in base-case scenario during early morning and evening in weekdays and from 9 am to 11 pm during the weekend days. Also, there is a slight increase of 0.2 kWh in heating load during the whole heating time span. Besides, there are not important variations in remaining heat flows due to lighting system upgrade. Overall, it seems that internal heat gains drop due to lower lighting power density needs are compensated with higher heating power input to achieve same comfort temperature. The graph shows that energy efficient lighting accounts for higher heating consumption. However, in further energy demand analysis, overall electricity consumption saving is expected due to lower lighting load.

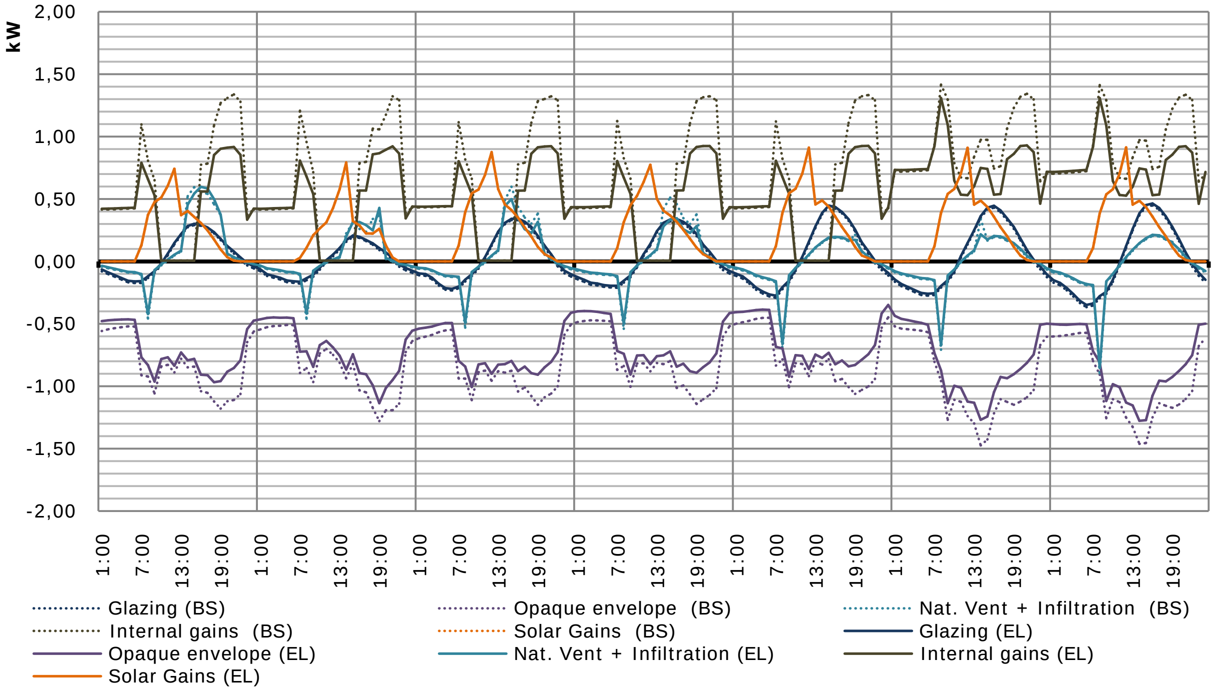


Graph 20 - Efficient lighting. Winter week. Heat gains and losses

Graph 21 shows internal temperatures in both case-study house with original lighting and energy-efficient lighting during winter design week. It can be seen that temperature variations between both scenarios are barely noticeable. However, internal temperature is 0.2ºC lower with energy-efficient lighting during early morning period, which it might be due to the lighting heat gain fall inside the building. Remaining period of the day internal temperature is same in both scenarios, since either lights are off or heating system is on.



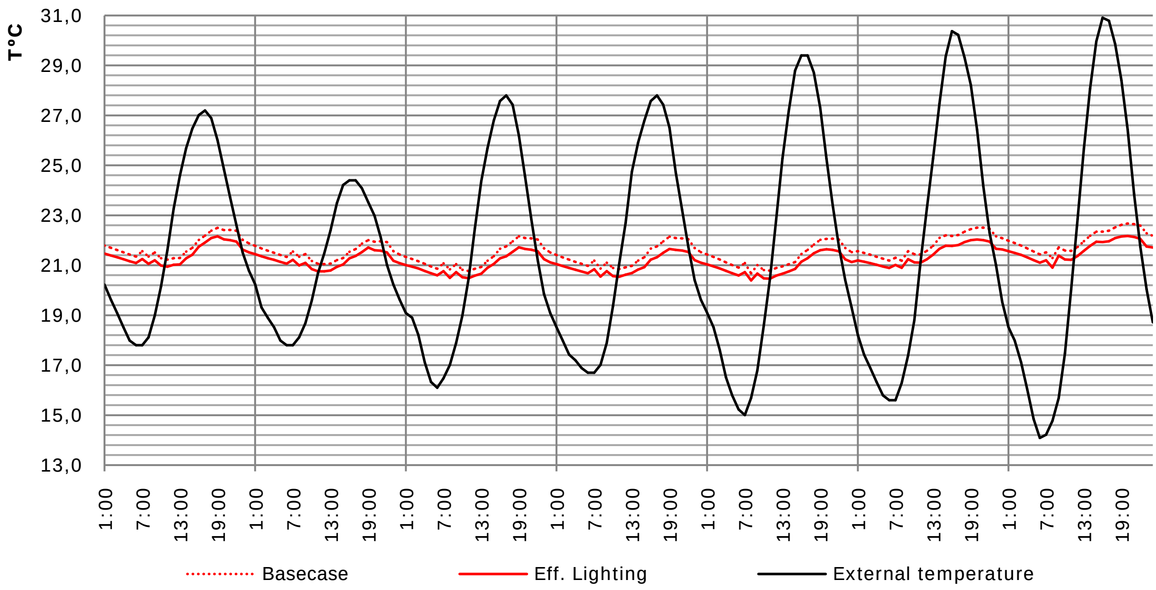
Graph 21 - Efficient lighting. Winter week. Internal temperatures



Graph 22–Energy-efficient lighting. Summer week. Heat gains and losses

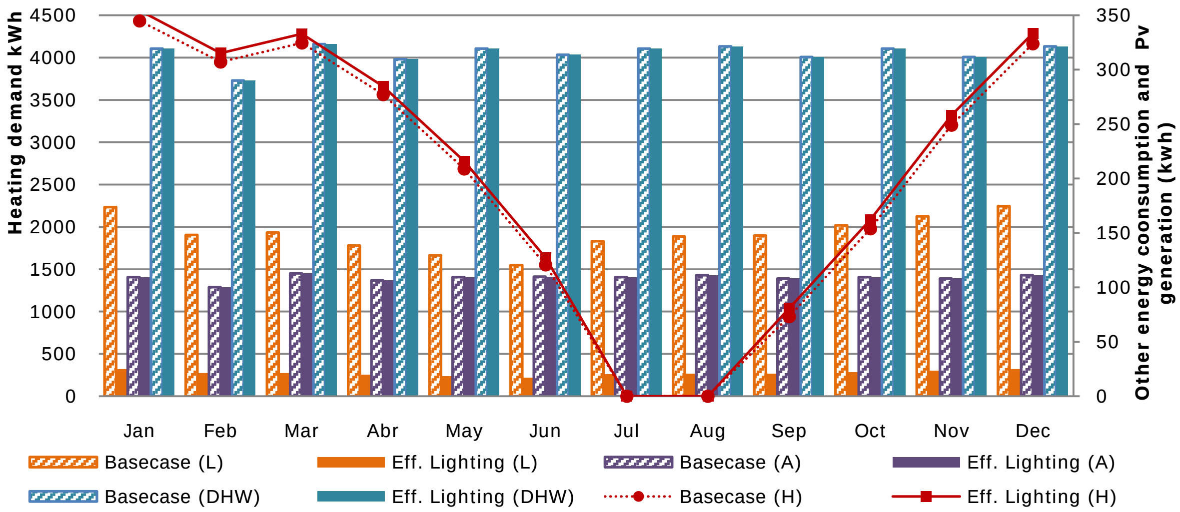
Graph 22 depicts heat gains and losses in case-study house with original lighting (BS) and with energy-efficient lighting (EL) in summer design week. Internal gains are 0.4 kW lower with improved lighting system during early morning and evening in weekdays and roughly throughout the whole daylight time during weekends. Obviously, variations in lighting heat gains only occur when lighting system is on. Also, envelope conduction heat flow is lower with energy-efficient lighting. Finally, it can be noticed slight ventilation heat flux reduction at isolated hours and when the heat flow is positive (towards inside the building), such as 0.2 kW heat flow reduction at mid-day hours on the fourth day. In conclusion, it seems that higher energy-efficient lighting accounts for lower lighting power density and hence, lower lighting heat emission. This fact leads to lower envelope heat flow to achieve thermal balance inside the house.

