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Universidad del País Vasco Euskal Herriko Unibertsitatea

PhD Thesis

Adaptation of single-family houses to the nZEB objective in cool-temperate climates of Spain

Optimisation of the energy demand and the thermal comfort by full-scale measurements and simulation assessments, with an insight into the global warming scenarios.

Doctoral dissertation of:
Juan María HIDALGO BETANZOS

Supervisor:
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2017

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Optimización de la demanda energética y el confort térmico mediante mediciones a escala de edificio y análisis de simulaciones energéticas, con una visión hacia el cambio climático.

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UPV/EHU, School of Engineering of Gipuzkoa, Donostia-San Sebastián

July 2017

GIPUZKOAKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE GIPUZKOA

Makina eta Motor Termikoak Saila
Departamento de Máquinas y Motores Térmicos

PhD in Thermal Engineering

Doctorado en Ingeniería Térmica

Escuela de Ingeniería de Gipuzkoa / Gipuzkoako Ingeniaritza Eskola
Universidad del País Vasco/Euskal Herriko Unibertsitatea
Curso 2016-2017
Donostia-San Sebastián, Gipuzkoa

This PhD Thesis was supported by the Basque Government,
through the Department of Education, Language Policy and Culture's
Predoctoral Scholarship Program for Research Training (BFI-2012-311 A)

Agradecimientos

"*Si he logrado ver más lejos, ha sido porque he subido a hombros de gigantes*", es la conocida frase que utilizó Isaac Newton para resaltar la importancia de sus colegas predecesores. Durante el desarrollo de esta tesis, he tenido la gran suerte de contar con verdaderos gigantes a mi lado. Me gustaría agradecer a todos aquellos que han trabajado conmigo y me han ayudado a superar los retos de esta tesis.

En primer lugar, agradecer a mi director José Antonio Millán García, por haber confiado en mi trabajo desde el principio y hacer posible esta aventura. Hemos crecido juntos y espero que sigamos muchos años trabajando y aprendiendo juntos.

Deseo reconocer que he sido muy afortunado al contar con el apoyo y los sabios consejos de José María Pedro Sala Lizarraga. Su capacidad de trabajo y calidad humana han sido un gran referente.

Sin duda, este trabajo no hubiera sido posible sin las ideas, trabajo e ilusión de todos mis compañeros del Área Térmica. Especialmente de Carlos, César, Dani, Eider, Imanol e Iván. Nunca olvidaré los intensos días de calibración de sensores, el montaje de la monitorización, los análisis de datos, los modelos matemáticos y las discusiones apasionadas sobre transmisión de calor.

Estaré siempre agradecido a Adelina y su familia, por abrir las puertas de su casa y convivir pacientemente con la monitorización de su hogar durante un año.

Quiero dar las gracias a todos mis colegas del grupo de investigación ENEDI y del Departamento de Máquinas y Motores Térmicos por su ayuda y disposición en todos estos años, especialmente a Ana, Álex, Alvaro, Esti, Iker, Isa, Jon, Koldo y Moises.

Estoy muy agradecido al Laboratorio de Control de Calidad en la Edificación del Gobierno Vasco (LCCE-GV), especialmente a Agustín, Elvira y Alberto por facilitar el uso de las instalaciones e instrumentación para los trabajos de la tesis.

Este trabajo fue posible gracias a la financiación del Gobierno Vasco. Estaré siempre agradecido al programa de becas predoctorales y confío en devolver a la sociedad esta inversión con mi trabajo futuro.

También deseo reconocer la gran importancia de mi estancia internacional en la Aalborg Universitet (Dinamarca) y estoy muy agradecido por la supervisión de Per Heiselberg. Además, quiero recordar todo lo que aprendí de grandes profesionales como Rasmus, Hicham, Jérôme, Fanis y Francesco.

Deseo dar las gracias por la ayuda de Germán Campos de Ecoeficiente y de Mathew Larson de Big Ladder Software durante la definición de los modelos de simulaciones energéticas con Design Builder®.

Por último, quiero agradecer de corazón a mi familia todo su cariño, ayuda y comprensión. A mis aitas Joaquín y Garbiñe, por su ejemplo de superación y trabajo duro. A mi hermano Jokin, por mostrarme el valor de la tenacidad y valentía en proyectos de investigación. Os quiero. Finalmente agradecer especialmente a Greta, mi mujer, por estar a mi lado durante la escritura de la tesis, ser mi gran apoyo y dar inicio a uno de los periodos más bonitos de mi vida. Ella es, sin ninguna duda, lo mejor de todos estos años de tesis doctoral. Aš tave labai myliu!

Probablemente me haya olvidado de otras tantas personas y profesionales que han aportado en una u otra manera a la realización de la tesis. A todos ellos, espero que me puedan disculpar y decirles que siempre tendrán todo mi agradecimiento.

En Donostia-San Sebastián, mayo de 2017.

Juan María Hidalgo Betanzos

Acknowledgments

"If I have seen further it is by standing on the shoulders of Giants". This famous quote was used by Isaac Newton to reinforce the importance of previous scientists to move forward. During the work of this thesis, I have been very lucky to have the help of “tall giants”. I would like to thank everyone who worked by my side for helping me overcome the challenges of this work.

Firstly, I want to thank my supervisor José Antonio Millán García, for believing in my work from the beginning and making possible this adventure. We have learnt a lot together and I hope to keep doing it for many years to come.

I would also like to acknowledge my fortune of having the support and wise insights of José María Pedro Sala Lizarraga. His hard-working capacity and kindness were a great example.

Without a doubt, this work wouldn’t have been possible without the ideas, work and illusions of my colleagues of the Thermal Area. I want to give thanks to Carlos, César, Dani, Eider, Imanol and Iván. I will never forget the intense days of sensor calibrations, monitoring installations, data analysis, mathematical models and passionate discussions about thermal transmission in buildings.

I will always be grateful to Adelina and her family, for opening the doors of their home and living together patiently with the instrumentation to monitor their house for more than a year.

I want to say thank you to all my colleagues of ENEDI research group for their help and assistance during these years, especially to Ana, Álex, Alvaro, Esti, Isa, Jon, Koldo and Moises.

I feel grateful for the chance to use the equipment and facilities of the Laboratory of the Quality Control of buildings of the Basque Government, especially to Agustín, Elvira and Alberto.

The present work was funded by the Basque Government. I will always be grateful to the PhD scholarship programme and I trust in returning this investment to society with my future work.

Also, I want to acknowledge the importance of my stay in Aalborg Universitet (Denmark) and I am especially grateful for the supervision of Per Heiselberg. I remember how much I learnt from great professionals and I want to give a big thanks to Rasmus, Hicham, Jérôme, Fanis and Francesco.

A special thank you to Germán Campos of ecoeficiente and Mathew Larson of Bid Ladder Software for their help during the definition of the building energy simulation models in Design Builder®.

And last but not the least, I want to send strong hugs and best wishes to all my family for all their care, help and support. To my parents Joaquín and Garbiñe, for giving me the best of the examples of persistence and hard-work. To my brother Jokin, for showing me the value of determination and courage in research. I love you. Finally, the greatest thank you to Greta, my wife, for being by my side during the writing of this thesis as my main support and starting one of the most beautiful periods of my life. With no doubts, she is the best outcome of these years of PhD. Aš tave labai myliu!

I might have forgotten some other people and professionals who had contributed in one way or another to this work. To all of them, the biggest thank you and they will always have all my gratitude.

In Donostia-San Sebastián, May 2017.

Juan María Hidalgo Betanzos

Extended summary

The European construction sector was called to lead the implementation of nearly Zero Energy Buildings (nZEB) with the well-known EPBD Directive 31/2010. Seven years later, the adaptation of the nZEB principles to the local conditions of the European Members States is still ongoing. In the case of Spain, the adaptation of the nZEB requirements is being considerably delayed because of the economic context and the slow recovery of the construction sector after the explosion of the housing bubble in 2008, dragging the sector to conservative designs and little innovation.

Single-family houses are a crucial typology for the European strategy, because despite their limited number in the Spanish housing building stock, their energy consumption is very high. At present, the average Spanish single-family house can almost double the greenhouse gas emissions of a standard multifamily apartment. In order to significantly cut down this energy demand, this study analyzed the capacity of adaptation of the Passive House design principles to the cool-temperate climates in Spain.

Firstly, one of the first passive houses built in Spain was monitored in detail to evaluate the real performance of this type of constructions in the local context. The long-term monitoring was based on a multilevel analysis of the indoor air, the thermal envelope, the ventilation unit and the heating system. 18 air DB sensors were used to control the indoor air temperatures in every room of the house, including some additional ones to control the air stratification in the biggest rooms. 6 relative humidity sensors registered the moisture levels in the house. To complete the evaluation of indoor conditions, two sets of thermal comfort sensors were installed for at least one week of winter, spring, summer and fall. The envelope was controlled by a large set of surface temperature sensors located in the walls, floors and ceilings, together with 3 thermal flux meters in the North East and West façades, and some sensors placed on the outer side. The local climatic conditions were measured by a climate station and a solar radiation meter mounted on-site.

The study confirmed a good winter performance with a very low heating use of 17.6 kWh/m², slightly over the PH limit. The monitoring permitted to improve several aspects of the house thermal behaviour. For instance, the temperature gradient among distant rooms which was caused by the pellet stove heating. It was solved by the installation of supplementary electric heaters in the opposite side of the house. The thermal envelope of the house fulfilled the

expectations of the design but some moderate thermal bridging was detected in the ground contact of the building walls.

The thermal behaviour of the house during summer was more complex. During the majority of temperate summer days, the operation of the MVHR with the summer bypass was able to provide enough free-cooling. The evaluation according to PMV indicated warm discomfort for 3.7% of annual hours, but the EN15251 assessment evidenced how the occasional ventilation permitted to avoid overpassing the upper temperature limits.

Thus, the occasional natural ventilation periods applied by the inhabitants to cool down the indoor were advantageous but also insufficient to maintain the indoor temperatures inside the PMV range. Overall, the observations suggested the high potential of the natural ventilation but also underlined the difficulties to apply it regularly.

Secondly, after studying the monitored thermal response of the house, a dynamic Building Energy Performance Simulation (BEPS) was developed. The purpose was to represent as well as possible the measured thermal behaviour of the case study. The calibration was complex and the iteration process was driven by the parameters of heating use and indoor temperatures, supported by the potential of graphical analysis. The reference model was verified monthly with the Mean Bias Error (MBE) and the Coefficient of Variation of Root Mean Square Error, CV(RMSE).

Based on this model, certain measures were implemented intending to fix the problems identified during the monitoring. For example, the hot hours registered during summer or the cool temperatures in some rooms during winter.

The improvement of the MVHR unit maximising the airflow of the summer bypass permitted to boost the free-cooling and reduce almost by 20% the indoor hours above 25 °C. However, the limited cooling capacity of the summer bypass was insufficient for the hottest months and still would require the use of natural ventilation. With respect to the natural ventilation, the cooling capacity would be more than enough. However, there were issues related with the manual operation of the ventilation which limited its use in this type of houses.

The tested solar shading devices were supplementary and lightweight, to follow the non-invasive approach. The obtained shading was low and despite its combination with the enhanced MVHR it would be unable to cool down the temperature inside the desirable range. Thus, it would still require occasional heat purge with natural ventilation for the warmest weeks.

Thirdly, another modelling study was applied in a broader perspective, considering the most common features of the single-family passive houses built in Spain in recent years. This way a detailed review of the passive houses permitted to define three simplified reference models with the average characteristics of size, window to floor ratios, construction materials and ventilation. The levels of thermal insulation were calculated in order to comply with the main PH requirements. A short review of the Spanish cool-temperate climates was done, showing the winter and summer severity levels. The study selected three locations: Bilbao as a capital with Atlantic climate in the coast, Burgos as typical cold-continental climate city and Madrid as a warm-continental area.

The winter analysis established the minimum thermal insulation levels of the models. These were approximately 15 cm in detached housing and 10 cm in attached housing in medium severity climates (Bilbao and Madrid). These values increased up to 20 cm for detached housing and 15 cm for attached housing in the coldest areas (Burgos). This way, both the requirements for the heating demand and the heating load could be met with an average design.

The summer analysis of the selected models was improved with the implementation of several passive measures. The results confirmed that all the cases in the studied climates could completely avoid the use of active cooling with the proper combination of supplementary feasible measures of ventilation and solar shading.

Regarding the future climate and global warming effect in these buildings, the selected cases showed increases of the indoor temperatures in summer by about 1-2 °C by 2040 and around 2-5 °C by 2080. These higher temperatures may deteriorate considerably the indoor environment in many cases and all new designs should verify the resilience of the buildings for this reality. Unless these climate scenarios are applied in the early building design, frequent indoor temperatures over 30 °C may be common in the new constructions inside the Spanish continental climates.

Keywords: Building monitoring; Thermal comfort; Overheating; Building energy simulation; nZEB.

Resumen

El sector de la edificación fue convocado para liderar la implementación de los Edificios de Consumo de Energía Casi Nula (nZEB) a través de la Directiva 31/2010 EPBD. Siete años más tarde, la adaptación de los principios nZEB a las condiciones particulares de los Estados Miembros está todavía en proceso. En el caso de España, esta adecuación de los requisitos nZEB está siendo considerablemente retrasada por el contexto económico y la lenta recuperación del sector de la construcción desde la explosión de la burbuja inmobiliaria en 2008, que arrastró a todo el sector hacia posiciones conservadoras de diseño y poca inversión en innovación.

Las viviendas unifamiliares son una tipología crucial para la estrategia europea, debido a que, pese a su reducido peso en el parque inmobiliario español, su consumo energético es muy elevado. En la actualidad, la vivienda unifamiliar media puede emitir casi el doble de gases de efecto invernadero que un apartamento medio en España. Para reducir significativamente su consumo energético, este estudio analizó la capacidad de adaptación de los principios de diseño Passive House a los climas templados de España.

En primer lugar, se monitorizó en detalle una de las primeras viviendas pasivas construidas en España, para evaluar el comportamiento real de este tipo de construcciones en un contexto local. La monitorización se prolongó por 14 meses y se basó en un estudio múltiple del aire interior, los cerramientos, el sistema de ventilación y el sistema de calefacción. Se instalaron 18 sensores de bulbo seco para conocer las temperaturas en todas las habitaciones, incluyendo algunos sensores adicionales para analizar la estratificación del aire en las mayores habitaciones. Mediante 6 sensores de humedad relativa se monitorizó el contenido de humedad en distintos puntos de la casa. Los cerramientos fueron controlados mediante un gran número de sondas de temperatura superficial ubicados en las paredes, suelos y techos, combinados con la medición del flujo térmico en 3 puntos de las fachadas Norte, Este y Oeste; así como la medición de las temperaturas superficiales exteriores de las fachadas. Las condiciones climáticas fueron registradas in-situ mediante una estación meteorológica y un solarímetro.

El estudio confirmó el buen comportamiento térmico en invierno con un consumo energético muy bajo de 17,6 kWh/m², ligeramente por encima del límite PH. La monitorización permitió aplicar ciertas mejoras al comportamiento térmico inicial. Por ejemplo, el gradiente térmico entre habitaciones causado por la calefacción mediante estufa de pellets fue compensado con unos pequeños calefactores eléctricos ubicados en la parte opuesta de la casa. El

comportamiento de la envolvente térmica de la casa cumplió las expectativas de diseño, con la salvedad de algunos puentes térmicos moderados detectados en el encuentro entre las fachadas y el terreno.

El comportamiento térmico de la casa en verano fue más complejo. Por un lado, el funcionamiento de la unidad de ventilación mecánica con recuperación de calor (VMC-RC) en modo bypass aportó una refrigeración gratuita suficiente en la mayor parte del verano. Por otro lado, la evaluación del confort térmico mediante el modelo del voto medio estimado (PMV) mostró un 3,7% de las horas anuales por encima de los valores admisibles y la norma EN 15251 evidenció que los pequeños ciclos de ventilación natural nocturna fueron los que evitaron sobrepasar los límites de temperatura superior.

Por lo tanto, los periodos de ventilación natural aplicados ocasionalmente por los habitantes para refrescar la casa fueron beneficiosos, pero también insuficientes para mantener las temperaturas interiores dentro del rango recomendado por el PMV. En general, las observaciones sugirieron que la ventilación natural tiene un alto potencial pero también ciertas dificultades para su aplicación real.

En segundo lugar, tras estudiar la respuesta térmica de la casa mediante la monitorización se desarrolló un modelo de simulación del rendimiento energético (BEPS). Su propósito era representar con la mayor fiabilidad posible el comportamiento medido en la casa. LA calibración del modelo es un proceso complejo y el proceso de iteración fue guiado por los valores de consumo energético y temperaturas interiores, apoyado por análisis gráficos avanzados. El modelo de referencia fue validado mensualmente mediante el “Mean Bias Error” (MBE) y el “Coefficient of Variation of Root Mean Square Error”, CV(RMSE).

A partir de este modelo se pudieron implementar ciertas medidas pasivas para solucionar los problemas detectados en el comportamiento térmico del edificio real durante la monitorización. Por ejemplo, las horas de verano por encima de las temperaturas admisibles o las temperaturas bajas en algunas habitaciones durante el invierno.

La mejora de la VMC-RC aplicando un aumento del flujo de aire cuando se activa el bypass permitió ampliar un 9% la refrigeración gratuita de todo el verano y reducir un 20% el número de horas por encima del límite superior de confort. Sin embargo, su limitada capacidad era insuficiente para los meses más cálidos del año y seguiría necesitando la ventilación natural. Si bien la capacidad de refrescamiento de la ventilación natural sería suficiente, los problemas prácticos de operación manual, ruido y seguridad limitan su uso en esta tipología.

Los sistemas de sombreamiento analizados en este modelo fueron ligeros a modo de medidas no-invasivas para un edificio existente. Por ello, el sombreamiento obtenido era menor que en otros sistemas de obra nueva y pese a su combinación con la VMC-RC mejorada seguiría necesitando la ventilación natural en las semanas más cálidas a modo de purga de calor.

En tercer lugar, se realizó otro estudio con una perspectiva mayor, considerando las características más comunes de las viviendas unifamiliares pasivas construidas en España en los últimos años. De este modo, se definieron 3 modelos de referencia con las principales cualidades de las casas pasivas existentes con los valores medios de dimensiones, proporción de ventanas, materiales de construcción, sistemas de ventilación y calefacción. Los niveles de aislamiento se ajustaron para cumplir los requisitos principales del estándar PH. Estos niveles se ajustaron en base a las tres principales zonas climáticas aplicadas en el estudio. Se seleccionaron 3 ciudades: Bilbao como una capital de la zona Atlántica, Burgos como una típica ciudad de la zona continental fría y Madrid como indicador de la zona continental-cálida.

El análisis de invierno estableció los niveles mínimos de aislamiento por tipología y zona. Siendo aproximadamente 15 cm para las casas aisladas y 10 cm para las casas adosadas en las zonas de severidad climática invernal media (Bilbao y Madrid). Así como 20 cm y 10 cm aproximadamente en las zonas más frías (Burgos). De este modo, se cumplirían los dos criterios de carga máxima diaria de calefacción y de demanda anual máxima de calefacción.

Posteriormente, el análisis de verano de los modelos seleccionados fue mejorado mediante combinaciones de mejoras de ventilación, sombreamiento solar e inercia térmica. Los resultados confirmaron que es posible evitar la necesidad de refrigeración activa en todas las zonas climáticas estudiadas mediante una selección adecuada de medidas de refrescamiento pasivo.

Respecto al comportamiento frente al clima futuro el efecto del calentamiento global en esta tipología, los cases estudiados mostraron aumentos de la temperatura interior de entre 1-2 °C para 2040 y entre 2-5 °C para 2080. Estos elevados valores podrían deteriorar considerablemente el confort térmico en muchos casos lo que indica que los diseños actuales deberían verificar la resiliencia de los edificios a esta realidad. Si no se aplican estos escenarios futuros en los edificios actuales, las temperaturas interiores por encima de 30 °C podrían ser frecuentes en los nuevos edificios ubicados en las zonas de España con clima continental.

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CHAPTER 1
INTRODUCTION

1. Introduction

1.1. Background and motivation

In 2010, the European Union made public a new ambitious goal for constructions: by 2050 the EU must reduce their CO_2 emissions up to 80% below the levels established in 1990. This was far from the conditions of the present average constructions, but it was the first and global definition of the nearly Zero Energy Buildings (nZEB) in the EU. According to this policy agenda, every new construction should be a nZEB by the end of 2018 for public buildings and by the end of 2020 in the case of private constructions (Directive 2010/31/EU, 2010). Despite to the fact that many policies have reinforced this main concept (Directive 2009/28/EC, 2009) (Directive 2009/125/EC, 2009) (Directive 2012/27/EU, 2012), the real implementation along the European Member States (MS) has been diverse and the results in many countries have not been satisfactory from the European Commission point of view (ECOFYS et al., 2014) (EPISCOPE & BPIE, 2015). For that reason, in 2016 the European Commission published a new Recommendation with some guidelines for the promotion of nZEB and best practices to ensure that, by 2020, all new buildings would be nZEB (European Commission, 2016b). This way, it is patent that many MS are struggling to implement the nZEB solutions described by the EU framework. The present study analyses the features of residential single-family nZEB in northern Spain climates and offers a common ground to develop a proper definition of local nZEB.

It is very important to understand the reasons behind this nZEB policy and keep in mind the big picture of this nZEB strategy. The effects of the Climate Change (CC) are now present all over the world, and our decisions today will limit greatly the possibilities to keep a good quality of life of our future generations. After many years of discussion between believers and sceptics of the CC, a large amount evidence about climate, human impact and scenarios was collected worldwide which lead to a global consensus. Firstly, this is not just a periodical or seasonal warming. The last report of the Intergovernmental Panel on Climate Change (IPCC) has presented countless real evidence and future scenarios simulations, which demonstrate that the "*scientific evidence for warming of the climate system is unequivocal*" (IPCC et al., 2013), see CO_2 levels in Figure 1.1. Secondly, even though the cause of this change was discussed for a long time, the scientific community now accepts that the main factor is actually human. Recent research about all the studies published in peer-reviewed scientific journals shows that at least 90% of the studies point to human activities as the main driving factor of the climate warming phenomena (Cook et al., 2016). A key year was 2013, when abundant evidence was published in the IPCC last report (IPCC et al., 2013) and the World Meteorological Organization (WMO) also declared that "there is a strong scientific consensus that the global climate is changing and that human activity contributes significantly" (WMO, 2013). It is important to keep in mind that this consensus required a very long time to settle. Already in 2005, the Academies of Sciences of the world's main countries warned saying that "*climate change is real*" and asked Nations to "*prepare for the consequences of climate change*" (Joint Science Academies, 2005). To sum up, nZEB design will face a progressive climate warming in upcoming years and the constructions should be adaptive.

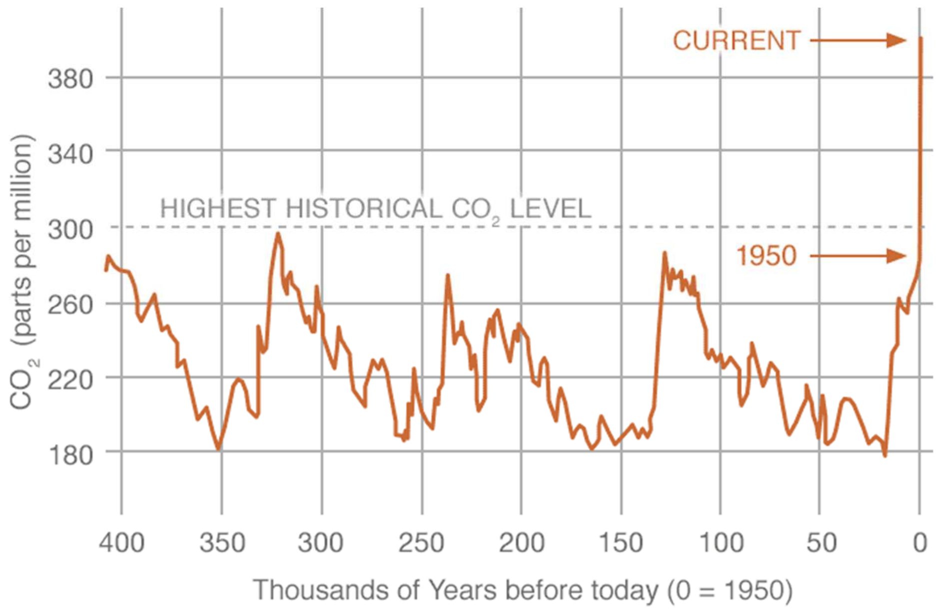


Figure 1.1. Reconstruction of worldwide CO_2 from ice cores
(taken from National Oceanic and Atmospheric Administration, NOAA).

This way, the social consciousness was slowly growing during decades together with the scientific evidence and eventually the governments also got involved in CC strategies. Since the Kyoto protocol of 1997, many organizations have helped developing the basic principles of that first agreement, like the United Nations Framework Convention on Climate Change (UNFCCC), WMO, IPCC, National Aeronautics and Space Administration (NASA) and many others. Finally, despite all the economic and political impediments, a first global and binding agreement became true in Paris in 2015. A document consisting of obligations for the countries and tools to hold global warming below 2 °C was established. The contents of this document was negotiated and approved by consensus of the 195 countries present in the 21st Conference of the Parties of the UNFCCC (COP21). Afterwards, these measures were ratified by each country and the Paris agreement entered into force on the 4th of November 2016, when a sufficient number of countries had ratified it, accounting for almost the 55% of global emissions. As a consequence, there are two clear aspects of future building regulations: the emissions related with the construction and use of buildings should be kept as low as possible, and at the same time the design of buildings must take into consideration the predicted scenarios of global warming and permit future adaptations.

Going back to the EU context, buildings are one of the most relevant aspects to minimise the human impact. According to the European Commission "buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU" (Directive 2010/31/EU, 2010). The challenge of this sector is precisely that the building stock across Europe is heterogeneous and diverse. The present study focuses on the residential sector as the European building stock is mainly residential. The European Commission created a building stock observatory and the most recent results show that the residential sector accumulates on average 75.82% of the total EU-28 floor area (EC Building Stock Observatory, 2013). Moreover, the type of dwelling affects greatly the energy consumption. For instance, recent studies have pointed out that the final energy demand for heating and cooling in single-family dwellings is considerably higher than the demand in multifamily blocks (EPISCOPE & BPIE, 2015) (Zangheri et al., 2014). A very detailed state of art conducted by the European Commission about the influence of building typologies on energy consumption has concluded that in the case of detached housings in rural areas the final energy demand can be double (European Commission, 2016c). Therefore, the energy reduction of the typology of detached single-family housing is one of the main challenges of the present and future European construction sectors.

At a Spanish scale, this typology is also very important for the global energy consumption in buildings. Firstly, the ratio of residential buildings is higher in Spain than in Europe. Many studies indicate that residential buildings constitute around the 82% of the Spanish total net floor area (ENTRANZE Project, 2012) (BPIE, 2011) (Eurostat, 2013). Secondly, the presence of this typology of dwellings is smaller than in average EU-28, that is around a 30% of single-family housing and 70% of multifamily blocks (SECH Project -SpaHousec, 2011). Besides, this presence changes depending on the part of Spain, and while in the north-Atlantic areas it is 26%, in the continental areas it is about 29% and in Mediterranean areas it reaches up to a 31%. However, the Spanish dwellings of this typology are much bigger (140.2 m^2) than apartments (86.5 m^2). As a result of this size difference, the net floor area of single-family dwellings account as much as the 35% of the total Spanish residential area (ENTRANZE Project, 2012). With regard to the energy consumption, the impact of this typology is indeed higher, see Figure 1.2. The SECH project (development of detailed Statistics on Energy Consumption in Households) reviewed the consumption of housing typologies and identified the main energy end-uses of European countries between 2009 and 2011. The study indicates that this typology consumes up to the 46% of the final energy use of Spanish residential buildings and also that the heating need of an average single-family dwellings quadruplicates the heating need of average apartment (SECH Project -SpaHousec, 2011). This higher energy demand was included in the limits of maximum energy demand of the Spanish Building Code. This surface factor for small buildings means that a new single-family housing of 150 m^2 is allowed to consume 15-38% more heating/cooling than a 1000 m^2 multifamily block.

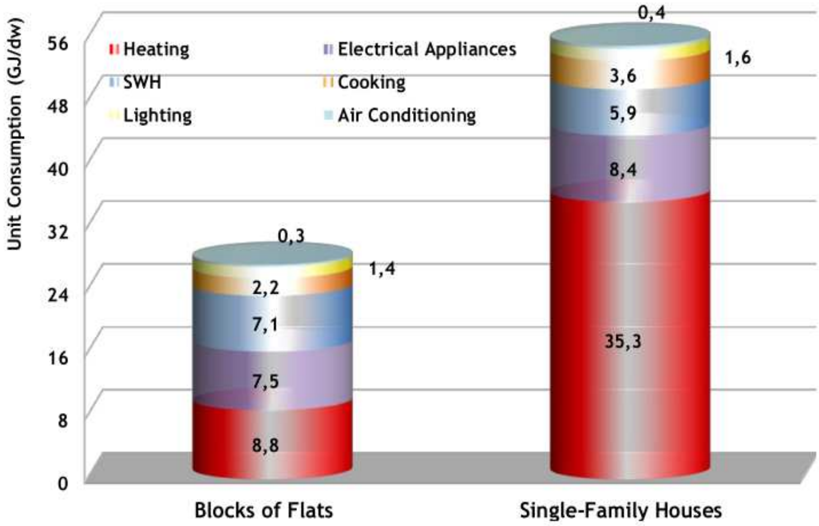


Figure 1.2. Energy consumption of average dwellings in Spain (taken from SECH-SPAHOUSEC, 2011)

The present study was strongly motivated by the great changes which happened in the residential sector of Spain during the last decade. These changes turned upside down the traditional construction sector and remodelled the features of new dwellings, as well as the requirements for existing building renovations. Among other small reasons, there were three main causes: (i) the world financial crisis which provoked the collapse of Spanish “housing bubble” in 2008, (ii) the new European regulation to reduce the energy consumption of buildings and (iii) the late spread of high energy performance buildings with international certificates like Passivhaus, MINERGIE, LEED, BREEAM, etc.

Firstly, the world financial crisis of 2007 whose effects landed in Spain in 2008. This crisis provoked the burst of the existing “housing bubble” and as a consequence, the Spanish construction sector was swept and reduced to its minimum expression. According to official data from the Spanish National Statistics Institute ("Instituto Nacional de Estadística", INE), the number of dwelling licenses, including new and renovated works, dropped up to 86% in only 4 years: from the peak of 820.000 dwellings in 2006, to 667.000 in 2007, 232.000 in 2008, 111.000 in 2009 and below 50.000 in 2016. These small numbers are considered to be insufficient to cover the housing need. Actually, before the "housing bubble", the number of dwelling licenses was 287.000 between 1980-1997 (García Montalvo, 2006). In brief, the paralysis affected the new developments and renovations all around the country, as it can be observed in Figure 1.3. This analysis is also supported by many publications like the last review published by Housing Europe (Housing Europe, 2015). In this context, the law of supply and demand increased the market competition and increasingly led to a higher specialization of architects, engineers and builders. The main two objectives for the construction sector stakeholders are the buildings with high Energy Efficiency (EE) and the renovation of the existing building stock (Consejo Económico y Social, 2016). At social level, the destruction of the construction sector was very dramatic and it boosted the unemployment level to more than 25% of the active people in 2012 and 2013.

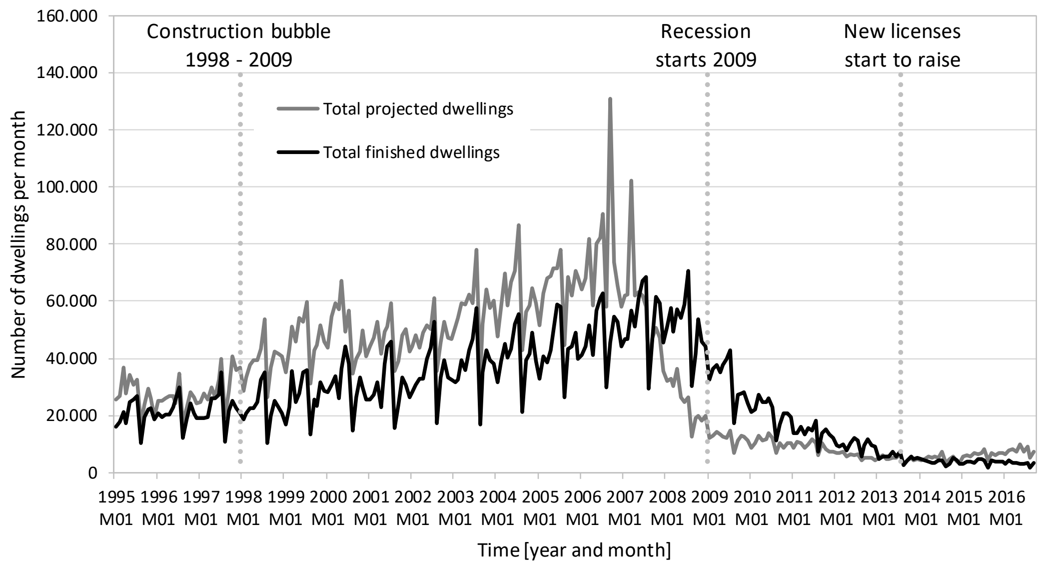


Figure 1.3. Monthly dwelling projects in Spain (1995-2016). Monthly project licences and finished constructions, including new and renovated housing (data source INE, 2016).

Secondly, another difficulty in Spain has been the slow application of the ambitious European plans to improve the Energy Performance of Buildings (EPB), as pointed out in a number of reports and publications (BPIE, 2011) (ECOFYS et al., 2014) (RePublic_ZEB Project, 2015) (EPISCOPE & BPIE, 2015). The European policy kept rising the EPB threshold every few years through a number of directives and this strategy has completely changed the requirements for new constructions and renovations. Meanwhile, the implementation of these directives into the Spanish regulation took very long time in most of the cases (between 3 and 5 years, as explained in the next paragraph). This fact, in combination with the aforementioned financial crisis, provoked a considerable delay in the adaptation of the construction sector to the new strategy.

The first requirements established by the EBPD (Directive 2002) were transposed to Spanish legislation 4 years later. They were included in two documents: the first Technical Building Code (CTE) (Royal Decree 314/2006, 2006) and the updated Regulation of Building Heating Systems (RITE) (Royal Decree 1027/2007, 2007). The CTE became mandatory for the licences given after the 29th of September 2006, less than two years before the burst of the "housing bubble". So there was almost no time to implement these improvements in new projects and the majority of ongoing constructions were based on older regulations. In any case, little by little the new regulations were applied in the scarce construction works and the society started to hear about more thermal insulated buildings and advanced HVAC systems. However, these changes were very slow and designers and builders were reluctant to change their conventional solutions (RePublic_ZEB Project, 2015). Many improvements of the energy performance like thermal bridging reduction or ventilation with heat recovery were often rejected due to the incomprehension of the real benefits and the additional expenses of the new solutions (NEEAP Spain, 2014).

The next update of the European requirements was made public in 2010 through the Recast EPBD, also known as the 20-20-20 Directive (Directive 2010/31/EU, 2010). In brief, it included specific new requirements to reduce the energy consumption and also the obligation to achieve nearly Zero Energy Buildings (nZEB) by the end of 2018 and 2020, for public and private constructions, respectively. According to the European timeline summarized in Figure 1.4, MS should publish their National Energy Efficiency Action Plans (NEEAP) in 2015. Unfortunately, the Spanish NEEEP published in 2014 (NEEAP Spain, 2014) didn't include a clear nZEB definition, only some guidelines (Observatorio Vasco de la Vivienda, 2016). Since the publication of the EPBD in 2010, the Spanish regulation has improved many aspects of the regulation framework to update the requirements and get closer to the nZEB objective (Orden FOM 1635/2013, 2013) (Royal Decree 238/2013, 2013). Moreover, a number of economic measures have been applied to promote the renovation of existing buildings, including aids for energy efficiency (Royal Decree 233/2013, 2013), ICO credit line for private housing, tax incentive for renovation works, PAREER and PAREER-CRECE aid programs as well as some others (RePublic_ZEB Project, 2015).

The last news from the nZEB strategy indicates that the present requirements on energy savings regulation in Spain are far from the nZEB horizon. The European Commission in July of 2016 published a brief assessment of the nZEB implementation and confirmed that the "progress by Member States has slowly improved but should be accelerated" (European Commission, 2016b). For that reason, they have provided many guidelines the MS should follow, including the specific ranges of energy demand and energy consumption of offices and single-family houses. Several months after this EC recommendation, in December 2016, the Spanish government published a draft of the updated nZEB indicators (Ministry of Development, 2016) and an EPB visualization tool (Ministery of Development, 2017). According to the Minister participation in the last nZEB workshop in Madrid in 2017, the ventilation update will come out in late 2017 and the Spanish nZEB definition in 2018 (7th EECN Workshop, 2017). The chapter 2 of this thesis gathers further details about the current regulation frame. Probably, this late nZEB definition in Spain is going to postpone the adaptation of the construction sector to the future nZEB scenario.

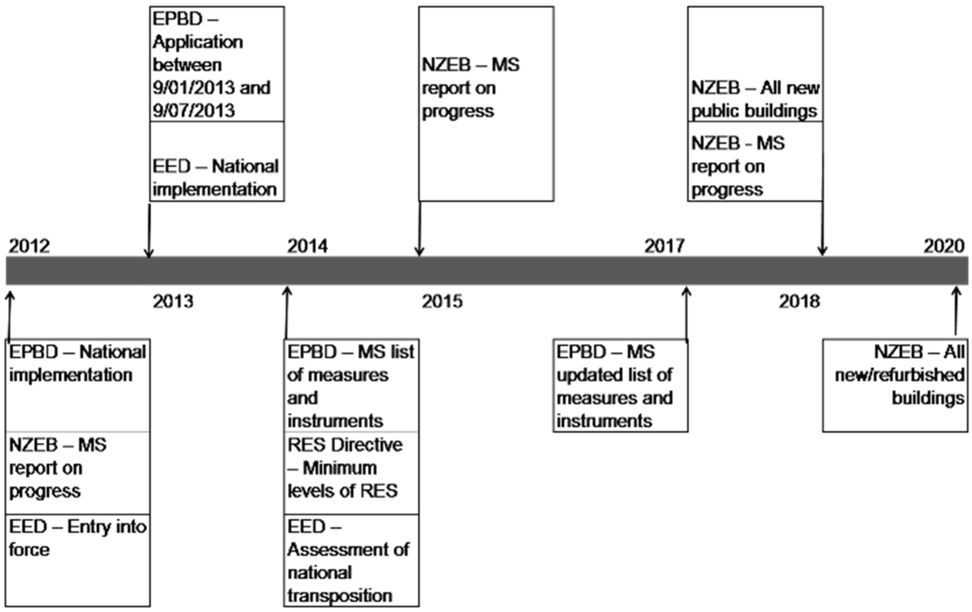


Figure 1.4. EPBD National implementation keystones (source: RePublic_ZEB,2015).

Thridly, another third special issue was the low acquaintance with the Energy Performance of Buildings (EPB) of Spanish citizens and private owners, as recognized by the National Energy Efficiency Action Plan (NEEAP Spain, 2014), in contrast with a great awareness of the private big companies, despite of the lack of economic aids (Observatorio de Eficiencia Energética, 2016). The public knowledge on this field was also diminished by the absence of any kind of public registry of the Energy Performance Certificates (EPC) until recent times. The public registry of EPC became mandatory only since 2013 (Royal Decree 235/2013, 2013). This way, the society for now is rather unfamiliar with the EPCs and the construction market doesn't commit with high EPC levels. In fact, the majority of the new constructions built in 2013, 2014 and 2015 ended getting a D or worse qualification, as shown in Figure 1.5. This problem has been analysed in detail in the annual report of the Spanish Institute for Energy Diversification and Saving (Instituto para la Diversificación y Ahorro de la Energía, IDAE) (IDAE, 2014) (IDAE, 2015a) (IDAE, 2015b). Despite the improvement of regulations, the final EPC at present are far from meeting the expected minimum performance. As aforementioned, the public awareness of building's energy performance is still in general low and insufficient, and the agents involved in construction haven't taken the risk to invest on projects with high Energy Efficiency.

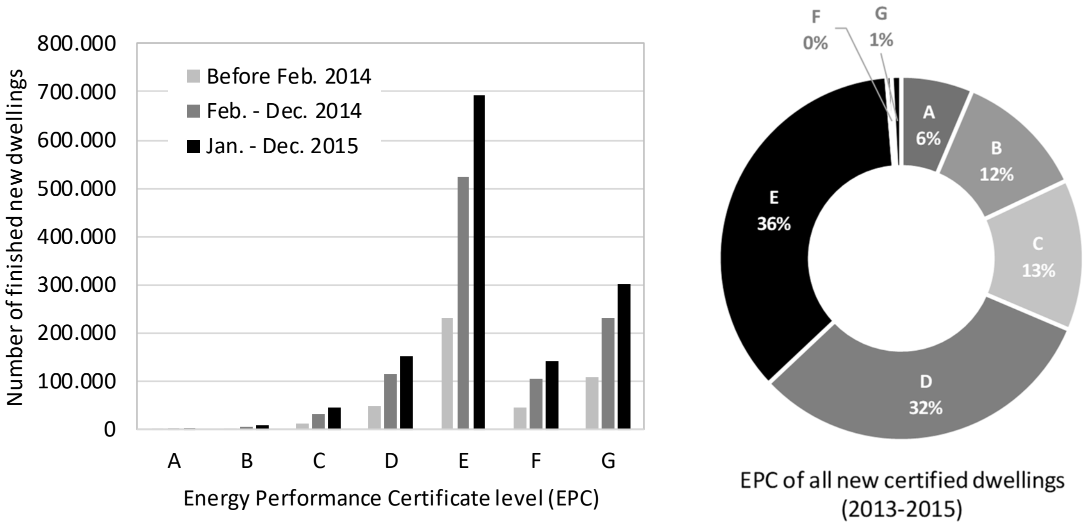


Figure 1.5. EPC levels of new dwellings in Spain in years 2013-2015 (data source: IDAE).

At the same time, some international standards such as Passivhaus, MINERGIE, LEED and BREEAM became the only alternative to identify low energy consumption buildings among the conventional construction sector. As seen before, the regulation was being slowly applied and this way the international standards took control as the reference for future nZEBs. In the last decade, the increase of international standards in Spain has been remarkable.

The first Passive House (PH) or Passivhaus building in Spain was finished in 2009, the first certificate was obtained in 2010 and one year later the first guide about Passivhaus in Spain was published (FENERCOM, 2011). The Spanish Passivhaus Platform (PEP, 2017) in their annual conference of 2015 presented the numbers of the finished PH buildings in recent years, demonstrating how the standard PH has multiplied its presence in all over Spain, see Figure 1.6 (PEP, 2017) (Wassouf et al., 2013). More recently, in 2015 and 2016 numerous projects have followed the PH design, especially in the northern Spain. The delay of the official regulation has convinced many local governments to apply these volunteer standards in order to reduce the energy consumption and boost local construction sector. In Euskadi, the Basque region, the social and protected housing company known as VISESA is building a big project of two high-rise towers with 361 dwellings in Bolueta (near Bilbao). In Navarra, another social and protected housing company known as NASUVINSA, has begun another project of 600 dwellings designed with PH standard. Regarding to the MINERGIE standard, the number of registered projects is very low. The first certificate building was a single-family dwelling in Bizkaia in 2012, and the second was a student residence in Barcelona. At present, there are approximately 23 certified and 29 non-certified passive houses in Spain, see Section 2.2.2 for further details.

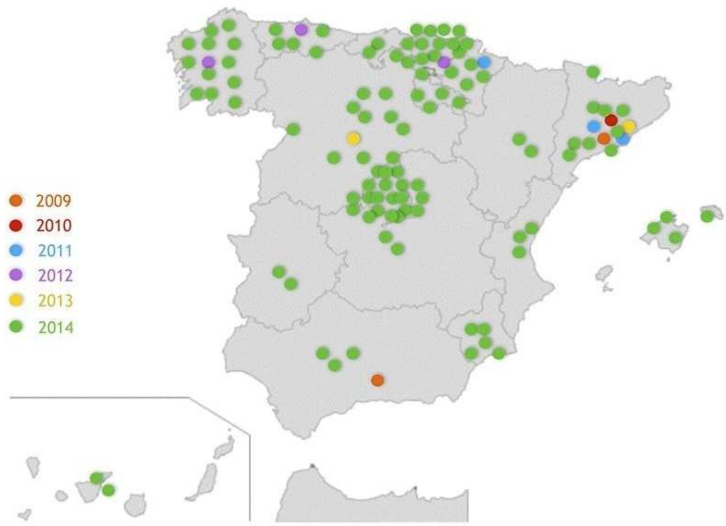


Figure 1.6. Map of Spanish PH buildings in 2015 (taken from PEP, 2017).

The sustainability certificates also gained a position in the construction sector. The BREEAM certificate created a Spanish division in 2010 and in two years they already had more than 60 projects certificated. Later on they kept increasing their presence and by January of 2017 there were 304 BREEAM certified projects according to the official database (BREEAM, 2016). Even though most of them are tertiary, there are also 46 residential projects, the 15% of the total BREEAM certificates. On the other hand, the LEED certificate has a considerable presence too. A decade ago there were less than 10 registered buildings in the whole Spain, but since 2008 the increase has been exponential. Nowadays more than 400 registered buildings demonstrate the importance of this certificate (SpainGBC, 2016). This is especially important in a country whose construction sector has been deeply affected by the recession.

After analysing the conditions of the Spanish construction sector, it was crucial to experience the real performance of low energy housing in order to improve the designs of single-family dwellings. This possibility appeared in 2012, after the construction of two Passivhaus single-family housings in the Basque region, see Figure 1.7. The building company and the architects were interested in collaborating with researchers in order to analyse the real performance of the buildings and detect improvement gaps for their future projects. To do so, the quality control laboratory studied the case and offered a monitoring campaign for the Passivhaus certified nZEB on-use. The planned monitoring system was oriented to verify the real heating performance and measure the heat losses of the house. Eventually, some additional objectives were reviewed as well, such as the air stratification, the thermal comfort, indoor air quality, ventilation performance and overheating risk. The monitoring campaign permitted the identification of the most relevant research areas for future single-family housing, included in the present PhD work.

Figure 1.7. Monitored case study house in winter (top) and summer (bottom).

From this overview of regulations and passive housing perspectives, one can be sure that the housing development is still going through a period of uncertainty. The Spanish construction sector has experienced quite bad times in recent years and the sector is little by little overcoming the financial crisis. During this time, even though some projects have adopted standards of high performance, the mainstream of construction follows the current regulations without further improvements. In reality, despite the fulfilment of the renovated Spanish building codes (Orden FOM 1635/2013, 2013) (Royal Decree 238/2013, 2013), the EPC levels of new constructions are mostly D and E, far below the European expectations.

Therefore, most of the buildings are not applying properly the criteria to reach the nZEB horizon. This situation required a deep study about the single-family housing features in northern Spain, to find out the best design conditions in this climate and guarantee high levels of thermal comfort. Additionally, it was also mandatory to analyse the present designs in the future scenarios of climate change in order to be aware of the adaptation potential of our future homes.

1.2. Research areas

The works conducted during this PhD study were focused on the thermal behaviour of single-family dwellings. As seen before, this typology has a great potential and also a high risk of failure of future designs. The works were based in several fields of knowledge, to support them and guide the tasks towards the main challenges. Below, a brief outline of the topics analysed during the PhD is given. For further details of any of them see the next chapter.

Climate change and global warming scenarios

In the last decade, the scientific consensus about human influence on global warming has reached an enormous 97% (Cook et al., 2016). According to the future climate scenarios calculated in the last IPCC review, there is a severe risk of extreme conditions in southern European countries (IPCC et al., 2013). These scenarios will probably lead to more frequent heat waves and the consequent increases of cooling need and warm discomfort in buildings (Hacker, Holmes, Belcher, & Davies, 2005) (Zampieri, Russo, Michetti, Scoccimarro, & Gualdi, 2016).

Thermal comfort and summer overheating risk

The majority of the European regulations for new constructions include indoor environment requirements which are essentially simplifications of the models of Thermal Comfort (Attia & Carlucci, 2015). In the case of Spanish regulation, the maximum and minimum acceptable indoor air temperatures for winter and summer are approximations of PMV model (ISO 7730, 2005)(European Committee for Standardization (CEN), 2005) (Royal Decree 238/2013, 2013). Besides, in the case of housing constructions there is no further verification of summer TC if the annual cooling load doesn't overpass 15 kWh per year (Orden FOM 1635/2013, 2013)(Ministerio de Fomento, 2013). This lack of control of the summer behaviour together with the global warming can lead to important problems in the future.

Local climate potential of passive measures

One of the best ways to prevent the issues of TC and minimise the OH risk consists of the improvement of building design to mitigate the upcoming warmer climate (McLeod, Hopfe, & Kwan, 2013). There are many different strategies to face this challenge and this study is focused on the passive measures which require the minimum intervention and the minimum amount of energy. The purpose is to show the potential of these aspects to adapt new buildings to changing climate and compensate the cooling need. This study includes several measures based on ventilative cooling (Kolokotroni & Heiselberg, 2015), solar shading (REHVA & ES-SO, 2010) and to smaller degree, some thermal mass and infiltration verifications (McLeod et al., 2013).

Passive House design

One of the most well-known standards to design low energy houses is Passivhaus (FENERCOM, 2011). It began 25 years ago in continental Europe and in the last 5 years it was also exported to warmer climates like Spain (Wassouf et al., 2013). This PhD work analysed in detail a real Passivhaus certified single-family housing (SFH) in order to measure and understand the real benefits and limitations achieved with this standard in southern latitudes (Bruno, Arcuri, & Carpino, 2015). The assessment is completed with simulations of feasible improvements and the evaluation of a general case located in northern Spanish climate.

Building Monitoring

The monitoring of a housing on-use is a big challenge, conditioned not only by the available instruments, the timeframe or the budget, but also by user's involvement and climate (Krüger & Givoni, 2008) (Guerra-Santin, Tweed, Jenkins, & Jiang, 2013). The house was monitored for 14 months and a number of verification tests and surveys were done to get a holistic perspective of the thermal behaviour of the house. The presented data is the result of a deep analysis and evaluation of the indoor environment of the real case.

Building Energy Performance Simulation (BEPS)

A detailed EnergyPlus® model was defined in order to evaluate the margin of improvement of the monitored performance of the real case. It permitted to apply different passive measures and operational configurations. The verification or calibration of the BEPS with the measurements was a long process with many challenges to solve (Coakley, Raftery, & Keane, 2014). As a result, the comparison of the real case measurements and the predicted indoor environment helped to specify a method to identify the best passive strategies.

1.3. Research aim and objectives

The main purpose of this research was to **improve the adaptation of passive single-family houses to the climatic conditions of cool-temperate climates in northern Spain**, considering their capacity to provide optimal thermal comfort with an ultra-low energy demand. The intention was to identify the most relevant parameters which affect the thermal performance of these constructions and provide guidance about the optimisation of their passive design. This way, the conducted assessment aimed to provide knowledge for the next steps towards the nZEB objective in a global warming scenario.

Thus, the main research question was:

How can passive house design adapt to the cool-temperate climates in Spain, minimising the energy need and providing optimal comfort also in summer?

To answer this question, a stepwise study has been conducted. Firstly, it was essential to know the real performance of these constructions and understand the potentials and limitations of this standard. To do that, a long-term monitoring of a local building on-use was planned and the following question was addressed:

Is the performance of the passive house as good as it was expected, considering the heating operation, the performance of the thermal envelope, the operation of ventilation and the thermal comfort?

Based on these findings, several aspects of the building design were found in need of improvement. To solve or minimise the identified issues, a detailed building energy performance simulation (BEPS) was defined as a tool to test the implementation of different passive measures in the case study. The simulations were oriented to answer the next question:

Would it be possible to implement non-invasive measures in the monitored passive house in order to reach an optimal thermal comfort during winter and summer without increasing the energy demand?

After the detailed survey of a particular case, the next step was to analyse the general features of single family passive houses and assess the need of passive cooling strategies. The purpose was to adapt these designs to the local climatic conditions of cool-temperate areas in Spain considering that these problems will probably increase due to the global warming scenario. In order to do so, the last question was intended to be answered:

Which passive cooling measures would be more appropriate to be installed in this housing typology to reach an optimal thermal comfort during winter and summer in the cool-temperate regions of Spain?

1.4. Structure of the Thesis

The thesis is divided into six chapters and several annexes.

The **first chapter** is the introduction. It includes the description of the background and the motivation for the study, the identification of the areas of research and the general aim and particular objectives of this work.

The **second chapter** is the state of the art of single-family dwellings. Firstly, the regulation frame is described, from the European EPBD to latest Spanish nZEB definition update. Secondly, the general definition of Passivhaus standard is presented with an outline of the principal criteria. Thirdly, the global warming scenarios for the European and Spanish climates are described, including the impact of the climate change on the building energy demand. Fourth, a review of the monitored passive houses is done which permitted to highlight the main problems detected in the previous studies. To conclude, there is a compilation of the methodologies to assess thermal comfort and overheating. It describes the formulas and the methods applicable for the analysed single-family housing typology.

The **third chapter** analyses the real performance of a case study on-use, through the monitored data of 14 months and a number of carried out tests. It begins with a description of the Passivhaus certified building, the monitoring system and the analysing method. Next, the experimental results are explained with a summary of all the monitored data sorted by the aspects and elements measured during the field works. Finally, the obtained results are discussed and compared with other recent works.

The **fourth chapter** aims to solve the problems detected in the monitored case using the potential of building energy performance simulations (BEPS). It starts with a detailed model definition, defining the building features, the systems and the inner activity templates. Later on, the model is tested under theoretically improved features to calculate the potential of each aspect. Then, the features are combined to find out the optimal integrated solution.

The **fifth chapter** optimises the energy demand of single-family passive houses in the cool-temperate climates of Spain in order to identify the best combinations to provide as much thermal comfort as possible. The assessment is applied to three reference models which contain the most common features of single family houses in Spain. The first stage calculates the minimum level of thermal insulation in each location and case. The second stage evaluates the capacity of different passive cooling measures to provide indoor thermal comfort in summer. The third stage calculates the risk of overheating according to PH standard and CIBSE TM52 method. The final stage analyses the impact of future climate on these buildings, based on the scenarios of the IPCC for 2040 and 2080.

The **sixth chapter** describes the general conclusions, distinguishing the main outcomes of the thesis and proposing future work.

CHAPTER 2
REVIEW OF SINGLE-FAMILY PASSIVE HOUSES, MONITORED CASES AND SITUATION IN SPAIN

2. Review of single-family passive houses, monitored cases and situation in Spain

2.1. Single-family housing regulation frame

2.1.1. European policy

The progress achieved by the European regulation of the Energy Performance of Buildings since the first regulation in 2002 is remarkable (Directive 2002/91/EC, 2002). Figure 2.1 below shows the main milestones of the EPBD strategy as planned by the EPBD recast of 2010 (Directive 2010/31/EU, 2010). The implementation of this regulation in the MS has been irregular and a review published in REHVA magazine in 2012 highlighted the considerable differences in the requirement levels and the implementation delays (Erhorn & Erhorn- Kluttig, 2012). They underlined the case of Denmark as the best nZEB approach and the German case as the most common progressive increase of the minimum thermal insulation levels.

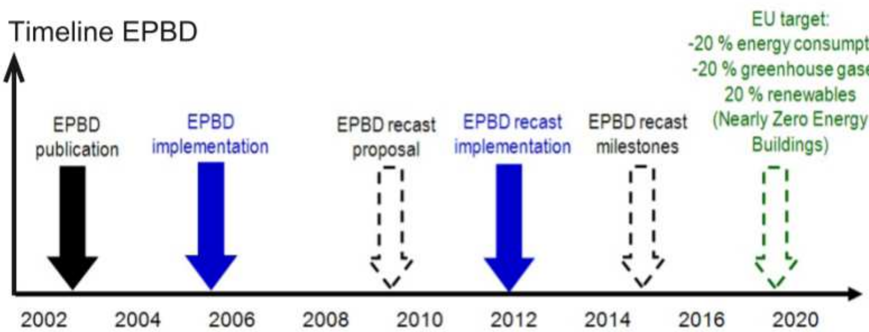


Figure 2.1. Timeline of the Energy Performance of Buildings Directive and its implementation (source: The Path towards 2020, Nearly Zero-Energy Buildings, REHVA 2012).

The primary objective of this regulation will be achieved soon, in 2018, with the implementation of nZEB definitions in every European MS. For now, many countries are working on these definitions. A number of reviews have updated the level of development of the nZEB rules in each country (EPBD Concerted Action, 2013) (ECOFYS et al., 2014) (RePublic_ZEB Project, 2015) (CA EPBD, 2015) (Agostino, 2016). The last updates evidence a general improvement from the previous Commission report of 2013. It shows how almost all countries, with the exception of Greece, Romania, and Spain, have submitted consolidated information about nZEB levels through the EC templates, as shown in Figure 2.2. However, it also recognises that Spain and Romania have already submitted national plans (NEEAP). These reports include multiple details and analysis of the definitions of EPBD and nZEB in each country, including the used metrics, the tolerated ranges, the typologies, EPC levels and controls, the calendar of application and many other details.

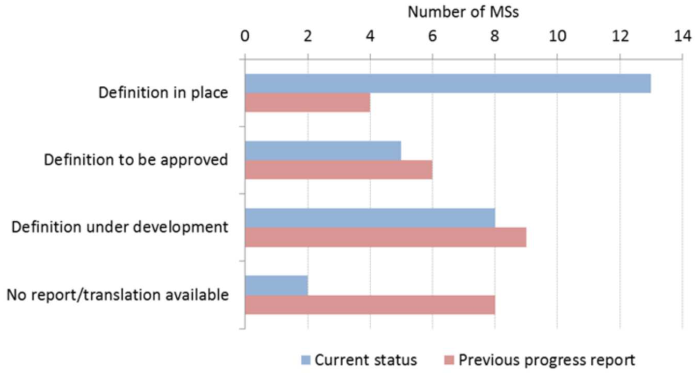


Figure 2.2. Status of development of the NZEB definition in EU Member States (source: Agostino, 2016).

Together with the EPBD, the Energy Efficiency Directive (EED) (Directive 2012/27/EU, 2012) and in an indirect way the Renewable Energies Directive (RED) (Directive 2009/28/EC, 2009) have reinforced the strategy to reduce the GHG emissions of European buildings (EC, 2016). Table 2.1 includes the main aspects promoted by the EPBD and EED regulations.

Table 2.1. Main aspects promoted by European EPBD and EED (source: EC, 2016).

Main aspects promoted by the EPBD	Main aspects promoted by the EED
Energy Performance Certificates (EPC) are to be included in all advertisements for the sale or rental of buildings.	EU countries make energy efficient renovations to at least 3% of buildings owned and occupied by central government.
EU countries must establish inspection schemes for heating and air conditioning systems or put in place measures with equivalent effect.	EU governments should only purchase buildings which are highly energy efficient.
All new buildings must be nearly zero energy buildings by 31 December 2020 (public buildings by 31 December 2018).	EU countries must draw-up long-term national building renovation strategies which can be included in their National Energy Efficiency Action Plans (NEEAP).
EU countries must set minimum energy performance requirements for new buildings, for the major renovation of buildings, and for the replacement or retrofit of building elements (heating and cooling systems, roofs, walls, etc.).	
EU countries have to draw up lists of national financial measures to improve the energy efficiency of buildings.	

Recently, the publication of the Clean Energy for All Europeans (European Commission, 2016a) proposed a deep review of most of the regulations related with the energy use. The purpose of the EC was to update the regulations, become the world leaders of the clean energy transition and coordinate all the European actions against global warming. One of the main assets was the reduction of building energy consumption, which in 2010 accounted for 40% of total GHG emissions in Europe (Directive 2010/31/EU, 2010). According to the EU surveys, approximately 75 % of buildings are energy inefficient. To improve this situation, the EC defined a program of investments and the implementation of a specific financing tool for deep renovations which will manage 10 billion of euros, this was known as the European Buildings Initiative. This initiative would work in co-operation with the European Investment Bank (EIB) and the MS. This way EC aimed to boost building refurbishments, renewable energy implementations and other projects to replicate the ideas tested in the successful pilot projects during the last decade.

As a result, the improvements observed in European construction sector since the first EPBD implementation in 2006 are most likely going to be overwhelmed by a radical boost of technologies as a reaction to the requirements imposed by all MS. The improvements will have to solve questions in every part of the nZEB definition in order to achieve cost-optimal buildings, as explained by the review of REHVA about nZEB (Kurnitski, 2013) and presented in Figure 2.3.

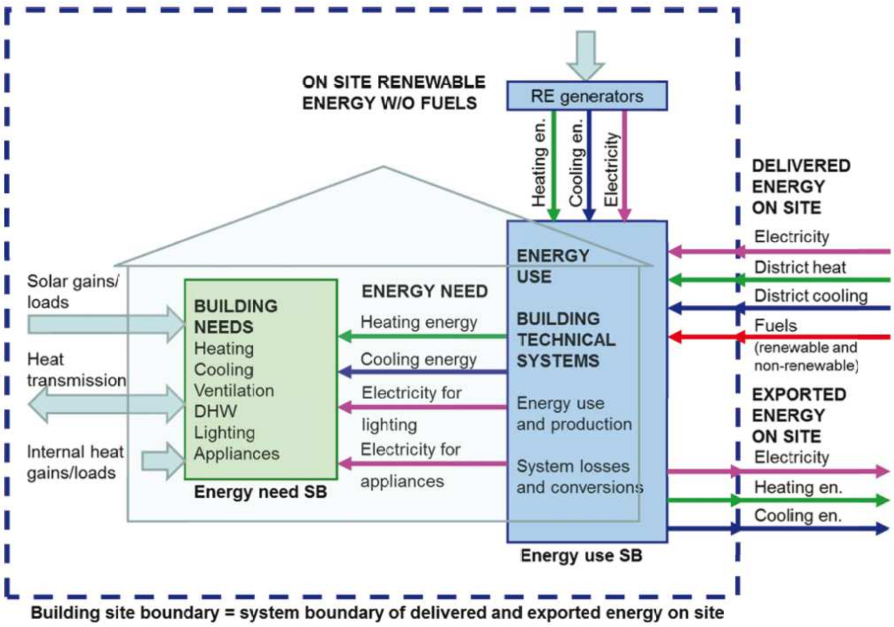


Figure 2.3. nZEB system boundaries and technical definitions by REHVA (source: Kurnitski, 2013).

2.1.2. Spanish regulation

As aforementioned, the implementation of European Directives into the Spanish regulation had been slow since the first EPBD. The last NEEAP of the Spanish government published in 2014 (NEEAP Spain, 2014) recognised this problem but justified it due to the economic context and the weakness of the construction sector. In any case, from a technical point of view the adopted measures to guarantee the nZEB implementation on time were rather insufficient to the eyes of the majority of the reviews (European Commission, 2016b) (Corrado & Paduos, 2015) (D'Agostino, 2015).

The first aspect to consider is the low efficiency level of the building stock in Spain. A study conducted by the Spanish Ministry of Development for EUROSTAT (SECH Project -SpaHousec, 2011) showed high energy uses on Spanish average dwellings, between 7859 kWh and 13141 kWh per dwelling, as shown in Table 2.2. This fact may probably be influenced by the large building stock of old constructions in Spain (Terés-Zubiaga, Campos-Celador, González-Pino, & Escudero-Revilla, 2015), but considering that the new housing is also achieving low EPC levels (Figure 1.5), it can be said that that Spanish construction sector has a lot to improve - specially in order to achieve enforcement of nZEB limits (on the 1st of January 2019 and 2021).

Table 2.2. Spanish housing average sizes and energy uses by typologies (data source: SECH project).

Spanish dwellings	Net floor (m²)	Average consumption	Heating		DHW		Electricity
		Final use (kWh)	ratio (%)	Final use (kWh)	ratio (%)	Final use (kWh)	Final use (kWh)
By zones:							
North-Atlantic	93.7	10331	40.1%	4,143	21.9%	2,262	3,926
Mediterranean	103.8	8959	40.9%	3,664	19.6%	1,756	3,539
Continental	103.5	13141	55.3%	7,267	17.4%	2,287	3,587
By typology:							
Multifamily	86.5	7859	32.2%	2,531	26.0%	2,043	3,285
Single-family	140.2	17012	63.9%	10,871	10.7%	1,820	4,321
Total average	102.4	10521	47.0%	4,945	18.9%	1,988	3,588

The present energy requirements of housing buildings were defined in 2013 with and update of the original CTE (Orden FOM 1635/2013, 2013), the main energy parameters and indicators are summarised in Table 2.3. Applying these formulas to the case of single-family dwellings and considering an average net floor of 150 m², the annual heating demand limit should be below 15 kWh/m² and 60 kWh/m² for the warmest and the coldest climate zones respectively. In a similar way, the limits of Primary Energy (PE) oscillate between 47 kWh/m² and 97 kWh/m², including heating, cooling and domestic hot water systems (DHW), see Figure 2.4.

Accordingly, these values are still considerably far from the nZEB values recommended for Mediterranean or Atlantic regions (European Commission, 2016b), summarised in Table 2.4.

Table 2.3. Main energy requirements for housing buildings in Spain (source DB-HE 2013).

Housing energy limits (DB-HE 2013)	Climate zone reference values and factors
Heating demand limits: $D_{cal,lim} = D_{cal,base} + F_{cal,sup} / S$ $D_{cal,lim}$: Heating demand limit of the building $D_{cal,base}$: Reference heating demand of each climate $F_{cal,sup}$: Net floor factor S: Conditioned net floor of the building	see table below
Cooling demand limits: 15 kWh/m²/y zones with summer severity 1, 2, 3 20 kWh/m²/y zones with summer severity 4	
Primary Energy limits, incl. heating, cooling and DHW: $C_{ep,lim} = C_{ep,base} + F_{ep,sup} / S$ $C_{ep,lim}$: PE limit of the building $C_{ep,base}$: Reference PE of each climate $F_{cal,sup}$: Net floor factor S: Conditioned net floor of the building	see table below

	Zona climática de invierno					
	α	A	B	C	D	E
$D_{cal,base}$ [kW·h/m²·año]	15	15	15	20	27	40
$F_{cal,sup}$	0	0	0	1000	2000	3000

	Zona climática de invierno					
	α	A*	B*	C*	D	E
$C_{ep,base}$ [kW·h/m²·año]	40	40	45	50	60	70
$F_{ep,sup}$	1000	1000	1000	1500	3000	4000

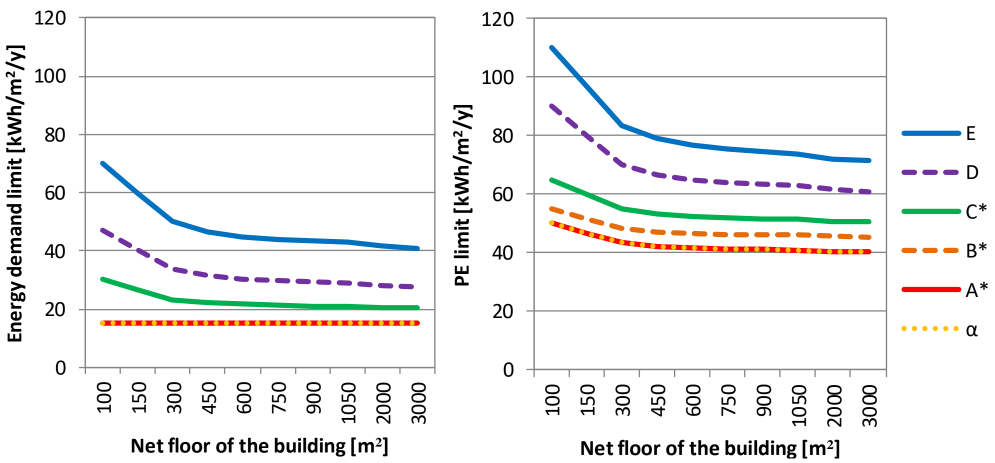


Figure 2.4. Energy requirements for housing according to the net floor and climate, in Spain (source DB-HE 2013).

Table 2.4. EC recommended nZEB limits applicable in Spanish climates (source EC 2016).

Climate zones (example of Spanish cities)	Mediterranean (Barcelona, Malaga)	Oceanic (A coruña, Bilbao)	Continental (Madrid, Valladolid)
Net PE use (non-renew.) (kWh/m²/y)	0 – 15	15 – 30	20 – 40
Total PE use (kWh/m²/y)	50 – 65	85 – 100	50 – 70
Renewable on-site gen.(kWh/m²/y)	50	45	30

At present, the indicators of the nZEB definition are almost ready and the involved Ministries are calculating the cost-optimal requirements. The draft of the new nZEB indicators was published in December 2016 by the Spanish Ministry of Public Works and Transport (Ministry of Development, 2016), see Table 2.5 below. Unfortunately, the values of these indicators are not published yet.

Table 2.5. Indicators of Spanish nZEB definition, proposal (source Ministry of Development, 2016).

Requirements	**Indicators**
Energy use	Net Primary Energy use Total Primary Energy use Renewable source implementation: - Minimum contribution of renewable energies - Swimming pool heated with solar energy - Open space heating with RES (halls, terraces, …)
Energy performance of thermal envelope	Building global transmittance value (K) Solar control (maximum heat gain in July) Maximum transmittances in housing enclosures Verification of moisture risk
Energy performance of systems	Minimum energy efficiency of HVAC systems Minimum energy efficiency of lighting

The situation of the EPC of existing buildings is complex because there are considerable discrepancies depending on the available certification tools, as underlined in a recent study conducted within QUALICHeCK project (Molina, Álvarez, & Salmerón, 2017). They found that the majority of the analysed EPC of existing dwellings bade with simplified EPC methods had 1 or 2 levels lower than the ones done with the detailed methods. According to the study, it was mainly due to inaccuracies of geometry or construction definition. The authors didn't find significant problems of the simplified calculation methods.

Besides, another main challenges for the future constructions and renovations is the compliance between EPC and reality (QUALICHeCK, Kurnitski, Kuusk, & Simson, 2015). For this reason, the author of this thesis also participated in the development of a methodology to improve the quality control of new constructions in the Basque region (Hidalgo-Betanzos, Iribar-Solaberrieta, & de Lorenzo Uríen, 2016). The methodology included a guidebook which describes how to control the thermal aspects of new housing constructions. Actually, the Basque region became one of the first regions to pay special attention to the compliance of EE features in project and reality. This work applies many of the aspects studied within the QUALICHeCK project and creates a set of checklists to control each stage of the construction process.

2.2. Passive House review

2.2.1. Passivhaus concept

"*A Passive House is a building in which thermal comfort can be guaranteed solely by heating or cooling of the supply air which is required for sufficient indoor air quality without using additional recirculated air*" (W. Feist, 2007). This is the most common definition of PH, explained by one of the founders of the Passive House concept, Dr Wolfgang Feist. The concept of Passivhaus was developed through state-funded research projects in the 80s and the first Passivhaus project was built in 1990. The project was coordinated by Professor Bo Adamson of Lund University (Sweden), and Dr Wolfgang Feist of the Institute for Housing and the Environment. It was a four-unit terrace house in Darmstadt-Kranichstein (Germany) and it was inhabited in 1991, see Figure 2.5. It became the first inhabited multi-family house achieving a recorded heating energy consumption of below 12 kWh/m²y - around 10% of a standard German house at that time. The annual energy use of the house is presented in Figure 2.6.

Figure 2.5. First Passive House in Darmstadt-Kranichstein (source www. passivehouseplus.ie)

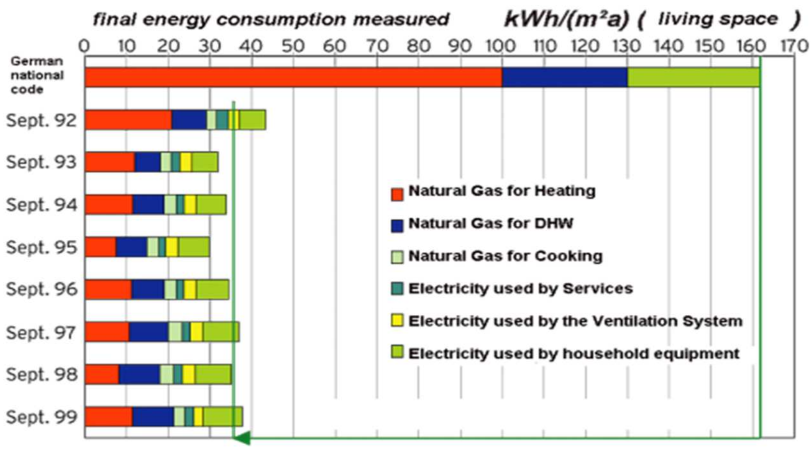


Figure 2.6. Energy consumption of the first PH (taken from V. Sariri, Passipedia, 2017)

Some years later, Dr Wolfgang Feist created the Passive House Institute (PHI) in Darmstadt (Germany) in 1996. In present days, according to PHI there are more than 20.000 certified buildings around the world, and the main features of more than 4000 are published in the PH database online (PH database, 2017). The main principles of PH design are shown in Figure 2.7: continuous thermal insulation, high-performance components, balanced MVHR, airtightness, solar shading and thermal bridge minimisation.

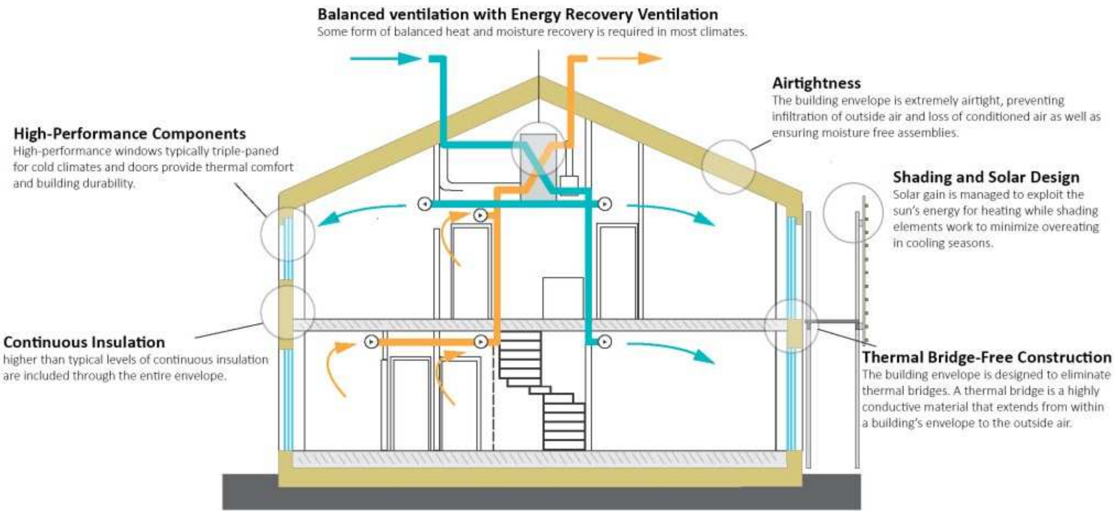


Figure 2.7. PH principles (source: Passipedia, 2016)

In any case, this concept wasn't new at all, since it was based on the historical cases of vernacular architecture and the findings of a number of experimental buildings. A long review of preceding projects and singular cases can be reviewed in (Passipedia, 2016), see Figure 2.8.

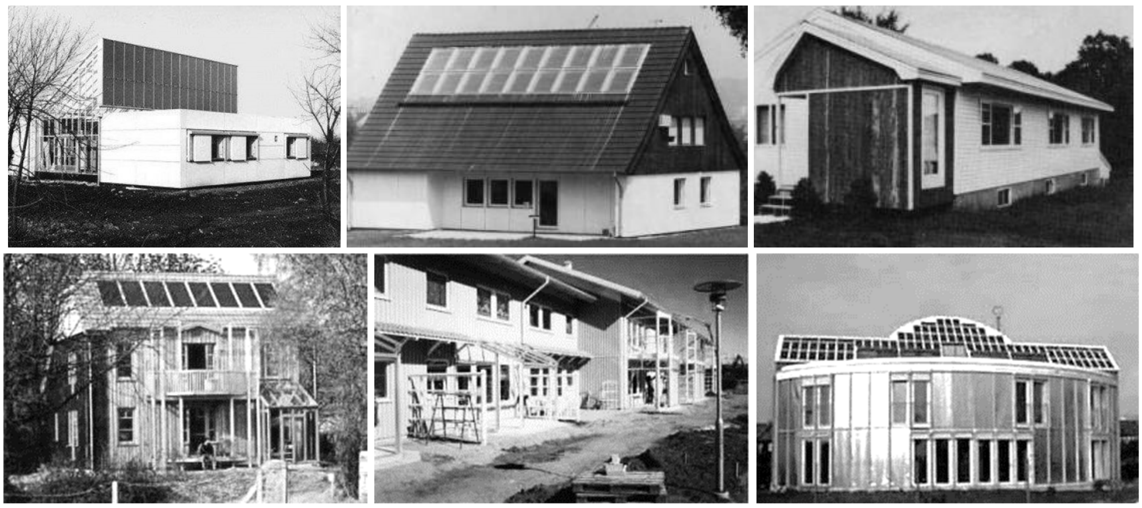


Figure 2.8. Experimental passive cases before PH definition from 1976 to 1991
(taken from Passipedia, 2016).

Apart from the Passive House standard, there are many other building types which can be considered passive to some degree, such as vernacular architecture, sustainable buildings, bioclimatic buildings, solar passive buildings, low energy buildings, self-sufficient buildings, zero energy buildings, net zero energy buildings, etc. All these building types share the importance of reducing the energy needed to provide good indoor comfort to inhabitants. The main difference was the common objectives for all passive house designs, using a simplified method which could be followed by building designers.

On the other hand, the passive concept is referred to a large variety of building features which can help reducing the thermal energy need: thermal mass, ground contact maximisation, earth sheltering, vegetal roofs, trees or vegetation shading-protections, solar shading, natural ventilation elements (solar chimney, wind tower, etc.), Canadian wells, earth to air exchangers, evaporative cooling, desiccant cooling, etc. (B. Givoni, 1984) (Mohammad Arif Kamal, 2012). Figure 2.9 shows several of these strategies in a modern housing.

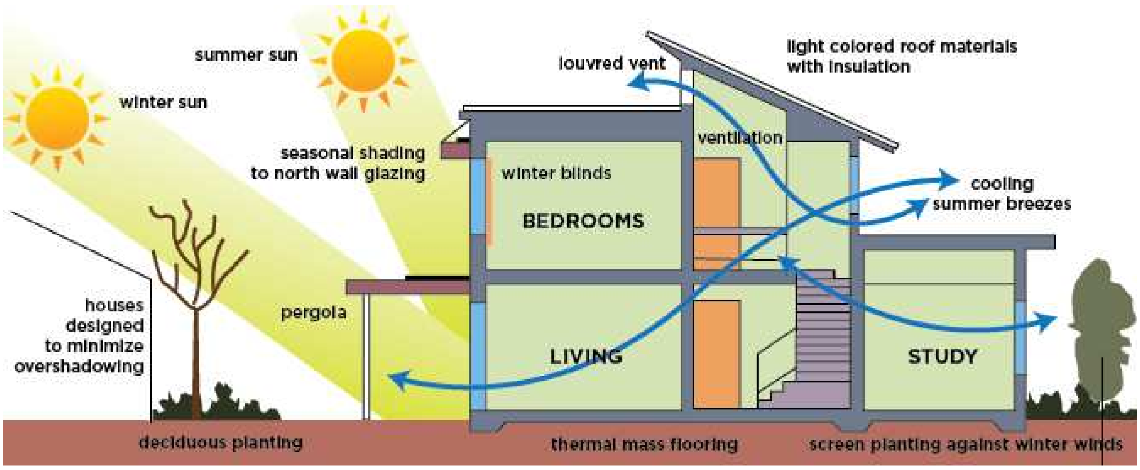


Figure 2.9. Passive design strategies (taken from www.inhabitat.com).

The requirements of PH for housing buildings are summarised in Table 2.6. For further details, review the specifications of PHI (Passive House Institute, 2016) and recent PH publications (Cotterel & Dadeby, 2012) (Wassouf, 2014) (Hopfe & McLeod, 2015) (Rodriguez Vidal, 2015).

Table 2.6. PHI criteria for PH Classic new housing buildings (source PHI, 2016).

PH Classic criteria for new housing buildings		Secondary criteria	
Heating demand	≤ 15 kWh/m²y	Min. surf. temp.	≥ 17 °C
alternative: Heating load	≤ 10 W/m²	Min. HR eff.	≥ 75 %
Cooling demand	≤ 15 + 0.3·DDH kWh/m²y	Max. FPS	≤ 0.45 W/m³h
alternative: Heating load	≤ 10 W/m², *only if also:*	Max. load by air	≤ 10 W/m²
	$C_d \leq 4 \cdot \theta_e + 0.3 \cdot DDH - 75$ kWh/m²y	Max. TB Ψ_e	≤ 0.010 W/mK
	$C_d \leq 45$ kWh/m²y	Max. hours>25	≤ 10 % (876 h)
Primary Energy Use	≤ 120 kWh/m²y		
Airtightness	$n_{50} \leq 0.6\ h^{-1}$		

The PH method to verify these requirements is implemented in a tool named the Passive House Planning Package (PHPP) which is basically a set of Excel spreadsheets in one workbook. The PHPP prepares an energy balance and calculates the annual energy demand of the building based on the user input relating to the building's characteristics. Additionally, it applies the monthly EN 13790 methods to verify the heating and cooling needs (EN-ISO 13790, 2008). The first version was released in 1998 and the last version v.9 was released in 2005. In the last version, the complementary 3D tool Design PH was presented as a new way to input the geometry of the house and make preliminary corrections through Google Sketch Up software. For further details and examples see Lewis book (Lewis, 2014).

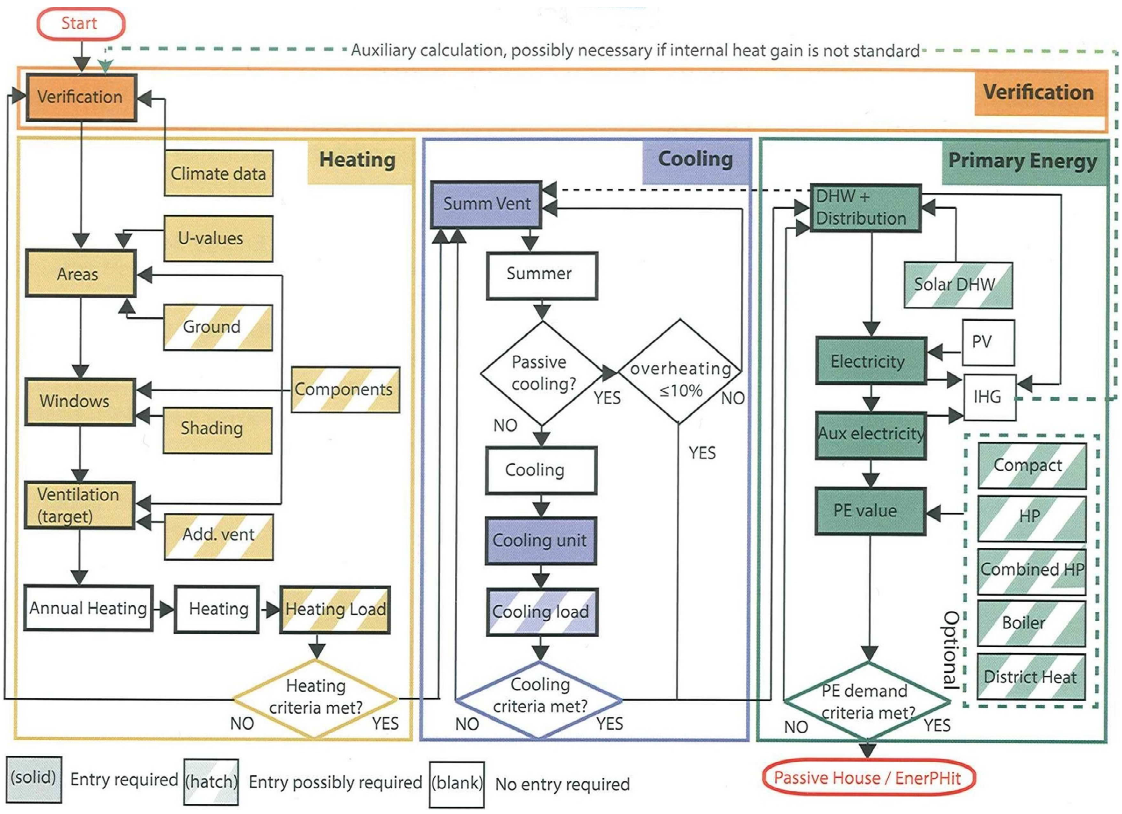


Figure 2.10. PHPP sequence of data entry for housing projects (taken from Lewis, 2014).

2.2.2. Spanish single family Passive Houses

As explained in the introduction, the Passive House standard settled in Spain less than a decade ago, in 2009. In the last years, the number of PH projects in Spain has been increasing rapidly and there is still little information about the features of these constructions. This section presents a full review of the 52 single-family passive houses built in Spain until January 2017. The information has been gathered from project sheets published in the Spanish Platform of PH (PEP, 2017) and the international database of PHI (PH database, 2017). Later, this information was compared with the websites of the architects and completed with the descriptions of the construction materials and systems from the websites of different manufacturers.

The analysis evaluates the most relevant characteristics of the Spanish stock of single-family passive houses. It checks if there is a predominant location or climate zones, which are the most common construction materials, what features the typical HVAC systems has, what is the energy performance of these houses and some other features. All the data used for this study are listed in detail in four tables in Appendix II.

After the analysis, the most frequent characteristics and the average values were used to define two cases with the most common features of the detached and attached single-family passive houses, these details are presented in Table 2.7. These two cases incorporate the average size and floor number, the typical construction materials, the common system and the average energy performance values.

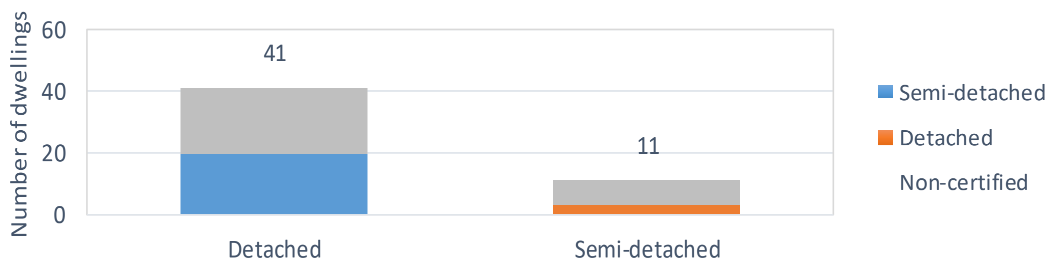


Figure 2.11. Number of single-family PH dwellings depending on their type
(data source: PEP & PHI, 2017).

According to PH official websites, there are in total 52 single-family passive houses. This includes 23 certified SF houses and 29 non-certified SF cases. The majority of the designed houses are detached. Actually, there are four times more detached PH in Spain than semidetached ones. Besides, these numbers also indicate that actually less than a half of the designed and published cases obtain the PH compliance certificate in the end. Such situation is present due to two main reasons. On the one side, the certification means additional costs, and on the other hand, the final construction quality might not accomplish all the requirements.

The fast expansion of PH standard can be seen in Figure 2.12, which evidences a fast growth since 2014. According to the quantity of projects presented in the Spanish PH conference in 2016, the number of PH dwellings should be over 15 in 2017 (PEP, 2016).

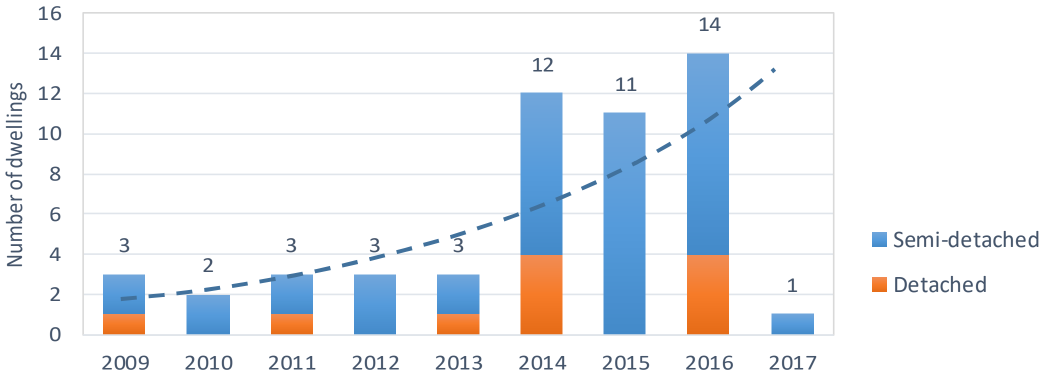


Figure 2.12. Number of SF PH dwellings by year of construction (data source: PEP & PHI, 2017).

The location of the passive houses is prevalent in colder climate zones of Spain. The dwellings in Figure 2.13 are sorted from the warmest climate zone (on the left) to the coldest one (on the right). Clearly, the implementation of PH design for now has been much larger in the cold areas.

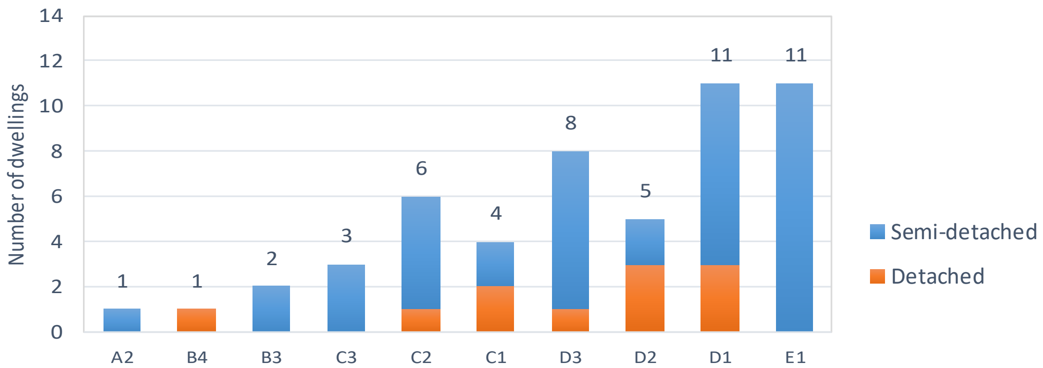


Figure 2.13. Number of SF PH dwellings by climate zone (data source: PEP & PHI, 2017).

Regarding the structural materials, the use of wood frames is the most frequent type, see Figure 2.14. The second and third most common types are solutions with concrete pillars and slabs combined with masonry or wooden enclosures. The rest of options are considerably less common. Figure 2.16 shows two typical houses with wooden elements

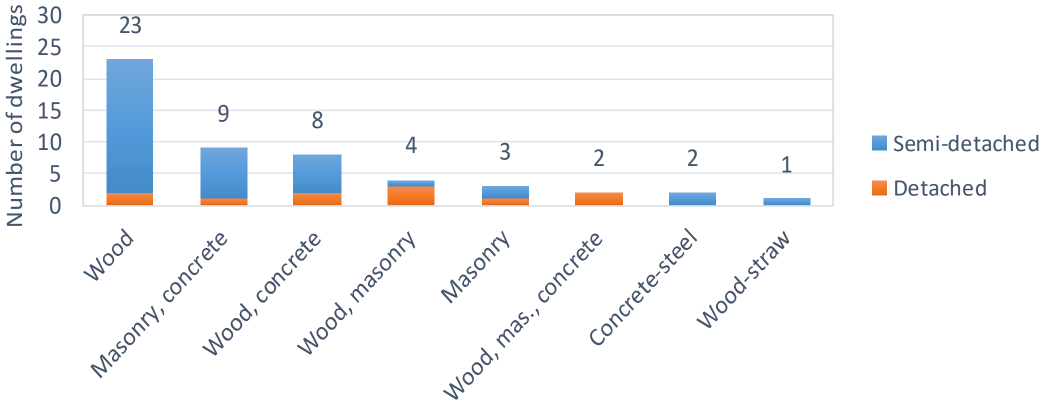


Figure 2.14. Number of SF PH dwellings by structural materials (data source: PEP & PHI, 2017).

With respect to the thermal mass of the houses, they have been studied classifying them into three categories: high, medium and low thermal mass houses. Dwellings are considered as high thermal mass if they had heavy construction elements in the structure and the envelope, low thermal mass if they didn't have any masonry, concrete or heavy wood elements, and of medium thermal mass if they had part of the elements with significant thermal mass. The medium level includes the houses which have heavy structural slabs (e.g. concrete) and also have the rest of the envelope made of lightweight elements (e.g. wooden frame elements). Even though majority of the cases have a low thermal mass, the diversity of cases suggests that there is no clear trend regarding this aspect (Figure 2.15).

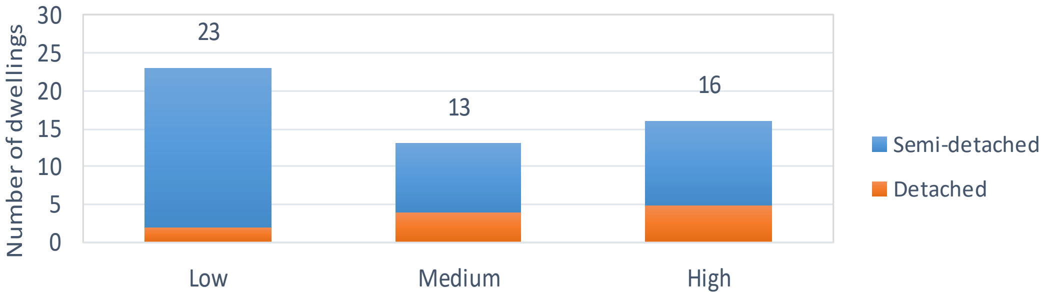


Figure 2.15. Number of SF PH dwellings by thermal mass (data source: PEP & PHI, 2017).

Regarding the materials selected for the windows, the majority of the cases used wooden frames or hybrid wooden-aluminium frames. Only few cases selected PVC units and a single case installed aluminium frames, see Figure 2.17.

Figure 2.16. Examples of wooden structure in “casa entre encinas” (left side) and “Cagical Passivhaus” (right side) (data source: PEP & PHI, 2017).

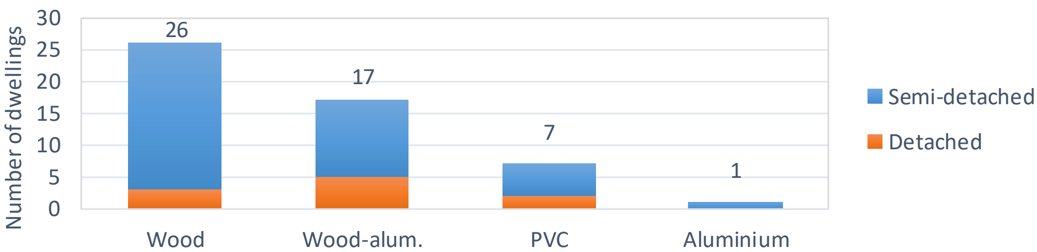


Figure 2.17. Number of SF PH dwellings by window frame (data source: PEP & PHI, 2017).

The ventilation with high ratio of heat recovery (HR) is one of the key principles of PH. For the Spanish cases, the majority of the SF PH dwellings present high HR ratios: between 80% and 85% (Figure 2.18). Some other cases have HR ratios even above 85 % and just a few have HR ratios below 80%.

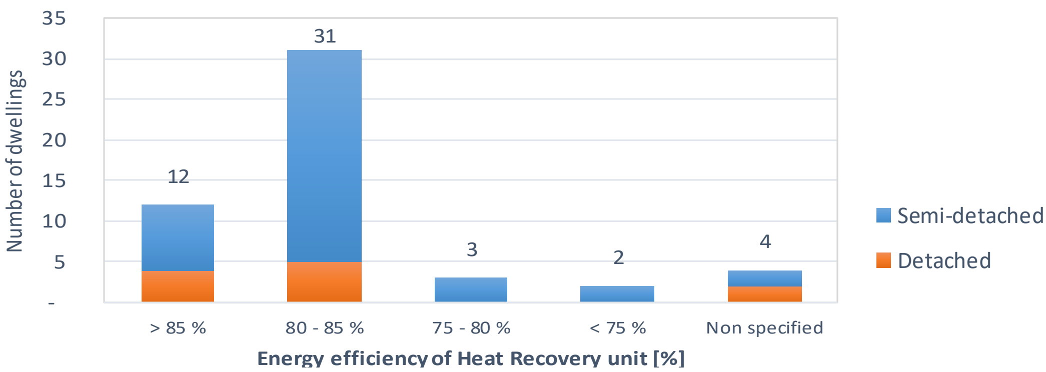


Figure 2.18. Number of SF PH dwellings according to efficiency of HR (data source: PEP & PHI, 2017).

Another key principle of PH is the airtightness of the building envelope. Figure 2.19 demonstrates that majority of the cases achieved the objective of a very airtight enclosure. Unfortunately, around 25% of all the single-family dwellings overpassed the limit.

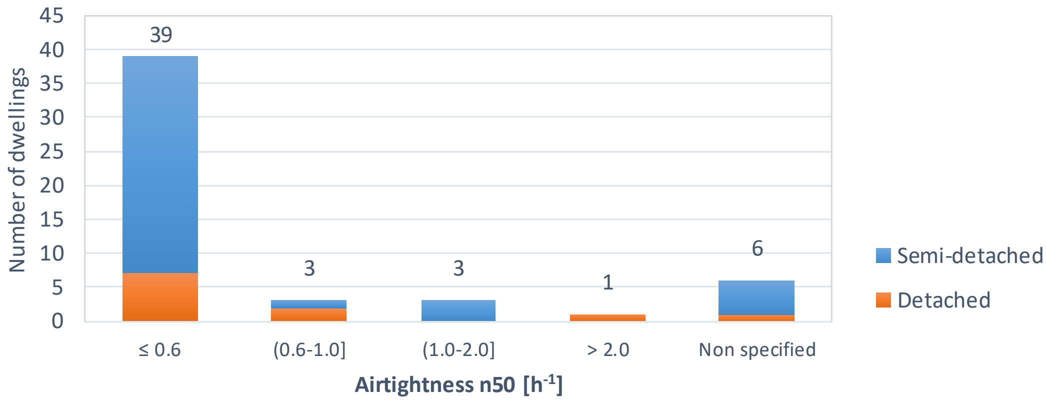


Figure 2.19. Number of SF PH dwellings according to airtightness (data source: PEP & PHI, 2017).

Regarding the types of systems installed in houses, Figure 2.20 shows the frequency of each type and evidence that there is a considerable variety of system types. It is important to notice that many of the cases actually combined two or more systems to satisfy the heating need. The numbers indicate that the majority of the constructions used small electric heaters located in bathrooms or certain spaces of the house to balance the heat distribution in coldest rooms.

Apart from these complementary devices, the most used heating systems are stand-alone pellet stoves and Heat Pumps (HP) connected to a post-heater battery inside the ventilation unit. To a smaller degree, there is a large diversity of systems, including electric post-heaters in the ventilation, Ground Source Heat Pump (GSHP), Canadian wells, pellet boilers and low temperature radiant floors with HP, GSHP or even gas condensing boilers.

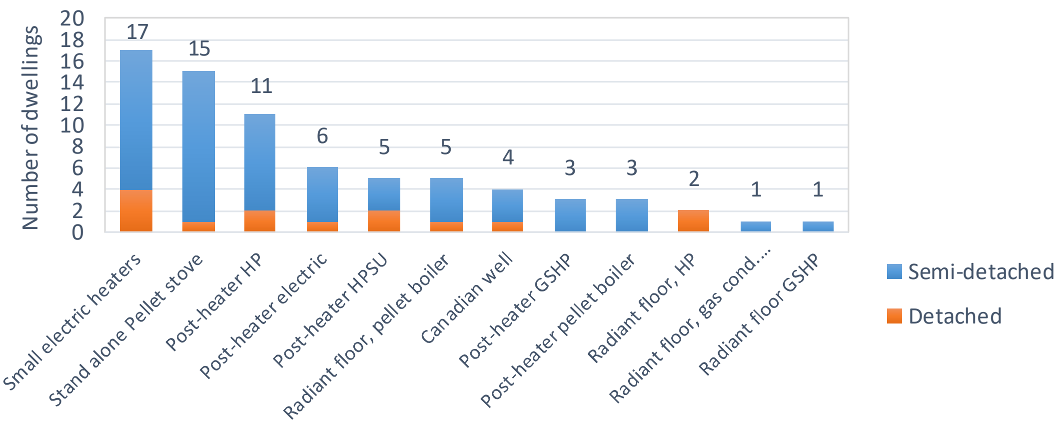


Figure 2.20. Number of SF PH dwellings by heating generation system (data source: PEP & PHI, 2017).

The generation of DHW is handled by a smaller variety of systems. In the majority of the cases DHW is provided by a HP, see Figure 2.21. The other cases used direct electric hot water systems, hybrid heat pump solar units (HPSU), pellet boilers, GSHP or gas condensing boilers. Additionally, many of these systems have support of thermal solar panels, as presented in Figure 2.22. The use of solar systems is generally quite high, however, 40% of the cases don't include any solar contribution.

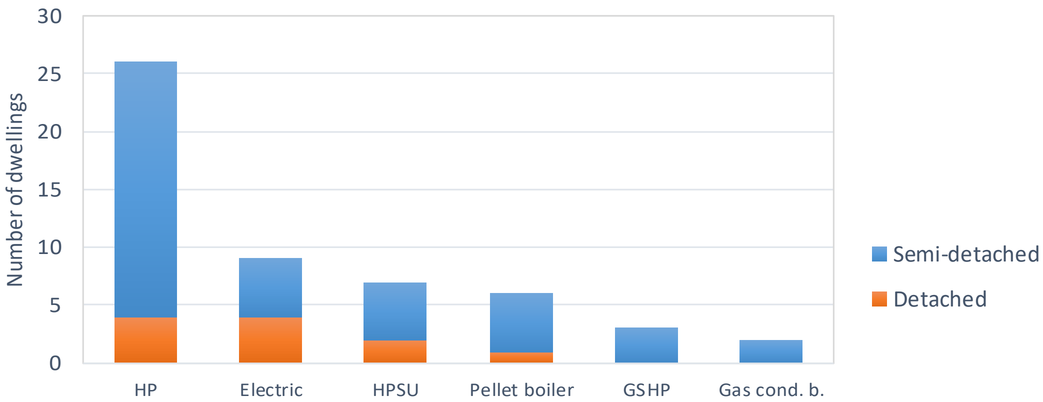


Figure 2.21. Number of SF PH dwellings by DHW generation type (data source: PEP & PHI, 2017).

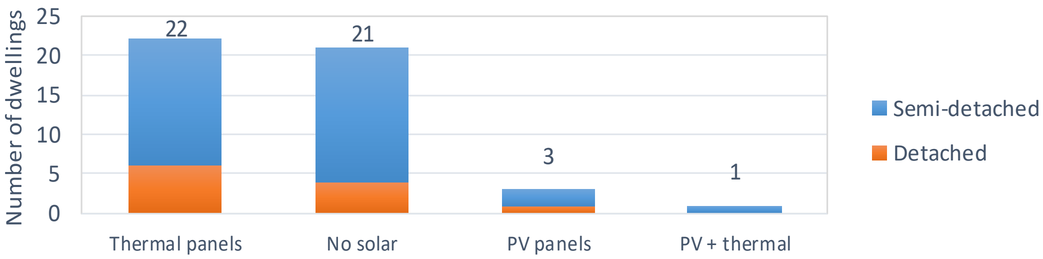


Figure 2.22. Number of SF PH dwellings by solar harvesting type (data source: PEP & PHI, 2017).

Regarding the amount of energy needed for heating and cooling, the majority of the cases have a low heating energy demand: annual values between 10 - 15 kWh/m² and maximum daily heating loads between 10 - 15 W/m², see Figure 2.23.

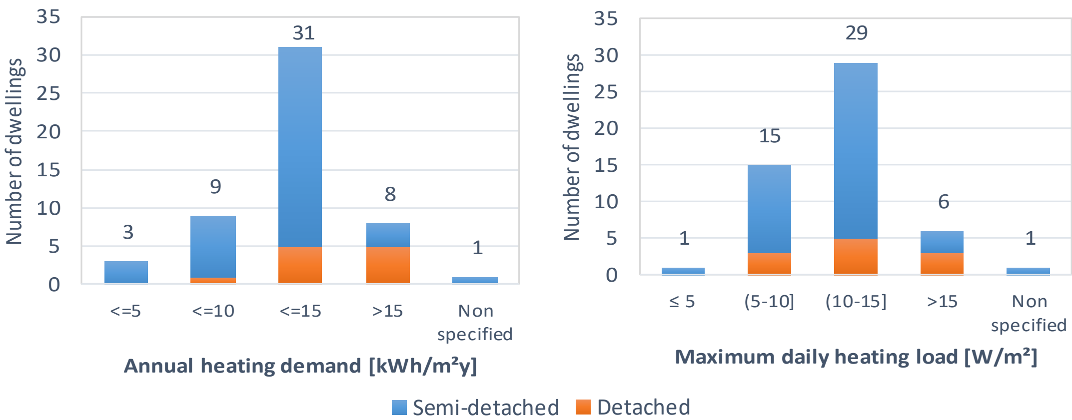


Figure 2.23. Number of SF PH dwellings according to heating needs (data source: PEP & PHI, 2017).

In general, houses don't include any cooling system. Only 29% of the cases have post-cooling batteries connected to HP units, that is 12 cases out of 52, see Figure 2.24.

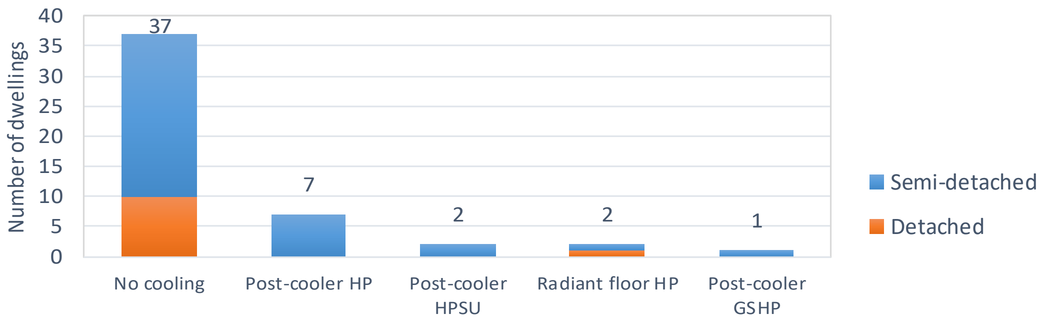


Figure 2.24. Number of SF PH dwellings by cooling types (data source: PEP & PHI, 2017).

To understand this lack of cooling system, Figure 2.25 indicates that majority of the cases have very low cooling loads, below 5 W/m², and this reduced cooling load can be easily compensated by occasional natural ventilation. In a similar way, the ranges of annual cooling demand are also low or very low - below 5 kWh/m²y. In any case, there is a larger uncertainty than with respect to heating analysis because many of the cases didn't specify their cooling needs.

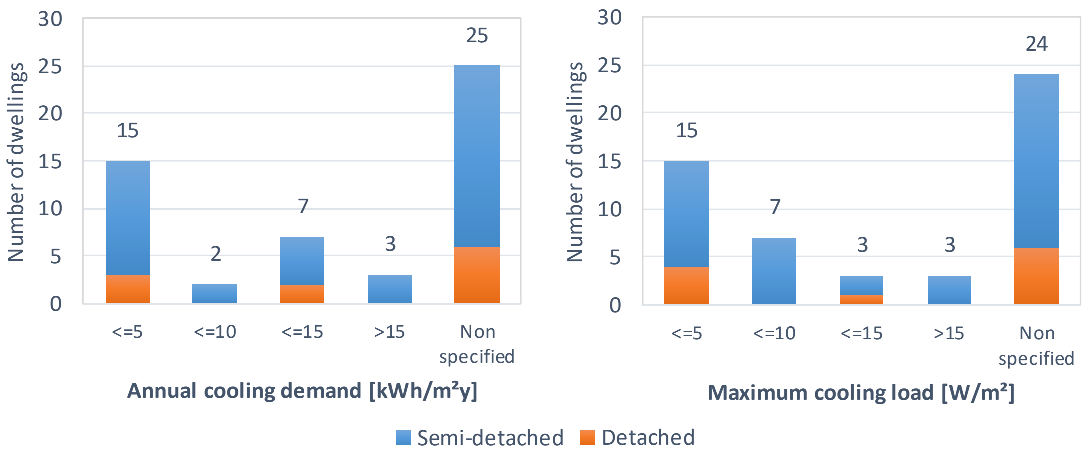


Figure 2.25. Number of dwellings according to the cooling needs (data source: PEP & PHI, 2017).

As a consequence of the high performance of all the analysed cases, the annual Primary Energy use (PE) of almost all the cases fulfils the PH primary objective of 120 kWh/m²y. Actually, only one case overpasses the limit, as seen in Figure 2.26.

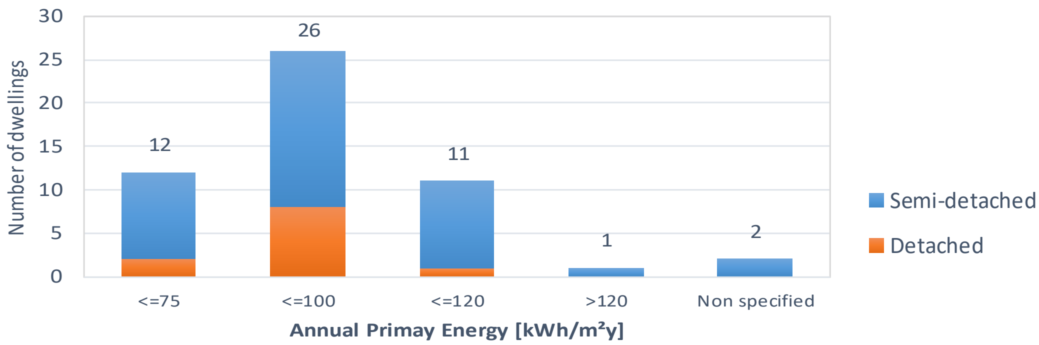


Figure 2.26. Number of SF PH dwellings according to annual PE (data source: PEP & PHI, 2017).

Regarding the cost of construction, it is commonly around 1000-1200 €/m². However, this value can be affected by the large number of non-specified cases, as shown in Figure 2.27.

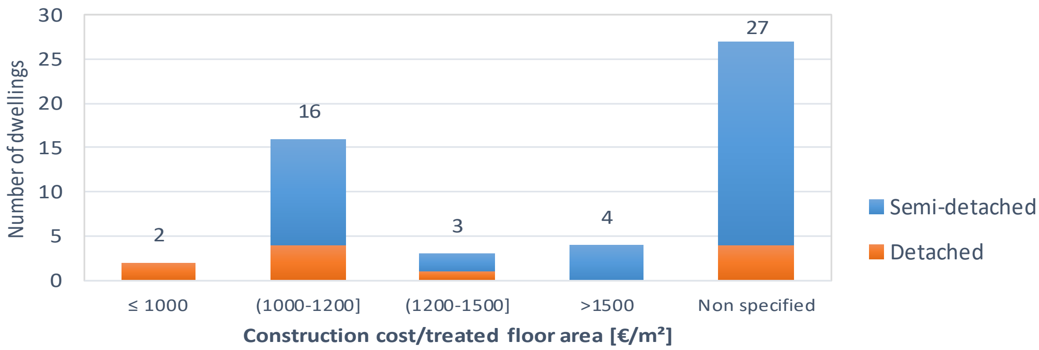


Figure 2.27. Number of SF PH dwellings according to construction costs (data source: PEP & PHI, 2017).

After the analysis, the most frequent characteristics of these houses were used in Chapter 5 to define the reference simulation models to evaluate their potential and limitations, see Table 2.7.

Table 2.7. Average values of single-family PH dwellings in Spain (data source PEP & PHI, 2017).

General features or average values	Detached	Semi-detached
Number of buildings in Spain	41	11
Number of floors	1.7	2.1
Net floor area [m²]	161	153
Structure materials	Wood	Wood. masonry
Type of construction	New	New / renovated
Passivhaus certified	Yes	No
Thermal mass	Low	High
Construction thermal insulation		
U wall [W/(m²K)]	0.204	0.168
U ground [W/(m²K)]	0.290	0.243
U roof [W/(m²K)]	0.172	0.146
U window [W/(m²K)]	1.109	1.102
U frame [W/(m²K)]	1.159	1.199
U glass [W/(m²K)]	0.767	0.780
Window g-value	0.53	0.51
Window frame material	Wood	Wood-aluminium
Ventilation and airtightness		
ACH 50 Pa [h^{-1}]	0.57	0.77
MVHR Maximum air flow (m3/h)	341	337
HR sensible recovery efficiency [%]	91.9%	92.0%
HR efficiency PHI method [%]	82.4%	85.2%
Bypass	Yes	Yes
Systems definition		
Heating systems	Pellet stove. post-heater HP and small electric heaters	Post-heater HP and small electric heaters
Cooling systems	No cooling	No cooling
DHW generation	HP	HP / electric
Heating thermal power [kW]	5.7	9.3
Hot water storage [l]	261	250
Solar harvesting	Thermal panels	Thermal panels
Other devices	-	-
Building energy needs		
Heating, annual demand [kWh/m²y]	12.4	17.1
Heating, max. daily load [W/m²]	12.1	12.8
Cooling, annual demand [kWh/m²y]	7.1	5.2
Cooling, max. daily load [W/m²]	6.6	3.2
Primary Energy annual use [kWh/m²y]	88.7	80.0
Construction costs		
Average cost per treated floor	1283 €	1075 €

2.2.3. Monitored single-family passive dwellings

After the analysis of the main principles of Passive House design, the present section aims to review the real monitored performance of this typology of dwellings and compare the theoretical calculations of PH projects with the real monitored performance.

The Passive House Institute (PHI) has made many studies regarding the real performance. One of the most relevant monitoring campaigns was conducted by the CEPHEUS project (Cost Efficient Passive Houses as European Standard), carried out from 1999 to 2001. the purpose was to extend the PH standard and demonstrate that it was suitable for the future social, ecological and economic sustainability (Schnieders, 2003).

This study was based on 14 projects with a total number of 221 dwellings to monitor. The majority were located in Germany and Austria, but also in Switzerland, France and Sweden. Different typologies were included, such as single-family and multifamily housings, as shown in Figure 2.28 below.

Figure 2.28. CEPHEUS project monitored cases (taken from Schnieders, 2003).

The heating consumption was monitored from November to February and the results were normalised to a standard value of 20 °C (Figure 2.29). The average consumptions were considerably over the expected value of 15 kWh/m²y. The average values of each location ranged from the lowest 12.3 kWh/m²y in Hörbranz, to the highest 35.4 kWh/m²y in Egg or 35.1 kWh/m²y in Gnigl. The average heating demand of all the locations was 24.8 kWh/m²y, what means an increase of 9.8 kWh/m²y or an additional 65% of energy need.

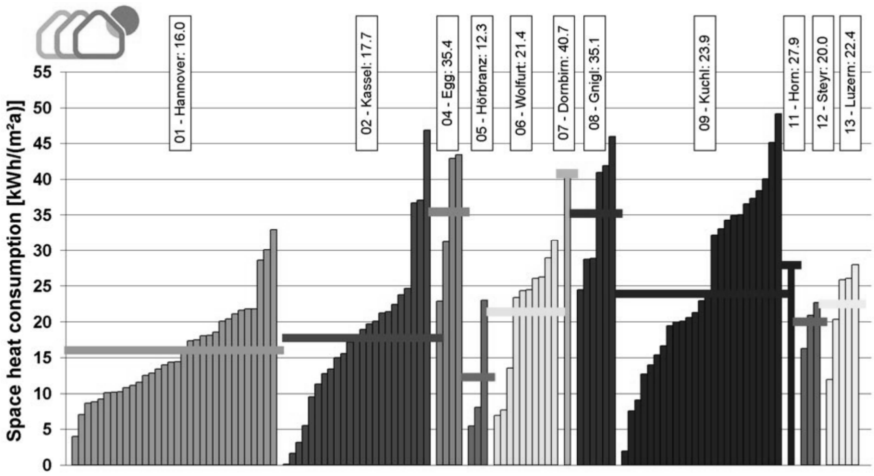


Figure 2.29. Measured space heating consumption of CEPHEUS dwellings, measured data normalised to 20 °C (taken from Schnieders, 2003).

In any case, the results showed the influence of occupant's behaviour and the final behaviour and the PHI made additional efforts to explain to the users how to use properly their passive houses (Hopfe & McLeod, 2015).

The next EU funded project was the Passive House Regions with Renewable Energies (PassReg) (PassREg, 2015). The project was developed from 2012 to 2015 and the focus was kept on making the Passivhaus solutions more accessible and implementing Renewable Energy Technologies into ultra-low energy buildings. Around 30 sites in 11 European countries were included in the project. One of the outcomes of this project was the new definition of PH Classic, PH Plus and PH Premium. Unfortunately, for now there is no monitored information about these cases.

More recently, between 2013 and 2016 the EuroPHit project was coordinated by PHI and PH related institutions with EU funding. This project was oriented to demonstrate the possibilities to refurbish the existing buildings in Europe in line with EU 2020 objectives. It defined how to conduct step-by-step refurbishment processes applying the PH principles. 13 buildings were renovated in all Europe, including four cases in Spain (see the database of previous Section 2.2.2). The outcome of the project was a series of examples showing how to turn the building stock into nZEB. Part of the monitored data was published in the International Passive House conference in 2016 (I.P.H. conference, 2016), but as the cases are being renovated step-by-step, the results will be presented in the future editions.

Regarding the scientific publications, analysing the real monitored behaviour of passive houses, there are some studies measuring the heating performance. However, only few of them involve a thermal comfort approach. In the following paragraphs, the cases which involve thermal comfort monitoring of Passive houses in different European climates are summarised.

One of the first passive houses constructed in Denmark was monitored for two years by (Larsen & Jensen, 2011). The authors found out that “several house owners from the first generations of Danish passive and low energy houses had overheated houses during several months during the summer period”. They provided some guidance about design stage verification with a simplified “24- hour average” method to calculate the average indoor temperatures. However, they recognised that the prediction of the maximum temperatures with this tool were still not accurate. They also analysed the thermal behaviour with dynamic simulations and concluded that a detailed calculation with summer occupant behaviour patterns would be sufficient to predict the real risk of too warm indoor environments.

There are several studies conducted in UK, probably motivated by the higher awareness about OH risk after the heat wave of 2003. The first PH certified new house in UK was studied in detail by Ridley et al. (Ridley et al., 2013). It was based on a detailed analysis of the electricity use and indoor environment conditions. After the monitoring, they concluded that the Camden Passive House presented a good performance, in correspondence with the PHPP calculations to a great extent. The work suggested that with careful design, robust testing and commissioning of heating and hot water services, it should be possible to deliver dwellings with total energy consumption of 60 kWh/m^2 in the UK. They also underlined some measured higher internal gains of 3.65 W/m^2, which means 43% more than the standard PHPP value of 2.1 W/m^2. The measured thermal losses with a co-heating test were lower than the project calculations. The study is very detailed and it also analyses other aspects, like the CO_2 levels, the electricity use or DHW consumption. Regarding the OH, the house failed CIBSE, PHPP and EN 15251 overheating criteria. However, the occupants reported a positive summer environment and didn’t complain of overheating or any cool winter periods. As a solution, frequent natural ventilation and solar shading would be advisable, but occupants didn’t plan to modify their use of blinds or ventilation patterns.

Another comparative study conducted in UK (Ridley, Bere, Clarke, Schwartz, & Farr, 2014) analysed two analogous houses in Wales, one built following the passive house standard and anther as a low carbon house. They monitored the performance of the houses for almost 2 years and analysed the differences between both houses, as well as between occupants' behaviour, paying special attention to summer overheating aspects. The study demonstrated that both houses have much larger internal gains than the PHPP design calculations, namely 6 W/m² and 5 W/m² in contrast with the PH typical value of 2.1 W/m². They analysed the origin of these deviations and discovered that many appliances in the houses were poorly energy efficient. Overall, they recommend verifying the summer OH risk at design stage with internal gains of 4.0 W/m², to detect risks before construction and install efficient passive cooling measures. They found many user behaviour issues, including winter natural ventilation and insufficient solar shading, which provoked considerable discomfort hours. The authors also analysed the target of PE consumption (120 kWh/m²) and estimated that social conventional usage should be reduced by approximately 25% – 45% without any PV panel generation or 13% – 34% with PV generation. The authors acknowledged that this study of two cases is limited, but as the number of passive houses in the UK was still relatively small, they considered it as a good first step for passive house research in the UK. It showed the performance of some of the first buildings and identified insights and research themes. The findings might be useful to the passive design and construction sector, and they should be explored in larger samples in the future.

More recently, another study in the UK monitored 4 low energy social dwellings for 2 years (Sodagar & Starkey, 2016). The dwellings were designed to meet the Level 5 of the Code for Sustainable Homes (the required performance would be similar to EnerPHit targets). The total gas use (heating and DHW) in the houses was 29%, 93%, 16% and 22% higher than the predictions. The families displayed significant differences with respect to their behaviour and activities at home, which affected the thermal comfort and the energy and water consumptions. The Post-Occupancy Evaluation (POE) also confirmed that the impact of occupants' behaviour on the real energy use was substantial. They recommended that focus should shift towards adopting a socio-technical approach to the procurement of sustainable low-energy homes, instead of too much reliance on technology alone.

Another house in Oslo was monitored two identical PH with two different renewable technologies for heating and DHW (Rekstad, Meir, Murtnes, & Dursun, 2015). One house was equipped with solar thermal heating and the other house with an air-to-water heat pump (HP).

The auxiliary heating demand was found to be below the PHPP calculations and the internal average temperatures were over 22 °C every month during the cold season. The overall results showed that solar thermal heating could be competitive to heat pump technology in the buildings for the Nordic climate. One major weak point was found to be the under-dimensioned 76 l DHW boiler, which operated at very high temperature and caused the increase in thermal losses.

One more study of a passive house located in Næstved (Denmark) used the monitored data to calibrate a Building Energy Performance Simulation (BEPS) (Paliouras, Matzaflaras, Peuhkuri, & Kolarik, 2015). They showed the steps to calibrate a model using Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)). As authors explain, new measures or improvements can be implemented in order to improve the thermal comfort or avoid OH in the house. This method was also used to adjust and calibrate the model of the case study analysed in the present theses and is presented in Chapter 4.

Another PH monitoring case showed how to complement the monitored data gaps with building energy simulations (Rehab et al., 2015). This study didn't present thermal comfort details, but verified the annual energy balance of the house. The authors used a model in TRNSYS to identify all the energy flows in the annual performance of the passive house. The tools and adjustment methods presented in this work were a good base for the Chapter 4 of the present thesis.

Regarding warmer locations, there is an extensive study conducted in the first PH built in Cyprus (Fokaides, Christoforou, Ilic, & Papadopoulos, 2016). The monitoring included air temperature, air velocity and relative humidity values in four thermal zones. They detected some initial overheating problems in all zones during summer. These issues were partly solved using natural night time ventilation. This study presented some insightful details about the commissioning of a low energy house in warm climates.

Another work conducted in Portuguese climate monitored during short periods of one or two weeks a passive house under real occupancy (A. Figueiredo, Kämpf, & Vicente, 2016). These periods were used to calibrate a model and analyse the annual performance. The purpose was to test the performance of this typology in 4 regions of Portugal and assess the adaptability of PH design to local climates. This study was a good base to define the simulation series of Chapter 5.

2.3. Global warming and future climate scenarios

The future climate scenarios for Europe indicate a great risk of extreme conditions in southern Europe. For example, heat waves or storms are predicted to have a direct impact on economies, agriculture and fresh water availability (Climate NASA Gov., 2017), see Figure 2.30. At the construction level, these scenarios will increase the overheating risk (McLeod et al., 2013).

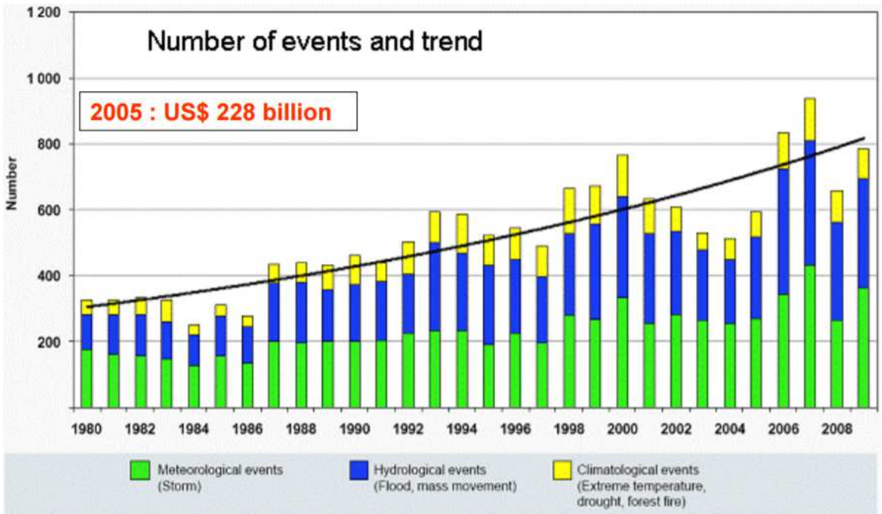


Figure 2.30. EU roadmap 2050 information about CC threatening future economic growth (taken from EC DC Climate Action, 2017).

The climatic conditions are going to keep changing in the upcoming years, this is the first fact architects and engineers should be aware of. The XXI century is a period affected by an anthropogenic global warming, which means that the climatic conditions are becoming warmer for future decades. The consensus about this fact is overwhelming: more than the 90% of the studies published during the last decade have concluded that the causes of this phenomenon are mainly human-related (Cook et al., 2016). Figure 2.31 and Figure 2.32 represent a variety of indicators of global warming and shows the impact of climate change on temperatures, sea level, sea ice extension, snow cover and glacier mass. This humongous evidence explain why the biggest economies in the world have finally joined in a real committing agreement in Paris in 2016 (UNFCCC, 2015). This way, all the countries are obliged to reduce the emissions of greenhouse gases (GHG) to a great extent and also to implement mitigation measures worldwide. There are specific common funding programmes for the developing countries. The reasons to act now were already explained in the Stern review on the Economics of Climate Change of 2006 (Stern, 2006). That well-known study compared the costs of early action to the business as usual (BAU). The conclusions showed a clear benefit of early actions.

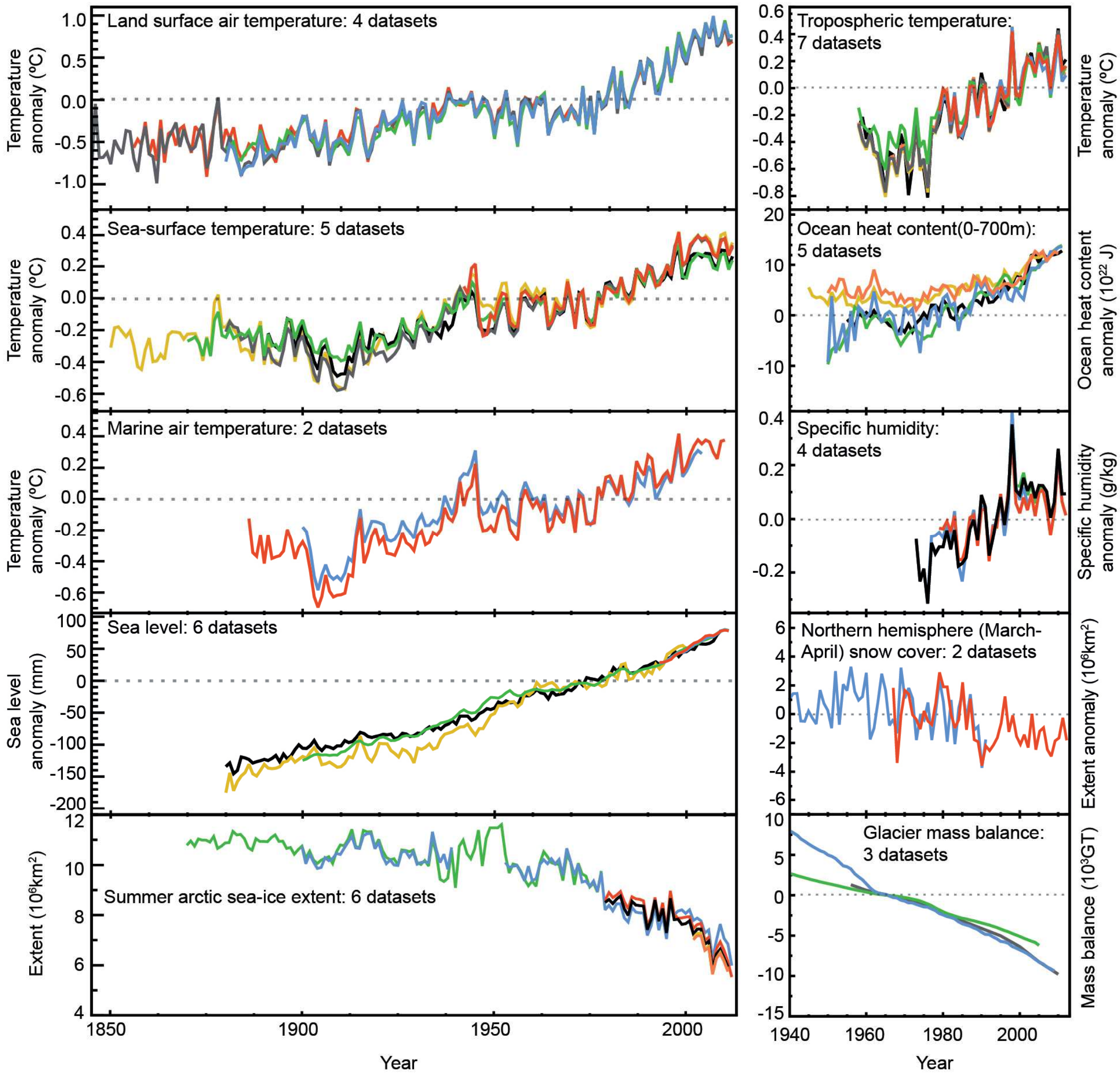


Figure 2.31. Global warming scenarios (source FigTS-15 of IPCC, 2013).

According to World Meteorological Organization (WMO), the measurements indicate that the global average temperatures have raised approximately 0.6 °C during the last century and 2001-2010 was "the warmest decade on record since modern temperature monitoring began around 160 years ago" (WMO, 2013). The future projections estimate a faster increase of temperatures in next decades with different scenarios according to the actions taken from now on. In the best scenario, the warming is already around 1 °C (CIMP5 simulations, RCP2.6) while the worst scenario attains three times higher increases, around 3.7 °C (CIMP5 simulations, RCP8.5).

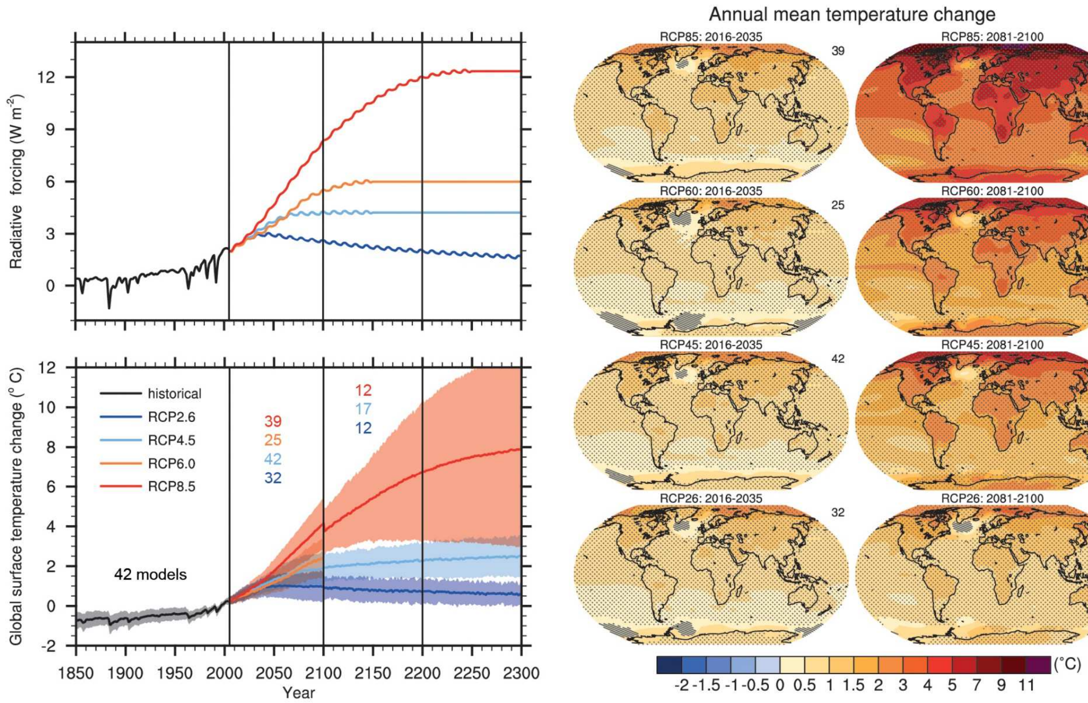


Figure 2.32. Global warming scenarios and temperature increase with different scenarios
(source FigTS-15 of IPCC, 2013).

With regard to building design, the increase of temperatures has already affected directly to the heating and cooling demand. Figure 2.33 shows how all the European countries have reduced their Heating Degree Days (HDD) since the 80s. This change is higher in the northern countries which usually had a bigger heating need.

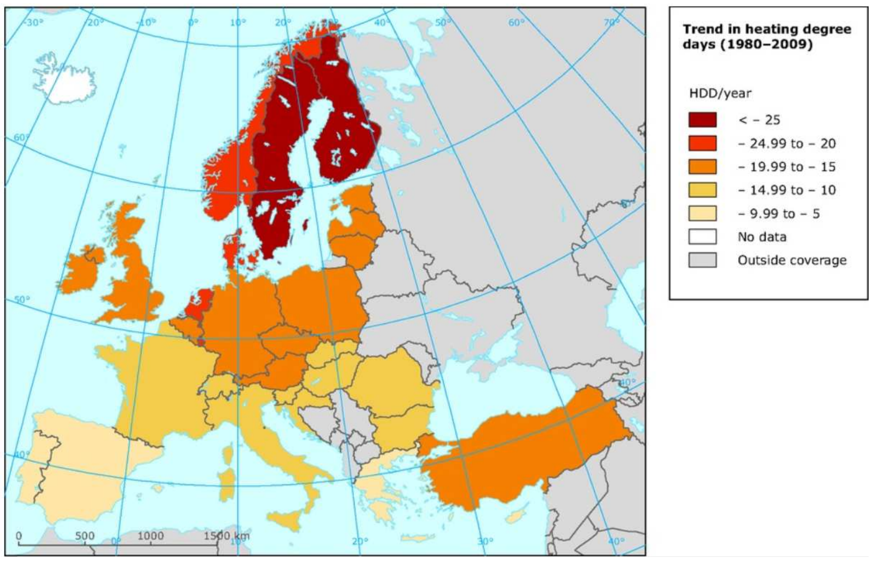


Figure 2.33. Trend in heating degree days in the EU-27 (1980-2009) (source EEA & EUROSTAT).

In a closer look, the average values of HDD and CDD of EU countries indicated that the change begun in the 80s of the XX century, see Figure 2.34. It shows a considerable reduction of HDD and a smaller increase of CDD. For now, the CDD value is considerably small, but it is worth paying attention to the ratio between HDD/CDD which was reduced by half in the last 30 years, namely from 34 to 17. Since 1983, there was an average reduction of 10 HDD per year and an increase of 0.7 CDD per year.

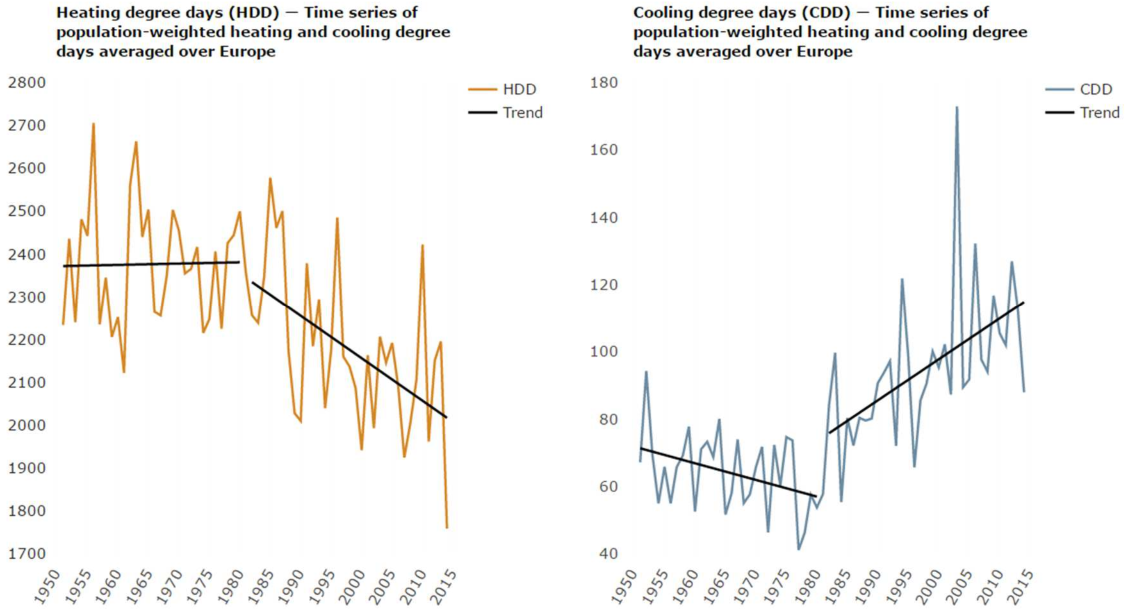


Figure 2.34. Weighted HDD (left side) and CDD (right side) in EU (1950-2015) (source EEA & EUROSTAT).

Apart from the aforementioned increase of the average temperature, all the studies announce that the extreme events like heat waves will occur with a higher frequency and longer duration in the future (IPCC Table SPM.1, 2013) (WMO, 2013). The reason is explained briefly in Figure 2.35. This future background will complicate the design of highly insulated buildings (Zaki, Nawawi, & Sh.Ahmad, 2012) due to their small cooling loads and long response time. Indeed, all constructions will have to deal with longer and more frequent heat waves in the close future.

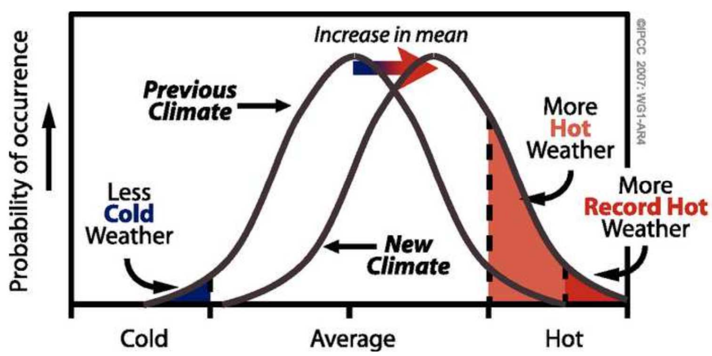


Figure 2.35. Extreme events (source IPCC WG1 AR4, 2007).

Unfortunately, there is strong evidence showing that the worst scenarios of IPCC are probably going to be real (IPCC et al., 2013). A revised study of the atmospheric CO_2 concentrations indicated that most likely the CO_2 levels will remain over 650 ppm by the end of the present century (Anderson & Bows, 2008). In such scenario, the temperature increase will largely overpass the expected increase of 2 °C of the global warming and it will highly likely reach a dangerous increase of 4 °C (Meinshausen, 2006).

This proven change of the heating and cooling needs is one of the most challenging aspects for nZEB design. It can become especially critical due to the more frequent heat waves and the exposure of highly insulated buildings to longer warm periods without enough night cooling. A deep study (McLeod et al., 2013) applied a parametric study for passive houses and low energy dwellings in the UK and evidenced how the warm discomfort will increase in the future decades. It pointed out that low energy houses in the UK can face severe risks after 2050, with significant number of hours with indoor temperatures over 28 °C. The authors warned about the importance of including the future scenarios in the present designs: "*Unless there is a move towards whole life design optimisation based on minimising future over- heating risks, active cooling systems may become a de-facto requirement in urban Passivhaus and low energy dwellings in the UK within the next 30-40 years*". The authors suggested that the consequences of the climate change in buildings are exponential, as presented in Figure 2.36 below.

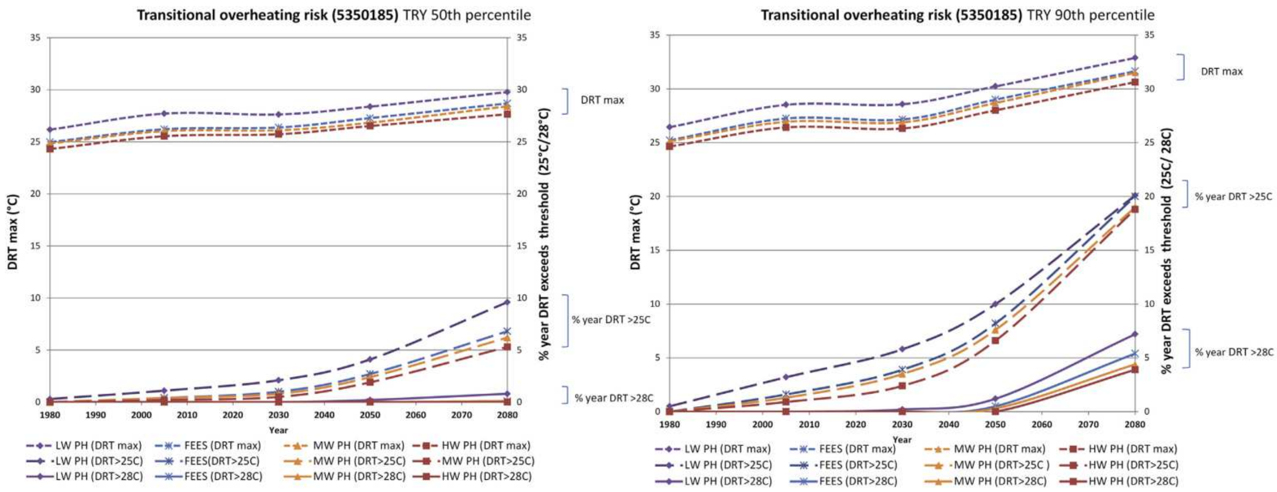


Figure 2.36. Transitional overheating risk for 4 dwellings at 50th (left) and 90th (right) percentile TRY under 'High Emissions' scenario (1980e2080) (source McLeod et al., 2013).

One of the last books for PH designers (Hopfe & McLeod, 2015) also underlined the influence of climate change in passive house design and pointed to possible variations of heating and cooling needs, see Figure 2.37.

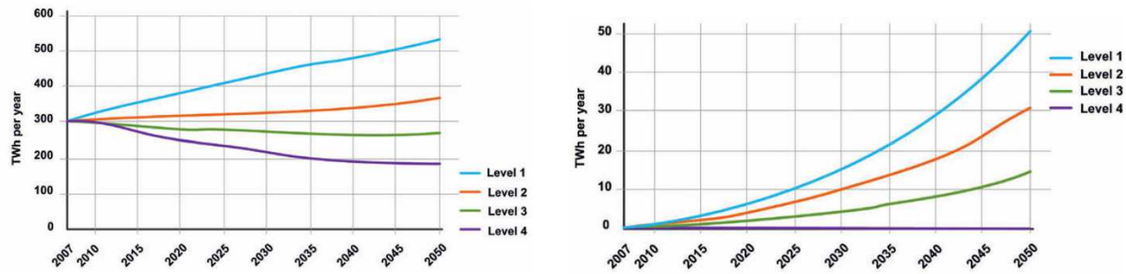


Figure 2.37. Trajectories for total domestic heating demand (left side) and cooling demand (right side) under four levels of climate change in the UK (taken from Hopfe & McLeod, 2015).

Consequently, if the IPCC A2 scenario becomes true, the European climates would become warmer and the climate of European cities wouldn't be the same at all. A study presented by EUROSTAT in 2014 showed the apparent climate shift between 2070 and 2010, which would reconfigure the location of the main capitals in similar climates of the present, see Figure 2.38.

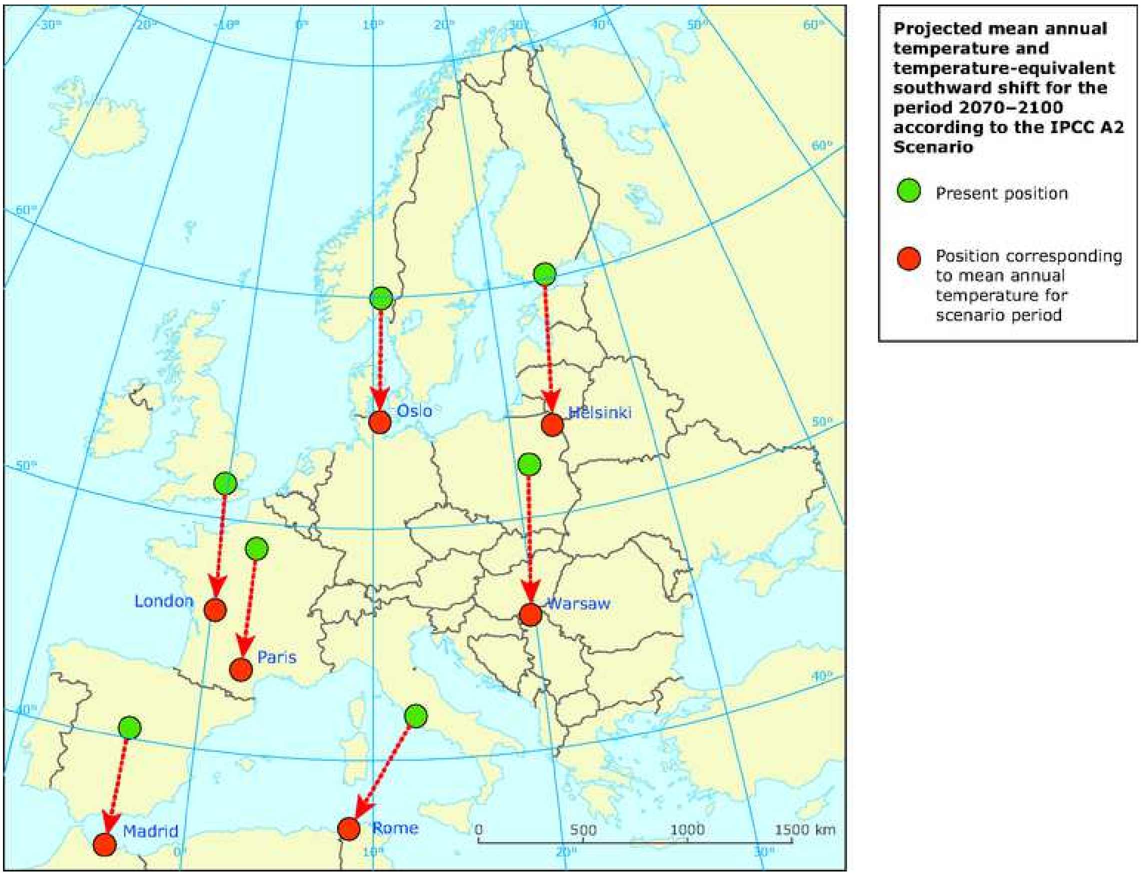


Figure 2.38. Apparent southward shift of European cities due to climate change, 2070-2100 (source EUROSTAT, 2014).

In a local context, the Spanish Meteorological Organization AEMET (AEMET, 2016) has also calculated a number of scenarios for the largest Spanish cities (Morata Gasca, 2014). They are based on three Representative Concentration Pathways (RCP) of the last assessments of IPCC (IPCC, 2013). All the scenarios conclude that northern regions of Spain will face a considerable warming. As an example, Figure 2.39 shows the future conditions of Bilbao, Burgos and Madrid. These cities represent the variety of climate conditions in the Atlantic and continental areas of northern and central Spain. Accordingly, the constructions located in northern and central Spain will have to face a significant change. By the end of 2050, the maximum temperatures in Spain will probably increase by 2 °C and the duration of heat waves will be two or three times higher than at the present.

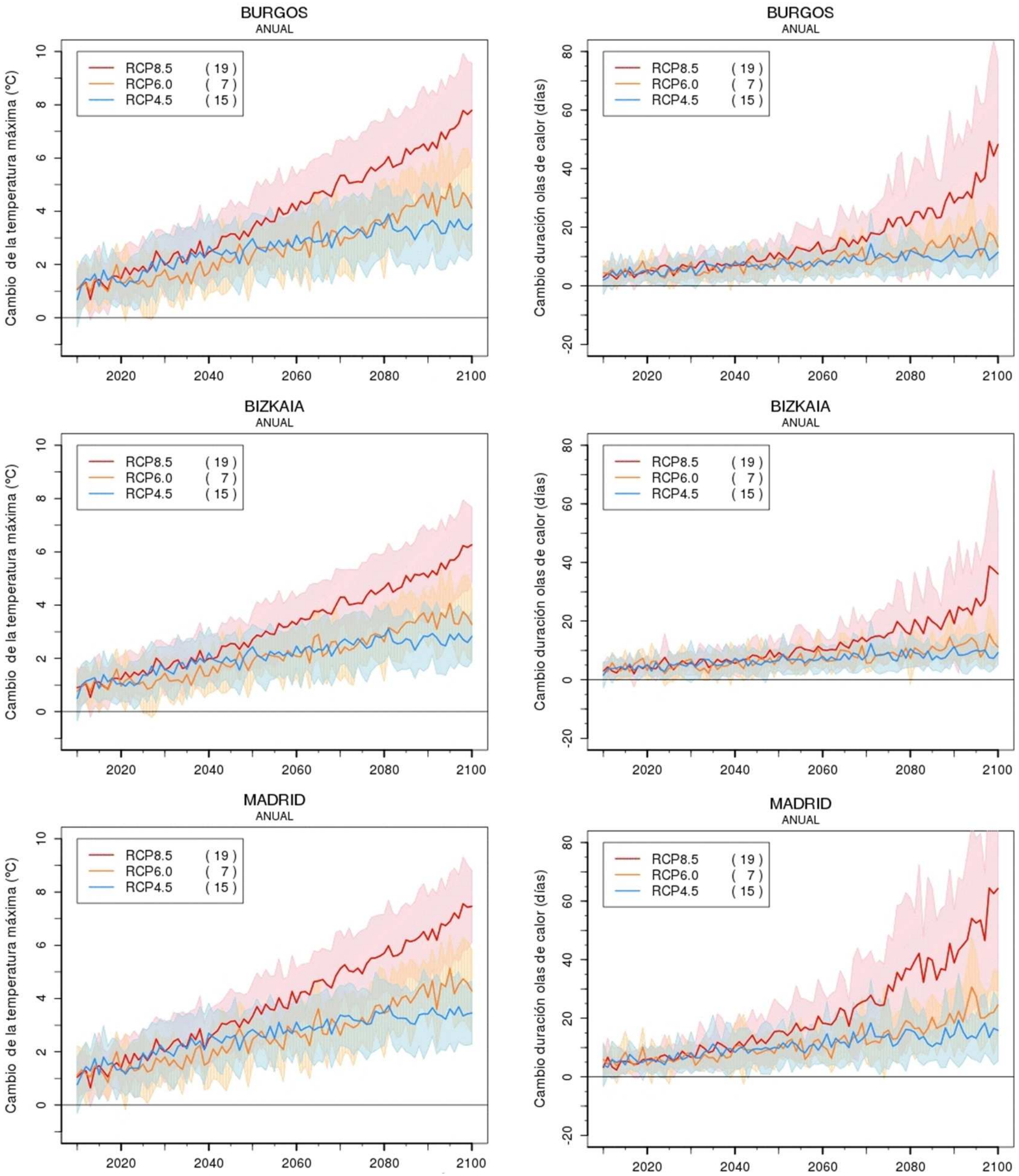


Figure 2.39. Future climates of Burgos, Bilbao and Madrid, showing the change of the maximum temperatures (left side) and the length of heat waves (right side) (taken from AEMET, 2017).

A recent thesis analysed in detail the adaptability of multifamily blocks designed according to present Passivhaus criteria in the Basque region and Navarra (Rodriguez Vidal, 2015). The research presented a large amount of results and included the assessments of passive house apartments in the scenarios of the IPCC for 2040 and 2080. According to its conclusions, there will be serious difficulties of OH in the majority of the analysed cities due to long warm periods without night-time cooling potential. Also, the problems related with excess of humidity in coastal locations were highlighted.

One of the main findings of the work conducted by Rodriguez was that after 2080, many of the cities will probably require the use of cooling systems in the houses to be able to reduce the hottest hours of summer. Figure 2.40 below shows the number of hours when indoor temperatures are over 25 °C in the case of an apartment with North-South orientation and using night natural ventilation. It includes the present and future climates for many cities in the North of Spain and demonstrates the expected high increase in 2080. This may be very complicated to solve in buildings without any cooling system, especially if the CO_2 emissions keep the trend of medium-high emissions scenarios (A1B or A2).

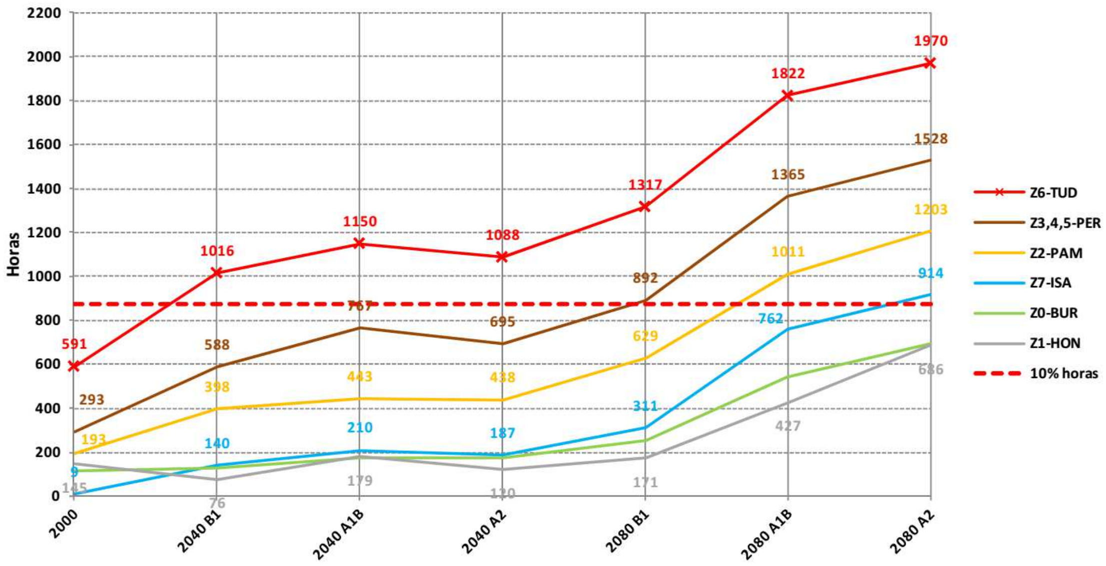


Figure 2.40. Climate change scenarios in several northern Spanish cities, number of hours over 25 °C in a North-South oriented apartment with intensive night natural ventilation. Present climate (2000-2009), 2040 (A1B, A2 and B1) and 2080 (A1B, A2 and B1) of Meteonorm (taken from Rodriguez Vidal, 2015).

For all the presented reasons, it is crucial to verify the resilience of the new projects to the upcoming conditions of global warming. The present thesis includes the analysis of some cases within the main scenarios developed by the IPCC. To do that, the data of the B1, A1B and A2 scenarios for 2040 and 2080 was obtained from METEONORM data series.

2.4. Thermal comfort and overheating assessment methods

The Thermal Comfort (TC) in buildings is an essential part of the Indoor Environment Quality (IEQ) and it is considered as one of the key principles of the EU nZEB strategy. For instance, the last EC recommendation for the EPBD strategy compelled MS to ensure the TC and IEQ as a compulsory condition to achieve the low energy requirements of nZEB: "*Proper indoor environment should be ensured to avoid deterioration of indoor air quality, comfort and health conditions in the European building stock*" (European Commission, 2016b). A literature review on how different factors affect human comfort in indoor environments, concluded that "*building users consider thermal comfort to be the most important parameter influencing overall satisfaction with IEQ*" (Frontczak & Wargocki, 2011).

This concept indicates the degree of satisfaction of users with regard to the indoor thermal conditions. This means that this concept is rather complex because it relates a number of physical parameters with the uncertainty of human feelings and individual behaviour. In the technical-scientific world, it is commonly defined as "*that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation*" (ASHRAE, 2013b).

In the beginning, the studies of TC were focused on predicting the best indoor environments for workers, as a way to increase their productivity. In late 60s, Fanger published what it would become the reference for many years later on (Fanger, 1970). This method permitted to predict the response of the majority of people inside a certain thermal environment with specific activities and clothing levels. This was especially useful for HVAC designers to define and dimension the HVAC systems. Since then, many other studies proposed improvements for the PMV model in order to extend the application of the PMV model to a larger variability of people needs and other climates. These publications were summarised in a review after the 40 years of PMV model applications (Van Hoof, 2008). In brief, this review reminds that the PMV was validated through many studies during following decades. At the same time, it also referred to many studies which revealed discrepancies of PMV or PPD estimations, the range of application, the value for the neutral thermal comfort, etc. This collection of works confirmed that after 40 years of practical experience, the PMV model can be trusted as one of the best tools to assess TC in mechanically cooled or heated buildings.

However, the aforementioned review also recognised that TC is affected by numerous aspects and it may need additional verifications if the particular conditions of a case differ greatly from the assumptions of the PMV model. One of the possibilities, suggested to compensate this personal discomfort risks, was the implementation of individual controls. This way, it states that it should be possible to create indoor environments that provide nearly 100% acceptability and comfort to all, based on the PMV model.

Accordingly, the present calculation methodologies are based on decades of testing and statistical studies about personal human feelings inside buildings and climate chambers, as described in (Carlucci, 2013) (Tabatabaei Sameni, Gaterell, Montazami, & Ahmed, 2015) (Danca, Vartires, & Dogeanu, 2016). It depends on a large number of personal and surrounding factors and it is limited by possible local discomfort situations. The main inputs or factors to evaluate TC according to PMV model are included in Table 2.8 and it also includes some local discomfort conditions included in (ISO 7730, 2005).

Table 2.8. Main indoor factors of PMV model and local discomfort conditions (source ISO 7730, 2007).

PMV model		**Local discomfort conditions**
Personal factors	**Environmental factors**	
Activity level	Air dry bulb temperature	Air stratification
Clothing insulation	Mean radiant temperature	Radiant temperature asymmetry
Thermal sensitivity	Relative humidity	Draft
	Air velocity	Floor surface temperatures

Apart from the mainstream PMV model, there is a number of international standards and methods to assess TC with different criteria and weighting factors. Carlucci made a long review and a classification of the methods (Carlucci, 2013). He differentiated methods based on the heat balance of the human body, the physiological strain or the physical parameters. He also reminded that the assessment can be referred to specific instant conditions or to a long-term evaluation. He also proposed new methods to integrate the personal feelings and physical parameters in a general evaluation.

Another relevant question in the TC assessment is the importance of the surroundings. Even though PMV model focuses on indoor parameters, it is also recommended to study the outdoor conditions which can affect the users' perception of comfort. This approach is known as the adaptive method and at present it is defined by two similar standards in American regulation

(ASHRAE, 2013b) and European regulation (EN-15251, 2007). Table 2.9 below summarises the most common methods to assess TC. The present study compared the obtained results with the Fanger and adaptive methods applied to a northern Spanish passive house and discussed the applicability of them and the challenges for future nZEB single-family dwellings.

Table 2.9. Most common Thermal Comfort assessment methods for buildings.

TC methods	Year	Description
Fanger (PMV/PPD)	1970	Based on the heat balance of human body, calculates the instant indoor comfort range with formulas applicable only for spaces with heating/cooling.
ISO 7730	2005	Updates the Fanger method with several types of long-term evaluation and local discomfort conditions.
EN 15251	2007	Based on Fanger, it specifies the adaptation limits in free-running or naturally ventilated buildings, according to the outdoor running mean temperature.
ASHRAE 55	2010	Based on Fanger, it calculates the Standard Effective Temperature and calculates the adaptation limits for free-running or naturally ventilated buildings. Includes the Graphical Comfort Zone Method for main cases and the Computer Model Method for other specific designs.
CIBSE Guide A	2016	Similar to ISO 7730 and EN 15251, it calculates the indoor air temperature ranges and establishes some criteria for the long-term assessment of TC.

The selection of one or another method can lead to truly different results, as demonstrated through many empirical studies (Pfafferott, Herkel, Kalz, & Zeuschner, 2007) (Attia & Carlucci, 2015) (Schnieders, 2015) (Hidalgo-Betanzos et al., 2015). In theory, the PMV method should only be applied to mechanically cooled or heated environments and the adaptive method should be applied to free-running buildings. However, the use of adaptive method can lead to the acceptability of considerably high indoor temperatures, meaning that in constructions placed in warm climates with long warm outdoor temperatures, the upper limits of indoor temperatures can overpass 30 °C. Especially if users don’t have direct access to window openings or if they have to close all natural ventilation overnight to avoid street noises... These aspects are both considered for the TC assessment in the present study.

Comparing the boundaries of TC according to PMV model and adaptive model, the comfort ranges vary considerably, see Figure 2.41. The adaptive method increases the ranges in winter, with 0.9 °C higher minimum and 0.2 °C maximum values. Note that these values for winter EN 15251 are fixed, but in the case of the PMV they are calculated with an average RH of 45% and with very low air velocity. In summer the EN 15251 values are highly influenced by the running mean temperature (RMT) and a direct comparison is not advisory. To understand the influence of RMT in adaptive boundaries and RH in PMV, the winter and summer boundaries are plotted in Figure 2.42 (for the PMV) and Figure 2.43 (for the adaptive method). This way, it can be observed clearly how the boundaries of winter PMV are at least 0.5 °C below the adaptive ones. In summer, when outdoor RMT is 13 °C, both upper boundaries of PMV and adaptive method are equal. If the environment get warmer than this value, the use of ventilation under those ranges may keep the TC within the acceptable range.

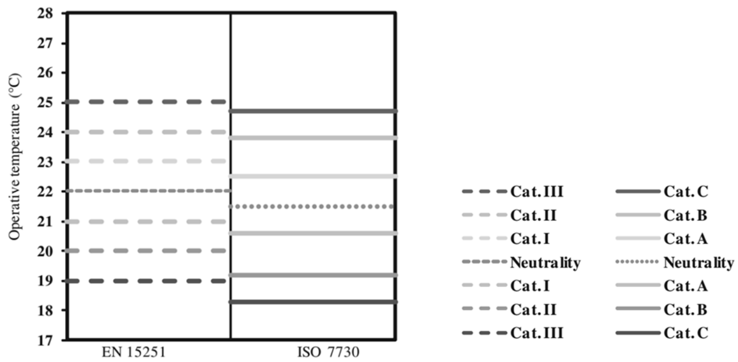


Figure 2.41. Comparison between winter operative temperature boundaries for every category of EN 15251 and ISO 7730 (taken from Carlucci, 2013).

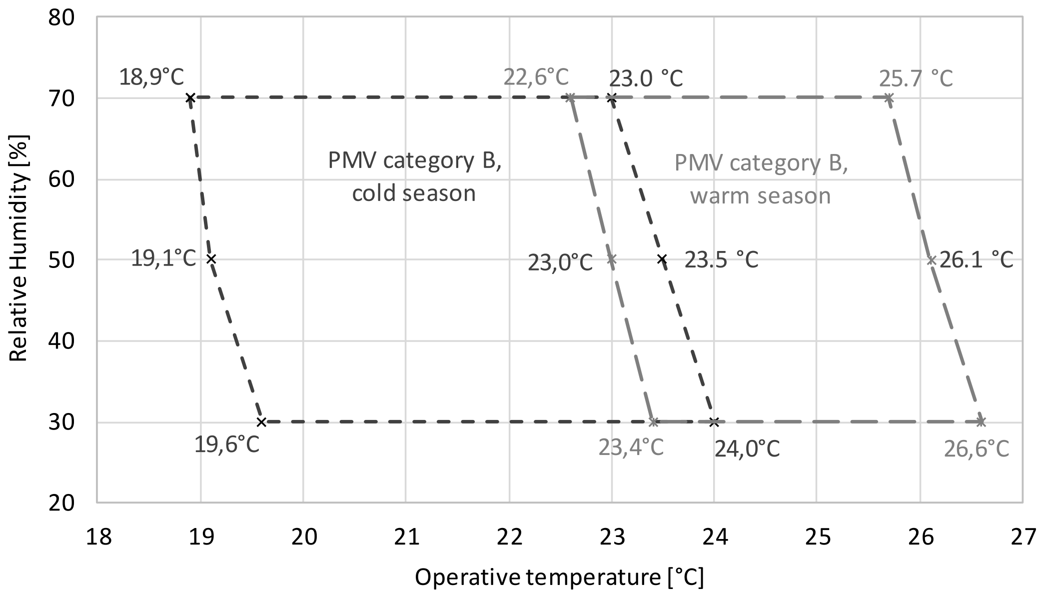


Figure 2.42. PMV acceptability boundaries by temperature and RH, cat. B (based on ISO 7730, 2005).

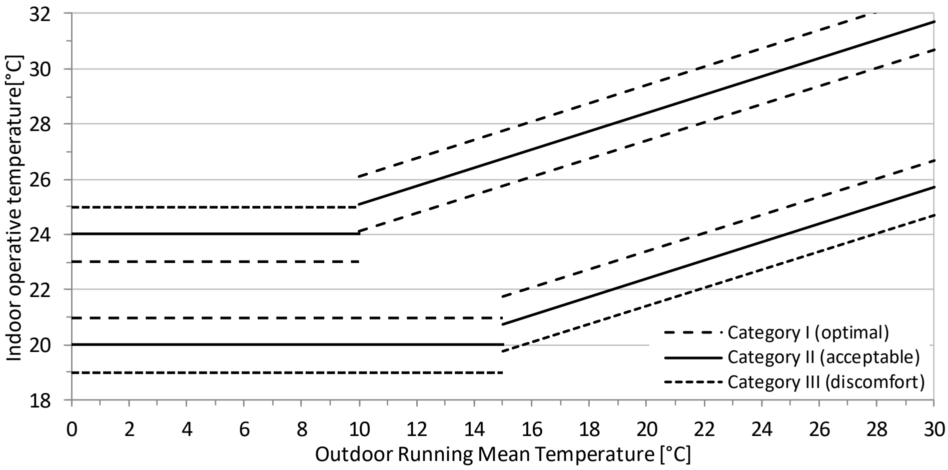


Figure 2.43. EN 15251 acceptability boundaries by RMT (based on EN 15251, 2007).

As a result, summer limits can vary remarkably according to one or another method, as summarised in Figure 2.44, taken from the book of Carlucci (Carlucci, 2013).

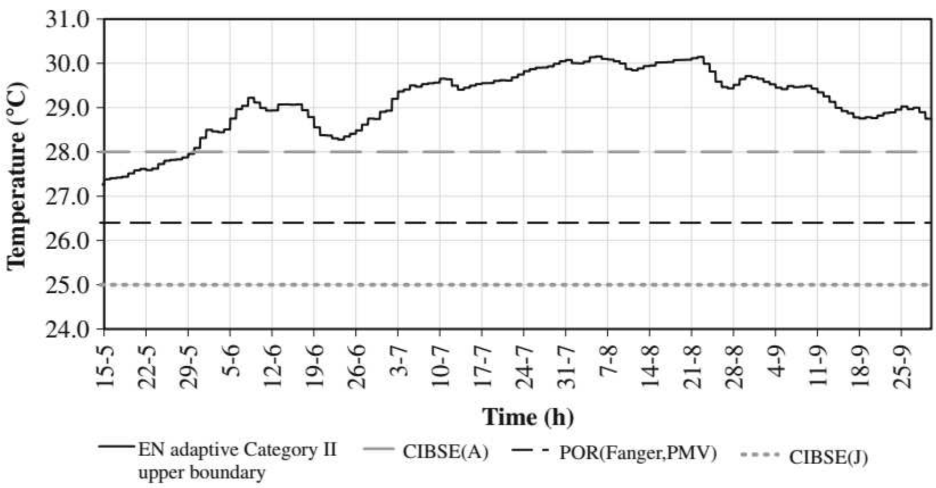


Figure 2.44. Comparison of the upper boundary temperatures of POR and CIBSE indices calculated for the climate of Rome (Italy) (taken from Carlucci, 2013).

Apart from the selection of the method, there are some other important details which can considerably affect the TC assessment.

Firstly, the occupancy levels of a building or a dwelling can show useful information for many purposes. Also, it shows a clearer image of the profile of the building use and internal gains which impact greatly OH risks at midday. On the other hand, the use of passive measures often requires the action of users. For this reasons, many standards and methods don’t include the unoccupied hours in the indoor assessment (EN-15251, 2007) (CIBSE, 2013a). Besides, if the use of natural ventilation is limited to short hours, the capacity to control TC in free-running buildings is dramatically reduced.

Secondly, the period identification can also hide to some degree the warm discomfort. As presented in (Hidalgo-Betanzos et al., 2015) there are many interpretations, which refer to the use of heating or not (ISO 7730), a fixed period (CIBSE TM52) or the identification of the warm period, when outdoor conditions overpass the comfort range. This last option was proposed by (Carlucci, 2013) and used in a recent study for Spanish Mediterranean climate (Ortiz et al., 2016). Since many assessments are based on a maximum percentage of discomfort hours in summer period, the proper identification of the period is a primary aspect which has to be clearly justified. An example of these variations is presented in Figure 2.45.

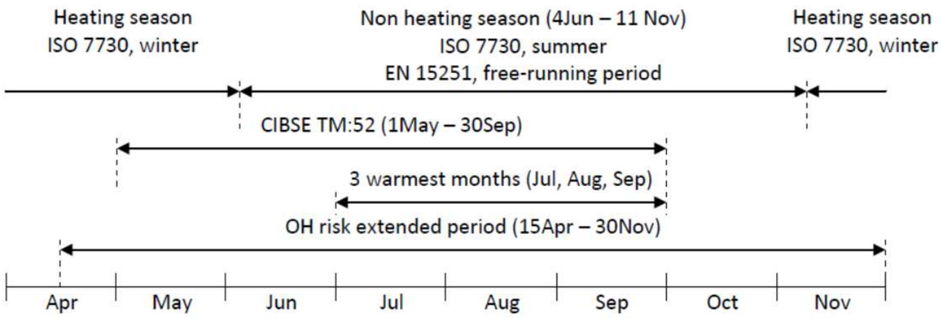


Figure 2.45. Periods of verification for summer TC conditions (taken from Hidalgo et al., 2015).

Thirdly, the compliance between the projected use of passive measures and the real final use has to be taken into account. A recent publication of QUALICHeCK project analysed the methods and indicators for OH assessment for 9 European building codes (Kuusk, 2016). In most of the countries there is no further verification of compliance, except Belgium and partly France, where a national sample control is applied. According to this study, the requirements for TC and OH in the analysed 9 European countries are these:

- Indoor temperature based requirements: Austria, France
- Indoor temperature excess based requirements: Belgium, Estonia
- Maximum cooling energy need based requirements: Spain
- Summer thermal comfort is regulated within the overall indoor climate requirements: Cyprus, Greece, Romania, Sweden

Additionally, in the last decade another concept has become increasingly relevant: building overheating (OH). Overheating can be defined as "*that state of mind that expresses dissatisfaction with the environment caused by prolonged high temperatures*" (Race, Balian, & Davies, 2010). According to CIBSE, "*ever increasing winter energy efficiency measures and external temperatures as a result of intense urbanisation and climate change will increase the* *risk of overheating in buildings especially in homes that primarily depend on passive measures to achieve year-round internal comfort*".

This topic relevance increased rapidly as consequence of the raise of highly-insulated buildings (McLeod et al., 2013) and their exposure to gradually more frequent heat waves, like the ones in 2003, 2006, 2010 and 2015 (IPCC, 2017) (Zampieri et al., 2016) (Russo et al., 2015). Consequently, the number of publications related to this topic increased exponentially since the heat wave of 2003, see Figure 2.46 based on SCOPUS® database (SCOPUS-ELSEVIER, 2017).

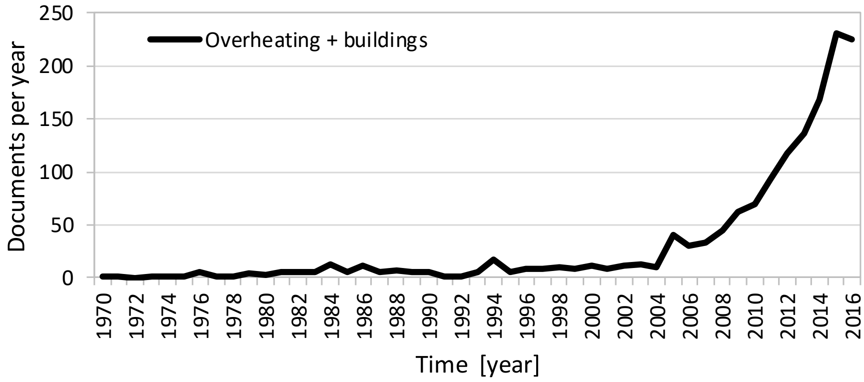


Figure 2.46. Documents indexed in SCOPUS with "overheating" keyword and "building" in the abstract (data source SCOPUS, 2017).

There are two main approaches for OH avoidance: fixed limits of indoor operative temperatures and adaptive limits. The first one limits the periods over 25 or 28 °C to a percentage of the total hours, while the second ones defines flexible limits based on outdoor conditions, like CIBSE TM52 (IES, 2013) or EN 15251 (EN-15251, 2007). This second group permits warmer thresholds in warmer locations with longer outdoor warm periods, as explained in the detailed review of the methods to assess long-term TC by Carlucci (Carlucci, 2013). In Table 2.10 a summary of the most common OH detection models is represented.

Despite the importance of this question, the strategies developed by European countries to avoid OH are not developed to the same degree. A recent review of thermal comfort approaches in Europe (BPIE, 2015) indicated that most of the central and northern countries have limits for the indoor air temperatures in housing constructions, either mandatory or recommended. However, the passive measures are still rarely included in most of their regulations and their use is rather uncommon. In southern European countries the situation is opposite, most of them don't have any specific requirements for OH but it is common to implement some passive measures such as the solar shading, thermal mass or natural ventilation strategies.

Table 2.10. Most common overheating detection methods for buildings.

OH methods	Year	Description
CIBSE Guide J	2002	Indoor air temperature limit is 25°C, exceeded less than 5% of summer hours.
CIBSE Guide A	2006	Indoor air temperature maximum limit is 28°C, exceeded less than 1% of summer hours.
EN 15251	2007	Formulas for adaptive limits, less than 3% of summer hours (or 5% for specific building typologies).
Passivhaus criterion	2007	Indoor air temperature limit is 25°C, exceeded less than 10% of total annual hours.
CIBSE TM52	2013	Only occupied hours, if 2 criteria are failed it is considered as OH: - Hours over limits < 3 % summer occupied h. - Daily weighted exceedance $\sum (h_i \cdot w_f) \leq 6$ - Upper max. limit ≤ 4K over adaptive limit

Regarding the application of these concepts to passive house buildings, several publications have analysed different points of view and limits to apply the PH principles.

A recent study of the PHI (Schnieders, Feist, & Rongen, 2015) shows the capability to adapt the PH standard to 6 climates in different locations all over the world: Yekaterinburg (very cold climate), Tokyo (subtropical warm climate), Shanghai (subtropical warm climate), Las Vegas (hot and dry climate), Abu Dhabi (hot and humid climate), and Singapore (tropical climate). The study concludes that PH classic standard can be achieved in all those extreme climates. In any case, it recommends that building design should define the building's layout, shape, orientation and solar shading situation according to local climate and practices.

Many other studies have also shown the potential and the risks to adapt PH principles for warmer European climates, like the Passive-On project (Ford, Schiano-Phan, & Zhongcheng, 2007a), a parametric study for the southern Italy (Bruno et al., 2015) and a simulation study with a sensitivity analysis for several locations in Portugal (A. A. Figueiredo, Figueira, Vicente, & Maio, 2016). All these cases show how PH design can be implemented with a careful control of solar gains and addition of extra ventilation recommendations.

Nevertheless, the risk of global warming is presented in Section 2.5 and a very detailed study conducted for the UK climate has proven that there is a clear risk of OH in all low energy houses due to the internal gains, high insulation and considerable warmer conditions which greatly diminish the potential of thermal mass and natural ventilation (McLeod et al., 2013).

Some studies have proposed a general approach to prevent OH, providing some practical guidance to consider in the design, construction and early occupation stages (Wright, Henderson, & Swainson, 2016). They point to the lack of integration as one of the main issues for TC and OH in houses in the UK. To detect the main issues, they presented a decision tree

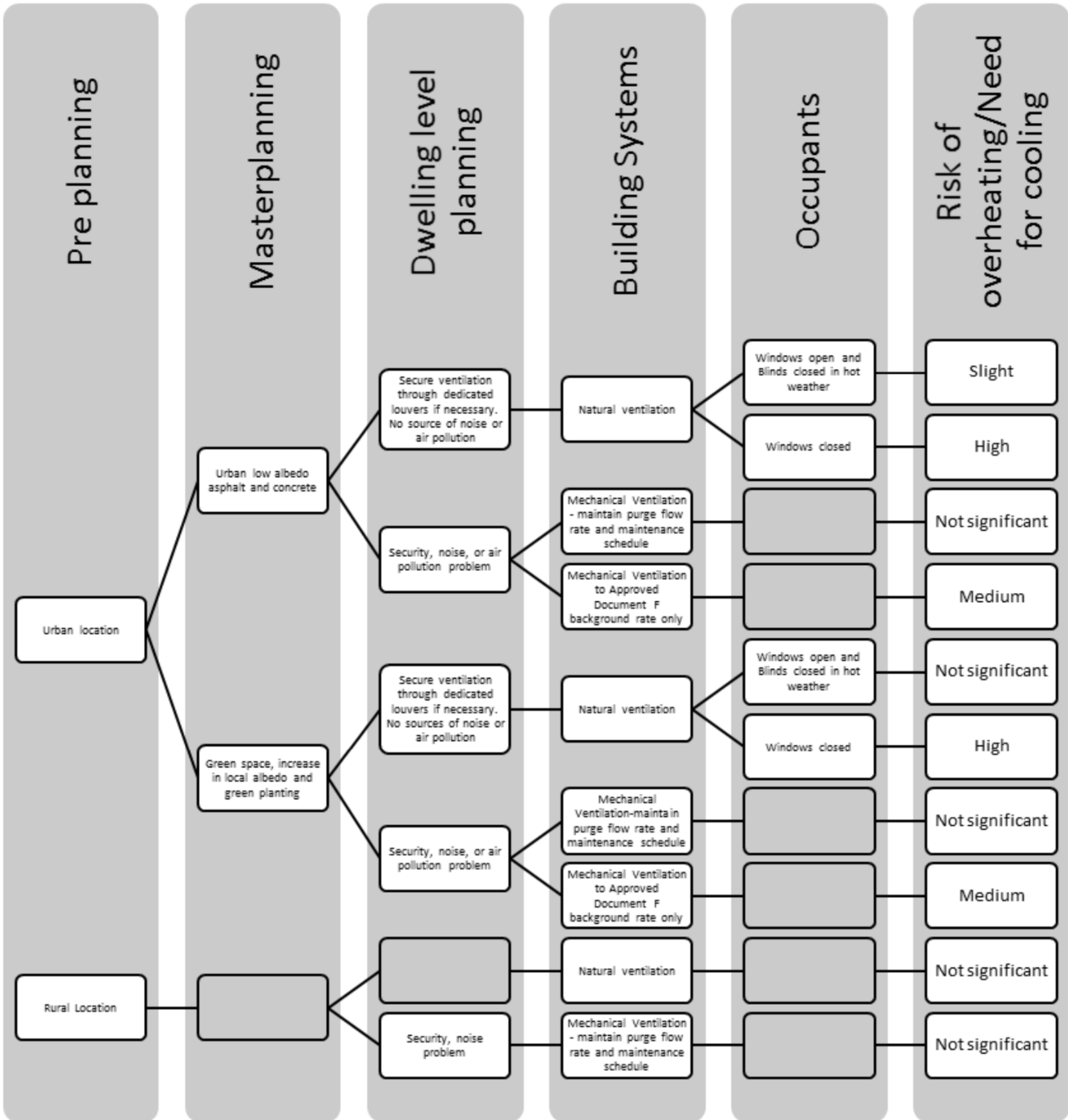


Figure 2.47. Decision tree (taken from Wright, Henderson & Swainson, 2016).

Thus, despite the fact that many highly-insulated cases can maintain the indoor environment inside the acceptable TC range at present, it is also certain that the risk of OH due to global warming is going to be severe in the next decades. For this reason, building design should verify TC in detail in order to identify the likely discomfort situations and provide complementary measures to occupants in order to avoid or minimise any additional energy use for active cooling.

2.5. Potential of passive measures in local climate conditions

This section analyses some of the most common measures to minimise the usage of cooling, while maintaining the passive heating capacity as much as possible. The concept of passive design of buildings takes advantage of the climate to maintain a comfortable temperature range in buildings (Zaki et al., 2012) (Wassouf et al., 2013). These strategies were common in vernacular architecture, but for years their potential was substituted by technologies and systems of modern constructions (Rodriguez Vidal, 2015). In recent years, the higher cost of energy, as well as the European policy has once again raised the importance of passive measures. Indeed, the passive measures are also recommended in many guidebooks of the most relevant engineering organizations, like CIBSE (Race et al., 2010), (CIBSE, 2013a) and REHVA (REHVA & ES-SO, 2010). It is not surprising that some European projects, such as VENTICOOL and QUALICHeCK, are working hard to improve the methods to design and verify these passive measures and collaborate with organizations like ES-SO and REHVA. Indeed, these measures are crucial for the EPC compliance, as stated in recent European reviews (QUALICHeCK, Bbri, Chalmers, & Cetiat, 2015) (QUALICHeCK, Kurnitski, et al., 2015). For all these reasons, passive design can make the reduction of energy use in nZEB. In order to do so, it needs to adjusted to the local climate conditions to achieve resilient constructions.

The basic passive principles of single-family dwelling designs are: solar harvesting, solar shading, thermal mass management and natural ventilation (Wassouf, 2014). The control of these aspects can lead to the reduction of the energy needs of a house to a great extent. There are some other possible hybrid systems that could be implemented in the envelope or the HVAC systems, as described in the study for Portuguese climate by (A. A. Figueiredo et al., 2016). The authors explain that passive design and the implementation of hybrid measures are especially interesting in warmer regions. A recent workshop of QUALICHeCK (Álvarez & Molina, 2016) ppresented some prototypes of active facades to boost natural ventilation and the use of evaporative cooling devices to cool down the facades exposed to direct sun. Both cases have proven to contribute greatly to reduce the cooling need. Even though these hybrid features for now are limited to the testing facilities only, soon they will probably be applicable to conventional constructions as well.

This way, Spain and Southern European countries, in general, have a considerable challenge to properly select and adjust the passive measures in the future nZEB. The present study analyses the benefits of the most feasible passive measures for the selected typology of single-family dwellings.

2.5.1. Ventilation strategies

As seen before, ventilation can contribute greatly to TC extending the limits of acceptable temperatures much further than the PMV assumption for mechanically ventilated buildings. This section reviews all the strategies related with ventilation to reduce the cooling need and provide an optimal indoor environment to users.

Natural ventilation is a key aspect which can contribute to reduce the cooling demand and it is recommended by the standards of adaptive thermal comfort (EN-15251, 2007) (ASHRAE, 2013b). There are a number of different ventilation strategies. On the one side, the ventilation airflow can be driven by different the natural forces like wind, solar radiation or pressure difference (stack effect). On the other side, these strategies can be controlled either manually, scheduled or automatically adjusted by different parameters. All these ventilation strategies oriented to provide cooling (not only natural ventilation but also mechanical ventilation) are denominated Ventilative Cooling (VC).

The study of Artmann, Manz and Heiselberg made one of the first studies about the free cooling potential of the natural ventilation across all Europe (Artmann, Manz, & Heiselberg, 2007). They used the climatic cooling potential (CCP) index to integrate the cooling capacity of night time hours and the temperature differences, as shown in Figure 2.49 below.

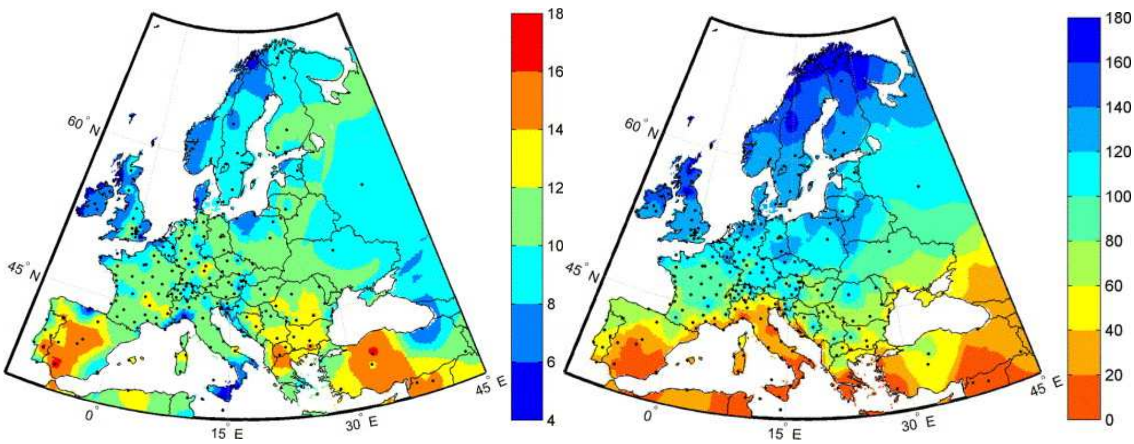


Figure 2.48. Maps of differences between minimum and maximum temperatures (left side) and mean climatic cooling potential (Kh/night) (right side) in July, based on Meteonorm (taken from Artmann, Manz, & Heiselberg, 2007).

After that study, many other works have assessed the best operation of natural ventilation in certain typologies. In general, a large number of aspects can limit the use of natural ventilation and so the ventilative cooling potential. A long review of the potential and limitations of VC is available in the Chapter 2 of the recent state of the art of VC (Kolokotroni & Heiselberg, 2015) and several tests were also presented in two works related with QUALICHeCK project (Wissen, 2016) (Álvarez & Molina, 2016). In a general approach, the principal limitations for VC are:

- outdoor climate (temperatures at night-time),
- fresh air need,
- maximum number of air changes per hour (ACH),
- thermal mass,
- flow pattern (convective heat transfer coefficients)
- and time span between dissipation period and cooling needs.

Therefore, these strategies are very related with climate and in the case of warm location they may be unavailable. To analyse this, Chiesa and Grosso have published recent studies about ventilative cooling strategies. They use a two stories office model in different locations of Mediterranean area (Chiesa & Grosso, 2015). In this work, they studied the potential applicability of controlled natural ventilation (CNV) comparing the wind-driven and the gradient temperature dependant operation. The authors found that climatic-dependent potential due to temperature gradient correlates with the simulation results of applying a CNV strategy, while it is less valid when considering a potential based on wind velocity. As a result, the cooling potential with CNV is considerably high in Mediterranean locations. Later, they repeated the methodology in central and southern Europe (Chiesa & Grosso, 2016) using a similar real office model and studying the potential of passive ventilative cooling (PVC). In this case, they showed that if wind-driven and buoyancy-driven controlled natural ventilation is applied, the potential of PVC is significantly high in the whole central and southern European territory.

An experimental study about the potential of night time ventilation on a full-scale test room (Le Dreau, Heiselberg, & Jensen, 2013) analysed the different convective heat transfer coefficients (CHTC) with different ventilation types (displacement and mixing ventilation), air change rates, temperature differences between the inlet air and the room, and floor emissivity values. Several indications regarding night time ventilation are underlined. The study reviews in detail the accuracy of existing CHTC correlations and analyse alternatives to model more accurately the heat transfer under relatively high airflows. They also confirm that when the thermal mass is located at the ceiling, the efficiency of night-time ventilation should not be affected by the presence of furniture.

Bearing in mind the publication of the European nZEB strategy in 2010 (Directive 2010/31/EU, 2010), the relevance of VC for the energy demand of buildings was becoming increasingly more important. Two years later, in 2012, the partners of INIVE EEIG helped creating the International Platform for Ventilative Cooling (Venticool) (Venticool, 2017), in order to address the growing need for international collaboration on VC.

The main purpose of this platform was to accelerate the uptake of VC, raising awareness about the strategies of ventilation to reduce the energy need of buildings and provide good indoor air quality (IAQ) and thermal comfort (TC). The international platform supported numerous events, training programmes and several AIVC conferences. During these years, a considerable number of studies and documentation has been supported by Venticool platform, including new methods to calculate VC potential and tools to improve the compliance of ventilation and airtightness in building construction.

Probably, the most relevant project developed within the platform was the Annex 62 'ventilative cooling'. It was initiated in 2013 through the funding of the IEA and the Energy in Buildings and Communities Programme (EBC). One year later, the platform also collaborated in the creation of the IEE project named QUALICHeCK, in order to improve the compliance of Energy Performance Certificates (EPC) and the quality of works, including ventilation and airtightness (QUALICHeCK, 2017). Recently, ANNEX 62 Venticool published a reviewed version of the state of the art of VC, including definitions of Climatic Cooling Potential (CCP) and a review of 26 case studies with VC strategies (Kolokotroni & Heiselberg, 2015). Figure 2.49 represents the ranges of applicability of ventilative cooling strategies.

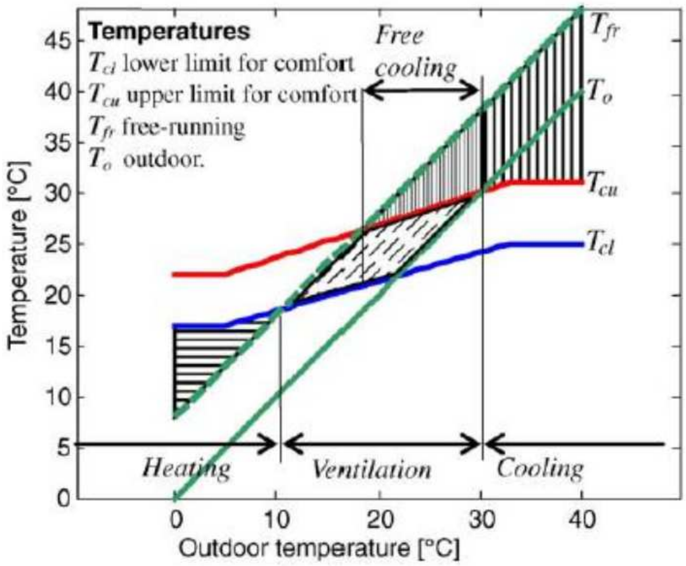


Figure 2.49. Ranges for heating, free-cooling and mechanical cooling when the free-running temperature is higher than the outdoor temperature (taken from Kolokotroni & Heiselberg, 2015).

Regarding the present implementation of ventilative cooling strategies in European countries legislation, a survey conducted in 2015 confirmed that despite their potential to reduce the energy use, the majority of the energy performance regulations only consider ventilative cooling in a simplified way (M. Kapsalaki, F. R. Carrié, 2015-2). The study shows wide differences along Europe and five out of eight countries already take into account some type of ventilative cooling in their national EPBD versions. Besides, they present different level of characterization for the ventilative cooling devices and natural ventilation is only required in Belgium and Denmark.

In general, the input parameters for ventilation units are basically the energy use and the control options, followed by fewer cases which also account the SFP in W/(m^3/h) and the peak power demand. They conclude recommending further studies to face the complexities of ventilative cooling and find a more pragmatic way of implementing these strategies in the Energy performance regulations.

However, the industrial manufacturers of domestic AHU and MVHR units are also developing more detailed interfaces to control and program VC strategies in small housing buildings. The implementation of user-friendly scheduling of the ventilation in residential constructions can help reducing the overheating risk and the energy use. Figure 2.50 represents the scheduled control possibilities in a control unit developed by Mitsubishi. In this example, the air volume level can be defined hourly up to 8 different stages for each day of the week (LOSSNAY LGH-15RX5-E).

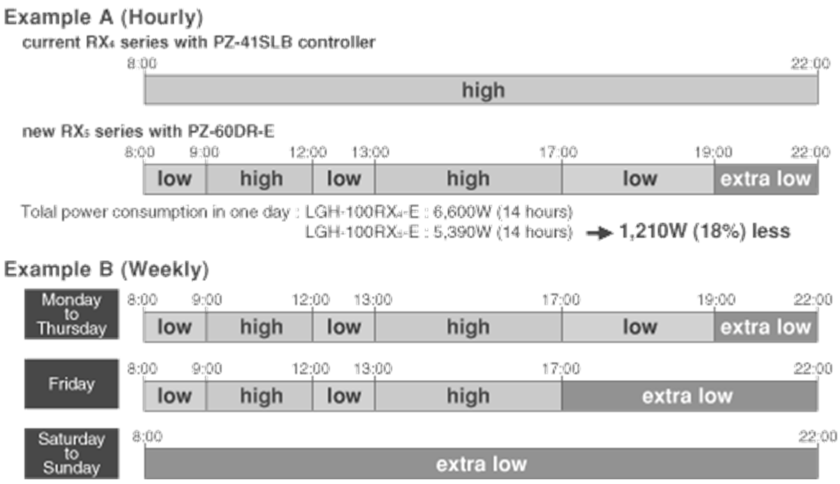


Figure 2.50. Example of an advanced control unit with scheduled airflows for MVHR (source mitsubishielectric.com).

Considering the development of EPBD implementation, Venticool platform also contributed analysing the current situation of VC strategies towards nZEB objective (M. Kapsalaki, F. R. Carrié, 2015). They reminded that overheating has become a key concern in Nearly Zero-Energy Buildings with serious socio-economic implications, which could be avoided without additional active cooling if the ventilative cooling principles are followed. To do so, summer comfort criteria need to be properly implemented in all member states for non-air-conditioned buildings.

However, the current situation of the VC strategies indicates that they are poorly rewarded in the regulations and standards related with the nZEB targets. For instance, designers must compensate the VC strategies with other conventional cooling systems to meet the regulatory requirements. Besides, ventilative cooling can help mitigating the peak load issues on electricity grids, especially in the case of Southern countries.

2.5.2. Solar shading control

Solar control is one of the most important aspects to prevent OH. Countless works have been published about solar design and still the majority of new designs don't include detailed dimensioned solar shading devices. The usage of overhangs, louvers and awnings have to become more common in building design. The European Solar Shading Organization (ES-SO) published in 2010 a guidebook useful tools and solar shading principles (REHVA & ES-SO, 2010) and keeps demonstrating in later studies the importance of dynamic shading calculation (Melorose, Perroy, & Careas, 2015). The use of one or another measure is largely conditioned by the features of each project.

Rating
++ excellent
+ good
o moderate
- not capable
n.r. not relevant

		Passive Cooling	Passive Heating	Reduction of heat loss (winter)	Thermal comfort	Visual comfort	Contact to the exterior	Preferred facade orientation	Wind resistance	Life expectancy	Typical g-value	Typical τv	Convection factor
External retractable	Venetian blinds	++	++	-	++	o	o	ESW	+	+	0,10	0,10	0,04
	Screens	++	++	o	++	++	+	ESW	o	+	0,15	0,10	0,10
	Roller shutters	++	++	+	++	o	o	ESW	++	+	0,10	0,02	0,15
	Awnings	+	++	-	++	+	+	ESW	o	+	0,17	0,12	0,15
	Daylight Saving Awnings	++	++	-	++	+	o	ESW	+	+	0,12	0,05	0,18
External non retractable	Horizontal solarfins, louvers static	o	o	n.r.	+	-	+	S	++	++			
	Horizontal solarfins, louvers dynamic	++	+	n.r.	++	o	+	S	++	++			
	Vertical solarfins, louvers static	-	o	n.r.	o	-	+	EW	++	++			
	Vertical solarfins, louvers dynamic	++	+	n.r.	++	o	+	EW	++	++			
Intermediate	Ventian blinds, non ventilated gap	+	++	n.r.	+	++	+	ESW	n.r.	++	0,23	0,10	0,21
	Ventian blinds, ventilated gap	++	++	n.r.	++	++	+	ESW	n.r.	++		0,10	
	Ventian blinds		++	n.r.									
Interior retractable	Interior Venetian blinds	o	++	-	o	++	o	NESW	n.r.	+	0,45	0,12	0,50
	Metalized screens	+	++	o	+	++	+	ESW	n.r.	+			
	Screens	o	++	o	o	++	+	NESW	n.r.	+			
	Honeycomb shades	+	++	++	+	+	-	NESW	n.r.	+	0,25		
Static	Solar protection glazing	+	-	n.r.	+	-	++	ESW	n.r.	++	0,34		0,04
	Sun protection foils	+	-	n.r.	+	-	++	ESW	n.r.	+	0,35		0,04

Figure 2.51. Summary of solar shading products and benefits (taken from REHVA & ES-SO, 2010)

Later, ES-SO published an update with a solar shading database in collaboration with QUALICHeCK project (ES-SO & Eycken, 2017). All these strategies are necessary to prevent OH risk, as explained in (Kuusk, 2016) (Álvarez & Molina, 2016) (Hacker et al., 2005). Figure 2.51 shows a large variety of possibilities with general benefits and functions by orientation.

2.5.3. Thermal mass management

Thermal mass refers to the parts of the building with have a higher thermal capacity and permit heat storage in the short term. This inertia is often used to lower the peak indoor temperatures and reduce the cooling load. One of the main limitations of this feature is that the thermal mass is often concentrated in the external walls and structural elements, which are not directly exposed to the ventilation air flow (Álvarez & Molina, 2016).

So, additional measures have to be taken to activate these elements and ensure the real outcome. A recent PhD study about Passivhaus multifamily blocks in northern Spain demonstrated that the potential of thermal mass is low in that climate and, in general, only provides a significant improve when it is combined with night-time natural ventilation (Rodriguez Vidal, 2015).

2.5.4. Case studies of combination of passive measures

This section reviews the most relevant studies addressing the combination of passive measures like ventilation, solar shading and thermal mass. They help understanding the potential of these measures for passive houses and future nZEB.

A study presented in 2012 analysed the situation of low energy terraced houses in the UK and simulated the climate conditions of the heat wave of 2003 (Porritt, Cropper, Shao, & Goodier, 2012). To solve the general problems of this typology they proposed a set of interventions to add or improve the existing solar shading, thermal insulation or ventilation measures. According to their findings, it would be possible to eliminate fully the OH in most of the cases with a proper operation and several improvements.

Another study of UK terraced houses (van Hooff, Blocken, Timmermans, & Hensen, 2016) calculated the potential reductions of the cooling needs with passive climate change adaptation measures. The reduction of cooling estimated to be between 59 % and 74 % with the use of external solar shading and natural ventilation. Besides, they checked that these measures may affect only around 2 % of the heating needs of well-insulated terraced houses. They also warn about lower thermal mass and indicate that cooling need may increase in 16 % with low thermal mass constructions. In the best tested case with well insulated, high thermal mass, natural ventilation and solar shading, the energy demand is reduced up to a remarkable 88 %. However, they also comment that these calculations are only applicable for limited similar constructions and they recommend further research and monitoring data.

In Scandinavian countries, many studies have analysed these combinations of passive measures. A monitoring campaign conducted by (Foldbjerg, Worm, & Feifer, 2012) in the first Active House built in Denmark - a standard based on low energy use and high IEQ, see (Active House Alliance, 2013) - found a good correspondence between window openings and acceptable thermal comfort. Which indicated that window openings contributed to achieving and maintaining good thermal conditions. The use of solar shading was in this case less relevant. Another study made in other two Active houses located in Denmark (Foldbjerg, Rasmussen, & Asmussen, 2013) confirmed the relation between window opening and good TC, especially in summer. Comparing the relevance of solar shading and ventilative cooling, they consider more important the use of ventilation to maintain the acceptable thermal comfort.

Another study of 3 Active Houses in Austria, Germany and Denmark. The study review the comfort in detail, including the opening of windows for natural ventilation. The optimal results demonstrate that despite the generous daylight conditions, very little OH was seen. So, the passive measures with an automatic control are providing an excellent result for summer comfort (Foldbjerg, Asmussen, & Holzer, 2014).

A study conducted in Holland climate indicated that uncontrolled natural ventilation could lead to several OH during summer with more than 10 % of hours over 28 °C (Barbosa, Bartak, Hensen, & Loomans, 2015). However, they comment that it may be very influenced by the lack of solar shading. As a solution, users may apply some predictive measures and close windows during daytime before the warm weeks arrive.

The review of passive measures potential conducted by (Tejero-gonzález, Andrés-chicote, García-ibáñez, Velasco-gómez, & Rey-martínez, 2016) presented an updated psychrometric chart with the more suitable strategies for different outdoor conditions, see Figure 2.52 below. This plot helps understanding the most suitable conditions for the passive solutions applied in the studies of this section, namely the boundaries of free-cooling, daytime natural ventilation, night time ventilation and evaporative cooling.

In warm locations like Israel or Greece, some studies have also analysed some less conventional passive cooling strategies. For instance, the study conducted by Givoni presented a detailed review of bioclimatic measures and uses data from both test cells and monitored real buildings to assess the benefits for the indoor thermal comfort (Baruch Givoni, 2011). The measures included are: natural ventilation, night time natural ventilation, radiant cooling, direct evaporative cooling with cooling towers, indirect evaporative cooling with roof ponds and cooled soil as a cooling source. Even though these measures prove being useful in extreme climates, they are suitable for the Spanish climate and construction background.

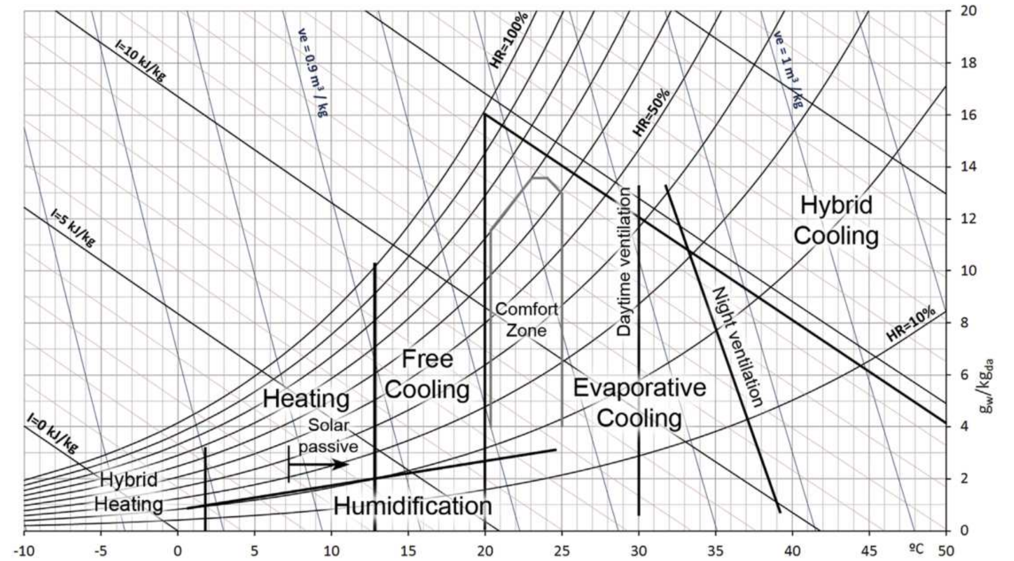


Figure 2.52. Comfort zone and boundaries for passive strategies application
(taken from: Tejero-gonzález, Andrés-chicote, García-ibáñez, Velasco-gómez, & Rey-martínez, 2016)

Regarding south West European climates, the work of Bruno et al. analysed the design parameters for a generic prefabricated passive house suitable in southern Europe climates (Bruno et al., 2015). The authors highlight that fixed roof extensions don't help significantly but acknowledge the role of night time VC as a substantial feature to maintain the summer comfort. They also propose the use of wood panels with inner sand filling in order to provide enough thermal mass and reduce peak loads.

The work of Figueiredo et al. studied the adaptation capacity of PH design to Portuguese climate (A. A. Figueiredo et al., 2016). They used dynamic simulations to analyse the thermal loads, thermal energy balance and ventilation systems. Regarding the ventilation types, they observed that the lack of a MVHR unit could lead to high discomfort periods in both winter and summer, together with a higher energy need. They pointed out to some issues modelling the night time ventilation driven by wind and they finally considered only the natural ventilation due to stack effect. Additionally, they also recommended a medium level of thermal inertia in lightweight constructions to reduce the discomfort of temperature swing and the use of solar shading activated automatically when outdoor temperature is high.

In Spanish climates, the work of Ortiz et al. studied the potential of different passive measures in the refurbishment of multifamily blocks in Catalonia (Ortiz et al., 2016). They used multiple simulations and economic analysis to assess the applicability of solar shading, thermal mass and natural ventilation. This study concluded that natural ventilation is one of the best strategies, especially because its impact on the thermal comfort is positive in warm season and also in cold season. On the other hand, the optimal use of the solar protection provided interesting improvements during the warm season, especially when there is no natural ventilation. They also underlined that internal thermal insulation and the consequent reduction of thermal mass activation can lead to overheating problems in many cases.

CHAPTER 3
CASE STUDY: MONITORING AND EVALUATION OF A SINGLE-FAMILY PASSIVE HOUSE

Abstract
This chapter describes the experimental part of the thesis which monitored and analysed the real thermal behaviour of one of the first single-family passive houses built in Spain. The detailed monitoring campaign for 14 months registered the indoor air conditions of every room, the surface temperatures of the main walls, floors and ceilings, the heat flux in facades, the heating power, the local weather conditions and solar radiation with a meteorological station mounted on-site. Some verifications were done to test the performance of the ventilation and the thermal insulation of the house. Complementary particular measurements permitted a more detailed evaluation of the local thermal comfort conditions in winter, summer and shoulder seasons.

The results confirmed a good winter performance of the house with a very low heating use of 17.6 kWh/m², slightly over the PH limit. The monitoring permitted to improve several aspects of the house thermal behaviour, such as the cool temperatures in certain rooms or the ventilation system unbalance. The summer performance of the house was analysed using the PMV method and the EN 15251, analysing the use of natural ventilation by the inhabitants and the operation of the summer bypass of the MVHR unit. No overheating risk was detected according to CIBSE TM52 method. The thermal envelope of the house fulfilled the expectations of the design, but some moderate thermal bridging was detected in the ground contact of the building walls with an infrared thermography survey. The differences between observed building energy performance and PHPP calculations were evaluated.

3. Case study: monitoring and evaluation of a single-family PH

3.1. Introduction

This chapter illustrates the main experimental part of the thesis.

The selected case of this study was the first Spanish Passivhaus dwelling monitored in detail. For this reason, there were a number of questions related with the suitability of Passivhaus design for warmer countries, which hadn't been answered before in the other European PH cases, as explained in Chapter 1.

Achieving a very low energy demand is a must in order to be able to construct real nZEB (European Commission, 2016b). The conducted study will clarify the benefits and drawbacks of a single-family passive house thermal performance, taking into consideration the real conditions of use and the northern Spanish climatic conditions.

3.2. Aim and objectives

The main goal consists on the **analysis of the real performance** of one of the first single-family houses with a very low energy demand built in northern Spanish climates. It is based on a long-term monitoring campaign conducted under real conditions of use. This detailed control will permit to detect the main issues related with the thermal behaviour of the building and evaluate the capacity of this design to provide an adequate thermal comfort.

To reach this goal, the next objectives are proposed:

Objective 3.1. Compare the measured heating demand with the estimated annual demand in the PHPP.

Objective 3.2. Assess the long-term thermal comfort for heating season and summer period.

Objective 3.3. Analyse the performance of the thermal envelope and the passive design of the building, evaluating the impact of thermal bridges and heavyweight structure.

Objective 3.4. Verify the ventilation rates, the efficiency of the HR and the by-pass operation.

Objective 3.5. Measure the differences between the thermal comfort provided by a stand-alone pellet stove and several electric space heaters.

Objective 3.6. Evaluate the influence of inhabitants' behaviour on the thermal performance.

3.3. Case study definition

3.3.1. Description of the building

The analysed single-family dwelling is located in a village near the city of Vitoria-Gasteiz. This area is on the north of Spain and it belongs to the southern part of Euskadi, see Figure 3.1. The morphology of the place is flat and it is rounded by several chains of mountains. The climate can be classified as Cfb, that is warm temperate with fully humid winters and warm summers, according to the updated Köppen-Geiger scale (F. Rubel et al., 2017). Further details of the climatic conditions are analysed within the experimental results of the Section 3.4.2.

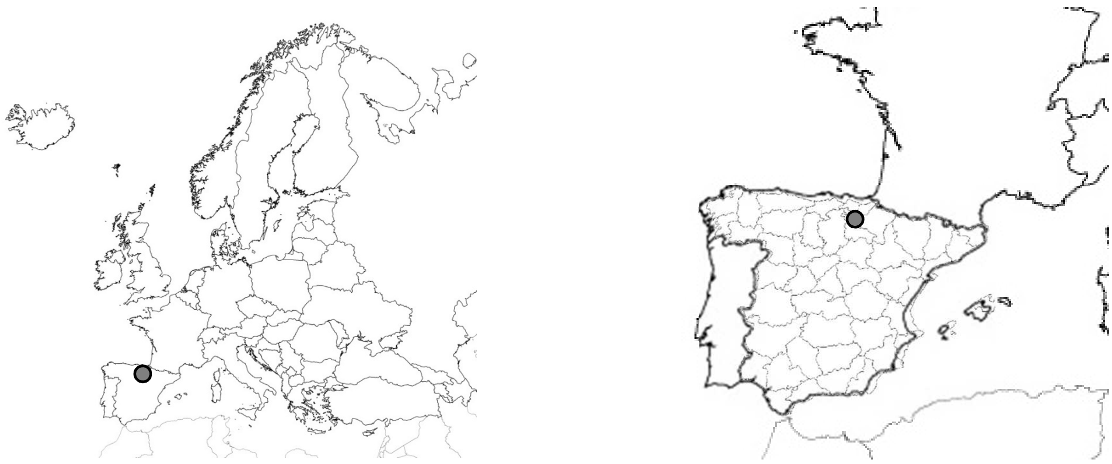


Figure 3.1. Situation of the case study.

The project was constructed between January and July of 2012, including a set of three detached houses with similar construction features. The three single-family buildings were designed following the Passivhaus criteria (PHPP v.7, 2012) and two of them obtained successfully the certification from the PHI in 2013.

The bioclimatic design of the passive dwellings was based on a long plan placed in a clear North-South orientation, so that it can maximise the solar harvesting and minimise the solar gains from the sides. The pitched roof works as the only solar shading element of the building from the outside. The angle of the roof was mandatory by the local regulation who obliges to keep the traditional architectural shapes in every new construction. This way, the roof has some remarkably longer overhangs above every southern window. The length of this roof extensions was calculated to allow the capture of winter solar radiation and avoid the direct radiation in summer, as shown in Figure 3.4. Apart from these features included in the calculations of the

Passive House Planning Package (PHPP), the design also implemented a and foldable glazing enclosure in the entrance hall. This glazing can remain opened or closed to create a buffer zone and increase to certain degree the solar harvesting with a greenhouse effect.

Figure 3.2. Aerial view of the dwellings and South-Western facade of the case study

The house plan is rectangular with a net floor area of 176.05 m² and a total heated volume of 500.58 m³. The general image and shape of the buildings is due to the requirements of local regulations, which require a certain angle and a tile roof. In the inside, there are suspended ceilings to correct partly the roof angle and reduce the maximum height of spaces. This way, the height of the rooms range from the lowest 2.30 m to the highest 3.60 m. The plans with general dimensions, elevations and a cross-section are shown in Figure 3.3.

The dwelling was built with high levels of thermal insulation, as usual in a Passivhaus housing, but in this case the construction materials were heavy and medium weight. The structure of the dwelling was made of reinforced concrete, as a very common construction style in the rural houses of the region. The foundations are a monolithic ground slab and there are three lines of columns to support the upper roof slab. The external walls were made of lightweight concrete blocks and the internal walls were made of lightweight aluminium stud frames with plasterboards.

The majority of the thermal insulation is placed on the outside. The external walls and the roof slab include 16 cm of EPS and the foundation slab is separated from the ground by 16 cm of XPS. On the other hand, there are also some layers of thermal insulation on the inner side of the thermal envelope. All the inner walls are filled with mineral wool and the wooden floor was placed over a layer of 5 cm of XPS. In Figure 3.4 a detail of the external wall cross-section shows the place of the materials. The composition of the main elements is described in Table 3.1, including the material characterization and global thermal transmittances.

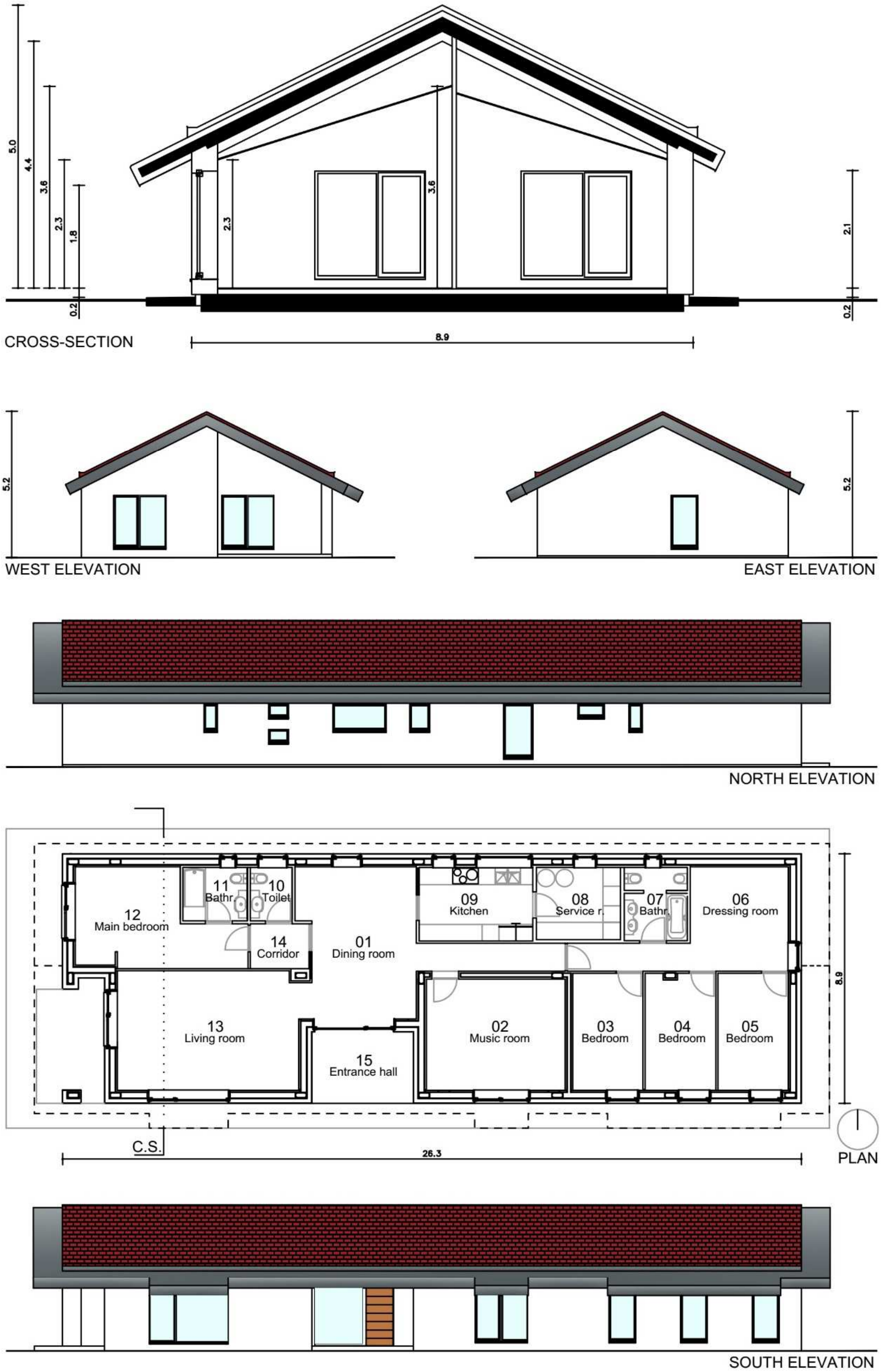


Figure 3.3. Plans of the monitored case study (plans provided by CliM arquitectura S.L.)

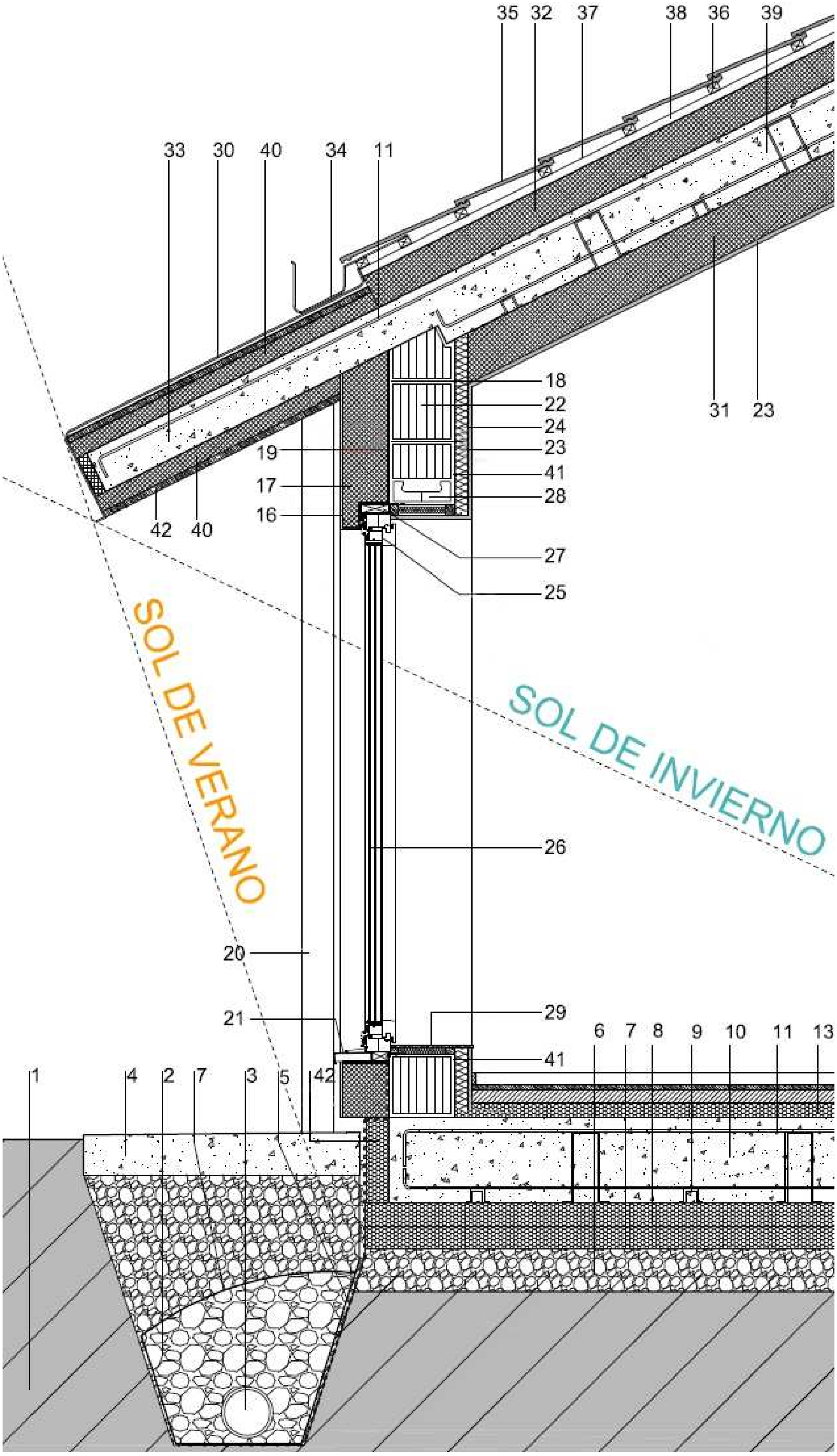


Figure 3.4. Construction detail of roof façade, window, roof overhang and sidewalk.
(plans provided by CliM arquitectura S.L.)

The airtightness solutions implemented during the construction to reach the Passivhaus requirements were diverse. First, rubber bands were mounted in every concrete block wall corner and also in the top and bottom of the walls. Second, specific sealing bands were applied around all exterior openings. Third, a layer of plaster lining was extended along all the inside to guarantee the airtightness layer continuity. As a result, the Blower Door test (BDT) conducted in the end of works certified a very high level of airtightness, i.e. an Air Exchange Rate of 0.21 h^{-1} at 50 Pa (the threshold of PHI states an ACH 50 Pa < 0.6 h^{-1}).

Table 3.1. Building external constructive elements

FACADE WALL	**0.143 W/m²K**	**46.2 cm**
Components:	**λ [W/(mK)]**	**thickness [mm]**
External coating	0.870	6
EPS Graphite	0.032	160
Adhesive mortar	1.500	5
Mortar, waterproof	1.300	15
Lightweight concrete block wall	0.460	200
Internal gypsum plaster	0.570	15
Rock wool	0.036	46
Gypsum board	0.250	15

ROOF	**0.111 W/m²K**	**50 cm**
Components:	**λ [W/(mK)]**	**thickness [mm]**
EPS Graphite	0.032	120
Reinforced concrete slab	2.400	220
EPS Graphite	0.032	160

GROUND SLAB	**0.160 W/m²K**	**57.5 cm**
Components:	**λ [W/(mK)]**	**thickness [mm]**
XPS Styrodur	0.036	160
Reinforced concrete slab	2.400	300
XPS Styrodur	0.036	50
Mortar levelling	1.300	50
Floating wood floor	0.130	15

WINDOWS	**0.9 W/m²K**	**g 0.50**
Components:	**U [W/(m2K)]**	
Wood frame, aluminium coating	1.073	-
Glazing, 3pan, argon/Low E.	0.600	-
Installation thermal bridging	Side 0.032	Upper 0.036

Table 3.2: Building internal constructive elements

PARTITION Wall	**0.603 W/m²K**	**7.6 cm**
Components:	**λ [W/(mK)]**	**thickness [mm]**
Gypsum board	0.250	15
Rock wool	0.036	46
Gypsum board	0.250	15

PARTITION Music r. w.	**0.302 W/m²K**	**24.2 cm**
Components:	**λ [W/(mK)]**	**thickness [mm]**
Internal gypsum plaster	0.570	15
Rock wool	0.036	46
Lightweight concrete block wall	0.460	120
Rock wool	0.036	46
Internal gypsum plaster	0.570	15

The potential thermal bridges of the building have especial solutions to compensate the possible negative effect to a great extent. The majority of the geometrical joints were calculated in the project and Table 3.3 shows the list of all the solutions. It is worth mentioning that with this level of thermal insulation many of them have a positive effect, since they reduce the heat losses of their adjacent walls, floors or ceiling elements.

Table 3.3: List of the thermal bridges of the case study

Thermal bridge description	**Type***	**Quantity**	**Unit length (m)**	**Total length (m)**	**$\Psi_{external}$ (W/mK)**	**$\Psi_{internal}$ (W/mK)**
Sidewalk-Porch	GF	1	14.5	14.5	0.049	0.206
Roof overhang	RE	1	78.2	78.2	0.036	0.156
Wall internal corner	WIC	2	3.9	7.8	0.031	-0.020
Wall internal corner (West)	WIC	1	4.8	4.8	0.031	-0.020
Wall external corner	WEC	6	2.6	15.7	- 0.066	0.042
Roof ridge	RR	1	26.3	26.3	- 0.032	0.011
Sidewalk-Facade	GF	1	63.7	63.7	- 0.010	0.147
Wall facade column	WC	8	2.6	20.8	0.012	0.012
Window to wall at head (spacer + installation)	WH	1	18.75	18.75	0.076	0.076
Window to wall at jamb	WJ	2	22.12	44,24	0.076	0.076
Window to wall at cill	WC	1	18.75	18.75	0.076	0.076
Door threshold (entrance)	DT	1	1.1	1.1	0.124	0.124
Door to wall at jamb	DJ	1	2.1	2.1	0.025	0.025
Door to wall at head	DH	1	1.1	1.1	0.023	0.023

** The thermal bridges are classified according to PH designer's manual* (Hopfe & McLeod, 2015)

The inner distribution is structured by two corridors and the rooms are grouped by use. In the centre, the dining room is united with the living room to create the core of the house. The west side contains basically the main bedroom with its bathroom and a toilet. The East side contains the rest of uses and if the kitchen and service room on the north side, the children rooms face the south, together with the music room. The dimensions are described in Table 3.4 below.

Table 3.4: Case study room identification with net floor and volumes

Room ID	Description	Net floor (m^2)	Air volume (m^3)
1	Dining room	27.54	76.98
2	Music room	19.64	60.68
3	Bedroom 1	10.43	30.72
4	Bedroom 2	10.37	30.45
5	Bedroom 3	10.43	30.72
6	Dressing room	17.45	49.02
7	Bathroom 2	5.76	13.43
8	Service room	7.76	19.89
9	Kitchen	10.70	27.63
10	Toilet	2.87	7.47
11	Bathroom 1	4.41	11.50
12	Main bedroom	17.25	50.76
13	Living room	28.00	82.60
14	Corridor	3.44	8.73
	TOTAL HEATED ROOMS	176.05	500.58
15	Porch (buffer zone)	9.15	26.82

The ventilation system is provided by a unit of Mechanical Ventilation with Heat Recovery (MVHR), a typical system in Passivhaus designed buildings. It is located in the service room, more or less in the centre of the house and from there multiple ducts deliver the fresh air to each final room. The efficiency of heat recovery is 93 % at 145 m^3/h, according to the Passivhaus method ($\eta_{WRG,t,eff}$) and the electricity consumption is 0.24 W/m^3 at 100 Pa of pressure difference.