Graph 23 shows internal temperatures in case-study house with original lighting system and with energy-efficient lighting system over a summer week period. Internal temperatures with improved lighting system keep same fluctuation trend over the whole week period, yet they are approximately 0.2ºC lower than with original lighting system. This effect might be due to the lower lighting heat gains in the building. Interestingly, the temperature difference occurs continuously over the whole period, whereas lighting heat gains are only present during occupancy period. Temperature lag due to thermal mass might explain this effect.



Graph 23–Energy-efficient lighting. Summer week. Internal temperatures

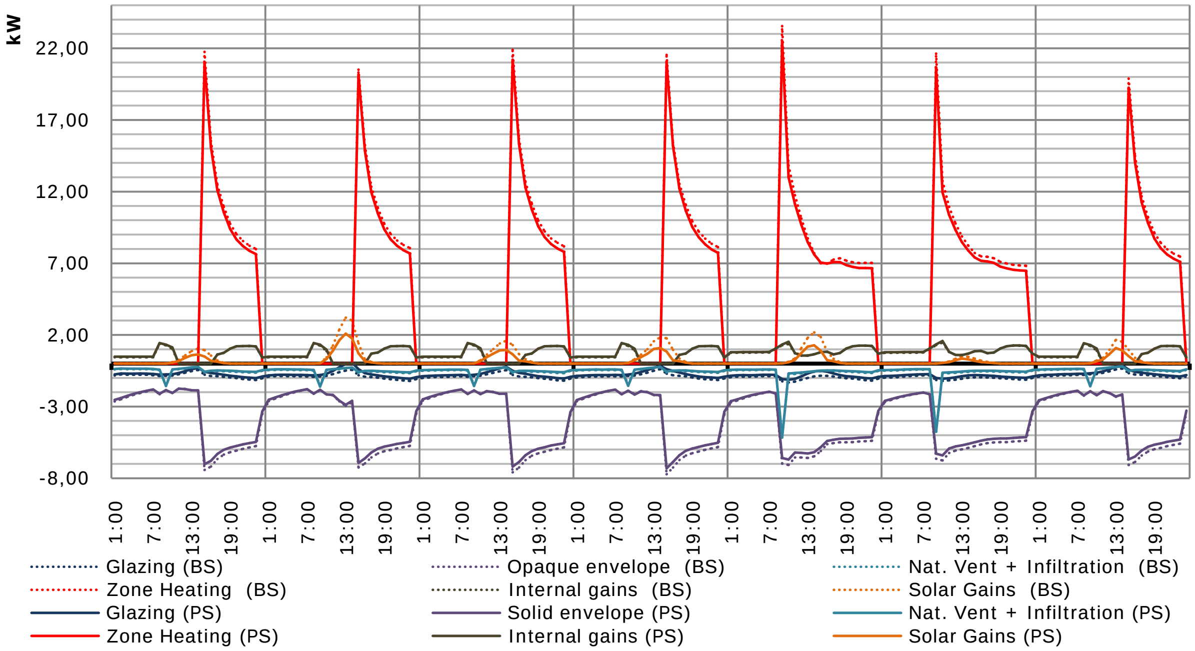
Graph 24 depicts monthly consumption of lighting (L), heating (H), appliances (A) and domestic hot water (DHW) in case-study house with energy-efficient lighting in comparison with as-built state. Improved lighting system accounts for around 100 kWh heating consumption increase in every month except July and August. Also, grid electricity consumption due to lighting needs decrease roughly the same amount in all months. No changes can be noticed in appliances electricity consumption and gas consumption for DHW and cooking. In general, we can state that lighting energy saving due to energy-efficient lighting system is neutralised by heating consumption rise due to lower lighting power density. In present conditions lighting retrofit strategy is definitely not worth the investment costs smaller they might be, since energy benefits are very limited. It might be possible that lighting system upgrade would be more efficient in better envelope insulating conditions where heating losses are lower.



Graph 24 - Energy-efficient lighting. Monthly energy consumption

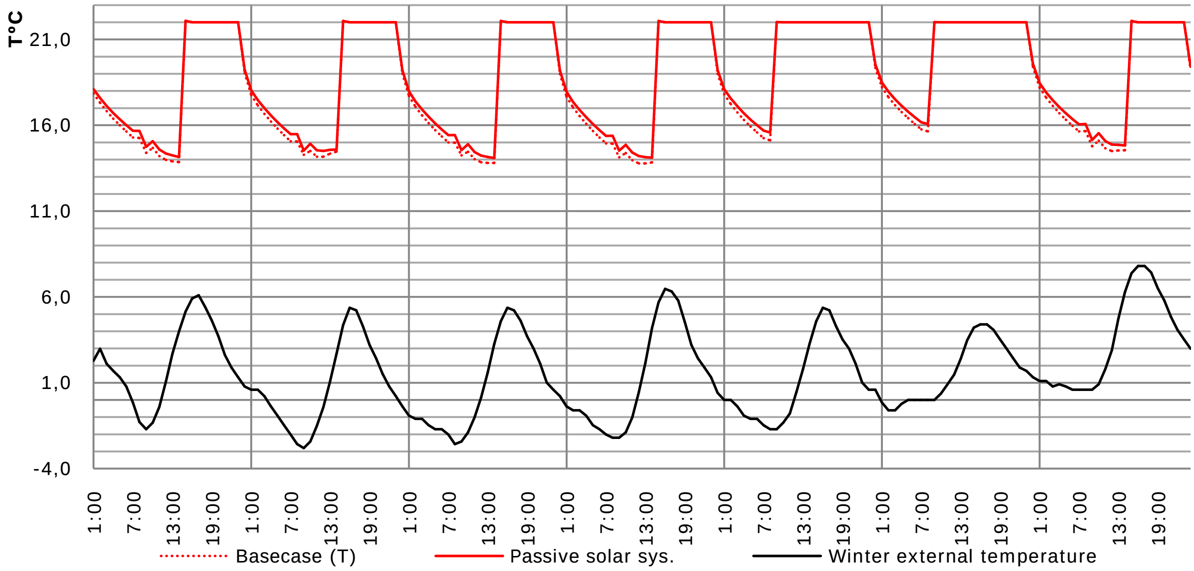
6.5. PV/Thermal Solar system

In this section, results of the solar system performance simulation are presented and discussed. Heat gains and losses, internal temperatures, monthly consumption and electricity production are analysed.



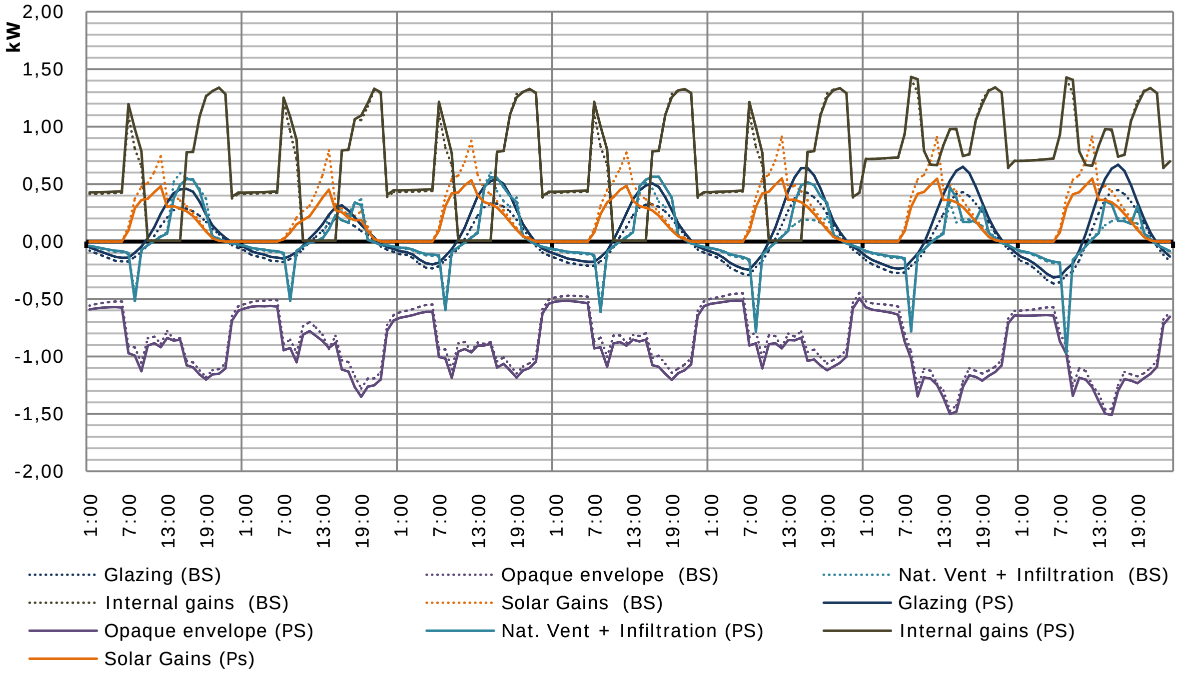
Graph 25 - PV/T system. Winter week. Heat gains and losses

Graph 25 shows heat gains and losses in case-study building with a photovoltaic-solar thermal buffer (PS) in comparison with its as-built state (BS) during a winter design week. Envelope conduction heat flux falls around 0.3 kW during heating system operating hours due to the impact of the solar buffer. Also, glazing conduction losses decrease slightly around 0.1 kW in the whole period, whilst infiltration heat losses drop approximately same value. In regard to positive heat fluxes, windows solar gains decrease from its original values to almost zero. Also, heating input drops slightly around 0.2 kW from original values and roughly 1 kW in peak heating hours. Probably, the most striking feature is the dramatic decrease of windows solar gains due to the solar buffer. The 10% transparent glass of the solar buffer might be preventing the sun radiation to heat the internal space of upper bedrooms. Although solar buffer is placed over only three windows, the building losses almost all solar gains, which might mean that the majority of the solar gains was due those upper floor south oriented windows. Interestingly, overall heating load in case-study house decreases with solar buffer, regardless the solar gains drop. This might be caused by the higher air temperature inside the buffer, which reduces negative heat flux. Also, solar buffer is reducing glazing conduction and infiltration losses in the upper part of south facade, which might also have some impact on the overall positive heat balance in the building.



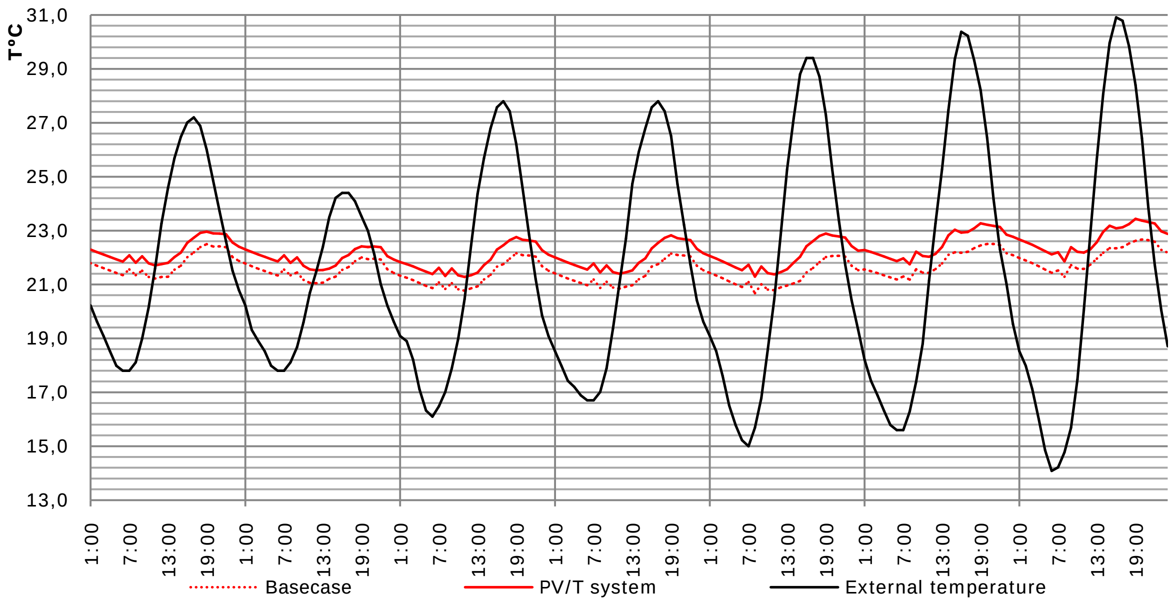
Graph 26 - PV/T system. Winter week. Internal temperatures

Graph 26 presents internal and external temperature curves of case-study building with thermal buffer and in its as-built state. Internal temperatures in the building remain in 22 degrees as long as the heating system is on. Then, both temperature curves drop sharply, yet house with buffer presents less steeply fall. Maximum internal temperature differences between both buildings scenarios is reached just before heating system operating hours with an average value of 0.2ºC. In conclusion, thermal buffer accounts for higher building internal temperatures.



Graph 27 - PV/T system. Summer week. Heat gains and losses

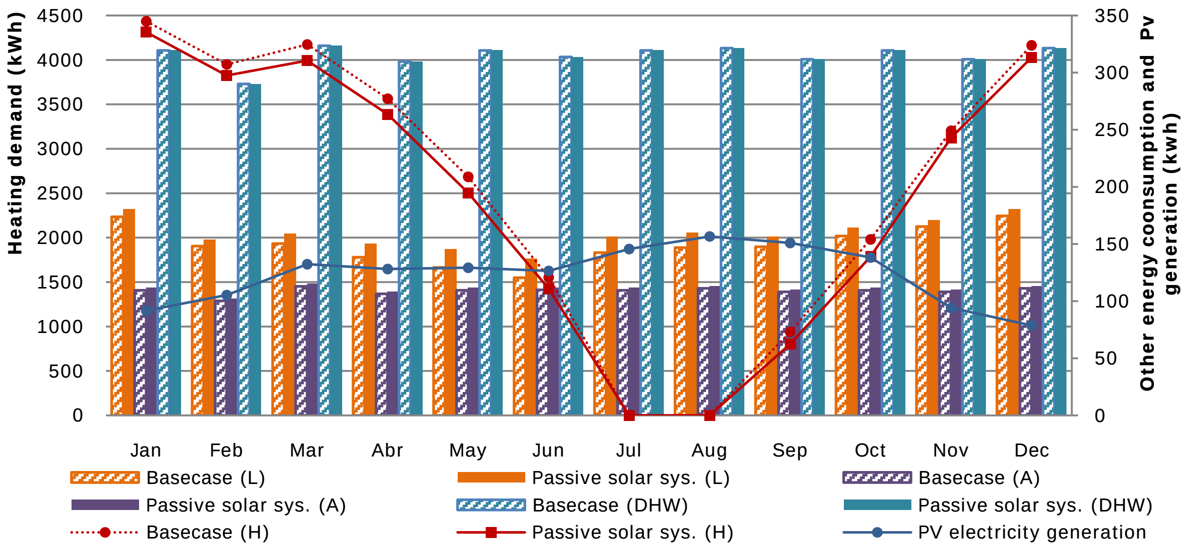
Graph 27 shows heat fluxes in case-study building with thermal buffer (PS) and in its as-built state (BS) during a summer design week. We can see significant window solar heat gains fall from roughly 0.8 kW at its peak value to just 0.1 kW in solar buffer case. Besides, envelope conduction heat losses are approximately 0.1 kW higher during the whole period. Glazing conduction heat flow is lower when negative and around 0.2 kW higher when it is positive during daylight period. Finally, infiltration and ventilation heat fluxes have same values than in base-case, yet they increase around 0.2 kW when these are positive. Overall, we can see that 10% transparency glazed thermal buffer is blocking solar radiation through upper south windows. However, perhaps higher internal temperature inside the buffer is raising heat flow towards the building. If this is correct, stack effect in solar buffer is not cooling down enough the buffer internal air.