The ventilation unit incorporates a by-pass module to supply fresh air directly from the outside (without HR). It is activated manually in summer and it reduces the cooling need of the house in summer when the outdoor temperature is cooler than the exhaust air temperature. In summer mode, it is automatically open whenever the indoor air temperature is over 18 °C (to prevent overcooling) and outdoor temperature is over 13 °C (to avoid condensing).

The operation of this ventilation unit is controlled manually, selecting one out of 7 power levels which can supply a wide range of air flow, from 75 to 300 m³/h. During the monitoring of the dwelling the ventilation was always set on 4th position, to maintain a constant air flow and facilitate the comparison of the Heat Recovery (HR) and by-pass unit. In the 4th position, the MV provides 182.3 m³/h with the 63 % of unit's nominal power.

It is important to specify that this ventilation rate was slightly over dimensioned in comparison with the values demanded by PHPP ventilation sheet, included in Figure 3.5. Considering that the maximum fresh air needed is 220 m³/h, the PH design criteria would recommend to use a combination of position 4 during day-time, supplying 82.9 % of the ventilation need, and position 3 during night-time, providing 68.2 % of the ventilation need. Therefore, the ventilation rate during the monitoring is 7.9 % over the basic ventilation need of the PHPP calculations.

Ventilation System Design - Standard Operation

Occupancy	m²/P	35				
Number of occupants	P	5.0				
Supply air per person	m³/(P*h)	30				
Supply air demand	m³/h	151				
Extract air rooms		Kitchen	Bathroom	Shower	WC	est+Est+Inst
Quantity		1	2		1	1
Extract air demand per room	m³/h	60	40	20	20	60
Total extract air demand	m³/h	220				
Design Air Flow Rate (Maximum)	m³/h	220				

Average Air Change Rate Calculation

Type of Operation	Daily Operation Duration (h/d)	Factors Referenced to Maximum	Air Flow Rate (m³/h)	Air Change Rate (1/h)
Maximum		1.00	220	0.50
Standard	24.0	0.77	169	0.38
Basic		0.54	118	0.27
Minimum		0.40	88	0.20
	Average value	0.77	Average Air Flow Rate (m³/h): **169**	Average Air Change Rate (1/h): **0.38**

Figure 3.5. Case study PHPP v.7 ventilation calculation sheet.

In order to analyse he ventilation properly, the ventilation rates were verified and characterised by several procedures, as explained in Section 3.3.1.1. The monitoring of the ventilation system is focused on the efficiency of the Heat Recovery (HR) and the capability of the bypass to reduce the cooling demand.

The heating need of the monitored house is very low in this house, namely 13 kWh/m² per year. For this reason, the original design included only one stand-alone pellet stove in the living room. The project estimated that the heat can be distributed to the other rooms through ventilation in order to keep home inside TC ranges. The pellet stove has a controlled combustion process with variable thermal power between 2.4 and 9.0 kW. The fresh air is taken directly from the outside and there is an independent circuit to exhaust the combustion gases safely. During the monitoring period, the pellet stove was analysed in the first weeks and afterwards it was turned off and replaced by a set of individual electric heaters. This was necessary to keep more balanced the inner temperatures in every room, stablishing a common set-point (20 °C) and measuring the heating provided instantly.

The Domestic Hot Water (DHW) is provided by a combination of a solar thermal panel and an air to water Heat Pump (HP) with a storage of 300 l of DHW. In a first stage, the solar panel supplies warm water to a complementary tank of 150 l. This solar storage permits to preheat the fresh water and save the 32 % of DHW need. The Coefficient of Performance (COP) of the HP is higher than 3.75. Overall, the renewable share of DHW is around 80 %.

The calculations of the PHPP indicated that the detached dwelling approves the PHI criteria successfully. Figure 3.6 includes the main results: 13.1 kWh/m²a of heating demand, 9.0 W/m² of maximum heating load (on daily average), 66 kWh/m²a of primary energy demand and 0 % hours of overheating with 4 W/m² of maximum cooling load (on daily average).

Year of Construction:	2012				
Number of Dwelling Units:	1		Interior Temperature:	20.0	°C
Enclosed Volume V_e:	600.0	m^3	Internal Heat Gains:	2.1	W/m²
Number of Occupants:	5.0				

Specific Demands with Reference to the Treated Floor Area

	Applied:	Monthly method	PH Certificate:	Fulfilled?
Treated Floor Area:	176.1	m^2		
Specific Space Heating Demand:	**13**	**kWh/(m²a)**	**15 kWh/(m²a)**	**Yes**
Heating Load:	**9**	**W/m²**	**10 W/m²**	
Pressurization Test Result:	**0.2**	**h^{-1}**	0.6 h^{-1}	**Yes**
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	**66**	**kWh/(m²a)**	120 kWh/(m²a)	**Yes**
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	**24**	**kWh/(m²a)**		
Specific Primary Energy Reduction through Solar Electricity:		**kWh/(m²a)**		
Frequency of Overheating:	**0**	**%**	over 25 °C	
Specific Useful Cooling Energy Demand:		**kWh/(m²a)**	15 kWh/(m²a)	
Cooling Load:	**4**	**W/m²**		

Figure 3.6: Case study PHPP v.7 sheet with the main values.

3.3.1.1. Verification of the ventilation

As seen before, the case study presented a very low energy demand according to PHPP. In order to be able to monitor and evaluate the real performance of this building, it was essential to confirm the design features before planning the monitoring.

Thus, apart from the monitoring explained in the following sections, the case study was tested to verify the thermal and energy characteristics defined in the project design.

Firstly, the ventilation system was checked with an air flow meter. Meaning that each inlet and outlet was measured and compared with the theoretical values. In the beginning, the results were successful due to an easy procedure and fast re-adjustment.

However, this method showed some limitations in big-connected spaces like the living room and the dining room where some ventilation short circuits could appear. To solve this issue, the testing was reoriented to verify the real ventilation rate. This is possible using a tracer gas methodology, that is defined in UNE EN ISO 12569:2002.

Figure 3.7: Ventilation verification done with different procedures, with an air flow meter (left) and the tracer gas method (centre), gas analysis equipment (right).

In brief, the method analyses the real ratio of ventilation in each room during at least 30 minutes. Firstly, the doors of the selected enclosure are closed and an auxiliary fan is activated to mix the air inside the space. Secondly, a high concentration of a tracer gas is released and the gas analysers measure the decay of concentration according to the following formulas (1) (2). Finally, the results or each room are put together and compared with the previously measured supply air values. The results are listed in Table 3.5.

$$n = \frac{\ln C(t_1) - \ln C(t_2)}{t_2 - t_1} \quad (1)$$

$$Q = n \times V \quad (2)$$

n Air Change Rate, ACH (h^{-1})
$C(t_1)$ concentration of the sample in t1
$C(t_2)$ concentration of the sample in t2
t_1 time in instant 1 (s)
t_2 time in instant 2 (s)
Q ventilation flow (l/s)
V inner volume (l)

Table 3.5: Ventilation rates in every room, measurements according to UNE EN ISO 12569:2002 and air flow values based on direct measures of inlets and outlets.

Room ID	Description	Ventilation (l/s)	ACH (h^{-1})	Room volume* (m^3)	Supply air (m^3/h)	Exhaust air (m^3/h)
1 + 13	Dining + living room	20.5	0.46	156.9	72.2	17.1
2	Music room	10.3	0.63	59.2	23.5	37.3
3	Bedroom 1	3.5	0.42	30.0	12.6	
4	Bedroom 2	3.3	0.41	29.6	12.2	
5	Bedroom 3	4.3	0.53	29.2	15.5	
6	Dressing room	7.6	0.74	37.0		27.4
7	Bathroom 2	6.3	1.68	13.4		22.6
8	Service room	3.7	0.74	17.8		13.1
9	Kitchen	8.6	1.42	21.8		31.0
10	Toilet	2.9	1.42	7.5		10.6
11	Bathroom 1	6.5	2.02	11.5		23.2
12	Main bedroom	11.8	1.04	41.0	42.7	
	Total values			455.0	178.6	182.3
Average air changes per hour, ACH (h^{-1})						**0.40**

** The furniture and other elements are deducted from the inner volumes*

Additionally, the two biggest rooms were also tested to control the Indoor Air Quality (IAQ) and verify the equal distribution of the ventilation all around the different sides of these rooms. It was conducted according to the NT VVS 019 “Buildings – Ventilation Air: Local Mean Age”. The measuring points are defined below, in Figure 3.8.

At first, several gas measuring points are installed in the corners of the room to control the decay of the concentration in all those corners. Second, the tracer gas is released in all the room and the auxiliary fans are used only shortly to ensure a balanced distribution of the gas before starting the measure. Third, the measuring of decay starts with the ventilation operating as usual (MVHR) and the auxiliary fans disconnected. The applied formula can be seen in (3).

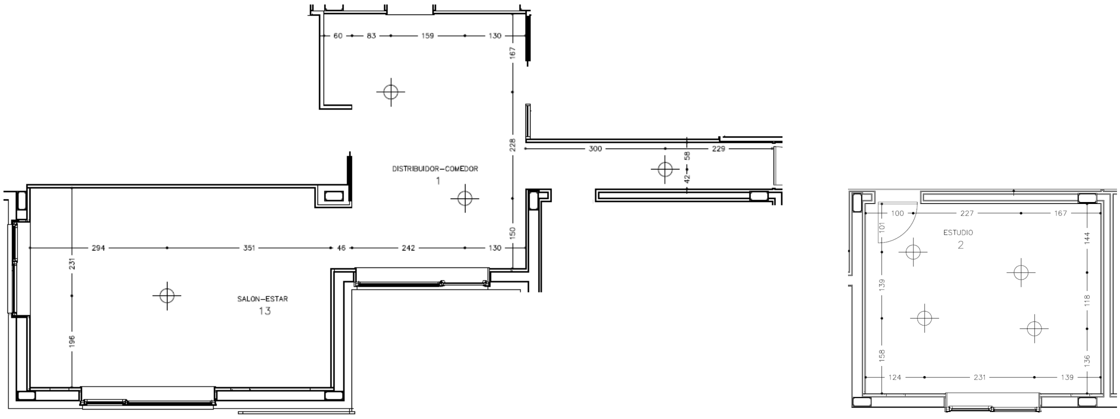


Figure 3.8: Ventilation verification with Local Mean Age method,
living-dining room (left) and music room (right).

In the end, the decay of concentration in every point help to identify any possible unbalanced ventilation in places with less fresh. The results for the two tested rooms demonstrated that the ventilation provides a god quality of renovation, because it is equally distributed along all the parts of the room. The results are listed in Table 3.6.

$$\bar{\tau} = \frac{\left(\sum_{i=0}^{M} C_i\right)\Delta t + \frac{C_M}{\lambda_e}}{C_0} \qquad (3)$$

Ci	instant concentration measure (ppm)
C0	initial concentration (ppm)
CM	final concentration measure (ppm)
M	total number of measures
$\Delta\tau$	measuring time-step (h)
λ_e	slope of the curve in exponential decay
τ_M	total time of measurements, $\tau_M = M \times \Delta\tau$.

Table 3.6: Local Mean Age in living-dining room and music room, NT VVS 019.

Music room	**Air Age (h)**	**Living + dining rooms**	**Air Age (h)**
Channel 1	1,73	Channel 1	2,0
Channel 2	2,07	Channel 2	2,15
Channel 3	1,73	Channel 3	1,98
Channel 4	1,80	Channel 4	1,67
Time nominal constant	1,60	Time nominal constant	2,13

3.3.1.2. Verification of the thermal insulation

Before evaluating the passive performance of the building, it was necessary to confirm the high level of thermal insulation. As seen in the description of, the major part is insulated with an Expanded Polystyrene with graphite (EPS), used in facades and roofs. In order to be sure of the performance, two verifications were planned: the verification of the thermal conductivity of the raw material and the direct measure of the constructed walls performance on-site.

The first step was carried out according to the method of the heat flow meter UNE-EN 12667, as presented in Figure 3.9. The result indicated a very good thermal insulation properties, inside the ranges specified in the manufacturer's technical sheet. The final conductivity value was 0.032 W/mK.

The second step was oriented to verify the quality of the construction works and to measure the final performance of the applied insulation. Besides, the present case has elements with high thermal insulation and high thermal mass and therefore the study required considerable long span measurements and several checking points. To be able to quantify on-site the thermal resistance of the walls under dynamic conditions two methods were selected: the integrated calculation of ISO 9869:1994 and the R-C method developed by the DYNASTEE network.

Figure 3.9. Heat flow meter (left) and detail of the EPS installation on facades (right).

In total, the heat flux was measured in three points of the façade for more than a month. The roof measurements were discarded because the ceiling cavity was open and it could generate bidirectional heat fluxes. In any case, the technique to install the EPS on the roof was very similar to facades. The heat losses were measured every minute and averaged to 10 m during 31 days. The measurement instruments were installed on homogeneous areas of façade, belonging to the dressing room and the main bedroom. The selected points were in the North, East and West orientations, to minimise the impact of solar radiation. In each point the temperatures of inner and outer surfaces were measured together with the internal heat flux. Further details of the instruments can be found in Section 3.4.

According to the first method, the integration of ISO 9869:1994, the results confirmed the estimated theoretical value of 0.143 W/m²K. Some small differences can be observed between the measured points, namely 0.128 W/m²K in the North, 0.144 W/m²K in the East and 0.146 W/m²K in the West facades. The average value of these three points is 0.139 W/m²K. In any case, considering the 5 % of uncertainty of the norm, the results indicate that the installed thermal insulation achieves the expected level of thermal resistance of facade.

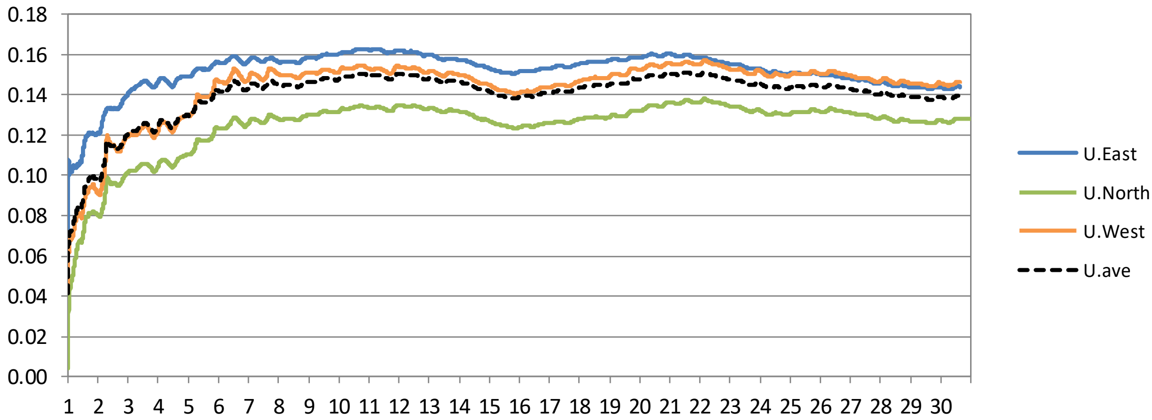


Figure 3.10: Thermal transmittance of facades, integrated method of ISO 9869:1994.

Once the direct measurements of the heat losses through facades and the heating use are completed. The last verification consisted of the definition of a mathematical model to integrate all the heat inputs and outputs and verify the thermal response of the building as a whole. This supplementary analysis of the measured values was conducted following the parameter identification method formulated by the DYNASTEE network.

The mathematical model involved the identification of the main heat fluxes in the house and the definition of an RC network which could integrate all these factors at the same time. This type of mathematical method has been widely used due to its adaptability to measured different physical parameters.

This capacity to identify accurately the global performance of constructions and match the final performance was highlighted in different studies. The study of Reynders et al. made a deep analysis of the robustness of this method and concluded that only few model types are needed to represent the majority of buildings (Reynders, Diriken, & Saelens, 2014). The work of J. Teres et al. (Teres-Zubiaga, Escudero, García-Gafaro, & Sala, 2015) tested the potential of the R-C network as a tool to assess the priorities to refurbish social collective housing. Another study conducted over a passive house in a cold climate used this tool to apply a model predictive control and successfully optimised the indoor environment while reducing the energy consumption (Fux, Ashouri, Benz, & Guzzella, 2014).

In the present study, the model was defined according to the available measurement points. Accordingly, the necessary resistances were inserted between the measured values. The measured data used for the model is described in Table 3.7 and the model structure is presented in Figure 3.11. Note that the building thermal mass was concentrated in two nodes, representing the envelope and the inner objects separately.

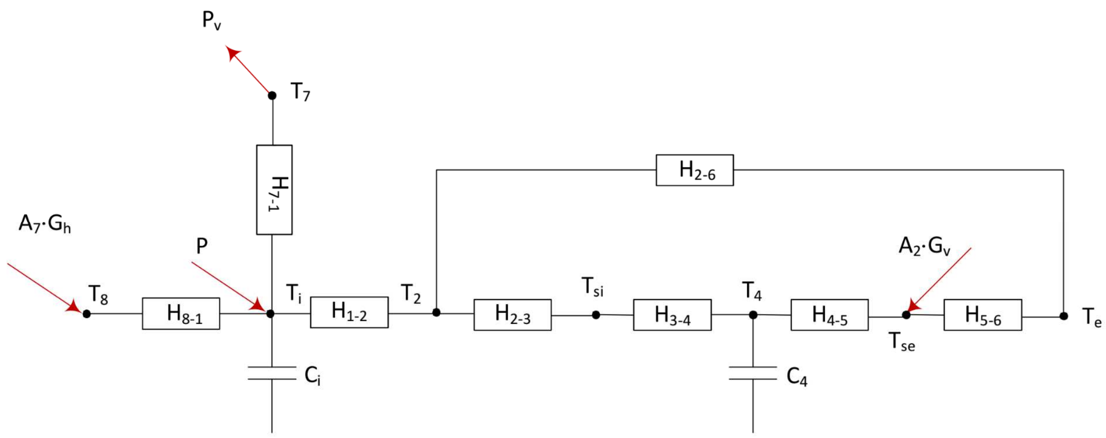


Figure 3.11. Model structure of the monitored house, 8R2C-model.

Table 3.7: Description of the data linked to nodes.

Node	Measured temperatures	Measured fluxes
1	House average indoor air DB temperature	Heating use and average hourly electricity use
3	Average wall inner surface temperature	
5	Average wall outer surface temperature	Solar global horizontal radiation
6	Outdoor air DB temperature	
7		Heat losses through ventilation
8		Solar global horizontal radiation

The software used to calculate the mathematical model was the LOgical R–Determination (LORD version 3.21). This software tool permits the modelling and calculation of thermal systems. This software was developed by the DYNASTEE Network (DYNamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings) and it is a further development of the software package "MRQT/PASTA". Further details are available in (DYNASTEE, 2012).

The definition of the model structure and the calculation boundaries set in the mathematical tool are presented in Figure 3.12 and Figure 3.13 respectively. For the calculations, measurements of 587 hours were used (24.5 days), from the 12th of March of 2013 to the 4th of April of 2013.

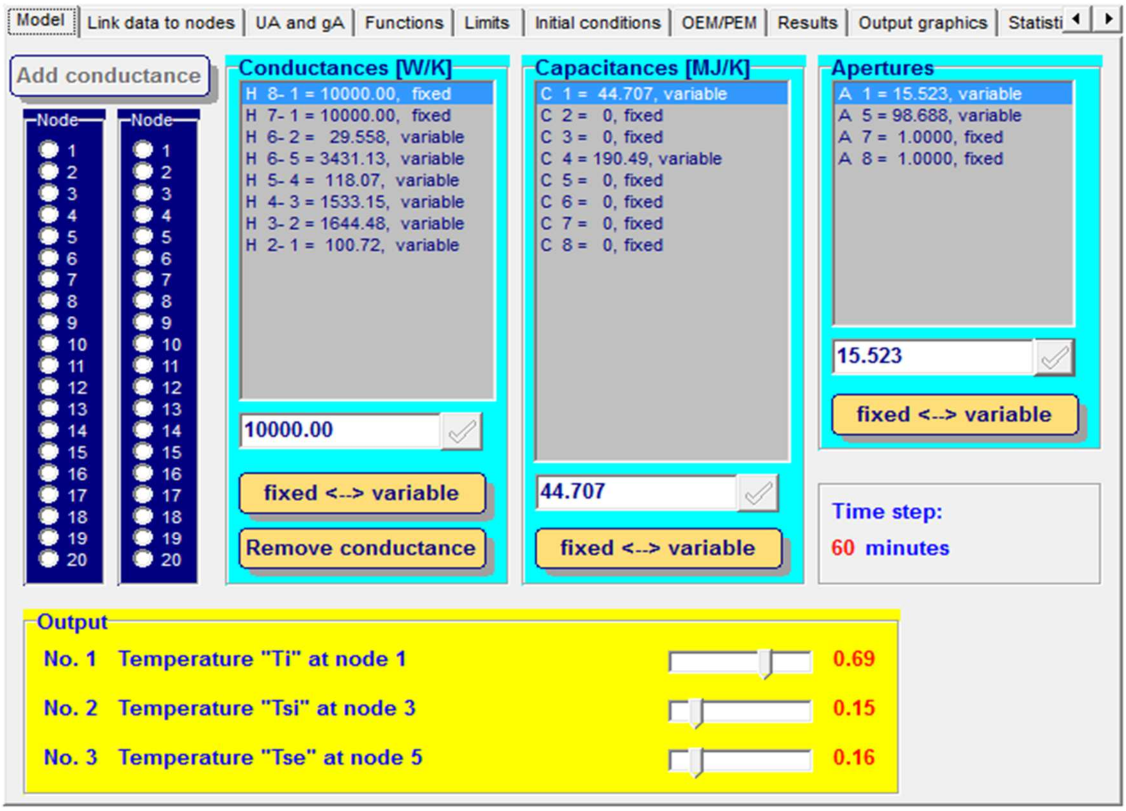


Figure 3.12. Model definition and calculation boundaries set in LORD 3.21.

In this model, one or more objective functions can be defined simultaneously, in order to minimise the error between the measure and the prediction.

In the present study three objective functions were selected: (i) T_i, as the indoor air DB temperature, (ii) T_{si}, as the façade inner surface temperature, and (iii) T_{se}, as the façade outer surface temperature.

This way, the input parameters were four: (i) T_e, as the outdoor air temperature, (ii) P, as the sum of the heating and electricity use hourly, (iii) P_v as the heat losses through ventilation, and (iv) G_h as the global horizontal solar radiation.

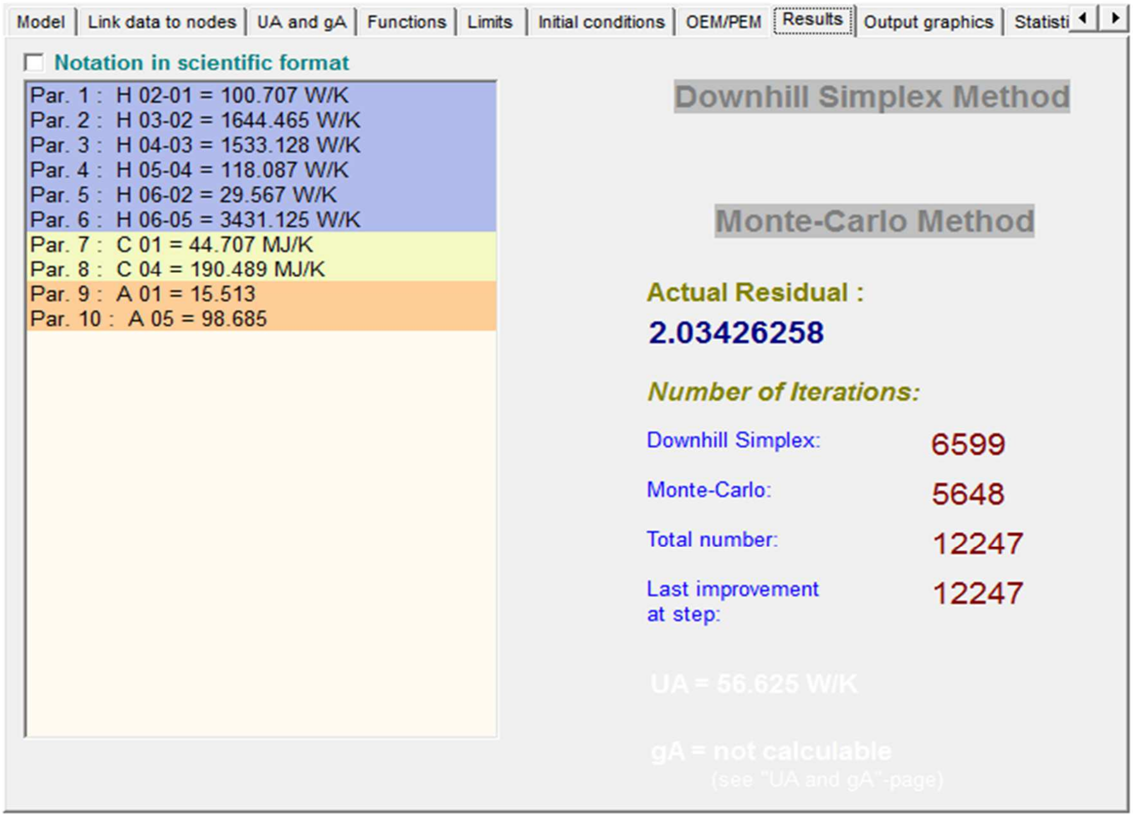


Figure 3.13. Results of the developed model obtained with software LORD 3.21.

The results of the model showed a good match with the measurements with reduced errors in the different measured parameters. IT is important to keep in mind that the measurements correspond to house average values which had certain particular deviations due to the averaging of different curves of temperature.

In the following figures, the differences obtained between the calculated and the measured values are presented. The indoor temperature in Figure 3.14, the façade indoor surface temperature in Figure 3.15 and the façade outdoor surface temperature in Figure 3.16.

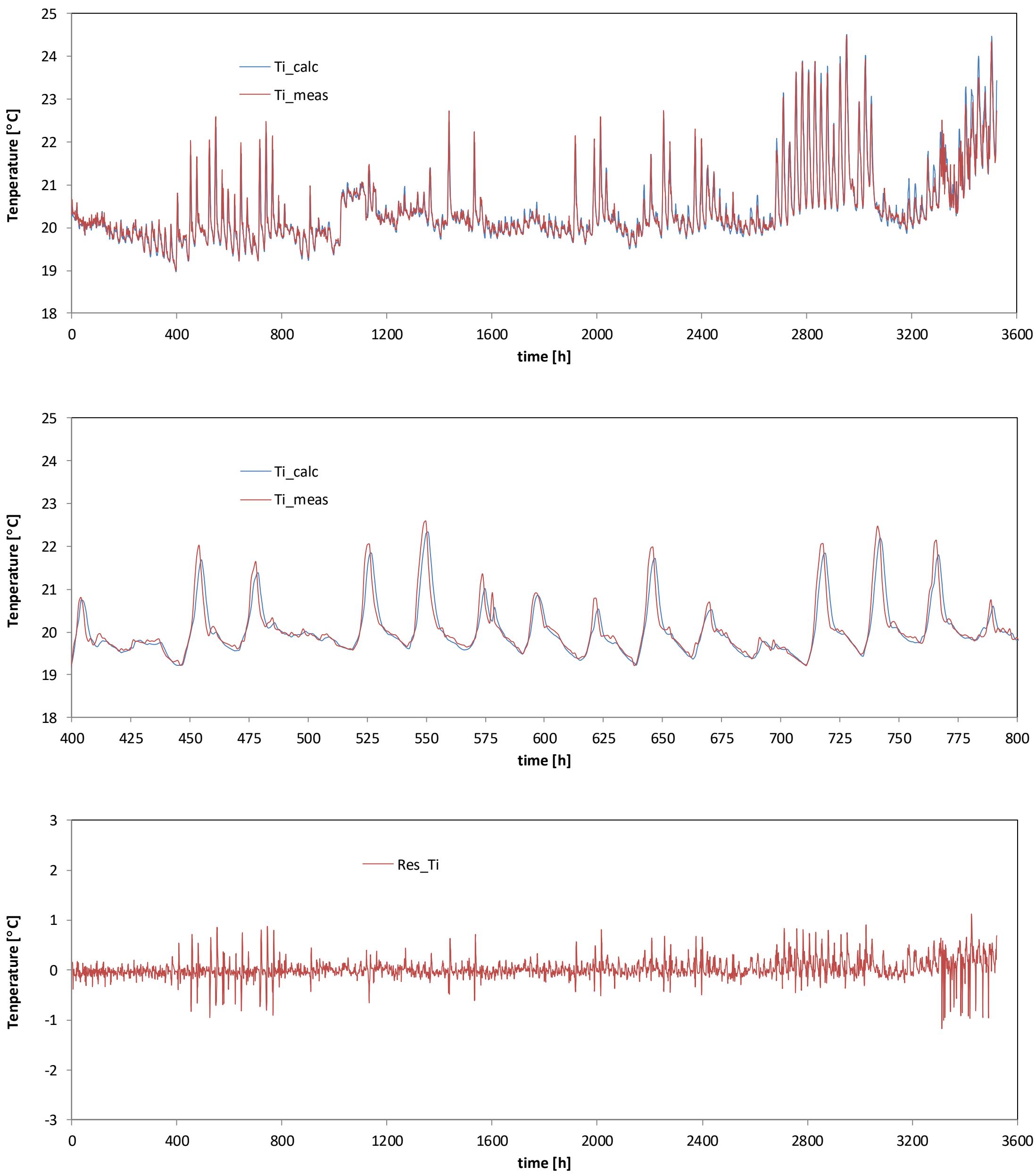


Figure 3.14. Measured and calculated indoor air DB temperatures with RC model.

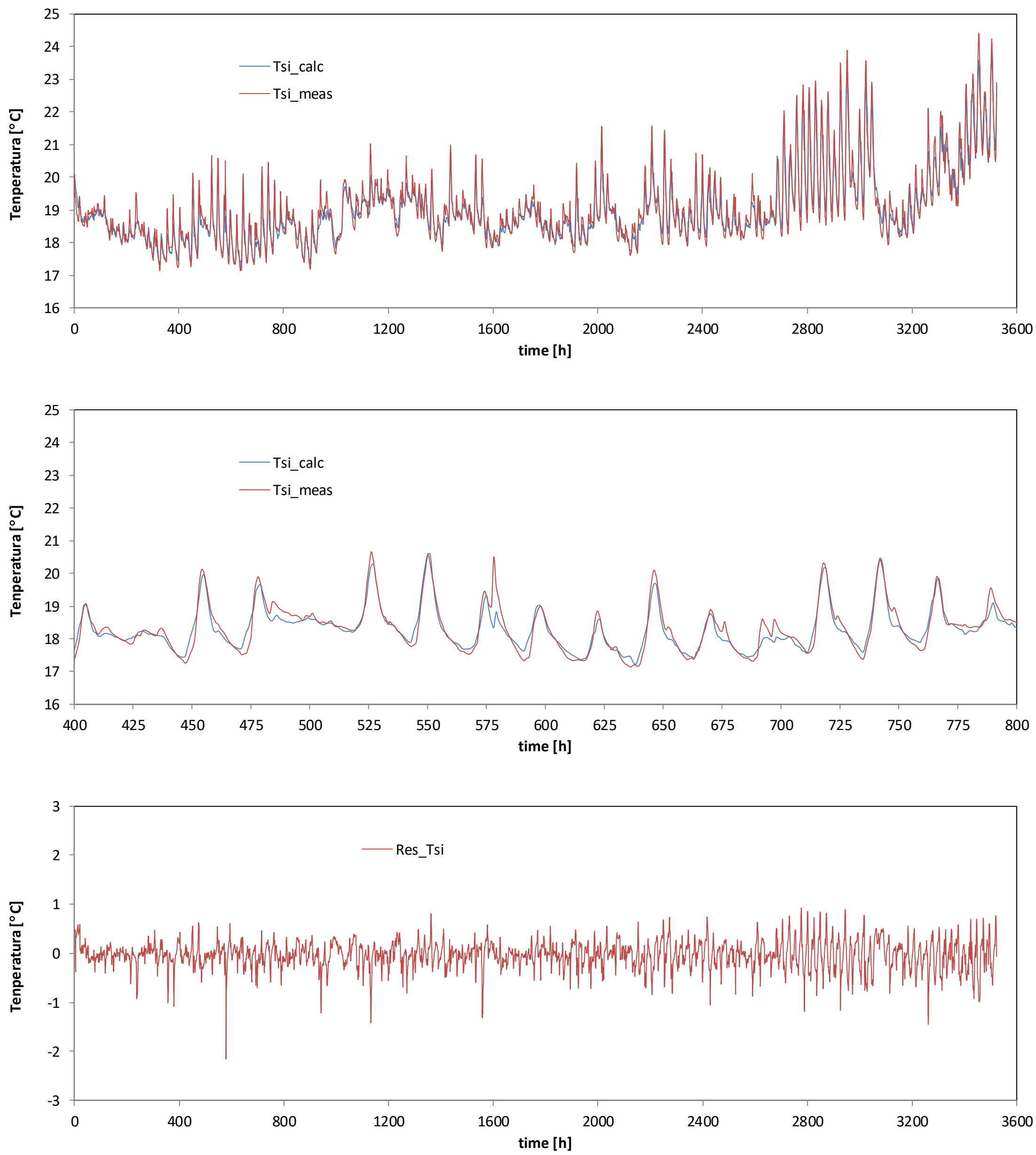


Figure 3.15. Measured and calculated façade inner surface temperatures with RC model.

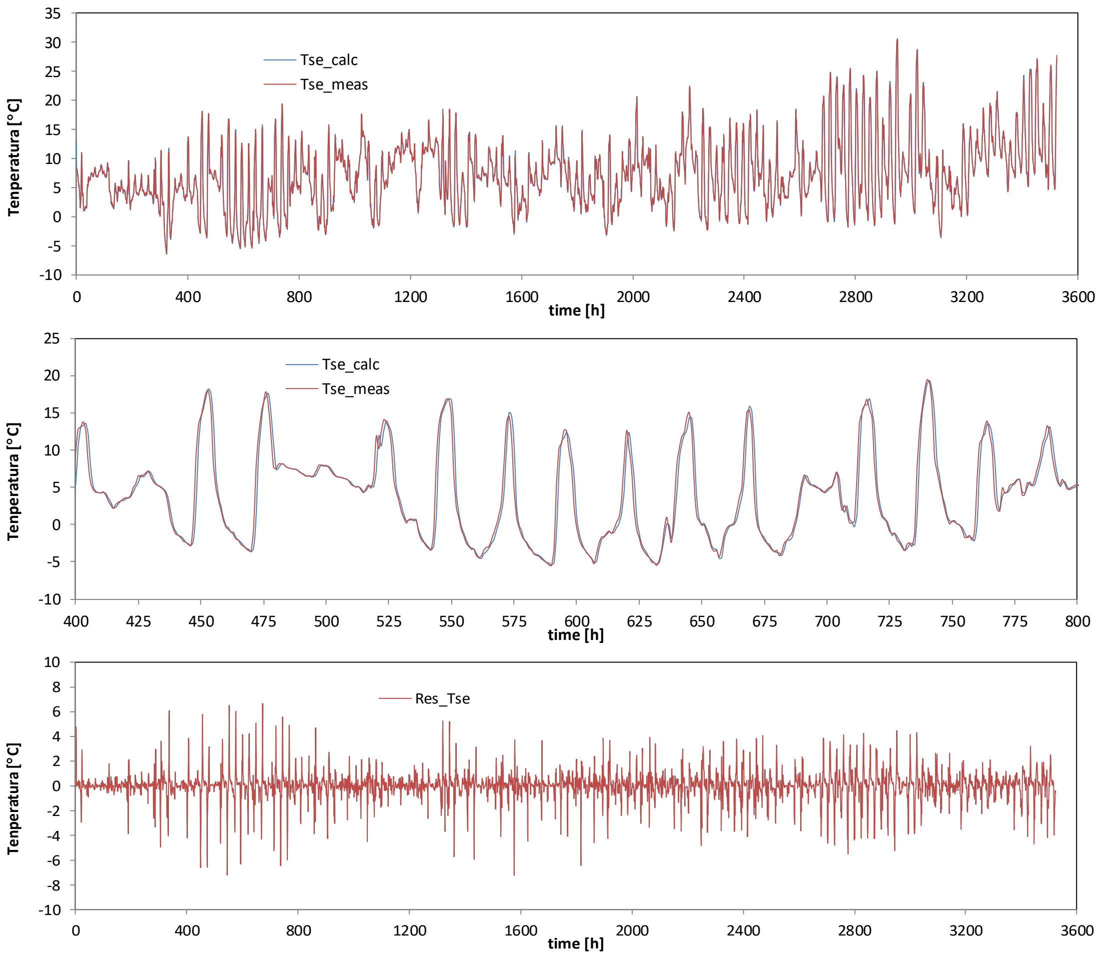


Figure 3.16. Measured and calculated façade outer surface temperatures with RC model.

The results of the model showed small deviations from the theoretical design. According to this data, the windows presented 5.7 % higher thermal transmittance and the opaque elements obtained 6.2 % lower thermal transmittance. This way, the measurements confirmed that the house presented on average a good response, considerably similar to the projected values. The results are summarised in Table 3.8.

Table 3.8. Summary of the thermal transmittances and thermal mass obtained from the RC model.

Elements	Units	PHPP data	RC Model	Difference (%)
Window thermal transmittance	W/K	28.0	29.6	5.7
Opaque average thermal transmittance	W/K	116.9	109.6	-6.2
Solar aperture of windows	m^2	-	15.5	-
Thermal mass*	MJ/K	129.0	190.5	47.7
Internal thermal mass	MJ/K	-	44.7	-
External convective heat transfer coefficient (h_{ext})	W/K	25	7.8	-68.8
Internal convective heat transfer coefficient (h_{int})	W/K	8	3.7	-51.4

** PHPP estimation, the maximum heat capacity of concrete structure was 297.2 MJ/K*

3.3.2. Description of the monitoring system

In the first place, the selection of the equipment was done to satisfy the particular goals of the present case. On the one hand, the monitoring had to be able to measure and integrate a wide range of parameters during a long-term monitoring. Meaning that it had to concentrate enough data to assess: heating, thermal comfort, thermal envelope, ventilation and local meteorological conditions. On the other hand, it had to meter accurately the thermal performance of a building with a high level of thermal insulation and provide a solid remote control system to reduce the disturbances in a building already on-use.

As a result, the installed monitoring system was controlled through a laptop on-site (with remote control) equipped with an emergency power supply unit, see Figure 3.17. The data was registered by a multifunction data logger, which was connected by cable to all sort of sensors. This instrument was configured channel by channel to read properly and provide the required voltage to some RH sensors.

The electric heaters were controlled by an amperemeter and a local air temperature with a set point. In Figure 3.18 a diagram of the monitoring system is presented, including the structure of the analysis in blue, the objectives in green, the indoor parameters in red and the outdoor parameters in purple.

In the diagram are also included some additional tests which were done only at certain moments to verify the features of the thermal envelope, ventilation flows or to get additional details for the thermal comfort (TC) assessment.

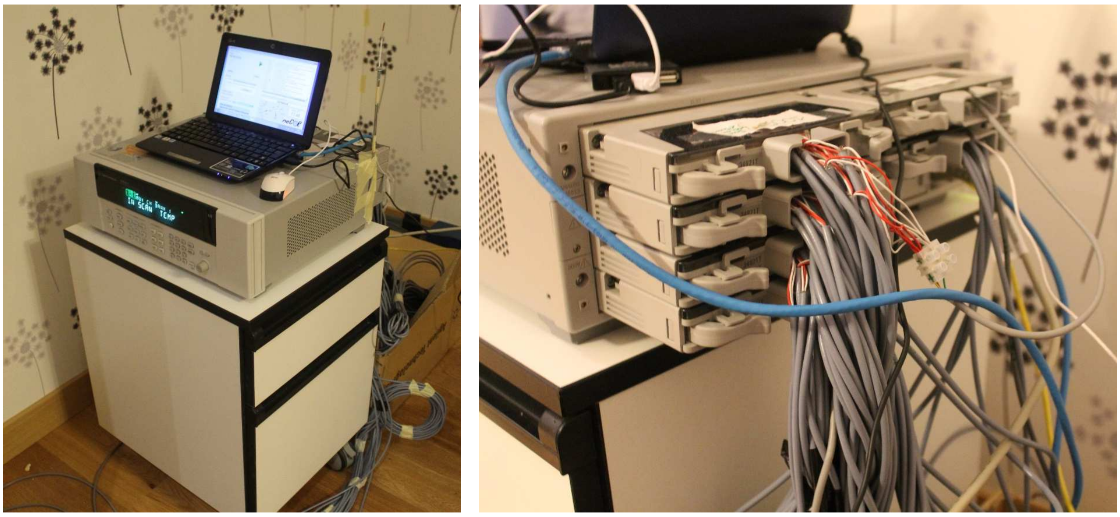


Figure 3.17. Datalogger and laptop with the monitoring software and remote control.

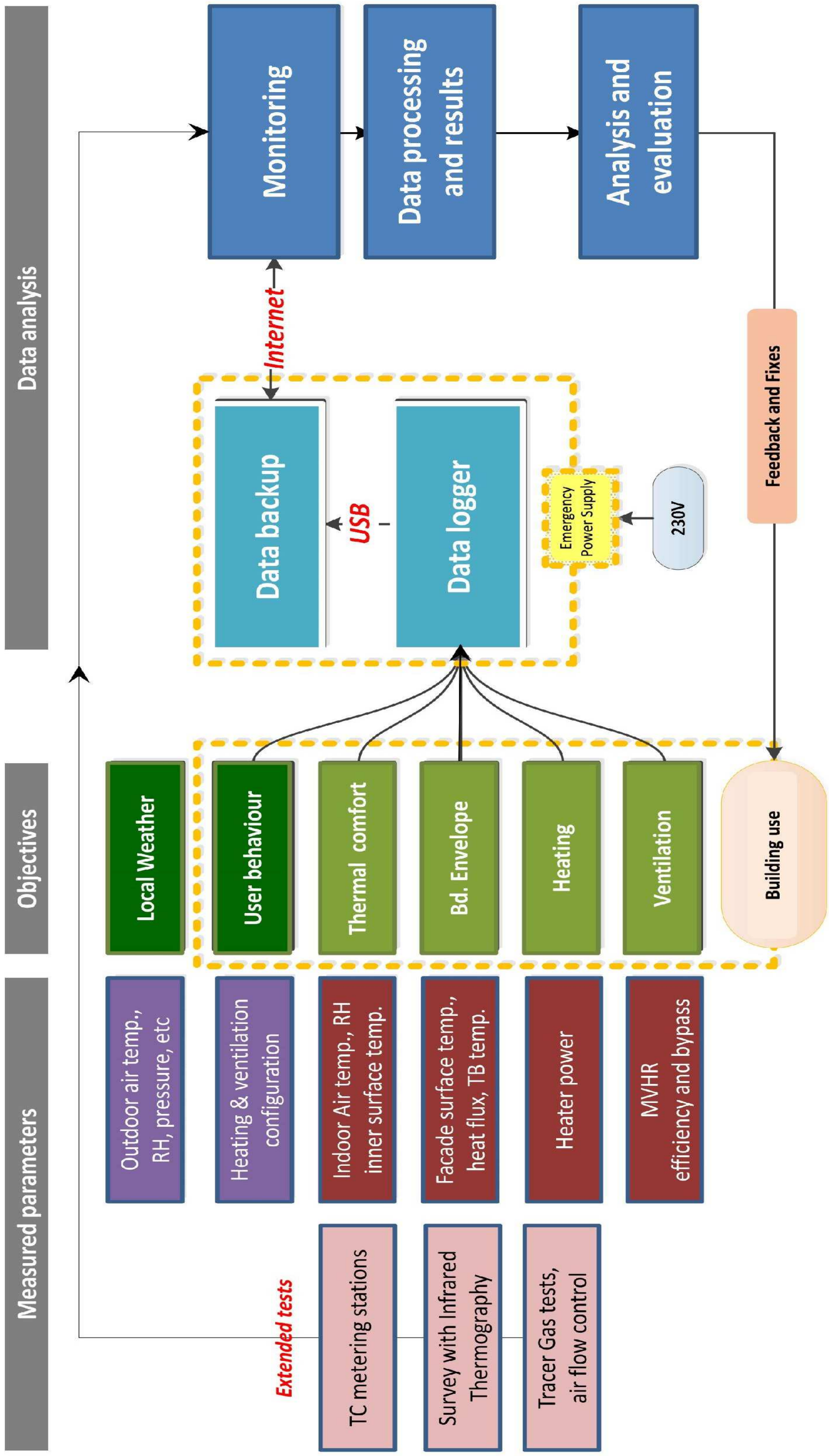


Figure 3.18. Diagram of the case study monitoring system.

The location of the sensors was decided according to the main objectives as explained in the following page and the positions can be checked in detail in the plan of Figure 3.24. Moreover, Table 3.9 summarises the included sensor types for each parameter, defining their uncertainty and the number of measurement points. All the sensors were calibrated before the testing and verified after the monitoring. For further details and images see Appendix II.

Air dry bulb temperature sensors:

- One in every room at 200 cm high, to control the differences inside the home.
- Three supplementary in the living room and three in the dressing room at 90, 180 and 270 cm high, to study the air stratification in the dwelling.

Air Relative Humidity (RH) sensors:

- In living room, dining room, main bedroom, dressing room at 200 cm high to verify the thermal comfort.
- In the entrance hall, to evaluate the latent heat and greenhouse effect.

Figure 3.19. Pt100 and RH sensors for living room air (left), surface temperature in column (centre) and surface temperature in the glazing and frame of a window in dressing room (right).

Surface temperature sensors:

- Outside every façade orientation, to know the inside-outside gap.
- Inside possible thermal bridges, to detect the decay of inner temperatures.
- In the ceilings and floors of representative rooms, to verify local discomfort conditions and the performance of the roof and the ground floor.
- In partitions, to analyse asymmetric temperatures locally.
- In frame and the pane of a northern window, to verify its performance.

- In the case of the pellet stove, to record its operation hours.

Heat flux meters:

- In the inner side of Northern, Western and Eastern facades.

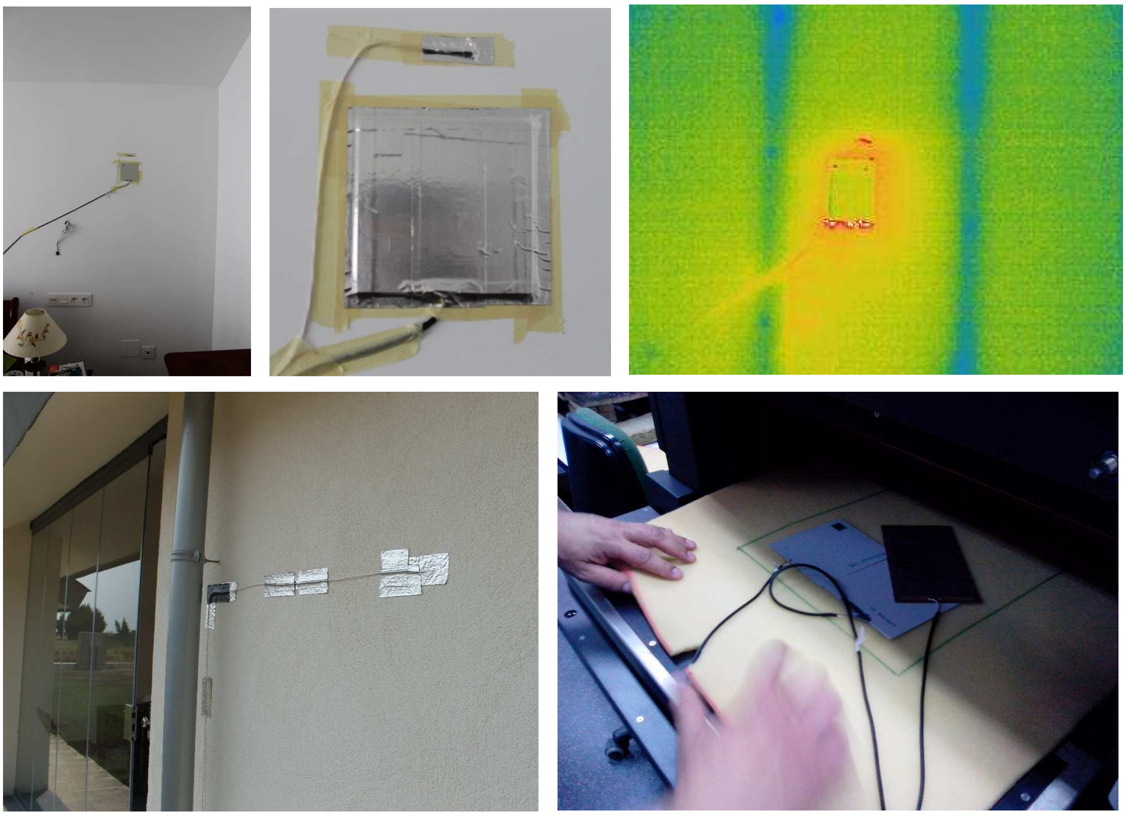


Figure 3.20. Indoor heat flux meters and Pt100 installed in north façade, IR placement verification (up), outside surface temperature (down left) and calibration of heat flux meters (down right).

Electricity power meters:

- Instant value of the electric heaters of the living room and dressing room.
- Monthly value of the house consumption.

Figure 3.21. Electricity power meter (left) and one of the installed electric heaters (right).

Meteorological data:

- Solar radiation meter in the garden of the house.
- Meteorological station on-site. It had to be disconnected some periods due to gardening works of inhabitants, in those periods it was replaced by the data of a very near meteorological station at 3 km.

Figure 3.22. Meteorological station location and integration of solar radiation meter on-site.

Operative temperature, RH, air velocity and air dry bulb temperature (TC station):

- Supplementary stations mounted in the living room and one bedroom.
- Periods of at least one week during winter, spring, summer and fall.

Figure 3.23. Thermal comfort station for PMV method, in bedroom 3 (left side) and living room (right side).

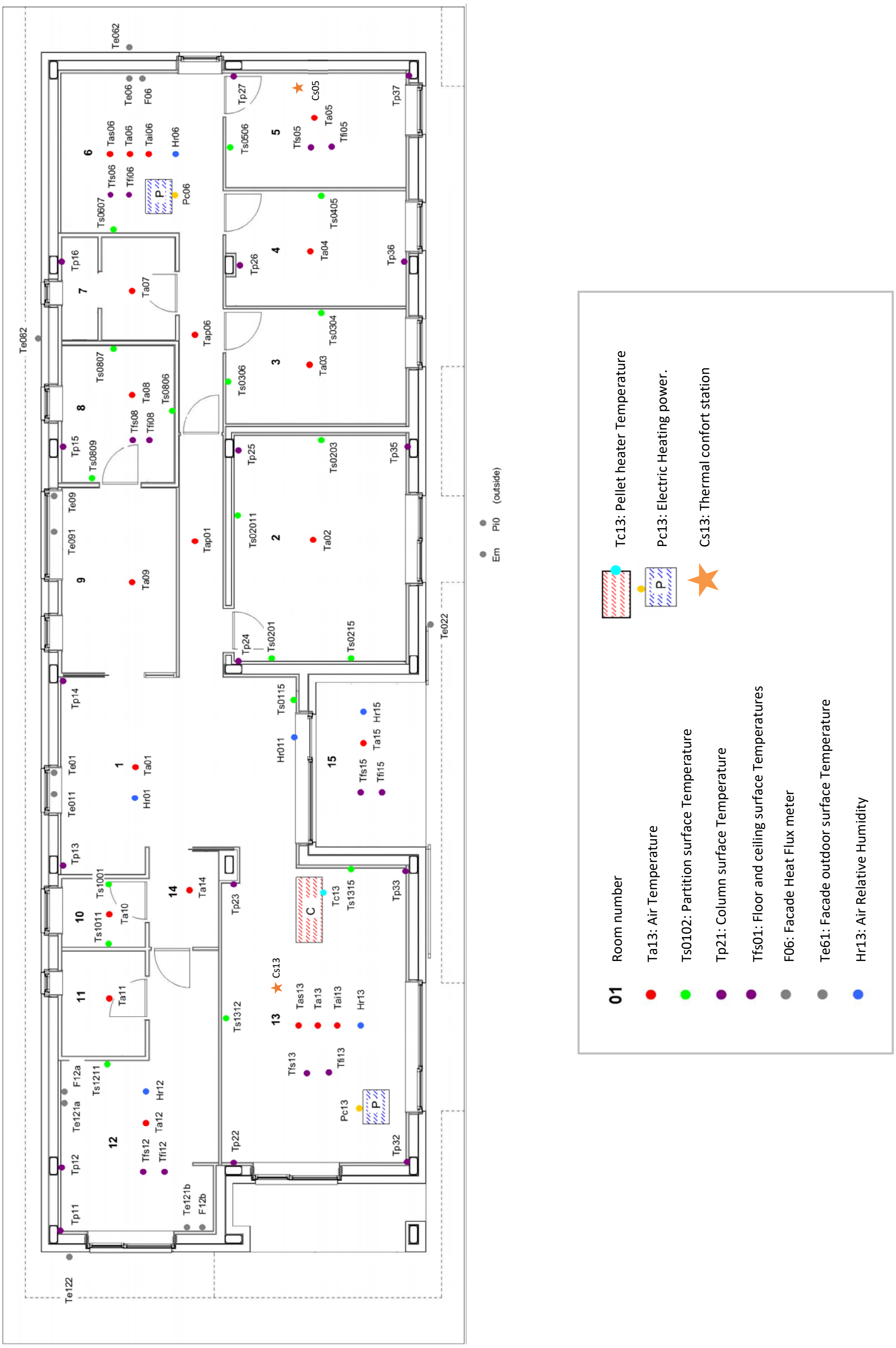


Figure 3.24. Location of sensors of the case study monitoring system.

Table 3.9. Summary of the sensors and the parameters measured by the data acquisition system.

Parameter	Sensor	Units	Num.	Uncertainty
T. air	RTD, PT100 (sheathed)	°C	21	±0,2 °C
T. surface	RTD, PT100 (encapsulated)	°C	57	±0,2 °C
Relative Humidity	HIH-4000-001	%	6	±3,5 %
Heat flux	Ahlborn, Wärmefluss	W/m²	3	±5 %
Electric power	JUMO, dTron 304	W	2	±4 %
Global H. Irradiance	Kipp&Zonnen, CMP11	W/m²	1	±3 %
Meteorological St.	VAISALA, WXT520	°C, mbar, mm, m/s, %	1	-
Data logger	AGILENT, 34980A	-	1	-

The connectivity of the monitoring system was a considerable challenge. It required a detailed planning to minimise the disturbance to the inhabitants and avoid mistakes during the long-term monitoring. The preparations began with the definition of the position of each sensor and the search of the best paths to extend the wires.

In total, more than 1800 m of cable were necessary to connect the whole system. The cables were cut beforehand at different lengths according to the amount of cables needed, from the shortest 5 m to the longest 50 m to connect the sensors outside (meteorological station, solar radiation meter ad outer surface temperatures). The cables were connected with specific sockets for 4 wire Pt100 to maintain the quality of the signal and permit fast replacement of sensors when necessary. All these preparations were done in advance in the laboratory facilities.

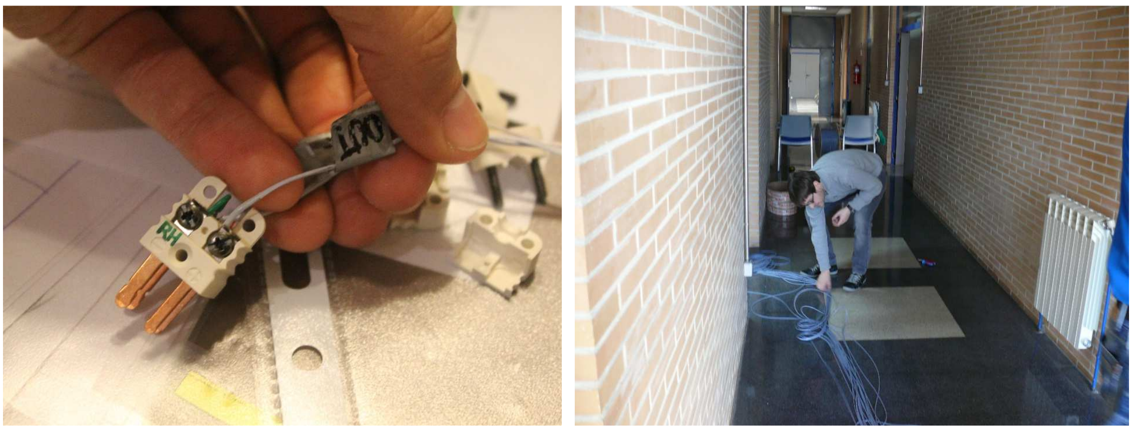


Figure 3.25: Preparation of connection cables and sensors in the Laboratory of the Basque Government.

Figure 3.26. Acoustic box for datalogger and laptop (top left side), crossing cables to outside sensors (top right side), installation of cables and finished works on-site (bottom).

3.3.3. Analyses method

As seen in Section 3.3.2, the method controls all relevant physical parameters to evaluate the real thermal performance of a passive dwelling. Besides, the methodology also facilitates the review of the registered values regularly and give feedback to users when possible. This method is an adaptation of the procedures to monitor and assess the dynamic performance of construction elements, developed by the Thermal Area of the Laboratory of the Quality Control of Buildings of the Basque Government (LCCE-GV), see (A. Erkoreka, 2015) (C. Escudero-Revilla, 2016). Apart from the main goal of the present study, this method can also provide high quality data and permits the creation of RC models to study the whole house thermal performance.

First, the monitoring system was programmed to register the data of all sensors every 1 minute and to send every night the file containing all the recordings of the day.

Second, the reviewer of the monitoring would insert these raw data files in a daily averaging template with the calibration of each sensor, to obtain automatically the corrected values of all the measurements and average them to a time step of 10 minutes. This template also contains plots to check at first sight the daily performance, see Figure 3.27 and Figure 3.28.

Table 3.10. Daily analysis strategy based on objectives, plots and items

Objectives	Daily analysis plots	Items included
1	Weather and building response	Outdoor temperature, RH, solar radiation, façades av. surface temp., porch air temp., indoor av. temp., av. RH
1	Wind conditions	Direction and intensity
1	Heating power	Heating power, outdoor temp., solar radiation, indoor av. temp.,
2 and 6	All room air temperatures	All room air temperatures, house average air temp.
2 and 6	All Relative humidity	Indoor RHs, average RH, entrance hall RH, outdoor RH, house average air temp.
3	Façade outside temperatures	Façade outside temp., outdoor temperature, solar radiation, house average air temp.
2, 5 and 6	Indoor temp. by zones	House average air temp., living, service and sleeping zones, North and South zones, East and West zones
2 and 5	Vertical air temperatures	Living room vertical temp., dressing room vertical temp., house average air temp.
2 and 3	Floor and ceiling temp.	Ceiling temp., floor temp., house average air temp.
3	Structure temperatures	Column temperature, house average air temp.
2	Partition temperatures	Partition temp., house average air temp.
3	Window temperatures	Window frame temp., window glazing temp., house average air temp., outdoor air temp., solar radiation
3	Porch performance	Porch air temp., ceiling temp., floor temp., RH, dining r. temp., outdoor air temp., outdoor RH, solar radiation

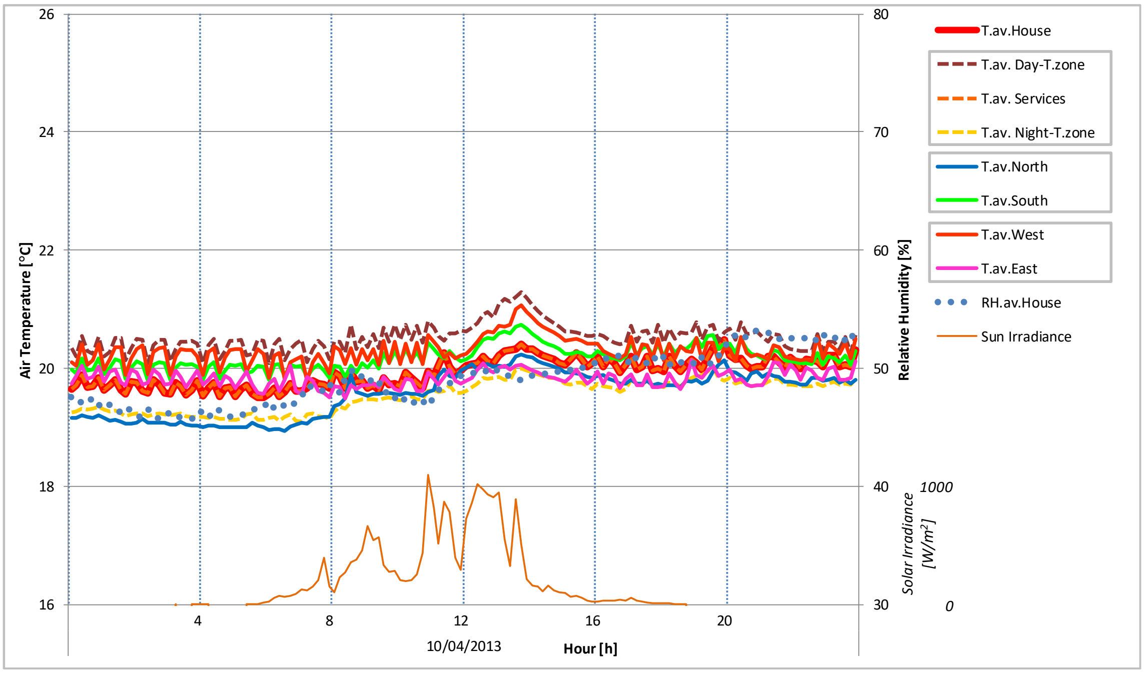


Figure 3.27. Example of daily analysis of temperatures by rooms orientations and activity.

Third, these values are exported to a weekly analysis template, to conduct a periodic review and fix any possible errors such as sensor malfunctions, accidents with the instruments, user related issues or other possible unexpected failures. During this period, the user's exceptional activity is recorded.

Fourth and last, all the measurements every 10 minutes are included within a big file of the monitoring. In order to facilitate the assessment of the full year performance in a multi-level analysis, this big file average the values to larger time steps: hourly, daily and monthly basis. This file contains plots and summary tables to evaluate the general results. Section 3.4 contains the main results of the study, the findings are discussed in Section 3.5 and the conclusion of each evaluated aspect are presented in Section 3.6.

Apart from this continuous and integrated monitoring, some additional tests were conducted in certain moments to verify the operation of the ventilation, the thermal comfort in detail, the effectiveness of the thermal insulation installation and the homogeneity with an infrared camera along the inside and the outside.

The monitoring system was prepared in January of 2013. After the installation of all the devices and sensors, the measurements started in the 4th of February and finished in the 11th of April of 2014. The main four stages of the monitoring are explained in Section 3.4.1. For further details of the timing of each monitored aspect see Figure 3.29 and Figure 3.30.

Table 3.11. Weekly analysis strategy based on objectives, plots and items

Objectives	Weekly analysis plots	Items included
1	Weather and building response	Outdoor temperature, RH, solar radiation, façades av. surface temp., porch air temp., indoor av. temp., av. RH
1	Heating power	Heating power, outdoor temp., solar radiation, indoor av. temp.,
2 and 6	All room air temperatures	All room air temperatures, house average air temp.
2 and 6	All Relative humidity	Indoor RHs, average RH, entrance hall RH, outdoor RH, house average air temp.
2	All indoor surface temperatures	Pillar temperature, partition temp., ceiling temp., floor temp., house average air temp.
3	Façade outside temperatures	Façade outside temp., outdoor temperature, solar radiation, house average air temp.
2, 5 and 6	Indoor temp. by zones	House average air temp., living, service and sleeping zones, North and South zones, East and West zones
2 and 5	Vertical air temperature	Living room vertical temp., dressing room vertical temp., house average air temp.
2 and 3	Floor and ceiling temperatures	Ceiling temp., floor temp., house average air temp.
3	Structure temperatures	Column temperature, house average air temp.
2	Partition temperatures	Partition temp., house average air temp.
3	Window temperatures	Window frame temp., window glazing temp., house average air temp., outdoor air temp., solar radiation
3	Porch performance	Porch air temp., ceiling temp., floor temp., RH, dining room temp., outdoor air temp., outdoor RH, solar radiation

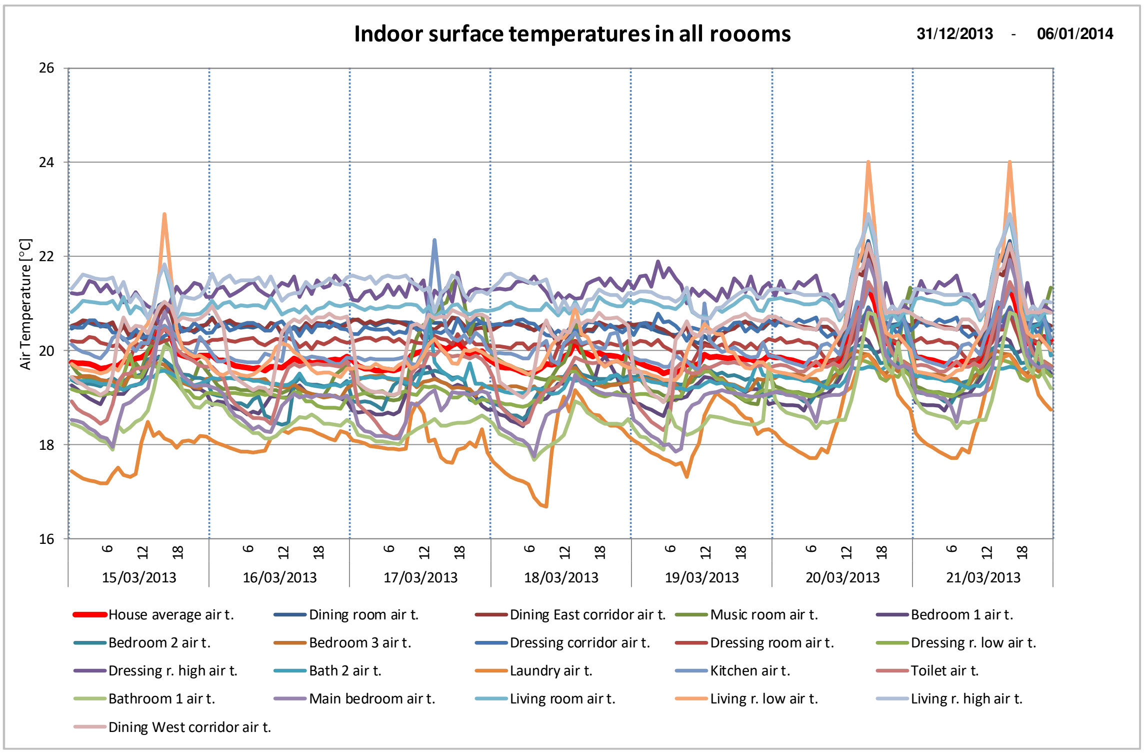


Figure 3.28. Example of weekly analysis of temperatures in every room.

STAGES AND EVENTS	Start date	End date
Monitoring system definition	15/12/2012	31/12/2012
Air exchange rate measurement	28/12/2012	-
Sensor calibration and setting up	02/01/2013	22/01/2013
Monitoring system installation	23/01/2013	03/02/2013
Start of House Monitoring	**04/02/2013**	-
Biomass heating connected	04/02/2013	11/03/2013
Met. Station placed in South side	-	-
Out. IR Thermographic full Survey	25/02/2013	-
Ind. IR (sensor check)	11/03/2013	-
Electric heating connected	11/03/2013	01/06/2013
Ind. IR full Survey	13/03/2013	-
Out. IR Survey (frost doubt)	19/03/2013	-
Facade Heat flux in-situ verification	13/03/2013	24/04/2013
Music room sensors disconnected		28/05/2013
Met. Station moved to West side	10/06/2013	-
Electric heating connected	04/10/2013	01/04/2014
Biomass heating connected	01/04/2014	10/04/2014
End of building monitoring		**10/04/2014**
INDOOR DATA	Monitored	No data
WEATHER DATA	On site W.S.	Near WS.data
THERMAL COMFORT	Measured	No data
VMC-HR DATA	Measured	No data

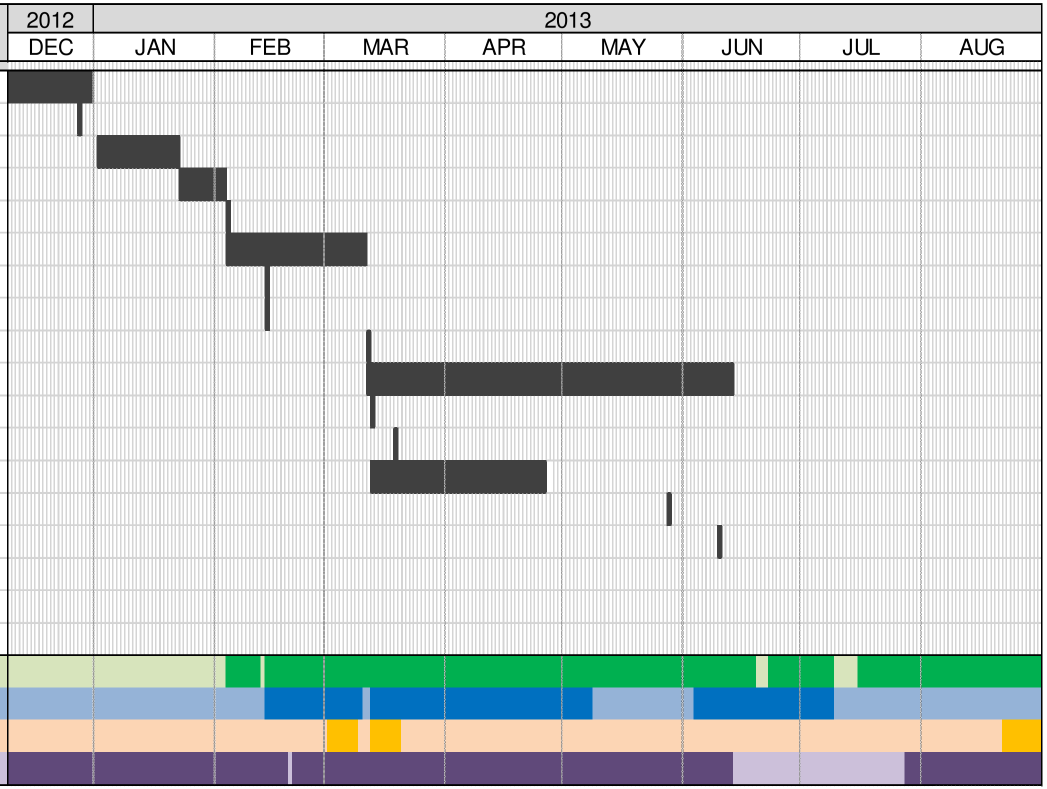


Figure 3.29. Timeline of the case study monitoring, part 1 of 2.

STAGES AND EVENTS	Start date	End date
Monitoring system definition	15/12/2012	31/12/2012
Air exchange rate measurement	28/12/2012	-
Sensor calibration and setting up	02/01/2013	22/01/2013
Monitoring system installation	23/01/2013	03/02/2013
Start of House Monitoring	**04/02/2013**	-
Biomass heating connected	04/02/2013	11/03/2013
Met. Station placed in South side	-	-
Out. IR Thermographic full Survey	25/02/2013	-
Ind. IR (sensor check)	11/03/2013	-
Electric heating connected	11/03/2013	01/06/2013
Ind. IR full Survey	13/03/2013	-
Out. IR Survey (frost doubt)	19/03/2013	-
Facade Heat flux in-situ verification	13/03/2013	24/04/2013
Music room sensors disconnected		28/05/2013
Met. Station moved to West side	10/06/2013	-
Electric heating connected	04/10/2013	01/04/2014
Biomass heating connected	01/04/2014	10/04/2014
End of building monitoring		**10/04/2014**
INDOOR DATA	Monitored	No data
WEATHER DATA	On site W.S.	Near WS.data
THERMAL COMFORT	Measured	No data
VMC-HR DATA	Measured	No data

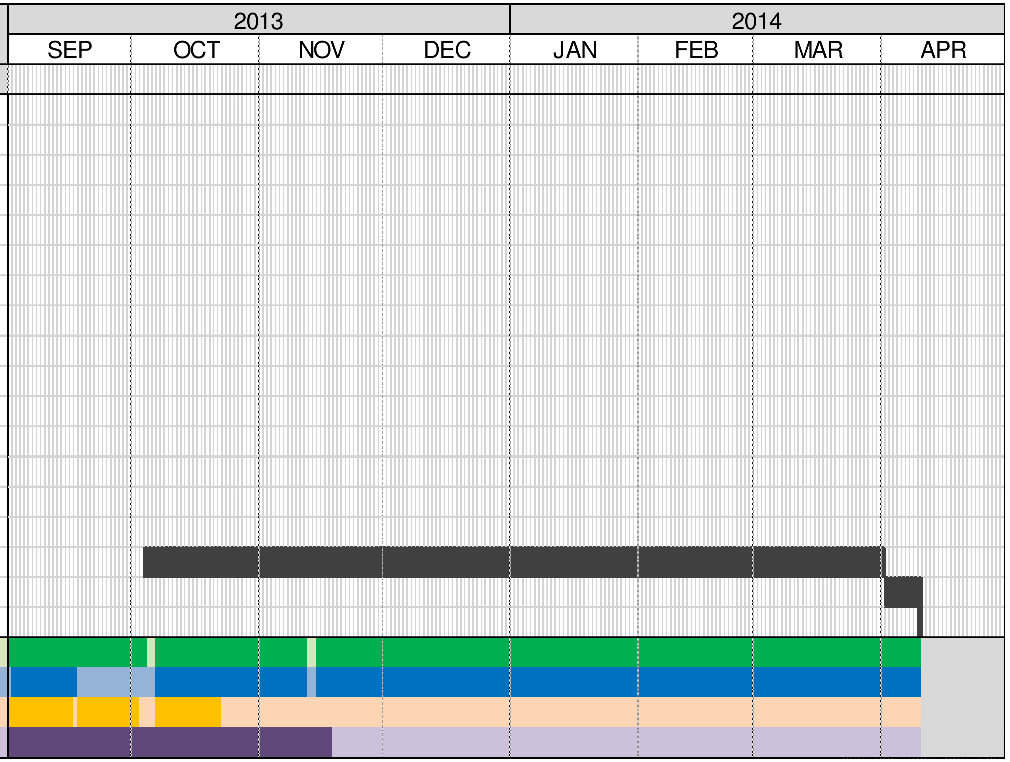


Figure 3.30. Timeline of the case study monitoring, part 2 of 2.

3.3.3.1. Criteria to divide the house in thermal zones

As seen in the literature review of Chapter 2, the assessment of the thermal performance of a low energy dwelling requires a detailed control of the indoor temperatures. In the monitored dwelling, the evaluation was very complex, due to the ambitious objectives and the detail of the monitored data, based on 14 room temperatures. For this reason, the analysis of the house was done at multiple levels.

On the one side, the assessment of the whole house required an average value and it was calculated weighting the temperature of all the rooms with the net floor of each room, so that the final value includes the sizes of each room and represents better the house air distribution. These weighted average values were calculated in a similar way for the house RH, floor surface temperature, ceiling surface temperature, window frame surface temperatures and window glazing temperatures.

On the other side, to be able to analyse the behaviour of different sides of the home, the rooms were classified by orientation and type of activity, as show in Figure 3.31. Accordingly, several weighted temperatures permitted analysing the deviations of some rooms in respect to the weighted house value. This type of classification was especially useful to visualize the thermal comfort in different areas of the dwelling, in Section 3.4.8.

This way, the final assessment includes:

- Full house average
- Living zones (mainly day-time use): Living room, kitchen, dining room, music room.
- Service zones: Dressing room, bathrooms 1 and 2, toilet, service room and corridors.
- Sleeping zones (mainly night-time use): Main bedroom and bedrooms 1,2 and 3.
- North rooms: Main bedroom, Bathroom 1, toilet, kitchen, service room, bathroom 2 and dressing room.
- South rooms: Living room, music room and bedroom 1, 2 and 3.
- East rooms: Dressing room and bedroom 3.
- West rooms: Main bedroom and living room.

Figure 3.31. Definition of thermal zones in the case study: house average, grouped by activities, West-East sides and North-South sides (from top to bottom).

3.4. Monitored data and experimental results

In the following sections, the measurements are classified by topic and objective of the study. The results are summarized and organized to facilitate the assessment in Section 3.5. For further details of the monitored values, see Appendix I, II and III.

3.4.1. Measurement stages and overall gathered data

The monitoring campaign lasted 420 days in total and it analysed the measurements of more than 100 sensors including a meteorological station on-site and some supplementary measures of TC stations. The measurements were performed correctly in the 96.5 % of the hours. Even though there were some incidents and external issues with losses of data, the global numbers demonstrate that the installed monitoring system was highly reliable.

In general, the monitoring campaign can be divided into four stages with specific objectives and outcomes in each one.

The first stage (4/02/2013 – 10/03/2013) was focused on the evaluation of the thermal performance under the conditions defined in the original passive design. This way, the users defined the heating of the pellet stove according to their own taste. To do that, there were installed two stations to measure TC during this stage. The effects of this type of heating were analysed in detail. Additionally, other particular behaviours were measured such as the thermal decay of the dwelling during a weekend off were the users disconnected the heating completely.

The second stage (11/03/2013 – 31/05/2013) was directed to measure the real heating demand of the dwelling on-use. To arrange that, the original heating system was replaced by some electric heaters which could cover the heating need accurately. These devices could adjust the amount of heat supplied in each instant in order to maintain the building just within the thermal comfort zone. Three supplementary electric heaters were equipped, two in the living room and one in the dressing room, to get a more homogeneous temperature among all the rooms. In this period, the thermal envelope was verified and characterised to a great extent. The TC stations were mounted again to compare the results with the pellet stove period.

The third stage (01/06/2013 – 06/10/2013) corresponded to the analysis of summer performance. During the non-heating season the building operated in free-running mode and the heaters were disconnected. TC measurers were installed by the end of August. Given that there was no cooling system, the assessment was focused in the ventilation performance, the benefits of by-pass and the usage of natural ventilation by the inhabitants at night-time. This period raised the concern about overheating (OH) and the importance of providing resources to the inhabitants in order to control OH. The sensors of the music room were dismounted to minimise the disturbances with the inhabitants.

The fourth stage (07/10/2013 – 10/04/2014) completed the year of measurements and it allowed the analysis of the performance during the coldest days of winter. Few changes were done, an extra heater was added in the living room to cover the maximum load at night-time hours and some low sensors were dismounted to reduce the impact on inhabitants' life for Christmas holidays.

3.4.2. External weather conditions

The climate of the region of Vitoria-Gasteiz is classified as Cfb in the Köppen-Geiger scale (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), which corresponds to a warm temperate climate with fully humid precipitation levels and warm summers. The full monitored external weather conditions are plot in Figure 3.32. It includes the daily average, maximum and minimum values of outdoor dry bulb temperature and relative humidity. Additionally, it includes the daily solar global horizontal radiation. The plots can be seen in large size in the Appendix I.

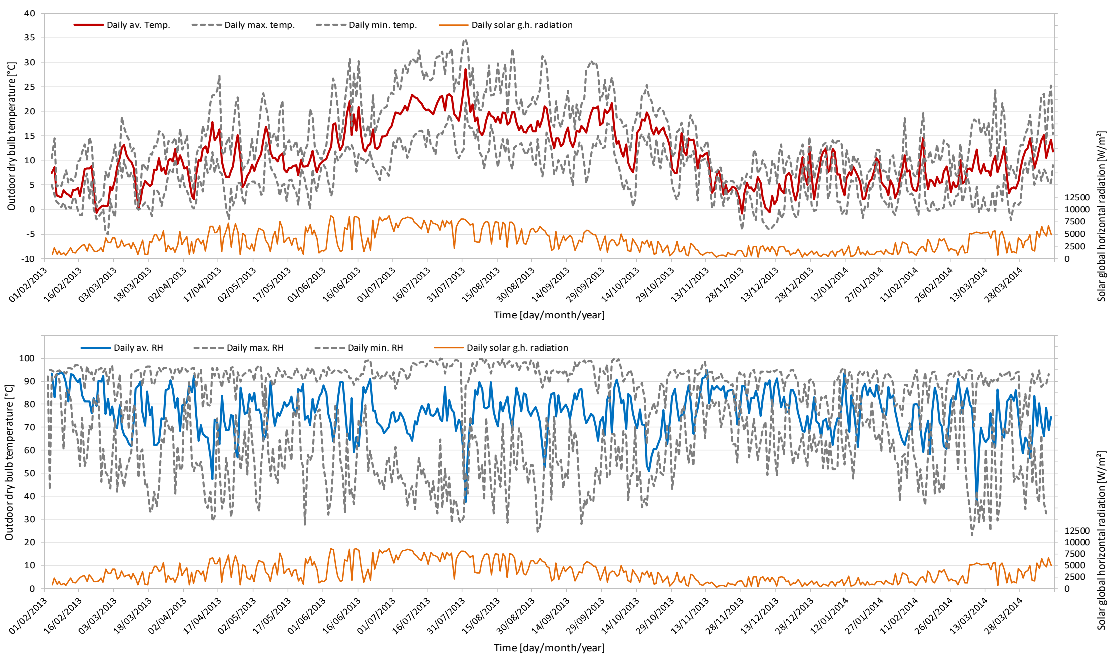


Figure 3.32. Measured outdoor air conditions and solar global horizontal radiation, air dry bulb temperature (left side) and relative humidity (right side).

To analyse the weather conditions during the monitored period, the measurements on-site are compared with other existing climatic databases: The Typical Meteorological Year (TMY) of Meteonorm of Vitoria-Gasteiz, the PHPP design climate file and the official D1 zone climate file of the Spanish Technical Building Code (Código Técnico de la Edificación, CTE) (CTE, 2013). The results are presented in Figure 3.33, based on the monthly average outdoor air dry bulb temperature and global horizontal solar radiation.

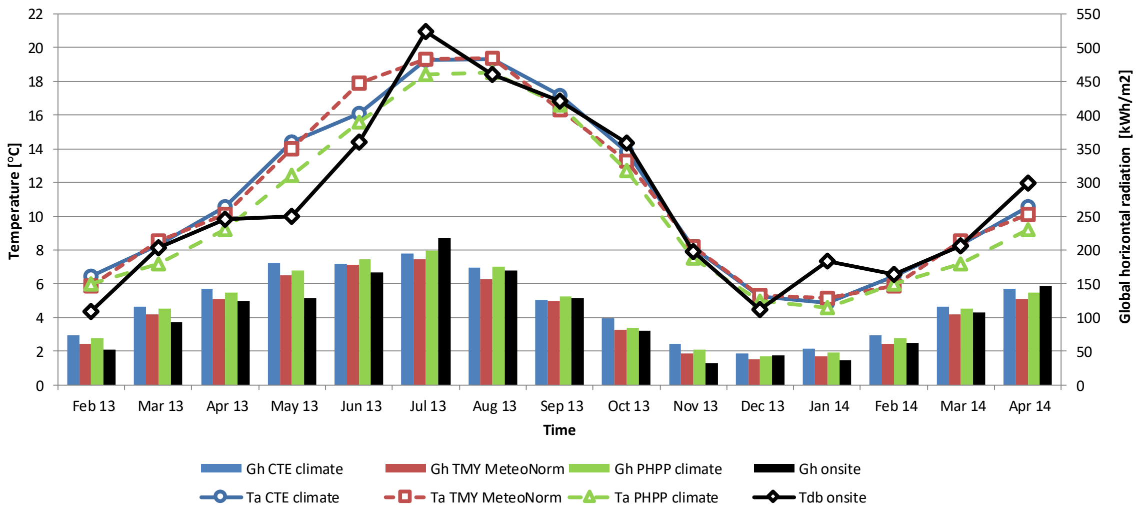


Figure 3.33: Average values or air dry bulb temperature and cumulated solar radiation during monitoring, compared with the climatic data of PHPP, Meteonorm and Spanish D1 zone of CTE.

In general, there are some differences between the monitored period and the reference climatic data series. So, in order to evaluate the impact of these differences on the energy demand of the dwelling, a very simple and well-known procedure is the Heating Degree Days (HDD) and Cooling Degree Days (CDD). It calculates the differences between the indoor comfort temperatures and the outdoor air. This procedure can be applied with some differences according to the selected base-temperatures, the time frame and using average temperatures or mean temperatures.

In the present study, four alternative calculations are applied in order to identify the trend of the monitored year in comparison with the other climatic datasets. The annual values are presented in Table 3.12 below. The monitored year refers to the period of 365 days with electric heaters, from 12/03/2013 until 11/03/2014. For the purpose of the study, the more relevant method is the daily calculation of the average temperature, which shows singular days. Further references and details of the HDD and CDD calculation are included in Appendix III.

The annual results of climate severity show that the monitored year (from 12/03/2013 until 11/03/2014) had a slightly colder winter than the climatic series of Meteonorm with 4.6 % more HDD and a milder warm season with 14.6 % less CDD. However, in comparison with the PHPP design climatic file it was considerably warmer, with 3.3 % less HDD and 8 times more CDD. With regard to the Spanish official D1 climatic zone values, the cold season is slightly colder with 4.1 % more HDD and the warm season is remarkably milder with 23.5 % less CDD.

Table 3.12. Annual HDD and CDD of the monitored period in comparison with other climatic datasets according to different methods.

	Monthly average		**Daily average**		**ASHRAE method**		**EUROSTAT met.**	
	HDD 18	**CDD 18**	**HDD 18**	**CDD 18**	**HDD 65**	**CDD 65**	**HDD**	**CDD**
Monitored year	2528	85	2593	138	2549	175	2376	175
Meteonorm v7	2371	65	2479	162	2417	160	2216	160
CTE D1 zone	2360	61	2492	181	2548	158	2382	158
PHPP V.G. *	2611	9	-	-	-	-	-	-

** PHPP design climate files is calculated monthly.*

In a more detailed analysis, the first stage of the monitoring (4/02/2013 – 10/03/2013) was slightly colder than usual. February was 13% colder than the PHPP design climatic file of Vitoria-Gasteiz and 12 % colder than Meteonorm. March was similar to the climatic series, being an 8% milder than PHPP and 4 % colder than Meteonorm. The solar radiation in both months was smaller than the climatic series, 22 % lower than PHPP and 13 % lower than Meteonorm values.

The second stage (11/03/2013 – 31/05/2013) was cold, especially in May. April was an average year with 7 % less HDD than the PHPP and 3 % more than Meteonorm. May was unusually cold, even colder than April, namely 41 % more HDD than PHPP and 85 % more than Meteonorm. The solar radiation values follow the same trend: April was slightly colder with 9% less radiation than PHPP and 2 % less than Meteonorm, while the cold May had 24 % less radiation than PHPP and 21 % less than Meteonorm.

The third stage (01/06/2013 – 06/10/2013) started with a cold June, followed by a very warm July and average August and September. June was similar to the previous May and had 45% more HDD than PHPP, 147 % more than Meteonorm and it almost didn’t have any CDD. July was atypically warm, with 25 times more CDD than PHPP and 51% more than Meteonorm. Later, August and September were normal, between the cold PHPP and the warm Meteonorm data series. The solar radiation levels confirm a cold June with 10% less than PHPP and 6% less than Meteonorm, a hot July with 10% more than PHPP and 17% more than Meteonorm and average August and September with intermediate values between PHPP and Meteonorm.

The fourth stage (07/10/2013 – 10/04/2014) began with a mild autumn and continued with a slightly mild winter. October was uncommonly warm, with 29 % less HDD than PHPP and 21 % less than Meteonorm. November was an average month, with 4 % less than PHPP and 3 % more than Meteonorm. December was slightly cold, with 4 % more HDD than PHPP and 6 % more than Meteonorm. In the next year, January was very mild, with 20 % less HDD than PHPP and 17 % less than Meteonorm. February was slightly mild, with 4 % less HDD than PHPP and 5 % less than Meteonorm. March was slightly milder as well, with 9 % less HDD than PHPP and 3 % more than Meteonorm.

Regarding the solar radiation, autumn and winter had lower levels than usual, especially November and January of 2014. This way, October was an average month with 4 % less than PHPP and 2 % less than Meteonorm, November was very cloudy with 35 % less than PHPP and 29 % less than Meteonorm and December had clear sky with 2 % more than PHPP and 16 % more than Meteonorm. In the next year, January was again very cloudy with 24 % less than PHPP and 14 % less than Meteonorm, February was slightly cloudy with 11 % less than the PHPP and 2 % more than Meteonorm.

Table 3.13 below shows the monthly values of HDD and CDD of the monitored months in comparison with the ones from the PHPP climate data file, Meteonorm v7 and CTE climatic zone D1, Vitoria-Gasteiz.

Table 3.13. Monthly HDD and CDD of the monitored period in comparison with other climatic datasets.

HDD 18	Feb 13	Mar 13	Apr 13	May 13	Jun 13	Jul 13	Aug 13	Sep 13	Oct 13	Nov 13	Dec 13	Jan 14	Feb 14	Mar 14
Measured	391	315	255	257	123	1	28	61	130	313	429	340	330	312
Meteonorm	349	303	247	139	48	23	23	74	157	305	404	408	349	303
PHPP *	344	344	273	183	81	0	0	51	174	324	412	425	344	344
CTE D1 zone	333	311	233	137	88	34	23	64	142	305	405	0	0	0
CDD 18														
Measured	0	0	0	0	5	81	30	15	7	0	0	0	0	0
Meteonorm	0	0	0	4	35	54	55	14	1	0	0	0	0	0
PHPP *	0	0	0	0	0	3	6	0	0	0	0	0	0	0
CTE D1 zone	0	0	0	14	21	62	53	28	2	0	0	0	0	0

** PHPP design climate files is calculated monthly.*

3.4.3. Measured indoor temperatures

The average air temperature of the house, weighted by net floor area are represented daily in Figure 3.34 and hourly in Figure 3.35. Besides, all the registered air temperatures are summarised in cumulative plots in Figure 3.36, Figure 3.37 and Figure 3.38. These plots permit to understand the deviation between rooms grouped according to activity or orientation and the average house.

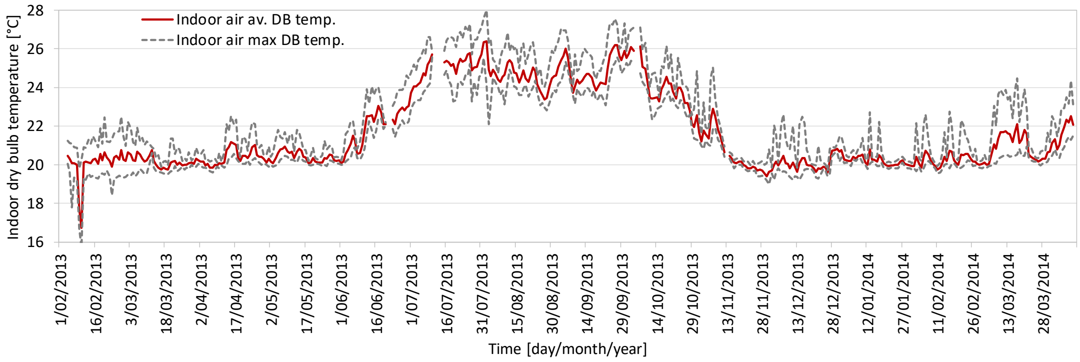


Figure 3.34. Monitored indoor air average temperature, daily average, maximum and minimum values.

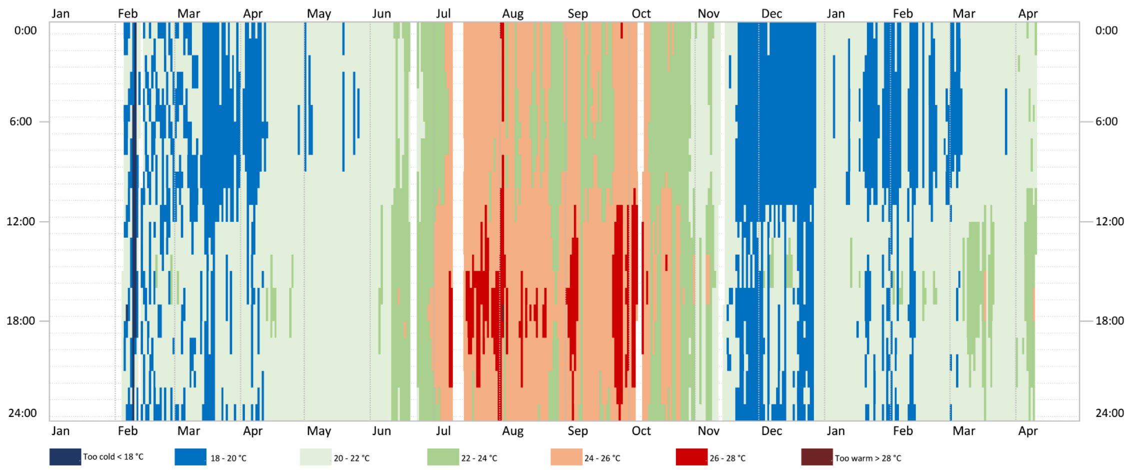


Figure 3.35. Monitored indoor air average temperature, hourly values.

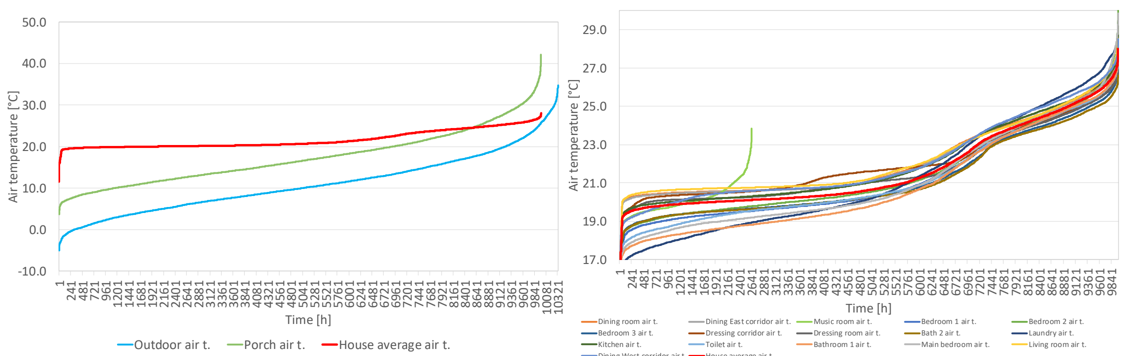


Figure 3.36. Cumulative air temperatures of house average (left side) and all rooms (right side).

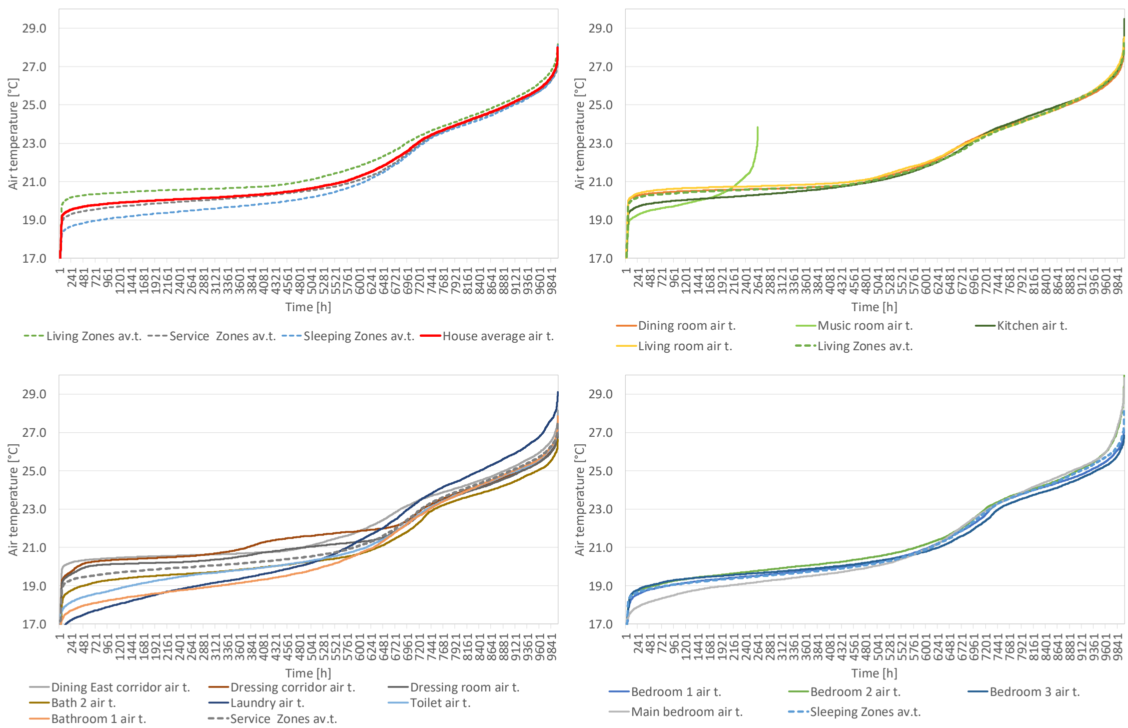


Figure 3.37. Cumulative air temperatures of dwelling rooms sorted by activity: comparison of the three activities (top left), living zones (top right), sleeping zones (bottom right) and service zones (bottom left).

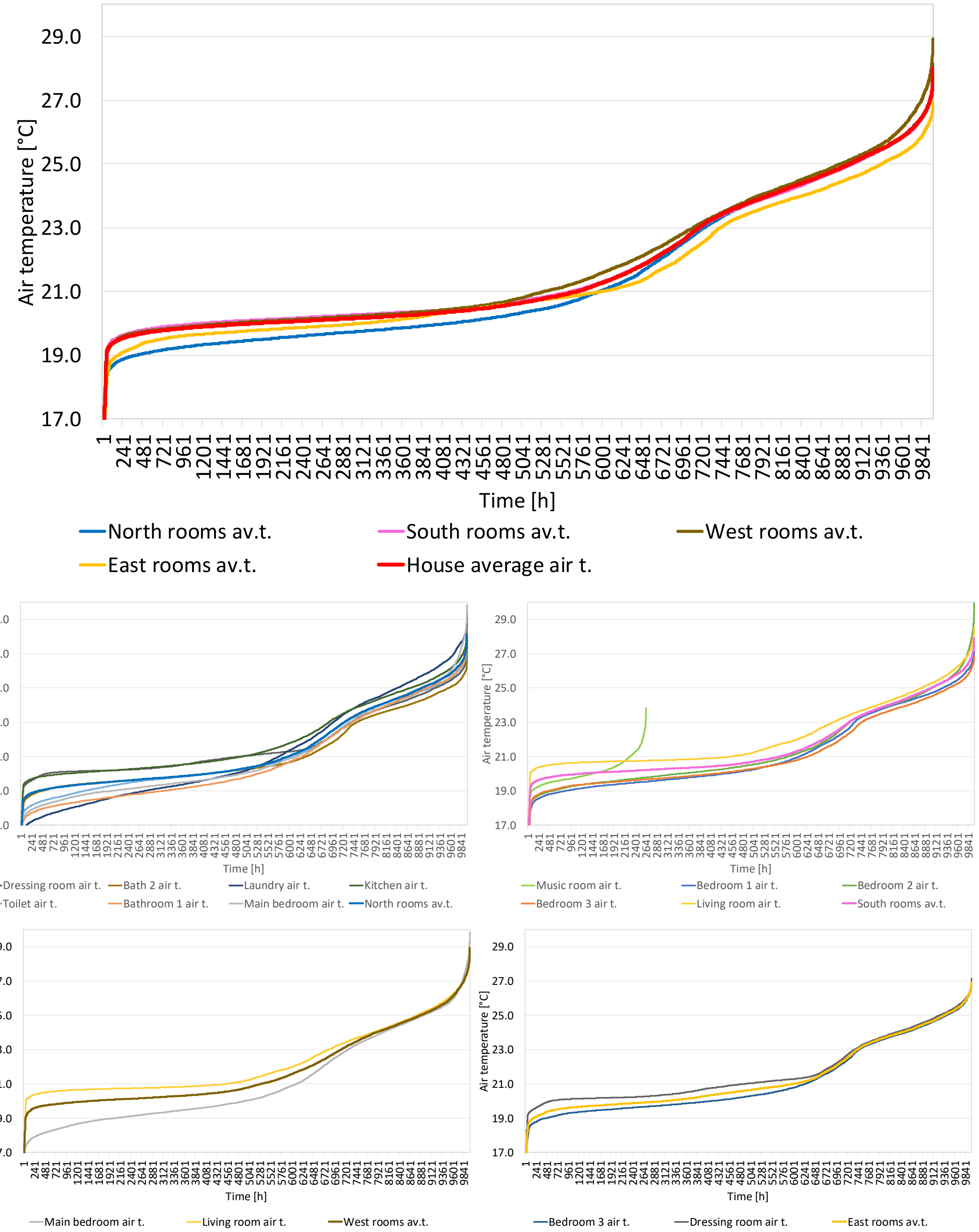


Figure 3.38: Cumulative air temperatures of dwelling rooms by orientation: comparison of the four orientations, South, East, West and North (clockwise).

In order to have a clearer perspective of the thermal response of the house, the extreme values registered are summarized in Table 3.14. It is noticeable the number of cold hours, i.e. 23.2 % of cold season below 20.0 °C and also the quantity of warm hours, highlighting the 40.6 % of summer hours over 25.0 °C. There are only 2 hours over 28 °C, but the 13.4 % of summer night-time hours were over 26 °C, considering the night-time hours from 23:00 to 7:00.

Table 3.14: Summary of extreme temperatures and RH of average house.

SUMMARY	**Monitored year**		**Cold season**		**Intermediate**		**Warm season**	
hours t <20 °C	1546	18.3%	1546	23.2%	0	0.0%	0	0.0%
hours t >25 °C	1058	12.5%	499	7.5%	14	3.2%	545	40.6%
hours t >28 °C	2	0.0%	0	0.0%	0	0.0%	2	0.1%
Max. temp.	28.2		50.1		50		28	
Night hours > 26°C	337	4.0%	153	2.3%	4	0.9%	180	13.4%
hours RH >70 %	5	0.1%	0	0.0%	0.0	0.0%	5	0.4%
Total hours	8451		6675		432		1344	

In order to understand the thermal response of the building in a deeper detail, this section contains a selection of representative weeks to visualize the most relevant aspects of the monitored parameters. This analysis is based on the charts of the weekly analysis, explained in Table 3.11 of Section 3.3.3. The selection includes one of the warmest weeks, one of the coldest weeks and another week from the shoulder seasons.

3.4.3.1. Analysis of the thermal behaviour in winter

To analyse the thermal behaviour in winter, the most important monitored parameters are shown in detail during a representative week. To do that, one of the coldest periods was selected. The week from 15/03/2013 to 21/03/2013 presented an average outdoor DB temperature of 3.9 °C, an average RH of 81.8 % and an average daily solar global horizontal radiation of 2026.3 W/m²d. This week is representative because it included diverse solar radiation levels which could show the differences between sunny and cloudy cold days.

The analysis of the global response is presented in Figure 3.39. The indoor air temperatures remain considerably stable and evidence the peaks of solar gains in sunny days. It is noticeable the positive response of the floor, which temperatures stay all the time over 18.7 °C.

The performance of walls and columns is considerably similar, which suggests that the thermal bridging on facades is very small, as explained in detail in the thermal bridge analysis of Section 3.4.9.

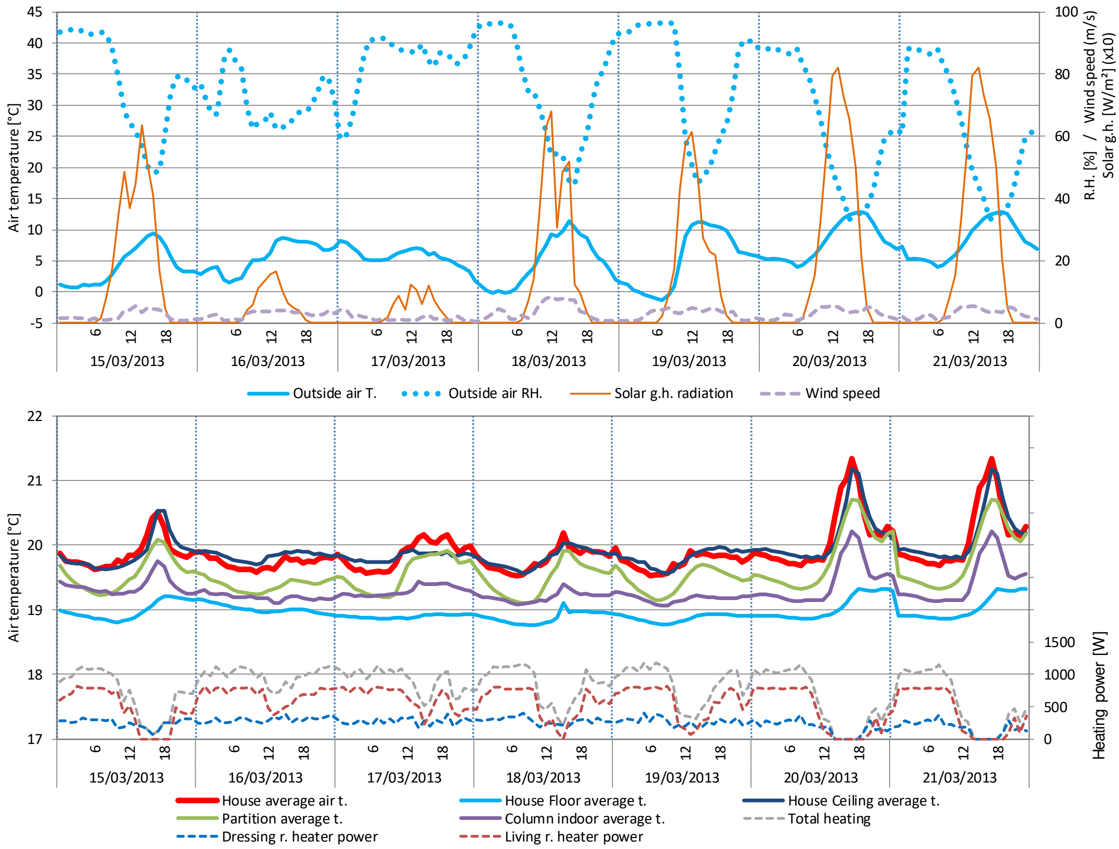


Figure 3.39: Outdoor conditions (top) and thermal response of the house with average values of room air temperatures and surface temperatures of floors, ceilings, walls and columns (bottom) (winter week 15/03/2013 - 21/03/2013).

Regarding the RH inside the house, the winter average values are around 45 %. Figure 3.40 presents the differences inside the house and show that southern rooms are slightly drier than the northern ones.

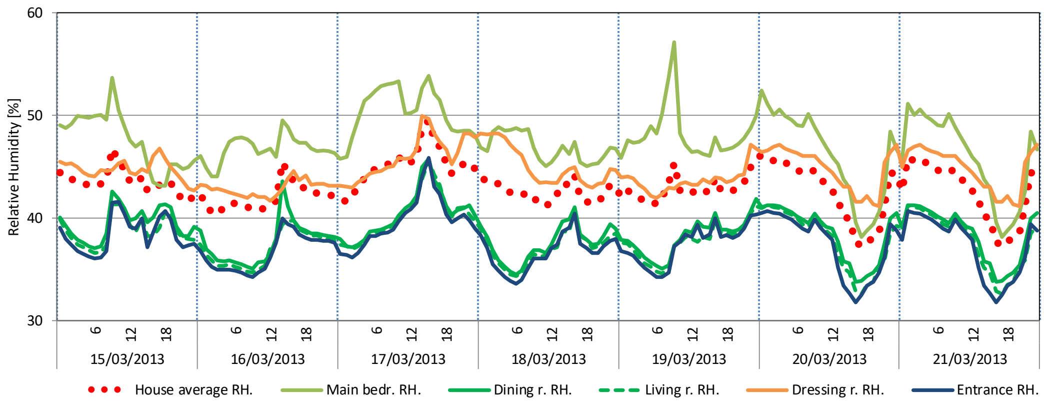


Figure 3.40: Rooms air RH (winter week 15/03/2013 - 21/03/2013).

This is consistent with the indoor temperature differences found between North and South oriented rooms, compared in Figure 3.41. The indoor distributions of temperatures confirmed the findings of the previous section, which pointed to considerable differences between rooms and orientations. This is caused probably by the heater distribution only on two rooms, creating differences of 1 - 2 °C. The temperatures of all the rooms are plot in Figure 3.42, this type of analysis was mainly used mainly as a control of the extreme temperatures.

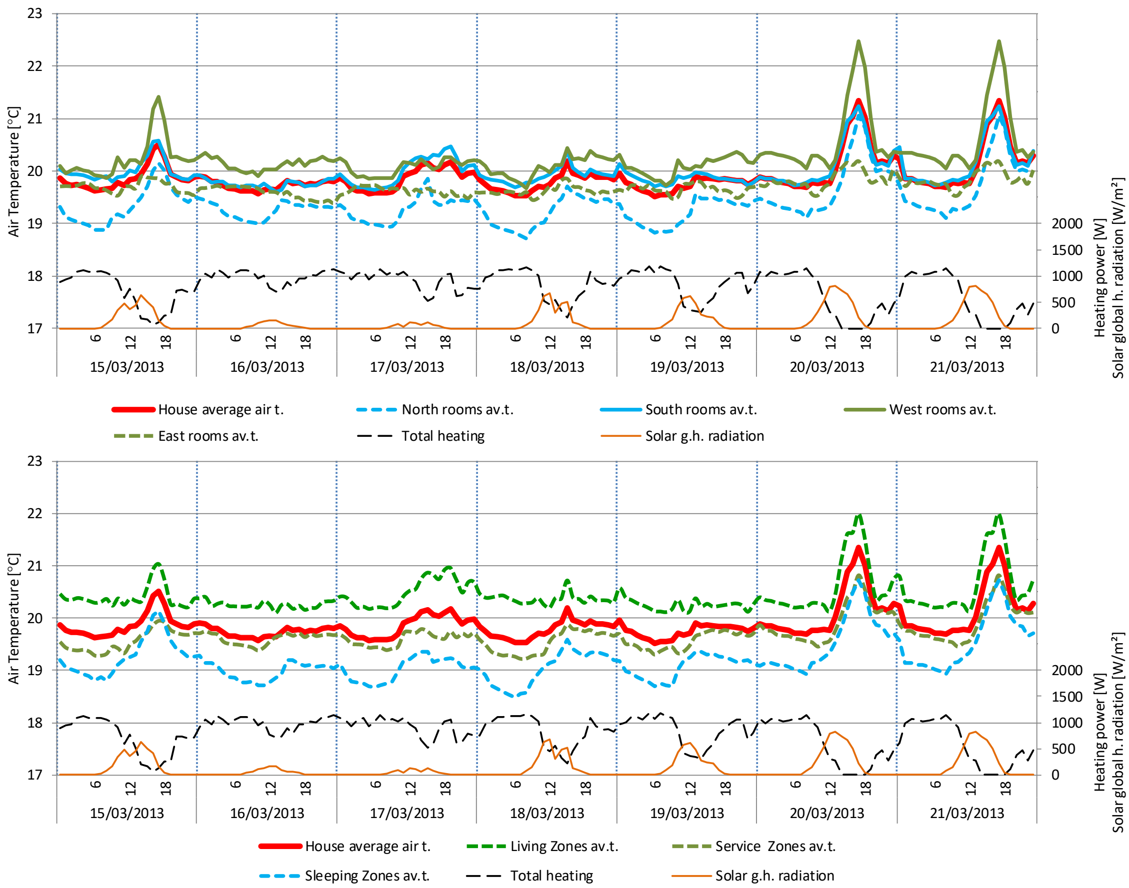


Figure 3.41: Room air temperatures by room orientation (top) and by room activity (bottom) (winter week 15/03/2013 - 21/03/2013).

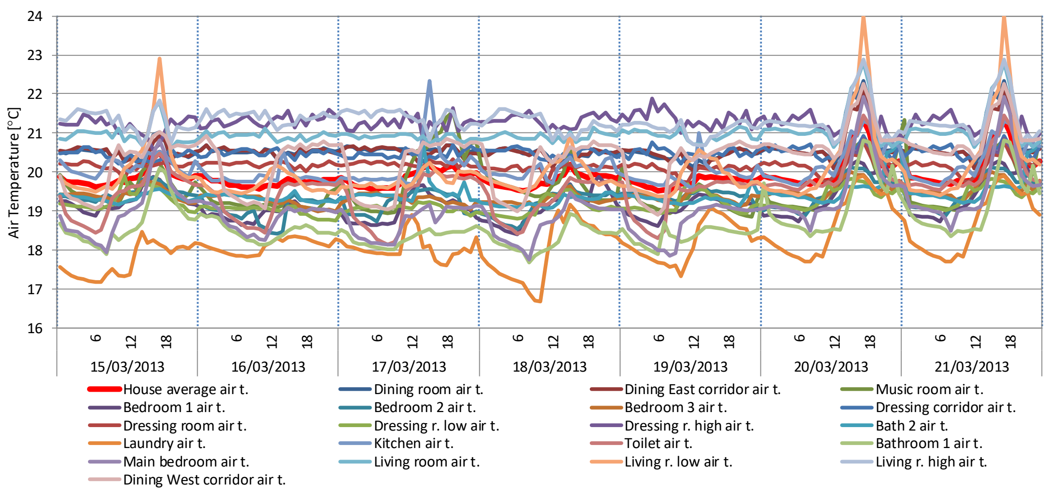


Figure 3.42: Room air temperatures in detail (winter week 15/03/2013 - 21/03/2013).

Regarding the internal surface temperatures, Figure 3.43 and Figure 3.44 show the temperatures of ceilings, floors and partitions and are consistent with the previous findings.

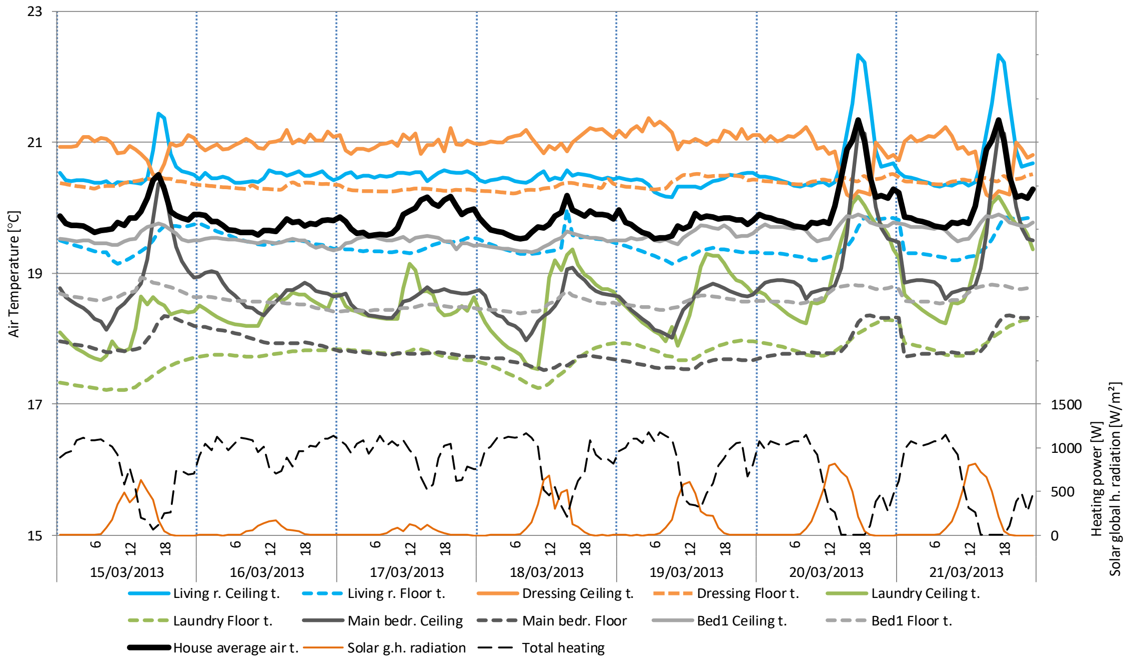


Figure 3.43: Ceiling and floor surface temperatures (winter week 15/03/2013 - 21/03/2013).

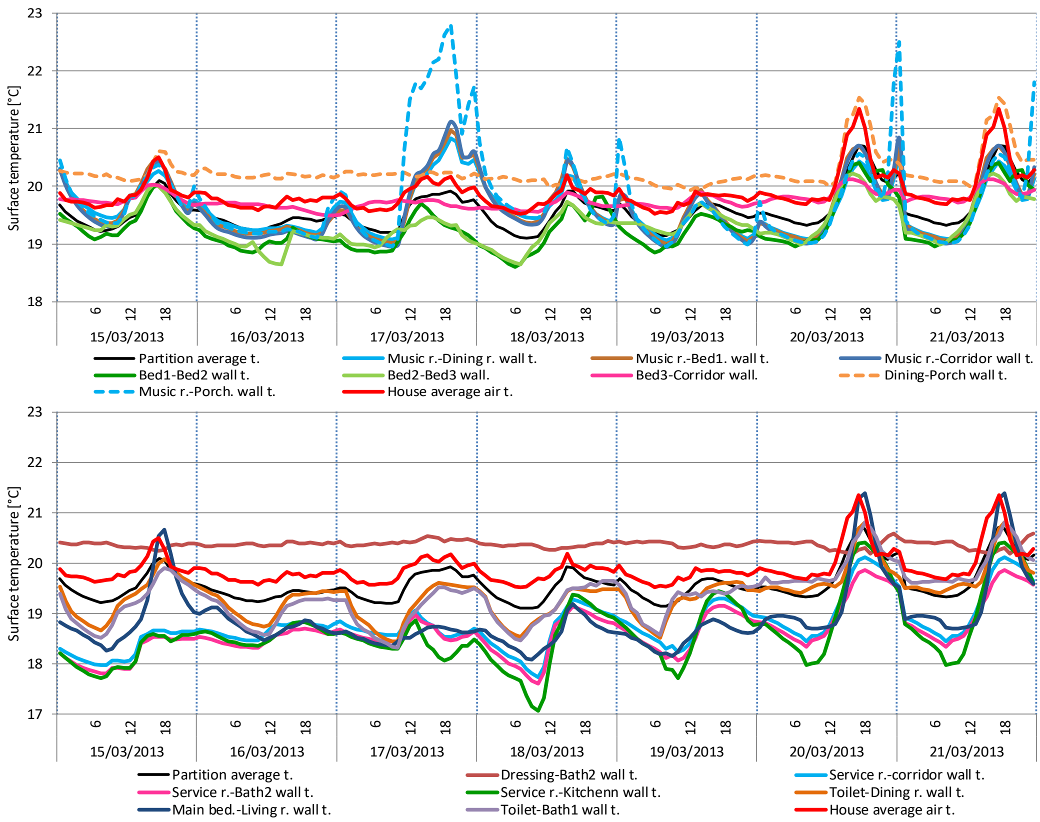


Figure 3.44: Partitions surface temperatures in South rooms (top) North rooms (bottom) (winter week 15/03/2013 - 21/03/2013).

About the performance of windows, Figure 3.45 shows a good performance of the windows, maintaining the frame coldest temperatures over 17.5 °C. The temperature of the glasses is influenced notably by the indirect solar radiation, despite to being oriented to North and below the roof overhang.

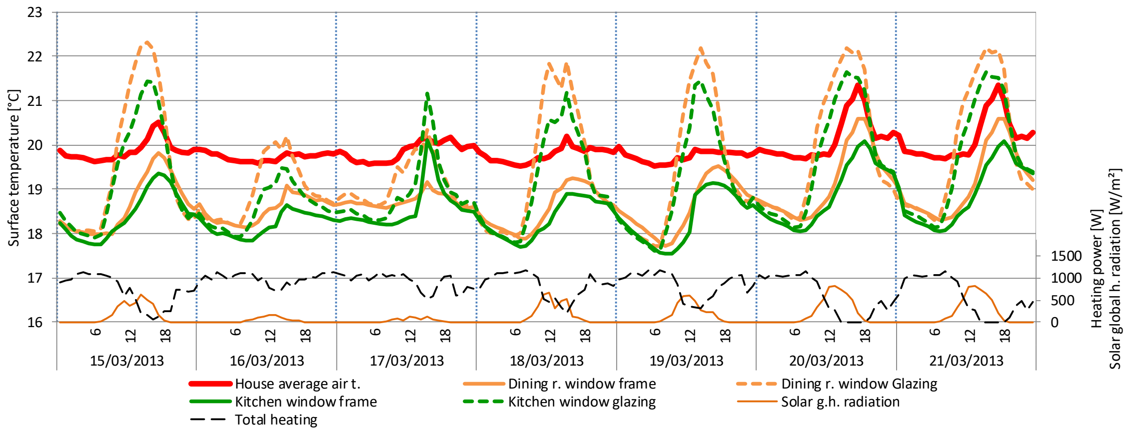


Figure 3.45: North window frame and glazing surface temperatures in kitchen and dining room (winter week 15/03/2013 - 21/03/2013).

Figure 3.46 represents the outside temperatures of the facades. The impact of solar radiation is clear in the last two days of the week which were very sunny, 20 and 21 of March of 2013.

The highest temperatures are located in South and West facades and the lowest in the North, as expected. It is also perceived the cooling effect of long wave radiation during the nights with clear sky, like in the 18th and the 19th of March of 2013.

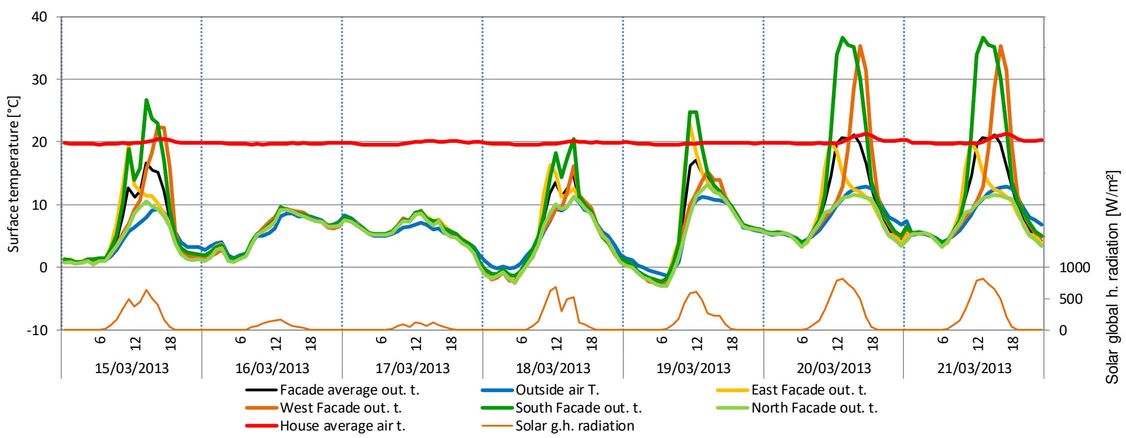


Figure 3.46: Façade external surface temperatures (winter week 15/03/2013 - 21/03/2013).

To conclude the analysis of the cold week, the thermal behaviour of the porch is plot in Figure 3.47. It shows the potential of these spaces to provide a comfortable area for drying clothes or even to capture certain solar gains. The peak inner temperatures overpass easily the 25 °C in cold but sunny days. Certainly, the inhabitants were aware of this fact and they often used this space to hang the washing.

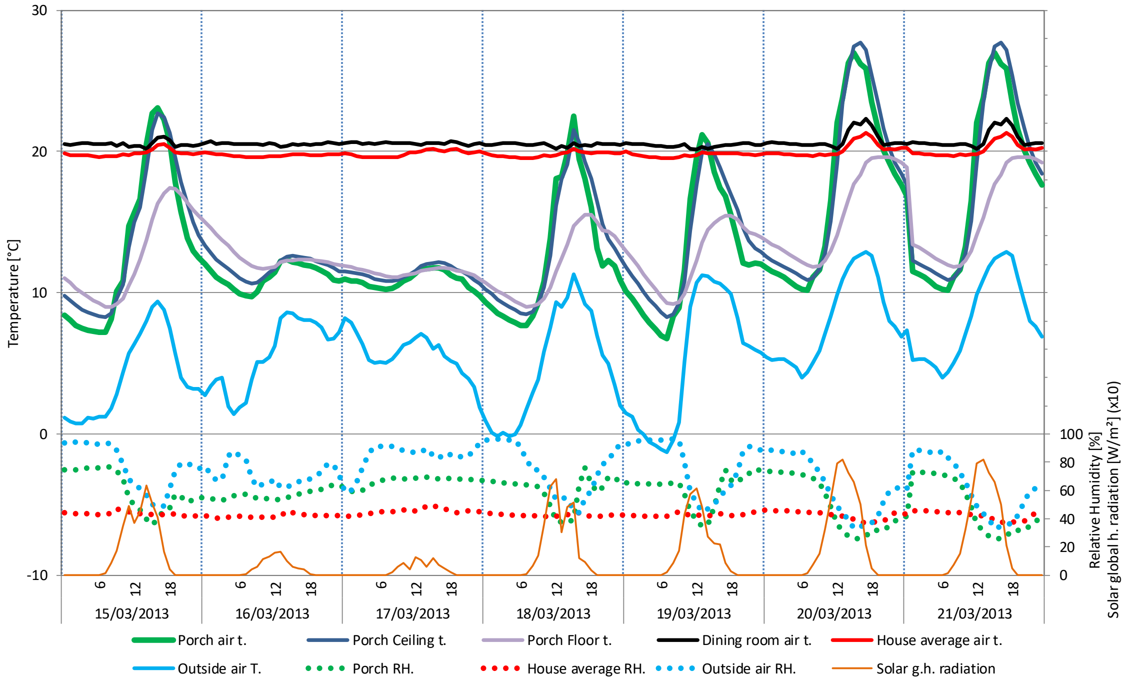


Figure 3.47: Porch thermal behaviour, greenhouse effect (winter week 15/03/2013 - 21/03/2013).

3.4.3.2. Analysis of the thermal behaviour in summer

To analyse the thermal behaviour in summer, the most important monitored parameters are shown in detail during a representative week. To do that, one of the hottest periods of July was selected because it presented high running mean temperatures, as proven later in Section 3.4.8.1. The week from 18/07/2013 to 24/07/2013 presented an average outdoor DB temperature of 20.8 °C, an average RH of 76.3 % and an average daily solar global horizontal radiation of 6676.8 W/m²d.

The analysis of the global response is presented in Figure 3.48. The indoor air temperature swings between minimum values of 24 °C and maximum values of 27 °C. There are short periods of natural ventilation in late evenings and early mornings, between 20-24 h and 7-8 h in some of the warmest days. The coolest temperatures are in floors, with stable temperatures around 24.5 °C. The hottest indoor temperatures appear in the ceilings at late evenings.

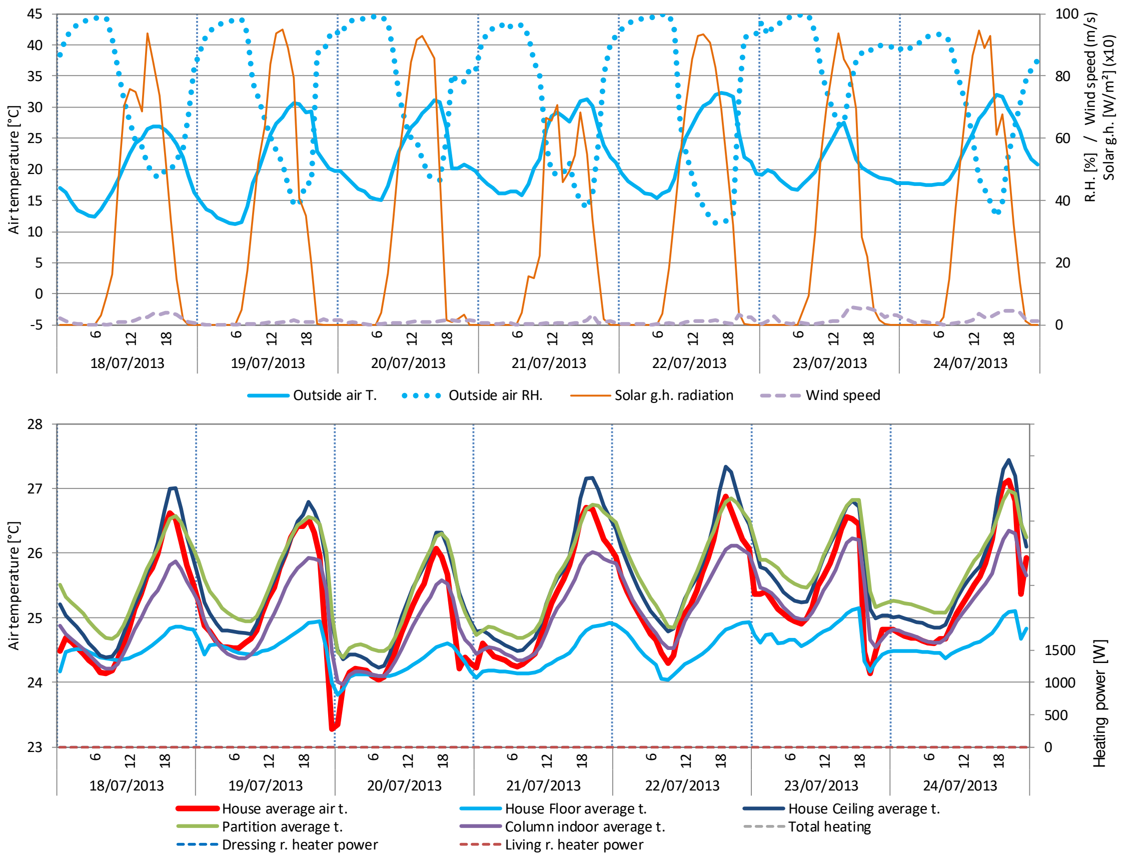


Figure 3.48: Outdoor conditions (top) and thermal response of the house with average values of room air temperatures and surface temperatures of floors, ceilings, walls and columns (bottom) (summer week 18/07/2013 - 24/07/2013).

Regarding the RH inside the house, the summer average values are around 60 %. Figure 3.49 presents the differences inside the house and show that southern rooms are slightly drier than the northern ones, as happened in the winter week before.

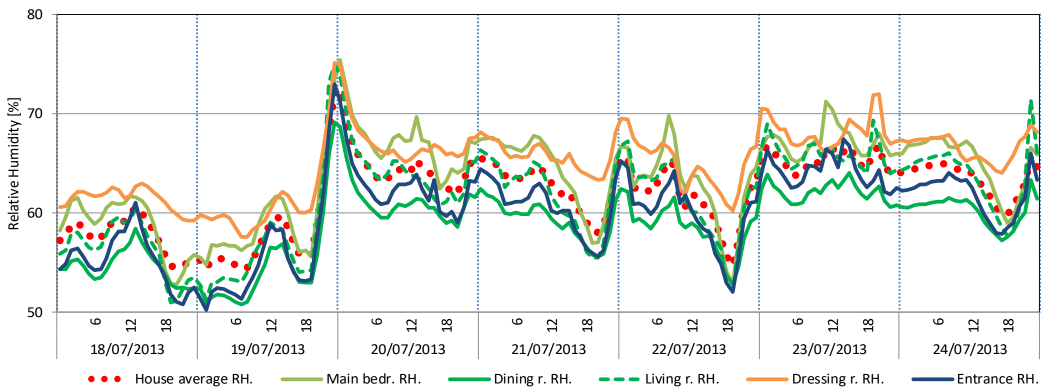


Figure 3.49: Rooms air RH (summer week 18/07/2013 - 24/07/2013).

In summer, the warmest rooms are located in the West and the coolest in the East side of the house, as compared in Figure 3.50. On contrary, the rooms facing North and South don't present any significant difference from the average value of the house. Regarding the activities of the rooms, there are also no significant differences between them. The temperatures of all the rooms are plot in Figure 3.51, the warmest part is the laundry room (in orange), probably caused by the internal heat gains of the washing machines and the HPSU for DHW generation. On the other hand, the coolest area is the dressing room (in green), in the East side.

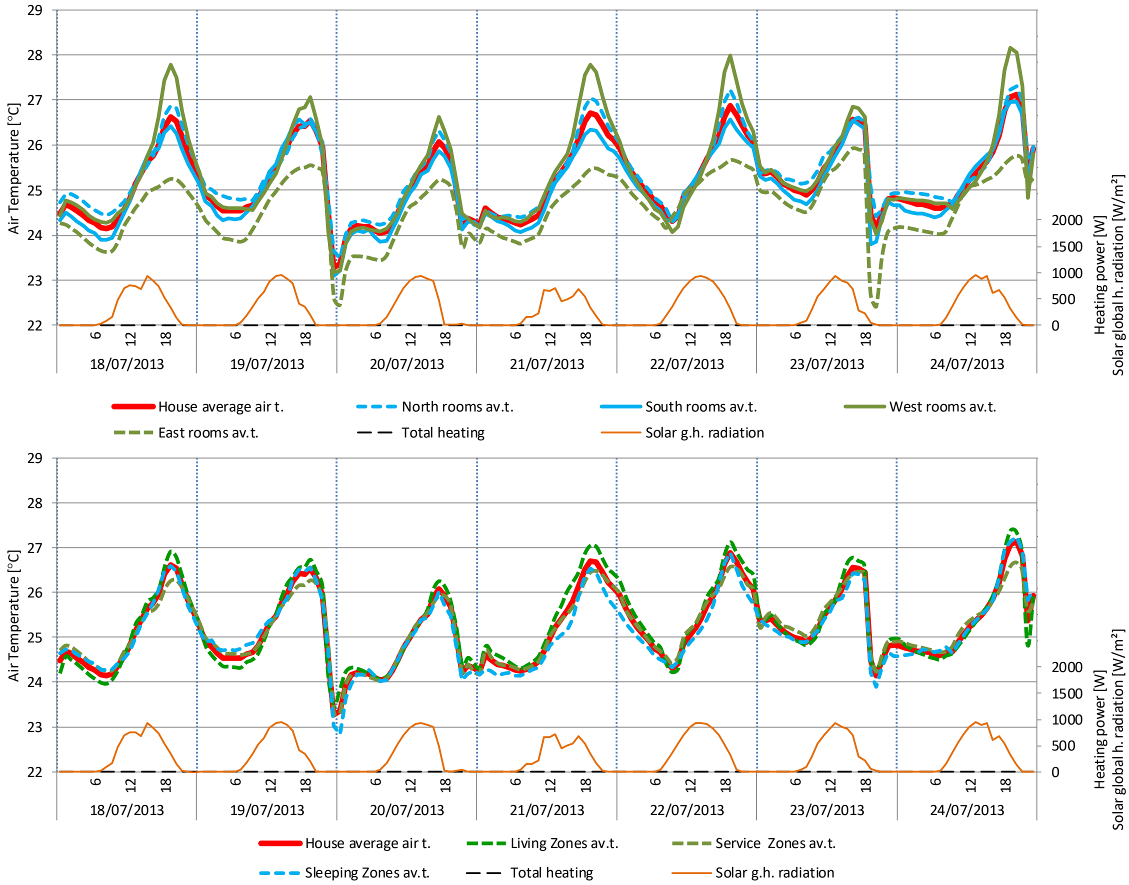


Figure 3.50: Room air temperatures by room orientation (top) and by room activity (bottom) (summer week 18/07/2013 - 24/07/2013).

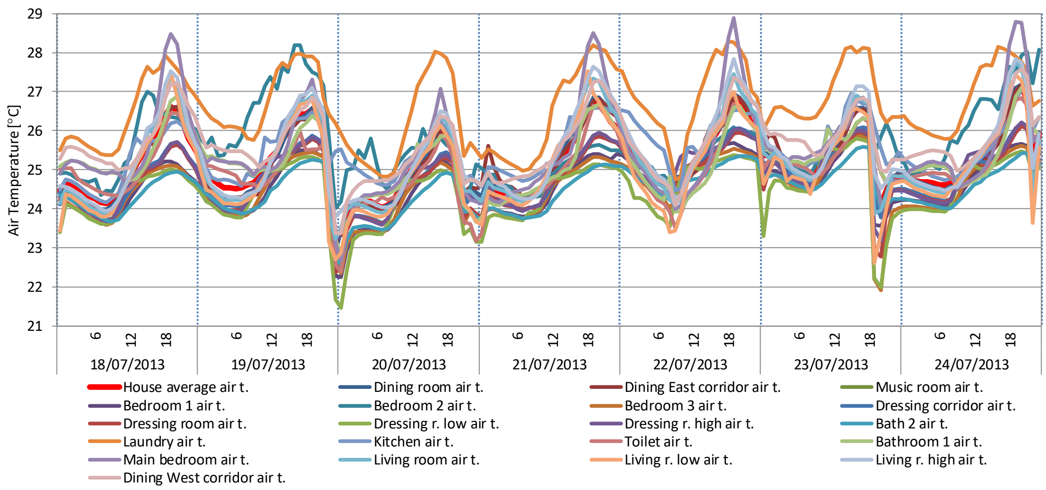


Figure 3.51: Room air temperatures in detail (summer week 18/07/2013 - 24/07/2013).

Regarding the internal surface temperatures, Figure 3.52 and Figure 3.53 confirm the high temperatures in the laundry room ceiling, which overpass 28 °C every day. Surprisingly, the floor temperatures of the living room and the bedroom 3 are the coolest surfaces.

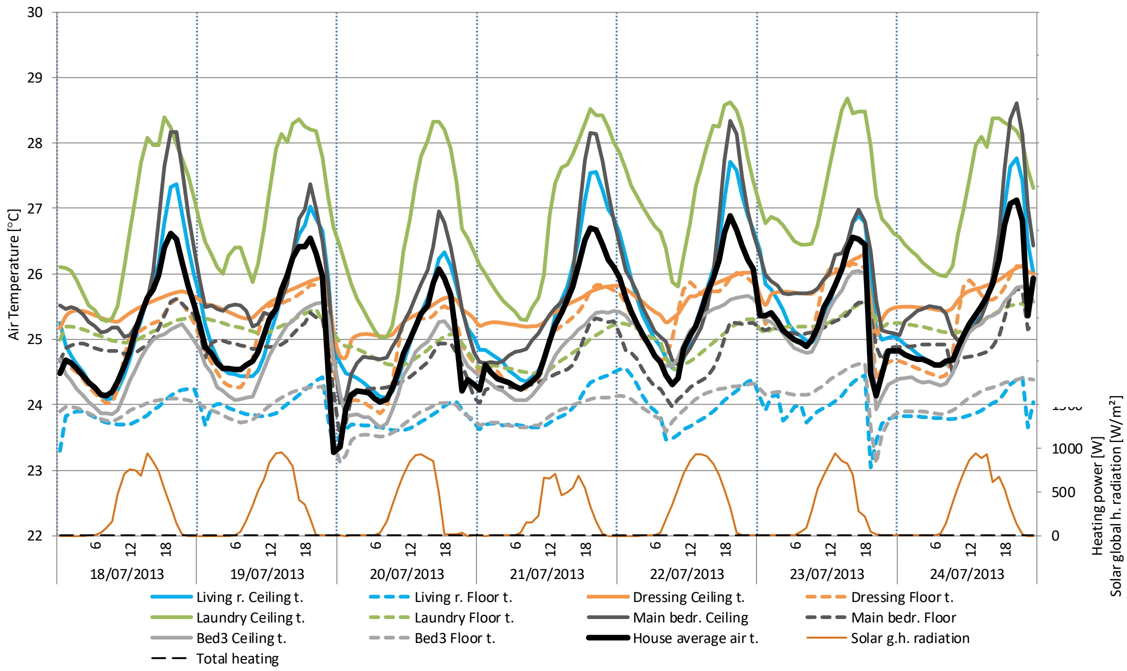


Figure 3.52: Ceiling and floor surface temperatures (summer week 18/07/2013 - 24/07/2013).

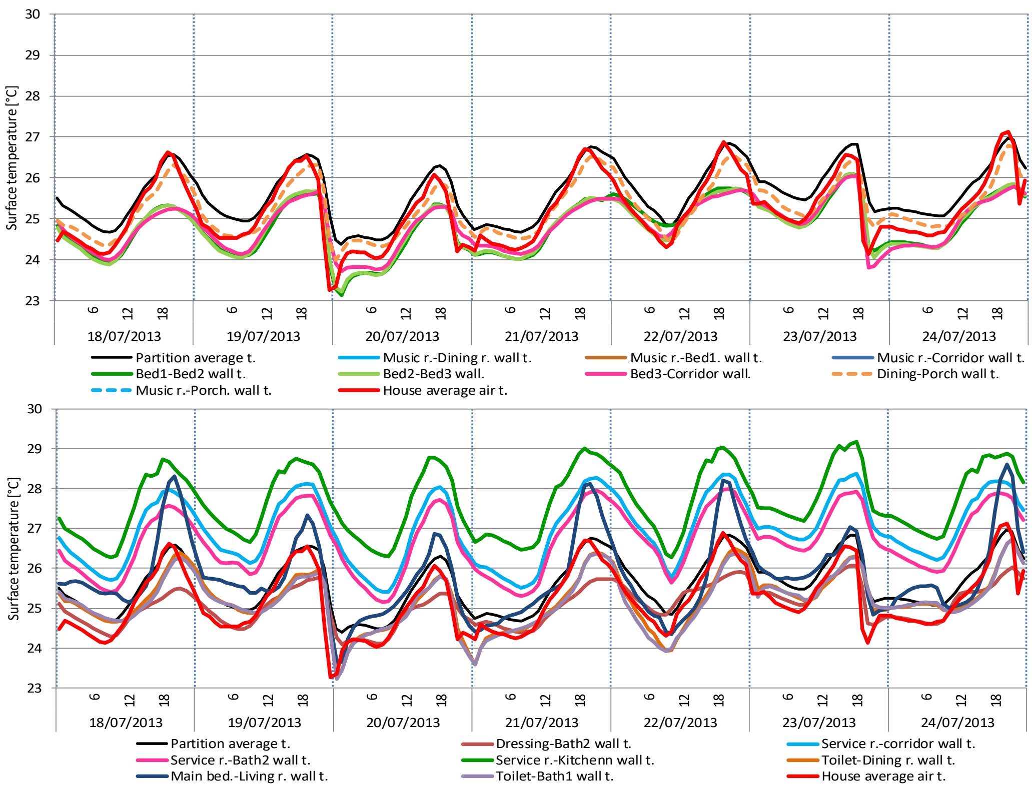


Figure 3.53: Partitions surface temperatures in South rooms (top) North rooms (bottom) (summer week 18/07/2013 - 24/07/2013).

About the performance of windows, Figure 3.54 shows a good performance of the windows, maintaining the frame warmest temperatures below 28.5 °C. The temperature of the glasses are again influenced by the indirect solar radiation and overpass the 30 °C in the hottest days, despite being oriented to North and below the roof overhangs. The frame temperatures are also showing the use of natural ventilation in some night, particularly opening the window of the dining room.

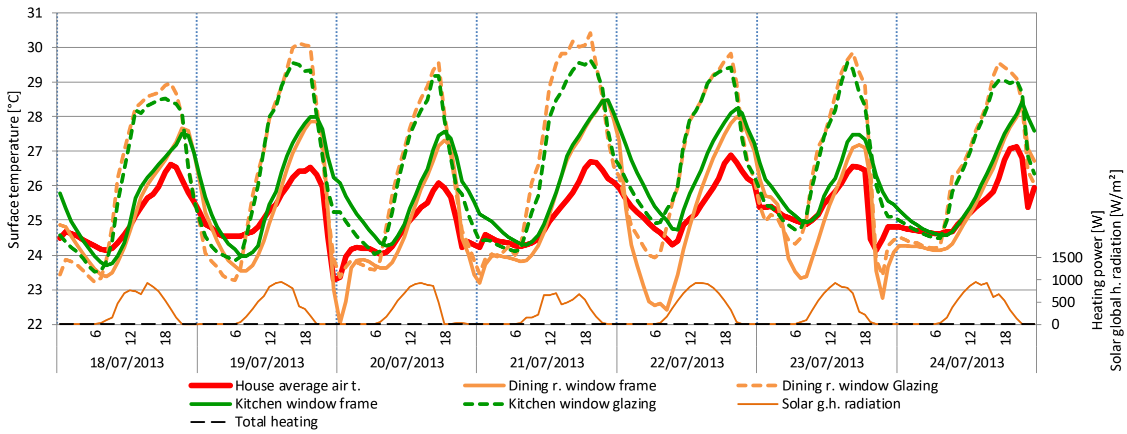


Figure 3.54: North window frame and glazing surface temperatures in kitchen and dining room (summer week 18/07/2013 - 24/07/2013).

The outside temperatures of the facades are plot in Figure 3.55. The impact of solar radiation is reduced by the shading of the roof extensions. The peak temperatures are located in the East and West orientations, while the sun elevation is low and for that reason the roof extensions don't cover these facades.

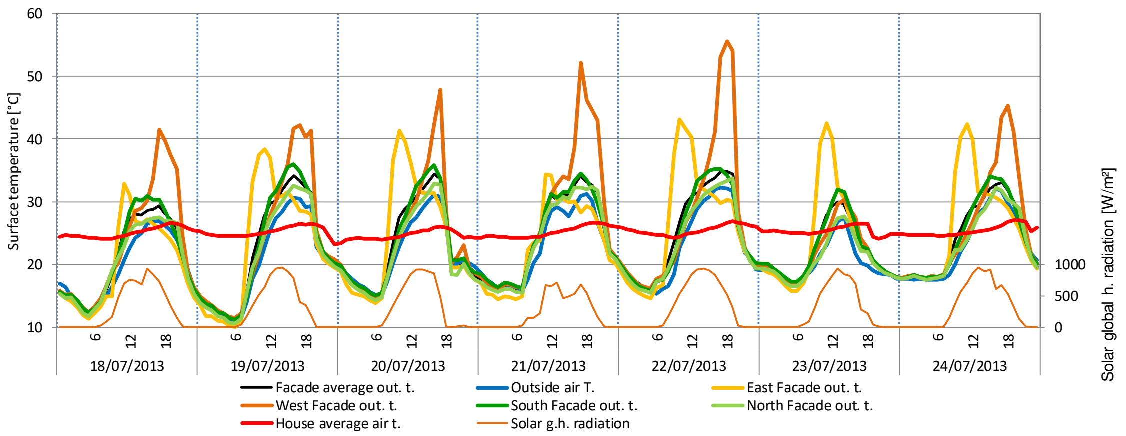


Figure 3.55: Façade external surface temperatures (summer week 18/07/2013 - 24/07/2013).

To conclude the analysis of the summer week, the thermal behaviour of the porch is plot in Figure 3.56. Even though the porch remained with the outer glazing door open, the temperature of the porch was considerably higher than the outdoor temperature. This may indicate that the air change rate (ACH) inside the porch space was low, especially because even the temperatures during night were 1-2 °C higher than outdoor temperatures.

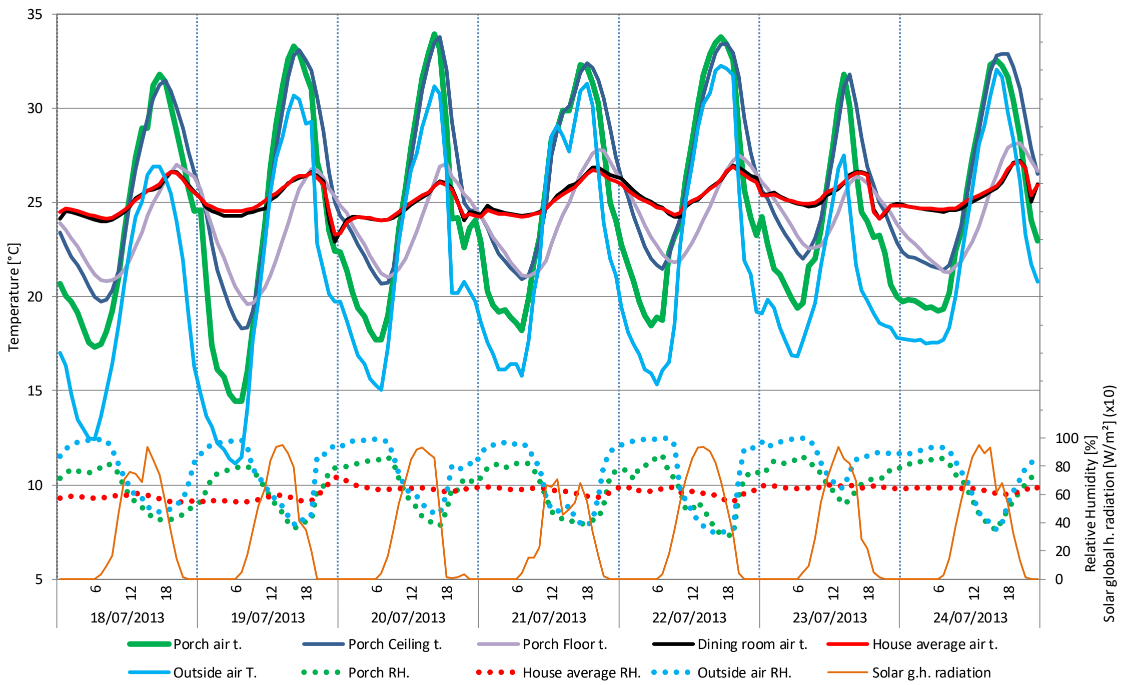


Figure 3.56: Porch thermal behaviour, greenhouse effect (summer week 18/07/2013 - 24/07/2013).

3.4.3.3. Analysis of the thermal behaviour in shoulder seasons

To analyse the thermal behaviour in shoulder seasons, the most important monitored parameters are shown in detail during a week which can represent the variability of some fresh days with heating and some other warm days with almost no heating. This period was selected considering also the running mean temperatures, as explained later in Section 3.4.8.1. So, the week from 6/05/2013 to 12/05/2013 presented an average outdoor DB temperature of 12.7 °C, an average RH of 75.4 % and an average daily solar global horizontal radiation of 4330.9 W/m²d.

The analysis of the global response is presented in Figure 3.57. The indoor air temperature remains quite stable around 21 °C. There is no evidence of natural ventilation periods in any room. The coolest temperatures are in floors and in smaller degree in the columns, which indicates that there is certain effect of thermal inertia and heat discharge through these concrete elements. Partitions present the warmest temperatures during several days and ceilings also manifest some peak temperatures in the evenings. These effects are analysed later in more detail.

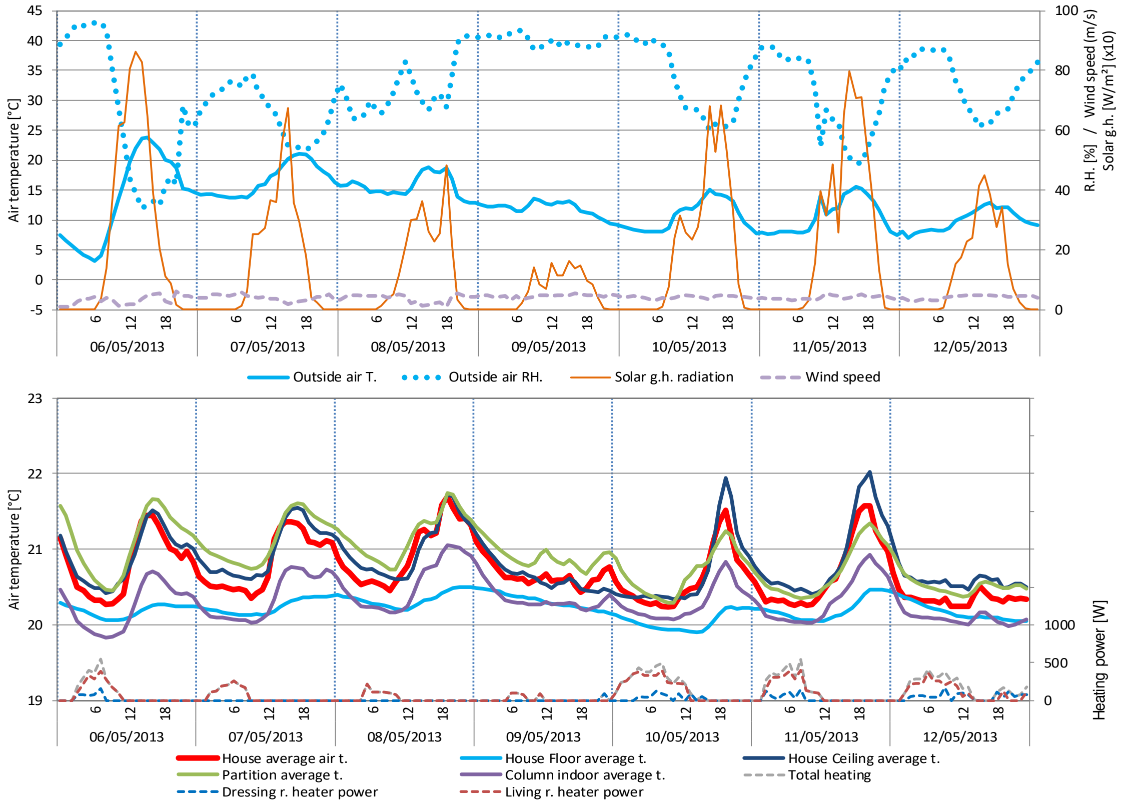


Figure 3.57: Outdoor conditions (top) and thermal response of the house with average values of room air temperatures and surface temperatures of floors, ceilings, walls and columns (bottom) (shoulder season week 6/05/2013 - 12/05/2013).

Regarding the RH inside the house, the intermediate or shoulder season values range between 45 % and 55 %. Figure 3.58 presents the differences inside the house and confirms once more that southern rooms are slightly drier than the northern ones, as happened in the winter and summer weeks before.

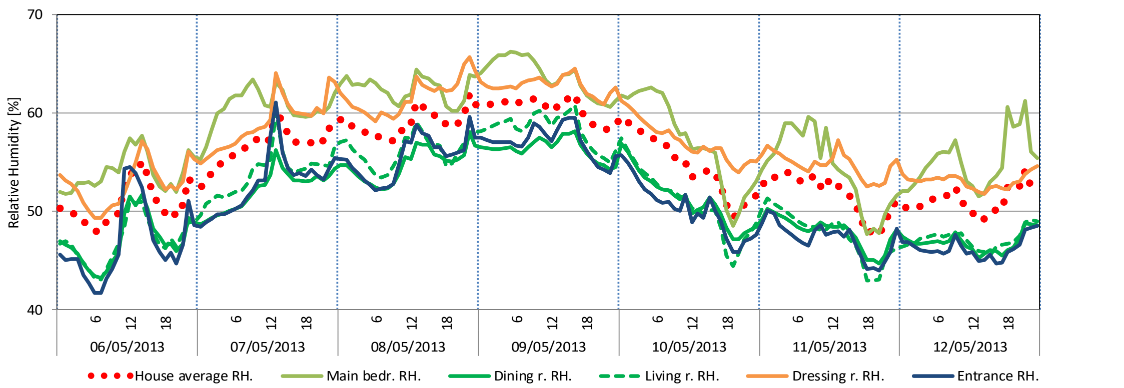


Figure 3.58. Rooms air RH (shoulder season week 6/05/2013 - 12/05/2013).

In period between winter and summer, the warmest rooms are again located in the West and the coolest in the East side of the house, as shown in Figure 3.59. On contrary, the rooms facing North and South don't present significant differences, as it would happen in winter. Regarding the activities of the rooms, the bedrooms are the coldest areas and the living zones are the warmest, but with smaller differences than in winter. The temperatures of all the rooms are plot in Figure 3.60Figure 3.51, it is noticeable the warmer temperatures in the laundry room during Monday and Tuesday, probably due to a higher demand of DHW. Besides, the high peak temperatures of the air temperature at low height in the living room, likely due to direct solar radiation.

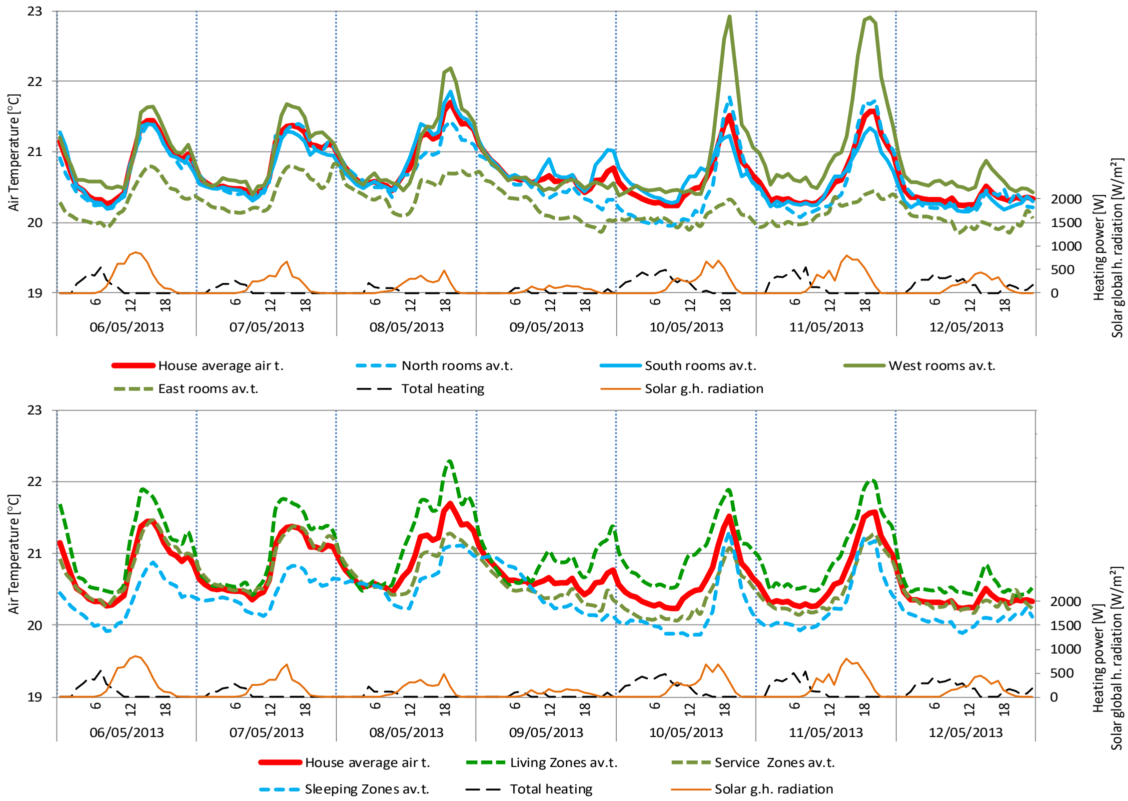


Figure 3.59: Room air temperatures by room orientation (top) and by room activity (bottom) (shoulder season week 6/05/2013 - 12/05/2013).

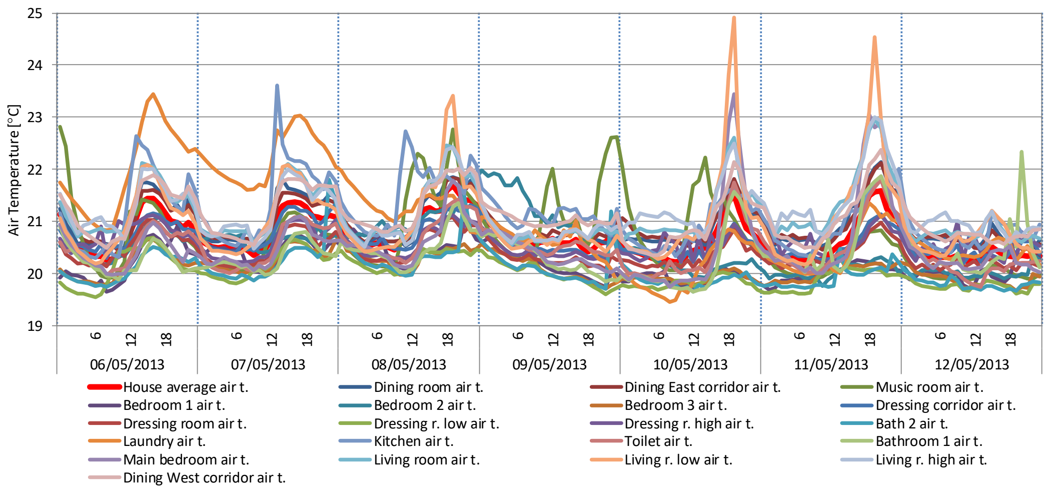


Figure 3.60: Room air temperatures in detail (shoulder season week 6/05/2013 - 12/05/2013).

Regarding the internal surface temperatures, Figure 3.61 and Figure 3.62 confirm the high temperatures in the laundry/facility room. Like in winter, bedroom floors are the coolest surfaces. Underline as well the high temperatures in the music room due to internal gains.

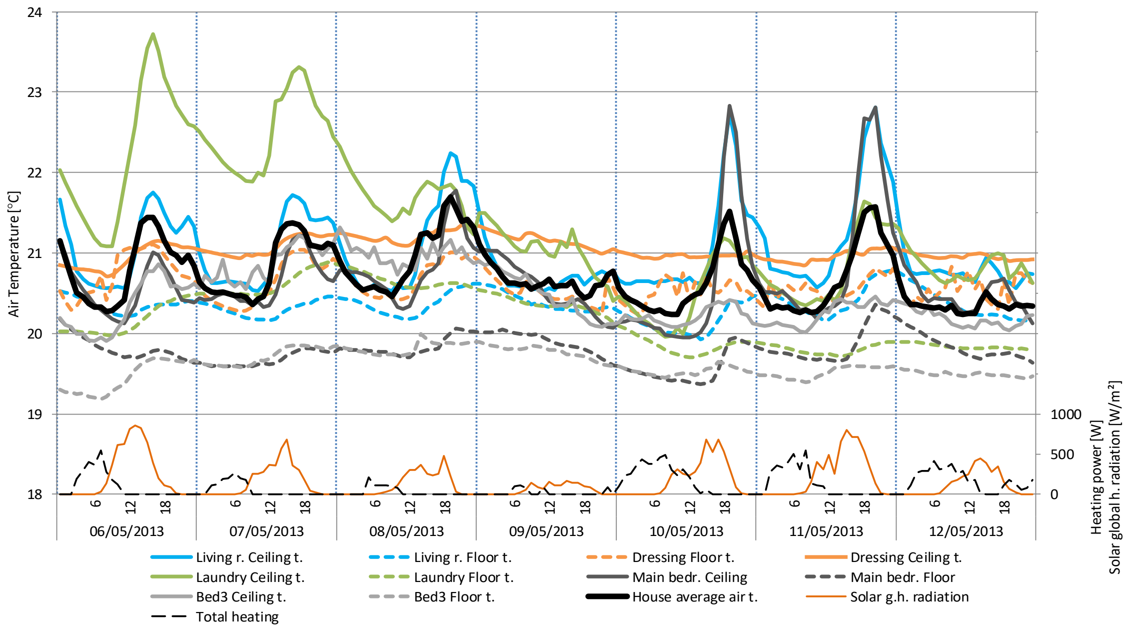


Figure 3.61: Ceiling and floor surface temperatures (shoulder season week 6/05/2013 - 12/05/2013).

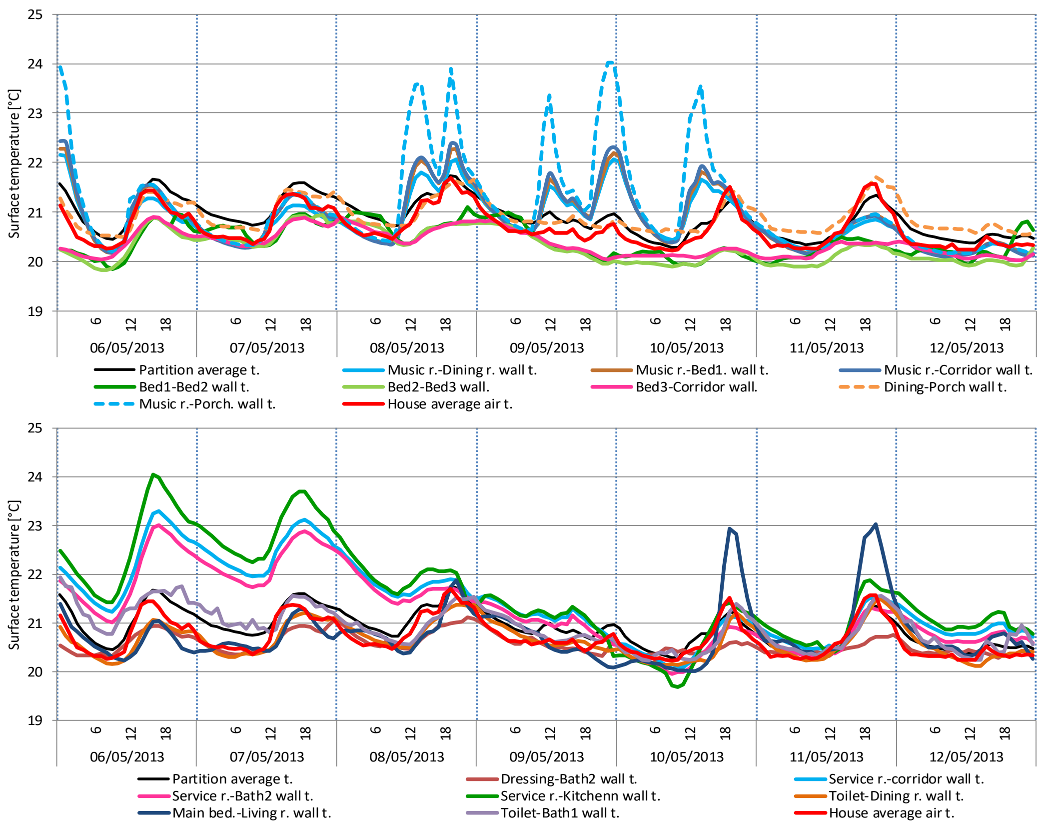


Figure 3.62: Partitions surface temperatures in South rooms (top) North rooms (bottom) (shoulder season week 6/05/2013 - 12/05/2013).

About the performance of windows, Figure 3.63 shows a good performance of the windows and frame temperatures stay between 19 °C and 23 °C. Glasses temperature are again influenced by indirect solar radiation and reaches almost to 26 °C in the warmest day, despite the North orientation and the roof overhangs.

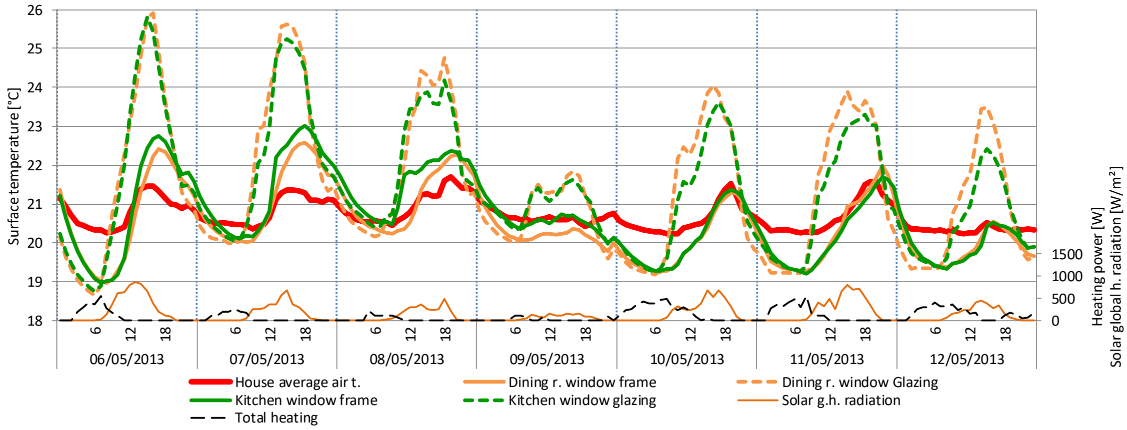


Figure 3.63: North window frame and glazing surface temperatures in kitchen and dining room (shoulder season week 6/05/2013 - 12/05/2013).

The outside temperatures of the facades are plot in Figure 3.64. The impact of solar radiation is reduced by the shading of the roof extensions and the lack of clear sky during long hours. However, in certain days the peak temperatures on East and West orientations are noticeable and reach up to 30 °C temporarily.

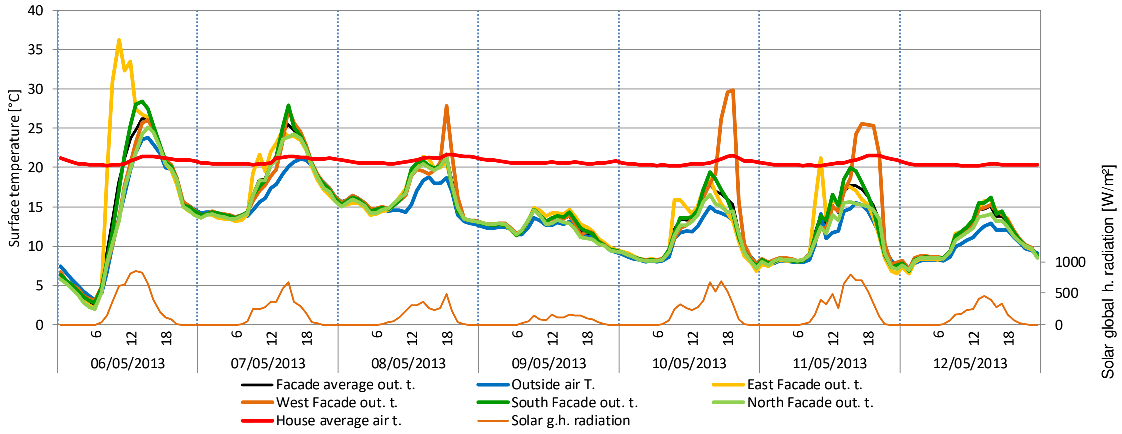


Figure 3.64: Façade external surface temperatures (shoulder season week 6/05/2013 - 12/05/2013).

To conclude the analysis of a mild week between winter and summer, the thermal behaviour of the porch is plot in Figure 3.65. The porch remained with the outer glazing closed during most of the time and the temperatures follow the inputs of solar radiation and outdoor temperature. There are not any significant findings.

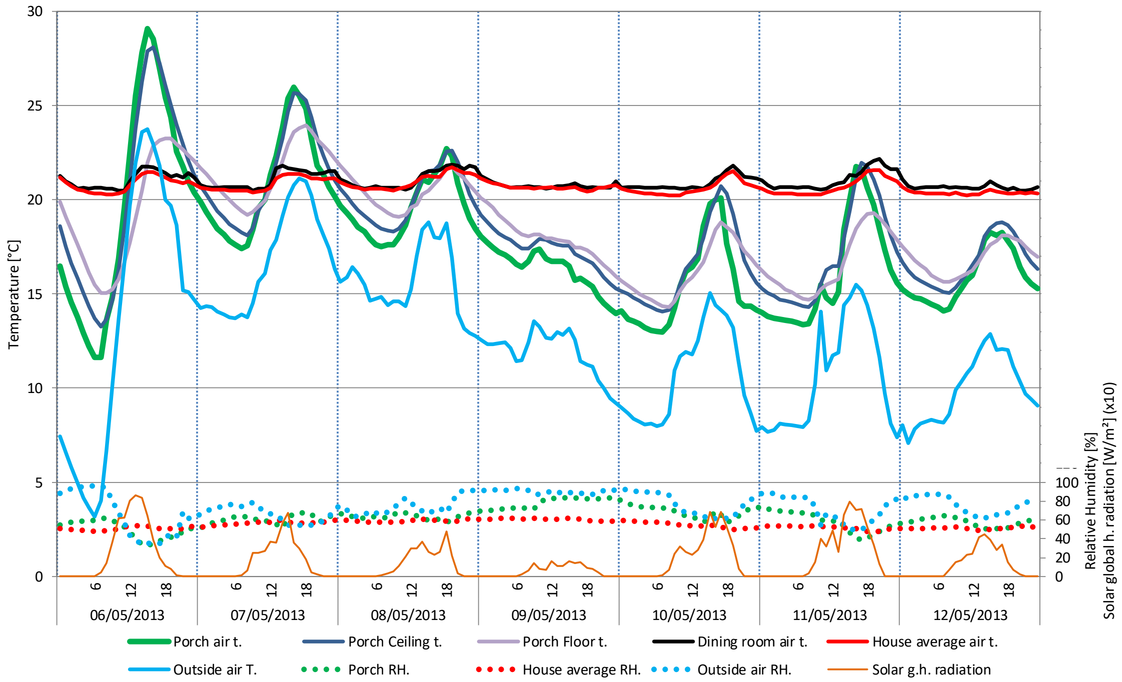


Figure 3.65. Porch thermal behaviour, greenhouse effect (shoulder season week 6/05/2013 - 12/05/2013).

3.4.4. Consumption of electricity

The annual electricity consumption is based on monthly registered values of the building whole consumption. Afterwards, it has been subtracted the particular electricity use of the monitoring, deducing the use of electric heaters and the devices such as the data acquisition, the laptop, sensors and so on.

This way, the annual electricity consumption of the case study was 3353.6 kWh in 2013 and 3253.5 kWh in 2014. These values include all the electric end-uses in the dwelling, without the monitoring and heating devices. So, they embrace the use of appliances, lighting, ventilation and also the auxiliary uses such as the Solar and Heat Pump system (SHP) for DHW.

The values are presented monthly in Figure 3.66 below, since the building's first occupation in 2012, until 2015 when the consultancy works finished. It can be observed a certain trend of higher consumption in winter than in summer. Moreover, it is also perceived an increase of the consumption in the winter of 2014-2015. This can be related to the fact that the inhabitants started using an additional electric heater in the East side of the building. See more details in the discussion of Section 3.5.

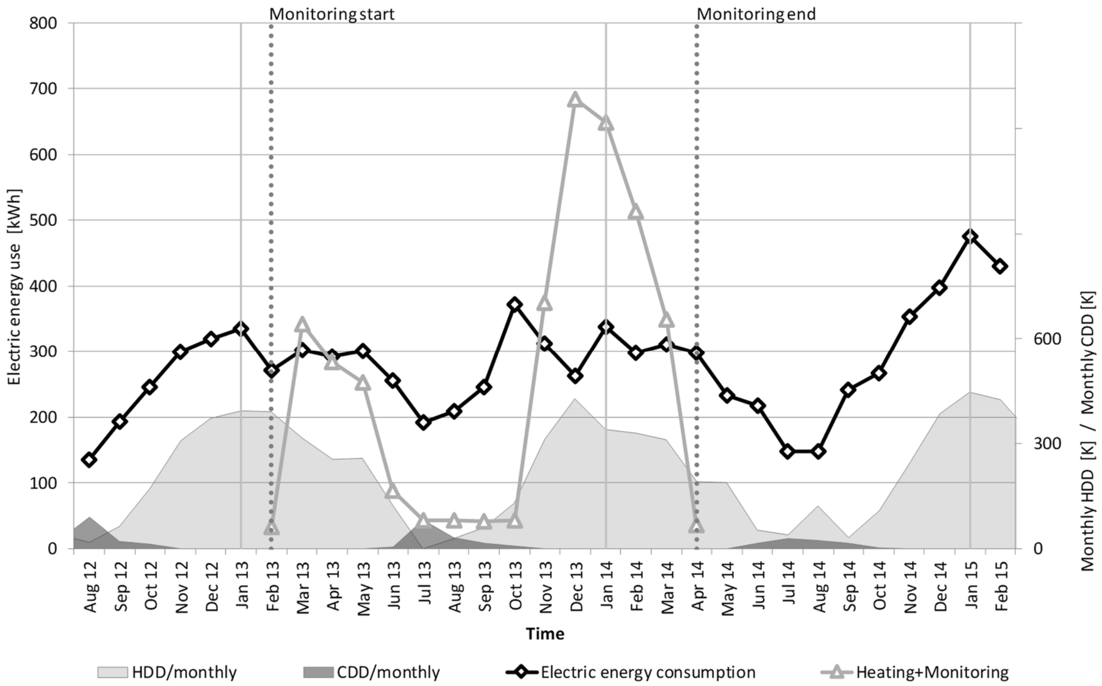


Figure 3.66: Electricity use monthly from August 2012 to February 2015
and heating use during monitored period.

In comparison with other consumptions of average dwellings in Spain, the registered electricity use is very low. Actually, the case study presents lower consumption than any of the reference values of Spanish typologies and areas. According to the detailed review of SECH-SPAHOUSEC project (SPAHOUSEC, 2011), an average single-family detached home in Spain consumes on average 4321 kWh only for electricity use and 6141kWh if the DHW generation is included. That means that the case study presents a reduction of 22.4 % and 45.4 % respectively. This very low electricity consumption is very remarkable if size is considered, because the net floor of the present case is 176 m², considerably larger than the Spanish average 140.2 m² for single-family dwellings.

On top of that, the consumption of this passive dwelling is smaller than the consumption of an average apartment. The present case reduces 37.1 % of the final use including DHW in comparison with an average apartment, that is 5328 kWh or 3285 kWh only for electricity use. In the end, it means that the total consumption of this case, including electricity use and DHW, is smaller than only the electricity use of a much smaller apartment, of only 86.5 m². This is probably related with PH requirements such as the choice of very efficient appliances, low consuming ventilation or the control of lighting units.

3.4.5. Heating performance and comparison between pellet stove and electric heaters operation

This section includes the analysis of two heating systems applied in the case study: a stand-alone pellet stove and a set of small electric heaters distributed in two rooms of the building: in the living room and the dressing room. The operation of both systems was configured with the same temperature threshold, namely 21.0 °C.

Firstly, to be able to compare the operation of both systems it is necessary to analyse the performance during a representative winter weeks with considerably cold weather. To do that, two similar weeks have been selected, with the same average outdoor temperature (5.9 °C) and a comparable solar radiation level (2.23 kW/m²d and 3.11 kW/m²d for week 1 and week 2 respectively). Figure 3.67 and Figure 3.68 below include a detailed comparison of the hourly values of outdoor dry bulb temperature and solar global horizontal radiation of weeks 1 and 2. The week 1 goes from 14/02/2013 to 21/02/2015 and the week 2 starts in the 15/03/2013 and reaches until 21/03/2013.

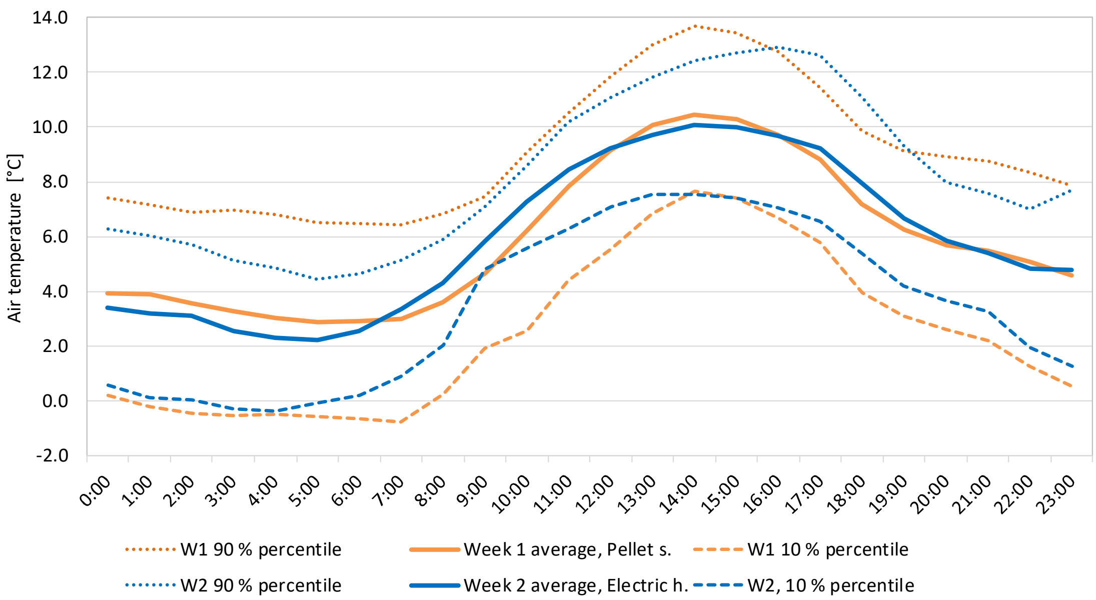


Figure 3.67: Outdoor dry bulb temperatures of the weeks selected to compare the operation of a pellet stove and distributed electric heaters.

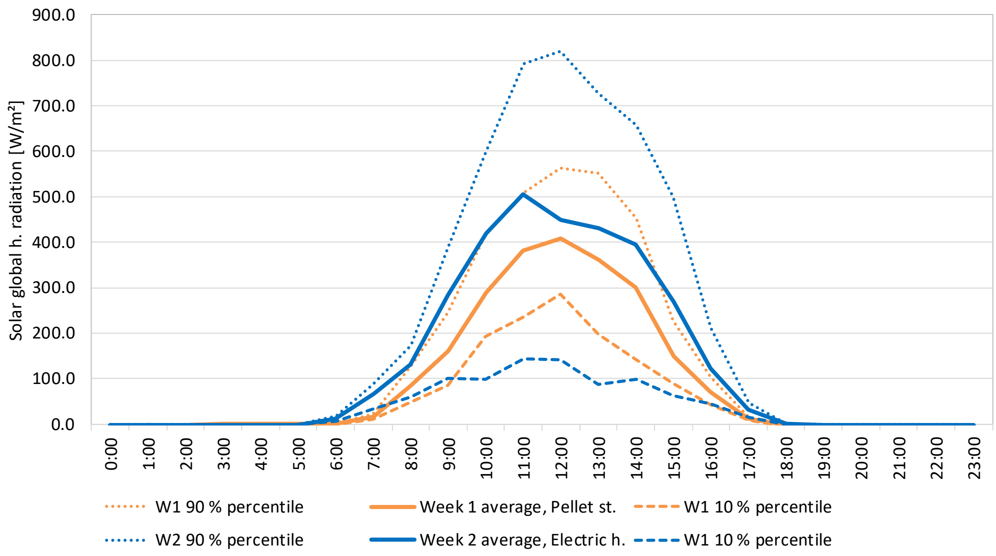


Figure 3.68: Solar radiation of the weeks selected to compare
the operation of a pellet stove and distributed electric heaters.

The main results at building scale are presented in Figure 3.69. The pellet stove induced a typical waving profile of temperatures in the building. Besides, the system operation was very precise and the temperature was on average always between 19.5 and 21.0 °C. There are few warmer hours due to solar gains, hours when the stove was inactive. The distributed electric heaters appear to maintain a more precise control of the temperatures along the dwelling. The heater placed on the dressing room works almost all the time, which indicates that the position of the original pellet stove was not enough to compensate the long shape of the building.

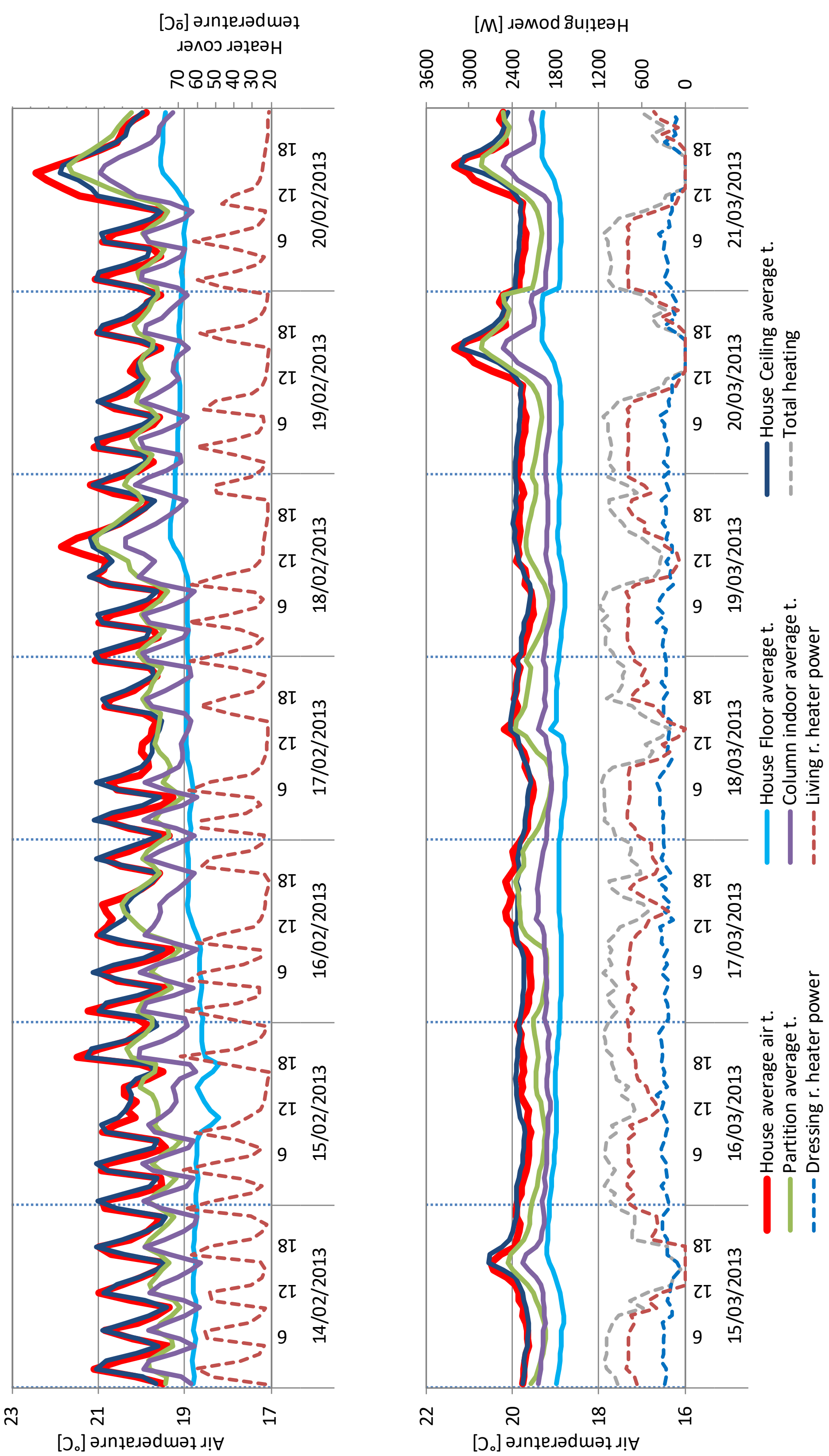


Figure 3.69: Comparison of the building response with a pellet stove (up) or distributed electric heaters (down).

In a closer look, Figure 3.70 presents the hourly profile of the dwelling with the operation differences. Both systems present similar average values, but the pellet stove has a wider range of temperatures due to the fluctuating operation. Regarding to the lower temperatures, the pellet stove drops more often to colder values than the electric distributed heaters, getting close to 19 °C eventually. The higher temperatures oscillate more in the pellet stove than in the electric heaters as well. The integration of the heating system and solar gains is more balanced in the distributed electric heaters than in the pellet stove, despite to the fact that the week 2 had more solar radiation.

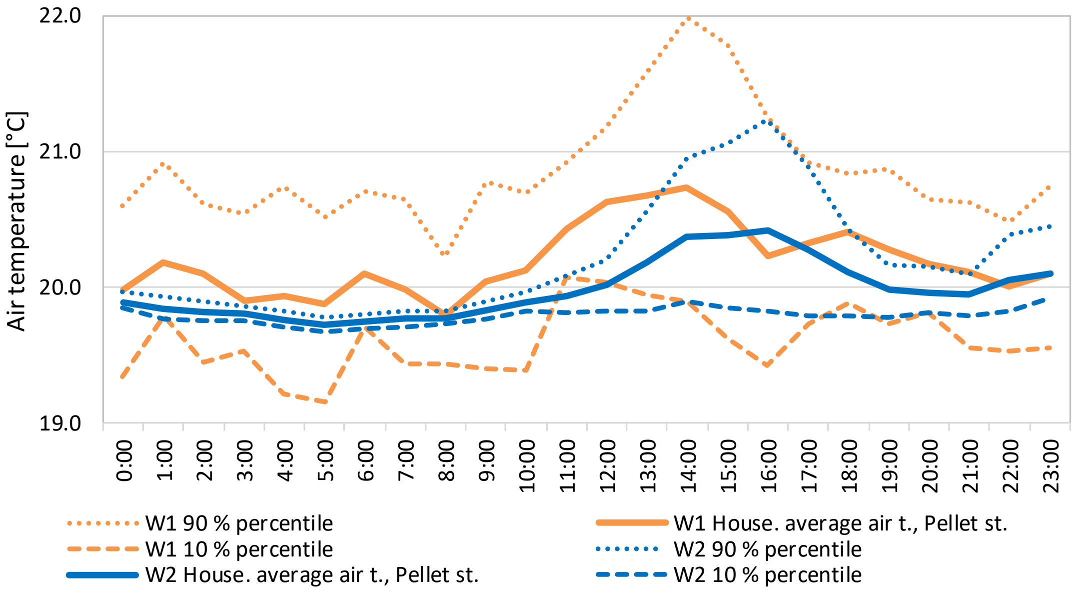


Figure 3.70: Comparison of the hourly profile of the dwelling average temperature, between a pellet stove and several distributed electric heaters.

Nevertheless, despite the balanced house average temperatures, the temperatures in the living room points to one of the main issues of the pellet stove operation: the high temperatures in the room where the stove is installed. In this case, the hourly profile of the living room indicates that this room is on average at 22.0 °C, with some hours over 23.5 °C. These high variations may lead to some problems of Thermal Comfort (TC) and for that reason a more detailed analysis is necessary.

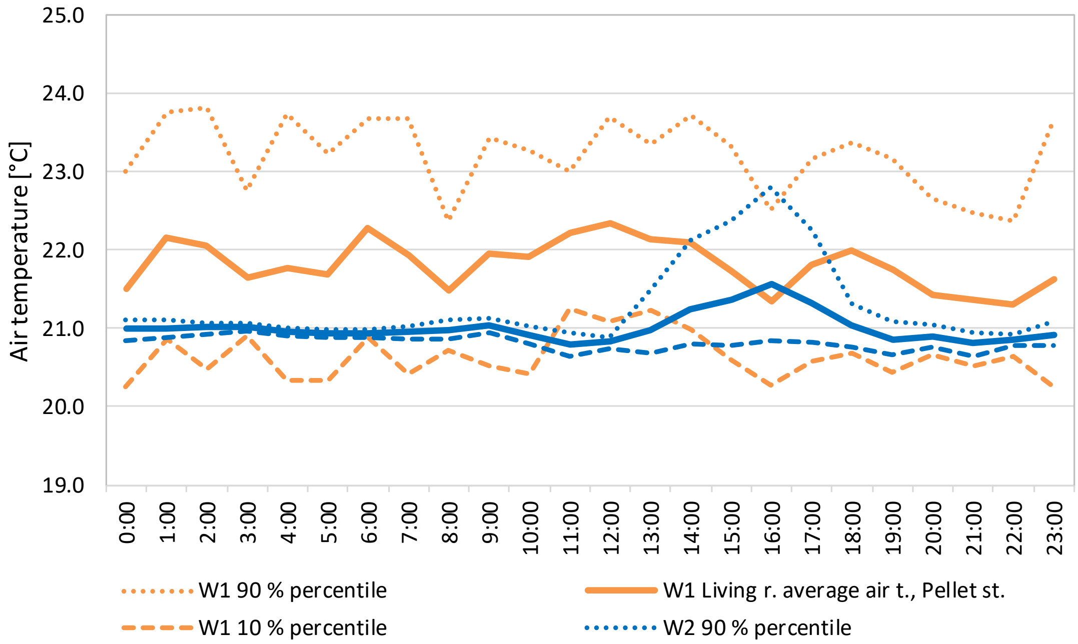


Figure 3.71: Comparison of the hourly profile of the living room temperature, between a pellet stove and several distributed electric heaters.

The TC has been analysed grouping the similar rooms according to their activity and orientation. The assessment of the TC provided by these heating systems is calculated first by ISO 7730, applying the following assumptions: residential activity (1.2 Met), standard clothing for winter (1.0 clo), low indoor air speed (below 0.1 m/s) and the air dry-bulb temperature and the operative temperature are very close in this construction typology in winter. Later, the EN 15251 is also applied to check if the application of this adaptive standard has any influence in the interpretation of the winter TC. It is assumed a full-time occupation in these weeks, since there is no need for natural ventilation in the cold period. A more detailed study of the TC is included in the Section 3.4.7 and additional information in the Appendix.

The temperature analysis indicates that neither of the heating systems provide enough heat to all the rooms of the home. Some parts of the house stay below 20 °C during long period of time, especially in the rooms which are far from the main heat source (living room). This happens mainly in the rooms in the east side of the building (dressing room and bedrooms) and in lower degree in the rooms in north orientation (main bedroom, kitchen, bathroom 2 and dressing room).

Regarding the TC with the PMV model, the set of electric heaters provides the best TC maintaining the global home all the hours within the acceptable categories A and B. The distributed electric heaters fix the cool periods in the East orientation, but deteriorate the TC in northern rooms and in sleeping rooms. Besides, the temperatures with these heaters are in general lower than the ones during the operation of the pellet stove. With the pellet stove, the average house achieves acceptable levels during the 99.4 % of the time, with only 1 hour (0.6 %) in category C (cool). The main results are included in Figure 3.72, Figure 3.73 and Figure 3.74.

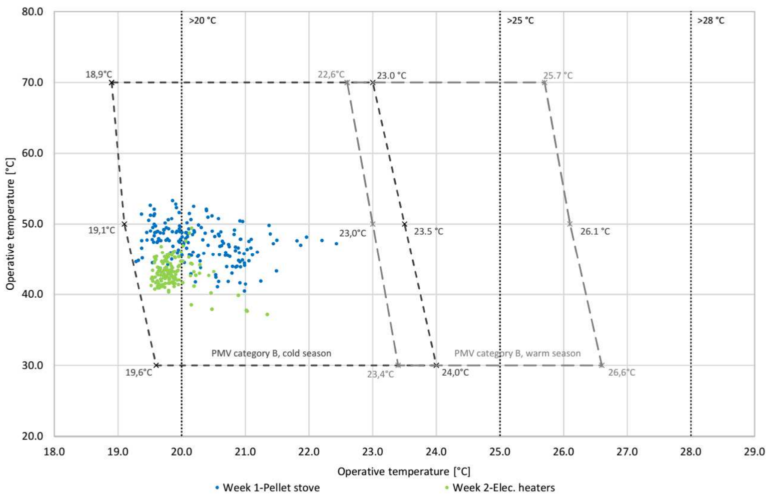


Figure 3.72: Comparison of heating systems in house average, PMV method.

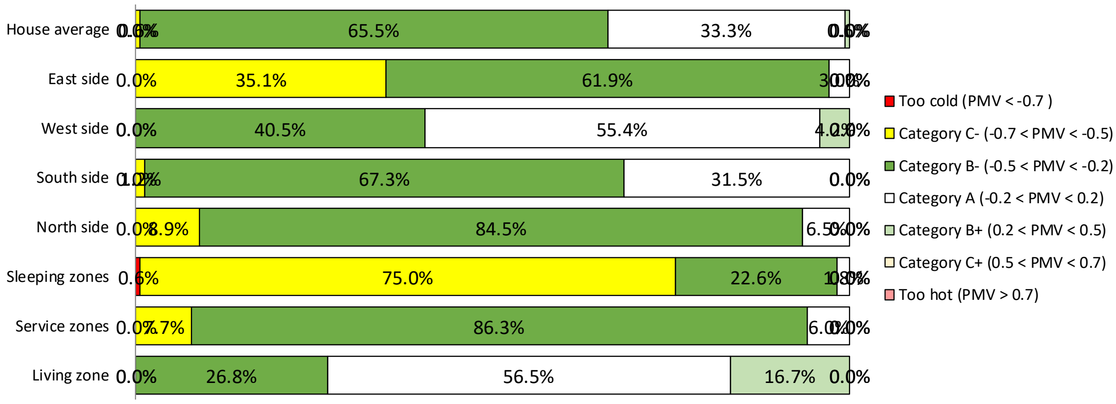


Figure 3.73: Thermal Comfort in winter week 1 with pellet stove, PMV method.

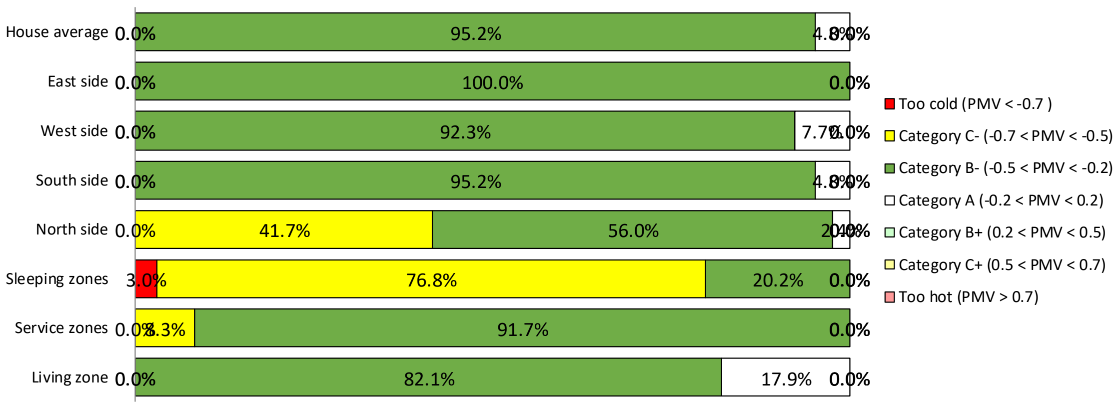


Figure 3.74: Thermal Comfort in winter week 2 with distributed electric heaters, PMV method.

On the other hand, the TC values based on EN 15251 show a relevant presence of cool temperatures during the operation of both heating systems. It indicates that in general the TC provided by the pellet stove is acceptable during 63.1 % of time, in contrast with the 21.4 % with electric heaters. This underlines the fact that temperatures remain long hours below 20.0 °C, as stated before, and shown in Figure 3.72. The results sorted by activity and orientation are included in Figure 3.75 and Figure 3.76.

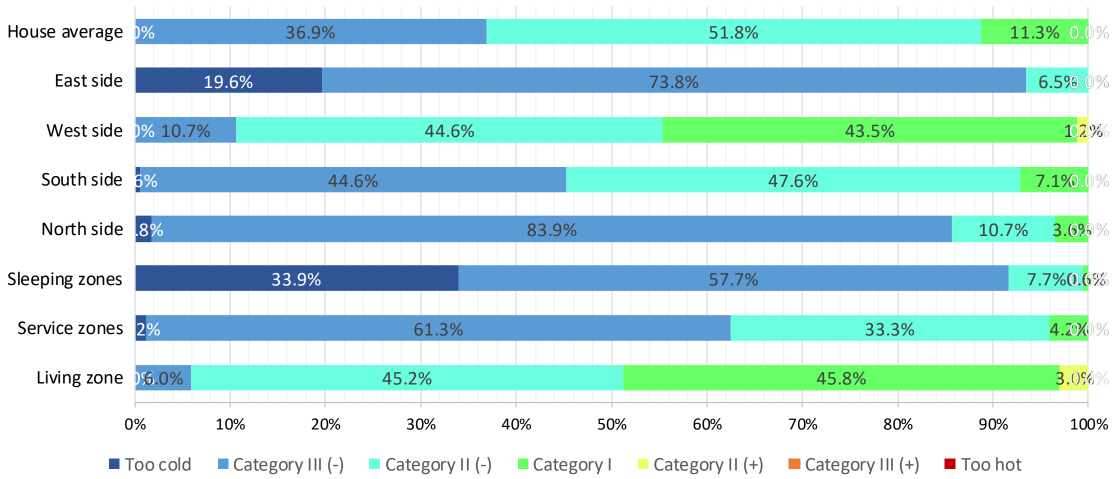


Figure 3.75: Thermal Comfort in winter week 1 with pellet stove, EN 15251.

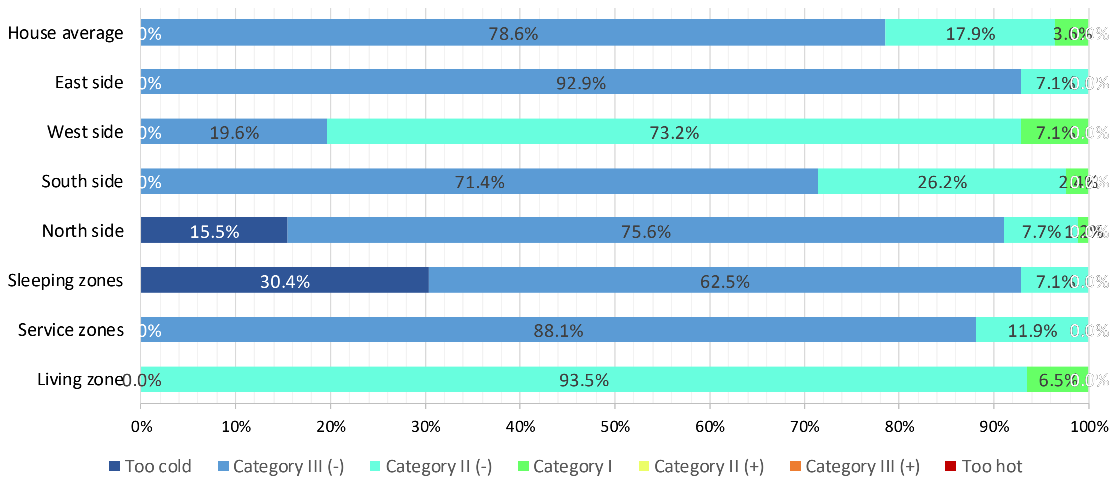


Figure 3.76: Thermal Comfort in winter week 2 with distributed electric heaters, EN 15251.

Consequently, the heating target temperature defined by the inhabitants is reaching the standard threshold temperatures.

Additionally, the temperatures of the living room are analysed in more detail. The variation of temperatures at different heights and also the cool and warm surface temperatures of floor or ceiling can provoke problems of temperature asymmetry, inducing to local discomfort.

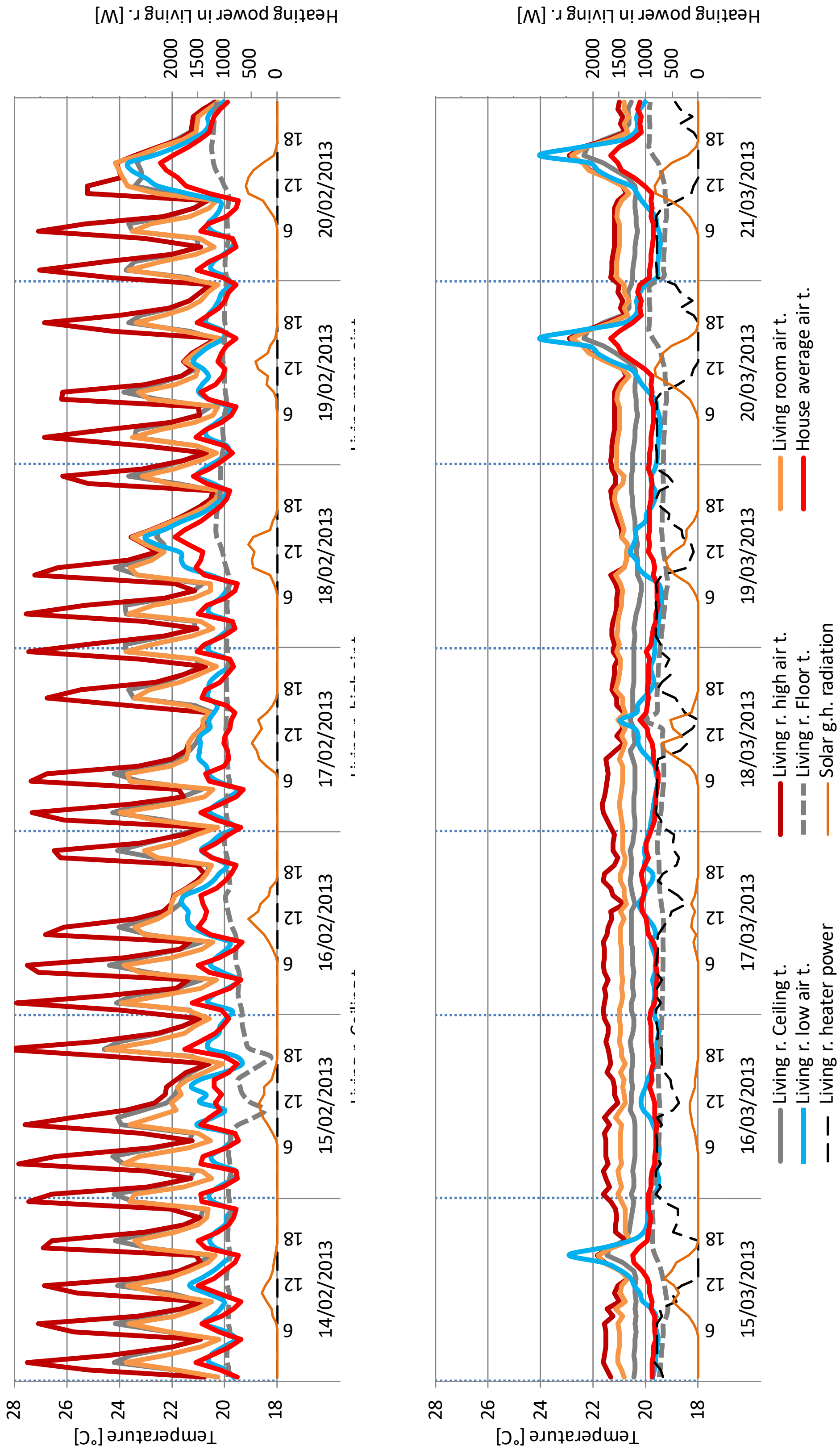


Figure 3.77: Comparison of living room temperatures by type of heating system,
week 1 with a pellet stove (up) and week 2 with several distributed electric heaters (down).

The verification of local discomfort is done according to ISO 7730 formulas. They are calculated the limits of the main causes of local discomfort to keep the Percentage of Dissatisfied (PPD) below 10 %. This way, on residential buildings running under normal conditions of use (50 % RH) the limits are 4.2 °C for air stratification and 3.7 °C the warm ceiling effect.

According to this procedure, none of the heating systems presented any local discomfort conditions. If the air stratification between the knees and the head remained during the monitored weeks around 2 or 3 °C and the temperature of the ceiling is approximately 1 or 2 °C higher than the air temperature.

3.4.6. Measured thermal losses

The measured annual heating consumption of the house was 2993.4 kWh, since the 12th of March of 2013 until the 11th of March of 2014. This value corresponds to the measurement of 365 days of the power provided by the electric heaters, which is distributed along the living room and the dressing room. The heaters were operating when the room temperature dropped from 20.5 °C in both rooms, this maintain an average temperature of the home in 20.0 °C. This temperature was slightly below the standard but it was stablished by the inhabitants, who didn't like a higher temperature during winter. Figure 3.78 below shows the daily values during all the monitored period. The average winter heating consumption, considered between November and March is 15.43 kWh per day. The maximum daily value was 29.33 kWh/d.

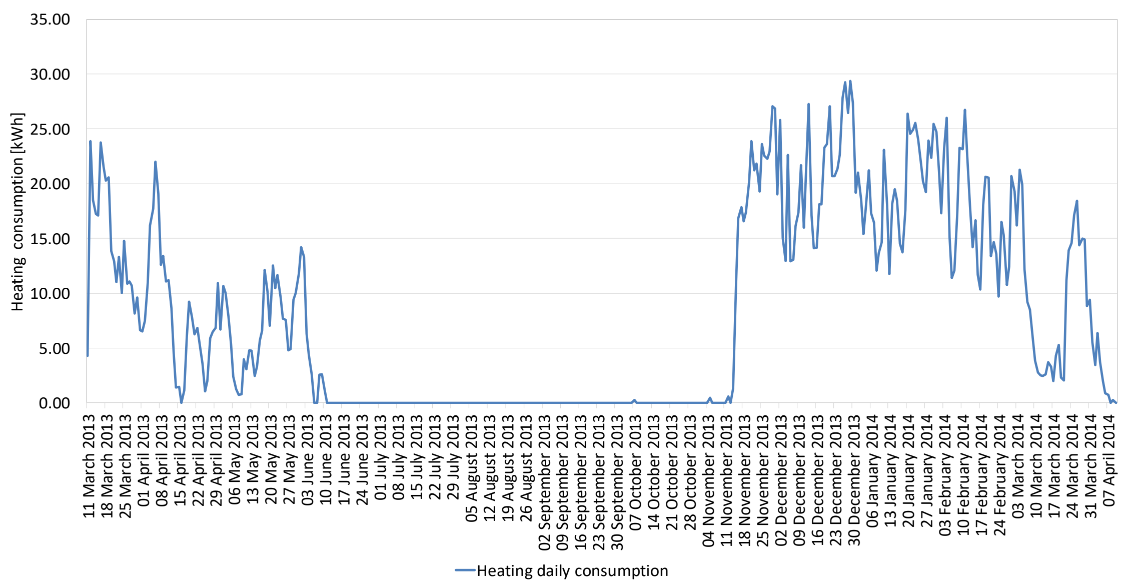


Figure 3.78. Monitored heating consumption daily, full period.

In order to analyse the real performance of the house, the measurements are contrasted with the expected heating demand on PHPP calculations. Firstly, the heaters are electric and with no additional thermal mass, their electricity consumption can be compared with the heating demand of the house design. Secondly, a correction by HDD severity is applied, namely a 3.3 % increase over the measured heating consumption. The corrected annual heating demand of the whole house is 3091.7 kWh. Thirdly, it is calculated the ratio over the treated floor area of the PHPP, that is 176.1 m². Thus, the measured and HDD corrected heating demand was 17.6 kWh/m²y.

3.4.7. Ventilation performance

Bearing in mind the features of ventilation explained in Section 3.3.1 such as the very high level of building air tightness and the average 0.40 h^{-1} ACH, the following results analyse in detail the long-term efficiency of the HR and the operation of the by-pass under real conditions of use. The data correspond to 321 days, registered every 15 minutes during three periods between the 20th of November of 2012 to the 18th of November of 2013.

According to the operation of the MVHR there are three possible operations and Figure 3.79 manifests three clearly separated trends: the operation under heating conditions in black, the operation under hot conditions in red and the bypass period in orange. There are also some instants where the efficiency is over 100% or negative, these values correspond to transition periods where the differences between the indoor-outdoor temperatures are small. It happens in all the operation types. Besides, the thermal inertia of the HR and the MV unit can also provoke some spread values. The main findings are summarised in Table 3.15. Afterwards, each period is analysed in order to know the efficiency of each type of operation and its potential.

Table 3.15: Monitored efficiency of the ventilation Heat Recovery,
sorted by operation and hourly average.

Type of operation	Num. hours	Num. days	Average HR efficiency*	10 % percentile*	90 % percentile*
Heating period HR	6651	277.1	86.3 %	79.9 %	92.7 %
Cooling period HR	186	7.8	72.1 %	54.5 %	88.2 %
By-pass operation	870	36.3	20.9 %	13.9 %	33.9 %
TOTAL	7707	321.1	-	-	-

** The HR is calculated only with the values between 0-100 %*

The MVHR was operating mainly under heating conditions (86.3 % of hours), which means that the ventilation tries to keep all the heat inside the building. On average, it presented 86.7 % of efficiency, slightly over than the Laboratory test result for the PHI certification (85.5 % when indoor is at 21 °C and outdoor at -10 °C). During this period, the bypass worked only if the extract air overpassed 25 °C, as a safety measure. This measure was activated occasionally in autumn, after the inhabitants deactivated the summer operation in the MVHR panel, see Figure 3.79.

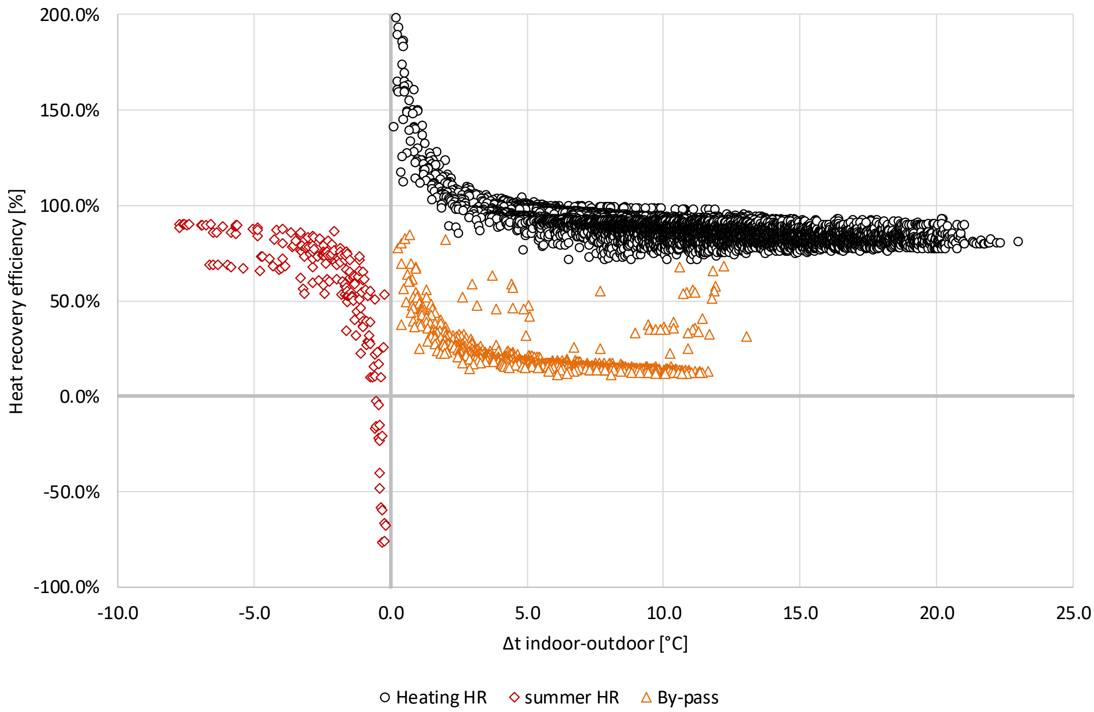


Figure 3.79: Monitored efficiency of the ventilation Heat Recovery in hourly average, full monitoring period.

In summer, the MVHR unit worked mainly as by-pass ventilation, namely 11.3 % of total hours. In contrast, it recovered the heat only in 2.4 % of the hours. As a result, the summer HR average is 72.1 %, lower than the winter average, as shown in Figure 3.81 and Figure 3.82. This smaller value can be related with the short time of operation and also with the smaller differences between the extract air and the fresh air, in contrast with the typical winter operation which is operating long-time and with higher differences of temperatures.

Figure 3.83 shows the ventilation operation in summer in detail, including three days of summer between 30th of July and the 1st of August of 2013. In the plot the types of operation can be identified: summer HR, by-pass and also a short period of too cold temperatures outside, when the condensing prevention is activated.

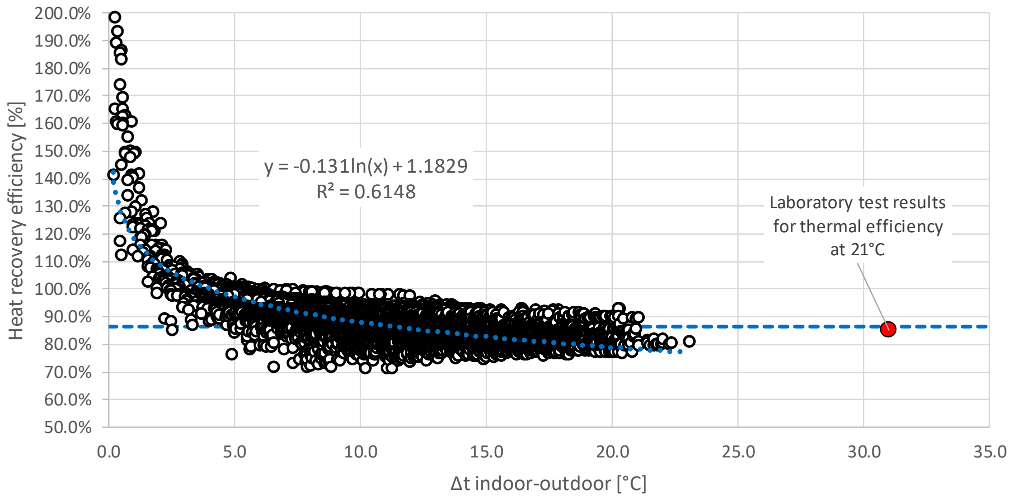


Figure 3.80: Monitored efficiency of ventilation heat recovery during the heating period, hourly average.

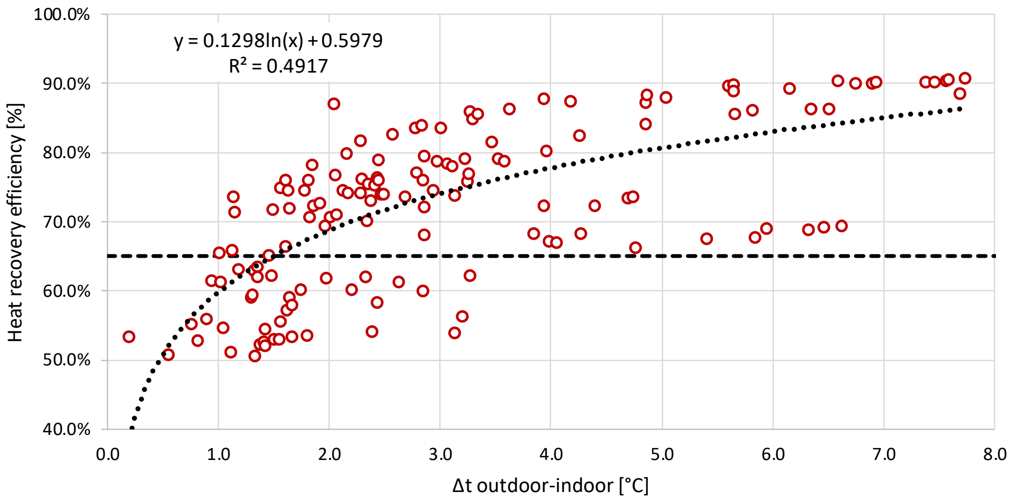


Figure 3.81: Monitored efficiency of ventilation heat recovery during the cooling period, hourly average.

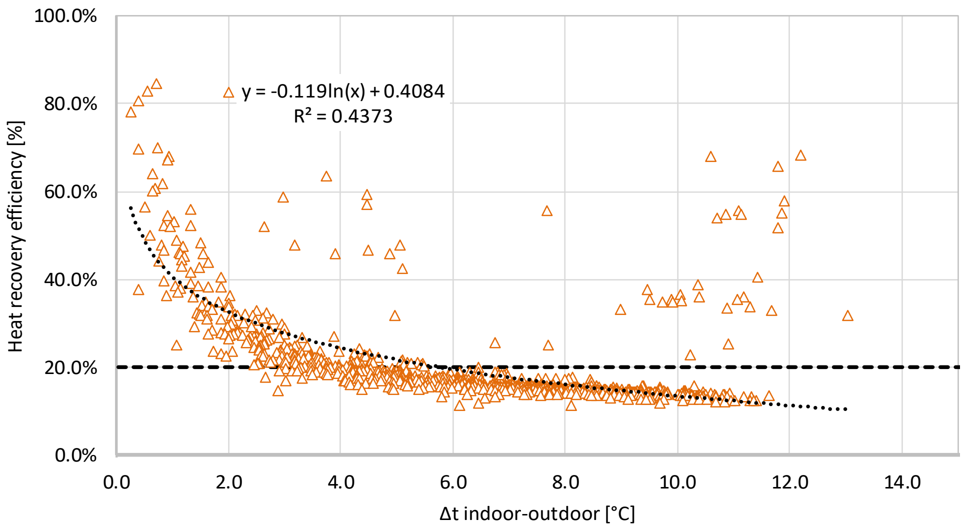


Figure 3.82: Monitored efficiency of the bypass during summer period, hourly average.

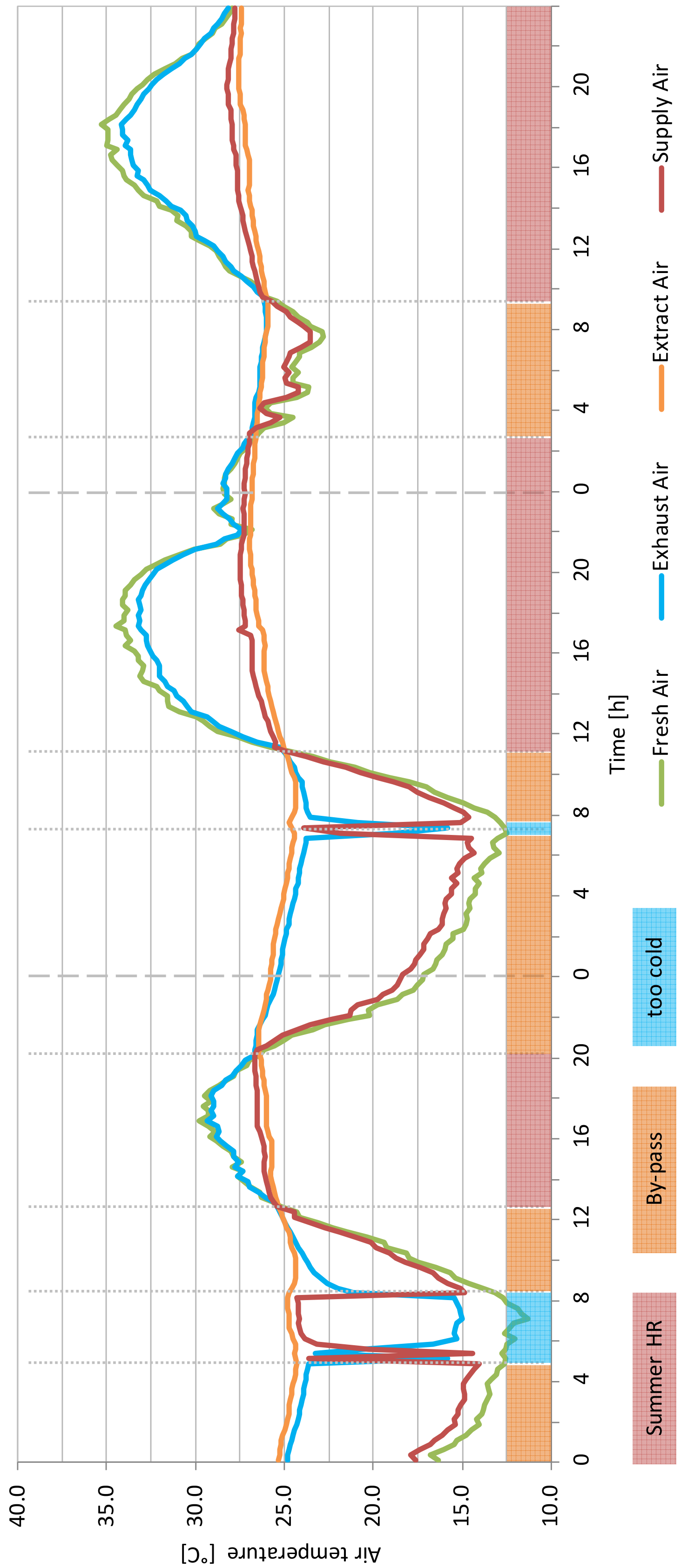


Figure 3.83: Detail of the ventilation monitoring, identified three periods.

The by-pass operation is also analysed, in order to know the real cooling potential during the monitoring period. It is calculated the cooling potential (4) and later compared with the real cooling obtained during each monitored hours of by-pass. The results indicate that 81.5 % of the total cooling potential was achieved during the 870 hours of by-pass. On average, this cooling power was 0.31 KW, as shown in Figure 3.84. In total, from a maximum cooling potential of 1191.34 MJ, the real obtained cooling was 971.51 MJ. That is 269.86 kWh or 1.53 kWh/m²y.

$$\text{Cooling potential} = \Delta T * c_p * \rho * \dot{v} \qquad (4)$$

ΔT temperature difference (K)
c_p specific heat (KJ/(kg K))
ρ density (kg/m³)
$\dot{v}$ acceptable air flow (m³/h)

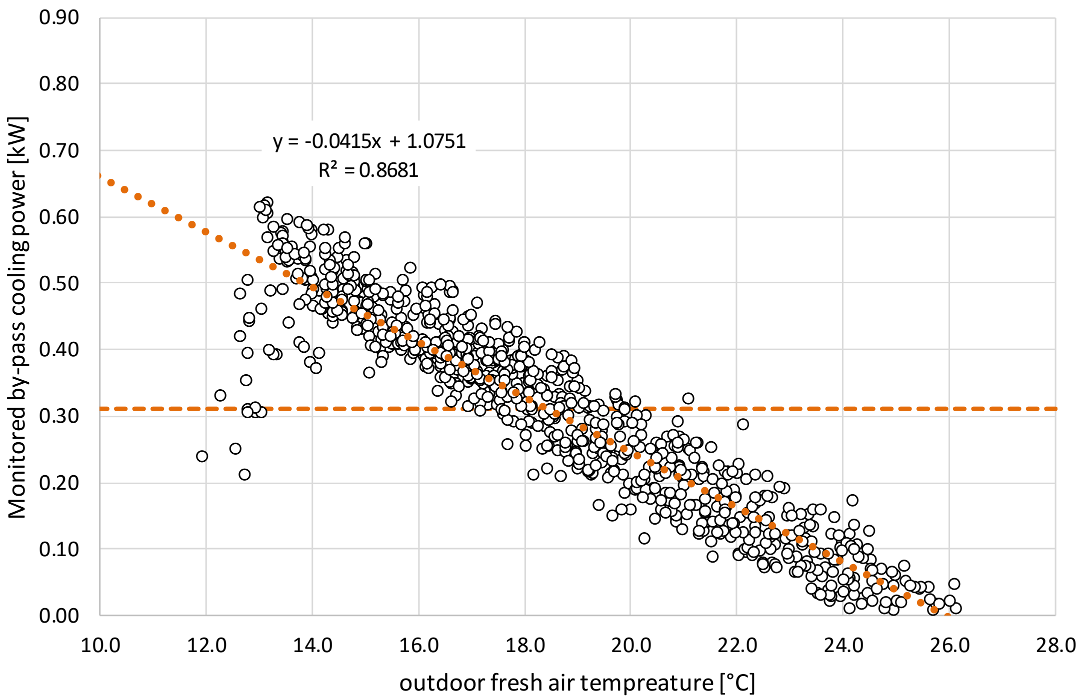


Figure 3.84: Monitored by-pass cooling power hourly.

Overall, the inhabitants manifested their high level of satisfaction with the ventilation and they only applied natural ventilation in several nights of summer. This aspect is analysed within the thermal comfort in the next Section 3.4.7. Further details of the monitored ventilation are included in Appendices.