Graph 28 - PV/T system. Summer week.Internal temperatures

Graph 28 depicts internal temperatures in case-study building with thermal buffer and in its original state. Internal temperature in house with thermal buffer fluctuates between 22ºC at 1 pm and 23ºC at 8 pm, whereas base-case internal temperature fluctuates between 21ºC and 22ºCat same peak and valley hours. It can be seen that temperature curve profile in both cases follows same trend, yet internal temperature in upgraded case is 1ºC average higher. It seems that thermal buffer has no significant impact on building thermal mass, since maximum and minimum temperature time-lag is the same in both cases (2h) in regard to external temperature.

Finally, Graph 29 presents monthly total heating (H), appliances (A), lighting (L)and domestic hot water consumption (DHW),and also electricity generation in case-study house with photovoltaic solar thermal system in comparison with base-case energy consumption. It can be seen that heating consumption in house with PV/thermal system decreases roughly 200 kWh in every month except June, September and November in comparison with base-case scenario. Lighting consumption in improved case is approximately 10 kWh higher than in base-case, yet this figure grows to almost 30 kWh in May and June. Also, electricity consumption due to appliances is slightly higher in improved house case than in base-case, whereas there are not changes in DHW consumption between both cases. In regard to PV generation, we can see that PV/solar thermal system is producing approximately 150 kWh from July to September, 130 kWh from March to June and finally, just below 100 kWh form November to February. Overall, we can state that PV/solar thermal system reduce 5% heating consumption in coldest months and slightly lower in milder months. It also increases 6% average lighting consumption since the translucent glass used in the sunspace is blocking visible light into the rooms. Finally, PV/thermal system performs better in hottest months than cold months. It seems that PV glass efficiency enhancement due to lower temperatures does not make up for low solar irradiance levels in winter.

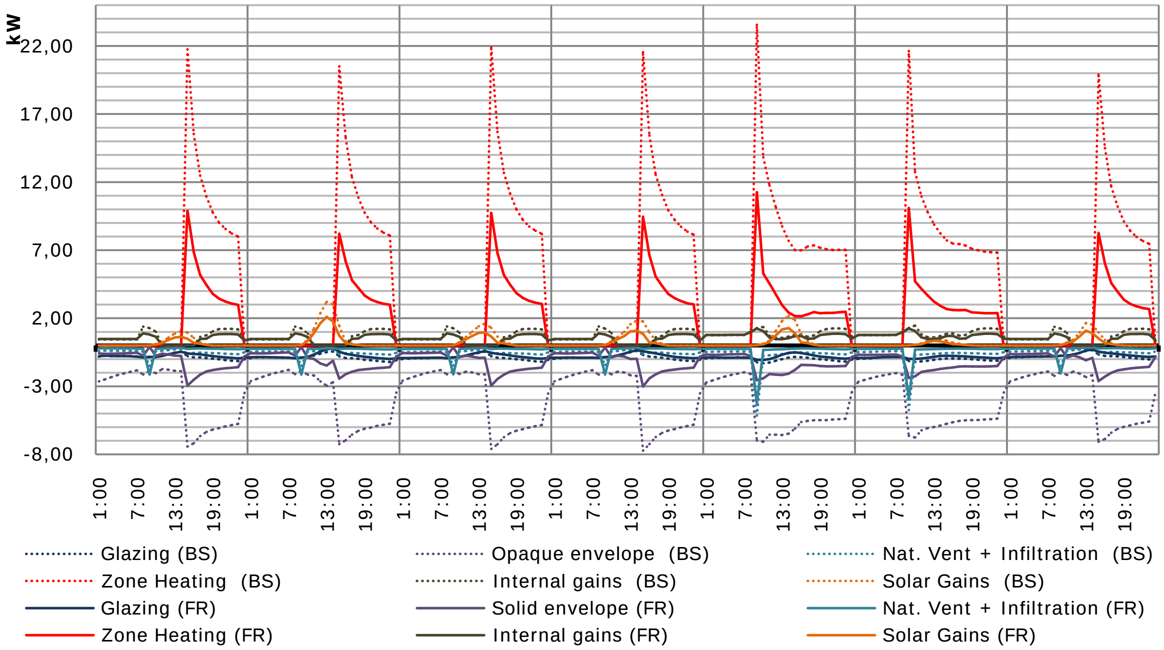


Graph 29 - PV/T system. Monthly energy consumption

6.6. Full retrofit scenario

Eventually, retrofit measures analysed previously were simultaneously implemented in case-study model, in order to make a performance assessment of their impact on building thermal behaviour. Similarly to previous sections, results of heat flows, internal temperatures, monthly consumption and electricity production are presented and discussed in this section.

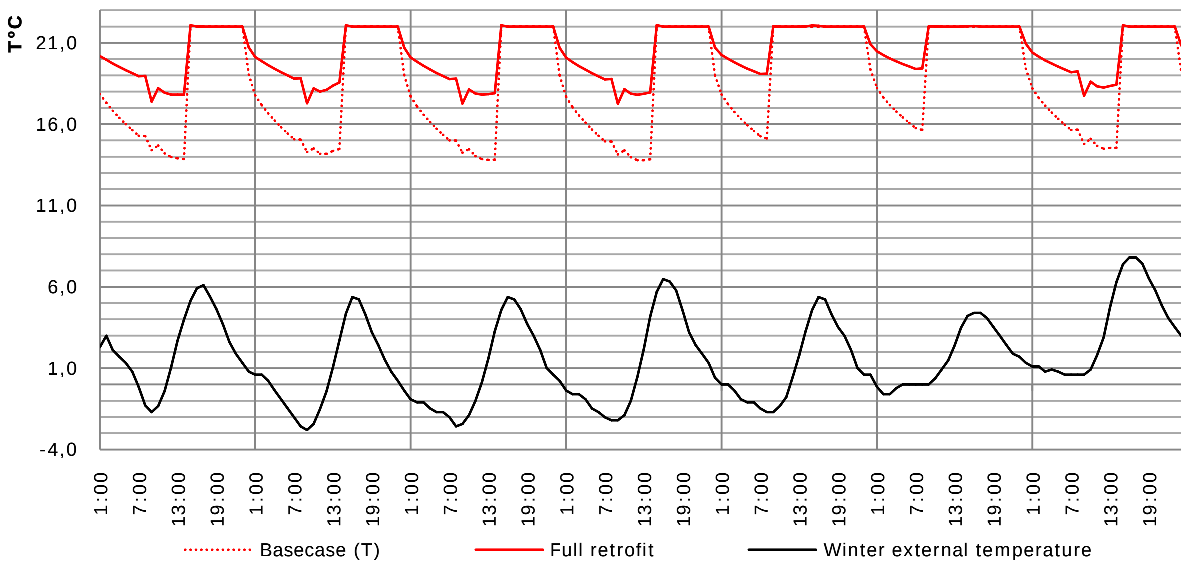
Graph 30 shows heat gains and losses in fully retrofitted case-study house (FR) in comparison with same house in its as-built state (BS) during a winter design week. At first glance, it can be seen a significant drop in heat fluxes and input. Heat flow rate through the envelope decreases just over 4 kW during heating period, whilst it drops 1 kW during remaining hours. Ventilation heat flow rate decreases approximately 0.5 kW over the whole period, whereas glazing losses fall same figure yet only during heating system operating hours. In regard to heat gains, we can see that solar heat input rate in retrofitted house scenario reduces proportionally to its load with a maximum drop of 1 kW at its peak value. Internal load also decreases around 0.2 kW during its peak values, yet it increases same amount during its lower values. Finally, peak heating load at 2 pm drops from roughly 22 kW to 10 kW on weekdays, whilst it goes down from 23 kW to 11 kW at 9 am on Saturday and Sunday. Accordingly, heating input drops 5 kW average rest of heating system operating hours. In conclusion, retrofit measures applied account for around 60% reduction of envelope conduction losses. Moreover, ventilation and infiltration, and glazing heat losses are reduced in minor proportion. Despite the lighting and other internal heat gains fall, overall heat balance brings 50% heat peak input reduction and around 65% mean heating rate reduction in cold conditions.



Graph 30 – Full retrofit. Winter week.Heat gains and losses

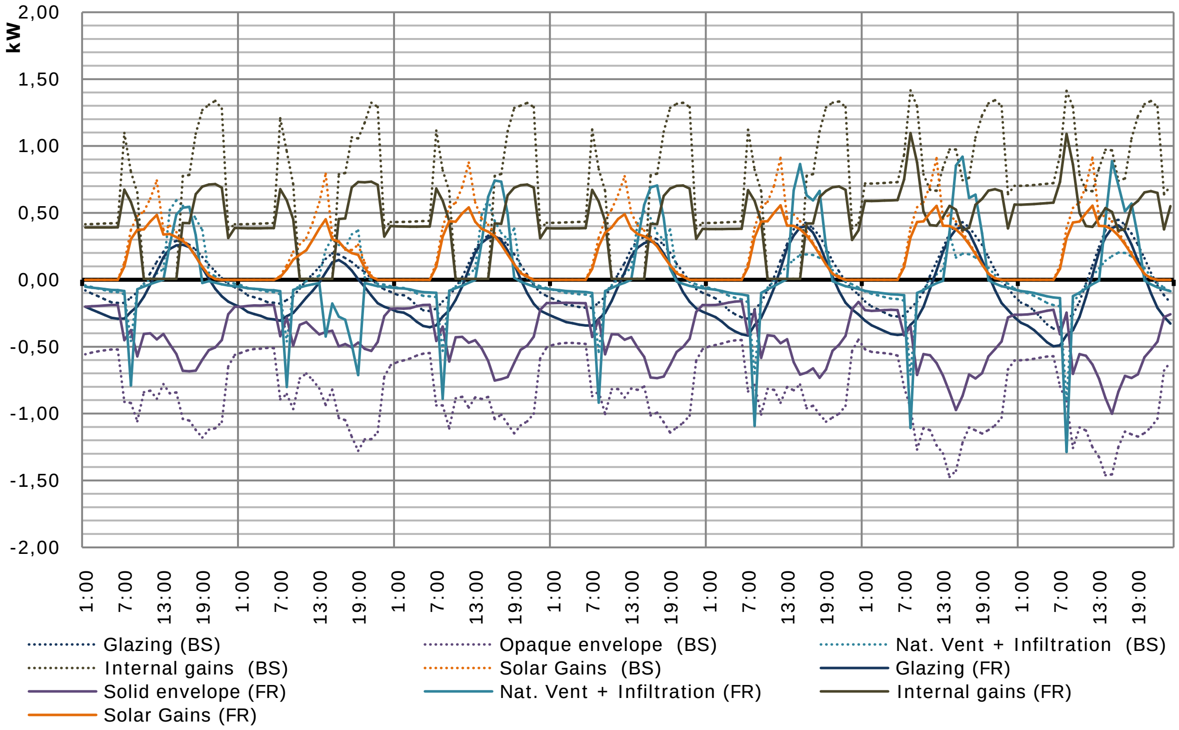
Graph 31 shows internal temperature curve profiles for fully retrofitted house and base-case over a winter design week period. Internal temperature in both scenarios is 22 degrees as long as heating system is operating. Then, temperature curve in fully retrofitted case falls steadily until 18ºC at 10 am in week days, whereas base-case temperature curve drops more sharply during the night until 14ºC at same hours.

Also, temperature in both cases drops steeply at 8 am due to morning ventilation, yet it falls almost 2 degrees in improved house case, whilst it decreases only 0.5 degrees in base-case. During weekend days, temperature curves follow same trend, although heating operating time is larger and they drop only until 19ºC in improved house case and 15ºC in base-case. Overall, we can see that retrofit measures buffer night temperature drop inside the building and hence, improves comfort conditions. Furthermore, heating system has to deal with lower temperature gap when rising temperature to comfort levels at the beginning of the heating period, which might be the cause of lower peak heating demand.



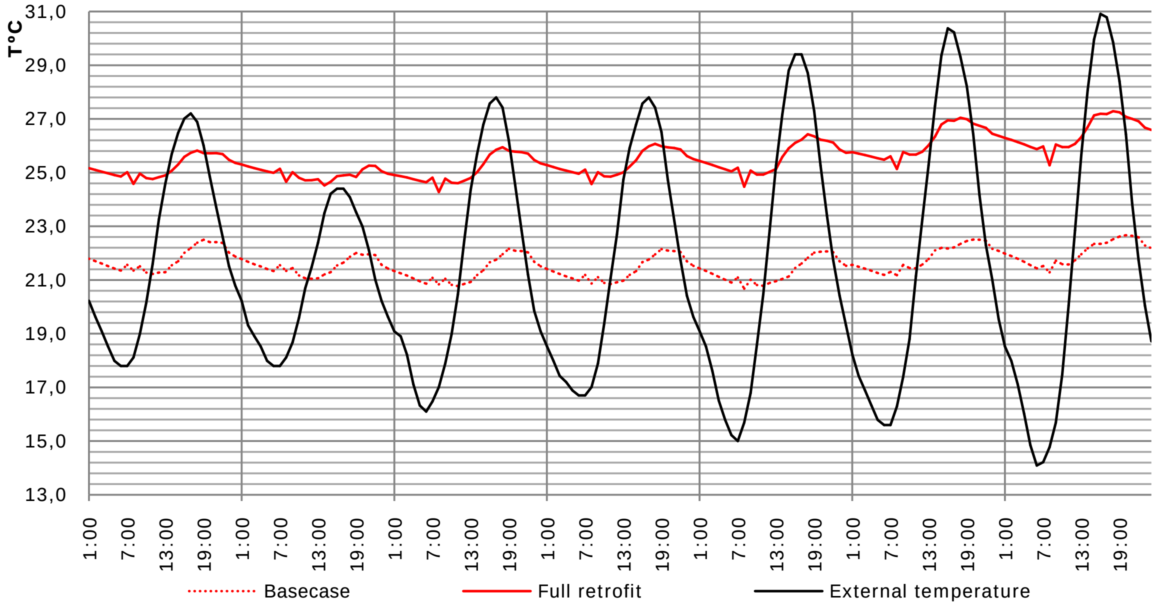
Graph 31 - Full retrofit. Winter week. Internal temperatures

Graph 32 shows heat fluxes in case-study house in a fully retrofitted scenario (FR) and in as-built scenario (BS) during summer design week. We can see a significant envelope heat flow reduction of 0.4 kW along the whole period in comparison with base-case. Ventilation and infiltration heat flow increases around 0.4 kW when it is positive and keep same values than base-case when the flow is negative. In contrast, glazing conduction heat flow increases around 0.1 kW with retrofit measures when it is negative and remains roughly in same values when it is positive. Solar gains decreases in refurbished house case around 0.2 kW at peak values, whereas internal gains drop around 0.6 kW during evenings and 0.3 kW in early mornings. On top of that, internal gains decrease also during weekend day afternoons. Overall, we can state that building become tighter to heat losses and diminish uncontrolled heat gains with these retrofit measures. As seen on previous analysis, solar gains drop might be due to lower solar transmittance of double glazed windows and to the solar thermal buffer.