3.4.8. Thermal Comfort assessment

Apart from the monitored air temperatures during the whole period, some particular measurements were also made to check the validity of air temperatures to assess the TC. For that purpose, TC was monitored in detail during some weeks in summer, winter, autumn and spring. Two TC stations were used to measure all the environmental parameters involved in TC: air dry bulb temperature, globe temperature, RH and air velocity.

It was confirmed that in the case of study the deviation of the operative temperature and the air temperature was low during the main part of the year. In winter, spring and autumn the differences remained in general below 0.2 °C, probably due to the high level of insulation of the building. There were only few occasions with direct solar radiation when that limit was overpassed. This fact was also cross-checked with the small differences between air temperatures and surface temperatures of ceilings, floors and walls. In summer, on contrary, the differences between operative temperature and air temperature are larger. Figure 3.85 shows the deviations in August and September in two southern rooms. Additional details of the TC stations can be found in the Appendix.

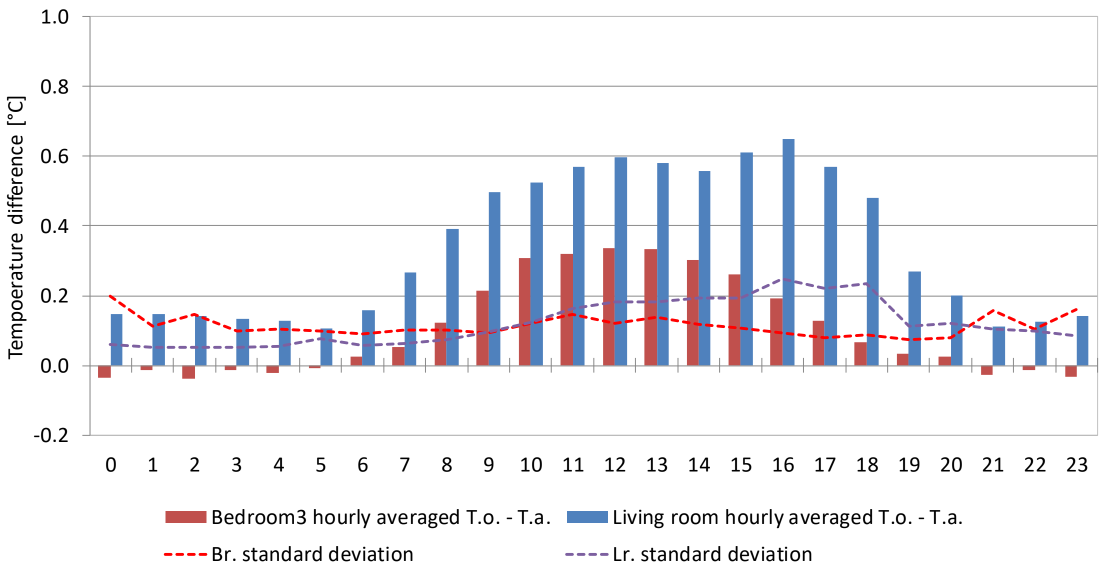


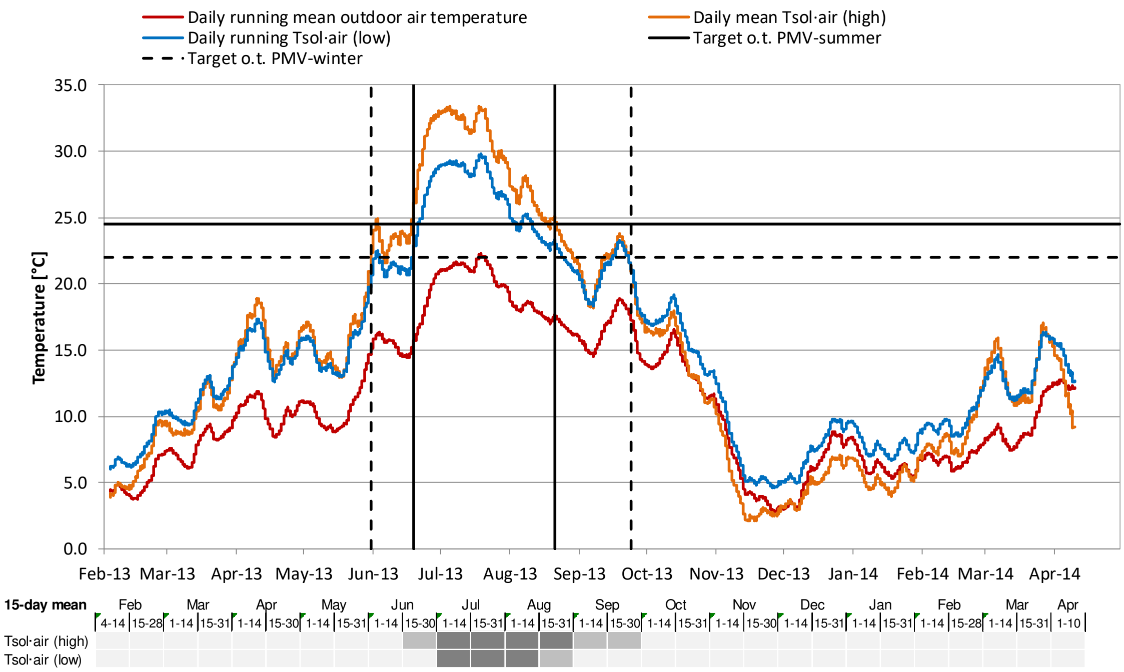
Figure 3.85: Comparison between the air temperatures and operative temperatures registered during one month of summer, 22/08/2013-24/09/2013.

For these reasons, the air temperature has been considered close enough to the operative temperature during the cold period. On contrary, in the warm period and the intermediate periods the air temperatures have been corrected to get closer to the real operative temperature.

3.4.8.1. Period identification

A precise thermal comfort assessment relies on a proper identification of the warm and cold periods. In the present case, this has been done following the method proposed by Carlucci (ref, 2013) and improved by (Catalan study, 2015) by the appliance of a daily basis for real measurements. According to these works, sol-air temperature represents better the weather conditions as a whole. To define the sol-air temperature applicable for the present case study, two possibilities have been calculated in correspondence with the considered surface: a vertical white surface (facades) with low effect of solar radiation and a horizontal dark surface (tile roof) with high effect of solar radiation.

The study has been done applying the low sol-air temperature to detect the limits of sold season and the high sol-air temperature to delimitate the warm season. Figure 3.86 shows the results and the comfort temperatures of summer and winter obtained with PMV.



15-day mean	Feb 4-14	Feb 15-28	Mar 1-14	Mar 15-31	Apr 1-14	Apr 15-30	May 1-14	May 15-31	Jun 1-14	Jun 15-30	Jul 1-14	Jul 15-31	Aug 1-14	Aug 15-31	Sep 1-14	Sep 15-30	Oct 1-14	Oct 15-31	Nov 1-14	Nov 15-30	Dec 1-14	Dec 15-31	Jan 1-14	Jan 15-31	Feb 1-14	Feb 15-28	Mar 1-14	Mar 15-31	Apr 1-10
Tsol·air (high)	2.9	4.9	9.7	11.0	13.5	15.5	17.1	13.2	21.8	24.1	33.0	32.0	28.5	25.2	21.6	22.2	16.4	15.9	11.3	2.2	3.1	5.0	6.9	4.7	7.0	7.5	12.7	11.5	15.6
Tsol·air (low)	5.3	6.3	10.6	11.5	13.5	14.5	16.2	13.0	20.4	21.3	29.0	28.5	25.9	23.3	20.8	21.7	17.0	17.4	13.6	5.1	5.0	7.5	9.6	7.3	8.9	8.7	12.4	11.8	15.9
Tdb	3.9	3.8	7.6	8.1	9.6	9.7	11.4	8.9	15.1	14.7	21.0	21.1	19.4	17.6	16.2	17.3	13.7	15.0	11.9	4.2	3.0	6.0	8.4	6.0	6.8	5.9	8.1	8.2	12.3

Figure 3.86: Comparison between period identifications based on Fanger-PMV comfort temperatures, daily mean values (up) and 15-day mean values (down).

Regarding to the selected time step, the 15-day mean period could be sufficient for general purposes but bearing in mind the level of detail of the monitoring it is more accurate to apply a daily basis to identify exactly the beginning and end of the Fanger-PMV periods. This way, the periods to assess the TC of the monitored case are delimitated in Table 3.16.

Table 3.16: Periods definition according to Fanger-PMV comfort temperatures in daily base.

Periods		**Tsol (high)**	**Tsol (low)**	**Selected period**
Cold period PMV	Monitoring start	4/02/2013	4/02/2013	4/02/2013
< 22.0 °C	To	31/05/2013	01/06/2013	01/06/2013
Intermediate	From	-	-	02/06/2013
	To	-	-	18/06/2013
Warm period PMV	From	19/06/2013	22/06/2013	19/06/2013
> 24.5 °C	To	21/08/2013	11/08/2013	21/08/2013
Intermediate	From	-	-	22/08/2013
	To	-	-	22/09/2013
Cold period PMV	From	24/09/2013	23/09/2013	23/09/2013
< 22.0 °C	Monitoring end	10/04/2014	10/04/2014	10/04/2014

3.4.8.2. Dwelling occupancy analysis

The occupancy levels of a home can show useful information for many purposes, as seen in the literature review. Regarding to the TC assessment, the occupancy is essential for many methods because in the majority of free-running buildings it is directly related with the possibility of natural ventilation. IT is important to keep in mind that this feature is also a requirement of the adaptive method (EN 15251, 2010). This TC method implies that inhabitants have direct access to windows and can create natural ventilation on demand.

Thus, the occupancy was studied in order to create an average profile of inhabitants' presence in the dwelling. 5 labour weeks and 3 holiday were analysed in detail to create a profile of occupancy in labour weeks and another profile applicable in holiday weeks. In Figure 3.87 are represented both typical weeks, where the number indicates the frequency of occupation in every hour of each day.

Apart from the hourly inoccupancy of the created profile, the periods when the family was out for more than 1 day have been fully excluded from the TC calculations, in order to focus on the real conditions of use.

Day \ Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon	5	5	5	5	5	5	5	5	0	0	0	1	4	4	3	1	0	3	3	3	5	5	5	5
Tue	5	5	5	5	5	5	5	5	0	0	1	1	4	5	4	1	0	1	1	2	4	5	5	5
Wed	5	5	5	5	5	5	5	5	1	0	0	1	4	4	4	1	0	1	3	4	4	5	5	5
Tue	5	5	5	5	5	5	5	5	2	0	0	1	5	5	5	3	1	2	5	4	3	4	4	4
Fri	5	5	5	5	5	5	5	5	0	1	1	0	4	4	4	2	1	2	1	1	2	3	3	4
Sat	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	2	3	3	3	4	3	3	3
Sun	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	2	2	3	4	4	5	5	5	5

Workweek

Occupancy check by hour along 5 weeks during workweeks within normal school calendar. Occupied if ≥ 3/5

Day \ Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mon	3	3	3	3	3	3	3	3	3	3	2	3	2	3	3	3	1	0	1	2	3	1	1	2
Tue	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	0	0	0	0	1	1	2	2	3
Wed	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	2	2	1	1	1	1	2	3
Tue	3	3	3	3	3	3	3	3	3	3	3	3	2	2	3	2	0	1	1	1	1	2	2	2
Fri	2	3	3	3	3	3	3	3	3	3	2	2	1	2	3	1	1	1	1	0	1	2	2	3
Sat	3	3	3	3	3	3	3	3	3	3	3	2	2	3	2	1	1	0	1	0	1	2	3	3
Sun	3	3	3	3	3	3	3	3	3	3	3	3	2	2	3	3	2	1	1	0	0	2	2	3

Summer week

Occupancy check by hour along 3 weeks of summer during school holidays. Occupied if ≥ 2/5

Figure 3.87: Carpet diagram of the occupancy in the case study for a typical labour week and a typical summer week.

3.4.8.3. Evaluation of the thermal comfort by the PMV model, ISO 7730

The first evaluation of the TC is based on ISO 7730 and the formulas of the PMV model, as explained in Chapter 2. The analysis is first done at building level. The weighted average temperature is calculated in correspondence with the net floor of each room. So, the TC of the average house is studied during one year of monitoring (12/03/2013 – 11/03/2014), see Table 3.17. It is remarkable the very high level of comfort achieved at the whole building: 97.6 % in the cold season, 98.4 % in the intermediate and 86.7 % in summer. This way, the main issues are located in summer, when there is a significant 13.3 % exceeding the highest temperature limits. During the cold season and the intermediate period, there are also certain periods of hot temperatures, 2.0 % and 1.6 % of each period's duration respectively. Moreover, very few cold hours are also registered in the cold season, that is 0.5 %.

Table 3.17: Summary of monitored year of thermal comfort in average house, PMV method.

PMV	Monitored year		Cold season		Intermediate		Warm season	
Too cold (PMV < -0.7)	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Category C- (-0.7 < PMV < -0.5)	31	0.4%	31	0.5%	0	0.0%	0	0.0%
Category B- (-0.5 < PMV < -0.2)	4347	51.5%	4205	63.0%	64	14.8%	78	5.8%
Category A (-0.2 < PMV < 0.2)	2496	29.5%	1691	25.3%	227	52.5%	578	43.1%
Category B+ (0.2 < PMV < 0.5)	1258	14.9%	616	9.2%	134	31.0%	508	37.9%
Category C+ (0.5 < PMV < 0.7)	214	2.5%	84	1.3%	7	1.6%	123	9.2%
Too hot (PMV > 0.7)	101	1.2%	46	0.7%	0	0.0%	55	4.1%
Total hours PMV	8447		6673		432		1342	

In order to get a clearer idea of the thermal comfort indoor, all recorded vales are plotted and organised in colours by every two months, see Figure 3.88 and Figure 3.89. It is very noticeable the homogeneity of the low inner temperatures (left side), meaning that the temperature and RH remain between 19.5 - 21.0 °C and 40.0 – 55.0 % from November to April (in light blue, dark blue and green). Summer period leads to higher RH, between 50 % and 65.0 % and higher temperatures between 23 °C and 26 °C.

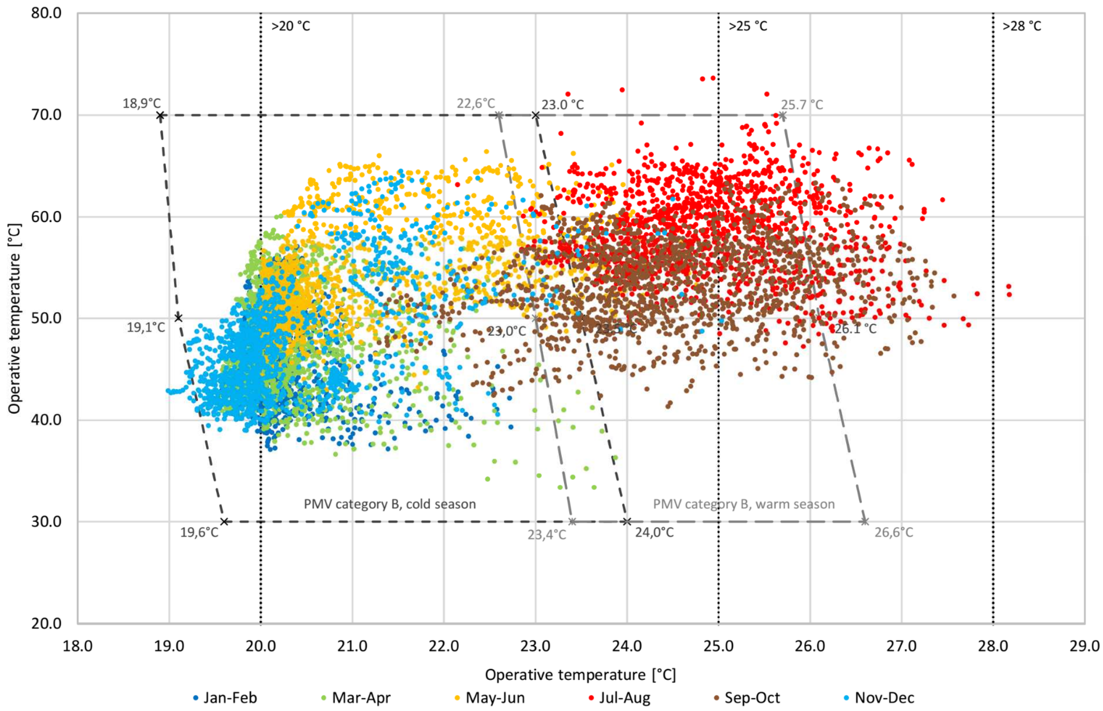


Figure 3.88: Monitored year of thermal comfort in average house, T-RH plot of PMV method

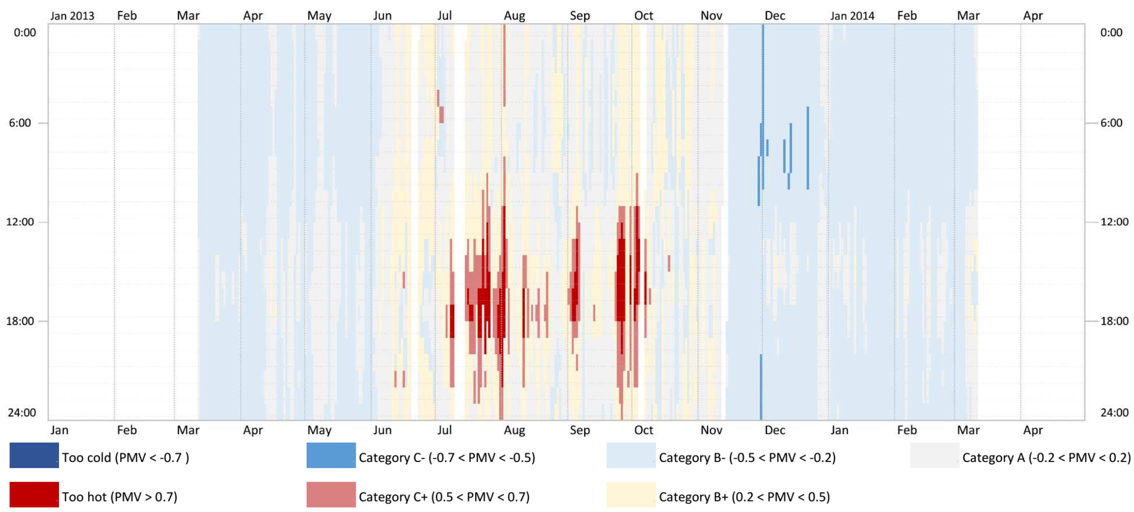


Figure 3.89: Monitored year of thermal comfort in average house, hourly diagram of PMV method.

Accordingly, the hourly results indicate that the majority of hot hours happen from 13:00 until 18:00 hours. Figure 3.89. It can be perceived a certain asymmetry in the transition periods, which means that in late spring and early summer the building is progressively warming up, on contrast with the end of summer when there is almost no transition and the temperatures drop in November. This was also explained before in the period identification section.

In a second step, the analysis in Figure 3.90 is conducted in more detail to assess the differences of TC between the rooms, sorted by orientation and type of activity. Overall, the main differences in the full year are located in the sleeping zones (bedrooms) and north areas (main bedroom, bathrooms, toilet, kitchen and dressing room) and in the living areas (living room, dining room, kitchen and music room). This way, a first view of the annual values indicate that the bedrooms are severely cool, because they are out of comfort during 18.8 % of the year hours. which are significantly cooler than the average of the house.

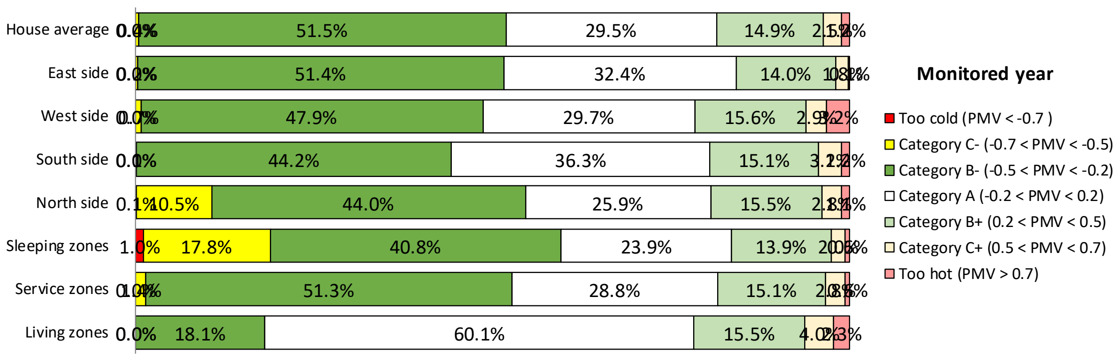


Figure 3.90: Comparison of TC of rooms by orientation and activity, monitored year of PMV.

On the other hand, the differences are considerably higher and clearer if the review is done each for each season separately, as in Figure 3.91. During the cold season, the sleeping zones manifest a very severe 23.8 % of hours under cold and very cold conditions. In a smaller degree, the situation of northern rooms is severe, because the cool conditions are maintained during 13.4 % of hours.

In the course of the intermediate seasons, the house presents a very low 1.0 % of discomfort hours on average and all the rooms have analogous performances.

Throughout summer, on contrary, the differences appear to be sizeable in the Eastern and Western sides. While the East side avoids to great extent the warm discomfort with only 5.3 % of hours over the PMV limit, the West side overpassed the limits during a very severe 22.3 % of hours. In smaller level, also the living zones remain warmer than average, with 18.8 % of hours.

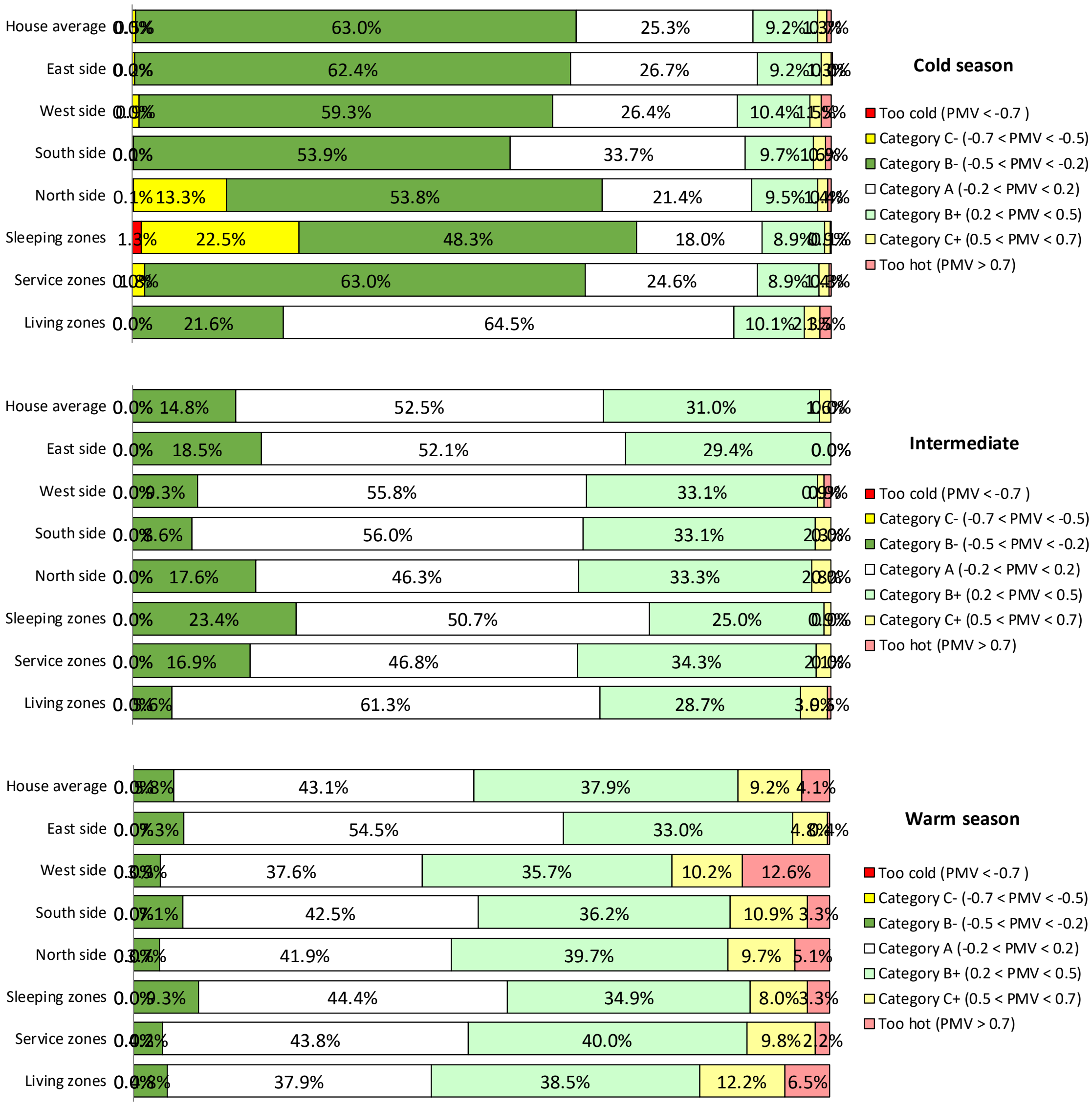


Figure 3.91: Comparison of TC of rooms by each season, orientation and activity, monitored PMV.

Therefore, the rooms with higher cold differences from the average home value are the ones in sleeping zones, followed by the ones with warmer differences, located in living zones and in West orientation. These differences can be observed in the annual T-RH plots of Figure 3.92, Figure 3.93 and Figure 3.94.

In an hourly basis, the sleeping areas indicate that they get cool mostly during the nights. This confirms the influence of closing the doors overnight, which cuts the natural air exchange with the corridor and isolates the rooms from the rest of the home. The West rooms indicate that their peak of warm temperatures is one or two hours later than in the rest of the house, happening more often between 17:00 and 19:00 h. See the following figures.

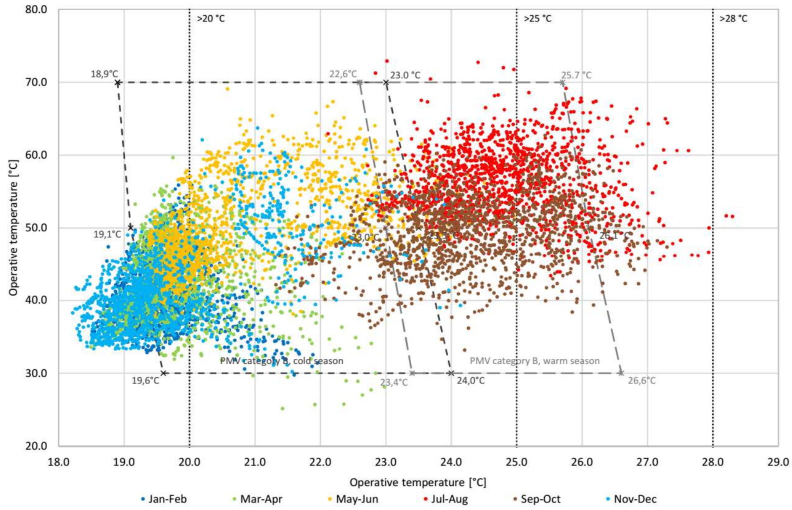


Figure 3.92: Thermal comfort of sleeping zones, T-RH plot of PMV method.

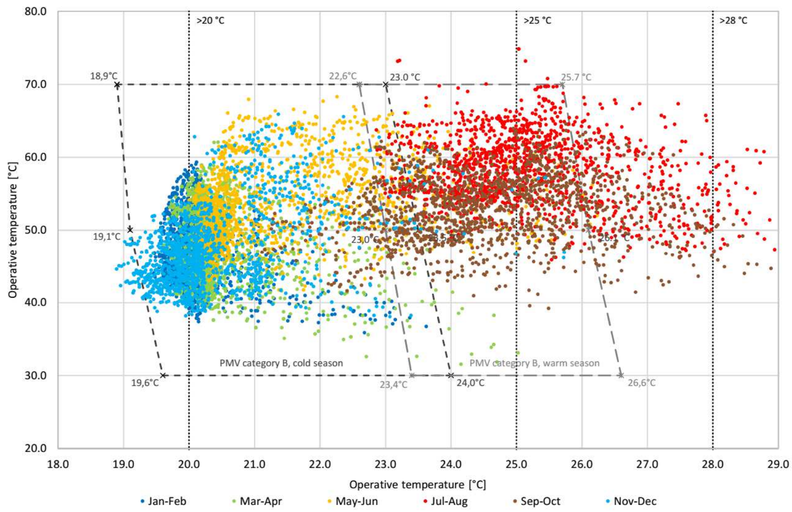


Figure 3.93: Thermal comfort of West rooms, T-RH plot of PMV method.

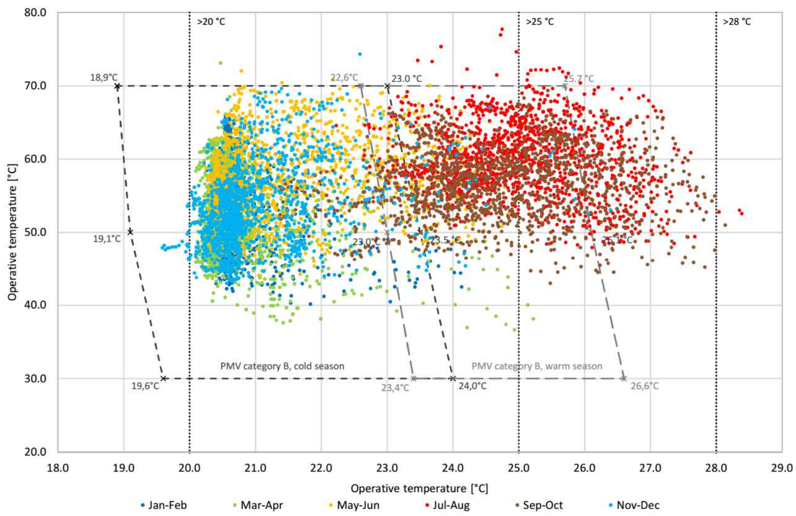


Figure 3.94: Thermal comfort of living zones, T-RH plot of PMV method.

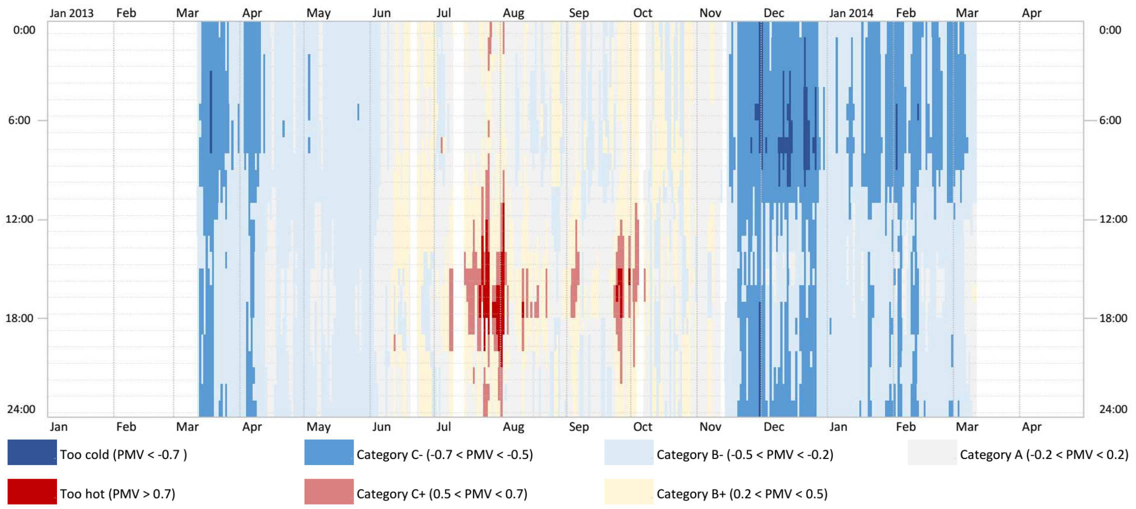


Figure 3.95: Thermal comfort of sleeping zones, hourly diagram of PMV method.

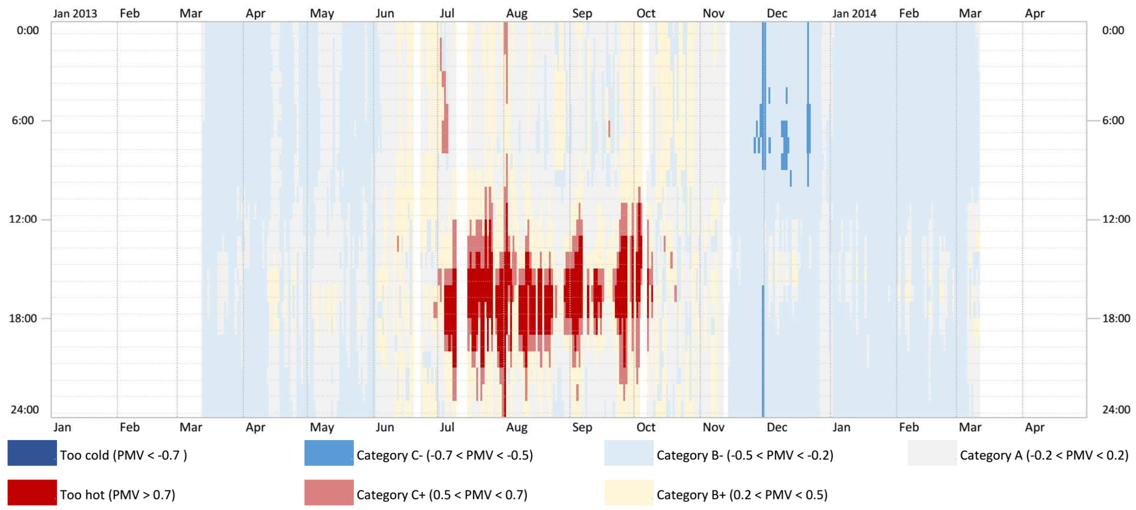


Figure 3.96: Thermal comfort of West rooms, hourly diagram of PMV method.

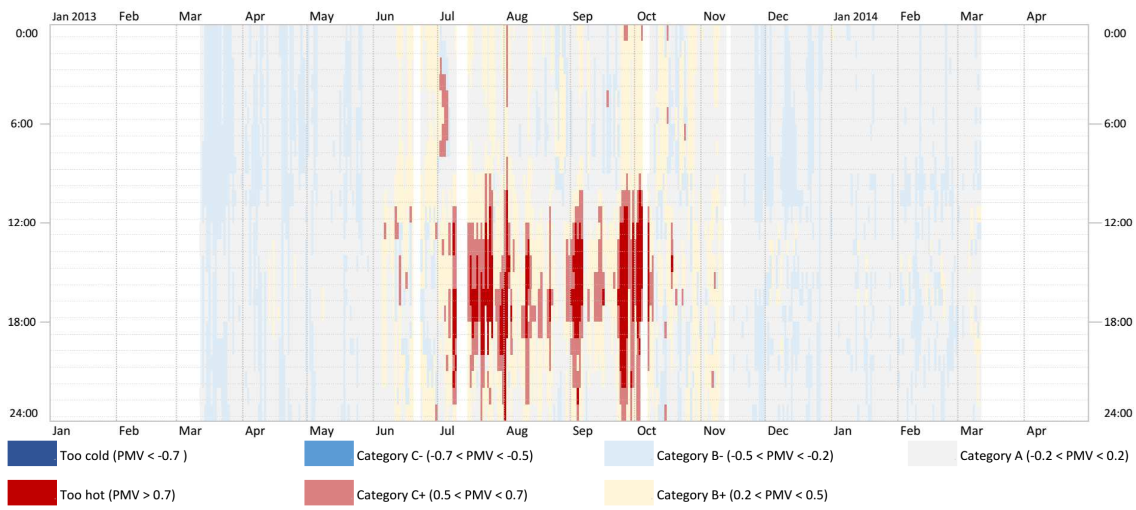


Figure 3.97: Thermal comfort of living zones, hourly diagram of PMV method.

3.4.8.4. Evaluation of the thermal comfort by the adaptive method, EN 15251

The second evaluation of TC follows the adaptive method in the terms defined in EN 15251 (EN-15251, 2007). This method relates the indoor conditions with the adaptation of users to the weather conditions of recent days. It is first calculated considering all the hours of the day. Later, the unoccupied hours are subtracted in order to detect the influence inhabitants and their decisions such as the opening of window or the use of solar shading elements.

In the building level, the main results included in Table 3.18 indicate that the discomfort is very high by cool periods, reaching to 23.9 % of the cold season hours. On contrary, there is almost no discomfort because the warm periods are extremely low according to the adaptive limits.

Table 3.18: Summary of monitored year of thermal comfort in average house, EN 15251 method.

	Monitored year		Cold season		Intermediate		Warm season	
Assessment of full time								
Too cold	3	0.0%	2	0.0%	0	0.0%	1	0.1%
Category III (-)	1596	18.9%	1592	23.9%	0	0.0%	4	0.3%
Category II (-)	3121	36.9%	2875	43.1%	181	41.9%	65	4.8%
Category I	3582	42.4%	2063	30.9%	251	58.1%	1268	94.3%
Category II (+)	145	1.7%	139	2.1%	0	0.0%	6	0.4%
Category III (+)	4	0.0%	4	0.1%	0	0.0%	0	0.0%
Too hot	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total hours EN 15251	8451		6675		432		1344	
Assessment of occupied hours								
Too cold	1	0.0%	1	0.0%	0	0.0%	0	0.0%
Category III (-)	1224	19.5%	1221	24.6%	0	0.0%	3	0.3%
Category II (-)	2376	37.9%	2159	43.4%	156	47.4%	61	6.3%
Category I	2592	41.3%	1514	30.5%	173	52.6%	905	93.3%
Category II (+)	75	1.2%	74	1.5%	0	0.0%	1	0.1%
Category III (+)	2	0.0%	2	0.0%	0	0.0%	0	0.0%
Too hot	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total occupied hours EN 15251	6270		4971		329		970	

The representation of the operative temperatures in combination with the running mean outside temperatures (TRM) shows the relationship between both environments, see Figure 3.98 and Figure 3.99. In winter the lower temperatures exceed the cold limits as mentioned before. Indeed, the temperature decay in the coldest days shows a global cooling process of the home when the outside cold periods are long (TRM < 8 °C). In the warm season, the thermal response of the house meets the comfort temperatures of the EN 15251 almost all the time.

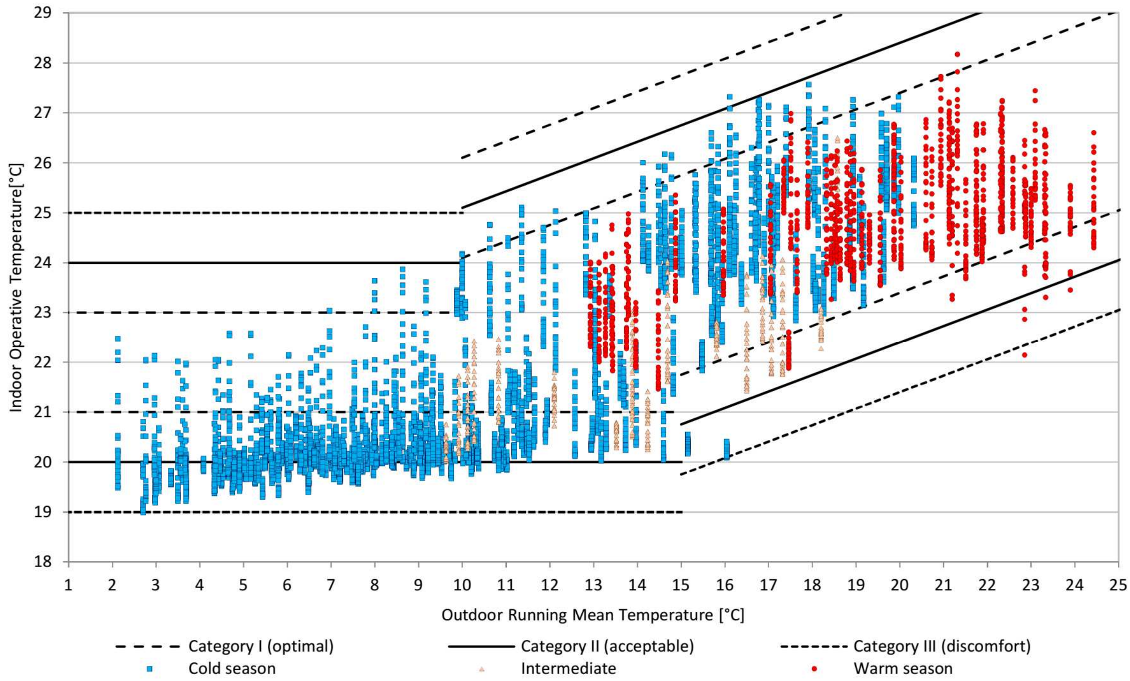


Figure 3.98: TC of average house and outside temperatures, adaptive method EN 15251.

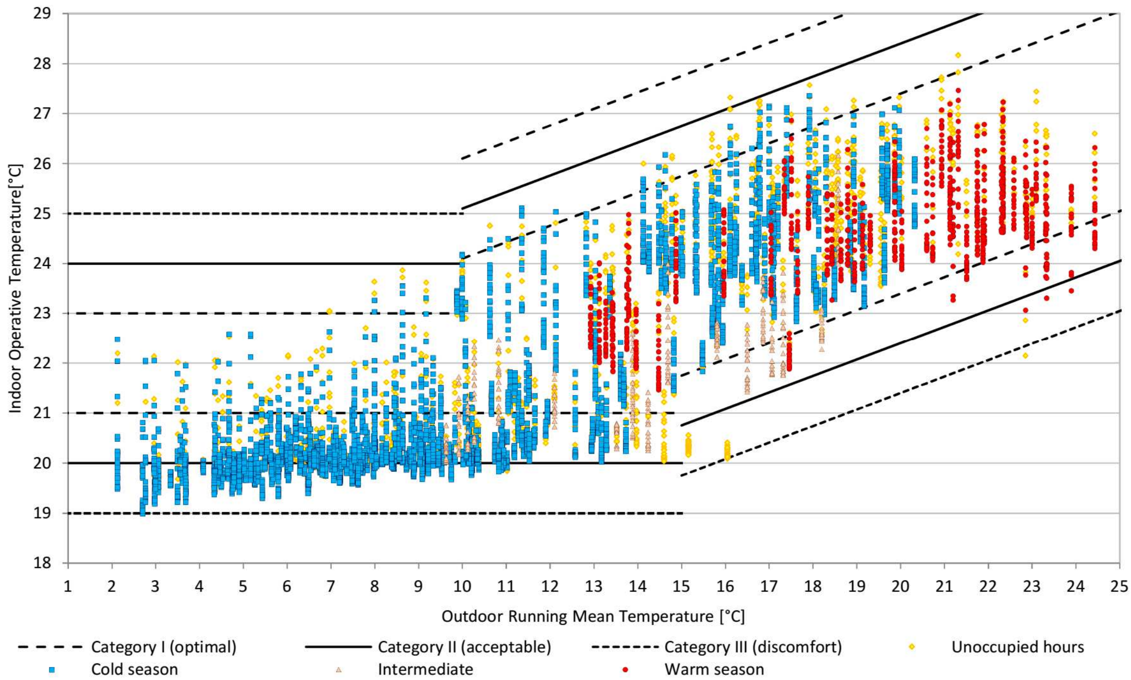


Figure 3.99: TC of average house and outside temperatures subtracting the unoccupied hours, adaptive method EN 15251.

Taking into consideration the occupancy of the home, some observations do help understanding the measured TC. For instance, some of the cool exceedance detected in the warmer days of the cool season is not a real discomfort because the house was empty for several days of holidays. Besides, the indoor peak temperatures correspond to the hours when the inhabitants are out from home and for this reason in the majority of the cases there is not any solar shading measures from the inside. In any case, the occupancy doesn't change the general assessment, which vary very slightly in the average home level from the full-time or occupied hours only, as seen in Table 3.18.

The hourly diagram in Figure 3.100 confirms the previous observations. In winter, the night-time hours are significantly cold during long periods of the cold season and the solar radiation compensates these low temperatures even in mid-day hours of December. In summer, the majority of the hours from June to November are acceptable and slightly warm, category II (+). The warmest hours happen in the late summer, around September and even in October. This way, the weighted average house has no periods out of the acceptable warm range.

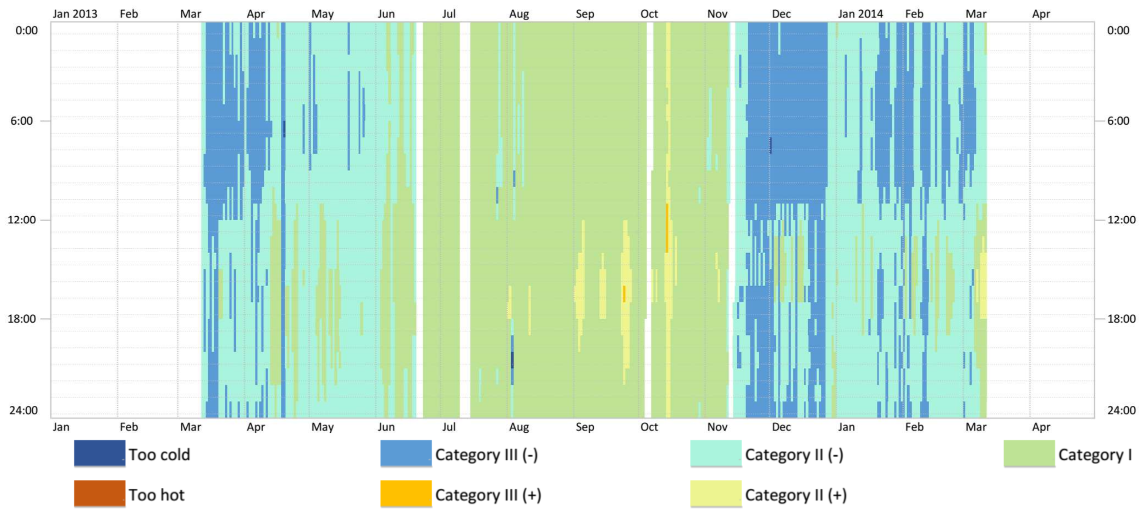


Figure 3.100: TC of average house, hourly diagram of EN 15251.

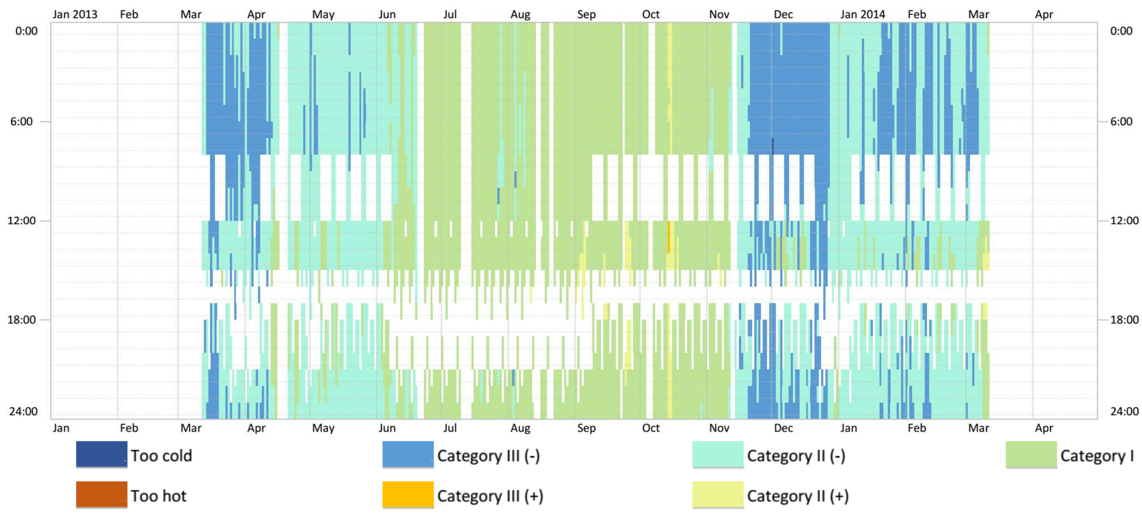


Figure 3.101: TC of average house subtracting the unoccupied hours, hourly diagram of EN 15251.

Additionally, the intermediate periods evidence an asymmetric duration. The transition between the category III (-) of cold season to the category II (+) of warm season is very different: the transition from cold to warm comfort lasts three months (April to June), the transition from warm to cold comfort happens much faster, lasting barely ten days (in November).

Considering the zones and sides of the building separately, some differences are also noticeable, as shown in Figure 3.102. First, the sleeping zones present the majority of the cold hours and the cold discomfort is extremely high, namely the 44.3 % of year hours. Besides, the northern rooms also present extremely high values around 40.7 % of the annual hours, followed by the East side with 28.3 % and the service rooms with 27.3 % of hours with cold discomfort annually. It is also remarkable that living areas have almost no hours of cold discomfort, only the 0.9 %.

Regarding the warm discomfort, the impact is very low or inexistent in general. Only the western side, the living zones and the Southern side manifest a 0.9 %, 0.8 % and 0.1 % respectively.

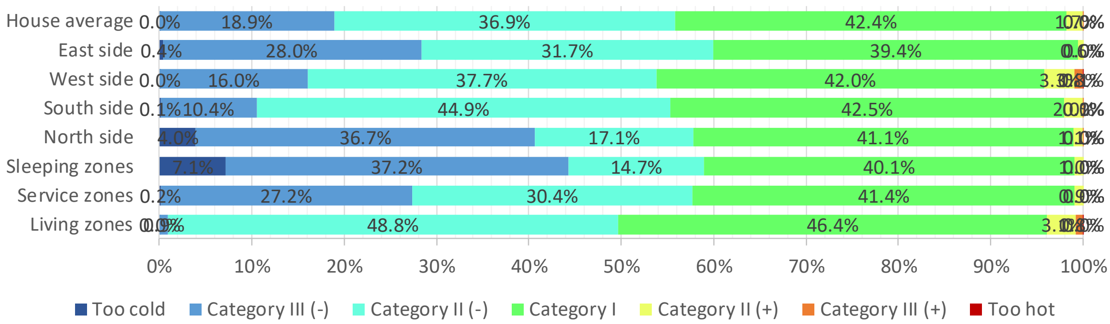


Figure 3.102: Comparison of TC of rooms by orientation and activity, monitored year of EN 15251 method.

In a more detailed analysis of the rooms per season the differences are clearer and higher in the aforementioned aspects, see Figure 3.103. The cold discomfort is mainly located in the cold season. The sleeping zones achieve an extremely high 55.4 % of the season hours, followed by the northern rooms with 51.0 %, the eastern rooms with 34.7 % and the service rooms with 34.1 % of the cold season. On contrary, living areas present only a very low 1.0 %. Overall, the average cold discomfort during the cold season reaches a very severe 23.9 % of hours.

Regarding the warm discomfort, it is nearly inexistent in average house, showing only a subtle 0.1 % of the cold season. There are only very low values in the western side with 1.1 % of the warm season and 1.0 % of the cold season, in the living room with 1.0 % of the cold season and in the southern side with 0.1 % of the cold season.

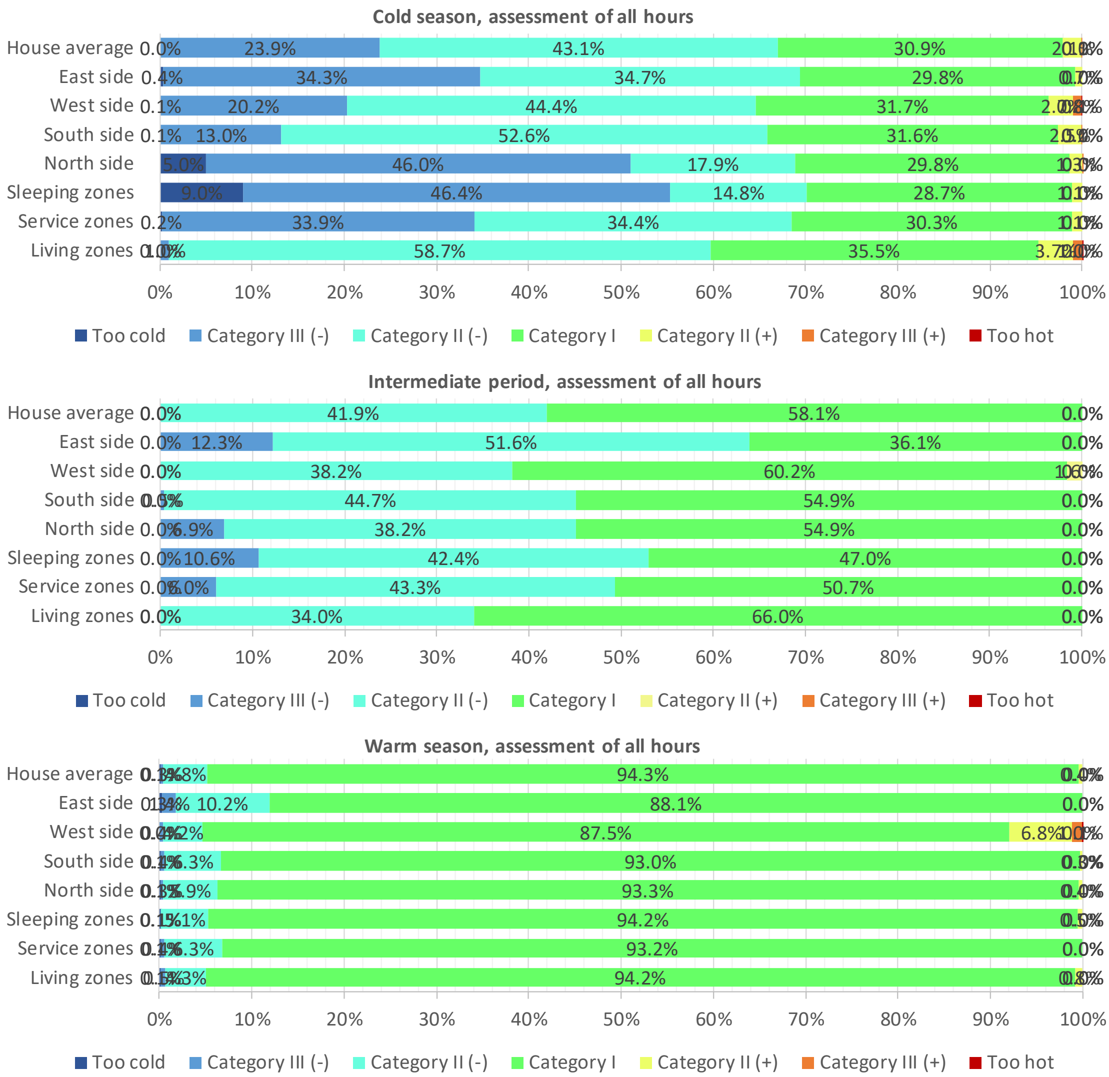


Figure 3.103: Comparison of TC of rooms in different seasons, orientation and activity, monitored results by EN 15251 method.

Ahead, the most relevant types of rooms identified in previous analysis are plotted individually. The sleeping rooms to see the winter coldest situations are presented in Figure 3.104, Figure 3.107 and Figure 3.110. The west side to see the warmest temperatures indoor are shown in Figure 3.105, Figure 3.108 and Figure 3.111. Finally, the living rooms to understand the rooms with the better comfort during the whole year are included in Figure 3.106, Figure 3.109 and Figure 3.112.

The most severe exceedance happens in the cold season, when sleeping zones are too cold (out of range) during 9.0 % of the hours and they stay below 19.0°C. The west rooms also present some occasional exceedances of the EN 152512 range, with 10 hours in 6 days out of range, a 0.1 % of the time.

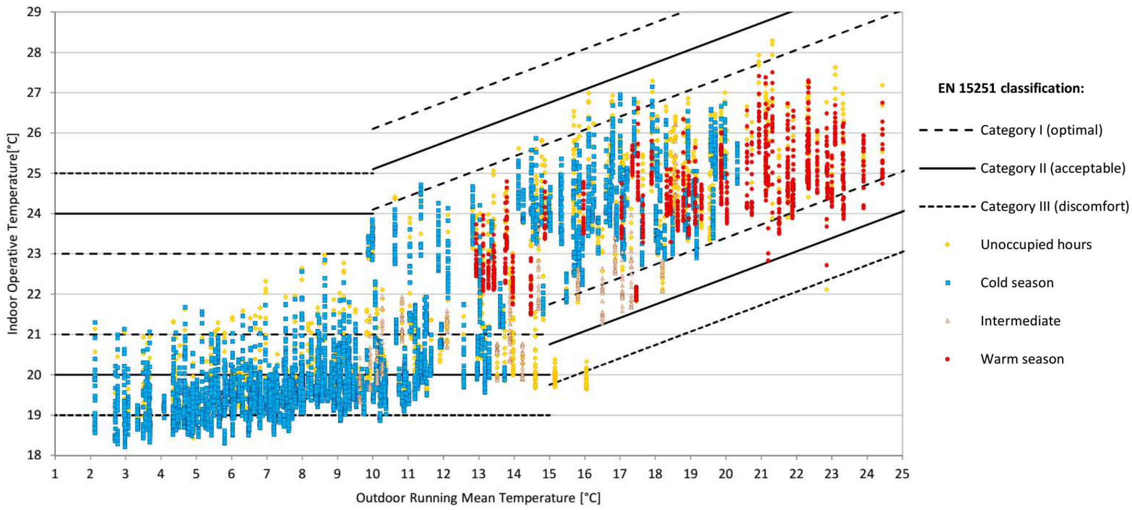


Figure 3.104: TC of sleeping zones and outside temperatures, adaptive method EN 15251.

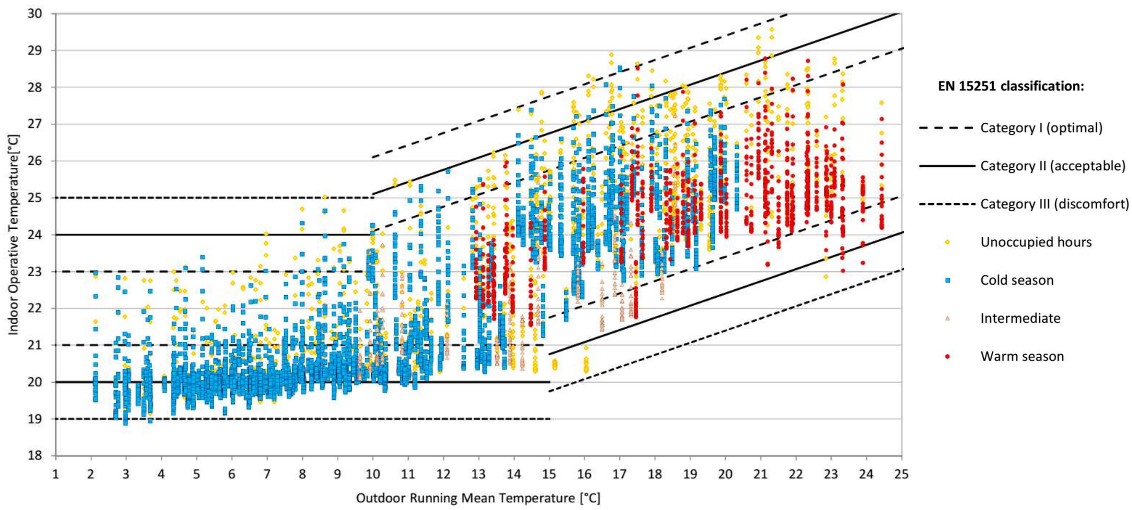


Figure 3.105: TC of West rooms and outside temperatures, adaptive method EN 15251.

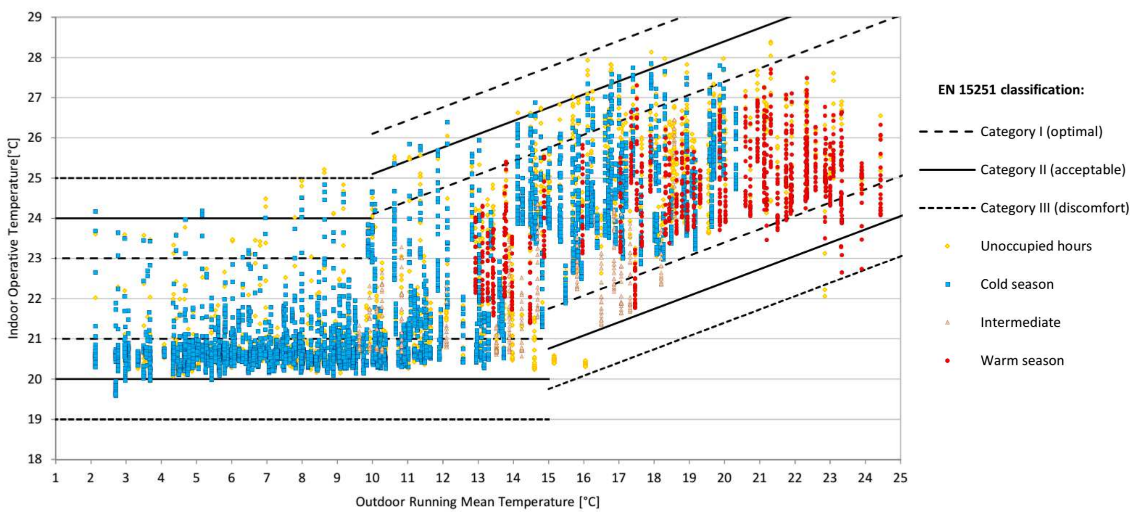


Figure 3.106: TC of living zones and outside temperatures, adaptive method EN 15251.

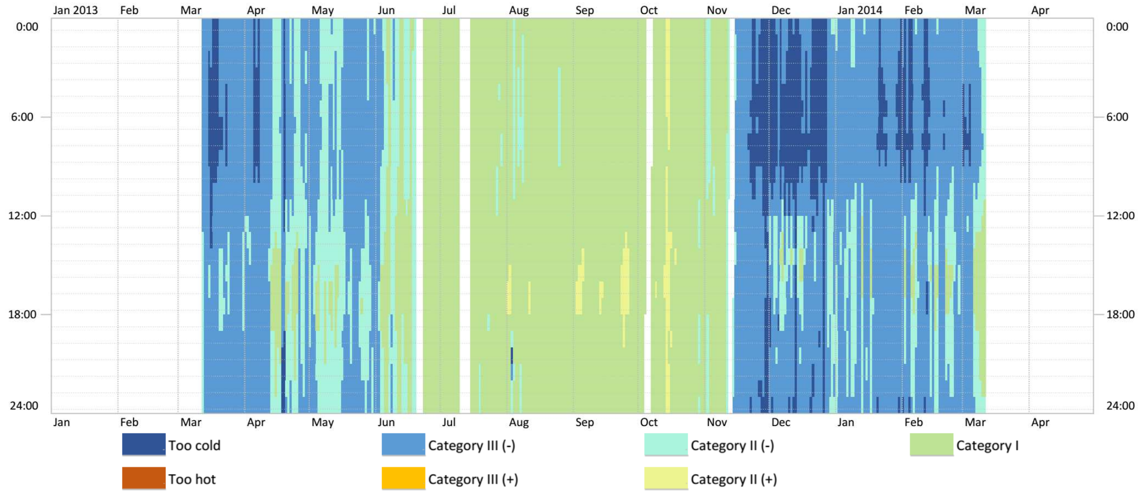


Figure 3.107: TC of sleeping zones, hourly diagram of EN 15251.

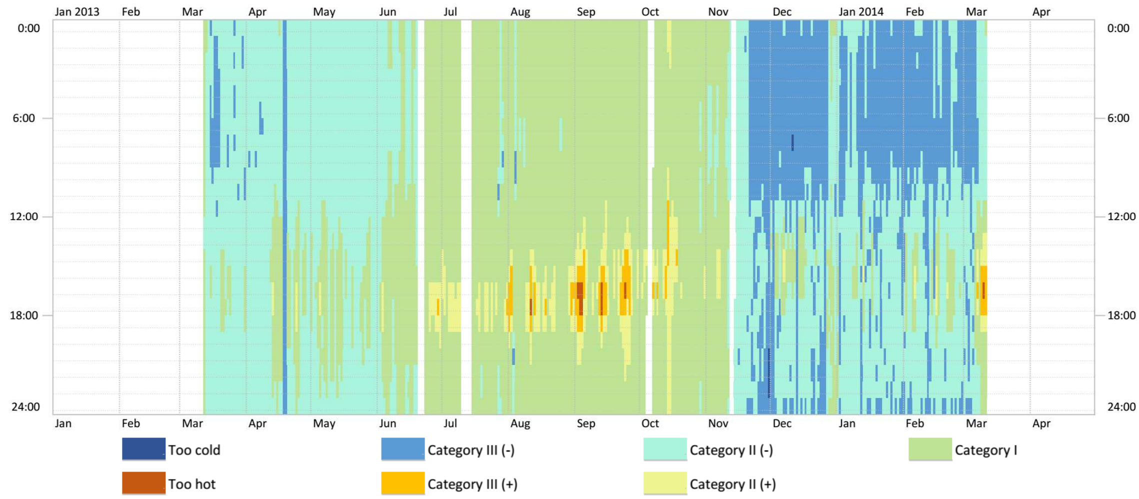


Figure 3.108: TC of West rooms, hourly diagram of EN 15251.

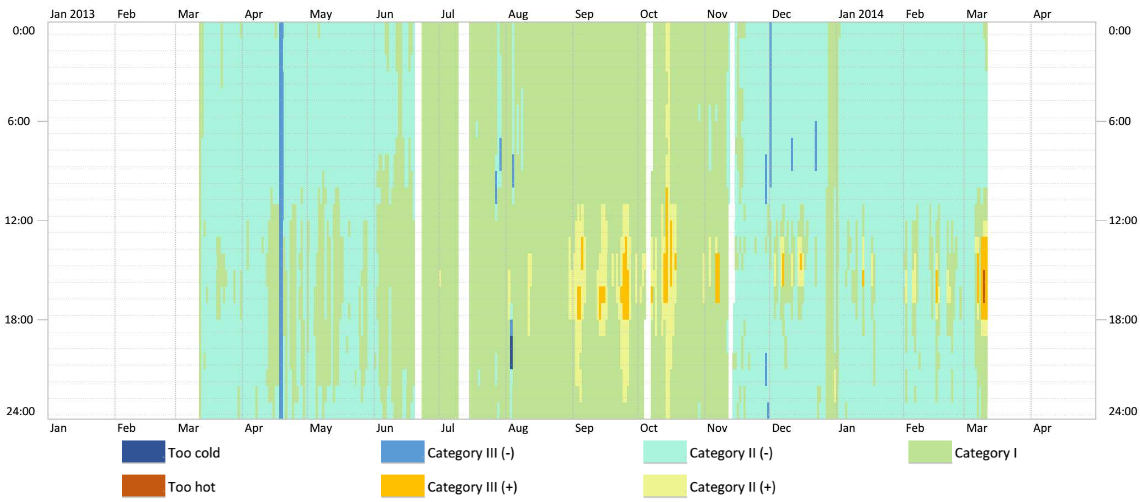


Figure 3.109: TC of living zones, hourly diagram of EN 15251.

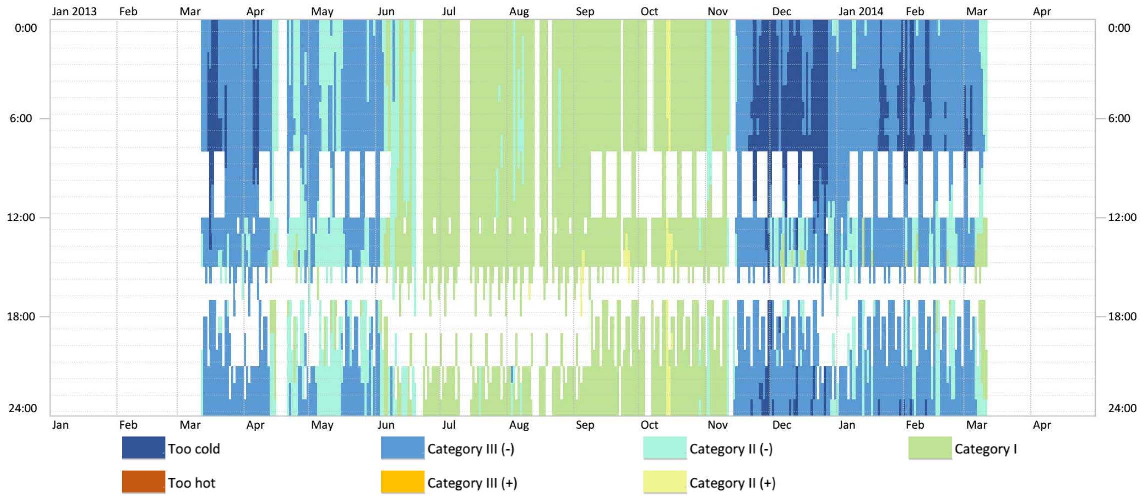


Figure 3.110: TC of sleeping zones subtracting the unoccupied hours, hourly diagram of EN 15251.

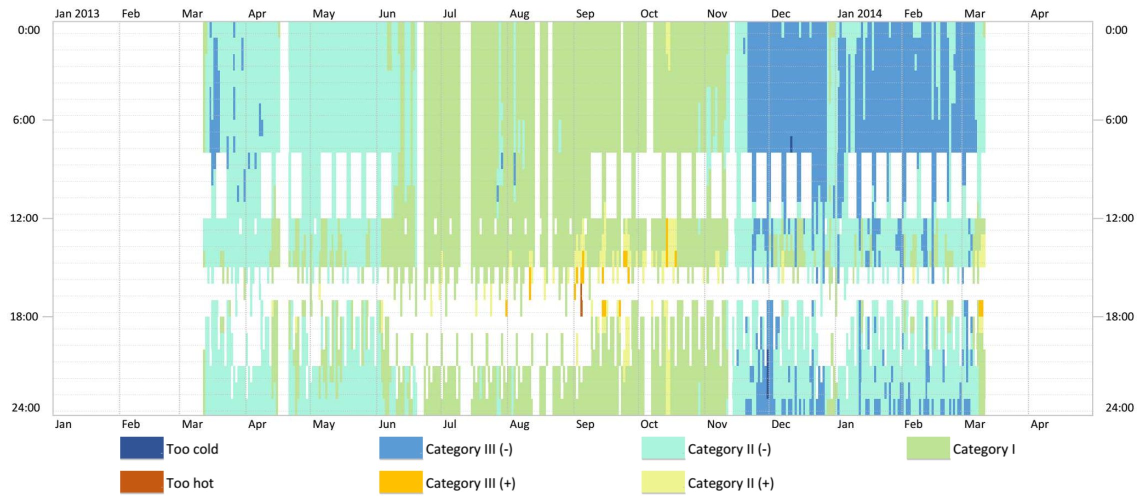


Figure 3.111: TC of West rooms subtracting the unoccupied hours, hourly diagram of EN 15251.

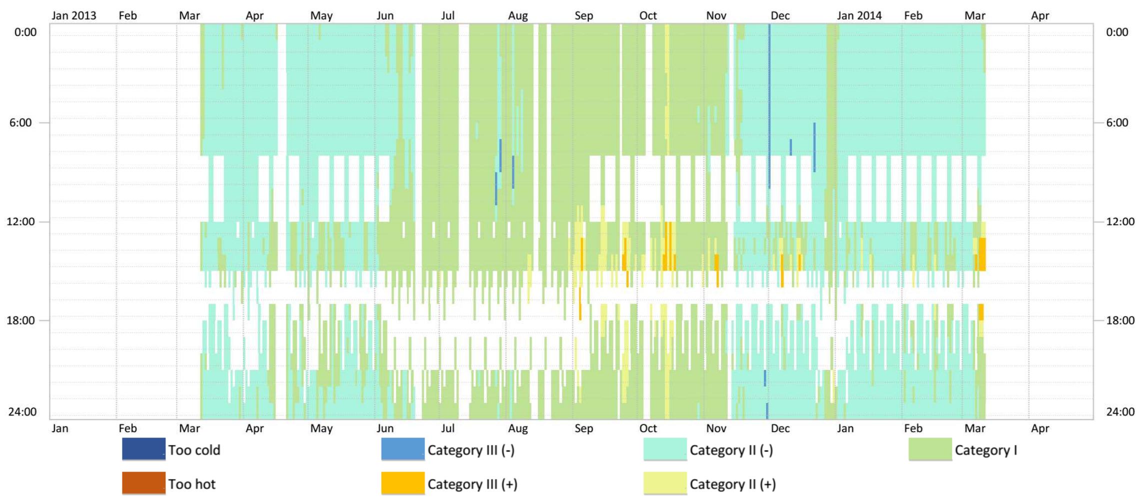


Figure 3.112: TC of living zones subtracting the unoccupied hours, hourly diagram of EN 15251.

3.4.8.5. Evaluation of overheating

The main assessment follows the CIBSE TM52 methodology, as explained in the proposal defined in Chapter 2. This method is based on the limits of EN 15251, but with particularity that it calculates the exceedance and rounds the difference to the nearest whole degree. What means that every exceedance below 0.5 °C is not considered for this overheating assessment method. In brief, the criteria are the following:

- The first criterion stablishes in 3 % the maximum number of hours of the season exceeding the warm limits.
- The second criterion controls the severity, using a formula to weight the daily exceedance, which must be equal or below 6 K.
- The third criterion set the maximum exceedance of any day below 4°C.

In the studied case, there are 4 hours over the warm limit (category III of EN 15251). Firstly, three of these hours happened in November, with the application of the fixed limits based on PMV (not related with the RMT formulas). Secondly, the exceedance of the remaining hour is only 0.2 K and as explained before it is rounded off to zero degrees. So, in this case the hours of exceedance can’t be included for the criteria of the OH. Therefore, the three criteria are successfully passed and there is no overheating in the monitored year of the case study.

Table 3.19: Monitored hours over the acceptable temperatures.

Date	Operative temperature (°C)	Running mean temperature (°C)	Maximum acceptable temperature (°C)	ΔT (°C)	Duration of overheating (h)
24/09/2013	27.3	16.1	27.1	0.2	1

3.4.9. Thermal bridging

The analysis of the thermal bridges is done in two levels: firstly, through the monitoring of the inner temperatures of certain corners and structural elements during the whole period and secondly, with a survey with an infrared thermography camera. In this section, the first level is analysed.

This way, the majority of corners and columns were controlled by measuring their inner surface temperatures. During the monitoring the construction solutions for the TB performed very well and the measured values matched with the expected values of the calculations of the 2D linear thermal transmittance. Figure 3.113 show the temperatures of the columns in Southern façade from 15/03/2013 to 21/03/2013. All the surface temperatures present stable trends and maintain the temperatures over 18.5 °C. This value indicates that the difference with indoor air temperatures is around 1.0 °C. The coldest point in the plot represents the column in the Southeast corner (in green) and its deviations are also lower than 1 °C in comparison with the bedroom's air temperature (dashed in green). The other cold point is the corner column located in the Southwest of the living room. It presents slightly higher values and their difference with the indoor air can reach up to 2.5 °C during the operation of the electric heaters in that room. The warmest lines represent internal corners such as the one in the living room (in brown).

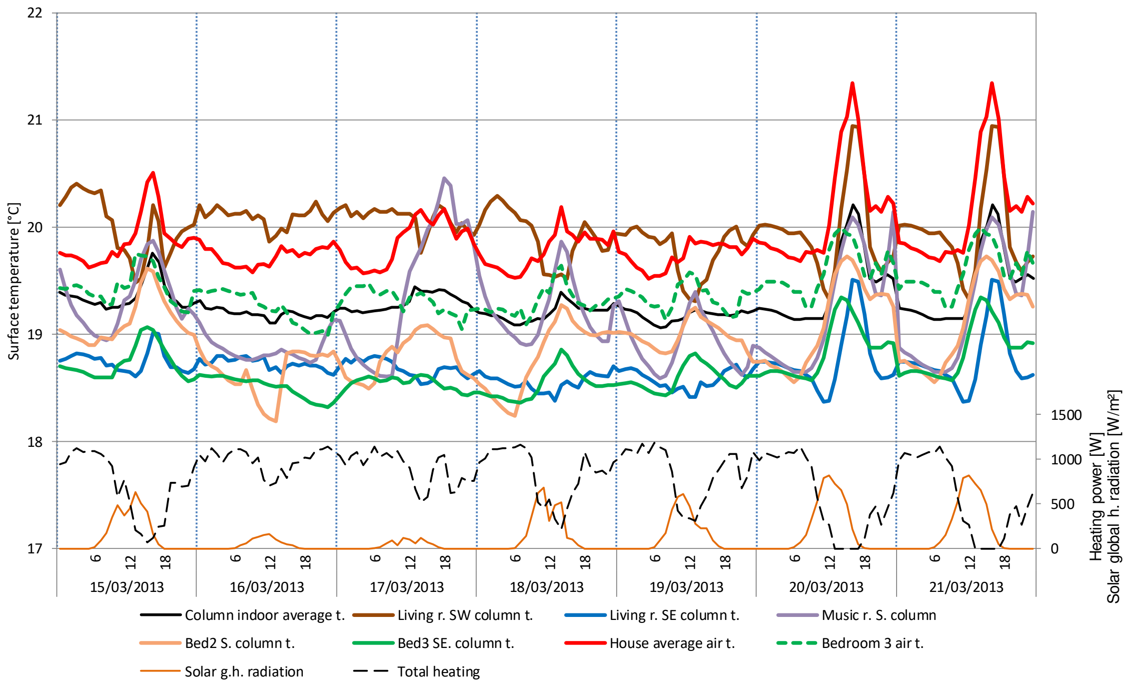


Figure 3.113: Columns in South façade, internal surface temperatures from 15/03/2013 to 21/03/2013.

The other columns are also monitored in Figure 3.114 and Figure 3.115. The first one shows the Northern columns and present an uncertain value in the laundry room (or service room, in grey). This curve is compared with the air temperature of the room and again the relationship is below 1°C. This case is particular because it is also affected by the operation of the systems in the room occasionally.

The central columns of Figure 3.115 present higher temperatures, almost the same than indoor air temperatures. The central columns of the living room are especially warm due to the warmer temperatures in that room.

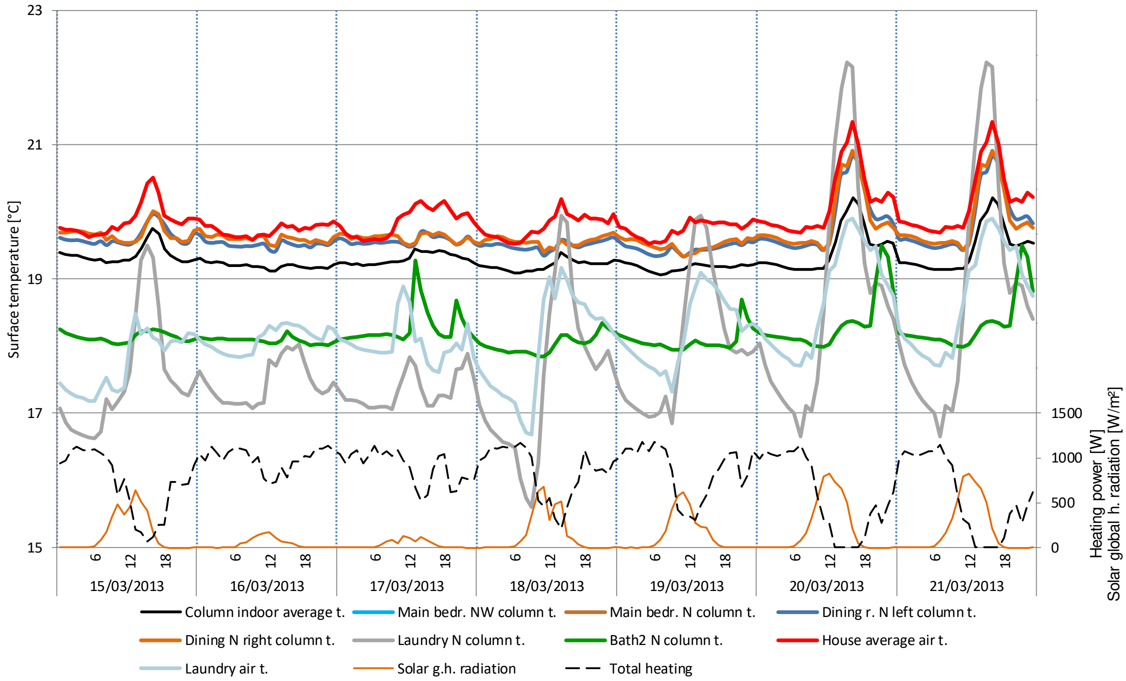


Figure 3.114: Columns in North façade, internal surface temperatures from 15/03/2013 to 21/03/2013.

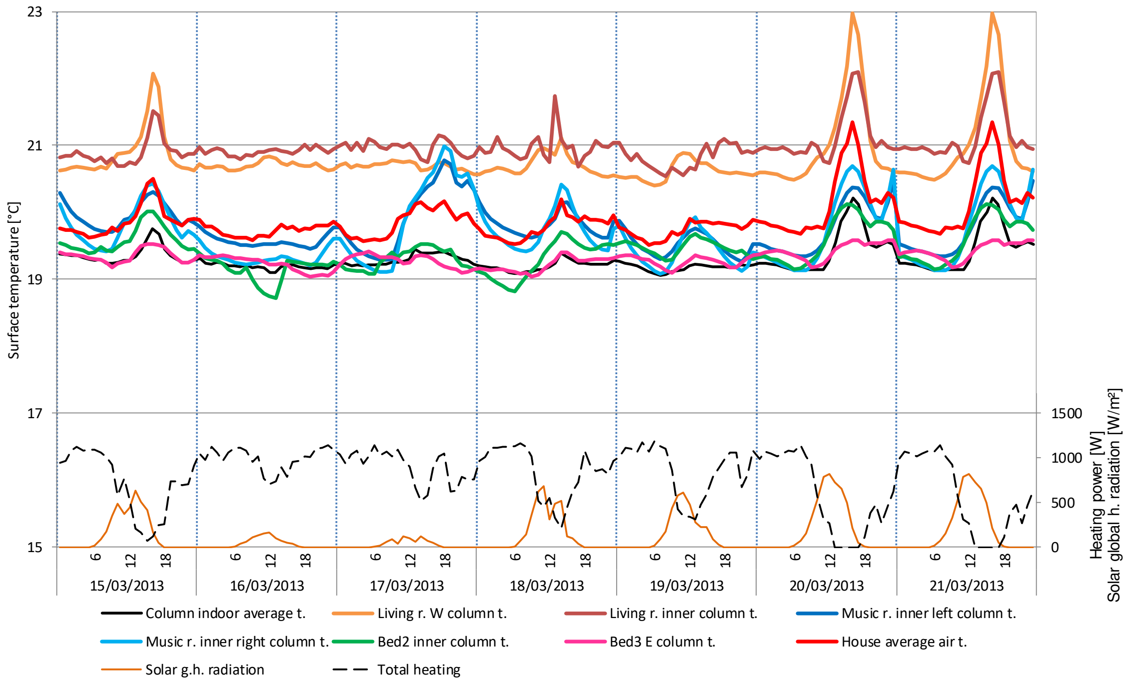


Figure 3.115: Columns in centre of the building, surface temperatures from 15/03/2013 to 21/03/2013.

3.4.10. Thermographic survey

This survey aims to detect any possible irregularities in the thermal envelope and analyse their impact on the passive design of the building. The infrared analysis was done following the EN 13187:1998 and its simplified methodology for buildings.

The survey was conducted in different days, starting from an inside review of the thermal envelope and continuing another day from the outside. Firstly, the indoor surfaces were tested to analyse in detail the internal irregularities and their possible effects, in 13/03/2013. Secondly, the preliminary findings were contrasted during an outdoor survey, in 19/03/2013. The details of the equipment and the conditions during the capture of images are defined in Table 3.20 and Table 3.21.

Table 3.20: Description of the instruments and accessories used in the infrared thermography survey

Infrared thermography cameras			**Other equipment**	
IR camera model	FLIR E60	FLIR ThermaCam P60	Emissivity contrast tape	0.93 (93.0%)
Serial number	490009506	21801711	Reflected temperature measurement	Low emissivity aluminium surface
Resolution	320x240	320x240	Outdoor conditions measurement	Temperature and RH, TESTO 175-H1.
Thermal sensitivity	< 0.05 °C at 30 °C	< 0.05 °C at 30 °C	Post-processing software	FLIR Tools+ 5.4
Temperature range	From -20 °C to +650 °C	From -20 °C to +650 °C		
Tripod (adapter)	T198486	-		

Table 3.21: Description of the instruments and accessories used in the infrared thermography survey

Indoor survey		**Outdoor survey**	
Date and hour	13/03/2013 11:00 – 13:30	Date and hour	19/03/2013 7:00 – 8:00
Outdoor air temp. (°C)	0.5	Air temperature (°C)	0.0
Dining room air temp. (°C)	20.5	RH (%)	95.0
Bedroom 3: air temp. (°C)	19.5	Wind speed	Soft breeze
Dressing room air temp. (°C)	20.2	Reflected temp. (°C)	From -5.0 to -15.0
Living room air temp. (°C)	20.8		
Kitchen air temp. (°C)	20.2		
Indoor RH (%)	38.0 – 47.0 %		

Figure 3.116 shows one of the most exposed points of the thermal envelope, in the southwest corner of the living room. It confirms the monitored values and indicates that the fall is below 2

°C, in this case the corner is 19.2 °C while the indoor is 20.8 °C. The rest of the wall and ceiling present homogeneous temperatures to a great extent.

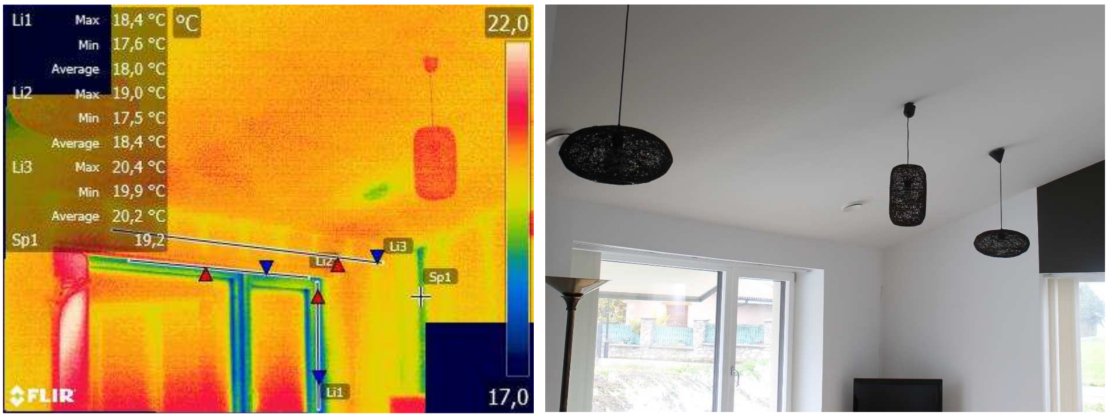


Figure 3.116: Living room temperatures, South-East corner, ceiling and window,
indoor IR image 13/03/2013.

Figure 3.117 analyses the impact of the heavy construction solution and shows the effect of the metal studs in the wall. The general performance is correct and there are no big cool areas. However, the minimum temperatures in the metal studs indicate that they are transferring a certain amount of heat to the structural slabs up and down. The differences are not very high but the head and the base are around 18.5 °C in an environment of 20.5 °C. These values are occasionally lower, showing the minimum in the lower corner: 17.5 °C.

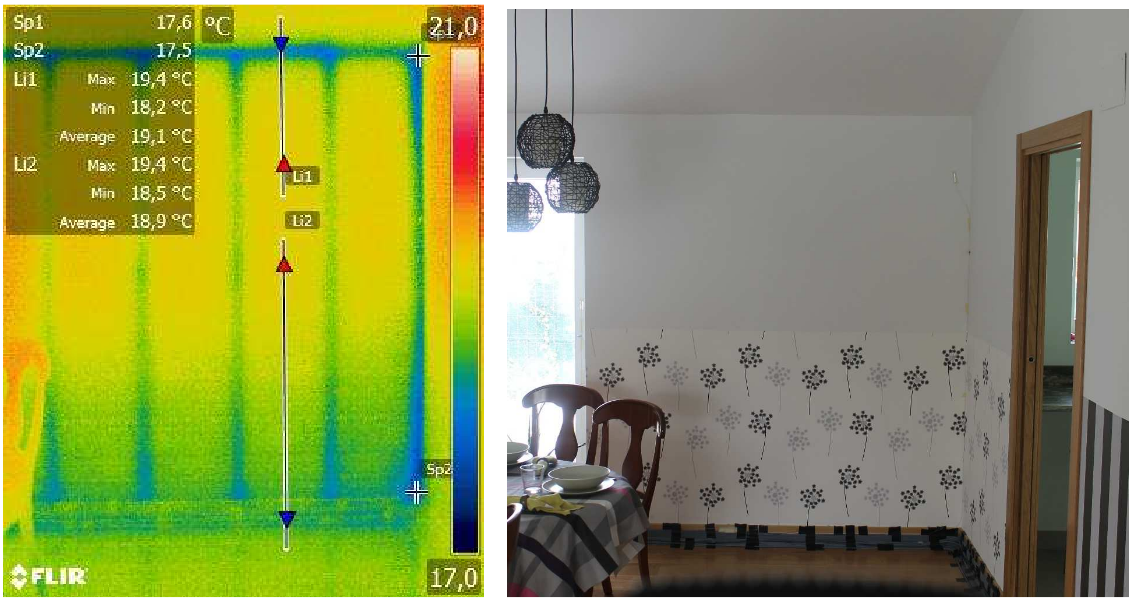


Figure 3.117: Dining room North wall, indoor IR image 13/03/2013.

Figure 3.118 and Figure 3.119 analyse the performance of windows, as one of the most critical points of the thermal envelope. In both rooms the measured temperatures in the windows comply with the expectations of a PH certified element, providing values over 17.0 °C in environments over 20 °C.

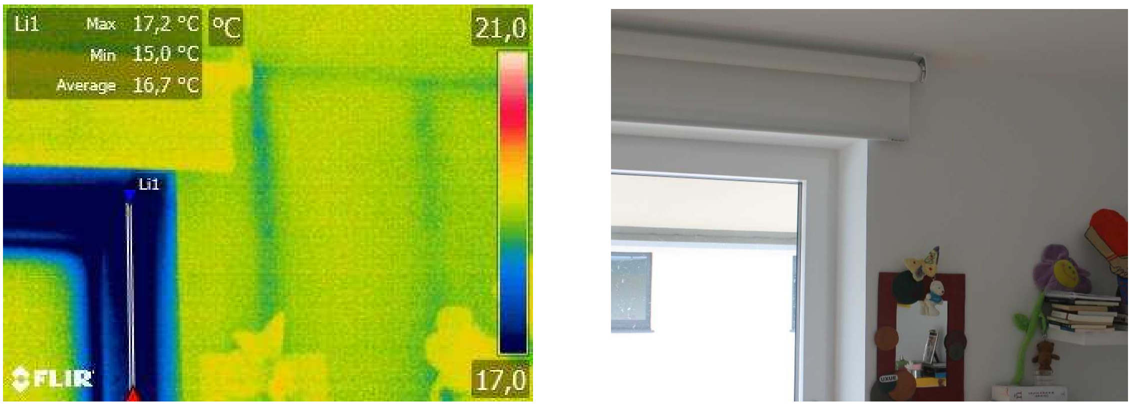


Figure 3.118: Window frame in bedroom 3, indoor IR image 13/03/2013.

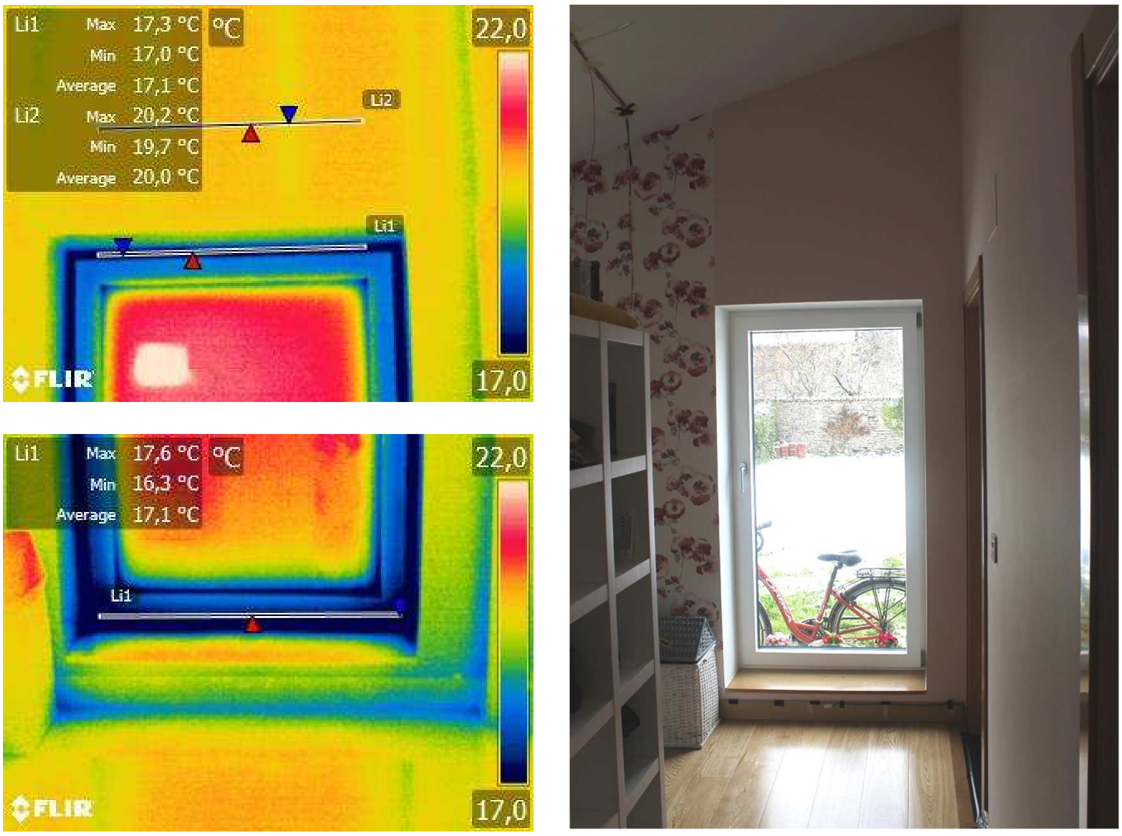


Figure 3.119: Window frame in dressing room, indoor IR image 13/03/2013.

Figure 3.120 permits to visualize the air stratification in the kitchen, confirming the monitored values which indicated an increase of around 2 or 3 °C in comparison with the air temperature at 90 cm height.

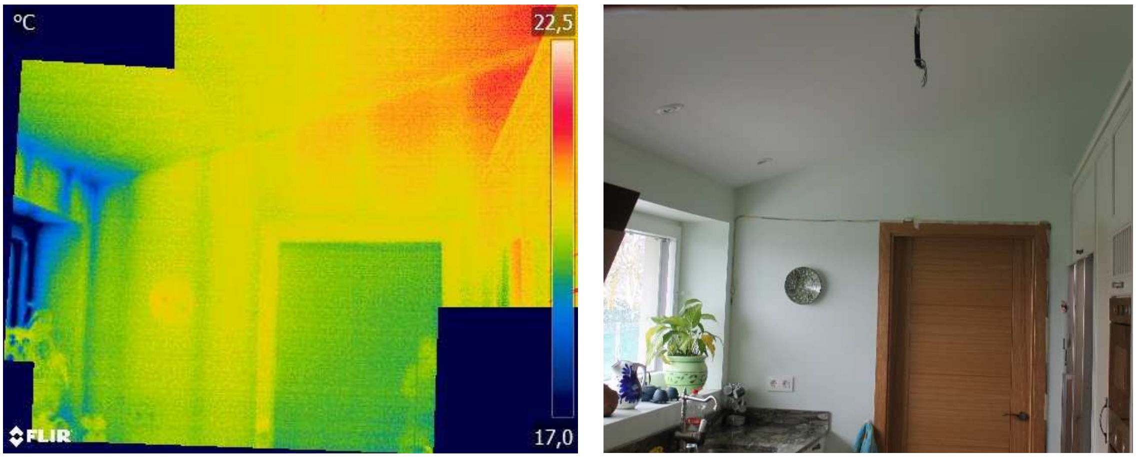


Figure 3.120: Air stratification in the kitchen wall and ceiling, indoor IR image 13/03/2013.

The outside survey shows homogeneous temperatures in the four facades of the building, as shown in Figure 3.121. Some deviations are observed in areas below overhangs, these are probably related with geometric phenomena such as lower thermal convention factors and less heat exchange by radiation with the sky due to the smaller angle of vision.

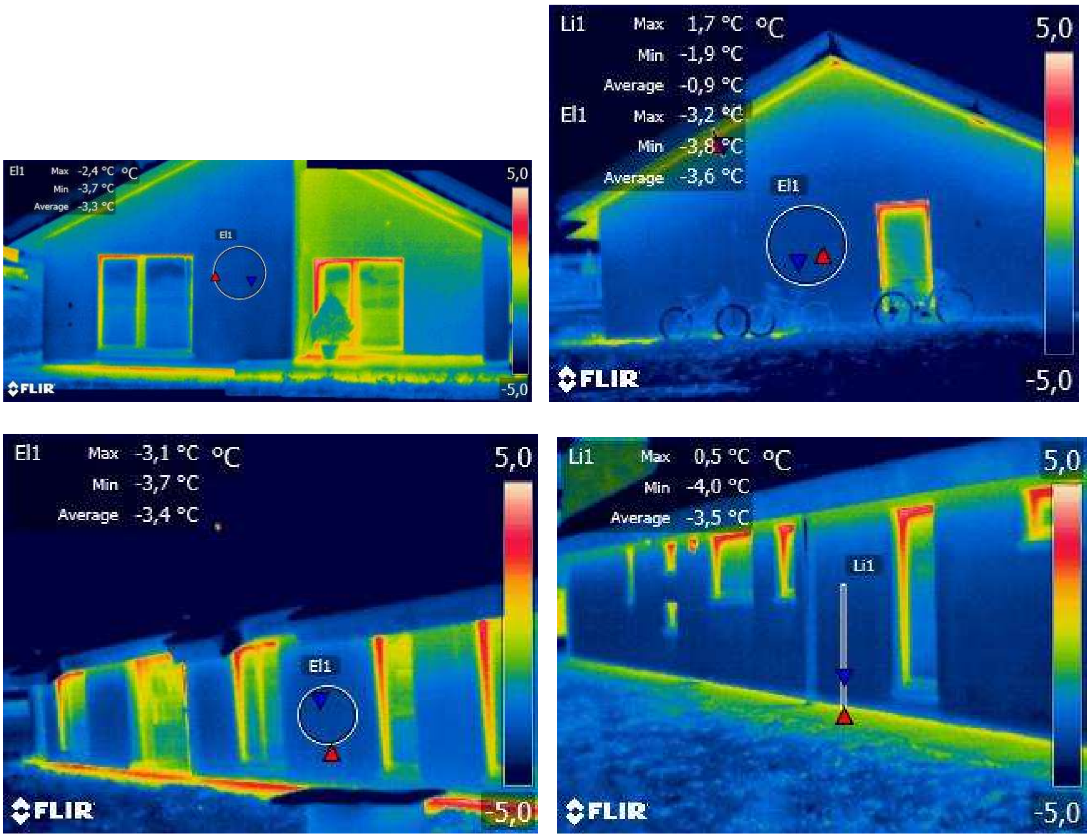


Figure 3.121: Comparison of façade temperatures by orientation:
West, East, North and South (clockwise), outdoor IR image 19/03/2013.

Analysing in more detail the thermal bridges, Figure 3.122 shows how the roof extensions present reduced variations of around 3 °C. This value corresponds approximately to the projected thermal bridge design. Regarding to the ground slab thermal bridge, Figure 3.123 evidences a considerable increase of around 6.5 °C. This value exceeds the projected solution which was approximately 3 °C.

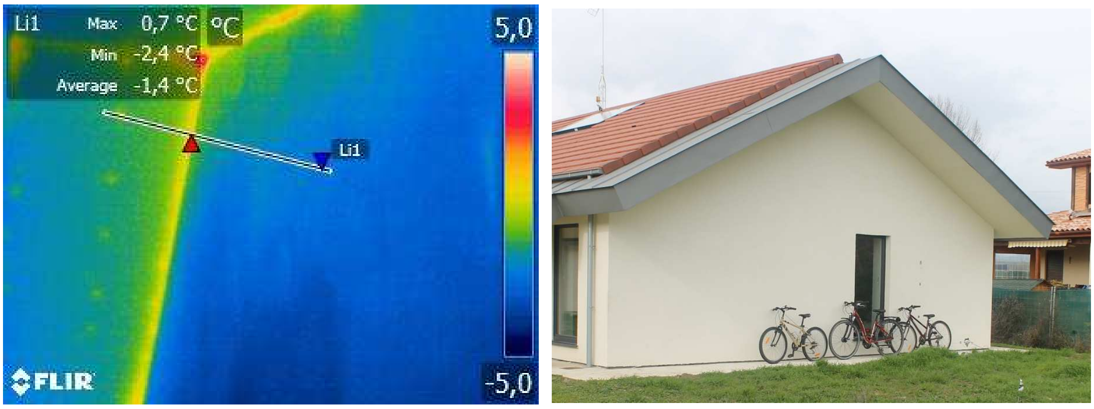


Figure 3.122: Roof overhang thermal bridge temperatures, outdoor IR image 19/03/2013.

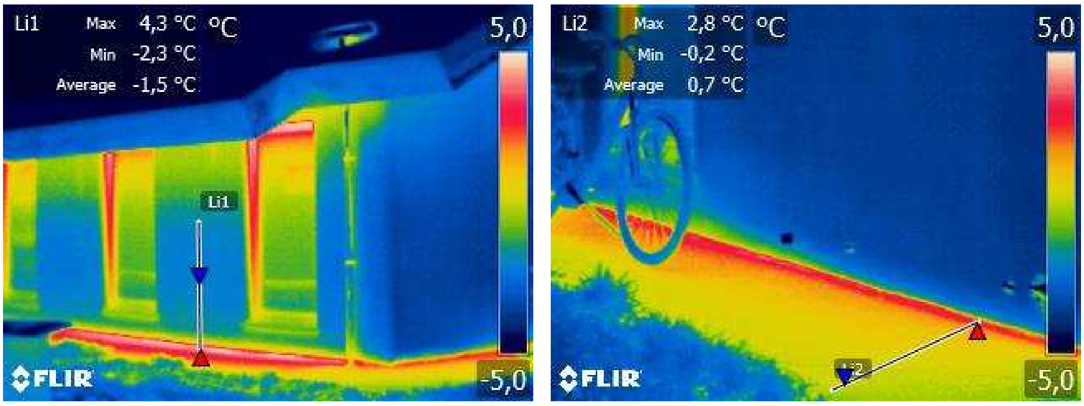


Figure 3.123: Ground slab thermal bridge and sidewalk temperatures, outdoor IR image 19/03/2013.

In general, the survey confirms a general homogeneity of the internal and external temperatures and detects some local issues related with thermal bridges and the heavyweight construction. This is patent from the inside in the observed heat exchange between the metal stud walls and the roof and ground slabs. From the outside, there is a main irregularity around all the ground contact, what means that probably the thermal bridge in this point is higher than the projected value.

In any case, the performance of the passive design is widely successful. Every comparison with nearby dwellings shows a huge difference, as demonstrated in Figure 3.124.

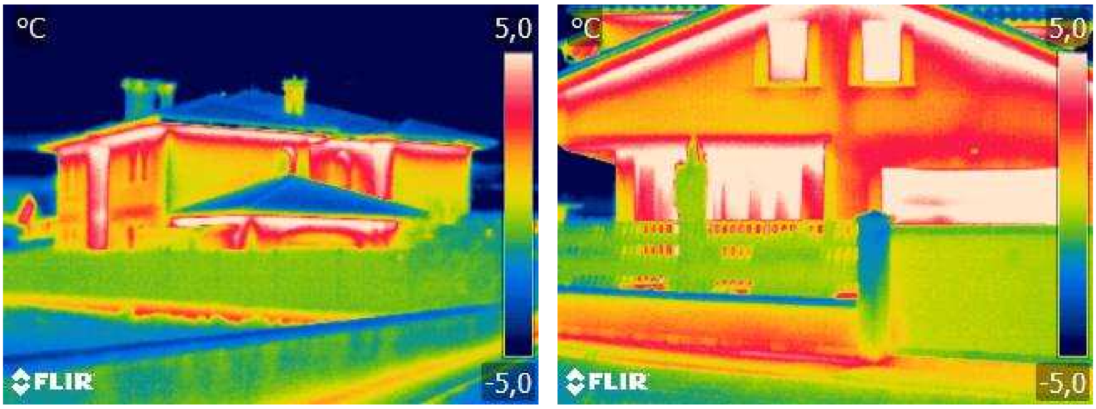


Figure 3.124: External temperatures of other nearby dwellings, outdoor IR image 19/03/2013.

3.4.11. Comparison with PHPP design targets

The measured heating demand is 17.6 kWh/m²y after a correction with HDD. Besides, the day with the maximum heading demand reached up to 29.33 kWh, i.e. 6.94 W/m² hourly during the coldest day registered during the 14 monitored months. The annual electricity consumption of the case study during the considered 12 months was 3383.5 kWh. Table 3.22 compares the deviations of the monitored values from the PHPP calculations and the general requirements of PHI. The electricity use includes the standard housing applications and also the auxiliary uses of the HP, storage and circulation of DHW.

Table 3.22: Comparison between monitored heating needs and PHPP calculations

	PHPP calculation	**PHI limit**	**Monitored value**	**Difference with PHPP calculations**	**Difference with PH limit**
Heating demand, annually (kWh/m²)	13.8	15.0	17.6	3.8 (+ 27.5 %)	2.6 (+ 17.3 %)
Heating load, maximum daily (W/m²)	9.0	10.0	6.9	- 2.1 (- 23.3 %)	- 3.1 (- 31.0 %)
Overheating hours, indoor > 25.0 °C (%)	0	876 (10 %)	1058 (12.5 %)	1058	182 (+ 2.5 %)
Electricity use, direct+ aux. (kWh)	3134.0 (2697.0 + 437.0)	-	3383.5	169.5 (+ 5.4 %)	-
Ventilation need, fresh air flow (m³/h)	169.0	-	182.3	13.3 (+ 7.9 %)	-

These values are conditioned by the real usage and activity levels inside the building. During the monitored period, several remarkable differences were detected in the case study in contrast with the theoretical or designed definition in the PHPP. The main ones are:

- The inhabitants selected a low temperature for the heating threshold, provoking that the thermal comfort levels are often slightly cool. This is a personal decision which remained out from the scope of the study.
- Despite the small size of the building there were some temperature differences in zones or sides of the dwelling, this is mainly caused by the operation of the heating system in combination with the ventilation. Consequently, to reach the minimum temperature in every room, some rooms must be maintained at considerably higher temperatures.
- The consumption of electricity was slightly lower. Even the dwelling included a music room which wasn't considered in the typical electricity uses of a dwelling in PHPP calculations, the measured electricity use was slightly below the PHPP calculation.
- The level of occupancy during the monitored period was occasionally low. There were weeks with only 2 inhabitants and the consequently lower internal gains, as highlighted in the Section 3.4.7.
- The dwelling was slightly overventilated with an extra 7.9 % fresh air. This will have probably increased the heating demand of the house.
- There were long periods over 25 °C. The ventilation in summer was below the planned in PHPP. Besides, the use of natural ventilation in summer nights was rather uncommon.

3.5. Discussion

Regarding the **measured thermal losses**, the house proven to have a very low heating demand. The measured and HDD corrected annual heating consumption is 17.6 kWh/m²y (**objective 3.1**). This value can be considered also as the real heating demand, because the distributed electric heaters maintained the minimum temperature threshold during all the year. Therefore, the consumption also confirms a very low heating demand for this typology.

In general, the comparison with the other targets of the PHPP indicate that the deviations are low. The real heating demand was 2.6 kWh/m²y over the PH limit and 4.5 kWh/m²y over the calculations of PHPP (13.1 kWh/m²y). This suppose significant increases of around 17.3 % and 34.4 % from the PH limit and the PHPP estimation respectively. On the other hand, the real maximum heating load daily was significantly below the expectation. Which shows that the thermal losses were correctly controlled as a whole.

Thus, bearing in mind the very low energy demand of this case, any deviations in the internal gains or occupancy may have affected considerably to the final energy demand. In the present study, the main causes identified were four. Firstly, the smaller electricity consumption reduces directly the internal gains and increases the heating need. Secondly, the ventilation ratio was slightly over the average estimation, increasing the heat losses as well. Thirdly, even though the construction quality of the thermal envelope was successfully verified in general, some points like the ground thermal bridging indicated some possible deviations which could have augmented the heat losses in all the perimeter of the construction. Fourth and last, the winter deviation on the measured climate can affect more than the applied 3.3 % of HDD correction, since the solar radiation was also smaller than the HDD basis, as shown in Appendix I.

The detailed **thermal comfort** (TC) study (**objective 3.2**) has permitted to understand in a high level of detail the performance of the dwelling and the differences between rooms by activity and orientation.

The climate period identification according to recent literature doesn't seem to fit completely to the real performance of the building. The plots based on EN 15251 reflect this problem, because a considerable part of the warm days is included in the cold season despite of the high RMT, like in Figure 3.98. Overall, the case study evidences a long delay in the reaction versus outside conditions. The transition periods are asymmetric and this complicates the identification of proper periods. This can be seen also in the weather data of Figure 3.86 and the fast decay between November and October.

The occupancy analysis doesn't change the results significantly in the study. Probably because inhabitants didn't apply often the natural ventilation strategy.

The PMV model has the potential to include the RH and it has reflected very well the lower limit of temperatures preferred by the inhabitants. For instance, the complains of inhabitants about TC were basically about the low temperatures in bedrooms and northern side bathrooms, precisely the only ones which have a significant cool discomfort. The use of winter or summer clothing leads to a considerably wide range in these mechanically ventilated buildings, but again the period identification can lead to misinterpretations of the reality. Further studies shall be made in future cases.

In summer, the tolerance of inhabitants was higher than the theoretical limits, probably the other method adapts better to free-running conditions. The warmest hours happen mainly between 13:00 and 18:00 hours, which evidences the potential of doing something specific at those hours in order to mitigate this temporal discomfort. The warmest effect is cumulated also in the west orientation and living zones during the evening. This fact underlines the need of additional measures to prevent OH problems.

The adaptive method of EN 15251 implies that inhabitants have a high level of adaptation to warm indoor conditions. However, the results of the present study indicate that the usage of these high limits into the average value of the dwelling can hide many local overheating issues. The west side of the house has some signs of local overheating because it reaches rather often the category III (+) in the peak hours. Actually, this happen not only in the warm season but also in some days from late June and until middle October.

Despite having only 1 hour out of range during the warm season, the occupants commented that the limit shall be lower to prevent the local discomfort by hot temperatures in every part of the home.

After the experience of the monitoring, the limit of 3 degrees over the comfort temperature of CIBSE seemed to be maybe too optimistic regarding the human response. Further studies should be done in other cases to confirm this trend.

Regarding to the building overheating, the results are diverse and rather contradictory. Firstly, according to the OH detection method of CIBSE TM52 show that there is no risk of OH. Secondly, according to the PH limits, the house fails with 12.5 % of the total annual hours over 25 °C. Thirdly, the average home temperature present 180 night-time hours over 26 °C in the warm period. It becomes largely frequent, with the 40.2 % of all the night hours of that season. That amount, including the beginning of the cold season (until November) increases the number of warm hours in bedrooms to a very significant 337 h, more than 42 nights in total.

The study of the passive elements of the case study have given positive results (**objective 3.3**). The indoor temperatures controlling the potential thermal bridges demonstrate a good performance, similar to the surrounding opaque elements. Except from two exceptions, the southwest corner with a column next to the porch of living room and the sidewalk-façade union which presented larger effects in the inside temperatures than the designed bridge solutions.

The thermographic surveys in this type of buildings permit to find severe problems or failures in the thermal insulation, but the small variations on the outside don't permit to distinguish with all detail if the observed performance is as good as expected in the design.

The summer passive design has proven to be also capable to prevent any overheating in the home. However, the bad local conditions in the western rooms have also raised the concern about local problems. In those rooms, the lack of solar shading elements such as shutter and blinds lead to significantly warm periods in late evenings. Additional shading elements should be given to users to avoid the influence of direct solar radiation.

Overall, the observations during the monitored year indicate that in highly insulated buildings every small and local divergence can lead to relevant local problems. These failures are especially severe in summer design due to the future global warming scenarios.

The monitored performance of the **mechanic ventilation with heat recovery** (MVHR) followed the expectations of the calculations to a great extent (**objective 3.4**). The average HR during 6651 hours of winter operation was a remarkable 86.3 %. The operation in summer was characterised by the use of the by-pass in 870 hours and the HR under warm conditions during 186 hours. The summer HR operation avoided the 72.1 % of the outside heat and the by-pass contributed largely to cool the indoor environment, supplying the 79.1 % of the outside fresh air.

However, the ventilative cooling potential is not fully used, since the air flow is constant during all the monitored months. Some calculations indicate that the average cooling power of the by-pass was 0.31 kW. This value could be easily doubled if the ventilation air flow during night-time hours was increased. Moreover, the air flow in warm hours could be probably reduced to avoid the extra gains, guaranteeing the IAQ with controls by CO_2 or other analogous methods.

The installed ventilation system proven to be able to supply fresh air according to the calculations in every room. The tests conducted with tracer gas showed balanced ACH values in the rooms and the quality of the air mix in the biggest rooms such as the living room, the dining room and the music room.

The **heating performance** of the analysed two systems permitted to discover the capabilities and the limitations of each type (**objective 3.5**): the stand-alone pellet stove and two sets of electric heaters distributed in two rooms of the home.

Both systems provided proper TC in the average house level on more than the 99 % of the hours, but they also showed some limitations to maintain a proper comfort in all the rooms of the home. The stand-alone stove kept the Eastern side of the home and the bedrooms very significantly cool during 35.1 % and 75.6 % of the hours respectively.

The electric heaters installed were meant be able to provide enough heating because they could provide up to 9 W/m², but the results suggest that their distribution was not able to avoid the drop of temperatures in all the rooms. Indeed, they compensate the Eastern side cool periods, but they don´t fix the comfort of bedroom and the northern rooms are cooler, with 41.7 % hours out of comfort, as seen in the hourly plots of thermal comfort in Section 3.4.8. Consequently, in big houses like this it seems to be recommendable to distribute the heaters along the building, so that at least the northern orientation and the sleeping areas can have a direct control of the air temperatures.

Besides, the stand-alone stove operation generated an oscillating profile of temperatures with very warm peaks and it was close to provoke local discomfort by warm ceiling and in smaller degree also by air stratification. Therefore, it's probably that the stove operation was near to its maximum feasible power in this location, before local discomfort stages may appear.

Consequently, the main limitations found are related with three aspects. Firstly, the location of the heater within the building should be more distributed, because despite the small energy needs, the balance has to be assured. Secondly, the distribution of the generated heat through the air and ventilation has to be considered to compensate the losses and increase the temperature target in the heater. Thirdly, the dimensioning of heaters has to consider also the local discomfort limits such as vertical air stratification and warm ceiling risk, to select a proper type adapted to the features of each case.

The **electricity consumption** on the house is very low, with measured annual electricity uses of 3353.6 kWh in 2013 and 3253.5 kWh in 2014. This supposes a very remarkable 45.4 % of reduction on the electricity use of average Spanish single-family dwelling. This values is 7.4 % below the estimations of the PHPP calculation, demonstrating that that the appliances and equipment selected throughout the PH design have achieved an extremely good performance.

The heating and energy uses are aspects which differ greatly from user to user, as demonstrated in a number of studies of low energy housings in Chapter 2. The use in the monitored house had some particularities (**objective 3.6**) related with the presence of children on alternate weeks or the presence of a music room where some electronic instruments with high energy consumption were not included in the PHPP estimation of electricity use.

After the lessons learnt with the monitoring, the inhabitants decided to install one electric heater in the bathroom 2, to compensate the heat losses in the eastern side of the house. This can explain the higher consumption on the next winter of 2014-2015.

In any case, bearing in mind that the measured average energy includes the use of MVHR at slightly higher ventilation rate, the DHW generation and storage and all the other electricity uses, the final electricity consumption is remarkably low.

The **climate conditions** are always a relevant aspect of the design but in the case of low energy dwellings this becomes crucial. The conducted studies have shown considerable differences in the climate severity of the location of the case study, depending on the calculation method and the source. If the differences in winter are low, around a 5 %, they can become especially large in the summer climate, with ten times more CDD in the measured year than in the PHPP design climate file. Most likely, this fact contributed to the dramatic increase of the number of indoor hours over 25 °C.
Furthermore, the levels of solar radiation of some climate files are also considerable different. Meteonorm presents slightly higher levels of radiation in winter, which boosts the potential of solar gains on the calculations and can hide the real severity of winter weeks. During summer, the PHPP design climate file presents significantly lower solar radiation in every warm month, which can reduce greatly the risk of overheating in the calculations.
These relatively small differences can be very important in small buildings, because they can induce to make wrong decisions in the design stage. For now, it seems that is better to verify the design under several climate scenarios, in order to equip the building with sufficient features for the possible diverse situations.

3.6. Conclusions of the monitored case

This study has successfully characterised in detail the real performance of a passive dwelling on-use with a long-term monitoring and tests. The main results confirmed that the studied single-family dwelling has a very low energy demand, namely 17.6 kWh/m²y (**objective 3.1**) based on the measured consumption after a climate correction by HDD.

The measured annual heating consumption of the electric heaters was 2993.4 kWh. In a typical year, this consumption would be 3091.7 kWh after applying a correction of 3.3 % by HDD severity. Besides, the maximum daily heating load of the house was 6.9 W/m². The average winter heating consumption from November to March was 15.43 kWh/d and the maximum heating consumption in the coldest day was 29.33 kWh/d.

Some differences were observed in comparison with the PHPP calculations. On the one side, the heating demand was 4.5 kWh/m²y higher than the expectations and it overpassed the PH limit in 2.1 kWh/m²y. On the other side, the maximum load was 3.1 W/m² lower than the calculations and it remained 3.1 W/m² below than the PH limit. This point may had been affected by the distributions of the heaters in the house and also by four main differences between the assumptions of PHPP and the real inhabitants' activity. Firstly, a 5.4% higher electricity use annually and occasional lower occupancy at home. Secondly, the ventilation ratio of 0.4 ACH was 7.9 % over the average calculation. Thirdly, some minor thermal bridges detected in the thermographic survey might have increased slightly the heat losses. Finally, the solar radiation levels of winter were below the PHPP climate file.

The thermal comfort was evaluated for one year of the monitored data, using 8447 hours from 12/03/2013 to 11/03/2014, evaluating first the TC of the full year and later the cold season and the warm season separately (**objective 3.2**).

The PMV method indicates that the indoor environment is comfortable during 95.9 % of the total annual hours. The discomfort hours correspond: 2.5 % of category C (warm), 1.2 % too warm (PMV>0.7) and 0.4 % of category C (cool). The warm season was inside the comfort limits during the 86.7 % of the hours, with 123 hours of discomfort (13.3 %) by high temperatures. The cold season was in comfort during the 97.6% of the season hours, with other 0.5 % of category C (cool), 1.3 % of category C (warm) and 0.7 % hours too warm (PMV>0.7). There were no issues due to local discomfort conditions, after verifying the surface temperatures and air stratification of every room. In the detailed analysis by room activity or orientation. The worst winter conditions happen in the bedroom and in northern rooms. They present higher discomfort ratios, with 18.8 % and 10.6 % of discomfort hours by cold temperatures respectively. The worst summer conditions are located in the western rooms and living zones, with 12.6 % and 6.5 % of discomfort by high temperatures respectively.

The adaptive method of EN 15251 underlines different findings, reducing the acceptable annual comfort to 81.0 %. The results point to the existence of a severe discomfort by cold temperatures in winter, as much as 23.9 % of the cold season hours. On contrary, it doesn't consider any discomfort due to warm temperatures, because only 1 hour of summer and 3 of the cold season overpassed the adaptive limits. The study per rooms in winter show extreme cold discomfort in the sleeping zones and northern rooms, during 55.4 % and 51.0 % of hours respectively. In summer, western rooms present a very infrequent 1.1 % of discomfort by high temperatures and some rooms present cold discomfort per short periods, being the eastern rooms the most affected with a 1.7 %.

Regarding the overheating, the assessment of CIBSE TM52 method concludes that there is no overheating, since all the criteria are passed. On the other hand, the case study was over 25.0 °C during 1058 hours, a 12.5 % of the total annual hours. This fact overpassed very significantly the zero hours estimated by the PHPP calculations. However, there were a very significant number of warm nights, namely 337 night-time hours over 26.0 °C in the monitored year.

The study of the thermal envelope verified a high quality and good performance overall (**objective 3.3**). The heat losses through the envelope were verified on-site positively, certifying the thermal transmittances of the project. Besides, the surveys with infrared thermography from the inside and the outside showed the homogeneity of the elements and the correct performance of the majority of potential thermal bridges and construction joints such as the roof extension or the window installation. Only two types of thermal bridges indicate a slightly worse performance that the projected: in the façade-ground contact and in some of the corner columns. Their inner temperatures remain over 18.5 °C in the worst day of winter, that is only 2.5 °C below the room air temperature. Therefore, the impact of the heavy concrete structure and the potential thermal bridges are in any case small.

The ventilation rates were verified on-use with tracer gas tests, so that the measured average ACH is 0.4 h^{-1}(**objective 3.4**). The ventilation rate is 7.9 % more than the average calculations of the PHPP. The sensible heat recovery (HR) was calculated from the registered 321 days. The average HR calculated from 6651 hours of the cold season is 86.3 % and the average value during 186 hours of operation in the warm season is 72.1 %.

The summer bypass of the MVHR unit was open during 870 hours with a 20.9 % of sensible heat transfer, which means that it supplied the 79.1 % of the outdoor temperature into the home. The measured free cooling power during the 870 hours was 0.31 kW on average. This provided 269.86 kWh in total, reducing the cooling need in 1.53 kWh/m^2y.

Both heating systems, namely the stand-alone pellet stove and the distributed electric heaters, have demonstrated the capability to provide an acceptable indoor TC during more than the 99 %

of the hours of a typical cold week (**objective 3.5**). However, each system has its limitations of application to small buildings with low heating demand.

The stand-alone stove kept the Eastern side of the home and the bedrooms very significantly cool during 35.1 % and 75.6 % of the hours respectively. Besides, the cyclic operation of the stove creates a wavy pattern of temperatures in all the house and increases the air stratification. The measurements show a significant warm ceiling and air stratification of 2 – 3 °C of deviations. These values don't imply local discomfort according to ISO 7730 limits, but they are considerably near to the calculated maximum, that is 3.7 °C for the warm ceiling risk.

The electric heaters can control very precisely the operation and maintain a very stable range of temperatures, reducing the air stratification to less than 1 °C. In general, they solve the problems of cold discomfort in East rooms. On contrary, they don´t fix the cool discomfort in the bedrooms or the northern rooms, which remain cold during extreme 41.7 % and 79.8 % of the hours respectively.

These results confirmed that the heating system should be more distributed to achieve proper comfort in every room. Indeed, despite the small size of this typology of building, the temperatures in the heaters could be lower and avoid local discomfort risk.

Finally, the behaviour of inhabitants (**objective 3.6**) and the measured performance in this case study suggests that small changes in the use and internal gains can actually affect considerably to the real heating/cooling need. Once the passive features of the building are verified, the deviations on the heating demand can highly probably be connected to the observed small deviations on the electricity use and the ventilation ratio. For instance, the temperatures registered when the house was empty during several days show that it can cool down considerably fast.

Another aspect which has affected greatly the real performance is the local climate. The differences between the TMY of METEONORM, PHPP and the Spanish official climate data in this location have some considerable differences. On theory, these typical climates have deviations are up to 13.6 % on the whole winter solar radiation or to ten times more CDD in summer. On the reality, the deviations of the monitored data have proven to be indeed larger. In the end, the design of this small buildings requires a more solid strategy, so that it can absorb the deviations of climate and provide tools to inhabitants in the future global warming scenario.

CHAPTER 4

ENERGY DEMAND OPTIMIZATION OF THE CASE STUDY

Abstract
This chapter developed the characterisation of a dynamic Building Energy Performance Simulation (BEPS) to represent the thermal behaviour of the monitored passive house. It was oriented to minimise and solve the problems identified during the monitoring, such as the hot hours during summer or the cool temperatures in some rooms during winter. The calibration process was complex, including a number of adjustments and iteration steps guided by a parametric analysis. The reference model was verified with the Mean Bias Error (MBE) and the Coefficient of Variation of Root Mean Square Error, CV(RMSE). A set of improvement strategies of ventilation and solar shading were implemented in the model, to evaluate the better combination of passive measures. The results are presented in a multilevel analysis, using indoor temperatures, thermal comfort (TC) and heating use with graphical and statistical approaches. The best combinations demonstrated a high potential to adapt to local climate conditions and eliminate any overheating risk.

4. Energy Demand optimisation of the case study

4.1. Introduction

The calibration of a Building Energy Performance Simulation (BEPS) is a very complex process, which includes a number of adjustments and iteration steps. This study attempts to identify the deviations of thermal bridging, building airtightness, internal gains and thermal mass of the case study as-built. The final result is verified with the formulas of the Mean Bias Error (MBE) and the Coefficient of Variation of Root Mean Square Error, CV(RMSE).

The potential and limitations of the tool are assessed through a multilevel analysis, using indoor temperatures, thermal comfort (TC) and heating use with graphical and statistical approaches.

4.2. Aim and objectives

The main goal of this chapter is to **analyse the potential of ENERGYPLUS® and Design Builder simulations to reproduce the real conditions of a passive house** and also the **capability to implement passive design improvements**. This will permit to define the level of detail of the model and the measures which can be calculated towards the energy demand optimisation of the present case.

To do that, the following particular objectives are established:

Objective 4.1 Integrate the real full-scale measurements and the design features in a detailed ENERGYPLUS® model.

Objective 4.2 Compare the thermal performance and the TC of the model with the results of the monitored case.

Objective 4.3 Assess the ventilation improvement possibilities.

Objective 4.4 Evaluate the solar shading improvement possibilities.

Objective 4.5 Analyse the impact of a lower airtightness in the thermal behaviour.

Objective 4.6 Examine the impact of a higher internal gains in the thermal behaviour.

Objective 4.7 Examine the impact of internal mass in the thermal behaviour.

Objective 4.8 Verify whether an optimal thermal comfort can be achieved with a combination of measures or whether an active cooling is necessary.

4.3. Optimisation methodology

This work analyses the potential of passive measures to correct the problems detected during the monitoring of the case study. Basically, these issues consisted of a slightly higher consumption of heating, some low temperatures in certain rooms during the coldest months and considerably long periods of warm temperatures inside (1058 hours measured over 25 °C), see Chapter 3 for further details. This study is based on the use of a detailed model and the potential of Building Energy Performance Simulations (BEPS) conducted with the engine of EnergyPlus® (U.S. DOE, 2016) and the interface of Design Builder version 4.7 (Design Builder, 2016).

In the first stage, the building was characterised, including the construction features, HVAC systems and internal activity levels, in Section 4.4. The model was configured according to the characteristics verified on-site and the PHPP project details.

In a second stage, the model was calibrated as much as possible, using different iterations or corrections in order to find out which configuration represents better the real behaviour of the house with the maximum degree of reliability, in Section 4.5. The process was based on the comparison of the real measurements of air temperature, RH, TC and heating use. The final verification was done using the Mean Bias Error (MBE) and the Coefficient of Variation of Root Mean Square Error, CV(RMSE). Additionally, this stage also evaluated the influence of several key factors which can differ between the project and built reality. A set of parametric simulations permitted to represent the influence of thermal bridging, airtightness, internal gains and thermal mass in the final building thermal behaviour. This study helps to understand the possible deviations provoked by construction quality and habits of inhabitants.

In the third stage, the strategies to improve the reference model were simulated, in Section 4.6. Firstly, several ventilation related measures were applied: (i) the reduction of the air flow to meet the minimum requirements, (ii) the summer bypass enhancement to verify the maximum potential of the installed MVHR unit and also (iii) the use of natural ventilation on evenings of night hours in order to estimate the reduction of the number of hours over 25 °C. Secondly, the benefits of supplementary solar shading measures were calculated. In this case, they were only considered the systems which could be installed with a minimum impact on the existing building: (i) venetian blinds and (ii) external roller blinds.

In the fourth and last stage, all analysed measures were combined to find out the maximum margin of improvement, in Section 4.7. The best combinations were simulated, analysing the indoor environment parameters and TC. Besides, the best combinations of measures with manual operation are also simulated and assessed.

To conclude, the results are discussed and the most relevant conclusions are underlined.

4.4. Definition of the simulation model

4.4.1. Potential and limitations of the modelling scope

The combination of real full-scale measurements and Building Energy Performance Simulations (BEPS) is very complex and needs to be supported by a deep analysis. This is probably the main problem highlighted by the majority of the BEPS calibration studies. For this reason, there are a number of techniques or methods to calibrate or match real observations and BEPS. A common classification of these methods (Coakley D, Raftery P, 2012) identifies four categories of calibrations: (i) the ones based on manual iterations to apply corrections (basically as trial-and-error method), (ii) the ones based on suites of informative graphical comparative displays, (iii) the ones based on special tests and analytical procedures and (iv) analytical/mathematical methods.

On the other hand, the latest review proposes a global separation of all the methods as either manual or automatic processes (Coakley et al., 2014). In their detailed study they review the main studies of the last 30 years and they propose an further detailed classification. On the one hand, the manual user-driven techniques can be based on: characterisation techniques, advanced graphical method, model simplification techniques and procedural extensions. On the other hand, the automatic techniques can be conducted with either optimisation techniques or with alternative modelling techniques (also known as grey-box or black box techniques). In any case, this study concludes recognising that “due to the sheer number of inputs required for detailed building energy simulation and the limited number of measured outputs, calibration will always remain an indeterminate problem which yields a non-unique solution”. This way they identify seven main issues for achieving a proper calibration: lack of standards, high expenses, inadequate simplification, uncertainty calculations, identification of personal decisions and automation of processes.

In the present study, the comparison between the BEPS and the real registered values has many limitations mainly due to the ambitious aim (full year assessment), the very low energy demand of the studied house and especially because of the high variability and uncertainty of inhabitant behaviour. This is precisely one of the main ideas of a recent study conducted in a passive house in Denmark (Paliouras et al., 2015), in their case “occupant behaviour could be considered as the most decisive source of uncertainty during calibration performed in the present study”.

This way, despite the adjustments applied on the model regarding the annual and monthly electricity consumption and the identification of occupancy profiles in the previous Section 3.4.8.2, obviously, the real daily activity during a whole year didn't always follow the average schedules… and so the internal gains and the indoor thermal behaviour of each day will have certain differences. As mentioned before, this activity variability affects especially passive buildings, because they are highly insulated and any small contribution of internal gains can vary significantly the heat balance (highly probably since internal gains can cover easily the 30% of the heating demand in PH).

Consequently, this chapter faces a difficult objective with the calibration of the BEPS. To evaluate the model, two approaches are used: a graphical comparison based on PMV model and another mathematical based on the Mean Bias Error (MBE) and the Coefficient of Variation of Root Mean Square Error, CV(RMSE). The results will show how the model presents several limitations due to the high variability along a full monitored year. However, the overall results permit to use the model as a tool to implement and analyse the potential of different passive strategies to solve the issues detected during the monitoring and improve the indoor TC. Thus, the BEPS will be able to represent the real behaviour of winter and summer typical weeks and months despite some deviations in certain periods.

4.4.2. Construction features

Bearing in mind the purpose of this study and the potential and limitations of the simulation tool, the model aims to reproduce the real conditions observed during the monitoring. To do that, the building definition includes the geometry, the construction materials and the indoor distribution with very high level of detail. This way, the model is divided in 14 thermal zones, to be able to adjust the type of use in each room, using the dimensions and features of the real building as described in the Section 3.3 of the previous Chapter 3. The model dimensions are summarised in Table 4.1, the construction material can be seen in Table 3.1 and Table 3.2. The model is presented in Figure 4.1 and Figure 4.2.

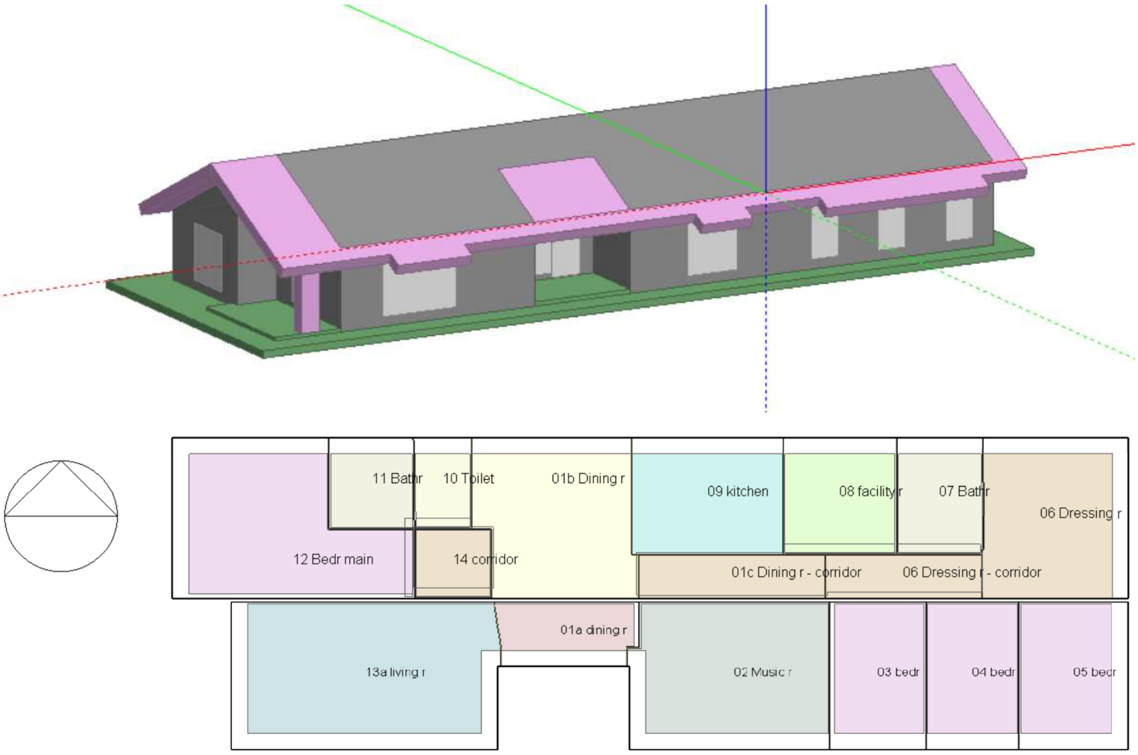


Figure 4.1: Simulation model geometry and thermal zoning plan.

This precise modelling allowed to establish and adjust in each room all the indoor parameters such as the activity, the internal occupation, equipment use, ventilation, solar shading operation etc. For instance, the doors of bedrooms were scheduled to remain closed during night to reflect the habits observed in the monitoring.

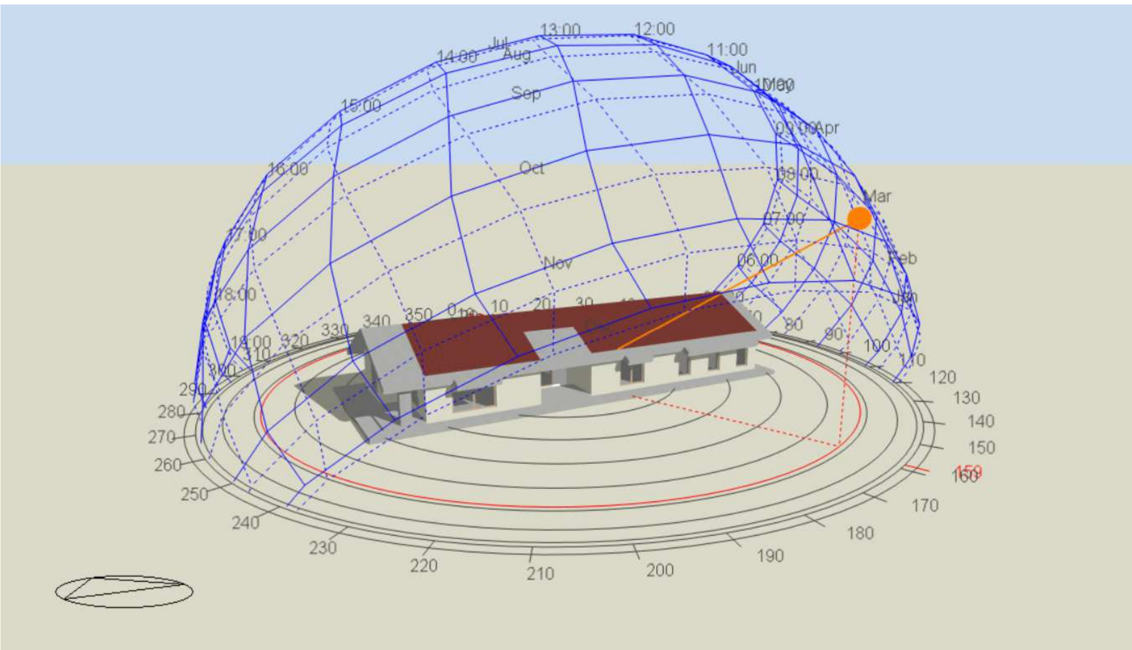


Figure 4.2: Model external visualization and sun path.

Table 4.1: Thermal zone summary and characteristics.

Zone ID	Area [m²]	Condit. (Y/N)	Part of Total Floor Area (Y/N)	Volume [m³]	Gross Wall Area [m²]	Window Glass Area [m²]
01ADININGR	24.13	Yes	Yes	65.40	22.43	4.42
01CDININGRCORRIDOR	6.29	Yes	Yes	13.88	0.00	0.00
02MUSICR	20.25	Yes	Yes	58.92	17.10	2.94
03BEDR	9.89	Yes	Yes	28.73	5.92	1.44
04BEDR	10.00	Yes	Yes	29.05	5.98	1.44
05BEDR	9.95	Yes	Yes	28.92	17.55	1.44
06DRESSINGR	17.76	Yes	Yes	42.26	23.23	1.09
06DRESSINGRCORRIDOR	5.26	No	Yes	12.98	0.04	0.00
07BATHR	6.26	Yes	Yes	16.48	5.17	0.19
08FACILITYR	8.26	No	Yes	21.74	6.96	0.25
09KITCHEN	13.39	Yes	Yes	31.12	10.50	1.61
10TOILET	3.02	Yes	Yes	7.59	3.51	0.19
11BATHR	4.55	Yes	Yes	11.80	5.10	0.19
12BEDRMAIN	18.85	Yes	Yes	55.44	23.84	2.94
13ALIVINGR	26.33	Yes	Yes	76.76	32.73	7.37
14CORRIDOR	3.79	Yes	Yes	8.34	0.00	0.00
SUSPENDEDCEILING	14.45	No	No	126.75	69.98	0.00
Total	187.97			509.41	180.05	25.49
Conditioned Total	174.44			474.69	173.05	25.24
Unconditioned Total	27.97			161.47	76.98	0.25
Not Part of Total	14.45			126.75	69.98	0.00

Infiltrations are a critical part of every design and even more in the case of a passive building. Ideally, the cracks in the envelope should be characterised in detail with a set of coefficients, as explained in the methods of Chapter 17 of ASHRAE Handbook of Fundamentals (ASHRAE, 2013a). That way, the ENERGYPLUS® engine could use the natural ventilation models to calculate accurately. This ideal definition should be based in a number of testing under different indoor-outdoor temperature differences and wind speeds, to characterise each particular curve of infiltration. However, this is highly unlike going to happen in the construction sector of this typology. In the best cases, the airtightness in single family dwellings is characterized by one or two BDT.

Therefore, in general it is assumed that a simplified approach is sufficient. In this case, the infiltration is defined as “scheduled” and it is based on the results of the BDT conducted once the works were finished, i.e. 0,21 h^{-1} at 50 Pa. However, the implementation of n50 or q50 values under 50 Pa difference are not directly applicable in the ENERGYPLUS® model. Firstly, the nominal air flow rate is estimated with the well-known rule of thumb developed by Sherman in 1987, that reduces the ACH at 50 Pa to normal pressure conditions by dividing it by a factor between 15 and 20 (Sherman, 1987). This way, the nominal ACH due to infiltrations in the studied case shall be at best between 0.0140 h^{-1} and 0.0105 h^{-1}. Later, the ENERGYPLUS® engine calculates the instant infiltration air flow according to the variability of the indoor-outdoor conditions, as explained in (1). In any case, the nominal values of infiltration can also increase slightly from the BDT conducted in the end of construction to the subsequent real use, caused by the procedure of BDT types A or B which may close some intended openings during the testing (EN 13829).

$$Infiltration = I_{design} \cdot F_{schedule} \left[A + B \left|T_{zone} - T_{obj}\right| + C \cdot Windspeed + D \cdot Windspeed^2 \right] \quad (5)$$

The default coefficients for scheduled natural ventilation in ENERGYPLUS® engine are (1, 0, 0, 0) and indicate that they are constant and do not apply the indoor-outdoor temperature difference or the effect of wind speed. In the present model, the coefficients were adjusted to be more similar to the typical real summer or winter weather conditions. To do that, the default configuration of BLAST engine (Department of Mechanical and Industrial Engineering, 1992) were used (0.606, 0.03636, 0.1177, 0). These coefficients estimate a factor of 1.0 at 0 °C indoor-outdoor temperature difference and 3.35 m/s wind speed, which corresponds to a typical summer weather. In cold winter conditions these coefficients increase the infiltration up to 2.75 times, based on 40 °C of temperature difference and 6 m/s wind speed (BigLadderSoftware, 2016).

Another key aspect is the thermal bridging, in DB they were defined according to their position in the building. They were calculated according to the internal values of linear thermal transmittance (Ψ_i) of the project, in Table 3.3. Some positions included different merged values weighted by the length of each particular type. The final values are listed in Table 4.2.

Table 4.2: Thermal bridges of the model according to Design Building categories, project values.

Thermal bridge position	Ψ_i
Roof-Wall	0.156
Wall-Ground floor	0.147
Wall-Wall (corner)	0.015
Wall-Floor (Int - not ground floor)	0
Wall-Floor (Ext - not ground floor)	0.206
Lintel above window or door	0.076
Sill above window	0.076
Jamb at window or door	0.076

4.4.3. HVAC systems

The proper definition of the HVAC has been one of the most difficult parts of the modelling. AS explained in the Section 4.4.1 there are many limitations due to the ENERGYPLUS® engine and the DB interface. For this reason, the modelling had to adapt the real features into another HVAC operation with an equivalent thermal behaviour.

After analysing different alternatives, the final model is presented in Figure 4.3. The HVAC system includes two electric heaters, the first with a power of 1600 W in the living room (r13) and the second with 400 W in the dressing room (r06).

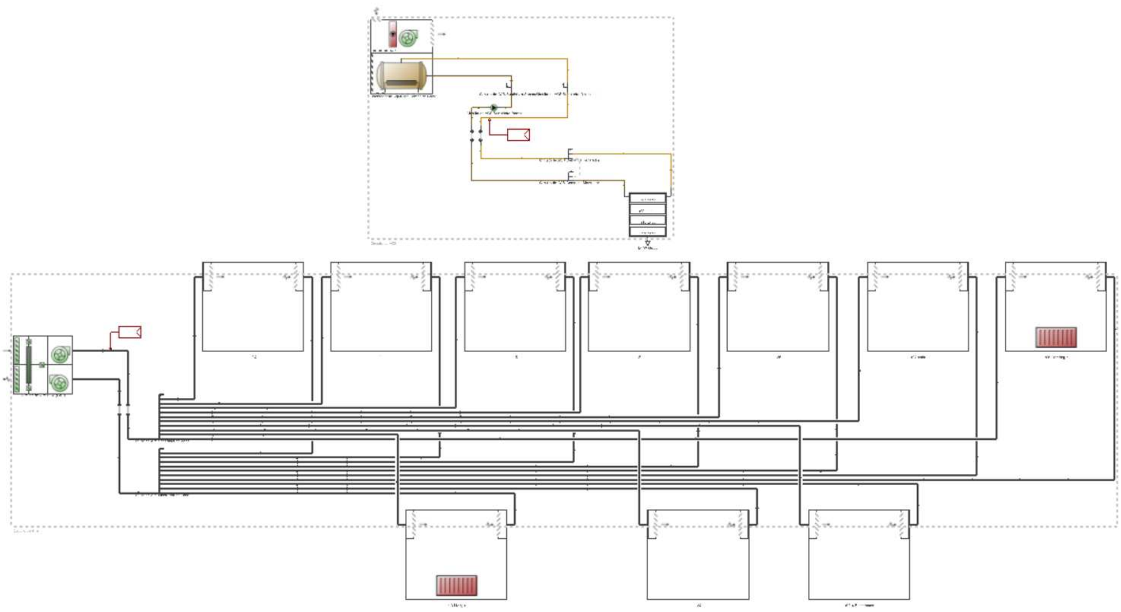


Figure 4.3: Model HVAC configuration diagram.

The ventilation of the house in handled by a central MVHR unit with constant air volume operation (CAV), 86 % sensible HR in winter, 72 % sensible HR in summer and a supply air temperature control linked with the average cooling demand.

The configuration of the AHU is rather complex because in DB there is no direct way to define a summer bypass. The combination of controls with cooling demand and airflow controls permited that the economiser is activated only as summer bypass, avoiding the standard airflow reduction of this operation. In the end, it works all year with a barely constant airflow, maintaining the hourly ACH between 0.38 h^{-1} and 0.40 h^{-1}. In Figure 4.4 is shown the operation of the summer bypass and the effect of free-cooling in the building.

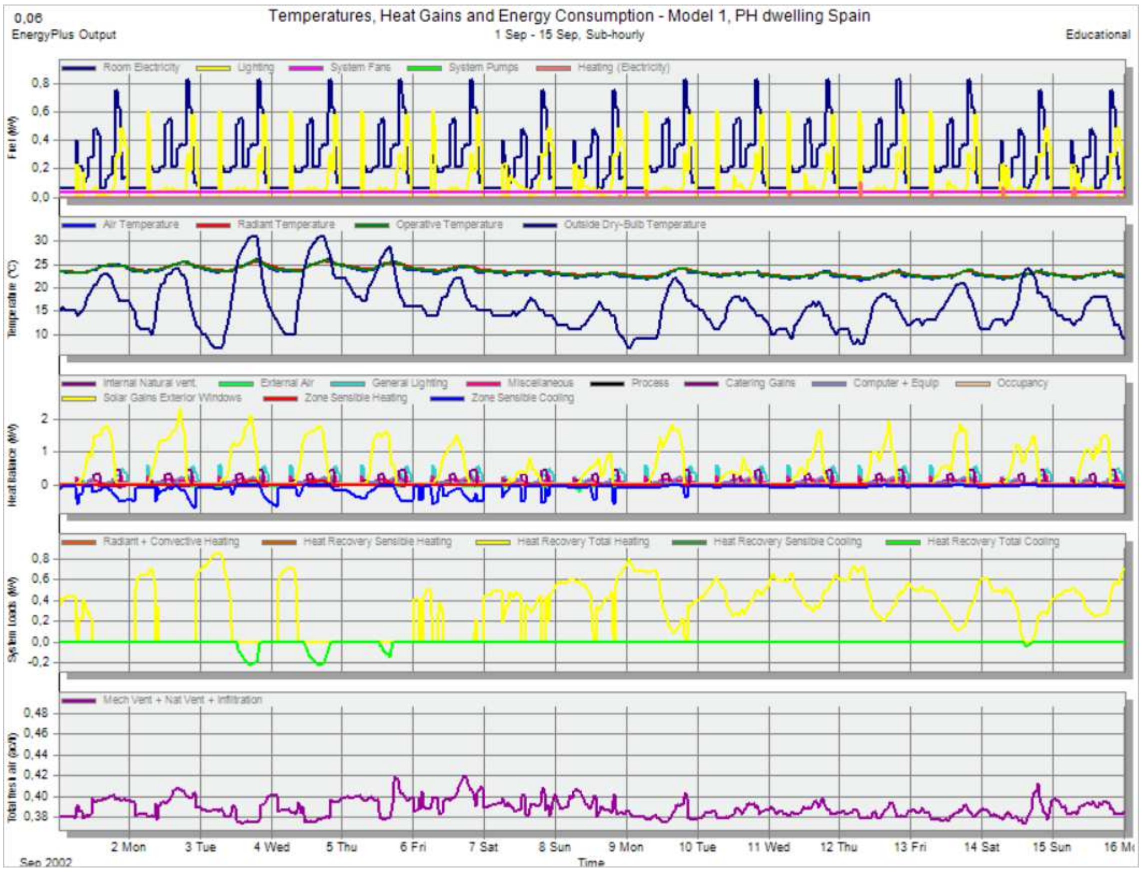


Figure 4.4: Summer bypass operation and deactivation on the 9th of September.

The ductwork provides supply and exhaust air in every room and the inlets have limited airflows in each room to match the model ACH of each enclosure with the real ACH tested with the tracer gas method, as explained in Section 3.3.1.1.

The generation of domestic hot water (DHW) is handled by an air to water HP with hot water storage. It is set with 3500 W of maximum heating power and a COP of 3.8 with 300 l of storage. All the features have been defined according to the technical sheet of the unit installed in the house, for further details see Chapter 3 definitions. The hot water consumption is defined in 25 l per person and day and it is distributed in each bathroom and kitchen, releasing latent heat in correspondence with the activity schedules of those rooms, as explained in the next Section.

4.4.4. Operational program, schedules, occupancy and internal gains

The heating set points in the real case was 21 °C but it was done by a sensor at 200 cm height. In the model, the heating set point is 20.8 °C, to balance the real air stratification observed in the monitoring with the perfect air mix of the model. In the analysed real case, the heating was inactive from 11th June 2013 to 4th November 2014.

The cooling set point is set in 23.5 °C, so that it can activate the summer by pass during a certain period. It is scheduled like in the monitored case, so the summer bypass was active between 15th June and 9th September.

Regarding the occupancy schedules, the model calendar was adjusted to the school holidays of the kids and the working calendar of Alava region in 2013-14. The holidays included within the analysed period (12/03/2013 – 11/03/2014) are listed in Table 4.3.

Table 4.3: List of holidays within the analysed period (12/03/2013 – 11/03/2014).

Labour holidays (17 days)	**School holidays**
28th and 29th of March and 1st of April 2013 (Easter)	25th March to 7th April 2013 (Easter)
1st May (Worker's day)	29th April to 5th May 2013 (Worker's day)
24th June (Regional holiday)	8th June to 8th September 2013 (Summer)
25th July (Santiago)	25 October 2013
5th August (Vitoria's holiday)	1 November 2013
15th August (Virgin's holiday)	6 December 2013 (Constitution of Spain)
12th October (Spanish National day)	23rd December to 6th January (Christmas)
25th October (Basque regional day)	
1st November (All saint's day)	
6th December (Constitution of Spain)	
25th December (Christmas)	
1st January (New year)	
6th January (Wise kings)	

The adjustment of internal gains to the analysed case was also complex. They are based on the annual electricity consumption measured in the house during the analysed period. The share of each activity has been done according to the percentages of use defined in the PHPP worksheet. The occupancy profiles have been defined according to the occupancy analysis conducted in the previous Chapter 3, see Section 3.4.8.2 for further details.

The routine in each room was adjusted to represent the levels of use detected during the monitoring, including the timetables of meals, cooking or the use of computers in children's bedrooms and living room and so on. The used electricity and the consequent heat sources of each room are identified in Table 4.4.

Table 4.4: Internal gains definition.

Rooms	**Net floor**	**Lighting**		**Computers**		**Processes**		**Cooking dishwashing**		**Appl. / misc.**	
		W	W/m²	kWh/y	W/m²	kWh/y	W/m²	kWh/y	W/m²	kWh/y	W/m²
Corridor	5	30	6								
Living room	26	110	4,2	55,5	1,9					191,2	3,1
Kitchen	13,4	80	6,0					723,0	37,0	366,0	3,1
Bathroom	6	45	7,5							78,8	18,0
Bedroom	10	40	4,0	31,3	6,0						
Dining room	24	100	4,2								
Dressing room	18	50	2,8								
Music room	20,25	40	2,0	208,6	4,0						
Service room	8,3	17	2,0			172,0	2,4			232,0	8,9

4.5. Thermal behaviour of the simulation model and comparison with real measured data

As explained in the Section 4.4.1, the combination of real full-scale measurements and model simulations is very complex and two methods are used to calibrate or validate the model. First, the manual iterative adjustments are described analytically and later the final version of the model is verified through mathematical methods, i.e. MBE and CV (RMSE). For further details of the manual corrections, see the next subsections.

The model is based on the construction features according to the verifications and tests conducted on-site during the monitoring, such as the ventilation rates or facades thermal transmittance. Besides, the corrections of the internal gains have been implemented according to the real global electricity use. To do that, the identified general occupancy profiles are used together with each room occupancy trends. Finally, the HVAC systems have been adapted to the limitations of the ENERGYPLUS® engine, in order to obtain the real summer bypass operation. Besides, one of the most crucial points is to correct the particular aspects detected with the monitoring in relation with construction quality and real thermal behaviour. For instance, the presence of some higher effect of thermal bridging was detected, especially in the contact between facade and ground, but also in smaller degree in the roof extensions and window perimeters. This will be done as part of the iterative corrections of the model. To orient the corrections, the objective parameters are indoor operative temperature and heating use.

The first model, with the definition according to the project data, presents a considerably lower annual heating use compared with the measured real case. As expected, this value is very similar to the PHPP annual calculation with only 1.4 % less heating use. So, the first model heating use indicates that the annual calculation PHPP meets the dynamic simulation to great extent.

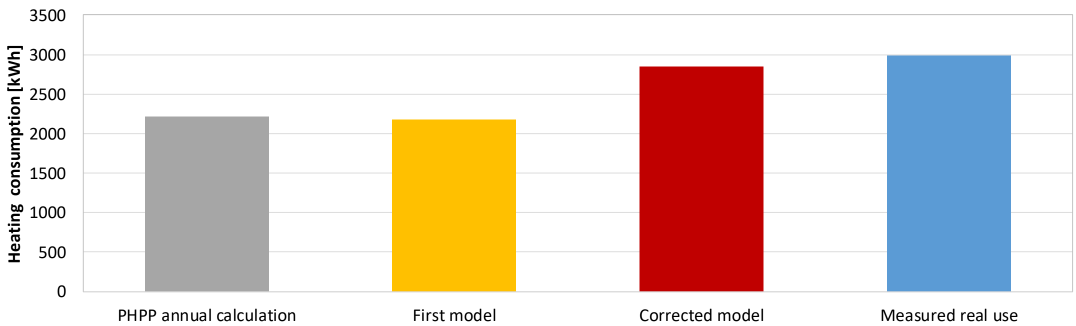


Figure 4.5: Comparison of the annual heating use of PHPP calculation, first model, corrected model and real measurements.

To analyse the impact of each correction, in a preliminary stage each modification was analysed separately and the results are included in the following sections. The controlled aspects are four: (i) thermal bridges, (ii) airtightness, (iii) internal gains and (iv) thermal mass.

This way, the iterative stages required many simulations to correct the deviations in summer, winter and shoulder seasons. During that process, apart from the indoor temperatures and heating use, the TC PMV index was also analysed. As a result, the model with the best combination of measures includes the following corrections: TB increased around a 35 %, infiltrations slightly increased to n50 0.4 h^{-1}, normal internal gains and 25 % less thermal mass in block wall and concrete slabs. The heating annual use of the corrected model is 4.7 % below the real measurement, as presented in Figure 3.124.

The monthly results indicate that the biggest relative deviations appear to be in June, May and November, however these months have rather small heating use. The largest absolute difference is in December, with 64.6 kWh less heating use, this may be due to Christmas holidays, days where the house was empty and to the temporal ventilation boost during parties at home. In any case, the maximum heating use of each month shows a good match in most of the months, as can be seen in Figure 4.6 below.

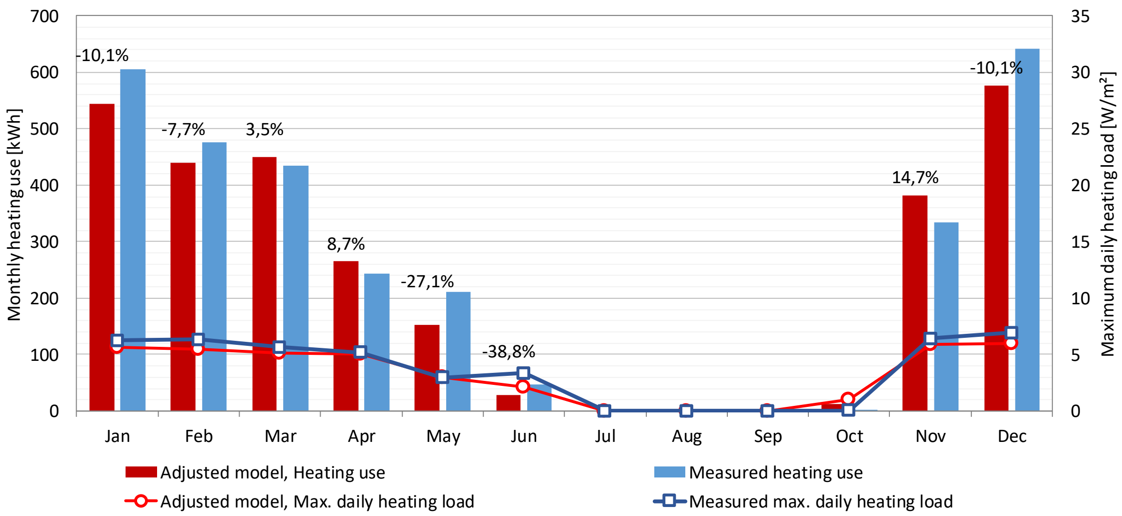


Figure 4.6: Monthly heating use and maximum daily heating load, comparison between the simulation model and real on-site values.

The analysis of daily average heating use and the monthly electricity use shows a good correlation, as shown in Figure 4.8. Nevertheless, there are significant deviations of electricity use, mainly from July to October. These deviations will have an effect in the TC analysis, which will indicate less warming hours in late summer, precisely in September and October.

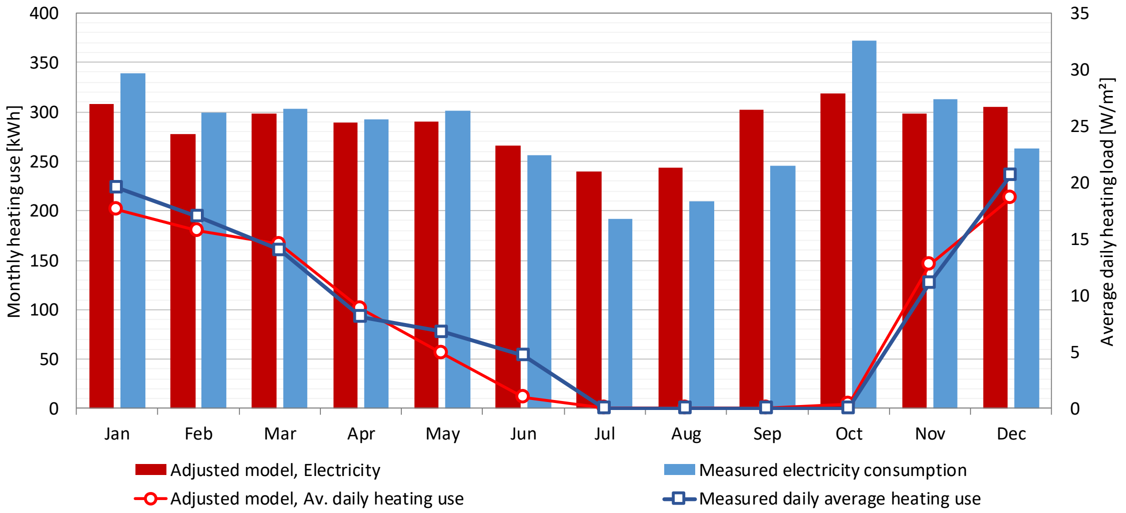


Figure 4.7: Monthly electricity use and average daily heating use, comparison between the simulation model and real on-site values.

In the daily basis, the heating use is analysed in Figure 4.8. The average difference between measured and predicted values is 1.6 kWh/d, which means a relative difference of 13 % in respect with the average consumption between January and April.

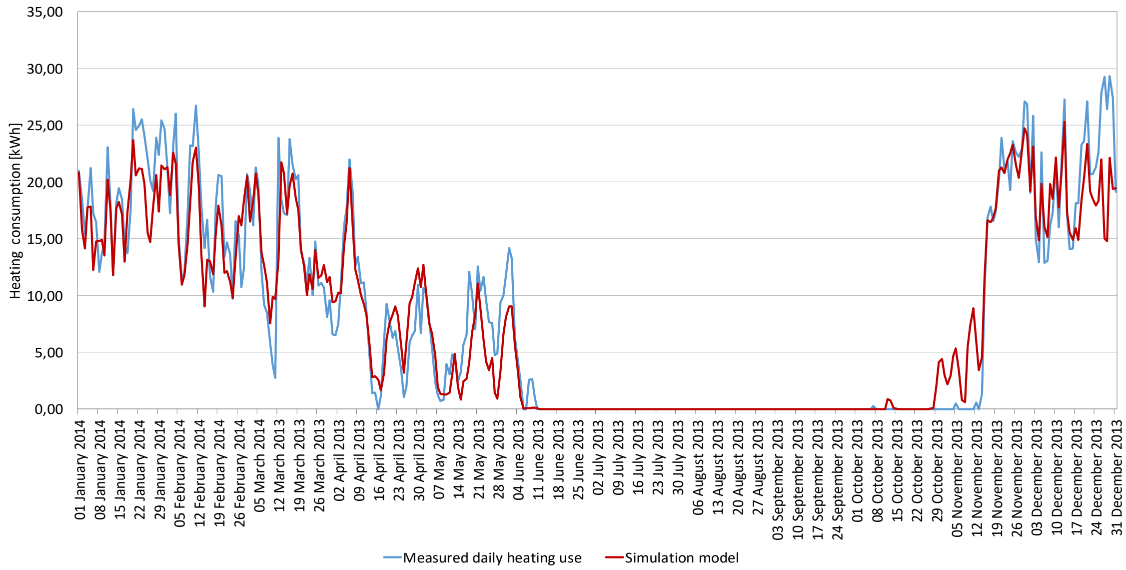


Figure 4.8: Daily heating use, comparison between simulation models and real on-site values.

Besides, bearing in mind that the purpose is the indoor and TC assessment, two typical winter and summer weeks are analysed in Figure 4.9 and Figure 4.10. In winter, the heating operation of both heaters follows the same pattern. However, the peak temperatures due to instant sun harvesting and occupancy changes are not appreciated with the same instant response. This might be like that because the model internal gains are defined in long hours to embrace the daily variability and represent general activity levels.

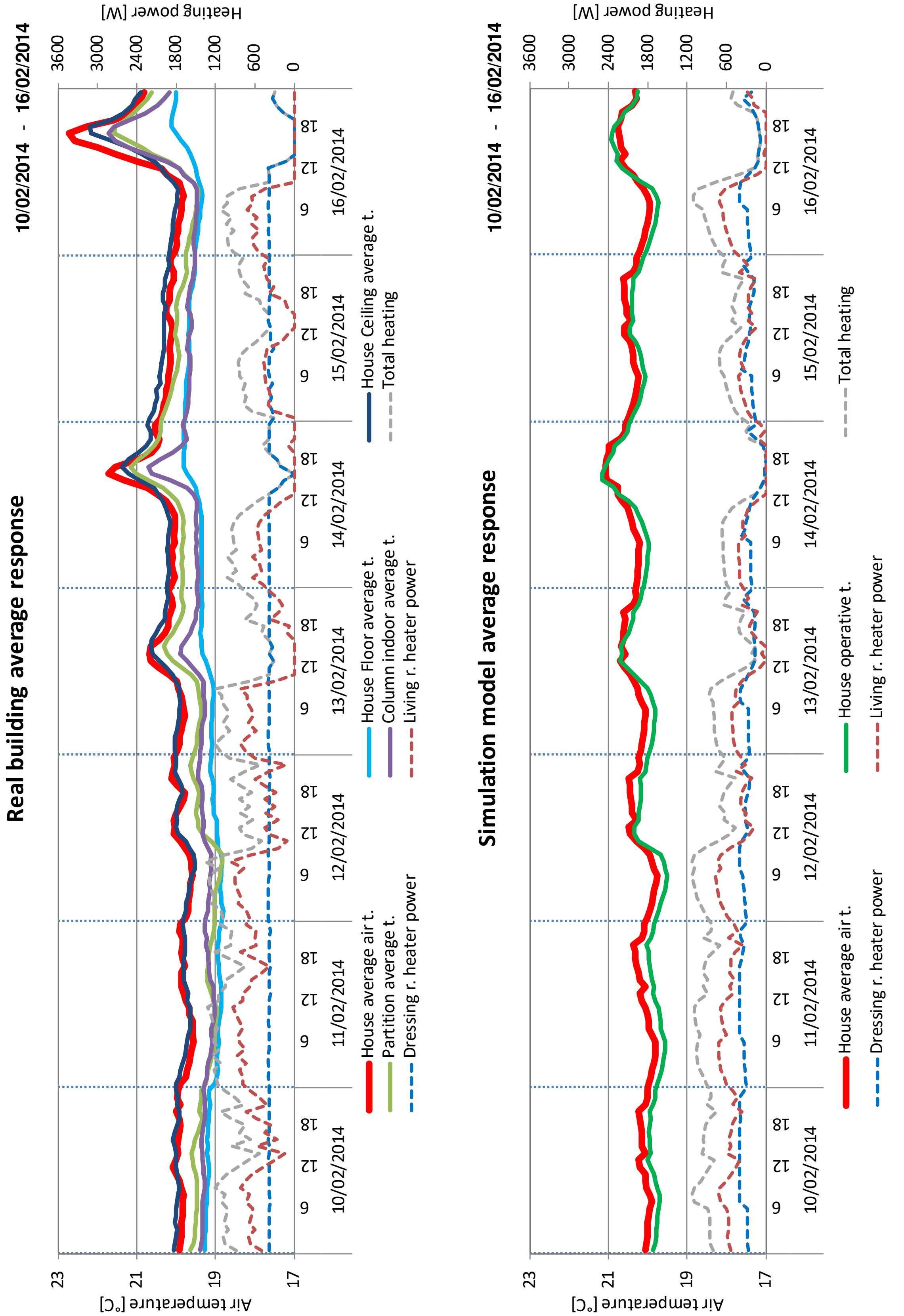


Figure 4.9: Winter week response of the building (10/02/2014 – 16/02/2014), comparison between the simulation model values and real on-site measurements.

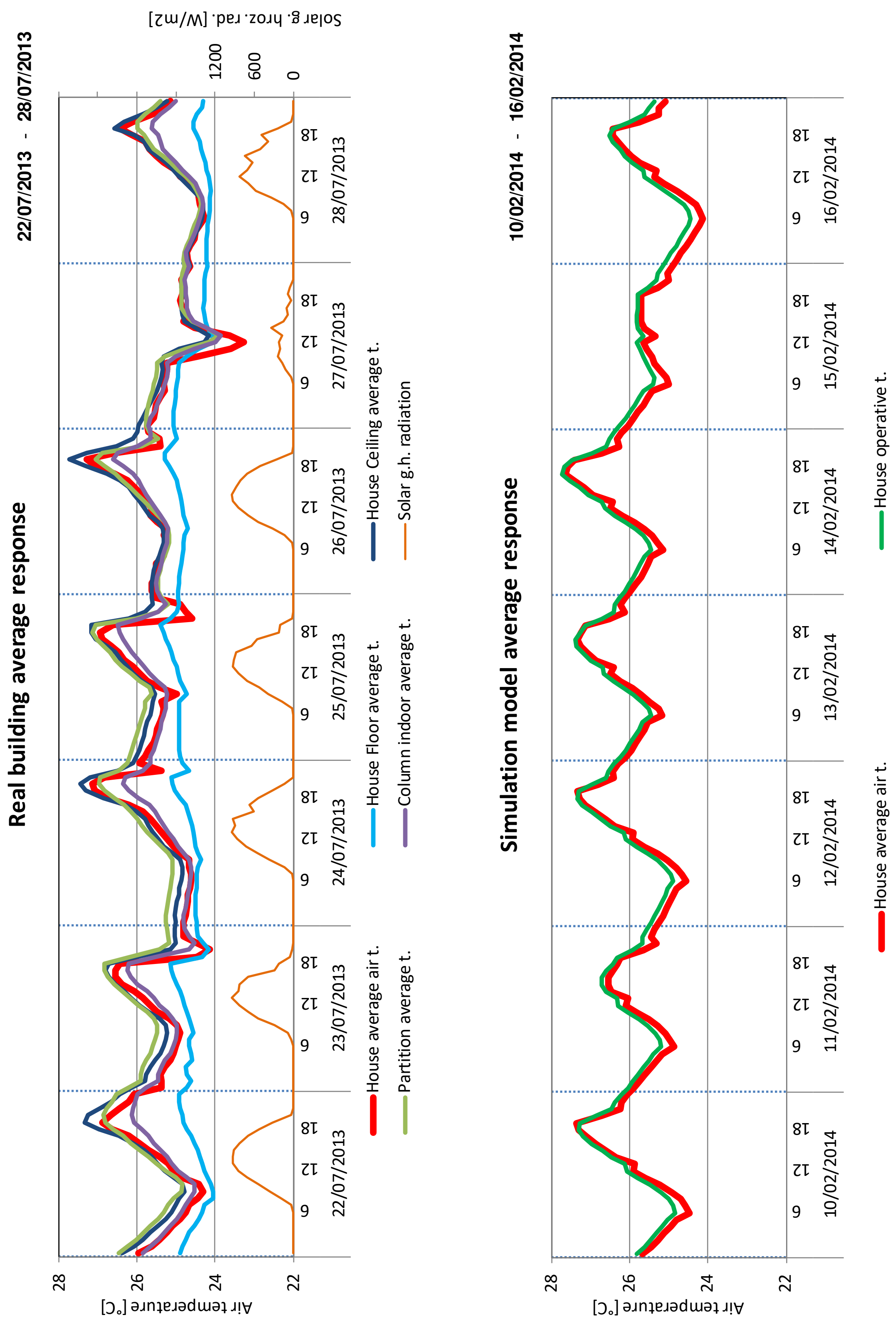


Figure 4.10: Summer week response of the building (10/06/2013 – 16/02/2013), comparison between the simulation model values and real on-site measurements.

The summer typical week also presents a good match, especially in the peak hours and the bypass operation. Nevertheless, there can be seen some short periods of natural ventilation in the real case, which are not included in the model.

In a more advanced graphic comparison, the indoor temperatures of the model and the real measurements are plot together in Figure 4.11. The model presents more stable temperatures but the trends of both cases are present in the majority of the months. As commented before, there is a significant deviation in September and October which coincides with an unexpected higher electricity use. Therefore, this abnormal activity variation is not a priority of the model.

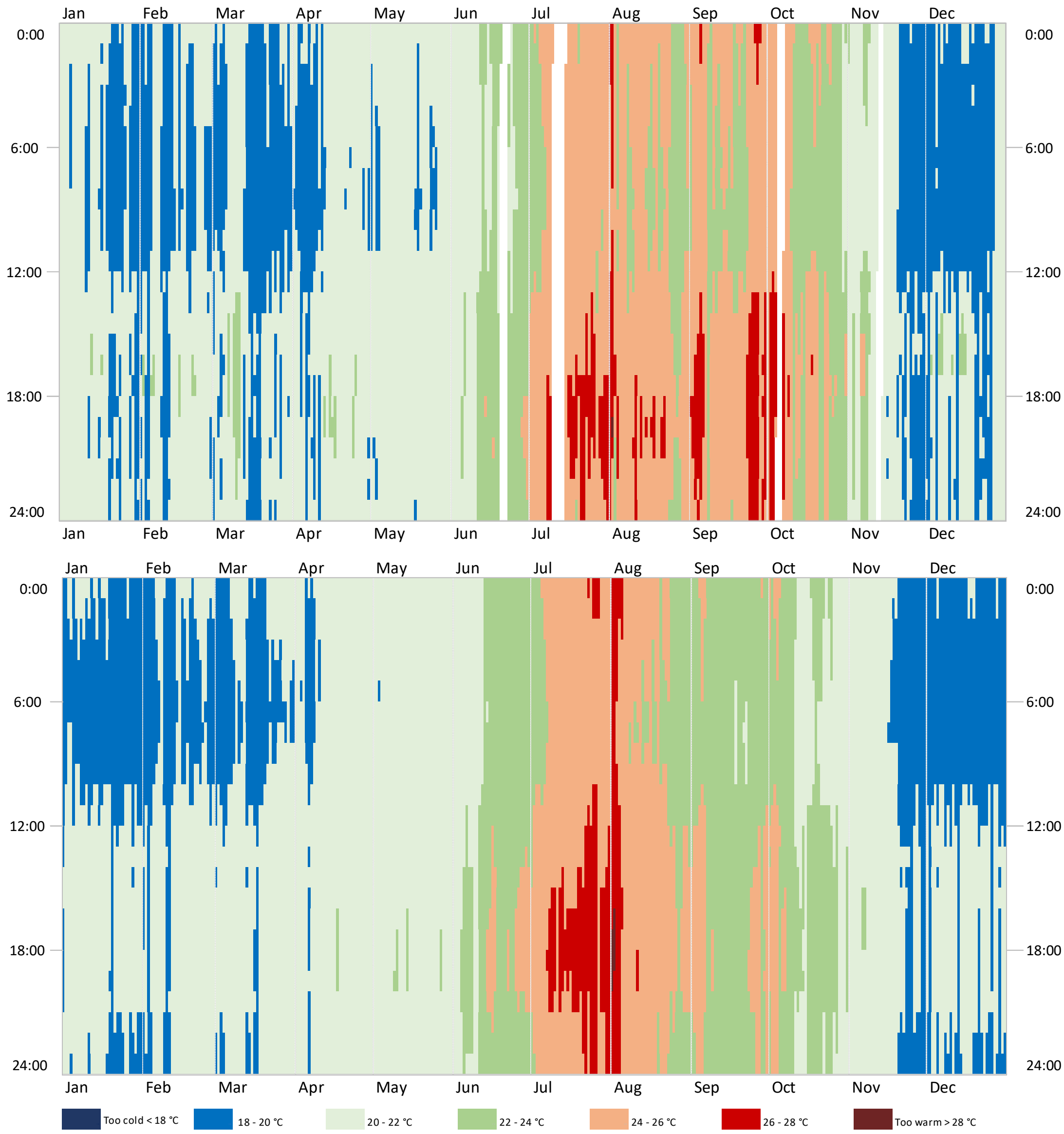


Figure 4.11: Comparison between hourly indoor temperatures, real measurements from 12/03/2013 to 11/03/2014 (t) and the predicted values of the corrected model simulation (bottom).

The final analytical aspect corresponds to the TC values according to PMV (Fanger's model). The annual hourly PMV values indicate that the model and the real measurements follow similar curves, as observed in Figure 4.12 and Figure 4.13. Again, the difference phenomenon in September and October is visible, but the majority of the transition periods look similar.

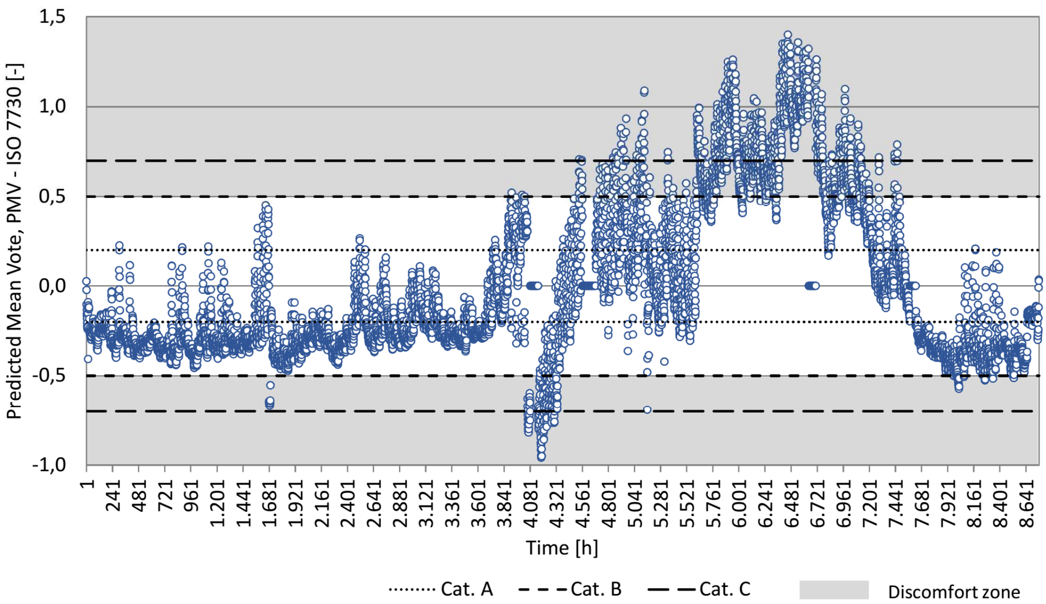


Figure 4.12: Real building measured hourly PMV ISO 7730 (12/03/2013 – 11/03/2014).

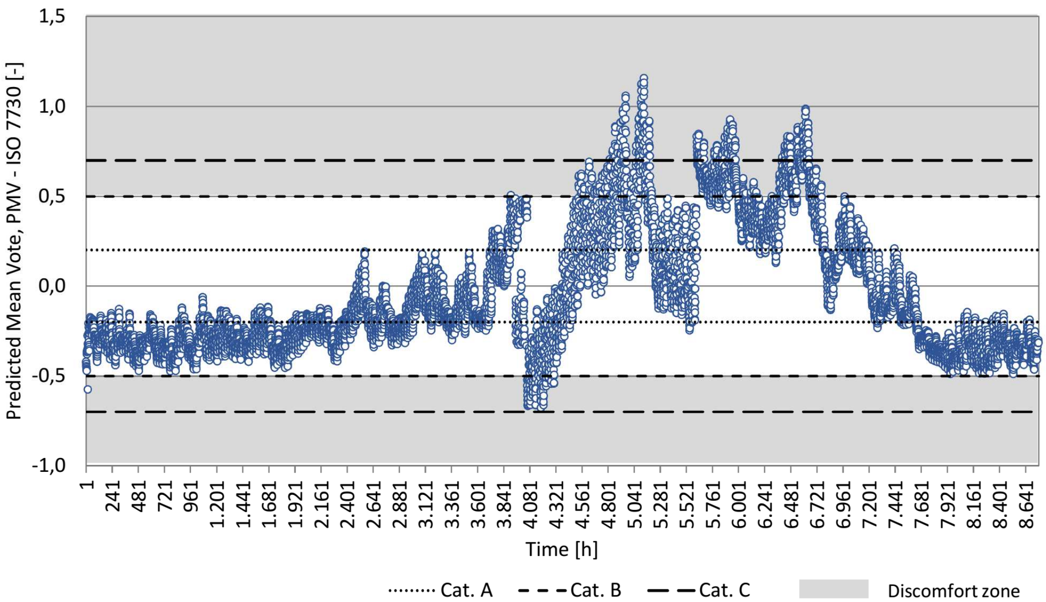


Figure 4.13: Simulation model calculated hourly PMV ISO 7730.

The final verification is conducted with mathematical methods of Mean Bias Error (MBE) and the Coefficient of Variation of Root Mean Square Error, CV(RMSE), as defined in the formulas (6) and (7) respectively.

$$\text{MBE } (\%) = \frac{\sum_{i=1}^{N_p}(m_i - s_i)}{\sum_{i=1}^{N_p}(m_i)} \qquad (6)$$

Where:

m_i measured data (temperature, RH, heating use)
s_i simulated data (temperature, RH, heating use)
Np number of data points at interval p (i.e., $N_{monthly}$ 12, N_{hourly} 8760)

$$\text{CV RMSE } (\%) = \frac{\sqrt{(\sum_{i=1}^{N_p}(m_i - s_i)^2/N_p)}}{\overline{m}} \qquad (7)$$

Where:

m_i measured data (temperature, RH, heating use)
s_i simulated data (temperature, RH, heating use)
Np number of data points at interval p (i.e., $N_{monthly}$ 12, N_{hourly} 8760)
$\overline{m}$ average of the measured data points (temperature, RH, heating use)

The results of the indoor operative temperature, humidity and heating are analysed hourly. Table 4.5 includes the values monthly and annually. The limits of these values are controlled by several standards like ASHRAE Guideline 14, IPMVP and FEMP. ASHRAE limits the acceptability in 5% of MBE and 15% of CV(RMSE) in a monthly criterion and increases the limits up to 10 % of MBE and 30 % of CV(RMSE) for annual datasets. Accordingly, the operative temperature is well calibrated and the RH fails only in 4 months. However, since the heating use presents a considerable error, the model doesn't fulfil all the criteria. These results confirms that the indoor environment of the model is almost calibrated but the heating operation shall need extra inputs to be adjust better. This way, the model is valid for the purpose of the study.

Table 4.5: Calibration of BEPS according to MDE and CV(RMSE).

	Monitored values			**Simulated values**					**Error calculation**			
	Temp.	**RH**	**Heating use**	**Temp.**	**RH**	**Heating use**	**t_m - t_p**	**RH_m - RH_p**	**H_m - H_p**	**$(t_m - t_p)^2$**	**$(RH_m - RH_p)^2$**	**$(H_m - H_p)^2$**
Jan	20,2	51,9	606,1	20,0	49,1	544,9	0,2	2,8	61,3	0,0	8,1	3.752,8
Feb	20,2	48,0	475,6	20,1	46,0	439,1	0,1	2,0	36,5	0,0	4,1	1.333,4
Mar	20,2	45,2	435,6	20,2	48,8	450,9	0,1	- 3,6	- 15,3	0,0	12,7	234,2
Apr	20,4	48,7	243,8	20,5	50,9	265,0	- 0,2	- 2,2	- 21,2	0,0	4,9	450,8
May	20,4	51,8	210,2	20,8	53,2	153,2	- 0,4	- 1,5	57,0	0,2	2,2	3.249,6
Jun	21,9	57,8	47,1	22,5	58,3	28,8	- 0,6	- 0,5	18,3	0,4	0,2	334,2
Jul	25,0	60,7	0,0	25,3	64,8	0,0	- 0,3	- 4,1	-	0,1	17,0	-
Aug	24,6	56,7	0,0	24,7	62,5	0,0	- 0,1	- 5,7	-	0,0	32,7	-
Sep	24,9	54,4	0,0	23,3	60,7	0,0	1,6	- 6,3	-	2,5	40,2	-
Oct	24,0	51,9	0,2	22,4	57,8	12,4	1,6	- 5,9	- 12,2	2,6	34,8	148,0
Nov	20,6	50,7	333,3	20,3	52,3	382,4	0,3	- 1,6	- 49,1	0,1	2,5	2.407,2
Ded	20,1	44,8	641,4	20,0	45,9	576,8	0,2	- 1,2	64,6	0,0	1,4	4.171,0
Error assessment								**MBE**			**CV(RMSE)**	
Monthly methods (monthly average values)							0,9%	-4,5%	4,7%	3,2%	7,1%	14,7%
Annual methods (all hourly values)							2,2%	-12,1%*	7,6%	4,1%	11,2%	66,0%*

** Values exceeding the ASHRAE Guideline 14*
(Monthly MBE < 5 % and CV(RMSE) < 15 %. Annually MBE < 10 % and CV(RMSE) < 30 %)

4.5.1. Impact of thermal bridges

Regarding the iteration of TB, four different scenarios of TB have been analysed, as presented in Table 4.6. The model has been simulated first without any TB and with the ideal thermal bridges, as a baseline range to compare the effect of the TB in the overall heating demand. The Ψ_i values of the project were extremely low as expected in a PH certified building.

Later, the linear thermal transmittance of some of the TB types has been raised in different degrees. The increase is conditioned by the findings of the thermographic survey and the measured indoor temperatures, results are plotted in Figure 4.14 and Figure 4.15. As explained in Chapter 3, there were no big construction issues, but some potential increases of heat losses were found on the building-ground contact and on the inside roof-wall and windows. Besides, some pillar-wall TB are added into the TB of wall corners. In any case, the increases have been limited to Ψ_i which can be considered as very low thermal bridges, according to thermal bridge database of Spanish regulation (DA CTE-DB-HE/3, 2016). This fact is possible due to the extremely low initial TB values.

Table 4.6: Calibration of BEPS according to MDE and CV(RMSE).

TB scenarios	Min TB Ψ_i (WmK)	TB 1 Increase (%)	TB 2 Increase (%)	TB 3 Increase (%)	TB 4 Increase (%)
Roof-wall	0,156	-	+ 10	+ 25	+ 25
Wall-ground floor	0,147	**+ 25**	+ 25	+ 40	+ 50
Wall corners	0,015	-	+ 10	+ 10	+ 25
Wall-floor	0,206	-	-	+ 10	+ 25
Windows	0,076	-	-	+ 10	+ 25

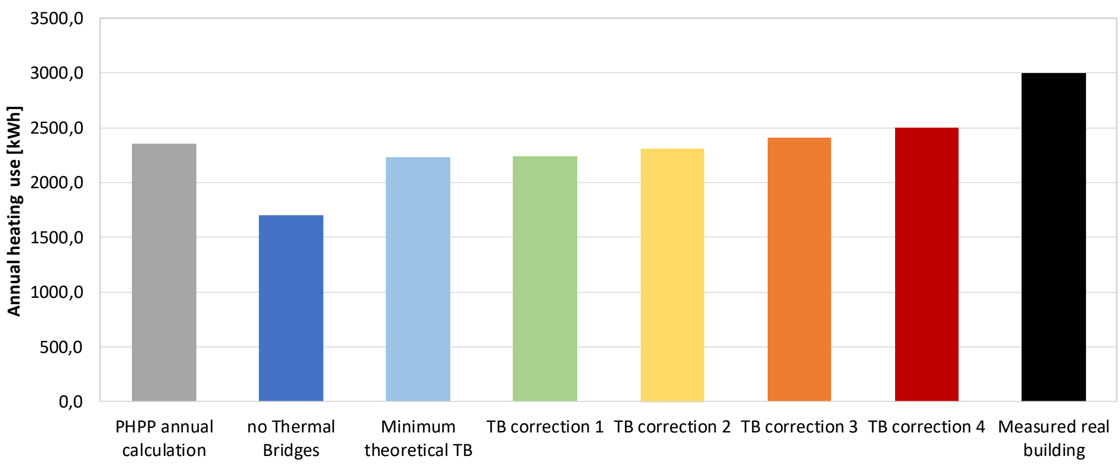


Figure 4.14: Impact of thermal bridging on the annual heating use of the model.

As a result, the selected TB correction is the number 4, meaning an average an increase of 35 % over the total TB heat losses. This way, it represents the findings of the thermographic survey and adjusts better the heating use.

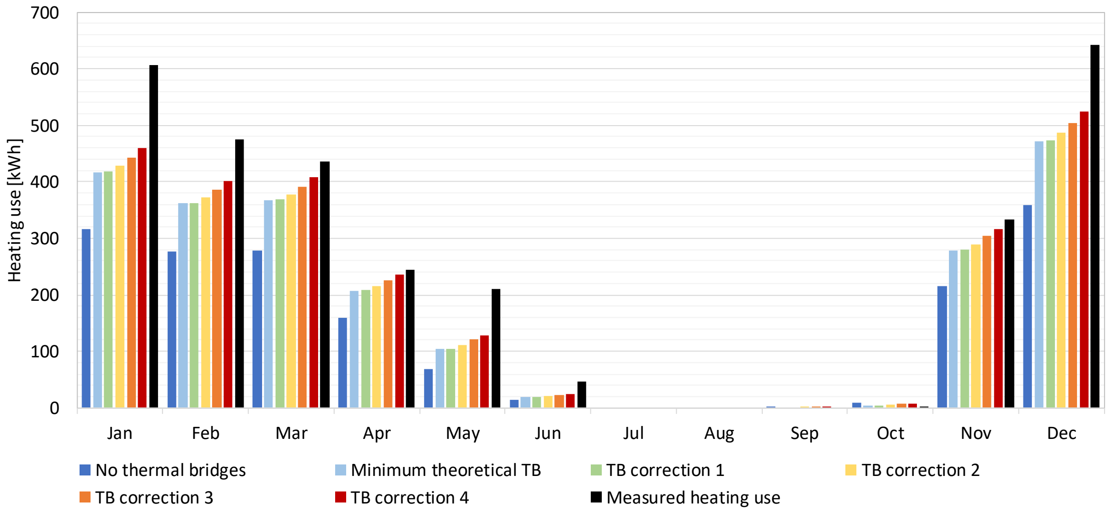


Figure 4.15: Impact of thermal bridging on the monthly heating use of the model.

4.5.2. Impact of building airtightness

The airtightness is another of the aspects considered for the iteration. The house was tested after construction with a BDT and it showed an excellent ACH of 0.21 h^{-1} at 50 Pa. However, since the BDT can be done sealing some intended openings, the final ACH after the commissioning can easily end being higher than the test value. Thus, to analyse the impact on heating use, the annual and monthly values were compared in Figure 4.16 and Figure 4.17.

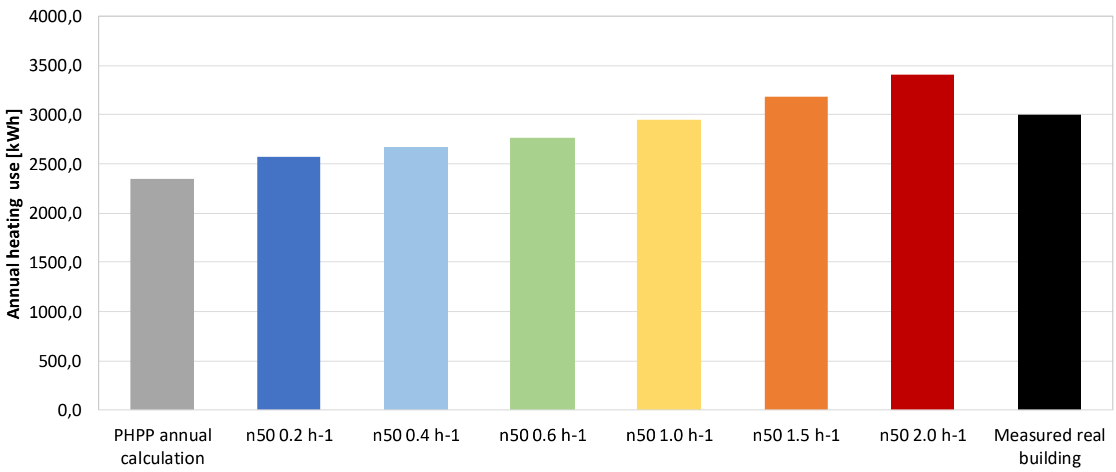


Figure 4.16: Impact of infiltrations on the annual heating use.

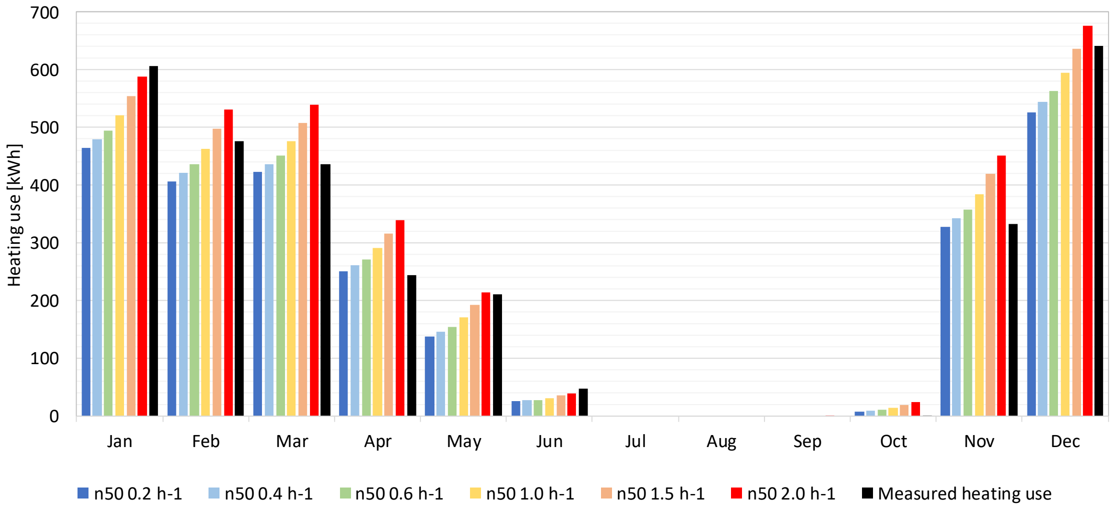


Figure 4.17: Impact of infiltrations on the monthly heating use.

Additionally, since this change can affect considerably the indoor temperatures, Figure 4.18 presents the monthly average indoor temperatures of all possibilities. In winter, the values are almost the same, with maximum differences of one or two tenths of a degree. In summer, these differences are also similar. However, there are some considerable differences in the shoulder season, with a maximum difference of 0.4 °C in October. This confirms the importance of infiltrations in the warm season and overheating risk.

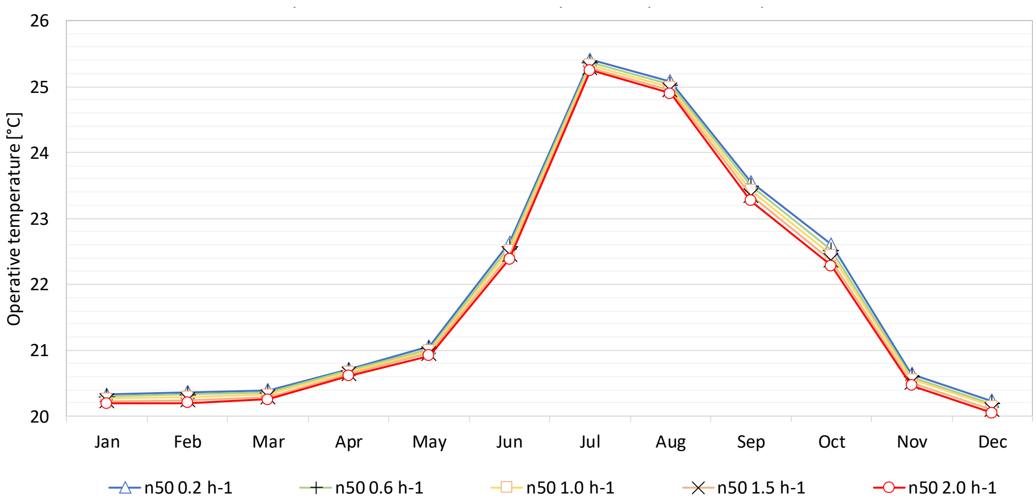


Figure 4.18: Impact of infiltrations in the monthly operative temperature indoor.

4.5.3. Impact of internal gains

This is one of the most uncertain aspects of the model adjustment. Firstly, the annual and monthly values were compared in Figure 4.19 and Figure 4.20, to check the general impacts on the heating need. Later, Figure 4.21 shows how a monthly deviation of internal use could affect the indoor temperatures.

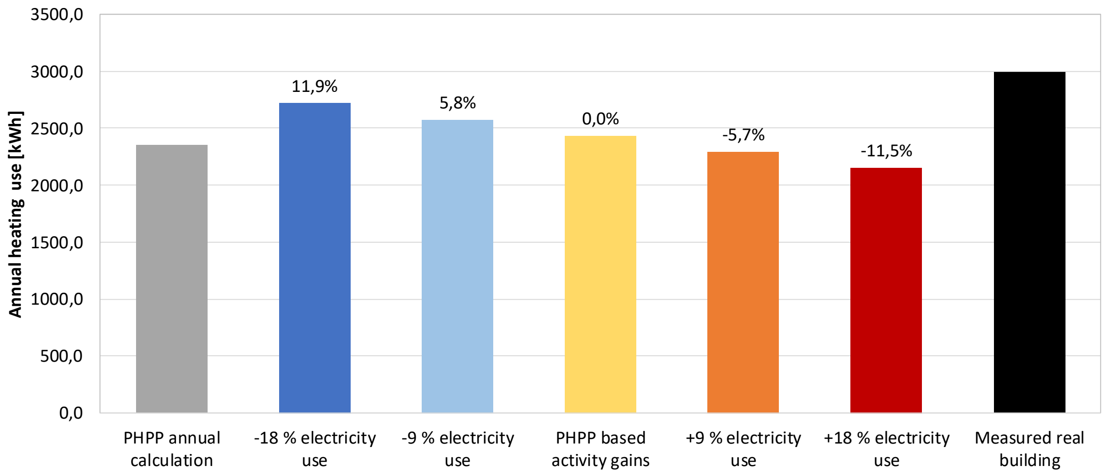


Figure 4.19: Impact of internal gains on the annual heating use.

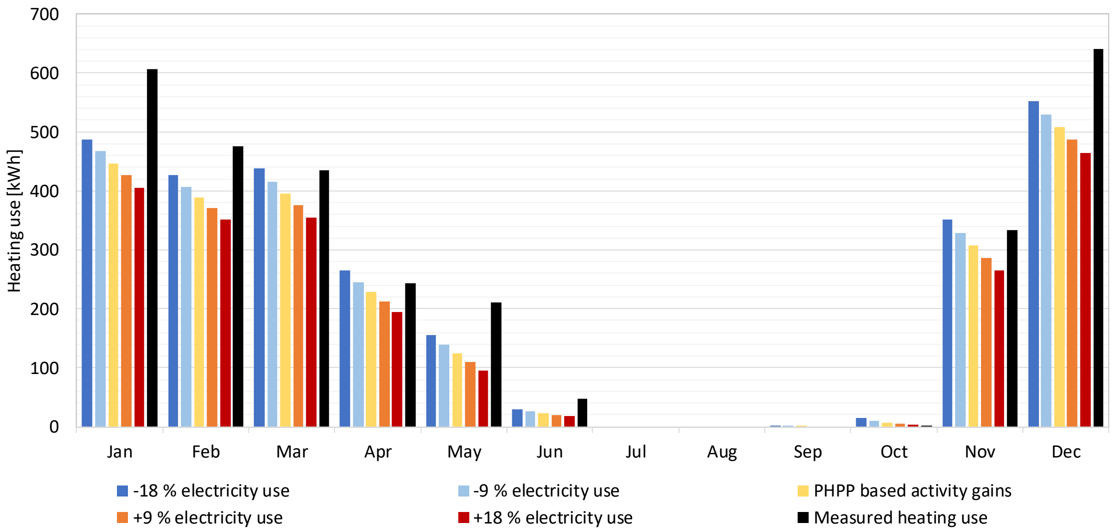


Figure 4.20: Impact of internal gains on the monthly heating use.

Based on these results, several particular corrections were made from the first homogeneous activity of summer and winter. This way, in the months were the deviations were too high, particularly between August and October the indoor activity levels were adjusted. In order to maintain the annual balance, the others months compensated the difference.

Consequently, the internal gains on the final model kept the measured and PHPP adjusted annual values of electricity use, but the monthly values were corrected.

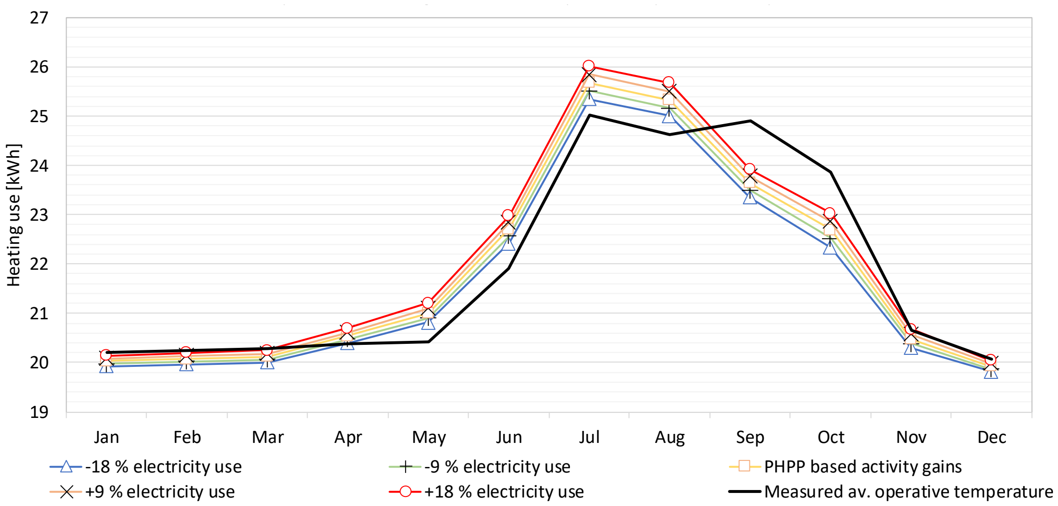


Figure 4.21: Impact of internal gains on the monthly operative temperature indoor.

4.5.4. Impact of thermal mass

The model is first defined with the theoretical thermal mass values, so the materials of the model were defined according to the density and heat capacity of their technical sheets. These values applied in the model ended becoming considerably large. Indeed, these values are larger than the PHPP assumptions and also larger than the heat losses predicted by the RC model of the house developed in Section 3.4.5, in previous Chapter 3.

To adjust the model, it was tested whether all the available thermal mass participates in the dynamic behaviour or not. To assess that, the heat capacity of the structural slabs and the concrete blocks was changed, with increases and reductions of 25 % and 50 %. As shown in the results of Figure 4.22, Figure 4.23 and Figure 4.24.

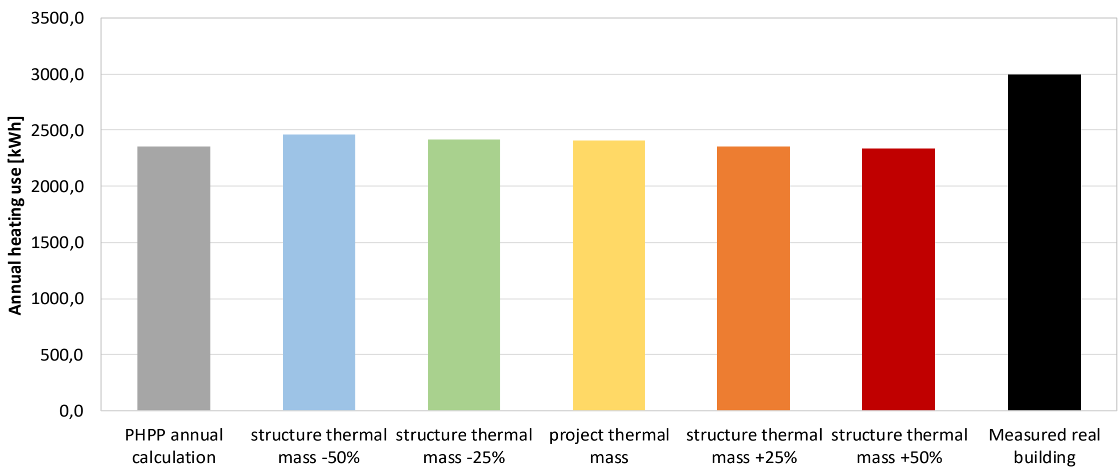


Figure 4.22: Impact of thermal mass on the annual heating use.

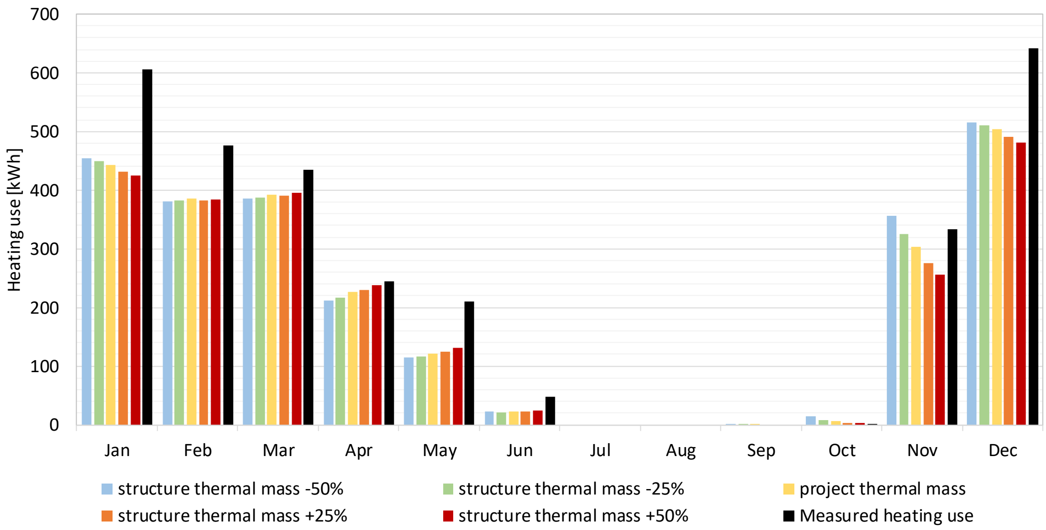


Figure 4.23: Impact of thermal mass on the monthly heating use.

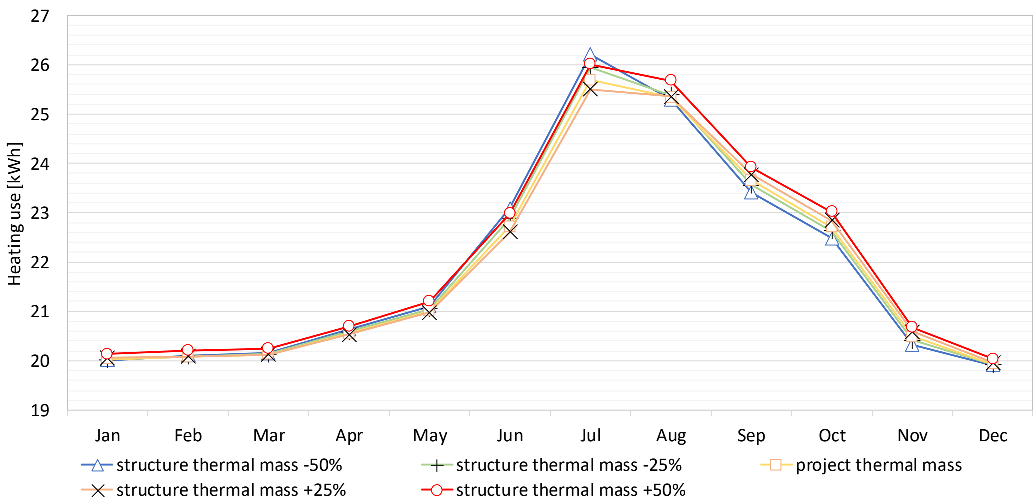


Figure 4.24: Impact of thermal mass on the monthly operative temperature indoor.

After the iteration process, the selected option includes 25 % less heat capacity in the concrete elements and provides a faster response to the indoor environment, which fits much closer to the real measurements, as shown in the error analysis of the Section 4.5.

4.6. Strategies to improve the thermal behaviour of the monitored case

Once the real case is represented in a model which can reflect the real behaviour with enough accuracy, a set of strategies are implemented to solve the problems identified in Chapter 3. The structure of the study is presented in Figure 4.25 below.

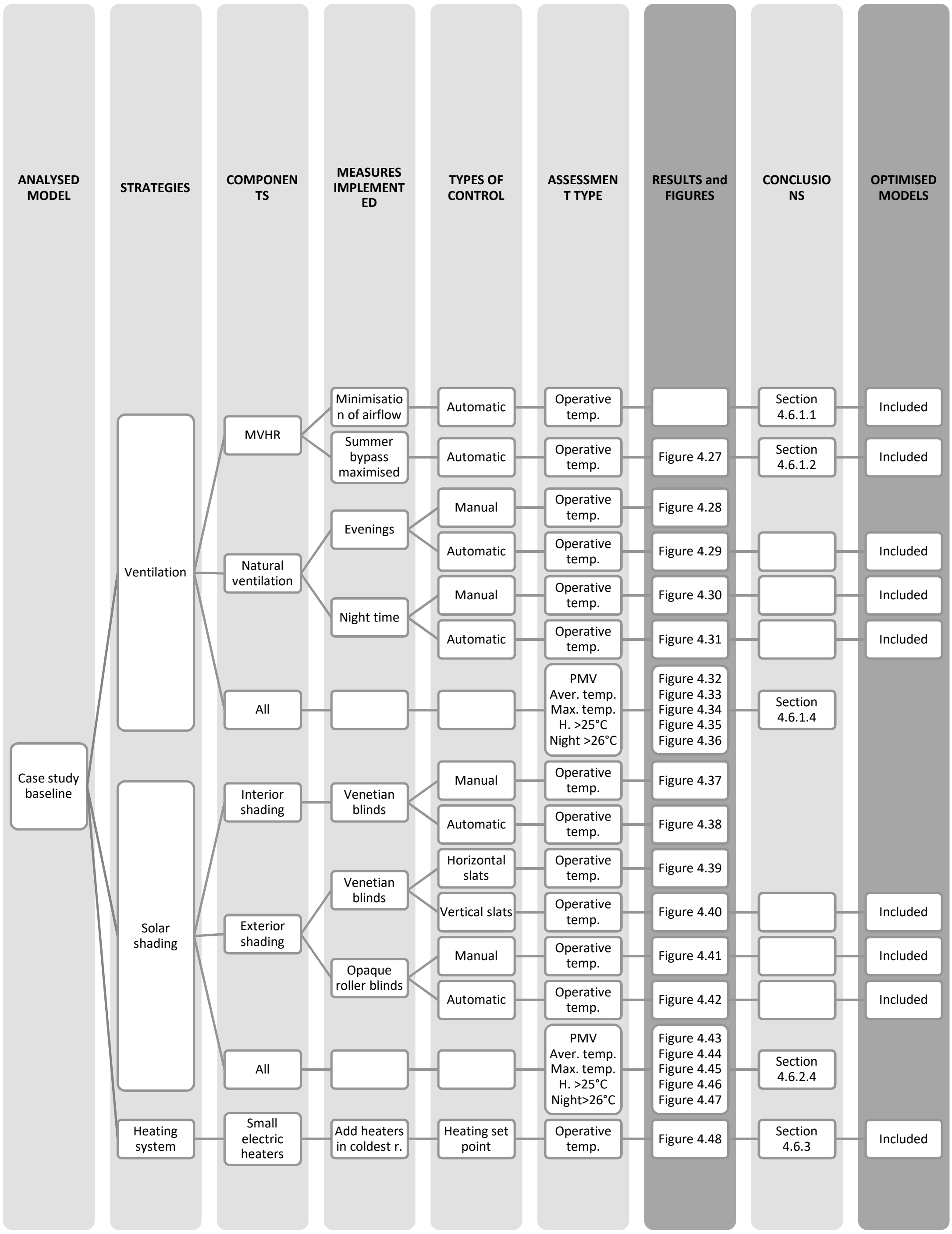


Figure 4.25: Diagram of the studied parameters and outcomes of Chapter 4.

The problems identified in Chapter 3 were mainly related with thermal discomfort, as explained in the thermal comfort study conducted in Section 3.4.8. Even though there was no overheating at the average house level, several rooms presented a large number of hours over TC limits of both Fanger and adaptive methods. For that reason, the users occasionally opened several windows to ventilate but the obtained effect was not enough. Thus, in order to help reducing the local discomfort, this study aims to identify the best supplementary components and strategies which can be installed in a passive house after its construction. The simulation model is the proper tool to test all possible strategies and reproduce the indoor conditions accurately. In Figure 4.26 and Table 4.7 are presented the hourly TC of the reference model and the indoor environment monthly.

The main optimisation objective consists of the reduction of the number of hot hours over 26 °C as much as possible in the carpet plots of the indoor temperature, since it can be considered a simplified value of the upper PMV summer comfort limit. The secondary objective is to improve the cool hours present in many winter weeks and specially in the night hours. Thirdly and last, the heating need should be also reduced or at least not increased by the strategies developed.

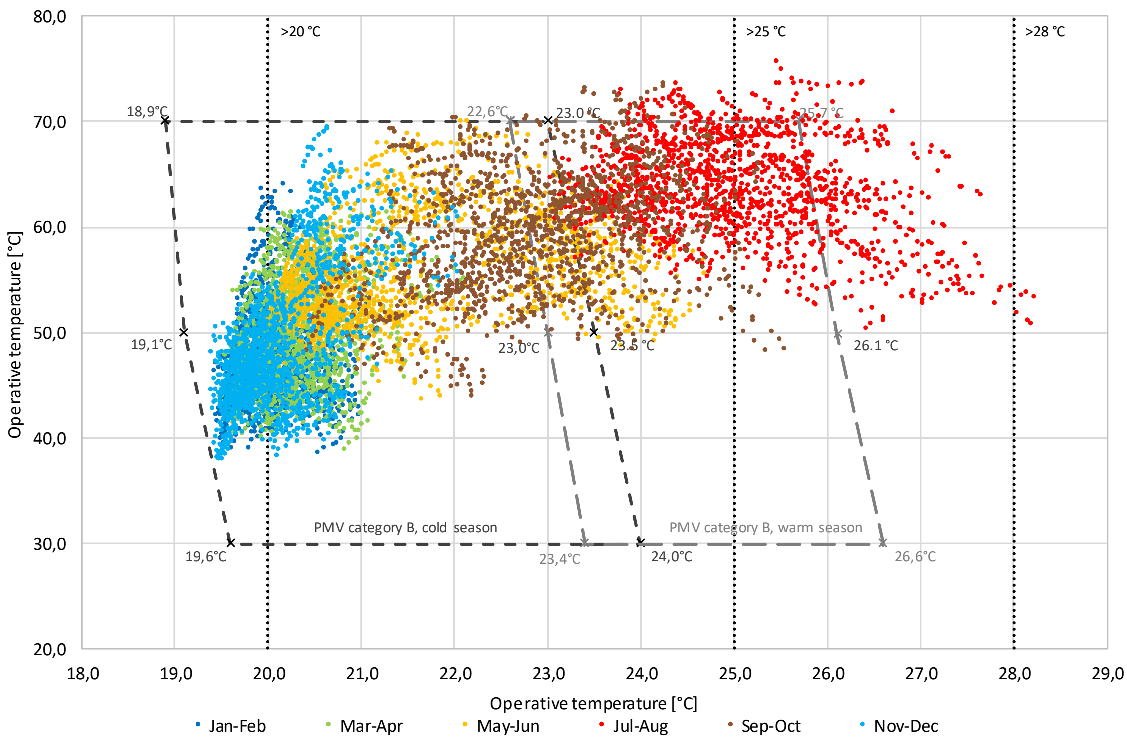


Figure 4.26: Thermal comfort of the reference model, PMV model of ISO 7730.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
CLIMATE CONDITIONS													
Monthly average temperature*	6,9	6,4	7,5	9,7	10,0	14,8	21,1	18,4	16,8	14,4	7,8	4,7	11,5
Min. daily average temperature*	2,1	2,2	0,3	1,9	6,8	9,9	17,8	15,3	12,5	7,4	-0,8	-0,6	-0,8
Max. daily average temperature*	12,6	14,8	12,7	18,0	16,7	22,1	23,9	28,8	21,0	21,8	15,9	12,4	28,8
Monthly average Relative Humidity	6,9	6,4	7,5	9,7	10,0	14,8	21,1	18,4	16,8	14,4	7,8	4,7	11,5
Global horizontal solar radiation	55,5	95,3	133,5	161,2	206,2	250,5	279,0	234,6	169,8	119,5	56,1	82,4	1843,5
HDD (18.3)	354	334	335	260	257	113	1	27	62	129	315	424	2612
CDD (25.0)	0	0	0	0	0	0	0	4	0	0	0	0	4
** All outdoor temperatures are dry bulb air temperatures*													
BUILDING HEATING/COOLING LOADS													
Heating: monthly use	544,9	439,1	450,9	265,0	153,2	28,8	0,0	0,0	0,0	12,4	382,4	576,8	2853,5
Daily average heating use	17,6	15,7	14,5	8,8	4,9	1,0	0,0	0,0	0,0	0,4	12,7	18,6	0,0
Max. daily heating load	5,6	5,5	5,1	5,0	3,0	2,1	0,0	0,0	0,0	1,0	5,9	6,0	6,0
Cooling: monthly use	0	0	0	0	0	0	0	0	0	0	0	0	0
Daily average cooling use	0	0	0	0	0	0	0	0	0	0	0	0	0
Max. Daily cooling use	0	0	0	0	0	0	0	0	0	0	0	0	0
INDOOR ENVIRONMENT													
Average temperature*	20,0	20,2	20,2	20,5	20,9	22,6	25,3	24,7	23,3	22,5	20,4	20,0	21,7
Min. daily av. temperature*	20,2	20,2	20,3	20,3	20,6	20,7	23,8	23,7	22,3	21,0	20,2	20,2	20,2
Max. daily av. temperature*	20,8	20,8	20,8	21,4	21,4	23,7	26,6	27,6	24,5	24,2	21,5	20,5	27,6
Max. temperature *	21,0	21,2	21,1	22,2	22,2	24,7	27,7	28,3	25,6	25,3	22,1	21,0	28,3
hours t* <20 °C	351,0	261,0	240,0	49,0	1,0	0,0	0,0	0,0	0,0	0,0	224,0	424,0	1550,0
hours t* >25 °C	0,0	0,0	0,0	0,0	0,0	0,0	454,0	234,0	22,0	8,0	0,0	0,0	718,0
hours t* >28 °C	0,0	0,0	0,0	0,0	0,0	0,0	0,0	6,0	0,0	0,0	0,0	0,0	6,0
Night hours t > 26°C	0	0	0	0	0	0	13	29	0	0	0	0	42
hours RH >70 %	0	0	0	0	0	1	84	32	6	27	0	0	150

** All indoor temperatures are operative temperatures*

Table 4.7: Reference model simulation results of the case study, summary of climate conditions, building heating load and indoor conditions.

4.6.1. Ventilation improvements and ventilative cooling strategies

Table 4.8 includes the details of all the tested ventilation strategies. The control limits of bypass and natural ventilation are related with the limits of PMV, since the house is mainly working with the MVHR unit and also because it is more restrictive.

Table 4.8: Summary of applied ventilation strategies

ID	Principle of ventilative cooling	Components used for ventilation	Control strategies	Schedule
Ref	Real case, bypass in summer	MVHR with bypass constant airflow	Bypass if indoor t. >24 °C Bypass closed if out. t. <13 °C	All year
V1	Minimum airflow, bypass in summer	MVHR with bypass constant min. airflow	Bypass if indoor t. >24 °C Bypass closed if out. t. <13 °C	All year
V2	Enhancement of bypass airflow	MVHR with bypass and programming function	Bypass increase airflow if indoor t. >24 °C Outdoor t. < indoor t. Min. outdoor t. 13 °C Max. airflow of MVHR PH certificate	All year
V3m	Natural ventilation evenings, manually	Tilt and turn windows, 10% upper opening	Manual opening of main windows if indoor t. >23.5 °C Outdoor t. < indoor t. Min. outdoor t. 13 °C Also, constant bypass of V1	June -September 3 days/w (M, W, F) 21:00 – 24:00 h.
V3	Natural ventilation evenings, automatic	Tilt and turn w., 10% upper opening Chain actuator	(Same as above)	June -September Everyday 21:00 – 24:00 h.
V4m	Night natural ventilation, manually	Tilt and turn w., 10% upper opening	(Same as above)	June -September 3 days/w (M, W, F) 21:00 – 07:00 h.
V4	Night natural ventilation, automatic	Tilt and turn w., 10% upper opening Chain actuator	(Same as above)	June -September Everyday 21:00 – 07:00 h.

4.6.1.1. Correction of the minimum ventilation airflow

As explained in the monitoring chapter, the airflow of the real case was slightly oversized because the operation of the AHU is limited to the programmed airflow levels. Consequently, the first improvement strategy (V1) consists of reducing this excess of ventilation and analysing the heating reduction potential. To do that, the MVHR airflow is reduced up to the recommended airflow of 169.0 m^3/h, as defined in the PHPP calculations. This reduces the 7.3 % of the fresh air supply and lowers the number of ACH from 0.41 to 0.37 h^{-1}.

As a result, the winter heating use is reduced in 1.3 %. This small reduction can be explained by the very high performance of the heat recovery unit, which actually recovers the 86.3 % of the sensible heat losses through ventilation, as explained in Section 3.4.6. On contrary, the summer behaviour of the house is also slightly affected by a smaller bypass air flow. Consequently, the free-cooling is reduced from 772.0 kWh to 714.8 kWh, precisely a 7.4 % less free-cooling during the warm season. However, this reduction is certainly small and the effect in the whole building is a subtle warmer environment, barely a tenth of a degree in the peak hour of August.

Considering these small changes, there is a small reduction of the heating use and the house temperatures remain almost the same, with very small variations.

4.6.1.2. Enhancement of the summer bypass airflow

The second improvement (V2) consists of the usage of increased airflow when the bypass is operating. So, the free-cooling obtained through the MV-bypass is increased as much as possible considering the recommended maximum airflow for the ventilation system.

In the case of passive houses, the ventilation units have a certain range of operation which is considered as high efficient. The PHI certifies the performance according to their own method, which embraces not only the sensible heat recovery but also the electricity consumption of the fans. This method is explained in Passipedia database, see Figure 4.27 below (Passipedia, 2016). In the case of study the maximum airflow supported by the PHI certificate is 245 m^3/h, as detailed in Table 4.9. Accordingly, the airflow during bypass is increased up to 0.55 h^{-1} ACH providing additional free-cooling.

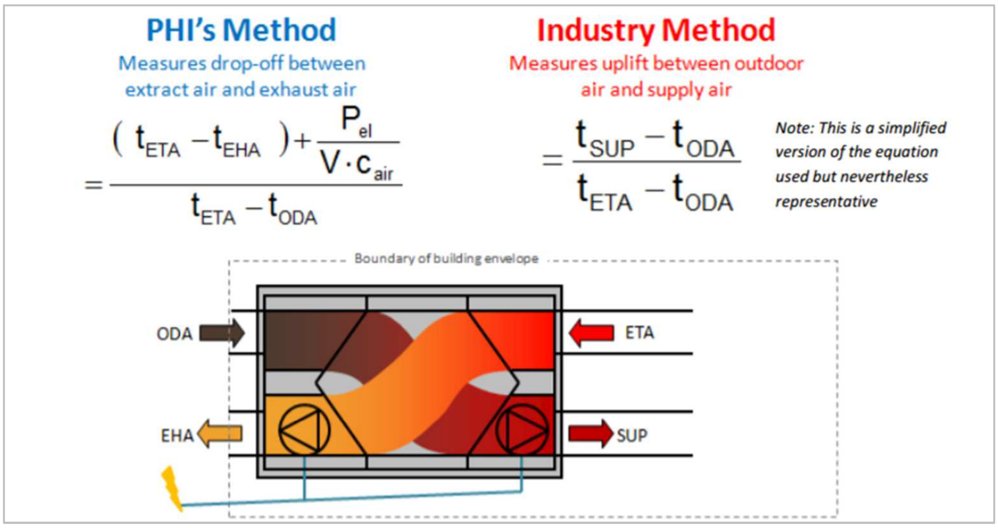


Figure 4.27: PHI and industry formulas for MVHR unit efficiency calculation (source Passipedia.org)

Furthermore, the limits of operation of the bypass remain the same. So, the bypass only operates if indoor temperature is over 24 °C and the outside is cooler than the inner space. Besides, the operation of bypass is closed during the coldest hours before sunrise because when the outdoor temperatures go below 13 °C the bypass is closed to prevent any condensation on the inner duct network.

As a result, the free-cooling augments in 9.0 % between June and September and the overall number of hours over 25 °C decrease a very significant 19.5 %, from 750 to 604 hours. Despite this general improve, the bypass shows little potential to reduce the peak hours, because the maximum temperatures of July and August decrease only 0.3 °C. Thus, the enhanced bypass doesn't fix the extreme temperatures and makes no difference in the hottest hours of summer. All these values are compared and analysed in the Section 4.6.1.4 in more detail.

Table 4.9: Case study MVHR specifications and operation levels

Level or position	**1 (min)**	**2**	**3***	**4***	**5***	**6***	**7 (max)**
Airflow (m³/h)	51	87	123	159	187	222	300
Operation (%)	17	29	41	53	63	74	100
Power use (W)	11	18	28	38	45	53	78
SFP (Wh/m³)	0,22	0,22	0,23	0,24	0,24	0,24	0,26

** Passive House Institute certified levels of operation*

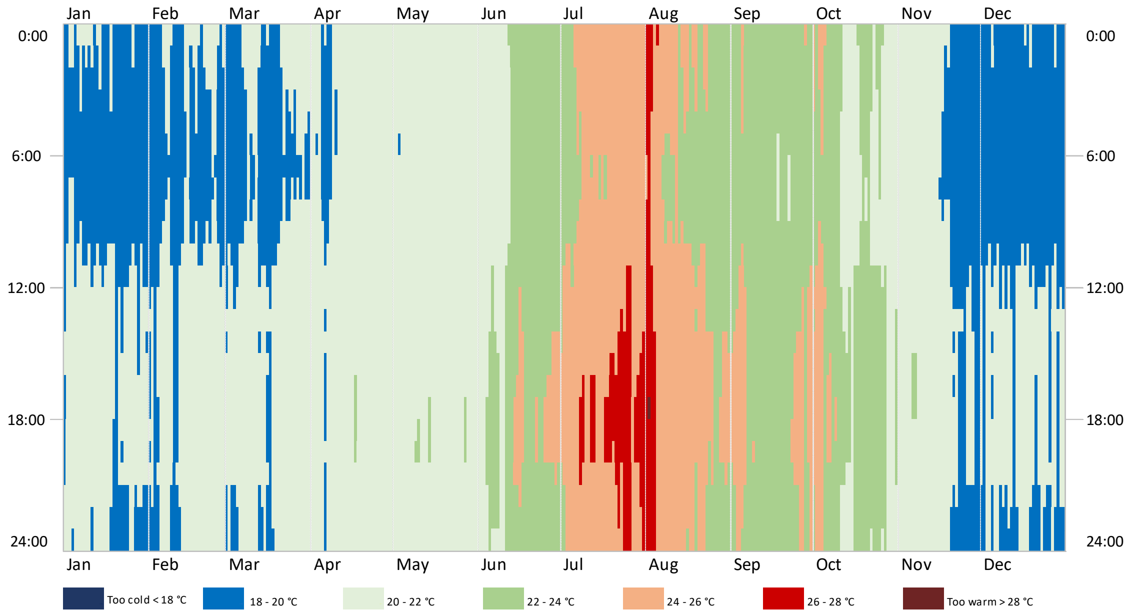


Figure 4.28: Summer bypass enhanced to maximum high efficient level,
from June to September when outdoor is cooler than indoor and outer temperature is over 13 °C.