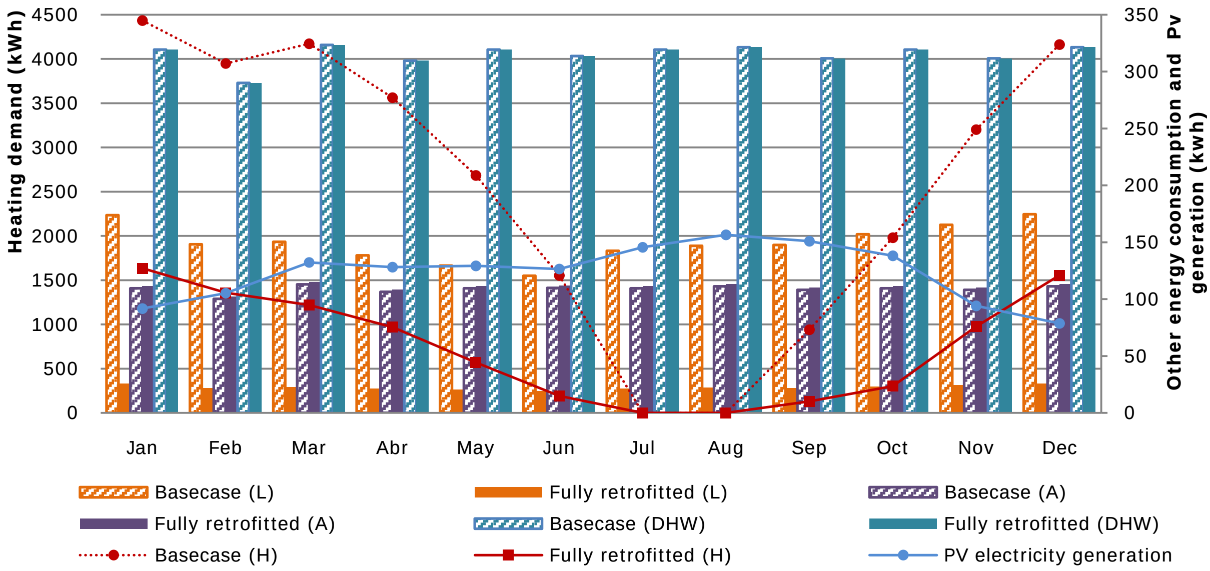
Graph 32 - Full retrofit. Summer week. Heat gains and losses

Graph 33 depicts internal temperatures in fully retrofitted case-study house and in its original state during a summer design week. It can be seen that internal temperatures in retrofitted case fluctuates between 24.5ºC and just over 27ºC during the whole week period, whilst internal temperature in original building case varies between 21ºC and 22.5ºC; that is to say a temperature variation of 2.5 degrees in former curve and 1.5 degrees in second curve. Interestingly, these curve's profiles show that temperature values in improved house are over comfort conditions limits most of the time. Actually, temperature in retrofitted case is higher than external temperatures over the whole second day. We can conclude that retrofit measures worsens building thermal performance in hot conditions, since it seems that the building losses its original thermal balance generated by earth walls' thermal mass.



Graph 33 - Full retrofit. Summer week. Internal temperatures

Graph 34 shows monthly total energy consumption in case-study house in fully retrofitted state and in its as-built state. Heating demand in refurbished state represents roughly 40% of the base-case heating consumption from December to March. Then, this proportion decreases as it approaches to summer months, i.e. heating consumption in retrofitted house decreases 90% in comparison with base-case. Lighting electricity consumption drops from 170 kWh to approximately 25 kWh from November to January, whereas it does so from 150 kWh to 25 kWh in rest of months, except in May and June when pre-retrofit lighting consumption is 120 kWh. Finally, electric appliances in refurbished house consumes slightly more than in base-case, while gas consumption due to DHW production is the same in both cases. In regards to PV electricity generation, PV/solar thermal system produce approximately 150 kWh per month from July to September, around 130 kW from March to April and less than 100 kWh in winter months. In conclusion, as shown in the graph, present holistic retrofit strategy mainly addresses heating consumption, since it represents the largest proportion of energy usage by far. In addition, it accounts for significant lighting consumption saving and electricity generation. In contrast, present retrofit measures do not have any impact either on gas consumption or appliances electricity consumption.

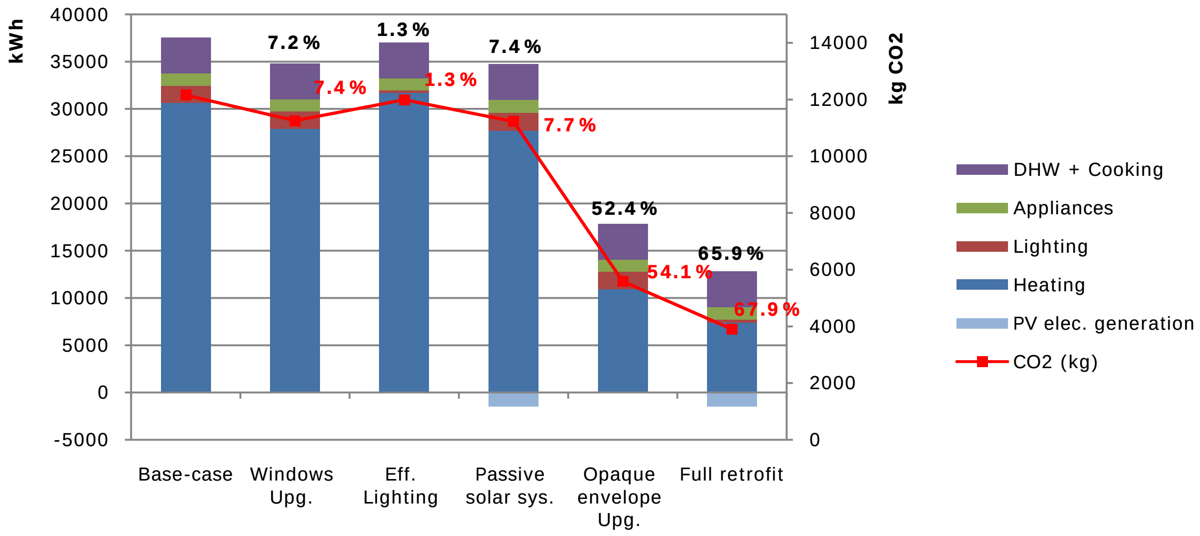


Graph 34 - Full retrofit. Monthly energy consumption

6.7. Annual total consumption and CO2 emissions

In this section, a comparison amongst every retrofit case and base-case in regard to total yearly consumption and CO_2 emissions is presented and discussed.

Graph 35 presents total fuel consumption breakdown and CO_2 emissions in case-study house in its as-built state and in each retrofit scenario previously analysed. It can be seen that heating electricity represents by far the largest fraction of total annual consumption in every case. Windows upgrade accounts for a total heating saving of 2000 kWh per year, yet it increases slightly lighting consumption. Upgrading original lighting to an energy-efficient lighting leads to an additional 1000 kWh heating consumption. However, lighting electricity consumption goes down from roughly 1800 kWh to 250 kWh per year in comparison to base-case. The PV/solar thermal buffer accounts for approximately 1500 kWh less heating consumption than base-case, plus it generates another extra 1500 kWh yearly. However, lighting consumption increases around 100 kWh a year on account of the PV/T system. Upgrading opaque envelope to current thermal transmittance standards leads to around 20,000 kWh heating consumption saving per year, whereas rest of fuel consumption remains in same values than base-case. Finally, applying all these measures simultaneously brings heating electricity consumption reduction of almost 22,000 kWh over a whole year and roughly 1500 kWh of lighting demand reduction. Besides, the PV/T system generates an additional 1500 kWh of electricity. Overall, we can see that the least energy-efficient measure is improving lighting system, which lead only to 1.3% total fuel saving and 1.3% CO2 emissions reduction. Then, upgrading windows and PV/T solar buffer bring 7.2% and 7.4% of total fuel saving and 7.4% and 7.7% CO2 emissions reduction respectively including PV electricity generation. Upgrading solid envelope seems to be the most energy-efficient measure by far with 52.4% of total energy saving and 54.1% of CO2 emissions reduction. Finally, overall fuel consumption in full retrofit scenario decreases 65.9% considering PV electricity on-site generation and CO2 emissions decreases 67.9% in comparison with base-case scenario.



Graph 35 - Total annual energy consumption and CO_2 emissions in five different retrofit scenarios

7. Conclusions

This chapter presents the conclusions drawn from the analysis of thermal simulation results of case-study house and different retrofit scenarios.

Analysis of thermal simulation of Gotarrendura case-study house show that it achieves adequate internal comfort conditions without active cooling and performs satisfactorily in summer conditions, whereas it demands a significant amount of heating to reach comfort levels in winter conditions. Results suggest that opaque building envelope has high thermal transmittance values, which leads to excessive heat losses in comparison with other contemporary houses in same climate. Specifically, ground slab is particularly leaky to heat flows, since it is single layered and poorly insulated. Interestingly, results shows that air infiltration heat flow is much lower than expected according to first on-site observations. This is probably due to the building location in an urban area amongst buildings, which provides a sheltered position from wind pressures. In addition, little solar gains and low glazing conduction heat flow shown by thermal simulations agree with expected values, since the building presents little fenestration areas in comparison with opaque areas. As suggested by other authors, high thermal storage capacity of earth walls might explain internal temperature curves profiles, which show time lag in temperature fluctuation in comparison with external temperature. Thus, it seems that adobe walls stores heat during heating hours, which is later released during the night preventing a dramatic temperature drop. In hot conditions, earth walls takes advantage of large daily temperature fluctuation by absorbing mid-day heat and releasing it during the night, creating a thermal buffer effect and hence constant temperatures of 21ºC. Accordingly, an effective retrofit strategy might be mainly oriented towards the reduction of envelope conduction heat flow, increase passive solar gains and boost the benefits of earth walls thermal mass. In contrast, fenestration retrofit might have limited impact on final energy consumption.

Opaque envelope upgrade

Opaque envelope enhancement seems to be the most energy-efficient measure in winter conditions, yet it worsens house thermal performance in summer conditions. As expected, results showed that conduction heat flow through envelope elements drop dramatically and hence the heating demand. Also, it seems that external insulation on earth walls improved comfort conditions in winter during non-heating hours. Probably, it prevents building earth walls to release heat stored towards the exterior during the night and therefore, temperature fall after heating hours is less steep in comparison with base-case. However, same effect seems to raise average internal temperatures in summer and hence, worsens building thermal performance. Perhaps, this issue might be solved by night natural ventilation. In conclusion, upgrading envelope thermal transmittance to current standard values might account for 52.4% energy saving and 54.1% CO_2 emission reduction.

Fenestration upgrade

Thermal simulation results proved that fenestration retrofit measures have limited impact on building energy consumption due probably to the little proportion of fenestration areas to opaque wall areas. Upgraded windows accounts for 9% of heating reduction over a year period, which is far less than estimated figures in other similar studies (Grynning, et al., 2013). However, lower solar transmittance values leads to higher lighting consumption, accordingly final energy saving achieved is 7.2% and 7.4% of CO_2 emissions reduction per year. In regard to internal conditions, fenestration retrofit causes slight improvement on internal comfort condition and house thermal performance in winter. In contrast, it does not modify substantially internal temperatures in summer months.

Energy efficient lighting

Energy-efficient lighting has a significant reduction effect on lighting consumption, although overall impact of this measure is limited due to the small fraction of lighting demand in its energy consumption share. Energy-efficient lighting reduces dramatically lighting consumption (85%) in every month. However, it might also cause an increase of heating consumption during cold months, since the majority of installed lighting energy was transformed into heat. Therefore, energy efficient lighting worsens slightly comfort conditions in winter, although benefits of a better lighting distribution and higher lighting quality might lead to a better user-comfort perception (Aman et al, 2013). Overall impact of lighting system retrofit seems to be positive, since house total energy consumption and CO_2 emissions decreases 1.3% in comparison with base-case.

PV/Thermal system

PV/solar thermal system seems to have a complex interaction with house heat flows. In winter condition, buffer air vents are close so solar radiation might raise internal air temperature. As consequence, temperature differential between building and buffer internal space drops and hence, wall conduction heat flow decreases where the thermal buffer is installed. Simultaneously, solar buffer accounts for a significant amount of solar heat gains fall through upper south windows plus an increase of lighting consumption. It seems that the 10% transparent glass of sunspace might be blocking a fraction of incoming sunlight. Besides, increase of internal temperatures in winter shows that passive solar system improves slightly comfort levels. In summer conditions, sunspace air vents are open, so stack effect may increase ventilation rate. However, internal temperature raises around 2ºC, which might mean that internal space ventilation rate is inadequate. Therefore, results suggest that either the solar system is inappropriate for this case-study house conditions or analysis method used is inaccurate in the assessment of this system. Finally, results showed that PV glass performs better in summer months. It seems that, higher solar radiation in from June to August overcomes PV cell efficiency drop due to cell temperature rise. In any case, PV system might require further analysis with different analysis method to get an accurate performance assessment.

All in all, we can state that PV/thermal system performs satisfactorily and enhances comfort conditions in winter, whereas it increases house internal temperature, yet not surpassing comfort limits. Analysis of simulation results proves that the PV/solar thermal buffer has an overall positive impact on energy consumption with a 7.4% yearly net energy saving, which entails 7.7% CO_2 emissions fall.

Full retrofit scenario

Finally, analysis of thermal simulation results showed that proposed holistic energy-efficient retrofit strategy reduces considerably energy consumption in current house configuration. Namely, present holistic strategy might account for 65.9% net energy consumption reduction and 67.9% of associated CO_2 emissions reduction. Nevertheless, present retrofit strategy worsens significantly comfort conditions in summer period as well, which might lead to the opposite desired effect. i.e. excessive high internal temperatures entails cooling energy consumption. Results suggested that thermal insulation might be interacting with building thermal mass, and hence altering house original thermal balance. Potentially, summer overheating issues might be addressed with night ventilation strategies to cool down walls mass during the night-time.

Besides, it can be concluded that the impact of a holistic energy-efficient retrofit strategy which involves simultaneous different measures is not equal to the sum of their effects measured individually.

HERB project

Thermal simulation results show that the holistic energy-efficient retrofit strategy proposed in the present work fulfils partially stipulated HERB project goal figures. Thus, HERB project guidelines estimate that a properly designed holistic retrofit strategy may account for end-use energy saving of 80%, whilst energy saving due to present retrofit strategy achieves only 65.9%. Also, global energy consumption (excluding appliances) of 50 $kWh/m^2/year$ is required, whereas only 67 $kWh/m^2/year$

is achieved with proposed retrofit measures. However, HERB guidelines state also that energy saving bring a minimum of 60% coupled CO_2 emissions reduction, which is clearly achieved by retrofit measures proposed (67.9%). In addition, at least 80% of energy saving for lighting over the installed base is estimated, whilst proposed retrofit measures achieve 85% of lighting energy saving. It can be concluded that further energy-saving measures should be added to present holistic retrofit strategy in order to reach HERB goal figures, yet they are not far.