4.6.1.3. Natural ventilation implementation

After verifying the limit usage of the MVHR, the need of additional ventilation is addressed considering the available components in the house. The majority of the windows are tilt and turn and so permit an easy opening control around the 10 % of their surface area. Besides, the biggest windows of the living room have also a smaller side-pane with tilt and turn option. This possibility was actually used by the users from time to time during the warmest days of summer nights. To assess the adequate degree of natural ventilation which solves the issue, several operation and schedule possibilities are analysed.

Firstly, a short natural ventilation operation is implemented during a maximum of 3h (V3m and V3 measures). As mentioned before, this type of natural ventilation was indeed used from time to time in the real case during short periods in the hottest days. The windows are open between 21 h and 24 h in the main rooms: bedrooms, living room, dining room, dressing room and music room. The windows stay open when the outdoor temperature is significantly lower than the inside, that is 3 °C lower than the indoor. The maximum ventilation is calculated according to the temperature and wind factors explained in (1) and it is also limited to 6 ACH, to avoid problems caused by excess of air speed.

This short ventilation is applied in two ways, manually (V3m) and automatic (V3). The first one implies that users have to control the opening and closure of the windows and naturally it has a considerable margin of uncertainty. According to the monitoring, the habits of the inhabitants allow natural ventilation after 21:00 in the majority of the days and until midnight. To reflect this lack of control, the natural ventilation is limited to operate only in 3 working days per week, what means that users will remember to open or close the windows only in Mondays, Wednesdays and Fridays. This manual approach is considered to be reasonable according to the measurements and the observed habits during the monitored summer. This way, the simulation can reflect a more realistic operation in the long run with a manual operation in less the half of the days. The second one, is an automatic control programmed during all days from June to September when the indoor and outdoor conditions are met.

The natural ventilation operation permits to lower significantly the indoor temperatures, as shown in Figure 4.29 and Figure 4.30. As a result, the number of hours over 25 °C decrease very significantly from 750 h to 553 h in the manual operation (3 days per week). The effect of the automatic operation (every day) is more successful, because the hot hours are cut down by half, being only 377 h over 25 °C. Regarding the night hours over 26 °C, they are also reduced from 26 h to 17 with the manual operation and to 11 with the automatic operation. On the other hand, the peak hours remain almost equal with subtle differences of few tenths of a degree.

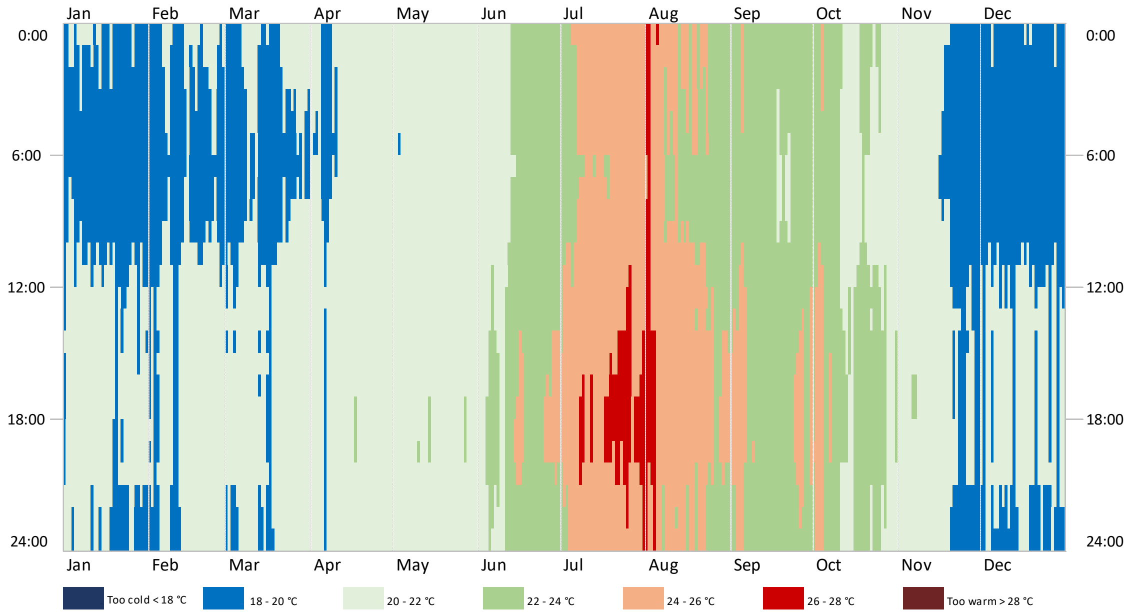


Figure 4.29: Natural ventilation manually, 3 days per week windows opened 10 % from 21:00 to 24:00 h (Monday, Wednesday and Friday) and closed if indoor operative temperature is below 23.5 °C or outdoor temperature is below 13 °C.

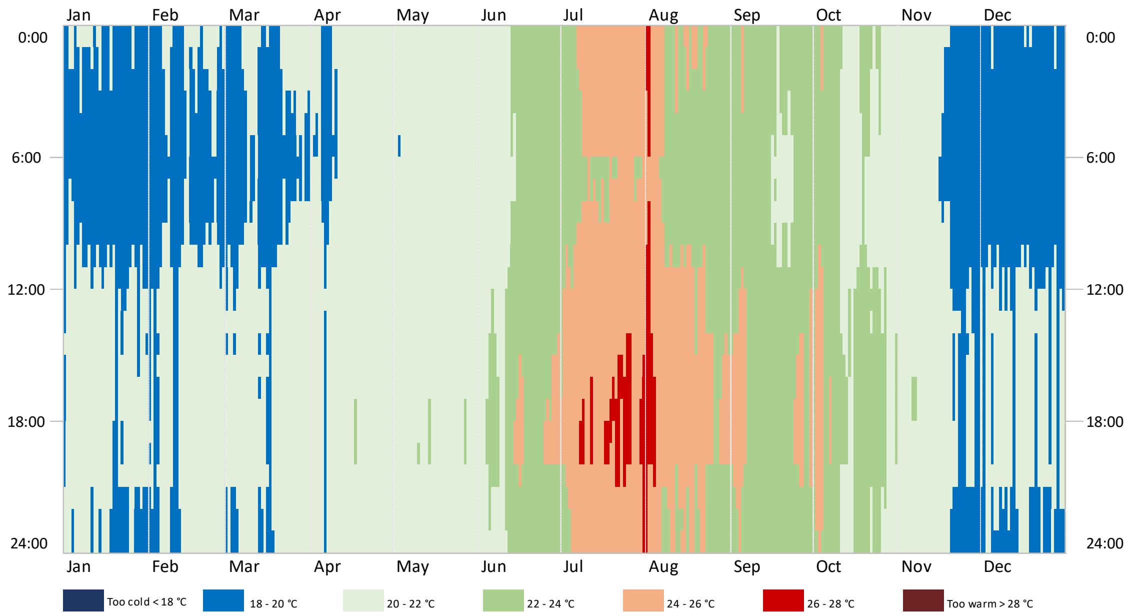


Figure 4.30: Natural ventilation with automatic control, every day windows opened 10 % from 21:00 to 24:00 h and closed if indoor operative temperature is below 23.5 °C or outdoor temperature is below 13 °C.

Secondly, since the 3 hours of natural ventilation seem to be not enough, the natural ventilation is extended overnight to use all the available free-cooling. Thus, the natural ventilation is used from 21:00 h until 07:00 h, in correspondence with the habits of the occupants. The doors of rooms are closed during night to preserve the privacy and the windows are closed in case the temperature of the rooms drops below 23.5 °C or the outside gets below 13 °C. Besides, two scenarios of control are analysed like in the previous strategy of natural ventilation: the manual operation three days per week and the automatic control.

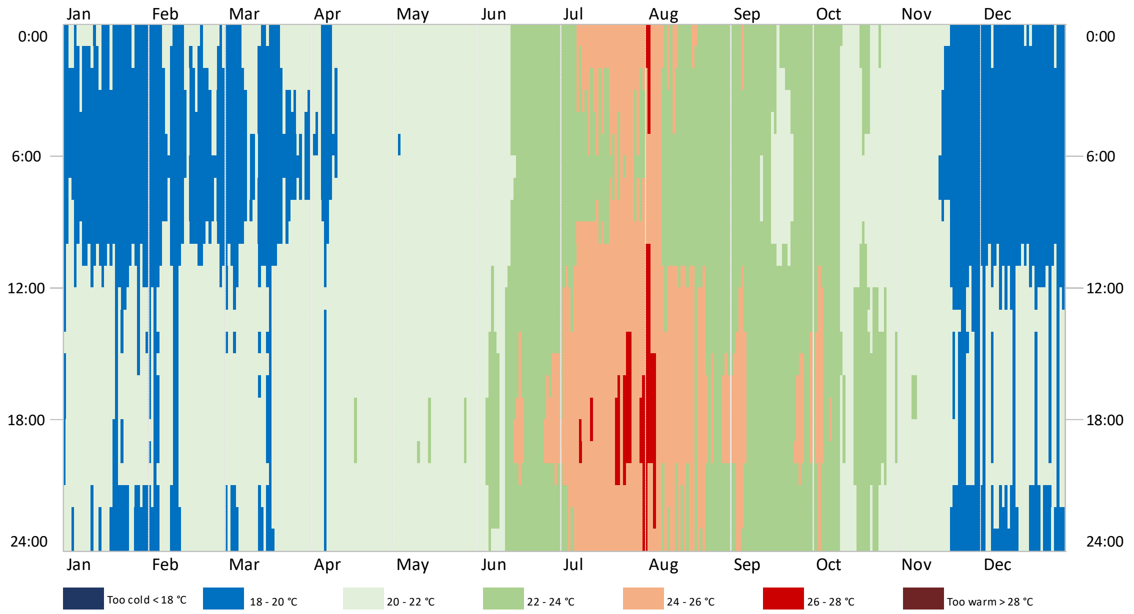


Figure 4.31: Night natural ventilation manually, 3 days per week windows opened 10 % from 21:00 to 07:00 h (Monday, Wednesday and Friday) and closed if outdoor temperature is below 13 °C.

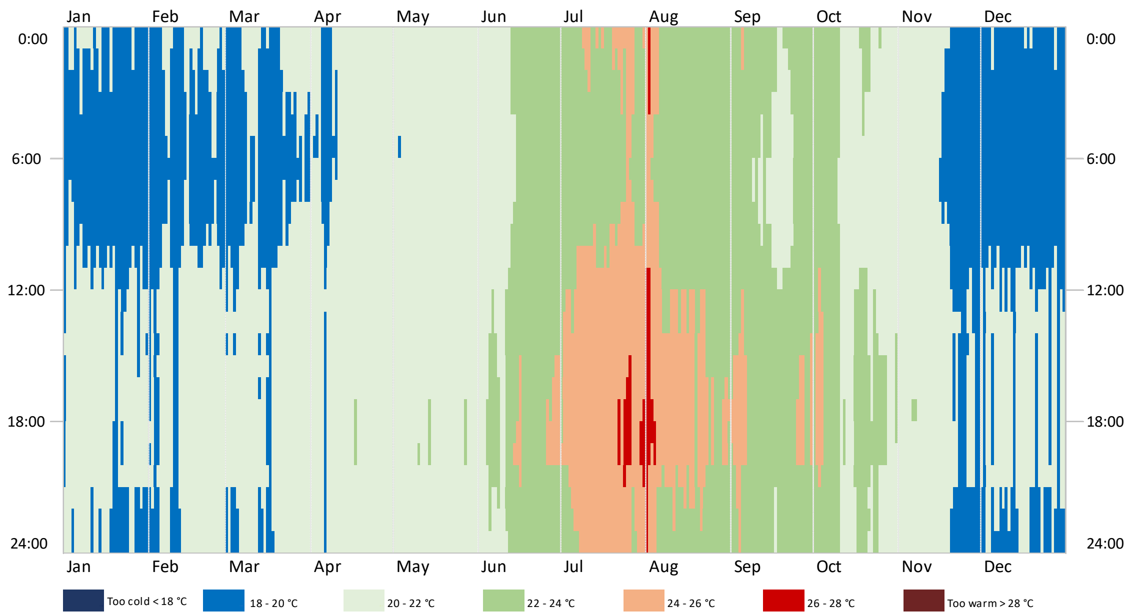


Figure 4.32: Night natural ventilation with automatic control, every day windows opened 10 % from 21:00 to 7:00 h and closed if indoor operative temperature is below 23.5 °C or outdoor temperature is below 13 °C.

This level of ventilation seems to be high but it is interrupted often due to the cool nights below the limit. To avoid this, windows should include a device to control accurately the ventilation airflow. As suggested by the SOTAR document of IEA-EBC Annex 62 Ventilative Cooling (Kolokotroni & Heiselberg, 2015).

In any case, the night natural ventilation can easily control the temperatures of the house during the majority of the summer, as shown in Figure 4.31 and Figure 4.32. The number of hours over 25 °C is decreased up to 341 h with manual operation and 253 h with automatic control (2.9 % of annual hours). The number of night hours over 26 °C are also reduced from the reference 48 to 8 h and 5 h respectively. In a similar way, the peak hours and the average hours are decreased. All these values are compared and analysed in the Section 4.6.1.4 in more detail.

4.6.1.4. Assessment of the improvements achieved with each ventilation strategy

To analyse the potential of each strategy, firstly the warm discomfort hours related with each strategy is plot in Figure 4.33. It shows the improvement reached by each strategy and it demonstrates how the warm thermal discomfort can be reduced below 3 % of the total annual hours using only ventilation strategies, without supplementary solar shading elements.

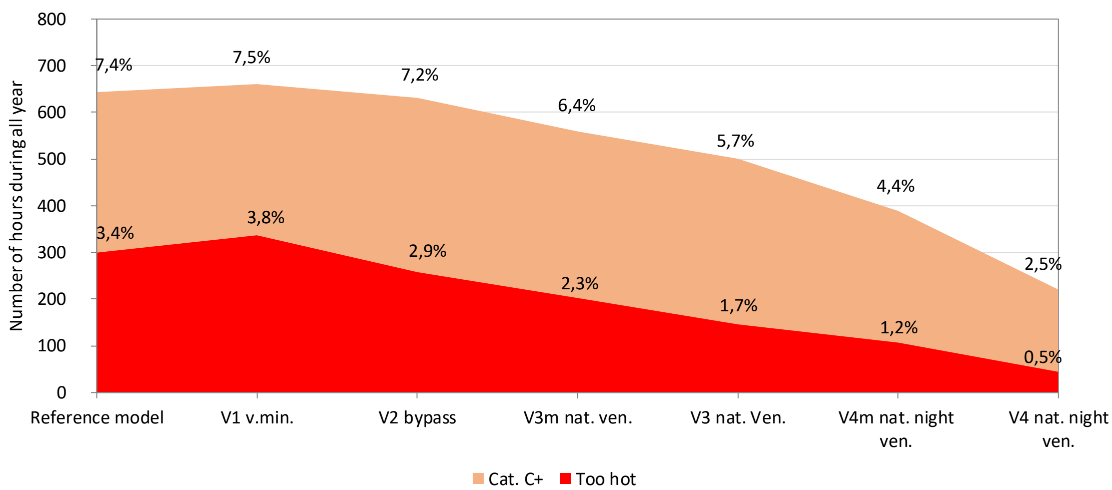


Figure 4.33: Ventilation strategies effect on the warm discomfort according to PMV model, ISO 7730.

Furthermore, the following plots gather the main indicators of the indoor thermal environment, including the monthly average temperatures, the maximum daily temperatures of each month, the hours over 25 °C in all summer and the number of hours over 26 °C during night-time (23:00 - 07:00 h).

Figure 4.34 represents the average values of each month in contrast with the reference model monthly average and the range of daily minimum and maximum indoor temperatures. Besides, Figure 4.35 indicates the hottest daily temperatures under each strategy. The ventilative cooling strategies are active when the indoor environment is over 24 °C or 23.5 °C in the cases of night time ventilation. So, the effect more patent in the warmest months.

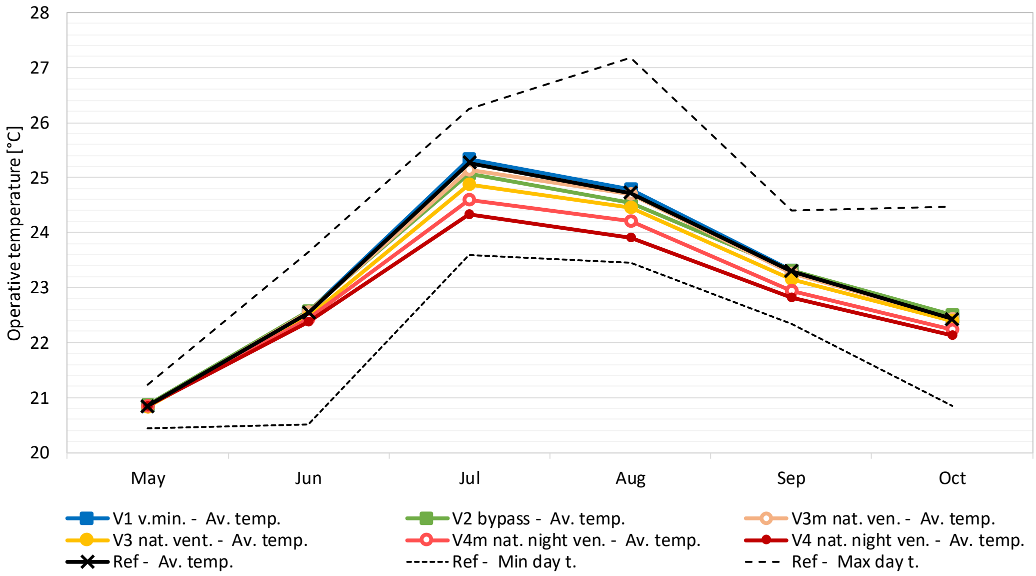


Figure 4.34: Ventilation strategies effect on monthly average operative temperatures.

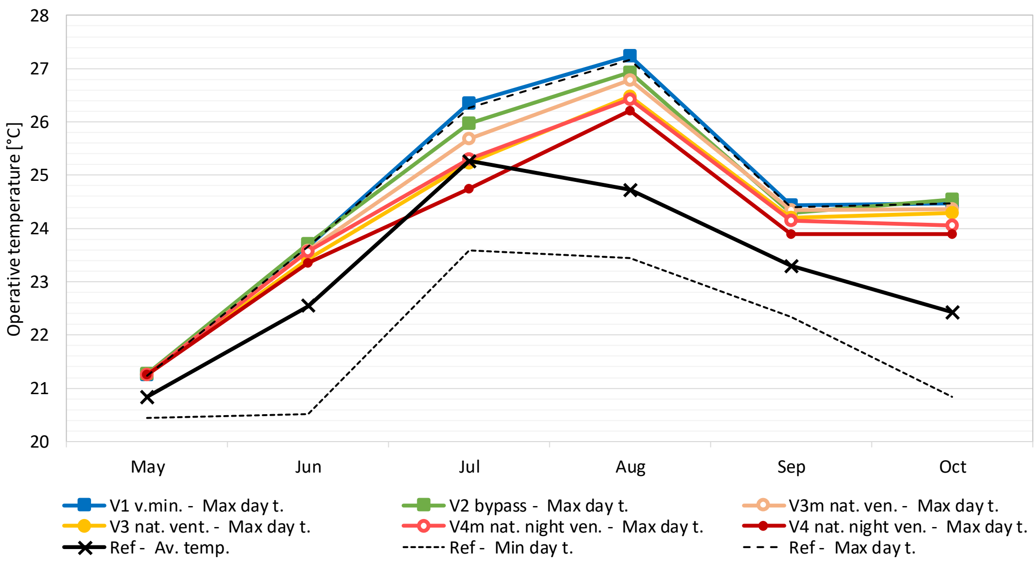


Figure 4.35: Ventilation strategies effect on maximum daily operative temperatures.

Figure 4.36 shows the number of hours over the Passive house threshold (25 °C) in each month. All the cases are within the limit of 10 % of annual hours, varying from the 8,6 % of the reference model to the 2.9 % with the automatic night natural ventilation.

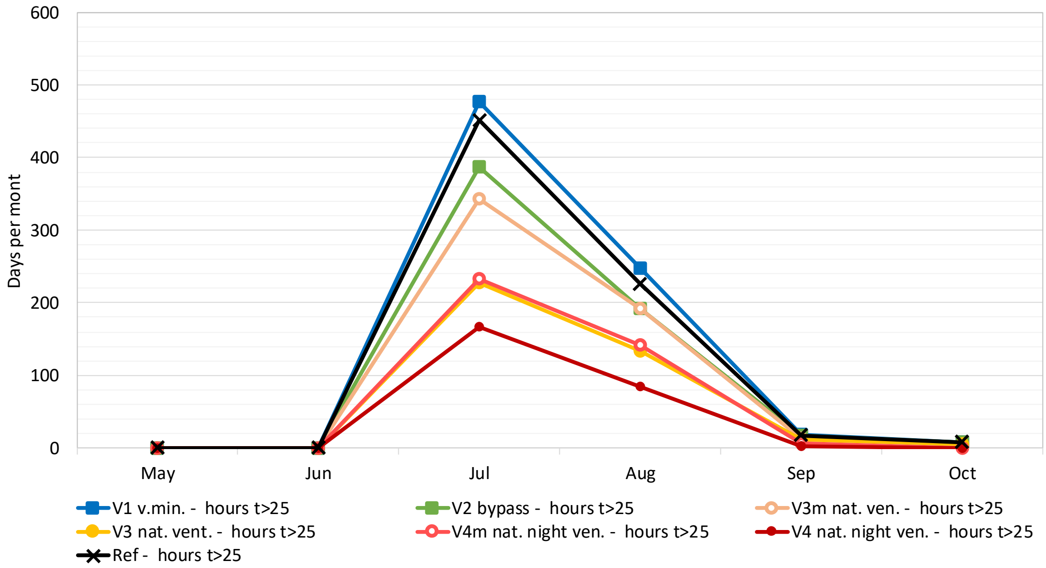


Figure 4.36: Ventilation strategies effect on number of total hours over 25°C.

On the other hand, considering the relevance of the night time comfort exposed in the Chapter 2, they are represented in Figure 4.37. It manifests how the lower ventilation rate of V1 can lead to hottest night hours and how the enhanced bypass can correct significantly this problem.

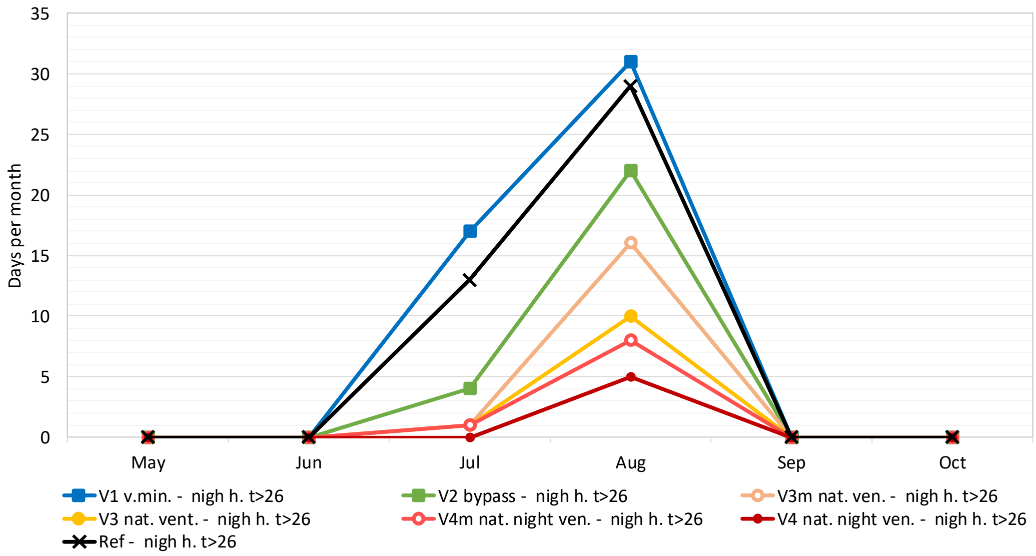


Figure 4.37: Ventilation strategies effect on number of night hours over 26°C.

4.6.2. Solar shading strategies

The need of an adequate passive solar shading is highlighted by the majority of the nZEB design manuals (REHVA & ES-SO, 2010) (Race et al., 2010) and the latest PH design guides (Hopfe &

McLeod, 2015) (Cotterel & Dadeby, 2012). Moreover, ventilative cooling strategies can be more efficient if they are applied in combination with solar shading systems (Kolokotroni & Heiselberg, 2015). This is especially important due to the high contribution of solar gains to the annual balance of passive houses, in our case it covers 30 % of the annual heating need.

The studied case presents already long overhangs, calculated according to the local sun elevation in summer and winter. These elements contribute certainly to reduce the excess of solar gains but according to the monitored comfort and the simulation results, they are unable for keeping indoor temperatures inside thermal comfort range, as seen in Chapter 3.

The use of external blinds or shutters is very common in all the regions of Spain in the vernacular architecture, as studied in further detail in a recent thesis of PH application into northern Spain (Rodriguez Vidal, 2015). They are commonly used for a double reason: as a way to avoid the heat gains due to sun radiation in summer and also to reduce the heat losses through the windows in winter nights. In Figure 4.38 there are some examples of conventional solar control elements.

Surprisingly, the majority of the Passive houses constructed in Spain for now didn't install any blinds (see Chapter 5, review of Spanish PH cases). This is probably related with the fact that traditional roller blinds can increase the thermal bridges between wall and windows. Besides, they are an additional risk for air leakages which are crucial to achieve a passive house certification.

Figure 4.38: Examples of blinds and shutters in Spain (sources: www.strugal.com, www.metalicasoleta.com, www.hunterdouglas.cl)

In any case, only the lightweight products are selected for the present case, because it is the only way they could be installed without affecting the thermal insulation of the existing construction or the airtightness. Since the facades are built with an outer EPS layer, as described in Section 1.2.2, the selected solar shading types are venetian blinds and external roller blinds. The venetian blinds are tested in the inside or outside and in horizontal or reflection position as explained in Table 4.10.

Figure 4.39: Proposed solar shading systems, external roller blind, external venetian blinds and internal venetian blinds (sources: www.dandcdesign.com, www.architectsjournal.co.uk and www.factorydirectblinds.com)

Table 4.10: Summary of applied solar shading strategies

ID	**Type of solar shading**	**Components used for shading**	**Control strategies**	**Schedule**
Ref	Real case, roof extensions	Construction design	Designed with summer and winter South solar elevation	Always
S1m	Int. retractable venetian blinds, manually	Venetian blinds to control glare and direct sun	Down if indoor t. >24 °C	June -September 3 days/w (M, W, F) 08:00 – 20:00 h.
S1	Ext. ret. venetian blinds, automatic	Venetian b. with automatic control	Down if solar >200 W/m²	June -September
S2b	Ext. ret. venetian blinds, automatic, in closed position	Venetian b. with angle regulation	Down and closed if solar >200 W/m²	June -September
S3m	Ext. opaque roller blinds, manual	Opaque roller blinds	Down if indoor t. >24 °C	June -September 3 days/w (M, W, F) 08:00 – 20:00 h.
S3	Ext. opaque roller blinds, automatic	Opaque roller blinds with automatic control	Down if solar >200 W/m²	June -September

4.6.2.1. Interior venetian blinds

Indoor venetian blinds can improve the glare control and visual comfort, however, from the thermal point of view they don’t avoid solar gains. Surprisingly, this type of blinds was installed by the users after the monitoring period in several rooms to reduce direct sunlight. The simulation results are summarised in Figure 4.40 and the values in comparison with the reference case are slightly warmer in summer.

This first case includes a manual control, similar to the used for the ventilation. This means that the shadows are down only during three days per week (Monday, Wednesday and Friday) and only if there is considerable sunlight to be noticed by users (over 200 W/m²).

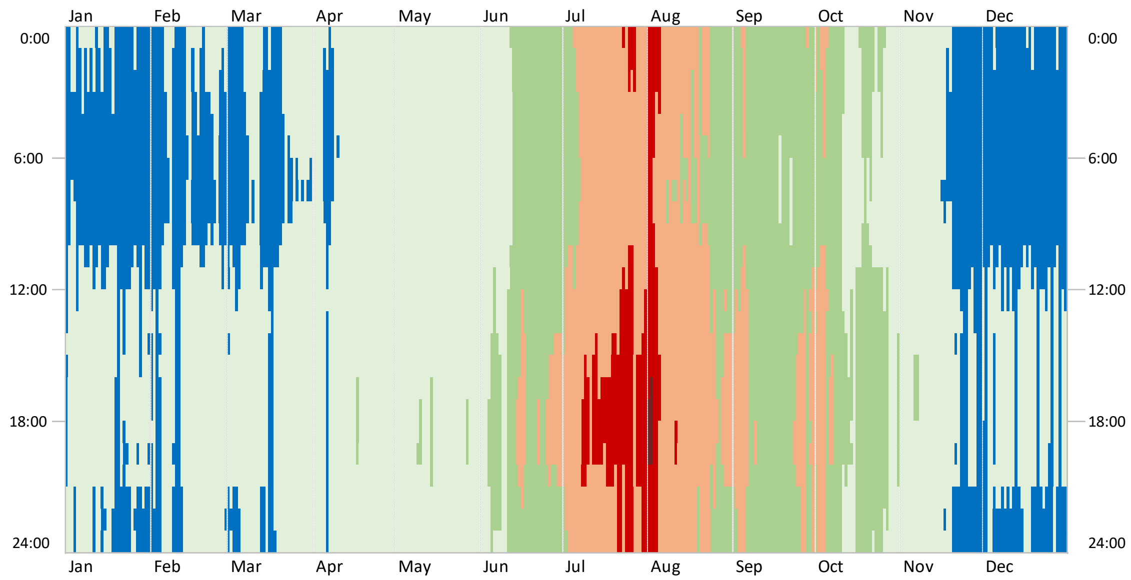


Figure 4.40: Indoor temperatures with interior venetian blinds with manual control, from June to September 3 days per week (Monday, Wednesday and Friday), down from 08:00 to 20:00 h if direct solar radiation is over 200 W/m².

The automatic control with daily activation after a overpassing 200 W/m² of solar radiation level is plot in Figure 4.41 and it almost doesn't affect the TC of the house.

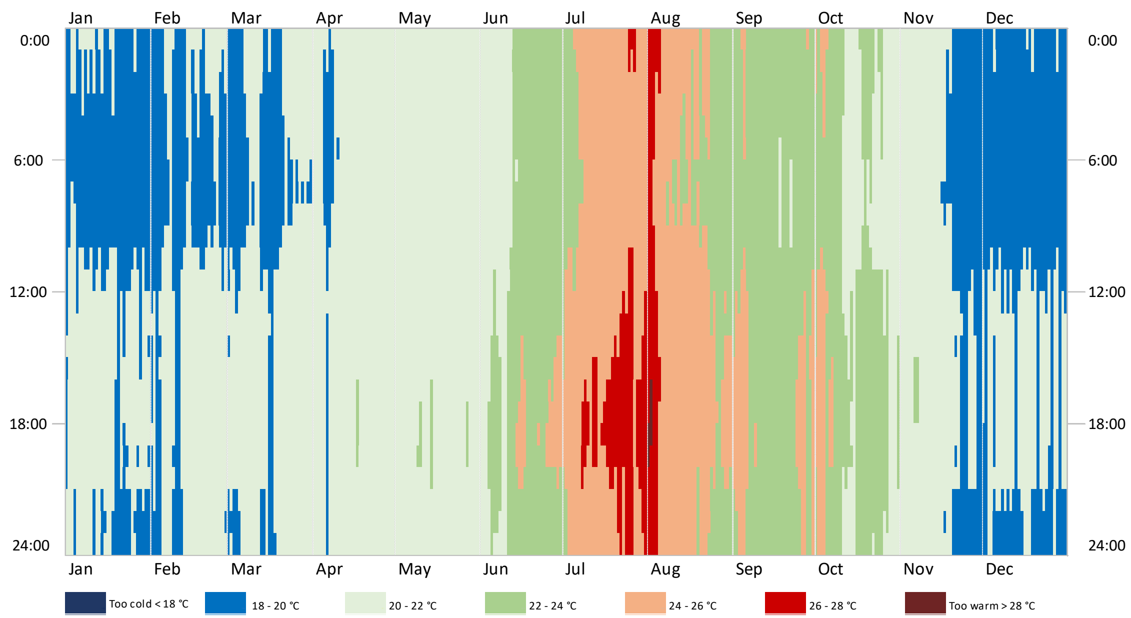


Figure 4.41: Indoor temperatures with interior venetian blinds with automatic control, every day down from 08:00 to 20:00 h if direct solar radiation is over 200 W/m².

4.6.2.2. Exterior venetian blinds

The use of external horizontal blinds in a horizontal position is plot in Figure 4.42 and it presents more hours over 26 °C. This can be observed in the first days of August, after a short heat wave when the outdoor minimum temperatures remain over 20 °C during three days. On contrary, the use of these venetian blinds with a protection angle can reflect the majority of the solar radiation and for this reason the Figure 4.43 evidences a very considerable reduction of hot hours. Therefore, this system has a high potential in combination with other measures.

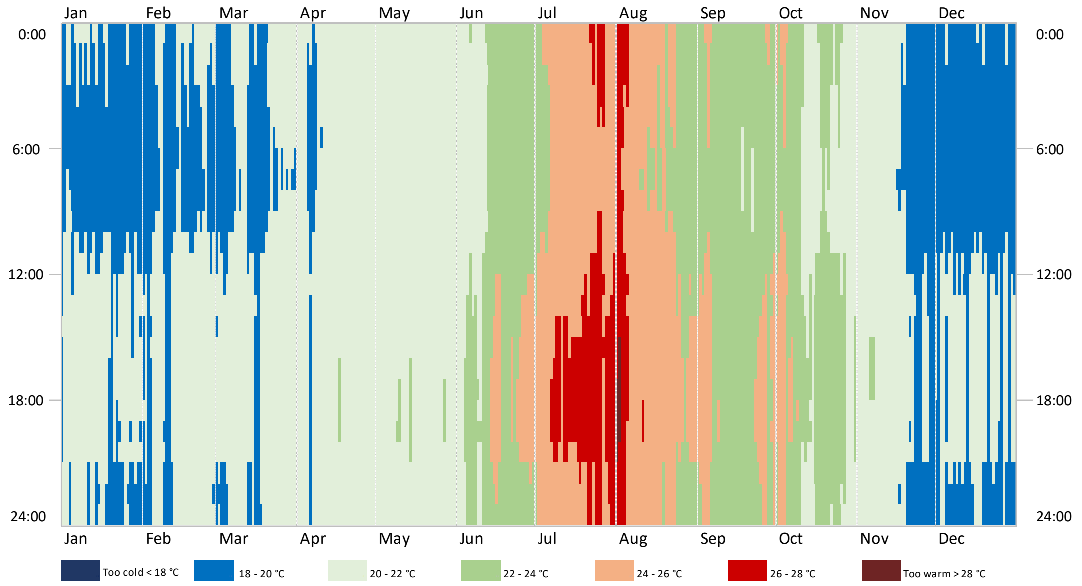


Figure 4.42: Indoor temperatures with horizontal venetian blinds outside with automatic control, from June to September every day, down from 08:00 to 20:00 h if direct solar radiation is over 200 W/m².

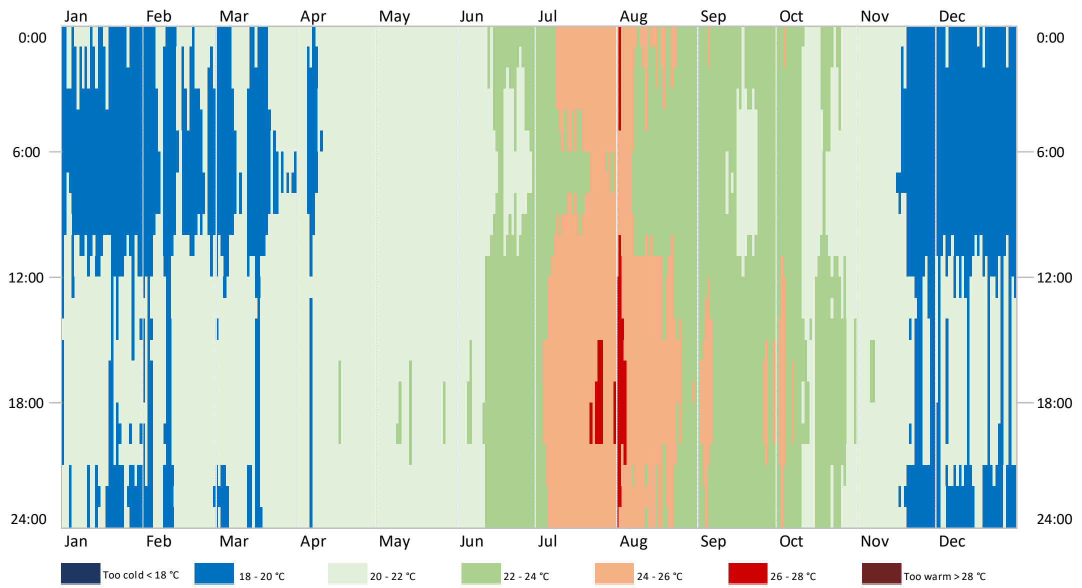


Figure 4.43: Indoor temperatures with external venetian blinds, in vertical position and automatic control, from June to September, down from 08:00 to 20:00 h if direct solar radiation is over 200 W/m².

4.6.2.3. External roller blinds

The use of external roller blinds with manual operation is plot in Figure 4.44. Despite the limited usage for the manual operation in 3 days per week, it shows a considerable reduction of the hours over 26 °C. It also eliminates fully the hours over 28 °C and many night hours over 26 °C. The automatic control of this system can provide a larger benefit, as presented in Figure 4.45. Overall, the tested sun protections are not able to suppress all the warm hours and it would require other passive cooling measures.

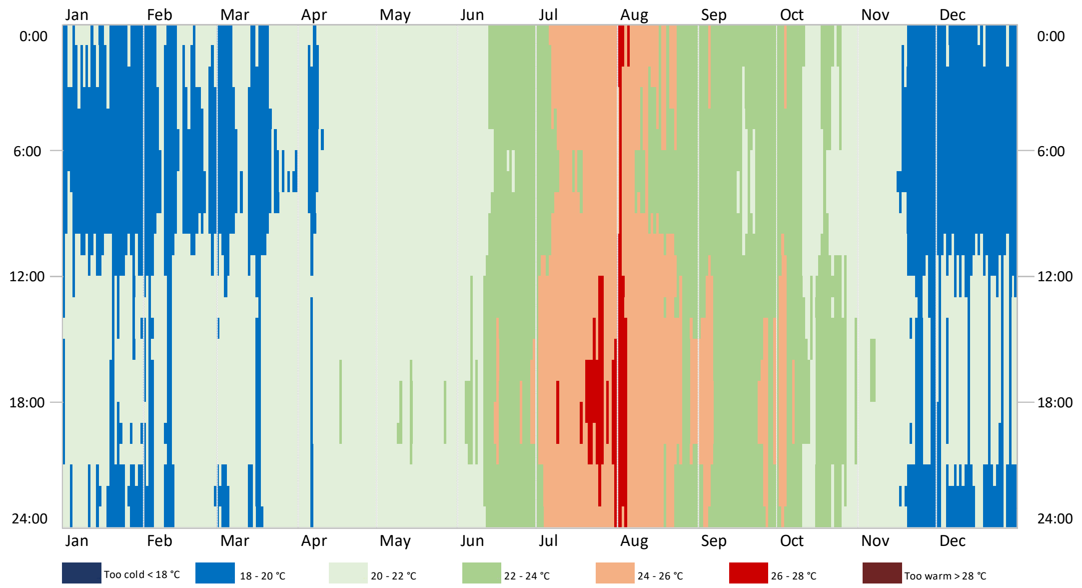


Figure 4.44: External roller blinds, from June to September 3 days per week (Monday, Wednesday and Friday), down from 08:00 to 20:00 h if direct solar radiation is over 200 W/m².

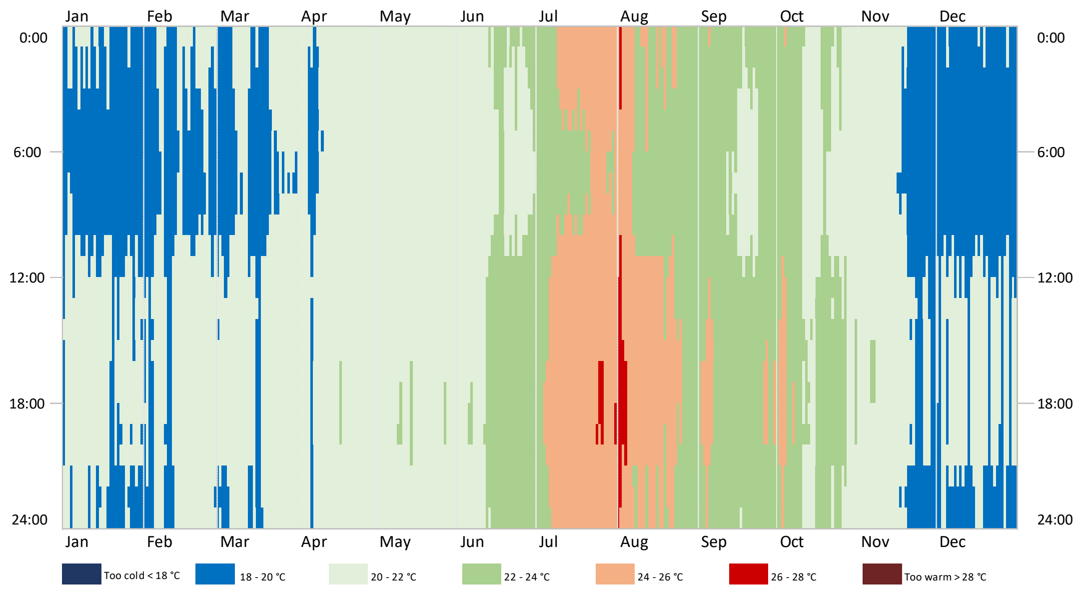


Figure 4.45: External roller blinds with automatic control from June to September, every day down from 08:00 to 20:00 h if direct solar radiation is over 200 W/m².

4.6.2.4. Assessment of the improvements achieved with each solar shading strategy

The strategies are analysed firstly according to the reduction of warm discomfort hours achieved with each strategy. The solar shading strategies demonstrate diverse responses regarding the type of shading element and the position. The first type S1 and S1m confirm that the venetian blinds placed in the interior don't help reducing the warm discomfort, actually they increase it. The second group S2, represents the exterior venetian blinds with automatic control. They show a good potential but require a highly reflection operation like in S2b. Otherwise, they may increase the solar gains if the outer venetian blinds are operating in a standard horizontal position, as happens in the S2 case.

The best performance appears to correspond to exterior roller blinds with 95 % of solar reduction, as plotted in Figure 4.46. The automatic operation presents considerable reductions of the too hot hours and also some improvement of the warm hours. In any case, these strategies seem to be insufficient to provide a good thermal comfort, so they need to be combined with other measures like the ventilative cooling.

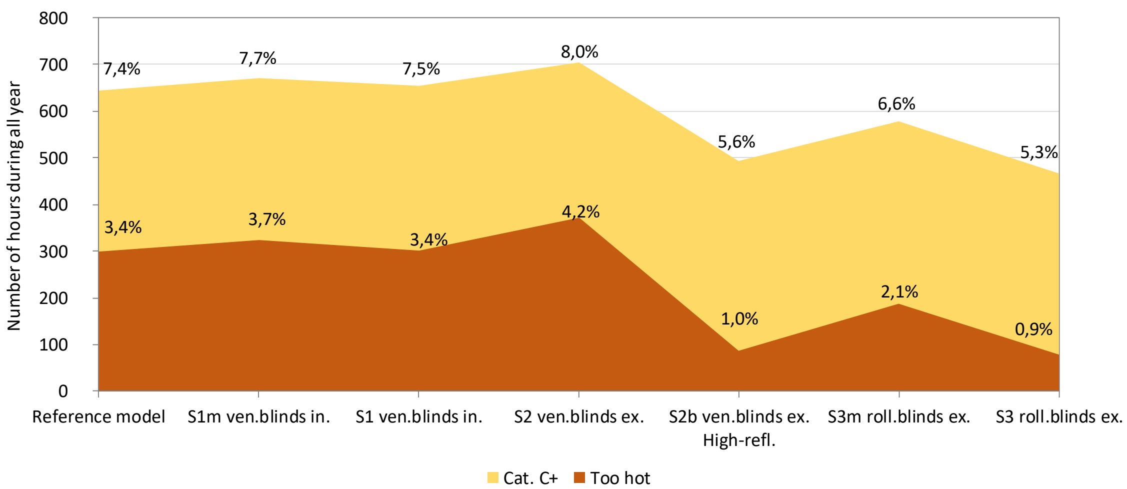


Figure 4.46: Solar shading strategies effect on the warm discomfort according to PMV model, ISO 7730.

The simulated solar shading systems are also analysed in regard with the main indicators of the indoor thermal environment, as it was done during the assessment of ventilation measures.

Figure 4.47 represents the average values of each month in contrast with the reference model and the range of minimum and maximum daily average temperatures in each month. The best two measures are the external automatic roller blind (S3) and the external venetian blind with vertical angle (S2b). On the hottest month, i.e. July, these systems reduce the average temperature up to 1.0 °C.

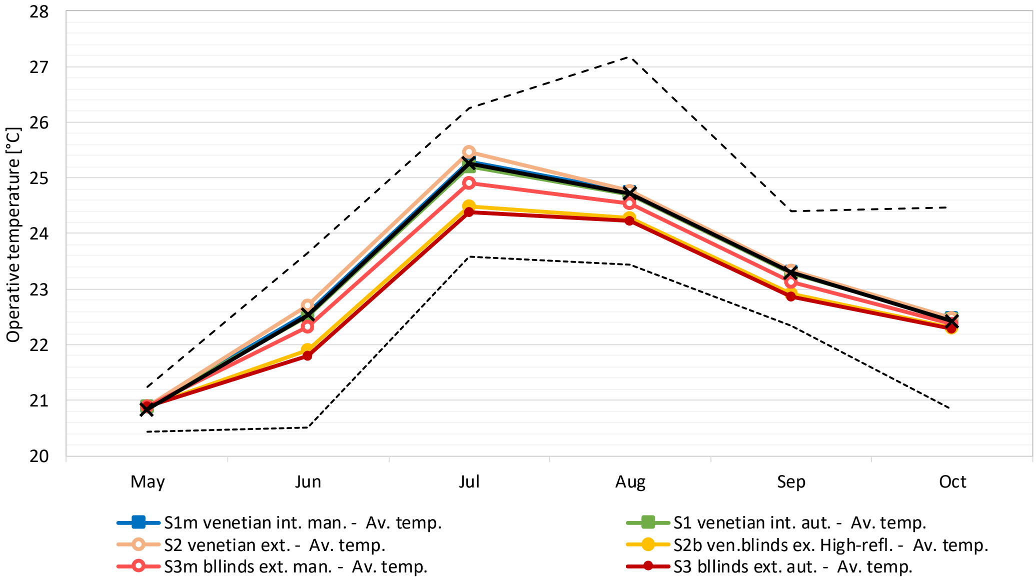


Figure 4.47: Solar shading strategies effect on monthly average operative temperatures.

Regarding the maximum temperatures, Figure 4.48 reflects a similar thermal behaviour. The same two best measures (S3 and S2b) keep reducing the maximum daily average temperature in one Celsius degree approximately.

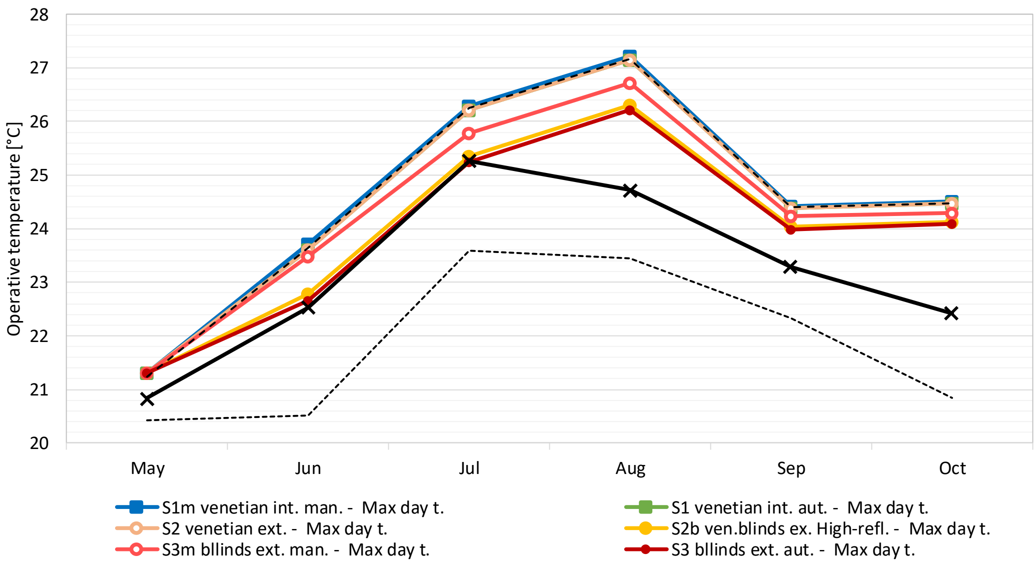


Figure 4.48: Solar shading strategies effect on maximum daily operative temperatures.

In relation with the number of hours over the Passive house threshold (25 °C), all the cases accomplish the objective (less than 10 % of annual hours), see Figure 4.49. The differences range from the 8.7 % of the worse case, S1 with internal venetian blinds, to the 3.3 % of the best case, S3 with automatic external roller blinds.

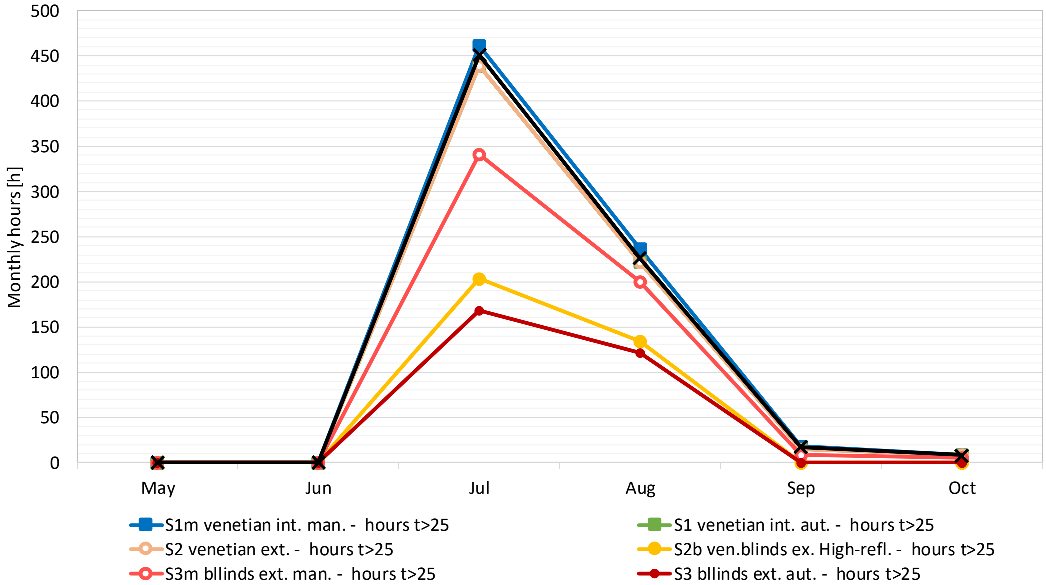


Figure 4.49: Solar shading strategies effect on number of total hours over 25°C.

Finally, the number of night hours over 26 °C indicate that indoor measures don't reduce almost any night warm hours, as can be observed in Figure 4.50. There are many more warm night hours in August than in July. This is mainly due to the outside minimum air temperatures, which in the beginning of August remained over 18 °C during six days. In any case, the outdoor shading elements can reduce almost completely this problem. Besides, their daily use is also crucial to keep indoor temperatures low.

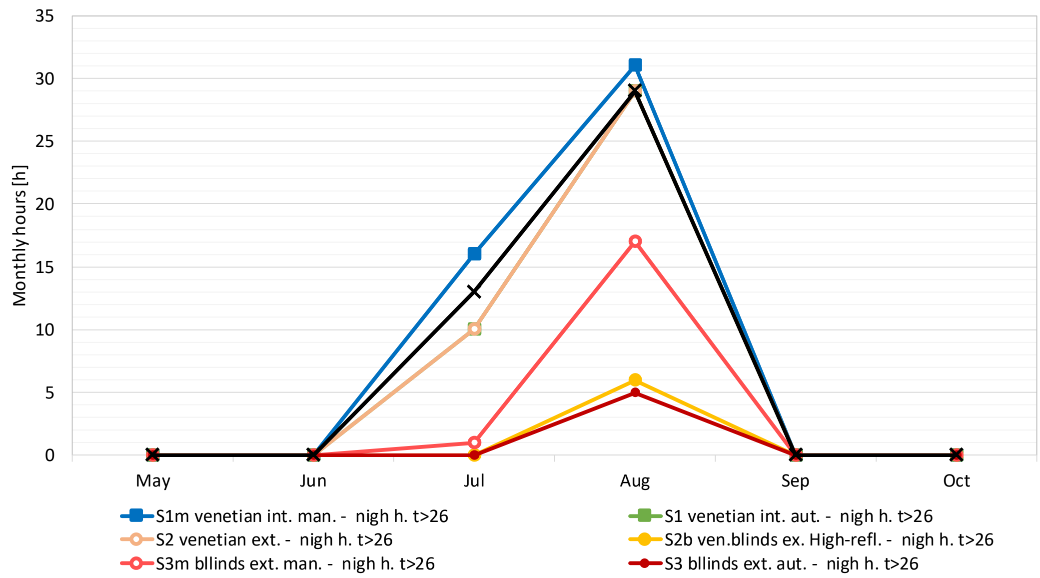


Figure 4.50: Solar shading strategies effect on number of night hours over 26°C.

4.6.3. Correction of the heater distribution

As pointed out in the Chapter 3, the distribution and sizing of heaters leads to cool periods in the coldest days of winter. This aspect can be corrected easily by the installation of several electric heaters in the most affected rooms. According to the monitoring results, the coldest rooms were the main bedroom (r12), the bathroom 1 (r07), the toilet (r10) and the bathroom 2 (r11). So, in these four rooms small electric heaters of 400 W are added, controlled by an air temperature configured to keep the room temperature over 20.0 °C.

After implementing these supplementary heaters in the reference model, the heating use is increased up to 2970 kWh. The difference of 116.9 kWh means a small extra 4.1 % annually but it corrects to great extent the cool discomfort appreciated in the real case.

The improvement of cool discomfort is huge. Figure 4.51 evidences how the blue areas are now remarkably smaller than in the reference model of Figure 4.11. The annual number of hours below 20 °C is reduced from 1720 h to 345 h, i.e. a very significant reduction of 80.0 %.

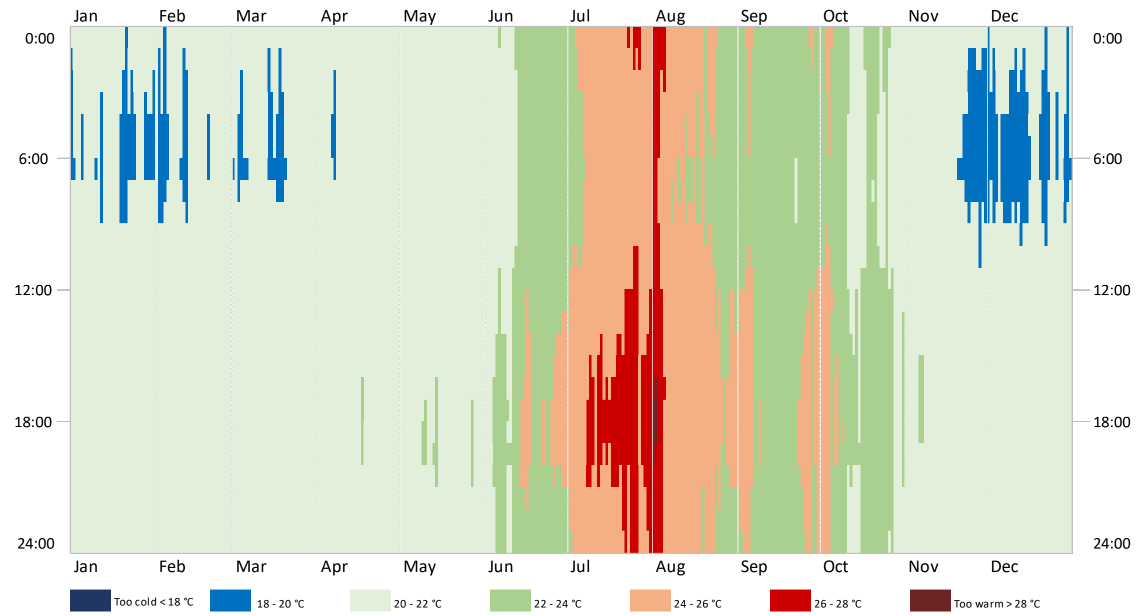


Figure 4.51: Indoor temperatures with additional heaters in main bedroom, bathrooms and toilet.

4.7. Thermal comfort optimisation with combined strategies

Until now, none of the strategies has achieved alone the optimal thermal comfort according to ISO 7730 or EN 15251. The objective 4.7 tries to define which combinations of measures can solve the TC problems detected during the real case monitoring.

This Section evaluates the best three combinations, taking into consideration the best strategies of ventilation and solar shading regarding reduction of thermal discomfort. Besides, these three combinations include the corrections of the minimum nominal ventilation airflow in winter (with nominal bypass operation in summer) and the supplementary heaters in the coldest four rooms. Additionally, the best combinations of manually controlled strategies are also evaluated, in order to verify if the automatic control is essential to have an optimal TC inside the dwelling or not.

The main findings are summarized in Figure 4.52, which represents the thermal discomfort reduction achieved through each combinations of measures. In general, all the combinations of measures can provide an almost optimal TC based on PMV model. All of them present less than 2% of annual hours of warm discomfort, even the manually operated ones.

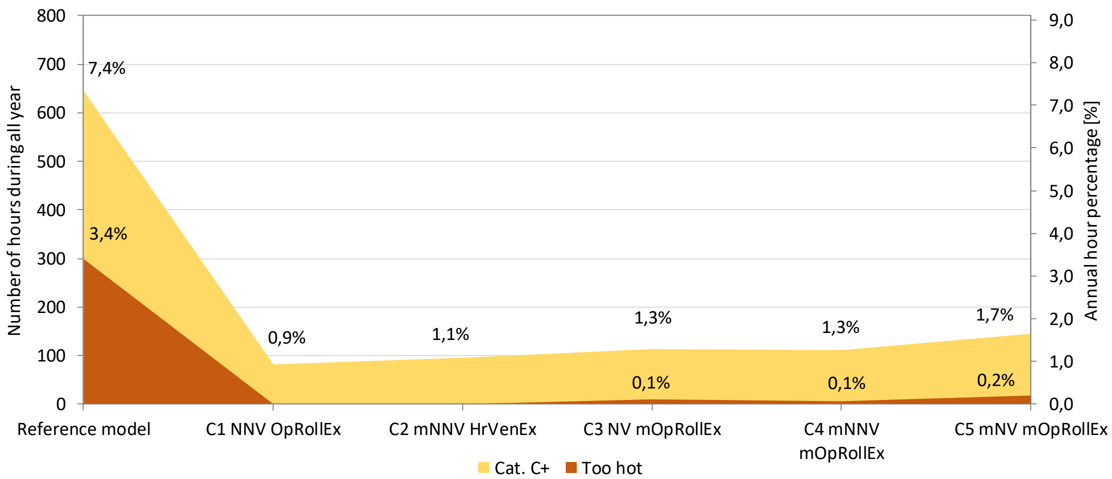


Figure 4.52: Combined strategies effect on the warm discomfort according to PMV model, ISO 7730.

Regarding the average indoor temperatures, the best combination can reduce the average temperature in the hottest month in a very significant 1.5 °C, as shown in Figure 4.53. This is directly related also with the control of the peak temperatures in the hottest days. Figure 4.54 evidences how the maximum daily average temperatures are reduced up to 2 °C in the hottest summer days in comparison with the reference model.

As a result, the passive measures improve the resiliency of the building during the heat waves, as happened during the first week in August.

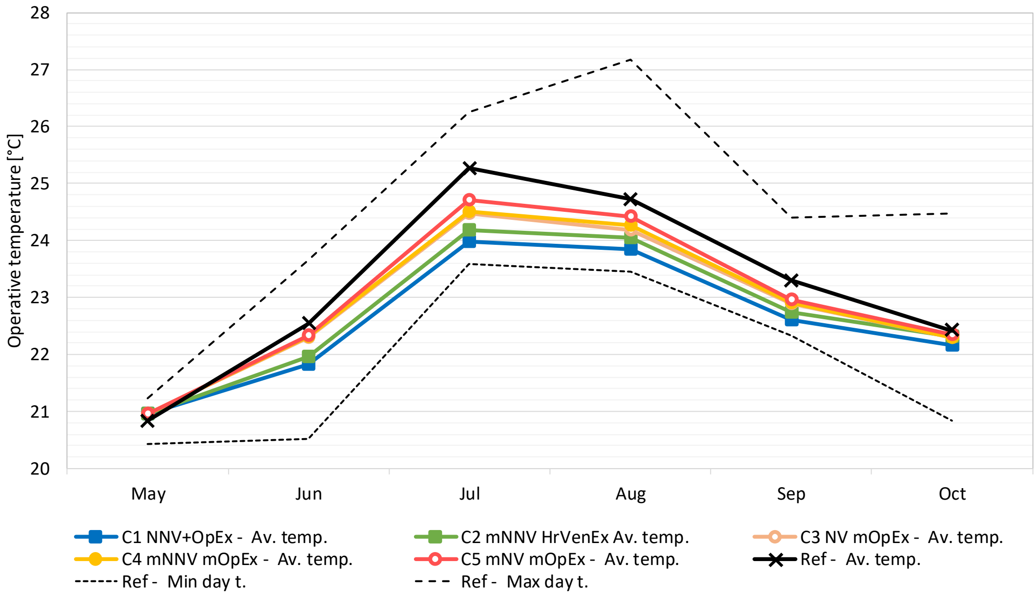


Figure 4.53: Combined strategies effect on monthly average operative temperatures.

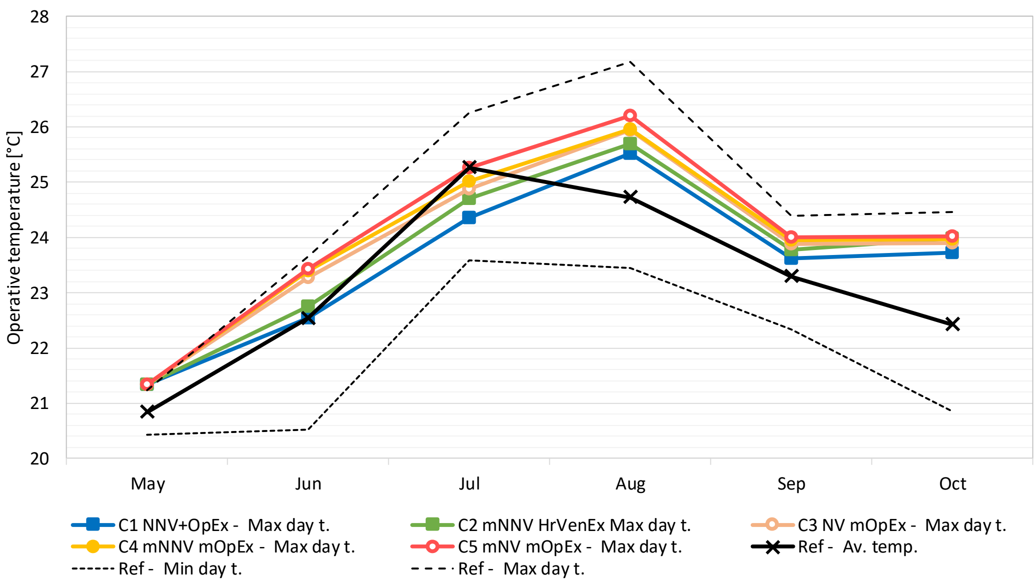


Figure 4.54: Combined strategies effect on maximum daily operative temperatures.

Regarding the overall number of hours over the warm thresholds, Figure 4.55 represents the time over 25 °C and confirm an incredible reduction from 702 h to 80 h in C1 combination (optimal automatic operation) or to 280 h in C4 combination (optimal manual operation). The less efficient analysed combination, that is C5, cuts down by half the total hours over 25 °C.

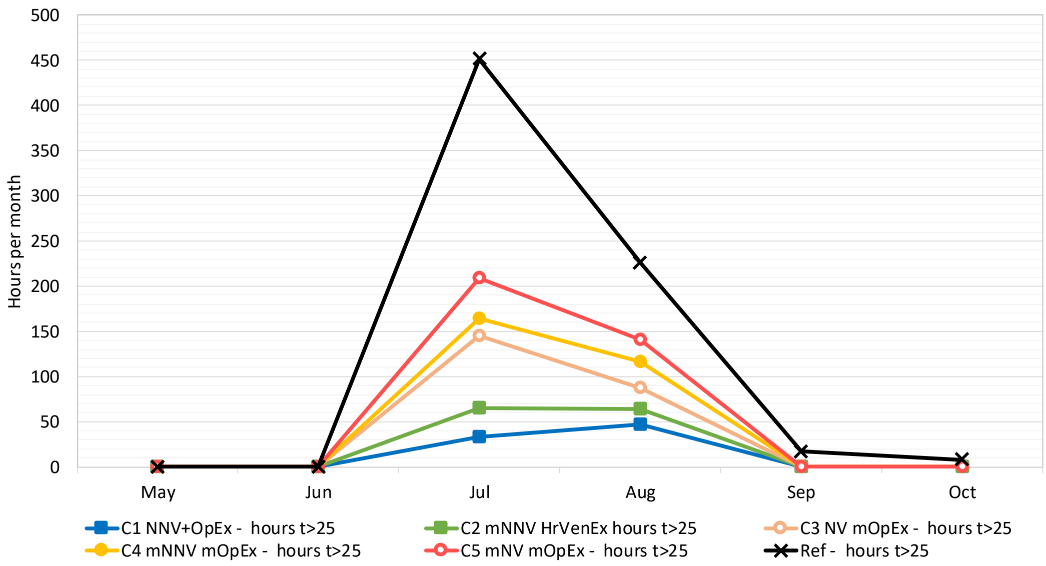


Figure 4.55: Combined strategies effect on number of total hours over 25°C.

Additionally, considering the relevance of night time thermal comfort, Figure 4.56 manifests a radical reduction of the number of night time hours (from 23 h to 7 h) over 26 °C. Actually, the less efficient combination (C5) can reduce the 42 hours of warm night time up to 7 h and the most efficient combination (C1) corrects completely all the warm night time hours.

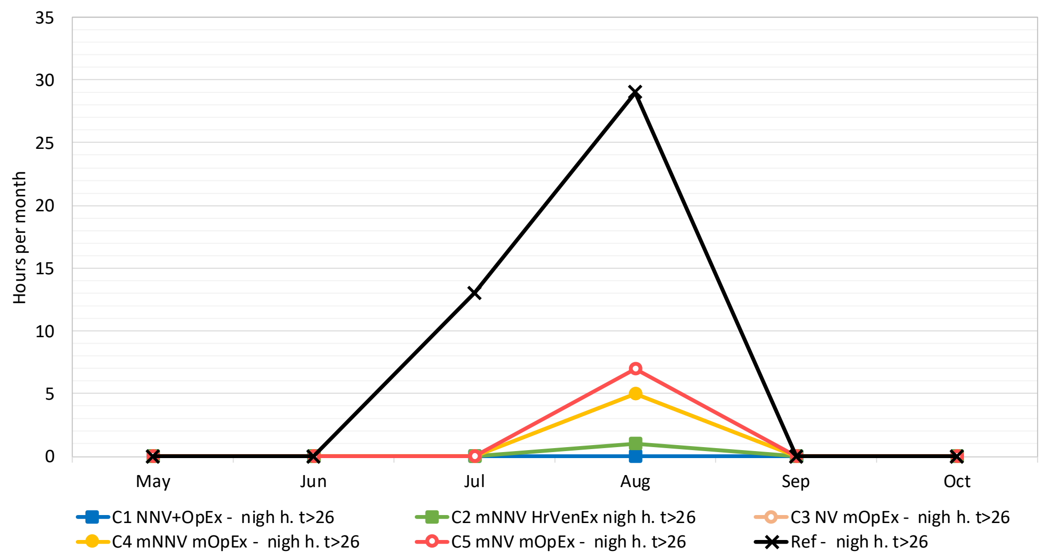


Figure 4.56: Combined strategies effect on number of night hours over 26°C.

4.7.1. Detailed TC of the analysed combinations

In this section, the thermal behaviour of each combination is presented. They are included four analysis: the annual hourly average temperature of the house, the annual TC profile based on the PMV model, the annual temperature and RH relationship with the PMV limits and finally the adaptive TC defined in EN 15251. The shoulder seasons have been extended in Autumn to permit clothing changes during the transition between summer and the beginning of heating season. All the combinations include the supplementary heaters and the corrected ventilation airflow adjusted to the minimum PHPP requirements, as explained in the previous sections. Each combination applied a different strategy of ventilative cooling together with a solar shading operation.

The **first combination** (C1) implements the most efficient measures, that is the automatic night time natural ventilation and the automatic solar shading with external opaque roller blinds. As a result, Figure 4.57 proves that the temperatures during all the year are far more stable than the reference model presented in Section 4.5. The total hours over 25 °C are reduced from 702 h to only 80 h. In winter, the wide blue areas below 20 °C have dropped from 1720 h to 332 h.

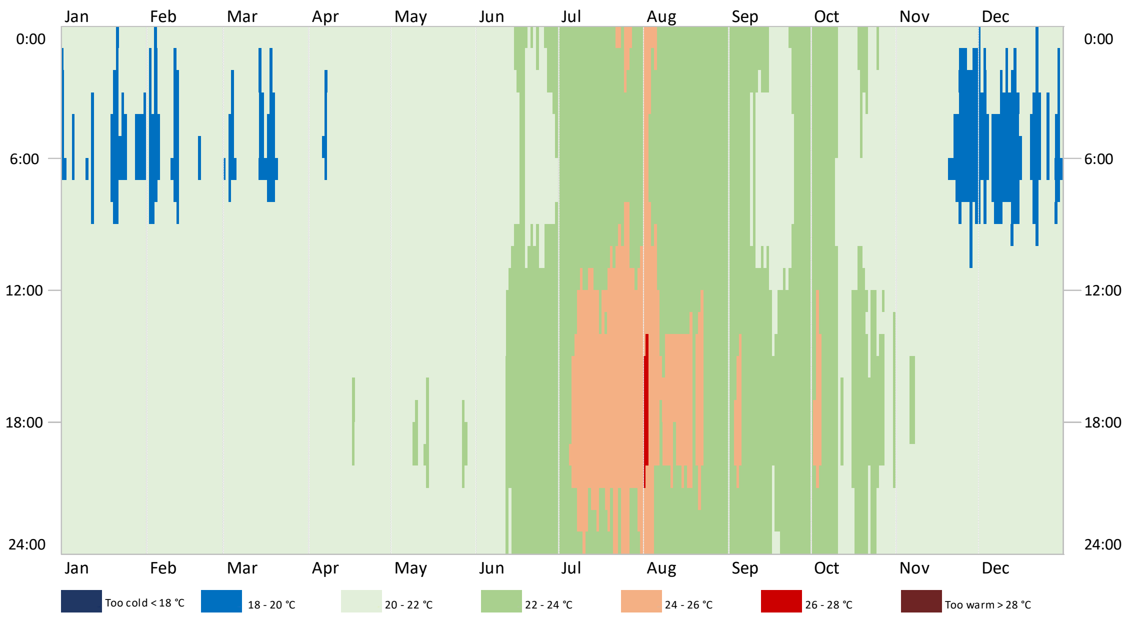


Figure 4.57: Indoor temperatures of 1st combination of strategies: minimum winter ventilation, additional electric heaters in coldest rooms, from June to September automatic night time natural ventilation 21:00 - 7:00 h and automatic external roller opaque blinds.

The analysis of the TC plot in Figure 4.58, Figure 4.59 and Figure 4.60 confirm that these measures are able to correct the issues identified during the monitoring. On contrary, the number of hours with high RH increase from 150 h to 297 h. They are mainly located in July, and they are related with the hours of natural ventilation. Besides, the TC according to the adaptive method is for sure avoiding any risk of too hot temperatures and so the risk of overheating is zero. There is a subtle overcooling in winter, but it is caused mainly by the low heating set point configured by the users of the real case.

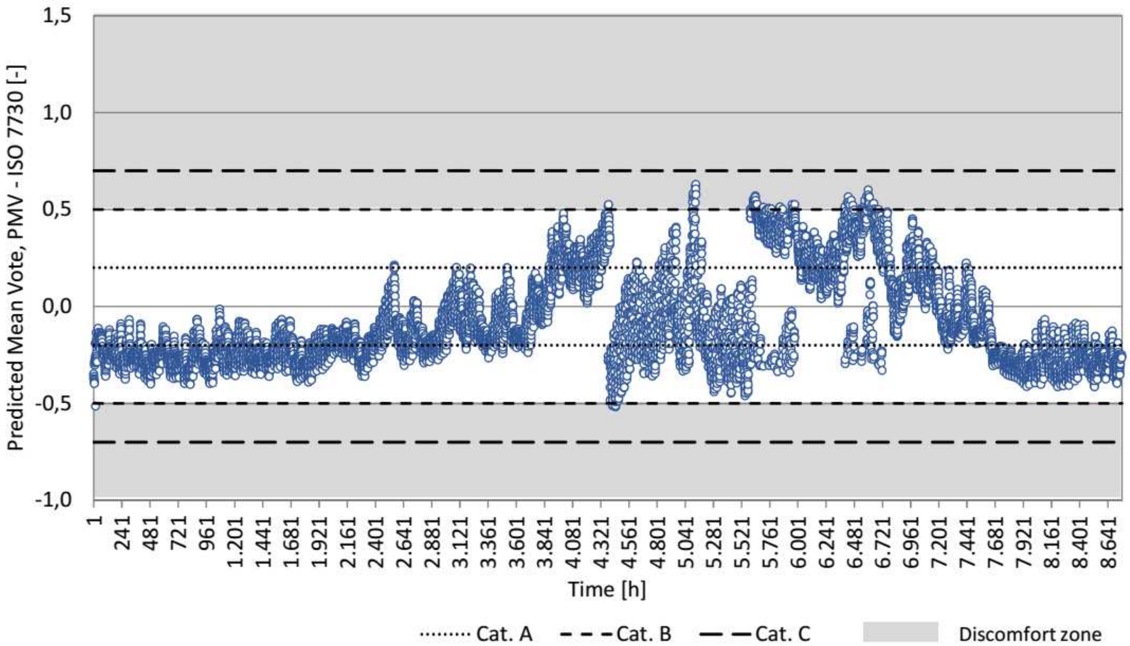


Figure 4.58: PMV of 1st combination of strategies.

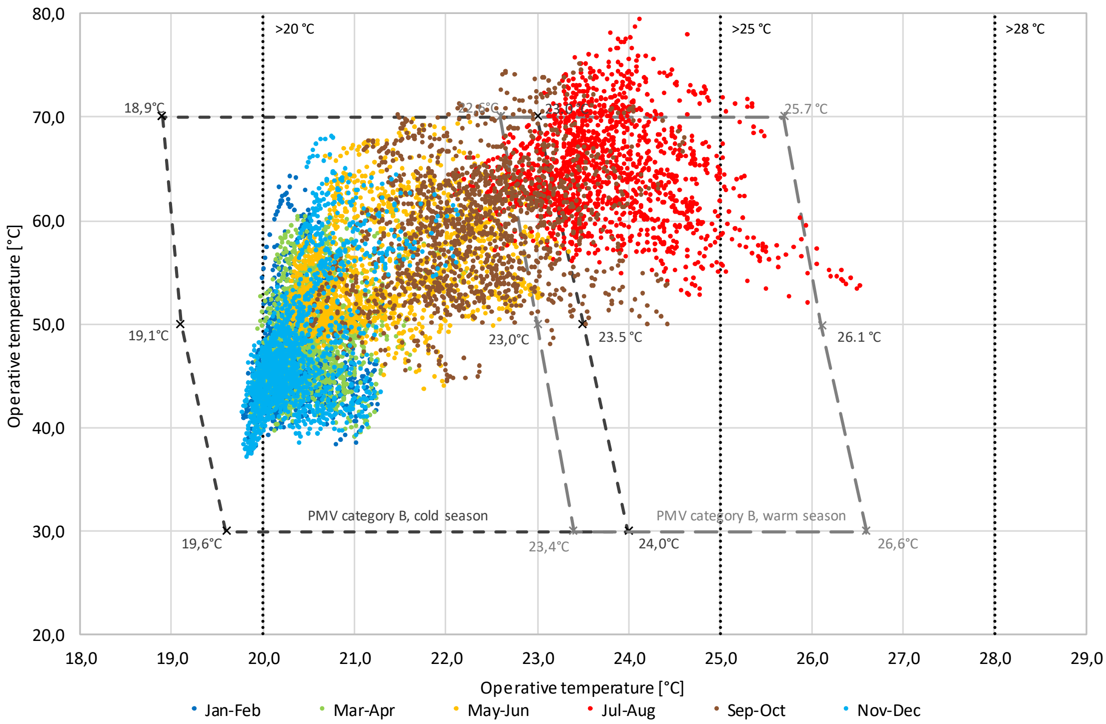


Figure 4.59: TC of 1st combination of strategies, average house T-RH plot with PMV limits.

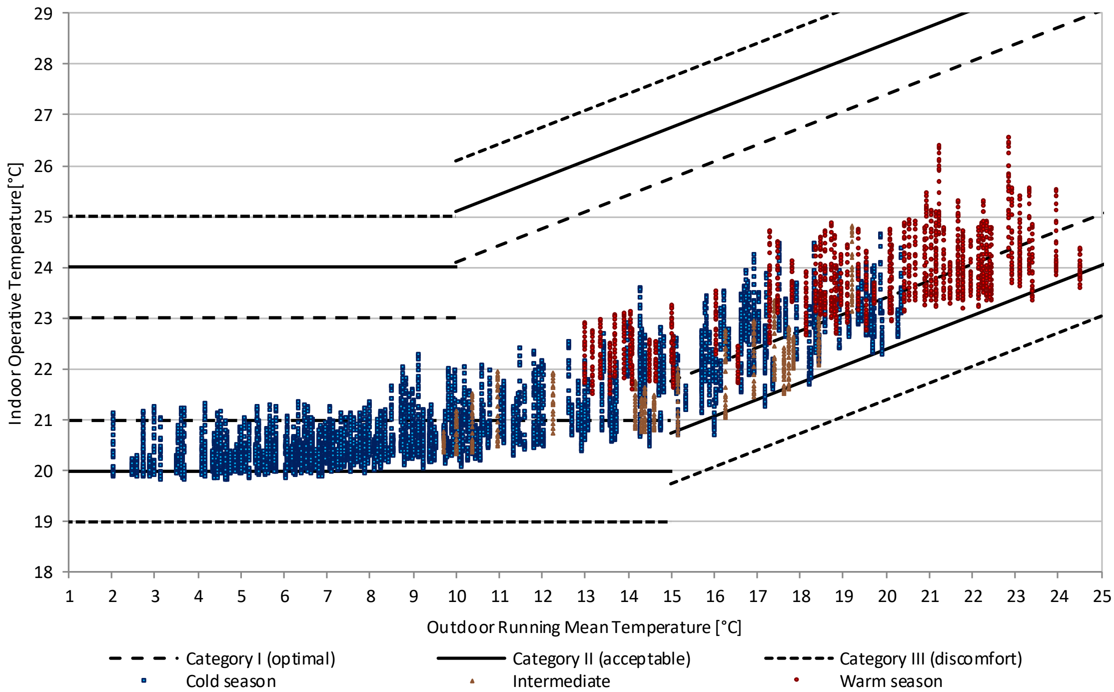


Figure 4.60: TC of 1st combination of strategies and outside running mean temperatures, adaptive method of EN 15251.

Table 4.11: Model C1 results, summary of climate conditions, building heating load and indoor conditions.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
CLIMATE CONDITIONS													
Monthly average temperature*	6,9	6,4	7,5	9,7	10,0	14,8	21,1	18,4	16,8	14,4	7,8	4,7	11,5
Min. daily average temperature*	2,1	2,2	0,3	1,9	6,8	9,9	17,8	15,3	12,5	7,4	-0,8	-0,6	-0,8
Max. daily average temperature*	12,6	14,8	12,7	18,0	16,7	22,1	23,9	28,8	21,0	21,8	15,9	12,4	28,8
Monthly average Relative Humidity	6,9	6,4	7,5	9,7	10,0	14,8	21,1	18,4	16,8	14,4	7,8	4,7	11,5
Global horizontal solar radiation	55,5	95,3	133,5	161,2	206,2	250,5	279,0	234,6	169,8	119,5	56,1	82,4	1843,5
HDD (18.3)	354	334	335	260	257	113	1	27	62	129	315	424	2612
CDD (25.0)	0	0	0	0	0	0	0	4	0	0	0	0	4

** All outdoor temperatures are dry bulb air temperatures*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
BUILDING HEATING/COOLING LOADS													
Heating: monthly use	553,3	444,7	455,8	266,3	152,1	46,7	7,8	8,4	10,8	27,3	399,9	585,7	2958,7
Daily average heating use	17,8	15,9	14,7	8,9	4,9	1,6	0,3	0,3	0,4	0,9	13,3	18,9	0,0
Max. daily heating load	5,9	5,6	5,4	5,3	3,1	2,3	0,1	0,1	0,1	1,3	6,1	6,3	6,3
Cooling: monthly use	0	0	0	0	0	0	0	0	0	0	0	0	0
Daily average cooling use	0	0	0	0	0	0	0	0	0	0	0	0	0
Max. Daily cooling use	0	0	0	0	0	0	0	0	0	0	0	0	0
INDOOR ENVIRONMENT													
Average temperature*	20,3	20,4	20,4	20,7	21,0	21,8	23,9	23,7	22,6	22,1	20,5	20,3	21,5
Min. daily av. temperature*	20,3	20,3	20,4	20,4	20,6	20,6	22,6	22,8	21,8	20,9	20,3	20,3	20,3
Max. daily av. temperature*	20,6	20,8	20,8	21,4	21,3	22,5	24,4	25,5	23,6	23,7	21,4	20,6	25,5
Max. temperature *	21,2	21,3	21,3	22,2	22,3	23,3	25,5	26,5	24,4	24,6	22,1	21,3	26,5
hours t* <20 °C	59,0	41,0	39,0	6,0	0,0	0,0	0,0	0,0	0,0	0,0	61,0	126,0	332,0
hours t* >25 °C	0,0	0,0	0,0	0,0	0,0	0,0	33,0	47,0	0,0	0,0	0,0	0,0	80,0
hours t* >28 °C	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Night hours t > 26°C	0	0	0	0	0	0	0	0	0	0	0	0	0
hours RH >70 %	0	0	0	0	0	0	191	41	23	42	0	0	297

** All indoor temperatures are operative temperatures*

The **second combination** (C2) implements the manual night time natural ventilation and the automatic external high reflectivity venetian blinds. This combination avoids the installation of window automatic controllers, and provides an excellent control of the summer normal conditions. The potential of night cooling is bigger than the daily need and for that reason the temperature field is almost the same than in the C1 combination, see Figure 4.61.

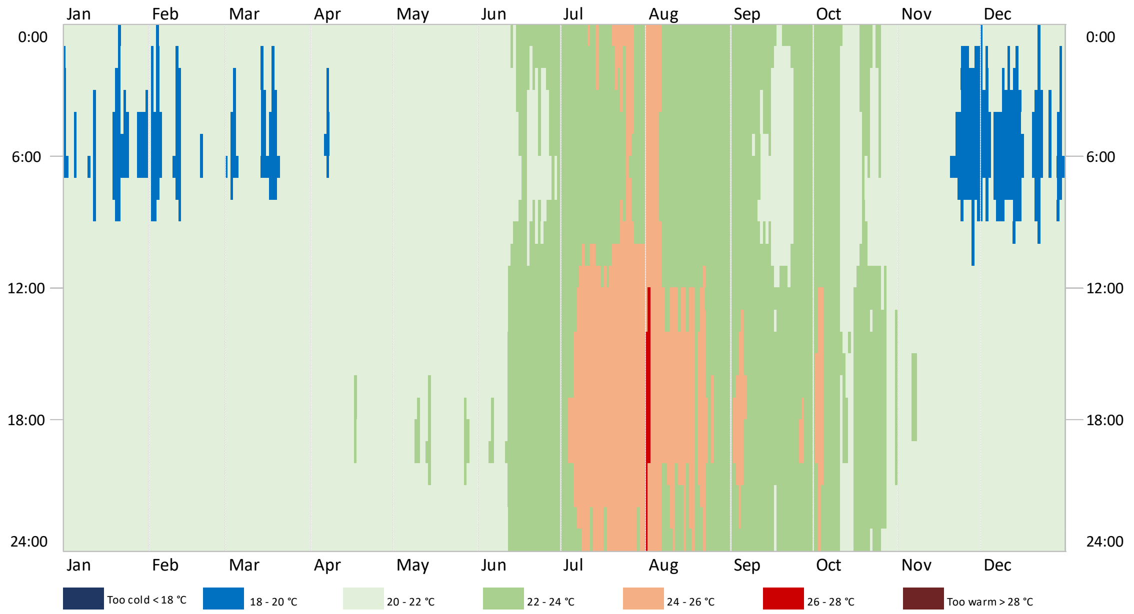


Figure 4.61: Indoor temperatures of 2nd combination of strategies: minimum winter ventilation, additional electric heaters in coldest rooms, from June to September manual night time natural ventilation 21:00 - 7:00 h and automatic external high reflectivity venetian blinds.

The analysis of the TC plots in Figure 4.62, Figure 4.63 and Figure 4.64 indicate that these measures can correct the issues identified during the monitoring. In general, it presents the same characteristics than the C1 combination seen before. The adaptive comfort present some small differences in the peak hours in summer, namely around 0.5 °C warmer.

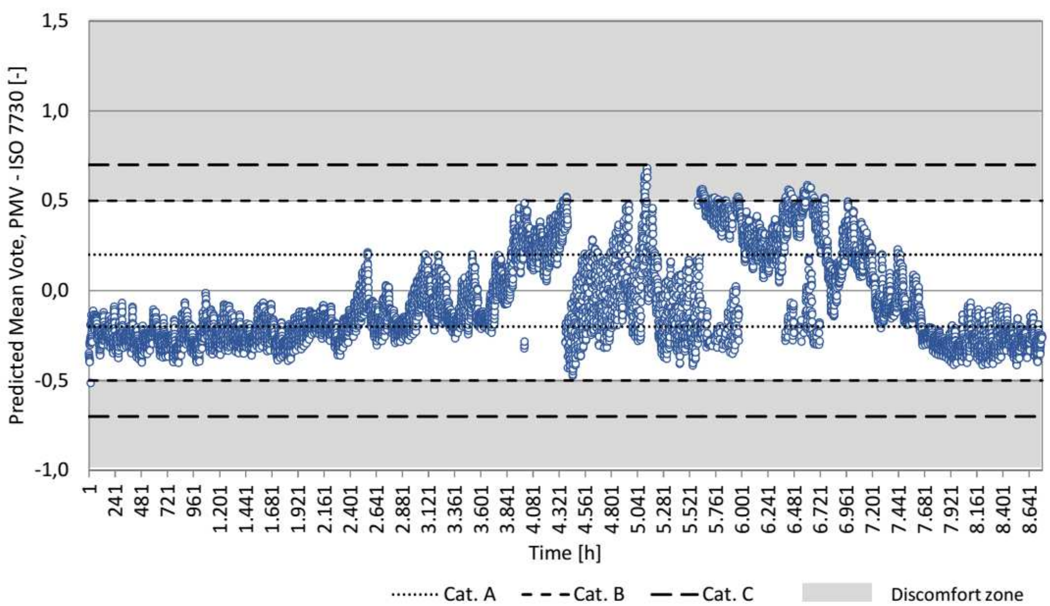


Figure 4.62: PMV of 2nd combination of strategies.

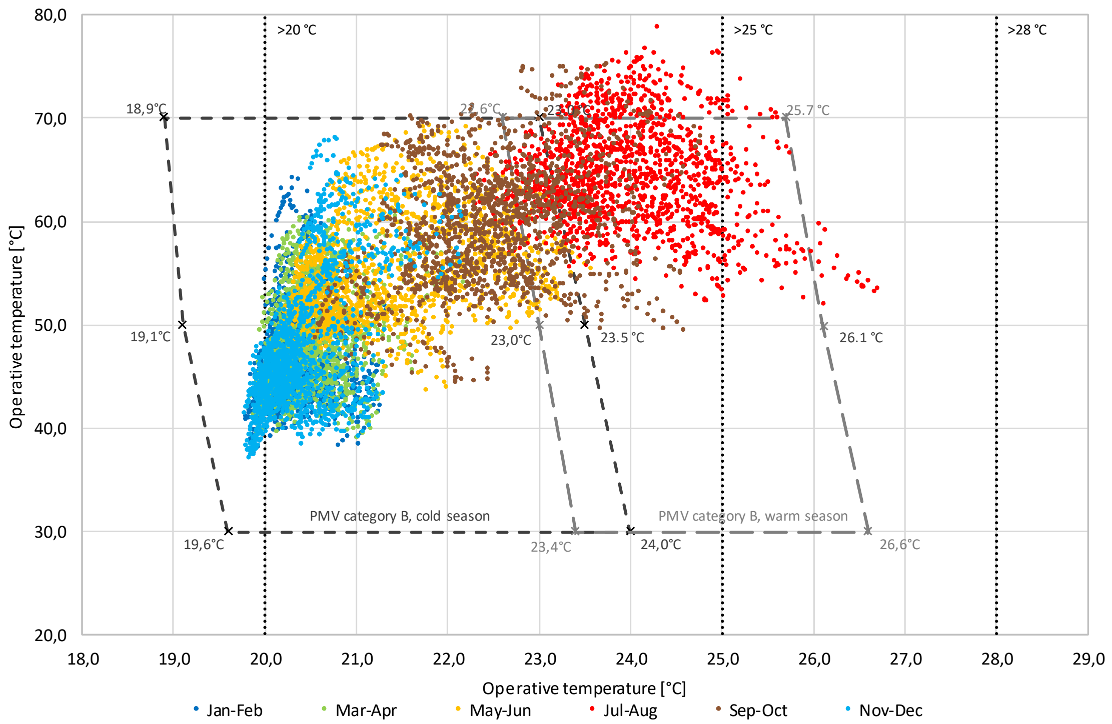


Figure 4.63: TC of 2nd combination of strategies, average house T-RH plot with PMV limits.

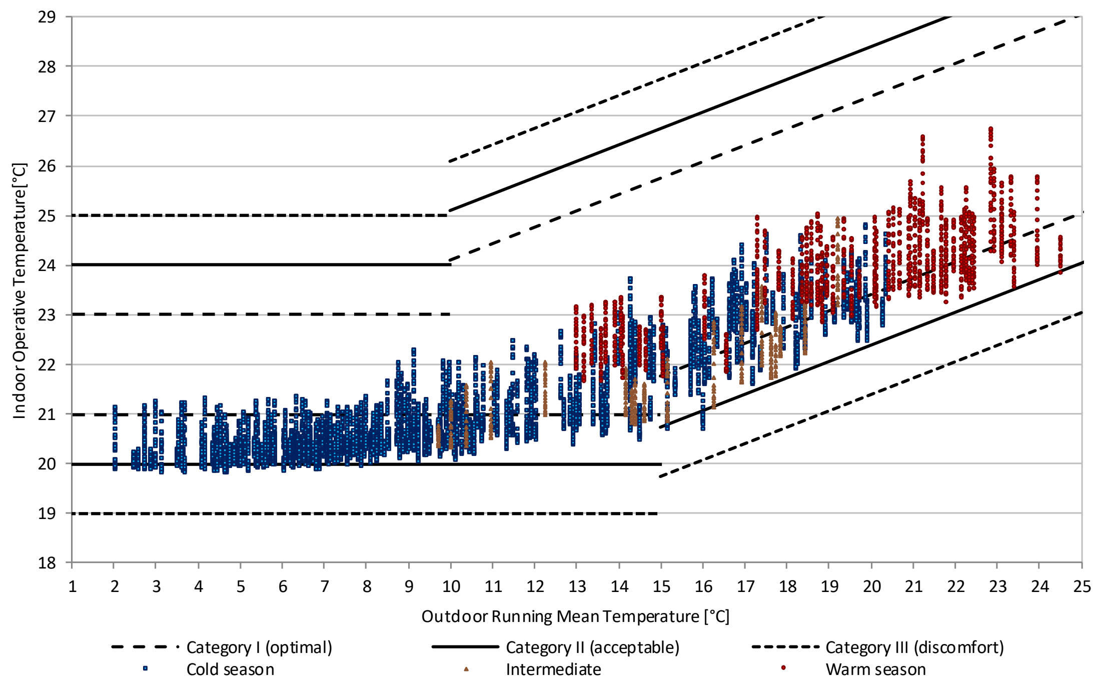


Figure 4.64: TC of 2nd combination of strategies and outside running mean temperatures, adaptive method of EN 15251.

The 3rd **combination** (C3) implements the automatically controlled evening natural ventilation and the manual external opaque roller blinds. As seen in Figure 4.65, the manual operation of the solar shading allows some additional warm hours during day time, but they are compensated to great extent with the 3 hours of automatic natural ventilation in the evenings. However, this doesn't avoid that in certain days the temperatures increase considerable without the use of solar shading.

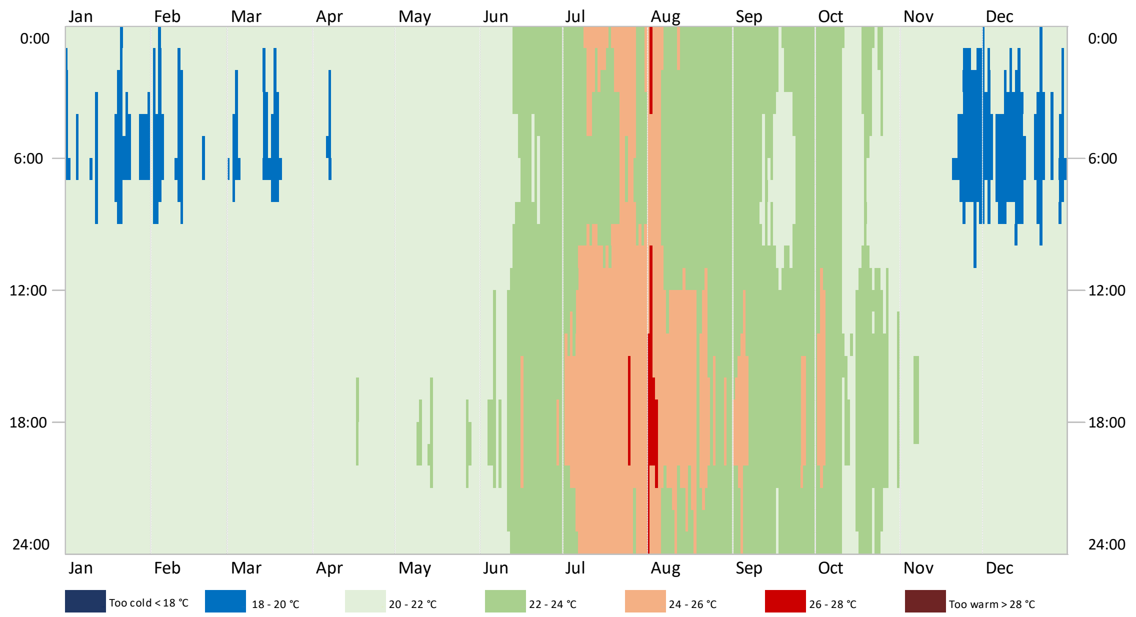


Figure 4.65: Indoor temperatures of 3rd combination of strategies: minimum winter ventilation, additional electric heaters in coldest rooms, from June to September automatic natural ventilation 21:00 - 24:00 h and manual external roller opaque blinds.

Regarding the TC, Figure 4.66 and Figure 4.67 show how the overall results are very satisfactory. Indeed, this combination also keeps the warm discomfort of PMV below 2 % of annual hours. As commented before, the number of hours with high RH has decreased since the natural ventilation is limited to few hours in the evenings.

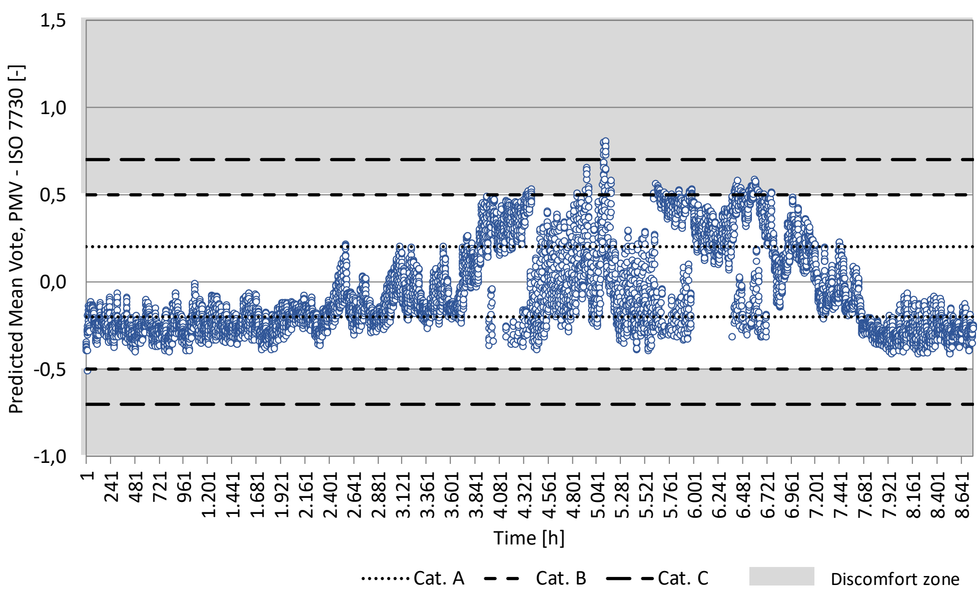


Figure 4.66: PMV of 3rd combination of strategies.

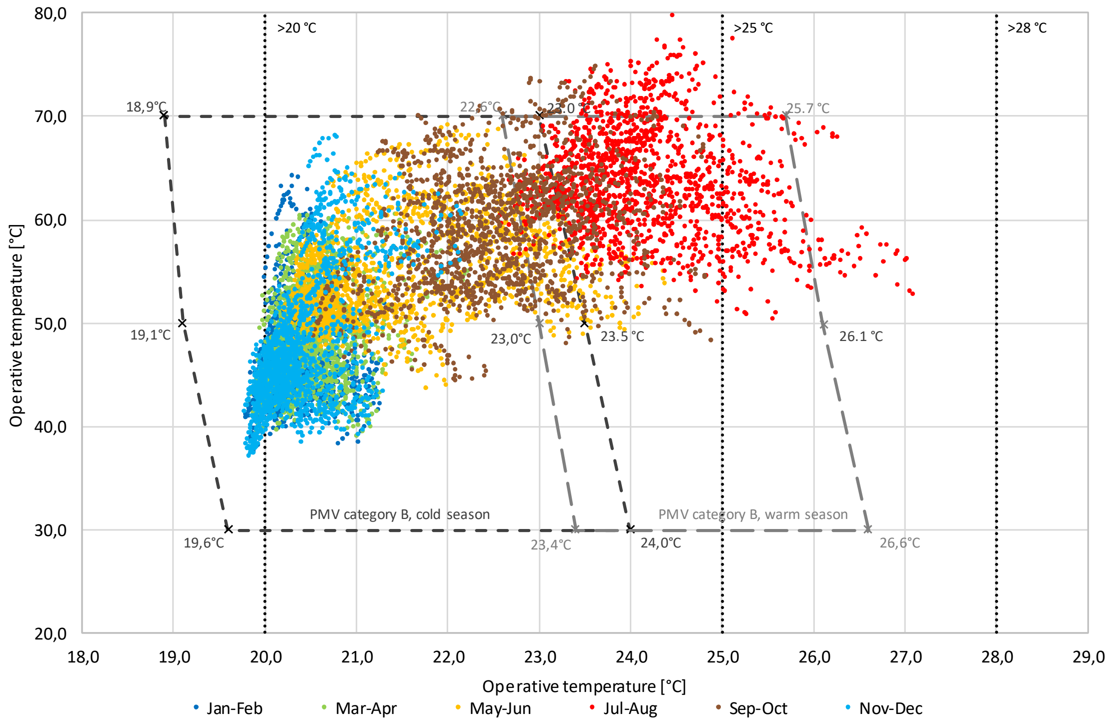


Figure 4.67: TC of 3rd combination of strategies, average house T-RH plot with PMV limits.

The peak hours every day are higher than in the previous combinations but they are still far below the adaptive warm limits, as evidences the Figure 4.68.

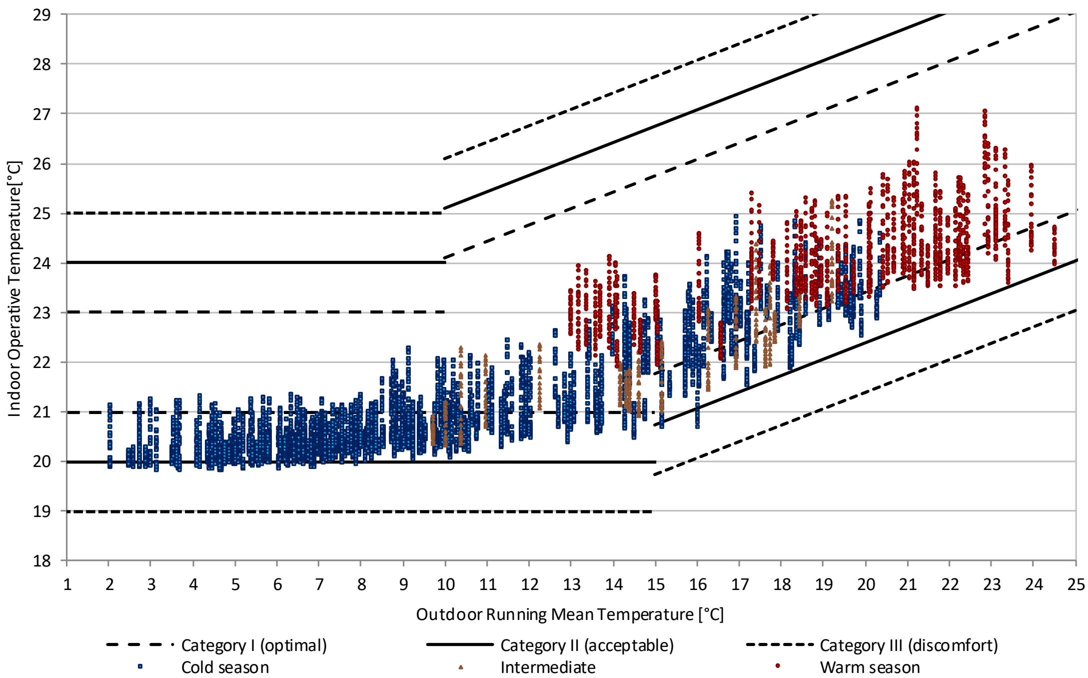


Figure 4.68: TC of 3rd combination of strategies and outside running mean temperatures, adaptive method of EN 15251.

In a second group of combinations, the **best manual strategies** are tested. The most feasible external opaque roller blinds are combined with two types of natural ventilation. On the one side, the use of night natural ventilation provides better comfort, on the other hand the natural ventilation is limited to evenings and presence, in order to prevent any security issues and any noise disturbance while inhabitants are sleeping. In both cases, the natural ventilation and the exterior opaque roller blinds are activated only 3 days per week, to reflect a reasonable level of usage of these passive measures, a decision based on the real habits observed in the monitored summer of the real case.

So, the **4th combination** (C4) includes night time natural ventilation and keeps the temperature balance in summer almost the same than the C3 combination with automatic ventilation. Overall, the number of hours over 25 °C are reduced from 720 h. to 350 h.

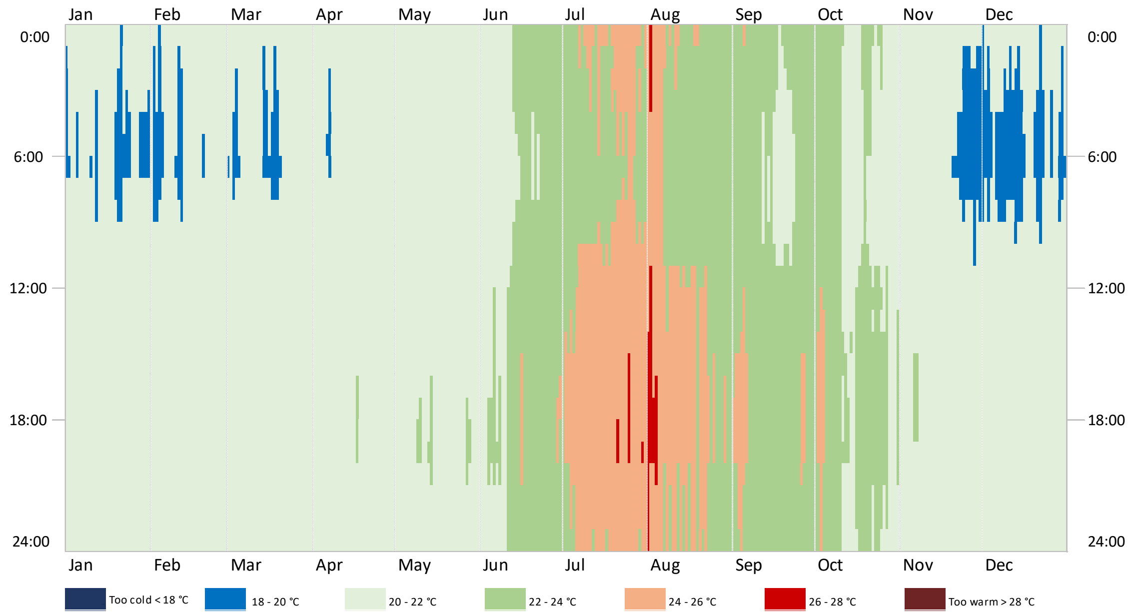


Figure 4.69: Indoor temperatures of 4th combination of strategies: minimum winter ventilation, additional electric heaters in coldest rooms, from June to September manual night time natural ventilation 21:00 - 7:00 h and manual external roller opaque blinds.

Regarding the TC, the PMV values remain within the limits reasonably well, with only the 1.9 % of warm discomfort. The representations in Figure 4.70, Figure 4.71 and Figure 4.72 demonstrate the good operation of the passive measure during all the summer.

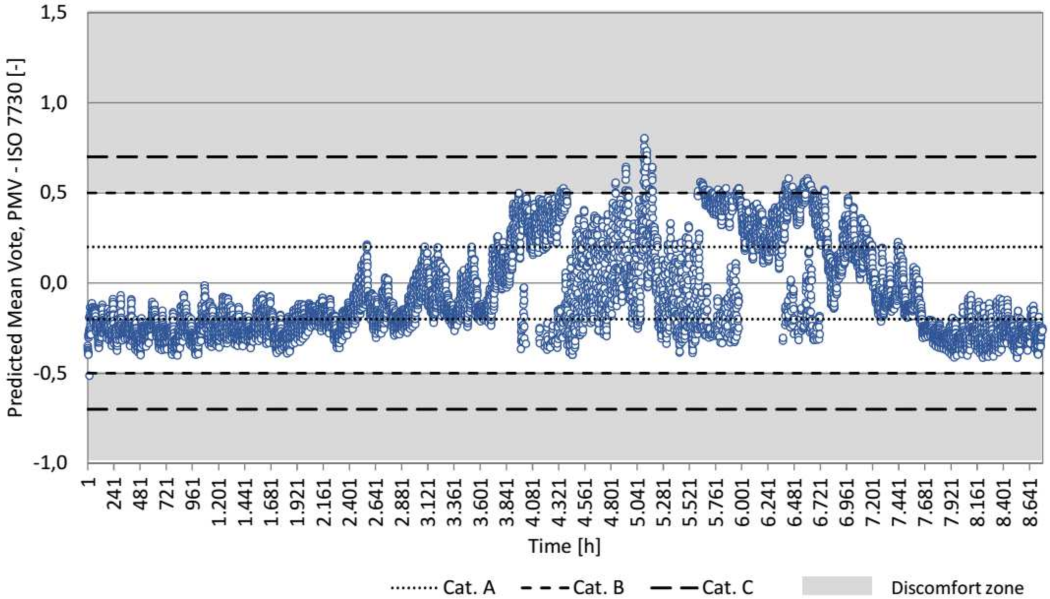


Figure 4.70: PMV of 4th combination of strategies.

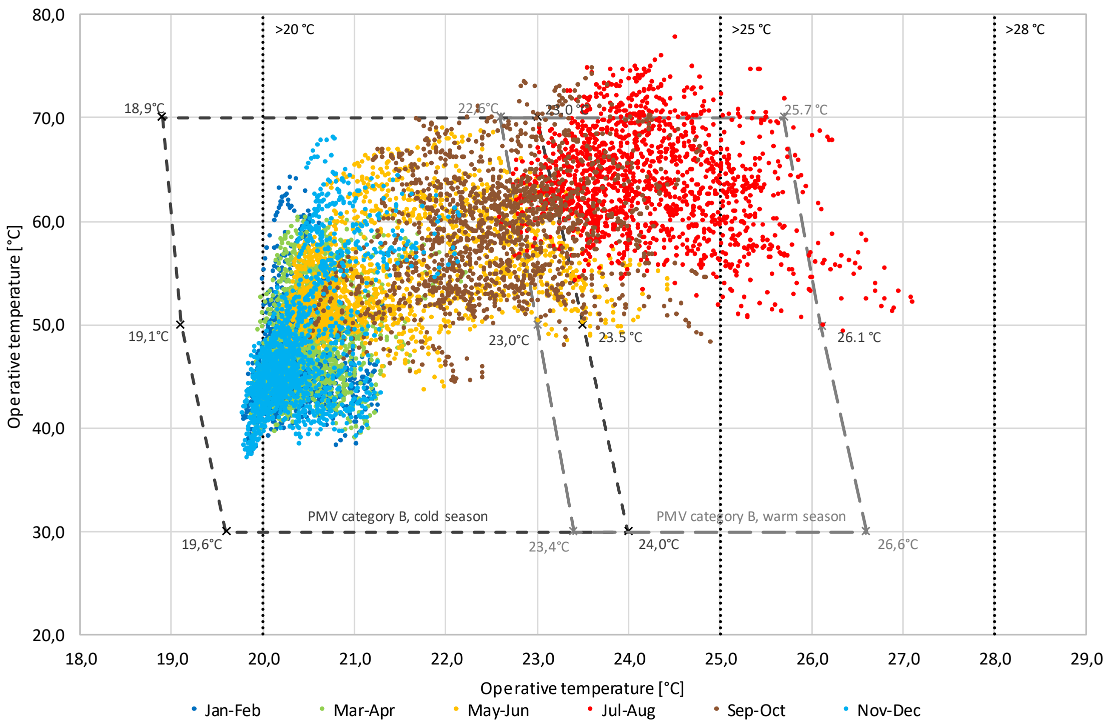


Figure 4.71: TC of 4th combination of strategies, average house T-RH plot with PMV limits.

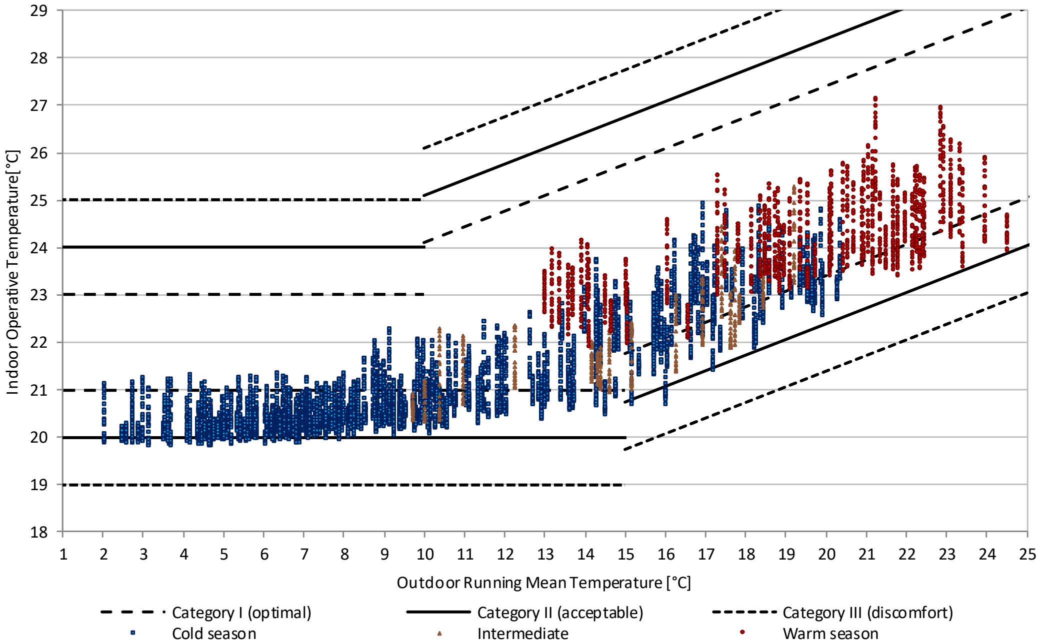


Figure 4.72: TC of 4th combination of strategies and outside running mean temperatures, adaptive method of EN 15251.