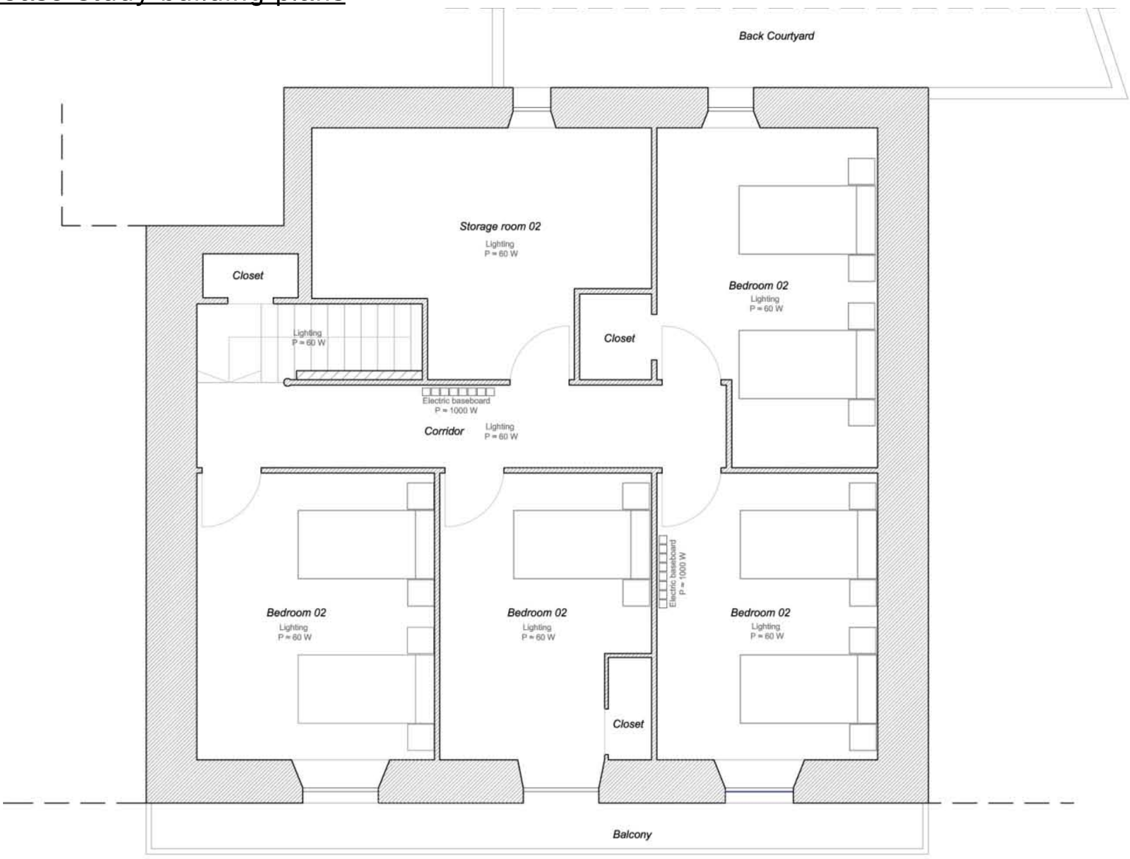
8. Recommendations for further studies

Present holistic retrofit strategy comprises a number of individual measures based on HERB project requirements and literature review conclusions. Nevertheless, other retrofit measures might be as much effective as those analysed in present study. Namely, the author observed an existing high inefficient heating system which present study strived to simulate, yet none of retrofit measures proposed addressed this issue. According to end-use fuel breakdown analysis, it seems that DHW gas consumption has a great saving potential, since a solar thermal collector might performs satisfactorily on this climate. Therefore, the author believes that significant energy saving might be achieved with both heating and domestic hot water production system refurbishment.

This study has proved that computer aided dynamic thermal analysis is an adequate method to assess residential buildings thermal behaviour and further retrofit measures. However, complementary studies with other methods might be advisable in certain cases to get accurate performance outcomes. Particularly, hybrid PV thermal solar system develops complex interactions between air thermal system and photovoltaic system, which might require fluid dynamics analysis for a comprehensive study.

9. Appendix

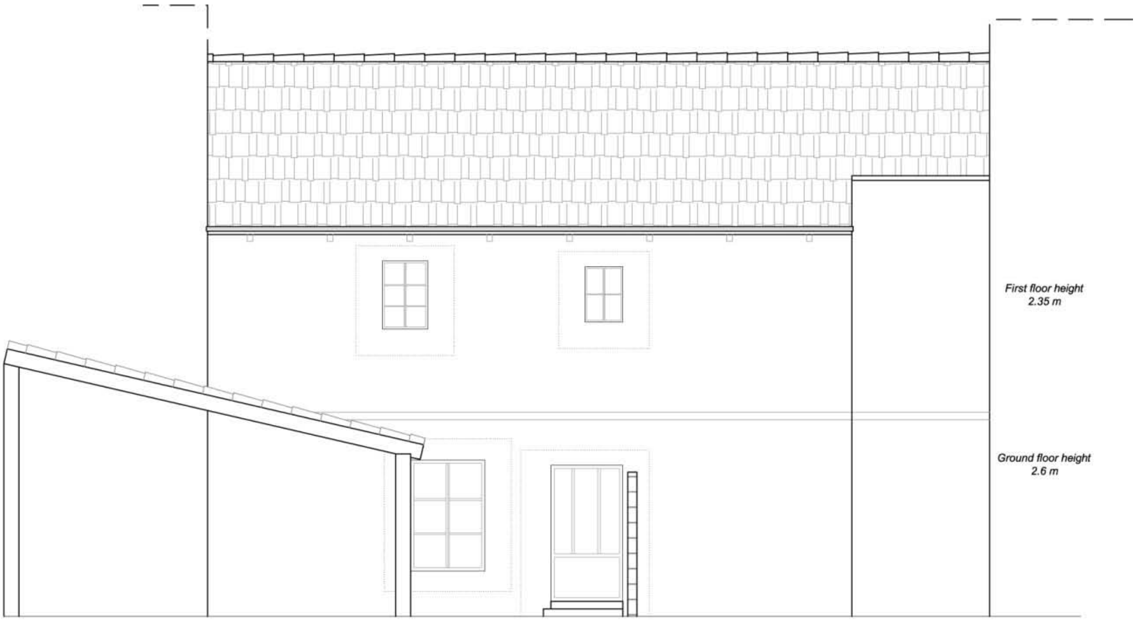
Case-study building plans



First floor plan. Scale 1/100

Ground Floor plan. Scale 1/100

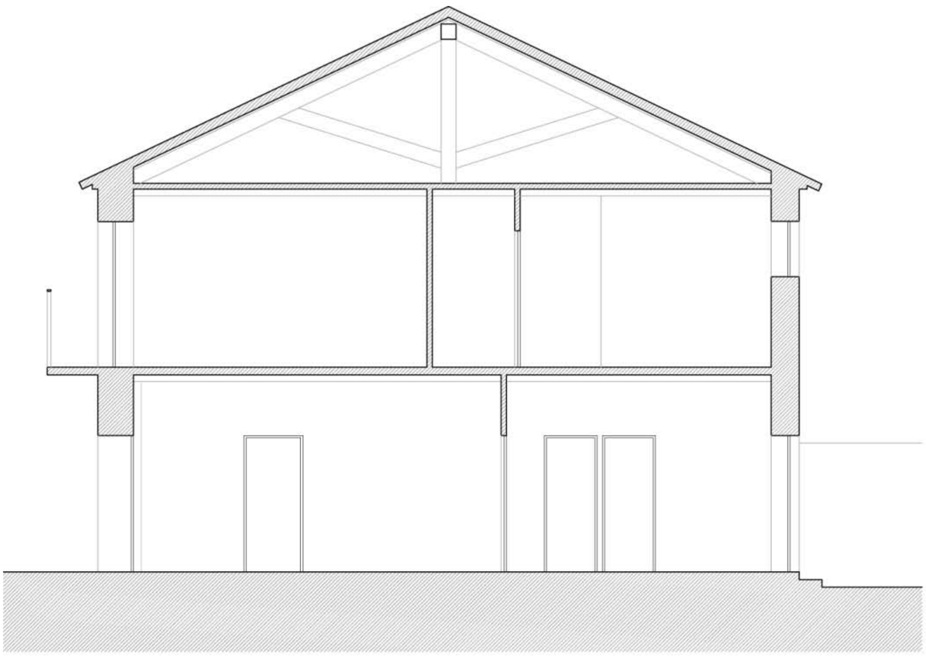
Case-study building elevations



North façade. Scale 1/100

South façade. Scale 1/100

Case-study cross section



Cross section. Scale 1/100

Building photographic report

South façade

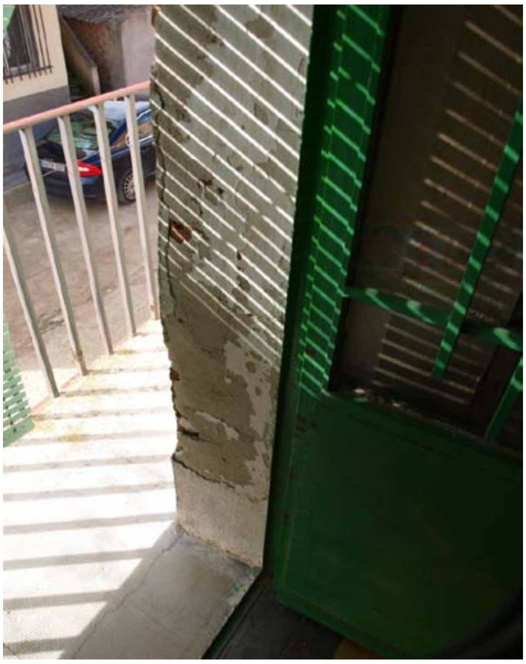
North façade

Kitchen - DHW boiler

Bathroom

Main entrance door

Balcony access door



Adobe wall close-up 1

Adobe wall close-up 2

Loft space

Loft space

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