The **5th combination** (C5) consists of the manual use of natural ventilation only in the evenings. This reflects the frequent case of houses in urban areas or close to roads where some noises can disturb the rest during nights. The manual activation of natural ventilation between 21 h and 24 h permit a clear reduction of the internal and solar shading during day time can be efficient even if applied only 3 days per week, as shown in Figure 4.73.

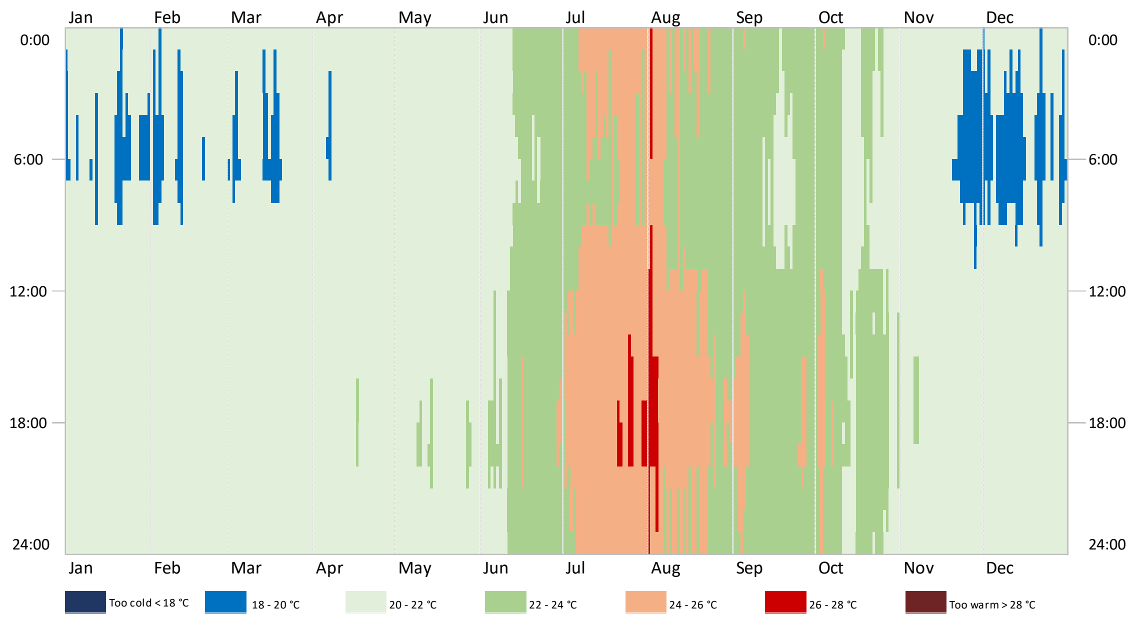


Figure 4.73: Indoor temperatures of 5th combination of strategies: minimum winter ventilation, additional electric heaters in coldest rooms, from June to September manual natural ventilation 21:00 - 24:00 h and manual external roller opaque blinds.

About TC, the manual operation doesn’t guarantee a very controlled environment but the main numbers indicate that the indoor conditions can be met easily if the passive measures are activated more regularly, as observed in the higher potential of the automatic control in C3. About the peak hours, the adaptive comfort reflects that the values are conservative enough and there is no risk of overheating, see Figure 4.74, Figure 4.75 and Figure 4.76.

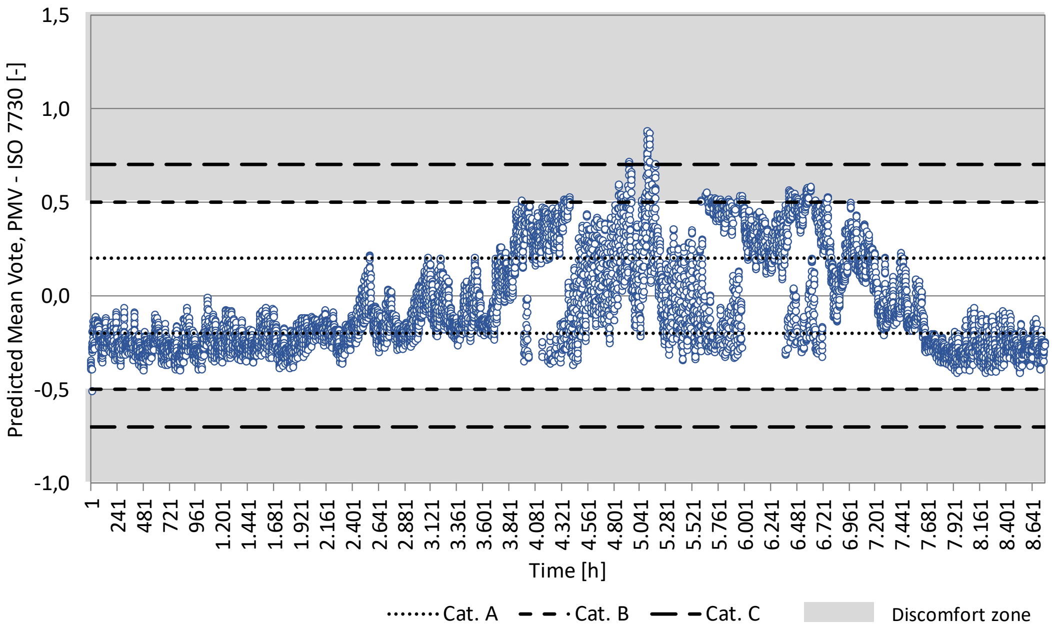


Figure 4.74: PMV of 5th combination of strategies.

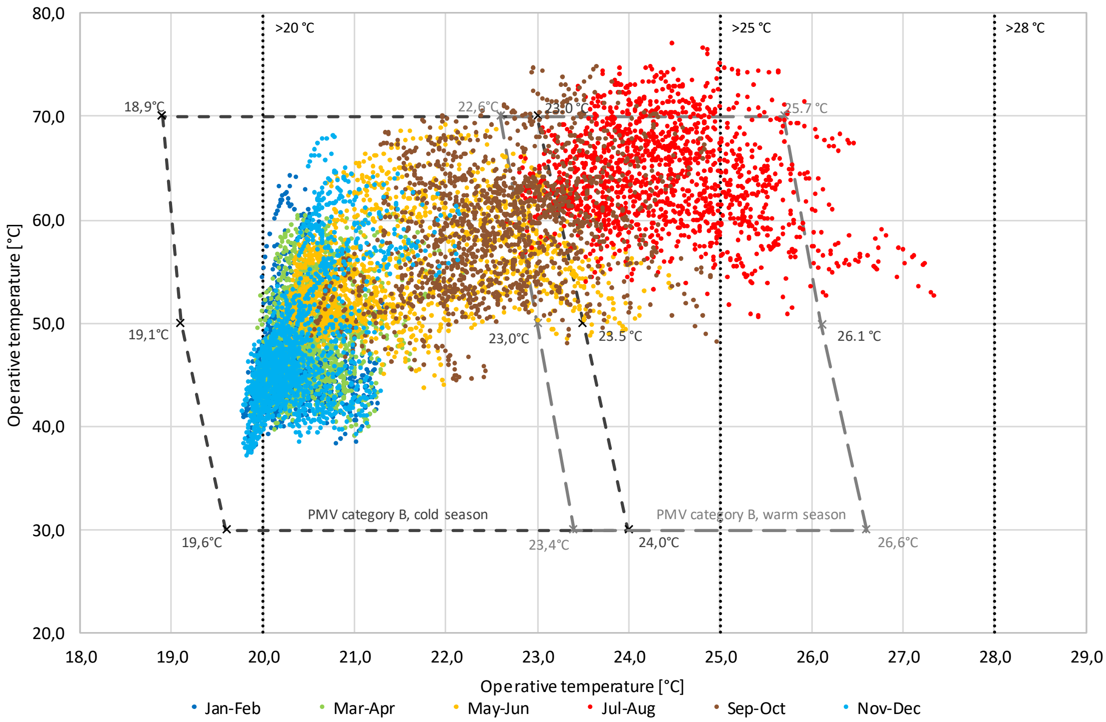


Figure 4.75: TC of 5th combination of strategies, average house T-RH plot with PMV limits.

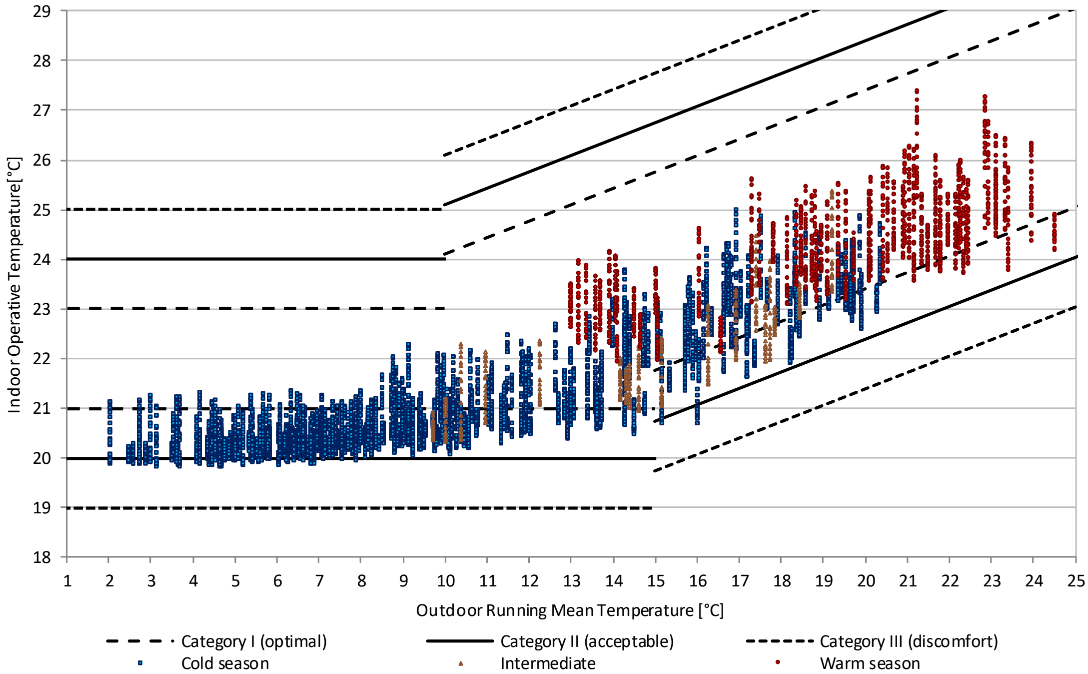


Figure 4.76: TC of 5th combination of strategies and outside running mean temperatures, adaptive method of EN 15251.

4.8. Discussion of the main findings

The presented study showed a wide variety of results for a number of strategies. In the following paragraphs, the potential of each tested strategy is explained, discussing the observed trends and the main problems in relation with the objectives established in Section 4.2.

The first challenge was to **integrate the verified features of the real case study in a detailed ENERGYPLUS® model** (**objective 4.1**). This could permit be used later to apply different strategies and analyse the best way of improving the original passive house design.

To do that, the first step was to transform the measured weather data of the meteorological station into a EPW file, considering the period from 12/03/2013 to 11/03/2014. It was necessary to cut the climate data in a yearly frame from January to December and create a transition day between the 11th of March of 2014 and the 12th of March of 2013. Otherwise the ENERGYPLUS® engine and natural ventilation calculations weren't able to calculate well. Besides, it was also necessary to correct the first 12 hours of the climate data. This was needed because the outside temperatures around New Year's Eve were abnormally warm and this fact altered significantly the warmup period of ENERGYPLUS® and led to a wrong setup of the initial temperatures in the model.

The second step, the geometric definition of the model was rather realistic. The dimensions of the building, included not only the sizes of rooms and openings, but also the very complex ceiling with an irregular shape and the outside sidewalk, as shown in Figure 4.77Figure 4.79. This way, all the relevant components for the thermal behaviour of the house were represented, according to the points identified during the thermographic inspection of the Section 3.4.10.

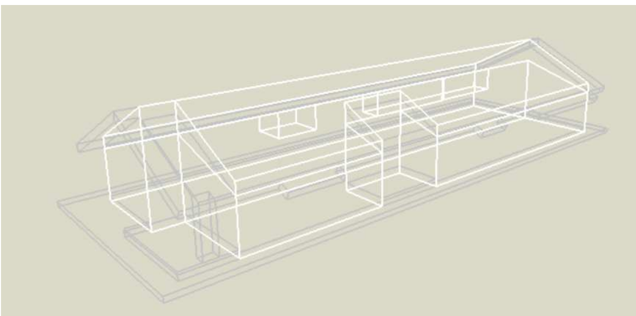
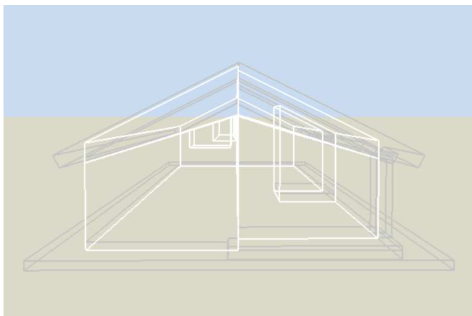



Figure 4.77: Model geometry in wire frame, showing the room space and the ceiling space above.

The third step, the definition of HVAC systems was simplified to fit the DB and ENERGYPLUS® capabilities. If the real ventilation of the building was based on rooms with either supply air (e.g., bedrooms) or exhaust air (e.g., bathrooms, kitchen), in the model the ventilation of all rooms was connected with the MVHR unit with both supply and exhaust air loops, as explained in Section 4.4.3. This is due to the limitation of air mass zero balance in ENERGYPLUS®. This limitation could be minimised manually in ENERGYPLUS® adding a certain air volume exchange hourly (using the ZoneMixing object), but bearing in mind the purpose of the model for future corrections and multivariable assessment it was too slow for the study. Instead, the global indoor environment was validated through the MBE and CV(RMSE) values for RH and temperature in the annual value and also in the majority of the months in detail.

The fourth stage, the operational definition was probably the most difficult part. Most of the works available about low energy building measurements confirm this idea, as underlined in the latest review of BEPS calibrations (Coakley et al., 2014). As explained in Section 4.4.1, a recent case of the calibration of a passive house BEPS with monitored data found the same limitation and had to base their iterative corrections in interviews and logbooks. In the present study, these corrections were based firstly on the measured monthly electricity use and estimated average daily values, as described in Section 3.4.3. Secondly, the share of electricity uses was defined according to the PHPP estimations corrected with the real annual values. These calculations separate the use for lighting, cooking, dishwashing, fridge and freezer use, small appliances, computers and so on, as listed in Table 4.4. Thirdly, these values were applied to each room according to the typical occupancy of the house (Section 3.4.8.2) and the variations of temperature and RH observed in high detailed curves (minute by minute) as explained in more detail in Section 3.4.7.

As a result, the **thermal comfort of the model matches successfully the monitored values to great extent** (**objective 4.2**), as shown in the plots of Section 4.5 and the error analysis conducted with MBE and CV(RMSE). The main differences were found not in the winter or summer typical weeks, but in the transition months. Therefore, they are more related the indoor activity levels than with the house performance itself. This is clear especially in October when the abnormally high indoor temperatures were warmer than August, a fact which can be explained by the abnormally high internal activity registered by the electricity measurements.

Apart from the positive results of the BEPS, the studied case had to face several issues which restricted considerably the scope of the assessment. On the one side, the building geometry, distribution and structural concept were rather particular. The review of the passive houses built in Spain up to date shows a very broad variability of shapes, as described in the next Chapter 5. On the other side, the occupancy variations detected during the monitoring demonstrate a broader study should include this aspect for OH risk prevention. This study was able to represent with a high level of detail the whole behaviour of the housing, focusing on the extreme winter and summer conditions and leaving in a second level the gaps observed during the shoulder seasons. Based on the experience of this case, a more precise control of the electricity use should solve the problem of matching occupancy and internal gains to great extent.

After the verification of the model, a number of possible strategies was evaluated. Firstly, the strategies related with **ventilation optimisation** have demonstrated to be highly efficient (**objective 4.3**). As explained in Section 4.6.1 and in the previous Chapter 3, the inhabitants of the house used natural ventilation occasionally, but only with some openings and during short ventilation periods. This way, they can reduce the warm discomfort hours to great extent thanks to the night cool hours in the location of the house (the minimum temperatures below 15 °C are frequent in all summer). However, the potential of this strategy is much greater if all the main windows are open or if the schedule of operation is extended to longer periods. Besides, the ratio of ventilation of the MVHR unit was also higher than necessary according to the PHPP calculations. All these questions were analysed in the study, to analyse the whole potential of ventilation as a way to provide an optimal thermal comfort and low energy need.

The first stage checks the improvement achieved with a lower and more accurate ventilation airflow during all year. As a result, the electricity use of fans is reduced in 7 %, the heating use is slightly reduced in 1.3 % and the summer indoor environment is very slightly warmer than in the reference model. This operation type was implemented in the combination of strategies.

The second stage calculates the maximum free-cooling potential of the MVHR unit. It is based on a possible improvement of the controller of the fans to increase the airflow when the summer bypass is open. This maximum airflow is defined according to the PHI certification of the unit, which guarantees a highly efficient ventilation based on very low Specific Fan Power (SFP) values. The results show an additional 9.0 % of the free-cooling from June to September which can reduce the number of hours over 25 °C in a very significant 19.5 %.

The third stage applies natural ventilation strategies to compensate the day time heat gains. The initial approach uses only the late evenings (21:00 - 24:00 h), because this is the period when occupants could open or close the windows. The second approach extends the ventilation period to overnight (21:00 – 7:00 h). Besides, the operation of the natural ventilation is also studied under to assumptions: an automatic opening every day or a manual operation only 3 days per week. The latter is a simplification of the complex occupancy schedule and the habits observed during the monitoring of the real case. In any case these two options aim to embrace the maximum potential and also the reasonable level of use in the warmer days of summer.

The results indicate that the best option would be to include an automatic control for the night natural ventilation. This way it could eliminate almost completely the warm discomfort hours. In fact, even though the manual operation doesn't get all that potential, it can reduce to one third the hottest hours (PMV > 0.7) and to half the warm hours (category C of PMV).

Actually, one of most difficult points of this analysis was the definition of the indoor and outdoor limits for the natural ventilation. These limits obviously reduce the free-cooling potential of the natural ventilation, but maintain the indoor comfort within an acceptable range. In this study, the maximum ACH was set in 6.0 h^{-1} and the DB temperature limits were fix according to the 90% acceptability of summer PMV conditions, that is 23.5 °C, and an outdoor limit in 13 °C to prevent draught. These conditions avoid any possible overcooling during night time. In any case, there are different possible approaches to set limits or controls to natural ventilation and it could be object of a further research, as suggested in the recent State of The Art made by Annex 62 (Kolokotroni & Heiselberg, 2015).

Another groups of analysed measures were the use of **solar shading** to improve the thermal comfort (**objective 4.4**), in Section 4.6.2. The potential of these measures was conditioned by their adaptability to the features of the studied house, whether they could be installed in the enclosure or not. Bearing in mind that the house is covered by an ETICS, the installation of these systems outside shall be done directly to the windows. So, in the first place they should be lightweight. Besides, the shading systems should not reduce the general performance of the housing, meaning that the solar gains in winter or the preservation of airtightness is essential. This way, two types are studied: roller fabric blinds and venetian blinds. These conventional solutions are commonly tested and affordable in the European market. They can include a small automatic control in the top, to pick it up the shading when not necessary. These types are tested inside and outside the openings, with manual operation (8:00 – 20:00 h and three days per week) or with an automatic control every day, which extends the blinds when the outside solar radiation overpasses 200 W/m².

The results indicate that placing the venetian blinds inside is not only ineffective but also harmful for indoor thermal comfort. If placed on the outside though, the venetian blinds present a very different performance according to the global reflectivity of the system, which is based on the angle of slats. Accordingly, if the automatic control lets the slats in horizontal position it ends warming up the indoor environment significantly, increasing the PMV warm discomfort from 10.8 % to 12.2 % of the total annual hours. On contrary, if the automatic control can change the angle to block the sun rays the system reflectivity increases and gets a very remarkable reduction of the warm hours up to only 6.6 % of the annual hours.

In any case, the use of opaque blinds from the outside is clearly the easiest ways to reduce the sun gains, see the comparison in Figure 4.46 for further details. The automatic control can get the best reduction of warm discomfort hours according to PMV summer limits. Nevertheless, as seen in the introduction and the literature review (Cotterel & Dadeby, 2012) (Race et al., 2010) (Hopfe & McLeod, 2015) (REHVA & ES-SO, 2010), the selection of one or another type is always conditioned by the user's preferences and the possibilities of each project.

The impact of **airtightness in passive houses** can be considerable (**objective 4.5**), because according to their standard they need to achieve very airtight constructions. According to the review of Spanish passive designs, their n50 range between 0.2 h^{-1} and 2.0 h^{-1} at 50 Pa, as described later in Chapter 5. For this reason, any small deviation in the construction quality can lead to big differences from the projected to the final real heating need. In Section 4.5.1 the impact of airtightness in the heating consumption of the studied house is very remarkable. For instance, a subtle increase from 0.2 h^{-1} to 0.6 h^{-1} can lead to an additional 7.6 % of heating need and a higher airtightness drop to 2.0 h^{-1} may boost the heating need in a very significant 23.0 %, as shown in Figure 4.16 and Figure 4.17. On contrary, a reduction from 0.6 h^{-1} to 0.2 h^{-1} can also reduce the 15.0 % of the heating use.

Regarding the effect on the indoor environment, a lower airtightness can cool down the indoor during summer and winter. As seen in the Figure 4.18, the differences are rather small in the monthly level, meaning that the temperatures can be on average 0.2 °C lower during the most part of the year. On the other hand, there are particular windy hours when the combination of stack effect and wind pressure con provoke higher temperature differences. To represent this issue, a detailed approach would have monitored the pressure differences under different outdoor-indoor conditions, but it would require another parallel study which goes out from the scope of this work. Instead, the present study applied the factors of natural ventilation of BLAST engine, see formula (1). This set of factors is a simplification based on the average behaviour of construction cracks. So, instead of the static constant ENERGYPLUS® calculations it uses the wind pressure and temperature difference. Figure 4.78 below represents the hourly variations calculated with this method.

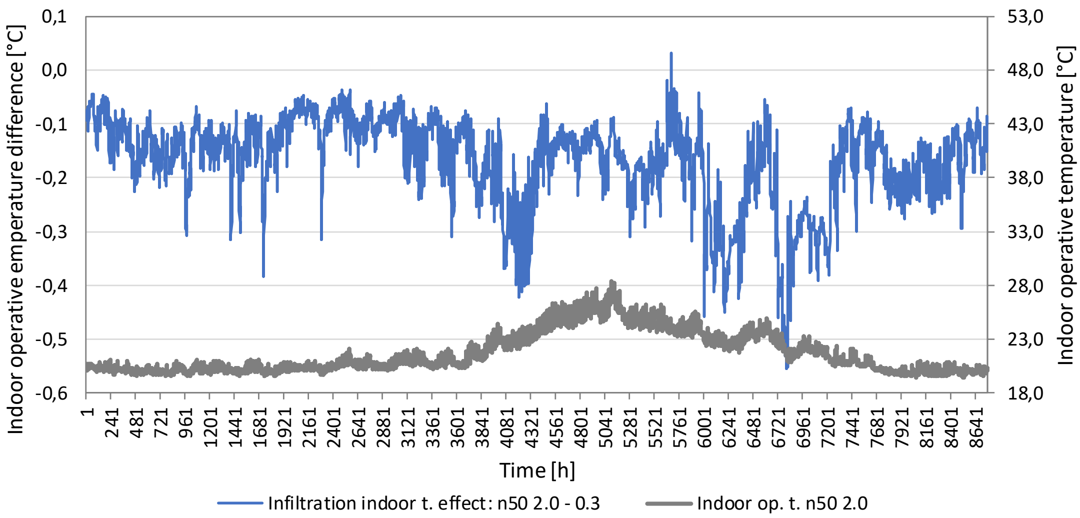


Figure 4.78: Indoor temperature differences due to airtightness degree, differences between n50 0.3 and 2.0.

Therefore, the maximum hourly differences inside the evaluated airtightness range are around 0.4 °C in winter and 0.5 °C in summer. Therefore, even though the influence of infiltrations in airtight buildings seems to be not too high, they can be crucial in summer when the indoor gets close to the higher comfort limits. In hot waves, for example, half a degree up or down can make the difference. Considering these results, the infiltration potential in the cases under warm environments should be studied in further detail.

Regarding the relevance of **internal gains** (**objective 4.6**), the analysis conducted in this chapter confirms the significant differences which will appear between the projected standard usage and the real use. Considering that the impact of internal gains represents approximately the 30 % of the annual heat balance in passive houses, the deviations of the internal activity in one or another day could have a very considerable impact on the indoor temperatures.

To assess the effect of internal gain variations in the studied case, the lightning and big appliances remain the same but modifying the use of computers, cooking and small appliances. These changes increase or reduce up to the 18 % of the global house internal gains, see Section 4.5.3.

Due to these internal gain changes, the heating consumption increases up to 11.9 % in winter, to compensate these temporal lower internal gains. On the other hand, the increase of the internal use in summer can raise the indoor temperatures and increase significantly the risk of OH. Figure 4.79 presents the maximum hourly deviations caused by those internal use differences, compared with the projected internal gains. It is very significant the average increase is 0.4 °C in summer and especially the temporal arises which reach up to 0.8 °C in certain moments.

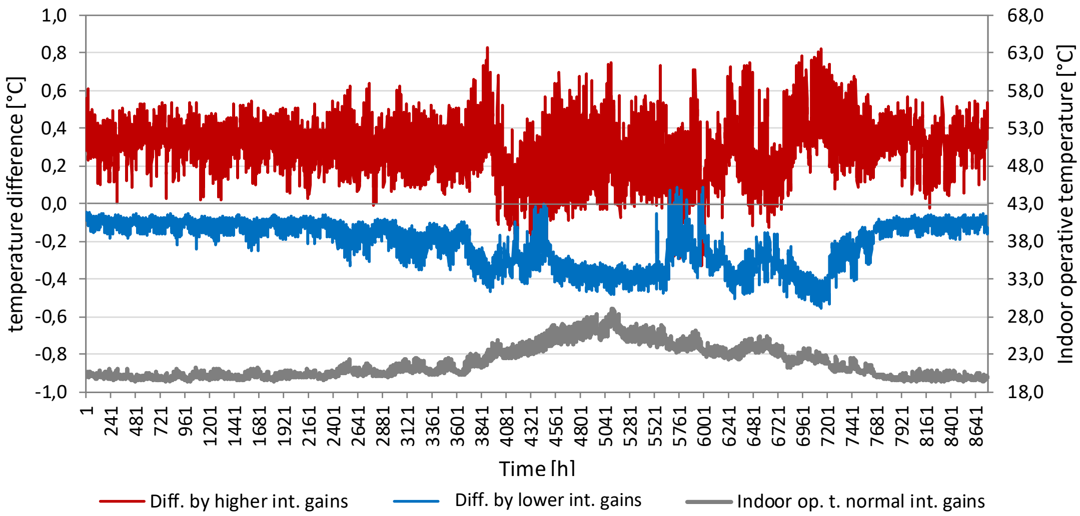


Figure 4.79: Indoor temperature differences due to internal gains level, differences of 18 % more or less electricity use during day time.

The fourth aspect of the model definition is the impact of **thermal mass** (**objective 4.7**). In recent workshops about the potential of thermal mass, the relevance of thermal mass activation is explained and related with the convection coefficients factors of the inner walls (Álvarez & Molina, 2016). As mentioned before, the use of Computational fluid dynamics (CFD) is out of the scope of the present work. However, to be able to reflect the thermal mass activation, the heat capacity of the main structural elements has been modified, as described in Section 4.5.4. This way, the model results represent scenarios where the activation of thermal mass is larger or smaller. The indoor operative temperatures of these scenarios are plot in Figure 4.80.

The hourly deviations related with more or less thermal mass can be especially relevant in summer, where there is no cooling system to respond. Overall, the increase due to smaller activation of the thermal mass in summer is around 0.6 °C. On contrary, the potential of a mayor activation of thermal mass can lead to significant cooling effects between 0.3 °C and 0.5 °C in all summer. Besides, it is observed how a higher thermal mass can help reducing the heating need in fall, thanks to the heat cumulated in the internal mass in summer.

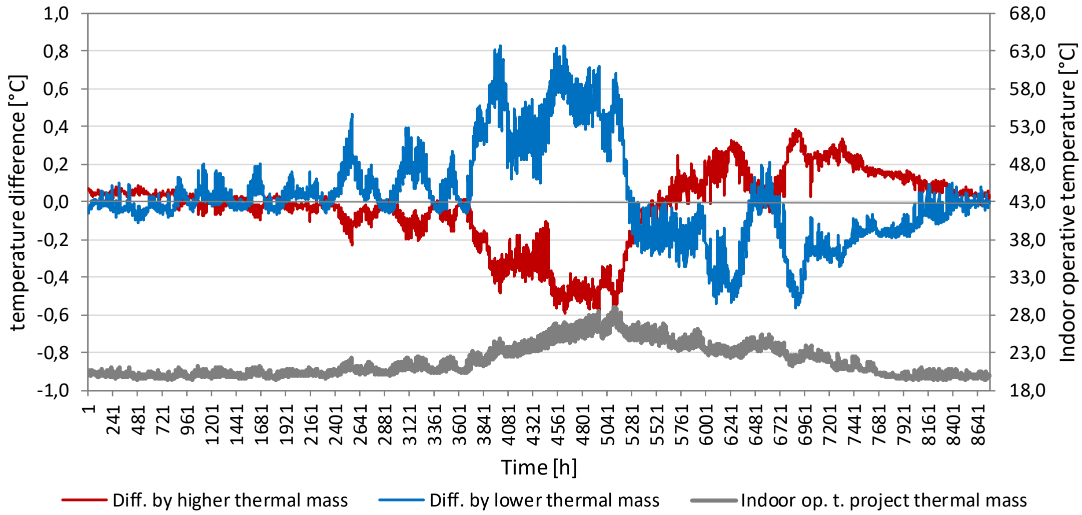


Figure 4.80: Indoor temperature differences due to thermal mass in construction, differences of 50 % more or less heat capacity in structure and walls.

Finally, in order to face the last objective which asked whether an **optimal TC can be achieved with a combination of passive measures** or whether an active cooling is necessary (**objective 4.8**), the previously analysed measures have been combined and analysed in Section 4.7. The analysed strategies have been merged into the three most efficient solutions together with another two additional manually controlled combinations.

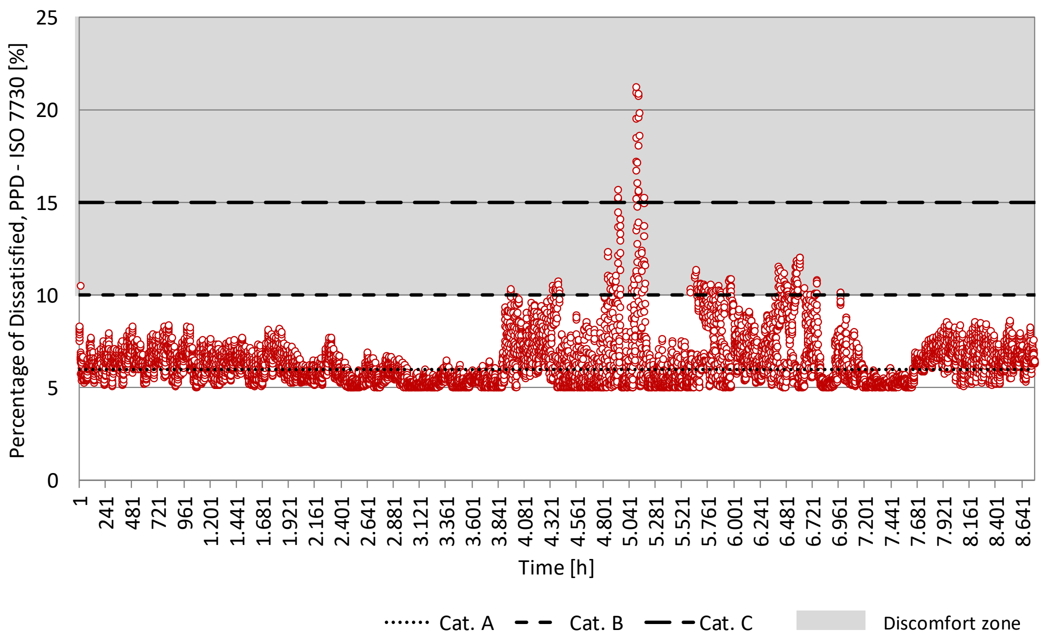


Figure 4.81: PPD of the best combination of strategies (C1).

According to the results plot in Figure 4.52, the best combination implements some additional small heaters in the coldest rooms, MVHR with summer nominal bypass and automatic external roller blinds and night time natural ventilation. This configuration keeps the indoor environment during the 99.0 % of the hours within the good category B of PMV (PPD < 10 %), as shown in Figure 4.81. On the other hand, the best measures operated manually (C4) can also achieve a great 98.6 % of good comfort within the PMV category B.

In any case, there are a number of possible combinations of the analysed passive measures which could lead to successful TC environments, especially if they combine solar shading and any type of natural ventilation. These findings indicate that in this climate the outdoor cool air is probably the best way to prevent any summer OH, more than only shading or MV free-cooling.

4.9. Conclusions

The characterisation of the case study in a dynamic BEPS model was successful. The high detail of the monitoring, including many on-site testing and verification procedures were the key to correct the model and reach to error acceptability ranges. The iteration process was driven by the parameters of heating use and indoor temperatures, supported by the potential of graphical analysis. The indoor environment was also analysed comparing the thermal behaviour during two typical summer and winter weeks. Indoor temperature and heating response indicate an overall positive response of the model.

The final verification executed with the MBE and CV(RMSE) shows a positive calibration with the monthly method according to the ASHRAE guideline 14 limits. The model presents MBE of 0.9 %, -4.5 % and 4.7 % and CV(RMSE) of 3.2 %, 7.5 % and 14.7 % for operative temperature, RH and heating use respectively. In the annual hourly method, the values exceed moderately the limits of RH and heating use, with MBE of 2.2 %, 12.1 % and 7.6 % and CV(RMSE) of 4.1 %, 11.2 % and 66.0 % for operative temperature, RH and heating use respectively.

The margin of improvement due to improvements of the ventilation was enormous, especially regarding summer operation. The heating use reduction achieved with the correction of the of nominal ventilation airflow got a very small impact, this was expected due to the very efficient HR ratios. On contrary, the summer bypass airflow enhancement can augment the free-cooling in 9.0 % and reduce the number of hours over 25.0 °C in 19.5 %. However, the potential of summer bypass is very low in the hottest months because the small airflow requires either many hours or a big temperature difference to be able to provide any significant cooling load.

The measure with the highest potential on the analysed climate is the use of natural ventilation. The opening of windows during 3 hours in the evenings in bedrooms, dressing room, dining room and living room can make a difference and reduce by half the PMV warm discomfort hours. The use of night time ventilation can reduce the warm discomfort hours to only one third, maintain the PMV warm discomfort below 3 % of annual hours. Moreover, the limit of window open/close control is observed and it could be considerably larger with a more precise control of the opening degree or through smaller vents. The results have been analysed with the PMV method, since it is more restrictive than the adaptive method and the building is most of the time without any natural ventilation, with a very regular free-running indoor environment with MVHR.

The potential of the studied solar shading systems was paradoxically short. This might be related with the types selected for an existing building, the small cooling capacity of the MVHR and its summer bypass and also with the high thermal inertia of the house. The best measures correspond to opaque blinds or venetian blinds with angle control. The maximum TC improvement of external opaque blinds can reduce the warm discomfort from 10.8 % to 6.2 %, being this effect rather insufficient. This way, considering their limited impact on TC and the likely reduction of visual comfort or daylight, their use can be limited to the hottest days of summer. In any case, this aspect would require a further verification with the particular components.

Regarding the scope of the studied systems and their type of control. The automatic or manual controls applied to ventilation and solar shading elements have indicated the range of available improvements, showing the benefit obtained with an average manual control by the inhabitants in contrast with the optimal automatic operation. As a positive result, even the manually controlled systems have demonstrated a remarkable difference in TC. On the other hand, the analysed passive measures were limited to those components which could be installed in a building without requiring any mayor renovation. With this decision and results, it is proven that the TC of an incomplete initial design can be improved to great degree with simple supplementary elements and an average control by inhabitants. Thus, the OH risk can be minimised easily maintaining the nZEB energy consumption level.

CHAPTER 5
EVALUATION OF THE SUMMER ADAPTATION OF SINGLE-FAMILY PASSIVE HOUSES TO COOL-TEMPERATE CLIMATES IN SPAIN

Abstract
This chapter reviewed the features of Spanish single-family passive houses and evaluated their adaptation to the local climate conditions. The main objective was to assess their capacity to avoid the need of active cooling systems in the present and also in the future climate change scenarios for 2040 and 2080. The study calculated the minimum thermal insulation levels for the different cool-temperate climates in order to fulfil the PH requirements of heating demand and heating load. The summer performance was evaluated by the capacity to provide an optimal thermal comfort by the means of combination of passive measures based on solar shading, ventilation and thermal mass strategies.
The results confirmed that all the cases in the studied climates could completely avoid the use of active cooling, if the proper combination of measures is selected. The use of night-time natural ventilation was the best passive cooling measure for the tested three climates and three building models. In combination with roof overhangs and certain amount of thermal mass, natural ventilation could be sufficient in the three locations, without the need for additional shading on the windows. The use of the MVHR unit with enhanced airflow during summer bypass appeared to provide a limited cooling capacity which would require the combination with direct solar shading devices on the windows.
The importance of these measures was more visible considering the future climate scenarios, which showed increases of the indoor temperatures in summer by about 1-2 °C by 2040 and by around 2-5 °C by 2080. In all the cases of the studied climates the use of active cooling could be completely avoided, through an adequate combination of supplementary feasible measures of ventilation and solar shading.

5. Evaluation of the summer adaptation of single-family passive houses to cool-temperate climates in Spain

5.1. Introduction

The search of super insulated homes may lead to certain overheating issues if the building design is not well equipped with sufficient passive cooling measures or if the users don't use them properly (Ridley et al., 2014) (A. Figueiredo et al., 2016).

To study which measures of passive cooling would be necessary in the different cool-temperate areas of Spain, the first step was to define some average features which could summarise the global problems of these constructions. This was a considerable challenge because the reduced number of cases in Spain (52 single-family passive houses until January of 2017) and the variability of their design complicated the definition of a reference case.

Figure 5.1. Examples of the variability of single-family passive houses in Spain (taken from PEP, 2017).

The limited experience from these passive constructions and the upcoming nZEB challenges definitely require more investigations about the capacity of these houses to adapt to the cool-temperate conditions. This study aimed to help identifying the most feasible passive cooling strategies for each climate zone and provide some insights to assess the resilience of these houses in a context of climate warming. If not addressed, the present designs optimised for winter performance will highly likely have to face considerable increases of indoor temperatures.

5.2. Aim and objectives

The main goal of this chapter is to **evaluate the capacity of adaptation of single family passive houses to cool-temperate climates in Spain**, analysing the heating energy need, thermal comfort and the risk of overheating. The buildings were equipped with different ventilation and solar shading devices in order to evaluate their capacity to **avoid the need of active cooling systems in the present and also in the future climate change scenarios for 2040 and 2080**. This showed which features fit the best this typology under local climate conditions as well as pointed to a clearer definition of the solutions for future nZEB constructions.

To do that, the following particular objectives were established:

Objective 5.1 Define the reference models based on average single-family passive houses in Spain.

Objective 5.2 Identify the representative cities to analyse the conditions of Atlantic and continental climates.

Objective 5.3 Calculate the minimum thermal insulation levels for each case and location, so that they meet the main criteria of PH standard for winter energy demand.

Objective 5.4 Verify the capacity of the studied passive measures to reduce the cooling need and provide good thermal comfort without additional energy use.

Objective 5.5 Assess the present risk of overheating of the most relevant cases.

Objective 5.6 Evaluate the future behaviour in 2040 and 2080 scenarios of climate change of the selected relevant models.

5.3. Methodology

In this chapter, the average single family passive houses in Spain were reviewed and the capacity to implement passive cooling measures into the design was analysed so that there is no need for active cooling systems.

As a preliminary work, the representative models were defined through the review of the average values of Spanish single-family passive houses. This included the features of geometry, construction materials, heating and ventilation systems, occupancy levels and internal heat gains. These values were based on the state of the art of Section 2.2.2 and the outcomes are summarised in Section 5.4.

The first stage of the study evaluated the winter adaptation of the PH principles to the local heating need conditions. The study was conducted with ideal heating and cooling systems to quantify the heating and cooling needs with the typical PH operational set points (Passive House Institute, 2016). The steps and results are explained in Section 5.5. After the results of this stage, the most relevant three models were selected to continue in the next stage.

The second stage comprised the largest part of the study and the results were analysed in the Section 5.6 in detail. The measures and the cases are evaluated separately in a multiple analysis of indoor temperatures and thermal comfort with PMV method (ISO 7730, 2005) and adaptive method (EN-15251, 2007). Among the results obtained in this stage, three representative models were selected for a further verification by the future climate scenarios.

The third stage calculated the risk of overheating of the most relevant models, according to the CIBSE TM52 method (CIBSE, 2013b). This way, the main problems of the tested cases would be highlighted.

The fourth stage analysed the future behaviour of present designs. Three scenarios were taken from the most common families to represent the different CO_2 emissions hypothesis (IPCC et al., 2013): B1 (low), A1B (medium)and A2 (high).

Finally, the main conclusions are highlighted in Section 5.8

5.4. Definition of the cases of study

5.4.1. Building models

5.4.1.1. Construction features

The models of this study were based on the average features of single-family passive houses in Spain. This way, two buildings were defined as 1) the average single-family detached house and 2) the average single-family attached house; including the most common size, construction materials and ventilation systems. These values were identified through the detailed review presented in Section 2.2.2 of Chapter 2.

Regarding the size, both models were set with the average Spanish treated floor area to facilitate the comparison among the results. So, based on the review of Spanish house stock (SECH Project -SpaHousec, 2011) and the review of Spanish PH of Chapter 2, the floor area was set at 146 m².

Additionally, the geometry was set as simple as possible, since the review of PH in Spain demonstrated a high variability in shapes and design. On the other hand, as the PH dwellings are commonly presented with an average of two floors, the models of the study were also defined with two floors, as shown in Figure 5.2 below. Accordingly, the first model was defined with a simple square plan and two floors which contained the Spanish average net floor area of single-family detached houses, that is 146 m².

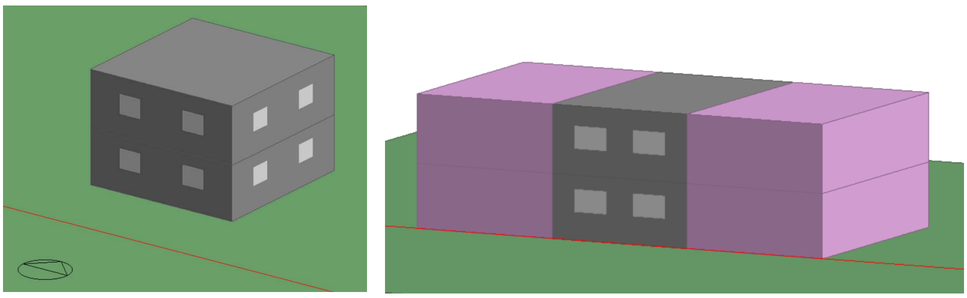


Figure 5.2. Geometry of single-family house models, detached (left side) and attached (right side).

The dimensions of the second model were more complex because this type of dwellings is strongly conditioned by the urban plot sizes. To find out the common plot dimensions, the city of Vitoria-Gasteiz was considered as a proper location, because it is an intermediate city between Atlantic and continental areas and also because this city had some new construction developments in the last decade. Local regulations established these plot sizes in the last version of 2003 (PGOU Vitoria-Gasteiz, 2003). The values were taken from four of these recently built promotions of different neighbourhoods, which are highlighted in red circles in Figure 5.3. The dimensions of these cases were averaged in Table 5.1 and the final size of the model was slightly increased in order to match the same net floor area of the detached case (146 m² approximately). These reference plots are shown as urban plan boundaries and also in an aerial view, in Figure 5.4 and Figure 5.5 respectively.

Figure 5.3. Location of selected attached housing typologies built in the last 15 years in Vitoria-Gasteiz (source: local construction regulations and updated plan of the *PGOU of Vitoria-Gasteiz, 2008)*

Table 5.1. Dimensions of the attached model based on recently built similar typologies

Attached housing examples	**Depth (m)**	**Width (m)**	**Brute floor area (m²)**	**Depth/width ratio**
Zabalgana RE-MOA2_28	11.5	7.0	80.5	1.6
Sansomendi RE-OA	10.5	6.5	68.3	1.6
Lakua RE-OA	10.5	6.8	70.9	1.6
Arriaga RE-OA	11.8	7.5	88.1	1.6
Average dimensions	11.1	6.9	76.7	1.6
Attached model	11.5	7.3	84.0	1.6

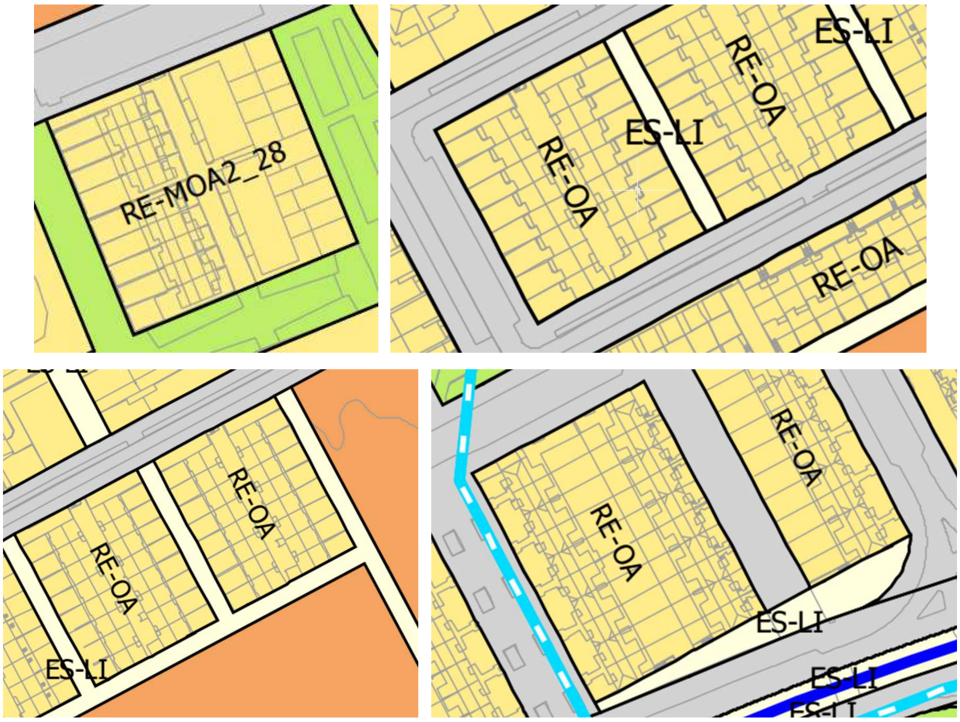


Figure 5.4. Examples of attached housing plot dimensions and typologies built in the last 15 years in the neighbourhoods of Zabalgana (top left), Sansomendi (top right), Lakua (bottom left) and Arriaga (bottom right) in Vitoria-Gasteiz (source: local construction regulations in Tomes II, III and IV of the PGOU of Vitoria-Gasteiz, 2003)

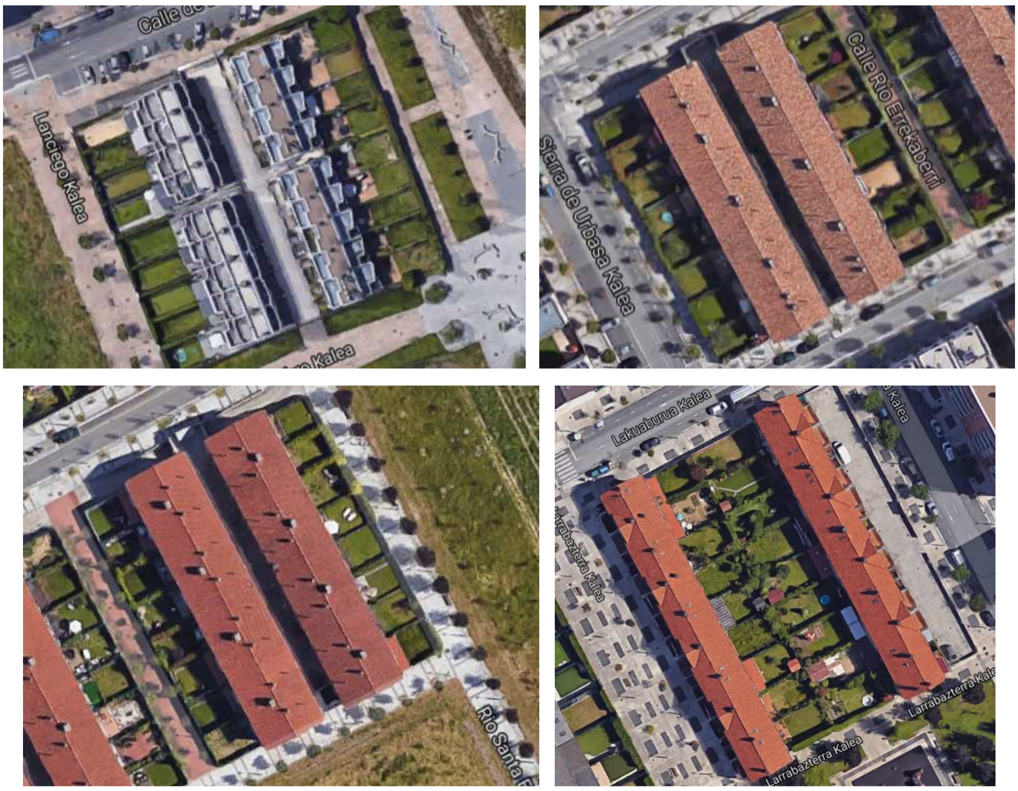


Figure 5.5. Examples of attached housing plot dimensions and typologies built in the last 15 years in the neighbourhoods of Zabalgana (top left), Sansomendi (top right), Lakua (bottom left) and Arriaga (bottom right) in Vitoria-Gasteiz (source: Google Maps*, 2017)*

As a result, the common features of the analysed two models are described in Table 5.2 below.

Table 5.2. Common features of studied models.

Model features	Detached	Attached
Size		
Number of floors	2	2
Net floor area [m²]	146	146
Type of construction	New	New
Construction thermal insulation		
Structure materials	Wood, concrete ground slab	Wood/masonry, concrete ground slab
Window frame material	Wood	Wood
Thermal mass	Low	Medium
Ventilation and airtightness		
ACH 50 Pa [h^{-1}]	0.6	0.6
MVHR Maximum air flow (m3/h)	350	350
HR sensible recovery efficiency [%]	90%	90%
Summer bypass	Yes	Yes
Systems definition		
Heating systems	Electric heaters distributed	Electric heaters distributed
DHW generation	HP	HP
Heating thermal power [kW]	5.0	5.0
Hot water storage [l]	300	300

The thermal insulation levels were set as parameters to be adjusted during the first stage of this study, to adjust the design to the maximum winter heating demand of PH standard. The evaluated values are described in Table 5.3.

The thermal bridges in this type of constructions are rather small due to the thick external thermal insulation (Lewis, 2014) (Hopfe & McLeod, 2015). However, in order to reflect the possible heat losses through TB in passive house designs, they were calculated as 50% of the recommended heat losses according to the PH standard (Ψ_e 0,10 W/mK) (Mead & Brylewsky, 2011). Accordingly, the linear thermal transmittance of the main TB of each level of insulation were calculated and summarised in Table 5.4.

Table 5.3. Thermal insulation levels of studied models.

Model thermal insulation levels		**MIN** **10**	**15**	**20**	**25**	**MAX** **30**
FACADE WALL						
Thermal transmittance (W/m²K)		0.271	0.190	0.147	0.119	0.101
Components:	λ [W/(mK)]			thickness [mm]		
External coating	0.870	10				
EPS	0.032	100	150	200	250	300
CLT panel	0.120	95				
Mineral wool	0.036	45				
Gypsum board	0.250	15				
Total	-	265	315	365	415	465
ROOF						
Thermal transmittance (W/m²K)		0.226	0.175	0.141	0.118	0.101
Components:	λ [W/(mK)]			thickness [mm]		
Roof membrane	1.000	10	10	10	10	10
XPS	0.036	100	150	200	250	300
CLT panel	0.120	180	180	180	180	180
Air cavity	(R 0.09)	10	10	10	10	10
Gypsum board	0.250	15	15	15	15	15
Total	-	315	365	415	465	515
GROUND SLAB						
Thermal transmittance (W/m²K)		0.303	0.213	0.164	0.134	-
Components:	λ [W/(mK)]			thickness [mm]		
XPS Styrodur	0.036	50	100	200	250	-
Reinforced concrete slab	2.400	300	300	300	300	-
XPS Styrodur	0.036	50	50	50	50	-
Mortar levelling	1.300	50	50	50	50	-
Floating wood floor	0.130	15	15	15	15	-
Total	-	465	515	615	665	-
WINDOWS						
Thermal transmittance average window (W/m²K)		*1.29*	*1.19*	*0.99*	*0.79*	-
Components:						
Number of panes and gap filling		Dbl L.E. Air	Dbl L.E. Argon	Tpl L.E. Argon	Tpl L.E. Argon	
Frame U (W/m²K)		1.500	1.410	1.200	1.000	-
Glass U (W/m²K)		1.200	1.100	0.900	0.700	-
g-value (%)		0.600	0.6	0.5	0.4	-
Installation thermal bridge (W/mK)		0.100	0.09	0.07	0.06	-

Table 5.4. Thermal bridge definition in the models.

Thermal bridge type	**$\Psi_{i\,10}$ (W/mK)**	**$\Psi_{i\,15}$ (W/mK)**	**$\Psi_{i\,20}$ (W/mK)**	**$\Psi_{i\,25}$ (W/mK)**	**$\Psi_{i\,30}$ (W/mK)**
Roof-Wall	0.204	0.174	0.142	0.124	0.119
Wall-Ground floor	0.270	0.217	0.182	0.157	0.153
Wall-Wall (corner)	0.044	0.050	0.057	0.039	0.034
Wall-Floor (Int - not ground floor)	0.072	0.060	0.044	0.039	0.037
Wall-Floor (Ext - not ground floor)	0.204	0.174	0.142	0.124	0.119
Lintel above window or door	0.100	0.090	0.070	0.060	0.060
Sill above window	0.100	0.090	0.070	0.060	0.060
Jamb at window or door	0.100	0.090	0.070	0.060	0.060

The openings were defined according to the recommendations of PH design for temperate-warm areas and guaranteeing at least the minimum glazing ratio of Spanish regulation.

Firstly, the minimum window sizes for housing constructions are regulated by minimum window-to-floor ratios and must be around 10-13% of the adjacent rooms, according to the current regional regulations such as (Parlamento de Cataluña, 2012) and (Parlamento del País Vasco, 2015).

Secondly, for the in temperate-warm climates, the PH design publications as a rule of thumb have recommended to set the window to floor ratios between 15-25% in the initial design (BRE, 2006) (Ford, Schiano-Phan, & Zhongcheng, 2007b) (Wassouf, 2014). Since this study aimed to analyse the inherent risk and limits of PH design, the minimum value of 15% was taken as a global ratio for the studied models.

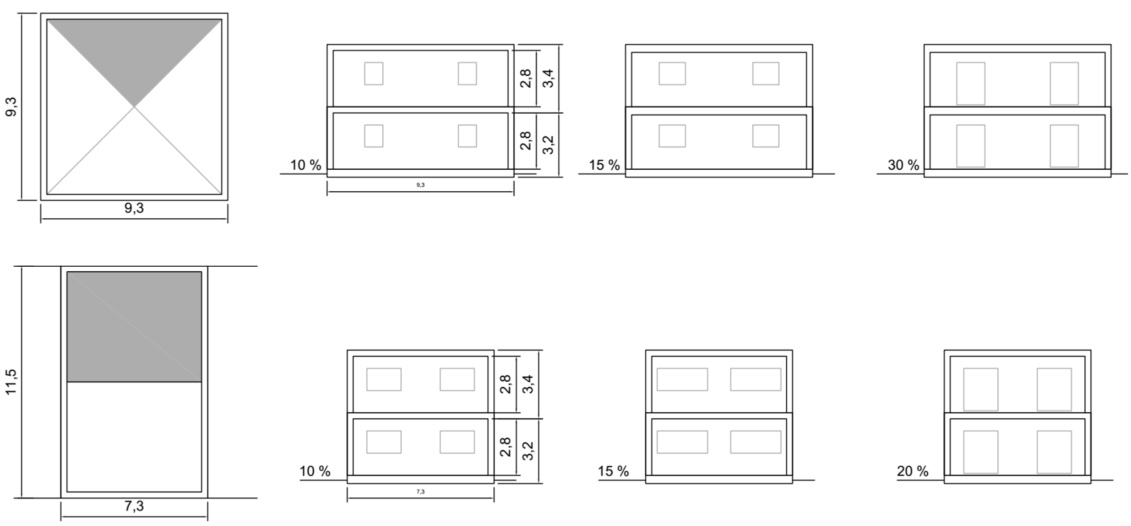


Figure 5.6. Plan and cross sections of the studied models with window to floor ratio.

Once the global opening area was set at 15%, the next step was to distribute the openings in different facades according to the common PH strategy. Considering South as the best orientations, the south facades augmented their glazing ratios as much as possible, with two limitations: firstly, the minimum opening ratio of local regulations (10%) and secondly, the maximum recommendation of around 25% of the external wall area in South orientations (BRE, 2006). Taking into account these considerations, the window areas are described in Table 5.5 and plotted in Figure 5.6.

After this analysis, the need to differentiate the attaches houses with East-West orientation from the ones with North-South orientation was observed.. Since their dimensions of windows should be different, as shown in Table 5.5 below.

Table 5.5. Window areas and opening ratios of the models.

	External wall surface (m²)	Net floor area per orientation (m²)	Window/ floor ratio (%)	Window/ wall ratio (%)	Window surface (m²)
Detached house					
North	57.6	36.6	10.0	6.4	3.7
East	57.6	36.6	10.0	6.4	3.7
West	57.6	36.6	10.0	6.4	3.7
South	57.6	36.6	30.0	19.1	11.0
Total	230.4	146.5	15.0	9.5	22.0
N-S attached house					
North	45.3	73.0	10.0	16.1	7.4
East	0.0	0.0	-	-	0.0
West	0.0	0.0	-	-	0.0
South	45.3	73.0	20.0	32.3	14.6
Total	90.5	146.0	15.0	24.3	22.0
E-W attached house					
North	0.0	0.0	-	-	0
East	45.3	73.0	15.0	24.3	11
West	45.3	73.0	15.0	24.3	11
South	0.0	0.0	-	-	0.0
Total	90.5	146.0	15.0	24.3	22.0

5.4.1.2. Systems operation, occupancy and internal heat gains

As this study is focused in the energy demand, the type of systems was simplified as much as possible. To provide heating, each thermal zone was equipped with electric heaters and the heating setpoint was set at 20 °C. On the other hand, the active cooling systems were used only during the first stage of the study, mainly as a way to quantify the impact of the decisions based on winter design in the summer behaviour. When used, it was active between 1st of June – 30th

of September with a cooling setpoint at 26 °C. Both systems were configured with an ideal performance of 100%, with ideal curves by capacity fraction and temperature.

The internal use of passive houses is a crucial aspect of the model definition, as underlined in the conclusions of the PhD thesis of Dr. Rodriguez (Rodriguez Vidal, 2015). Accordingly, the different IHG levels are analysed to determine which of them would fit better the purpose of the present study.

If PHI traditionally considered average internal heat gains (IHG) of 2.1 W/m² (D. W. Feist, Pfluger, Kaufmann, Kah, & Schneiders, 2007), this value has to be understood as a reference of passive houses with energy efficient appliances and also with good habits of electricity use of their occupants. The reality may lead to considerable deviations from this estimation and provoke a higher energy demand or even some severe discomfort problems in certain warm environments.

In general, PH standard applied some safety margins in the winter or summer verifications. In winter, IHG were lowered by up to 1.6 W/m² to dimension properly the heating system and compensate any possible low internal activity. In summer, the situation was opposite and the PHPP version 7 of 2009 suggested increasing the IHG by up to 2.6 W/m² as a recommendation to assess the overheating risk. On top of that, IHG could also be calculated in detail with the PHPP spreadsheets and the consumptions of each case.

At present, the last review of PHI analysed the risks of underestimating IHG in small constructions, and conducted a study to adjust IHG in relation with occupancy and treated floor area (PHI, 2015). As a result, in 2015 they published an updated formula to evaluate the IHG of each case, as presented in the correlation in Figure 5.7 and the formula (7) below. Applying the values of the models of this chapter, namely 5 people and 146 m² of treated floor area, the recommended average IHG for summer would be 2.51 W/m². This value suggests that the size and occupation of these models are not far from the conventional PH limits and therefore the value of 2.6 W/m² for summer calculations may be sufficient.

$$IWQ = 2.1\frac{W}{m^2} + \frac{50\,W}{A_{WE}} \qquad (8)$$

Where:

IWQ internal heat gains (W/m²)

A_{we} treated floor area (based on German standard density of 35 m²/person)

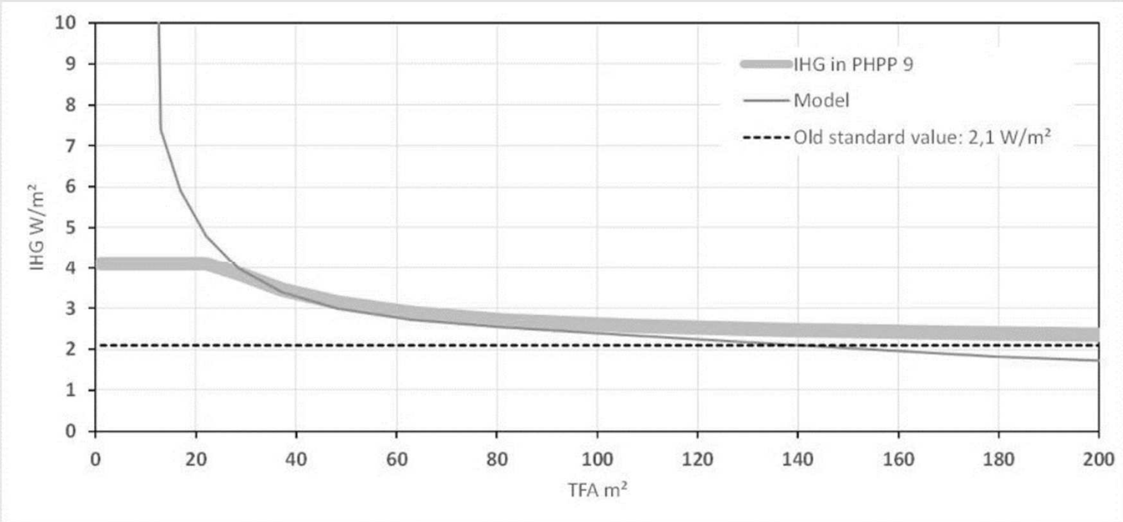


Figure 5.7. IHG depending on the living area, as used in the PHPP 9 (taken from PHI, 2015).

In contrast with the values recommended by the PHI, the Spanish regulation set a remarkably higher IHG for standard housing constructions. In fact, with an average 4.4 W/m^2 this regulation nearly doubles the PH value of 2.1 W/m^2. This standard IHG is an average obtained by the current standard operational conditions of housing constructions defined in (AICIA, 2009a) and (AICIA, 2009b). The conditions are presented in Table 5.6. These schedules to some degree represent a more realistic use than the constant IHG of PH assumptions, as for example, observed in the monitored hourly electricity consumption dwellings of a block of housing in Sevilla (Sendra Salas, 2011).

Table 5.6. Hourly operational conditions according to
standard certification of residential buildings in Spain (source *AICIA, 2009a).*

Ocupación sensible (W/m^2)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Laboral	2.15	2.15	2.15	2.15	2.15	2.15	2.15	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	2.15
Sábado	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Festivo	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Ocupación latente (W/m^2)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Laboral	1.36	1.36	1.36	1.36	1.36	1.36	1.36	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	1.36
Sábado	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Festivo	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Iluminación (W/m^2)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Laboral, sábado y festivo	0.44	0.44	0.44	0.44	0.44	0.44	0.44	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	2.20	4.40	4.40	4.40	4.40	2.20
Equipos (W/m^2)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Laboral, sábado y festivo	0.44	0.44	0.44	0.44	0.44	0.44	0.44	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	2.20	4.40	4.40	4.40	4.40	2.20
Ventilación verano[2]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Laboral, sábado y festivo	4	4	4	4	4	4	4	4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

As a result, the present study applied the hourly operation of the Spanish standard, with the reference values of PH for winter and summer verifications. So, in winter the IHG were lowered by up to 1.6 W/m² and in summer they were increased by up to 2.6 W/m². These reference values were implemented in the model as occupancy, latent heat, computers and lighting, as described in Table 5.7.

Table 5.7. Reference IHG for single-family housing and values used in the models of this study.

	Reference values		Model definition of IHG			
IHG types	**Average hourly IHG (W/m²)**	**Annual heat gain (kWh/m²)**	**Density* (person/m²)**	**Latent heat* (W/m²)**	**Computers* (W/m²)**	**Lighting (W/m²)**
PH winter	1.6	14.0	0.0120	-	1.6	1.6
PH standard	2.1	18.4	0.0165	-	2.2	2.2
PH summer	2.6	22.8	0.0195	-	2.6	2.6
RITE, standard IHG of housing EPC in Spain	4.4	38.5	0.0330	1.36	4.4	4.4
Average single family house electricity use (SECH project, 2010)	-	30.9	-	-	-	-

** Values based on the hourly operation of AICIA 2009*

5.4.2. Analysed climatic zones and selected locations

The Iberian Peninsula is a large area which presents different climatic zones. According to the (Kottek et al., 2006), the regions of Spain can be classified into three types: the south and eastern areas closer to Mediterranean sea, which can be characterized by low precipitation and hot summers (Csa), the western and northwestern areas with low precipitation and warm summers (Csb) and the remaining areas in the north and northeast areas which are highly humid with typically warm summers (Cfb). Figure 5.8 shows the world map of this classification.

The first Spanish Technical Building Code (CTE) (Royal Decree 314/2006, 2006) and the later update (Orden FOM 1635/2013, 2013) identified 5 levels of winter and 3 levels of summer. This way, the locations were described by winter severity (mildest winter is represented by a letter A and coldest by a letter E) and summer severity (the mildest scenario is given a score 1 while the warmest- a score 3). Figure 5.9 represents both severities.

The present study is focused on the areas where the heating need is still the driving need for building design. This is due to the detected predominance of passive houses in cooler areas of Spain, as underlined in the review of Spanish single family passive houses in Section 2.2.2. As a result, the areas selected for the present study were of the central continental climate and the northern Atlantic climate. This includes regions with cold winters (E1, D1, D2 and D3) and cool-temperate regions (C1), embracing approximately the northern half of the country, with 30 regions and approximately 27 million of inhabitants.

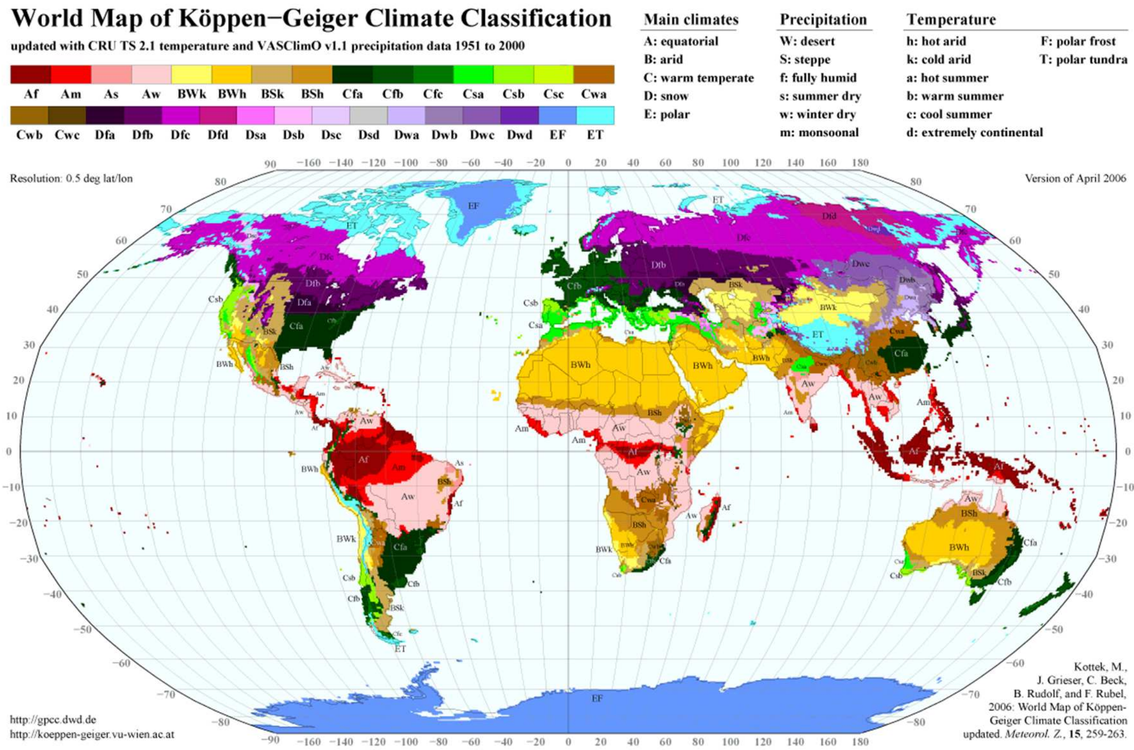
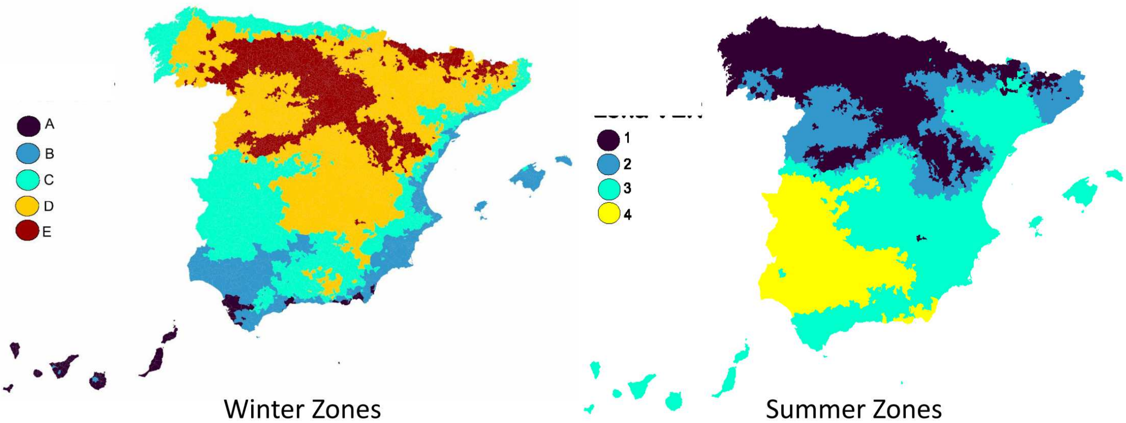


Figure 5.8. World map of Köppen-Geiger Climate classification (taken from Kottek et al., 2006).



Population	1	2	3	4	TOTAL
A	-	-	3,462,344	386,289	3,848,633
B	-	-	8,144,034	2,898,423	11,042,457
C	5,232,691	5,403,351	2,327,846	2,272,987	15,236,875
D	1,671,936	2,837,104	8,276,564	-	12,785,604
E	1,195,330	-	-	-	1,195,330
TOTAL	8,099,957	8,240,455	22,210,788	5,557,699	44,108,899

Figure 5.9. Maps of climate severity of winter (left) and summer (right) in Spain (taken from Álvarez & Molina, 2016)

In order to evaluate the differences to apply passive house principles in these climates, the most relevant cases were identified. Firstly, Burgos represents a location among the coldest winters (zone E1). Secondly, Madrid represents a location with cold winters and also with warm summers (zone D3). Thirdly and lastly, Bilbao represents a location in the coast, with mild winters and mild summers in the Atlantic coast. Accordingly, the climate zones included within this study are highlighted in Figure 5.11, with the selected cities in red: Bilbao, Burgos and Madrid. All Spanish climatic zones are shown in Figure 5.10 and the monthly values of Bilbao, Burgos and Madrid are shown in Figure 5.12, Figure 5.13, Figure 5.14 and Table 5.8.

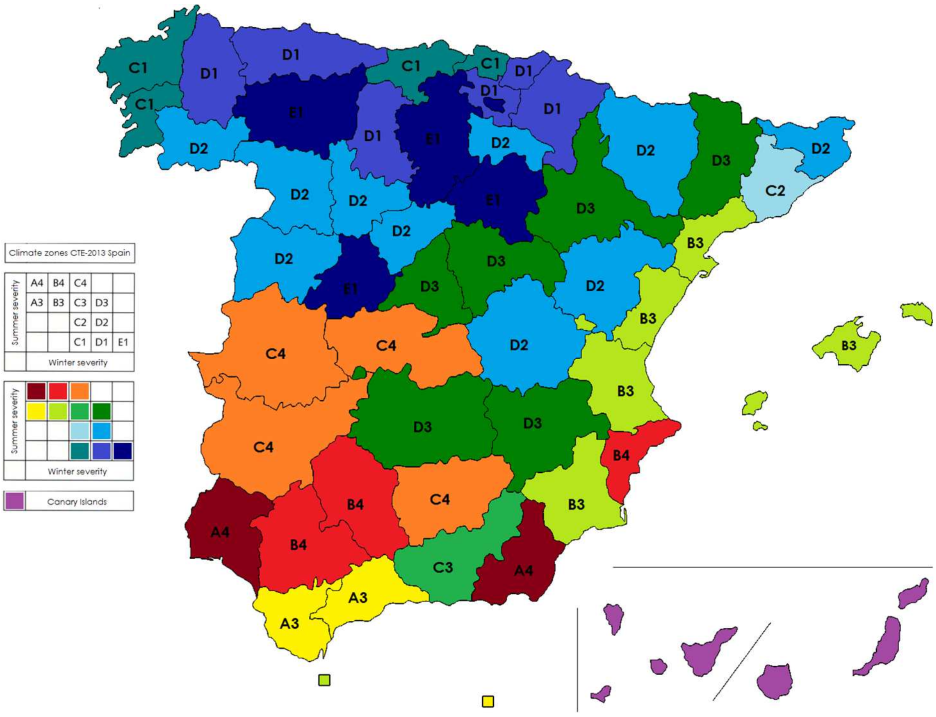


Figure 5.10. Climatic zones according to Spanish Technical Building Code (CTE)
(data source Orden FOM 1635/2013, 2013).

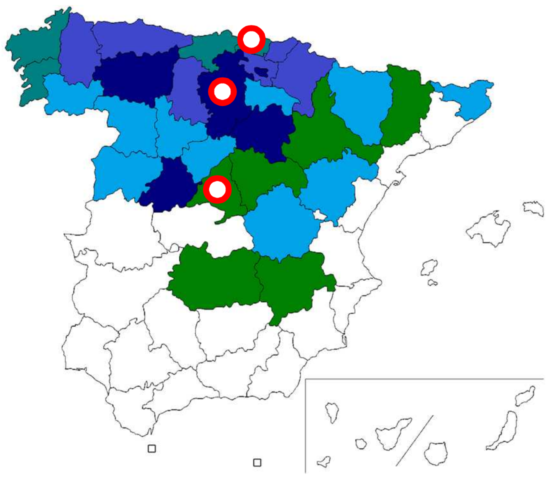


Figure 5.11. Climatic zones analysed within this study and selected capitals, Bilbao, Burgos, Madrid.

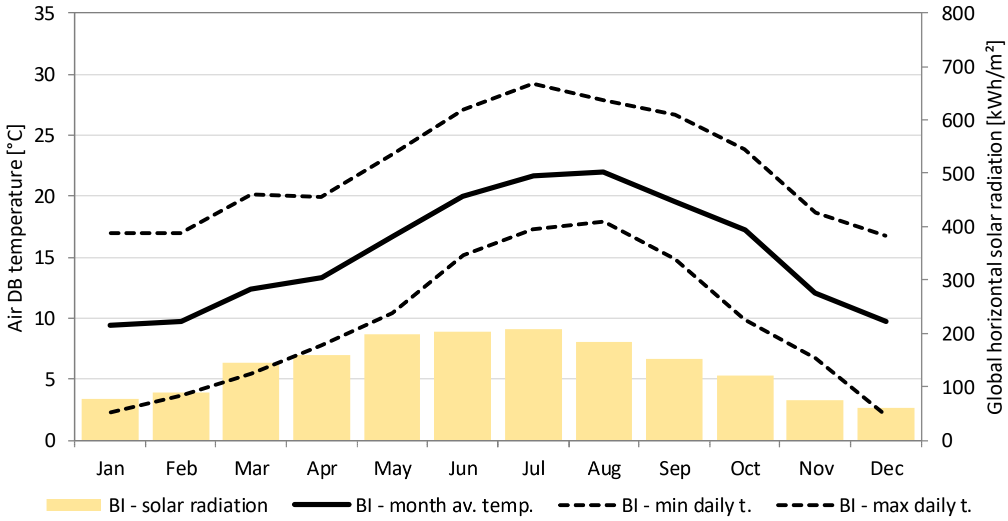


Figure 5.12. Climatic summary of Bilbao with daily temperature range.

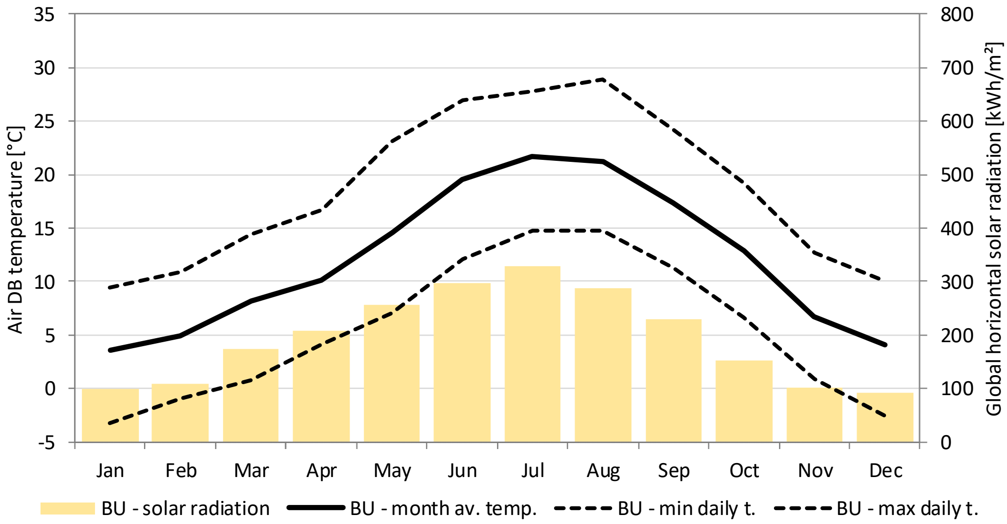


Figure 5.13. Climatic summary of Burgos with daily temperature range.

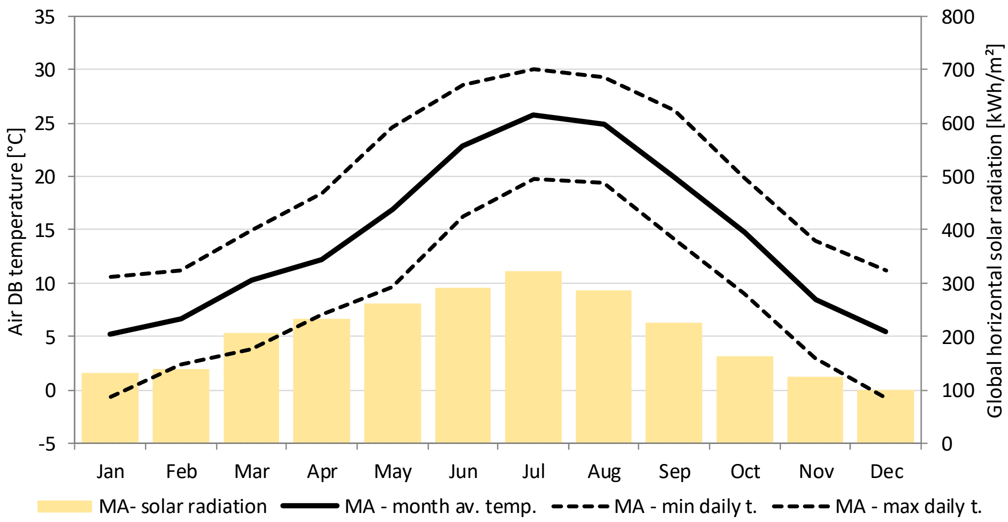


Figure 5.14. Climatic summary of Madrid with daily temperature range.

Table 5.8. Monthly values of the climates in Bilbao, Burgos and Madrid.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
BILBAO													
Monthly average DB temperature	9.4	9.7	12.3	13.3	16.7	20.0	21.7	22.0	19.5	17.2	12.1	9.7	15.3
Min. daily average DB temperature	2.2	3.7	5.5	7.8	10.5	15.1	17.3	17.9	14.9	9.9	6.7	2.1	2.1
Max. daily average DB temperature	16.9	16.9	20.1	19.9	23.4	27.1	29.2	27.8	26.7	23.9	18.6	16.7	29.2
Monthly average Relative Humidity	71.4	68.7	64.8	68.2	69.8	71.5	69.5	70.7	72.2	69.2	72.0	71.0	69.9
Global horizontal solar radiation	78.2	89.2	145.3	160.6	197.5	202.6	207.5	184.6	152.7	120.7	75.3	60.4	1674.6
HDD (18.3)	278	242	189	153	67	12	2	0	15	67	187	268	1480
CDD (25.0)	0	0	0	0	0	3	6	6	2	0	0	0	17
BURGOS													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Monthly average DB temperature	3.6	4.9	8.2	10.1	14.6	19.6	21.7	21.2	17.3	12.9	6.8	4.0	12.1
Min. daily average DB temperature	-3.2	-0.9	0.8	4.2	7.0	12.1	14.8	14.8	11.3	6.7	0.9	-2.5	-3.2
Max. daily average DB temperature	9.5	11.0	14.4	16.8	23.1	27.0	27.8	28.8	24.1	19.2	12.7	10.0	28.8
Monthly average Relative Humidity	76.6	67.7	63.7	60.8	60.3	51.7	44.4	45.8	53.5	65.2	72.2	75.2	61.4
Global horizontal solar radiation	98.6	109.3	174.4	209.2	256.0	297.1	328.0	286.7	229.4	152.5	102.9	92.3	2336.5
HDD (18.3)	456	375	313	248	128	27	10	12	56	170	347	443	2585
CDD (25.0)	0	0	0	0	0	3	8	9	0	0	0	0	20
MADRID													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Monthly average DB temperature	5.2	6.7	10.3	12.2	17.0	22.9	25.7	24.9	20.0	14.8	8.5	5.5	14.5
Min. daily average DB temperature	-0.7	2.4	3.8	7.1	9.6	16.3	19.8	19.4	14.1	9.0	3.0	-0.8	-0.8
Max. daily average DB temperature	10.6	11.2	14.9	18.4	24.6	28.5	30.0	29.3	26.2	19.9	13.9	11.2	30.0
Monthly average Relative Humidity	76.4	65.8	61.9	58.9	59.0	48.3	42.3	43.7	50.9	64.2	71.2	75.4	59.8
Global horizontal solar radiation	132.6	138.3	205.8	234.5	261.8	291.2	321.9	286.4	227.3	163.6	125.7	101.1	2490.1
HDD (18.3)	407	325	249	185	71	4	0	0	15	113	294	398	2060
CDD (25.0)	0	0	0	0	0	17	46	32	1	0	0	0	96

5.4.3. Climate change scenarios

In the last stage of this study the best adapted models were simulated under the future scenarios of climate change. This was possible through the regional scenarios of the IPCC predictions published by (Morata Gasca, 2014) in recent years which applied the global scenarios of (Nakicenovic & Swart, 2000) into Spanish climates. These scenarios are also related with the representative concentration pathways (RCP), explained in the introduction of Chapter 1 (IPCC, 2017). In Table 5.9 the general features of these scenarios which connect them with the global low, medium and high RCP are described and the trend of the global temperatures is plotted in Figure 5.15.

Table 5.9. Description of the studied future scenarios B1, A1B and A2.

Scenarios	**Description (taken from Morata Gasca, 2014)**
B1	Low CO_2 emissions. World based on the implementation of clean technologies and the efficient recycling of materials. It is based on a sustainable balance between economy, society and environment.
A1B	Intermediate CO_2 emissions. The worldwide economic growth is fast and it is based on a balanced use of diverse energy sources together with high efficient new technologies.
A2	High CO_2 emissions. Heterogeneous world, based on local traditions and family model. The economic growth and development are slower than in other hypothesis groups.

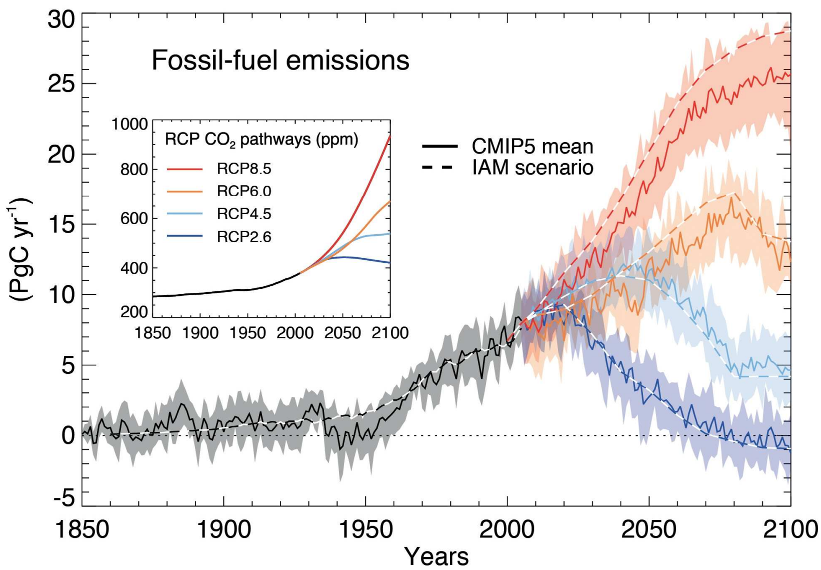


Figure 5.15. RCP ranges according to last review of IPCC (taken from IPCC et al., 2013).

5.5. Stage I, winter heating need reduction

This stage defined the minimum levels of thermal insulation of the three analysed models of single family housing in the selected climates. To assess that, each model was simulated with different thickness of thermal insulation, from 10 to 30 cm. The results show the variation of heating and cooling needs as well as the maximum daily loads for heating and cooling of each case. Even though the requirements of PH certificate verify either the annual demand or the heating load alternatively, in this study it was decided to apply both requirements at the same time in order to approximate to the nZEB limits. Apart from that, the simulation results are shown as heating use, obtained with performance levels close to the set points of PH standard, which can make them comparable with the limits of heating and cooling demand.

In this stage, the results were plotted as a summary to compare the models of the three locations. The full results of the heating and cooling energy need, as well as the heating and cooling loads and the number of indoor hours over 25 °C are described in Table 5.1.

The results obtained for the Atlantic climate confirmed that the heating need of this area is rather low. Almost all the models comply with the PH limits of annual heating demand and maximum heating load, see Figure 5.16. Only the detached house presented a slightly higher value of heating load which could require the increase of the thermal insulation levels. This way, approximately 15 cm for detached houses and 10 cm for attached houses would be sufficient to provide an ultra-low heating energy need.

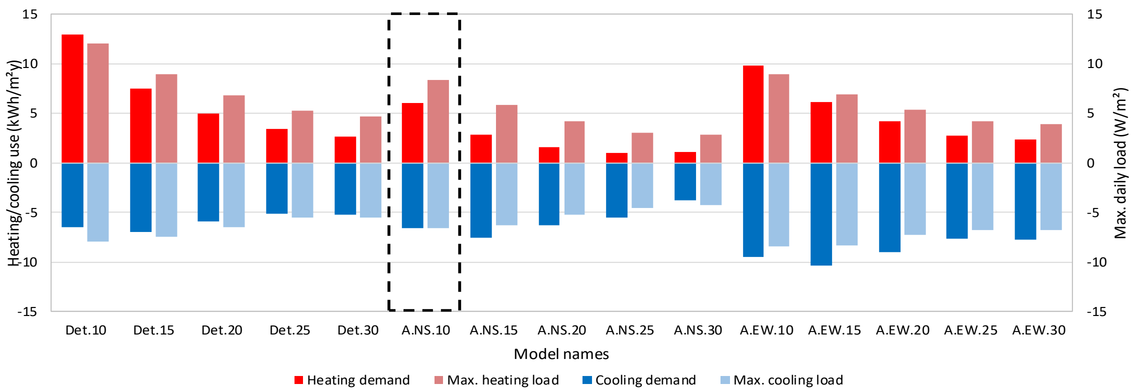


Figure 5.16. Energy need for heating and cooling of the models according to the thermal insulation of the envelope in Bilbao, Atlantic climate.

The results of the cold continental area indicated considerably higher heating needs. The detached house models required around 20 cm of thermal insulation and the attached houses required more intermediate values with 15 cm of thermal insulation, see Figure 5.17.

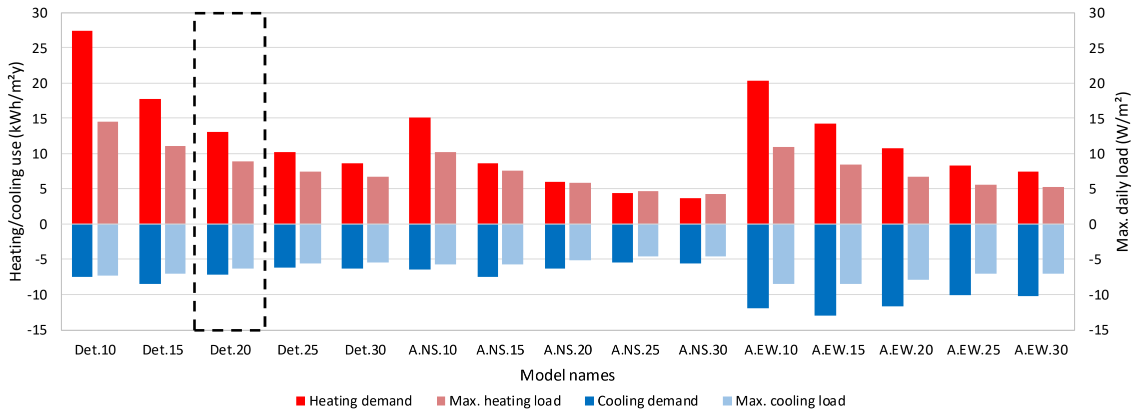


Figure 5.17. Energy need for heating and cooling of the models according to the thermal insulation of the envelope in Burgos, cold continental climate.

The results of the warm continental climate shown in Figure 5.18 confirmed an intermediate heating need and a considerable cooling need, which in majority of the models would overpass the heating needs. As a result, the minimum thermal insulation would be around 15 cm in detached houses and 10 cm in attached houses, noting that the cooling needs remarkably exceed the limits of PH standard.

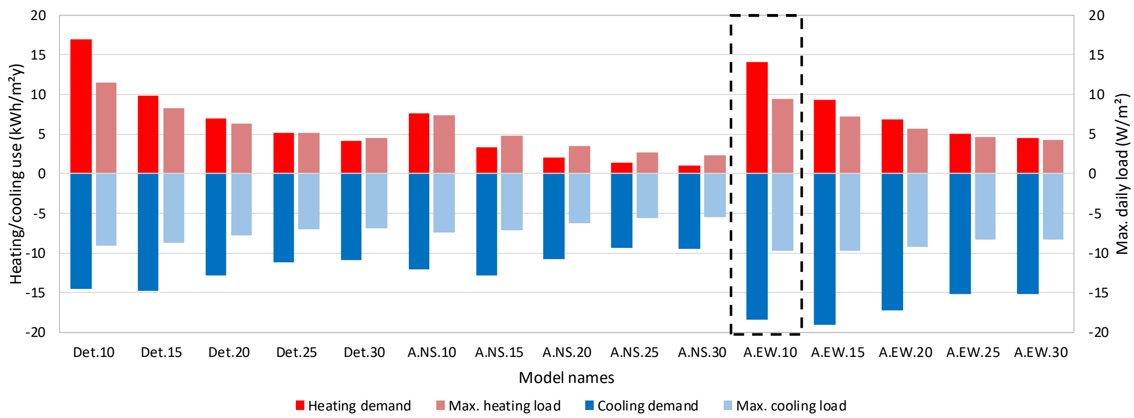


Figure 5.18. Energy need for heating and cooling of the models according to the thermal insulation of the envelope in Burgos, cold continental climate.

All the previous results indicated certain trends and differences between the tested models. They underlined that detached houses have the highest heating need and the East-West attached houses present the highest cooling need. This way, for the next stage of summer adaptation, three models were selected, one from each climate. Firstly, the detached house of Burgos was selected, because it presented the highest heating need. Secondly, the East-West attached house of Madrid was selected, for having the highest cooling need. Thirdly and lastly, the North-South attached house of Bilbao was selected as an intermediate case of a mild climate. The selected cases are highlighted by dashed lines in Figures 5.15, 5.16 and 5.17.

Table 5.10. Main results of the models tested in Stage I, winter analysis.

Models	Annual heating use (kWh/y)	Heating use per floor area (kWh/m²y)	Max. daily heating load (W/m²)	Annual cooling use (kWh/y)	Cooling use per floor area (kWh/m²y)	Max. daily cooling load (W/m²)	Num. hours t >25 °C	Annual hours t >25 °C (%)
PH limits	2190.0	15.0	10.0	-2190.0	-15.0	-10.0	876	10.0 %
D_Bi10	1890.0	12.9	12.1	-941.7	-6.4	-8.0	3219	36.7 %
D_Bi15	1090.2	7.5	8.9	-1024.8	-7.0	-7.5	3771	43.0 %
D_Bi20	721.0	4.9	6.8	-869.5	-6.0	-6.5	3903	44.6 %
D_Bi25	499.2	3.4	5.3	-748.4	-5.1	-5.5	3965	45.3 %
D_Bi30	389.3	2.7	4.6	-760.8	-5.2	-5.5	4122	47.1 %
D_Bu10	4015.3	27.5	14.6	-1094.8	-7.5	-7.3	2703	30.9 %
D_Bu15	2582.0	17.7	11.0	-1230.5	-8.4	-7.0	3063	35.0 %
D_Bu20	1906.7	13.1	8.9	-1055.8	-7.2	-6.3	3155	36.0 %
D_Bu25	1480.3	10.1	7.4	-903.4	-6.2	-5.6	3223	36.8 %
D_Bu30	1252.3	8.6	6.8	-918.5	-6.3	-5.5	3373	38.5 %
D_Ma10	2470.5	16.9	11.5	-2116.2	-14.5	-9.1	3400	38.8 %
D_Ma15	1439.7	9.9	8.2	-2161.1	-14.8	-8.8	3737	42.7 %
D_Ma20	1007.8	6.9	6.3	-1877.2	-12.9	-7.8	3796	43.3 %
D_Ma25	751.3	5.1	5.1	-1624.2	-11.1	-7.0	3850	43.9 %
D_Ma30	597.3	4.1	4.5	-1597.7	-10.9	-6.9	4075	46.5 %
Asn_Bi10	885.6	6.1	8.3	-961.6	-6.6	-6.6	3686	42.1 %
Asn_Bi15	409.8	2.8	5.8	-1100.5	-7.5	-6.3	4354	49.7 %
Asn_Bi20	235.2	1.6	4.2	-916.2	-6.3	-5.2	4441	50.7 %
Asn_Bi25	147.3	1.0	3.0	-807.8	-5.5	-4.5	4478	51.1 %
Asn_Bi30	157.8	1.1	2.9	-545.9	-3.7	-4.3	3119	35.6 %
Asn_Bu10	2201.0	15.1	10.2	-942.0	-6.5	-5.7	2862	32.7 %
Asn_Bu15	1254.2	8.6	7.6	-1096.5	-7.5	-5.7	3357	38.3 %
Asn_Bu20	879.3	6.0	5.8	-910.0	-6.2	-5.1	3419	39.0 %
Asn_Bu25	644.1	4.4	4.6	-788.8	-5.4	-4.6	3488	39.8 %
Asn_Bu30	533.4	3.7	4.3	-808.5	-5.5	-4.6	3584	40.9 %
Asn_Ma10	1116.1	7.6	7.4	-1771.1	-12.1	-7.4	3690	42.1 %
Asn_Ma15	489.7	3.4	4.7	-1865.9	-12.8	-7.2	4287	48.9 %
Asn_Ma20	301.4	2.1	3.5	-1575.7	-10.8	-6.2	4326	49.4 %
Asn_Ma25	197.6	1.4	2.7	-1373.4	-9.4	-5.5	4370	49.9 %
Asn_Ma30	137.6	0.9	2.3	-1385.1	-9.5	-5.5	4600	52.5 %
Aew_Bi10	1436.7	9.8	9.0	-1383.6	-9.5	-8.5	3894	44.5 %
Aew_Bi15	899.2	6.2	6.9	-1513.3	-10.4	-8.3	4531	51.7 %
Aew_Bi20	604.6	4.1	5.4	-1310.8	-9.0	-7.3	4697	53.6 %
Aew_Bi25	405.8	2.8	4.2	-1118.3	-7.7	-6.8	4802	54.8 %
Aew_Bi30	340.4	2.3	3.9	-1133.7	-7.8	-6.8	4946	56.5 %
Aew_Bu10	2975.4	20.4	10.9	-1747.7	-12.0	-8.4	3249	37.1 %
Aew_Bu15	2072.8	14.2	8.4	-1886.8	-12.9	-8.4	3729	42.6 %
Aew_Bu20	1567.4	10.7	6.8	-1702.1	-11.7	-7.9	3836	43.8 %
Aew_Bu25	1210.3	8.3	5.6	-1473.1	-10.1	-7.1	3887	44.4 %
Aew_Bu30	1085.9	7.4	5.2	-1495.2	-10.2	-7.0	4112	46.9 %
Aew_Ma10	2046.9	14.0	9.4	-2686.7	-18.4	-9.7	3999	45.7 %
Aew_Ma15	1352.4	9.3	7.3	-2783.8	-19.1	-9.7	4520	51.6 %
Aew_Ma20	994.0	6.8	5.7	-2526.2	-17.3	-9.2	4664	53.2 %
Aew_Ma25	741.7	5.1	4.6	-2211.0	-15.1	-8.4	4771	54.5 %
Aew_Ma30	648.7	4.4	4.3	-2218.7	-15.2	-8.3	4913	56.1 %

The thermal balance of the selected cases is presented in Figure 5.19 below. Additionally, these cases are also described in more detail in the following stage II, particularly in Section 5.6.4, Section 5.6.5 and Section 5.6.6.

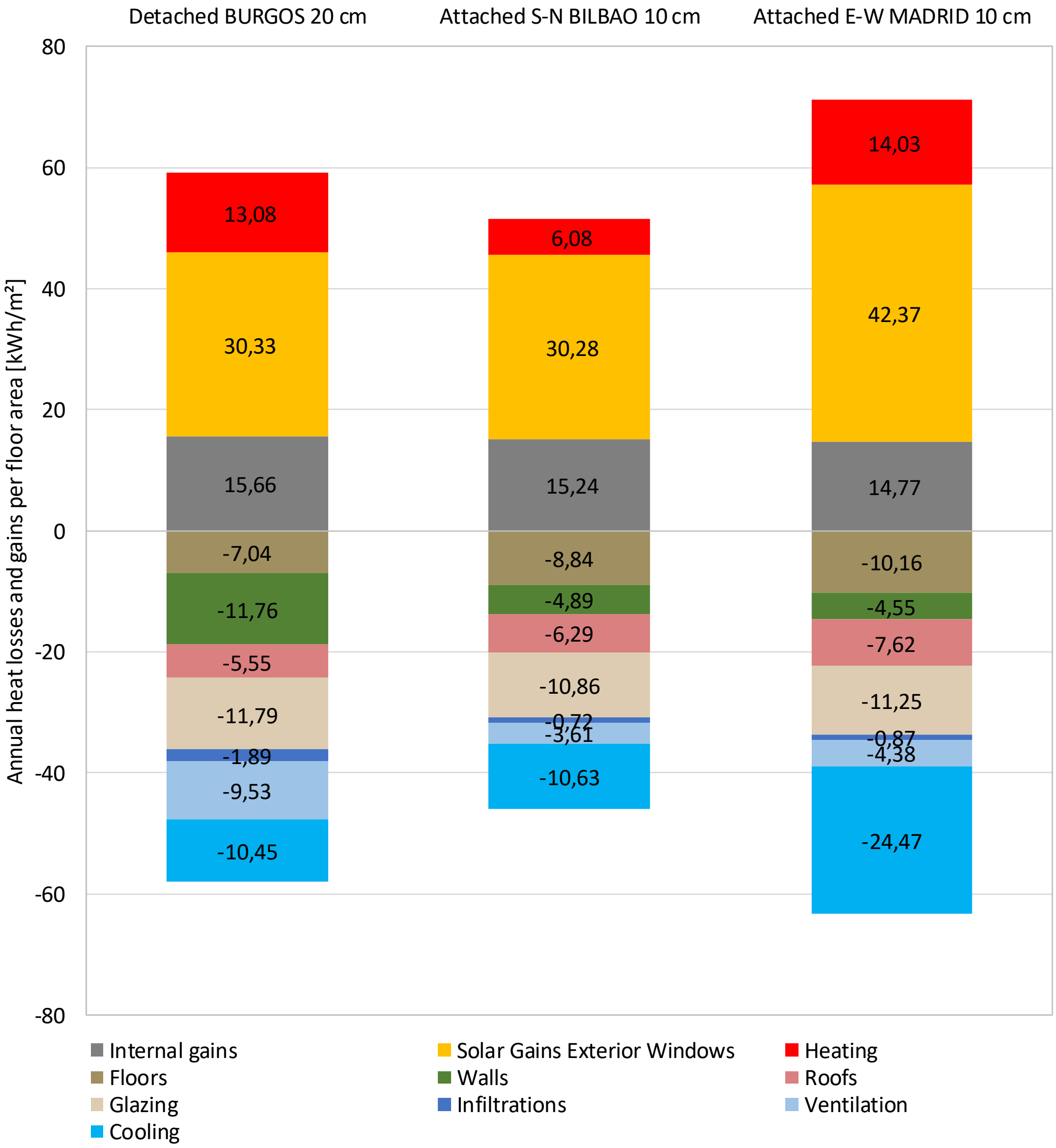


Figure 5.19. Thermal balance of the selected cases in Burgos, Bilbao and Madrid.

5.6. Stage II, summer cooling need reduction

Once the degree of thermal insulation was set according to the main criteria of Passive House for winter energy demands, the next stage consisted of the adaptation of the design through common passive measures in order to minimise the cooling needs as much as possible.

Firstly, the passive design elements studied in this stage are presented. Section 5.6.1 describes the solar shading measures, Section 5.6.2 defines the ventilative cooling measures and Section 5.6.3 explains the aspects of thermal mass considered during this study.

Later, the potential of each passive measure was analysed in detail, identifying the capacity of the measures in each model and climate. They were evaluated considering the capacity to maintain indoor temperatures cool and also the thermal comfort provided in summer.

5.6.1. Solar shading measures

Three solar shading options were tested: (i) roof overhangs of 1 m, (ii) traditional PVC roller shutters controlled manually and (iii) the same shutters with automatic control. The general features of the analysed solar shading devices are described in Table 4.10 below.

Table 5.11. Summary of the applied solar shading strategies.

ID	Type of solar shading	Components used for shading	Control strategies	Schedule
Base	No solar shading	-	-	-
Oh	Overhangs of roof	Construction design	Maximum length limited by local regulations up to 1 m	Always
Rm	Ext. opaque roller blinds/shutters, manual	Aluminium shutters rolled on top of the window, with automatic control	Down every day, 80% solar reflectance and narrow openings allow 15% of visible transmittance	Every day 09:00 – 21:00 h. Burgos and Bilbao: Jun.-Sep. Madrid: May-Sep.
Ra	Ext. opaque roller blinds/shutters, automatic	Aluminium shutters rolled on top of the window, with automatic control	Only in days with cooling and when solar >100 W/m², 80% solar reflectance and narrow openings allow 15% of visible transmittance	Every day Burgos and Bilbao: Jun.-Sep. Madrid: May-Sep.

Firstly, the overhang length was defined as 1 m in correspondence with the maximum allowed distances of local regulations like in Vitoria-Gasteiz (PGOU Vitoria-Gasteiz, 2003). It can be useful because it provides a protection for facades and openings which are actually independent of user's habits. As a matter of fact, many passive houses don't have any overhangs of roof extensions because they can complicate the thermal bridging and airtightness. However, this section analyses the passive cooling potential of the overhangs due to the very positive results demonstrated in the monitored case study (Chapter 3) and the simulations carried out in Chapter 4. Besides, roof overhangs are very common in vernacular architecture in central and northern Spain (Rodriguez Vidal, 2015). Also, many of the traditional passive houses built in Spain maintain this element. Furthermore, fixed solar protections are highly recommended by majority of PH designers' publications (BRE, 2006) (Cotterel & Dadeby, 2012) (Wassouf, 2014) (Hopfe & McLeod, 2015). The implemented roof overhangs are shown in Figure 5.20.

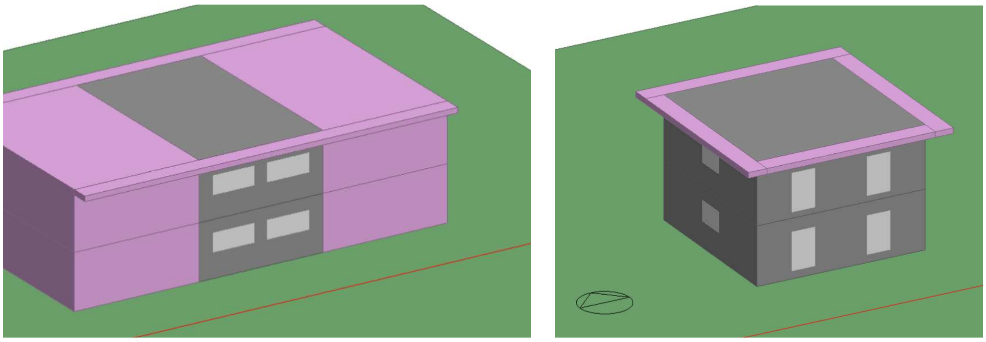


Figure 5.20. Roof overhangs of 1m in S-N attached house (left side) and detached house (right side).

Secondly, the use of shutters permit a great reduction of solar transmittance and offer some degree of control over the visible fraction. The aluminium or PVC shutters are widely used in Spain and their use would be probably more efficient than other non-conventional devices like venetian blinds or louvres.

When shutters are down, they block the majority of the solar gains through windows, meaning that they are set with a solar reflectance of 80% and a visible transmittance of 15%. The type of operation is tested as either manual or automatic. In manual control, they are closed every day before going to work and remain closed all day (9:00 h - 21:00 h) from the 1st of June until the 30th of September. The automatic control activates the blinds only for the days with cooling need (inside air temperature over 23.5 °C) and after the solar radiation on the window overpasses 100 W/m².

5.6.2. Ventilative cooling measures

As seen in Chapter 3 and 4, ventilation can contribute greatly to cool dwelling environments. In these cases, four types of ventilation are tested: (i) MVHR with constant summer bypass, (ii)

MVHR with enhanced summer bypass, (iii) natural ventilation during evenings and (iv) natural ventilation during night-time. In Table 4.8 details of the operation of these systems are presented.

Mechanical ventilation is limited by the maximum airflow of the MVHR unit, which was set according to the average maximum airflow of the MVHR units equipped in Spanish passive houses, that was precisely 350 m³/h. In this case the range of PH certification was not considered, in order to evaluate its maximum cooling potential for the studied local climates.

Natural ventilation is limited to evaluate a more realistic usage: maximum of 10 h^{-1} ACH, windows open on the top with only 10% of the gap and the windows are closed in outdoor temperatures are cooler than 15 °C, to avoid draught.

These strategies of ventilative cooling (VC) are applied first individually and later in combination with solar shading and thermal mass enhancements.

Table 5.12. Summary of the applied ventilation strategies.

ID	Principle of ventilative cooling	Components used for ventilation	Control strategies	Schedule
MV	Minimum airflow, bypass in summer	MVHR with bypass constant airflow	Bypass if indoor t. >23.5 °C Bypass closed if out. t. <13 °C	All year
MVe	MVHR with enhanced summer bypass airflow	MVHR with bypass and programming function	Bypass airflow 350 m³/h if: Indoor t. >24 °C Outdoor t. < indoor t. Min. outdoor t. 13 °C	All year
NVe	Natural ventilation in evenings	Tilt and turn windows, 10% upper opening	All windows open if indoor t. >23.5 °C Diff. indoor-outdoor > 2 °C Min. outdoor t. 15 °C Max. ACH of 10 h^{-1} MVHR with constant bypass	Everyday 21:00 – 24:00 h. Burgos: Jun.-Sep. Madrid: Apr.-Sep. (1/4-15/5 only evenings)
NVn	Natural ventilation in night-time	Tilt and turn w., 10% upper opening	(Same as above)	Everyday 21:00 – 07:00 h. Burgos: Jun.-Sep. Madrid: Apr.-Sep. (1/4-15/5 only evenings)

5.6.3. Thermal mass measures

The studied cases in the Spanish review showed the majority of cases with low or medium thermal mass. As this study represents the most common construction materials of that review, the envelope consisted of lightweight elements, as seen in Section 5.4.1. Basically, the detached house included all sort of CLT panels in the structure and only a ground concrete slab, but this thermal mass was separated with an XPS layer which avoids the direct transmission of heat. The other model, the semi-detached house (or attached dwelling) more often included some heavyweight elements which could contribute to mayor degree in this term.

After the first simulations of these models, it was clearly observed that there was a significant swing of internal temperatures, as highlighted in the results of Section 5.6.4, Section 5.6.5 and Section 5.6.6. This phenomenon was probably related with a lack of thermal mass stabilization. For that reason, some alternatives were implemented as a way to assess the need of higher thermal mass components. In Table 5.13 these supplementary elements are summarised.

Table 5.13. Summary of the applied supplementary thermal mass measures.

ID	Description	Num. per floor	Dimensions (m)			Vol. (m³)	Density (kg/m³)	Mass (Kg)	Specific heat (J/KgK)	Thermal Mass (MJ/K)
TM	Concrete levelling	1	8.4	8.4	0.05	3.5	2100	7350	840	6.2
TM2	Concrete levelling and Inner brick walls	1	8.4	8.4	0.05	3.5	2100	7350	840	6.2
		2	11	2.8	0.07	4.3	1700	7330	800	5.9
		2	6	3.8	0.07	3.2	1701	5430	800	3.2
TM3	Concrete slabs and inner brick walls	1	8.4	8.4	0.3	21.0	2100	44.100	840	37.0
		2	11	2.8	0.07	4.3	1700	7.330	800	5.9
		2	6	3.8	0.07	2.4	1701	4.001	800	3.2

Accordingly, after simulating the models with their original configuration of construction elements, the models were improved with additional elements which could be reasonably implemented in each case.

The detached model based on light construction and CLT panels, received an additional concrete levelling of 5 cm, which contributed with 6.2 MJ/K per floor (thermal mass measure TM). This improvement of the detached model is not too heavy, only 14500 kg, and this small amount of thermal mass could be implemented in these constructions in this or many other ways to reduce the cooling need, as suggested by (Álvarez & Molina, 2016).

The attached model was also based on wooden structure, but in many cases it also presented some masonry additional elements. So, in a first improvement the same concrete levelling was included in the model. In a second step, the four facades of the model were improved with an inner brick wall of 7 cm, which added another 9.1 MJ/K per floor (thermal mass measure TM2). In a third stage, the concrete levelling was substituted by a concrete slab of 30 cm, which, overall, added a considerable amount of thermal storage capacity (37.0 MJ/K per floor).

5.6.4. Attached single-family house in Atlantic climate, Bilbao

Firstly, the global analysis was done according to the number of indoor warm hours. It indicated that all the measures failed to control the number of hours over 25 °C (the PH limit is 10%). The best strategies always included night-time natural ventilation and also certain degree of solar shading. The other alternatives presented long periods over 28 °C, more than 8% of annual hours, see Figure 5.21 below.

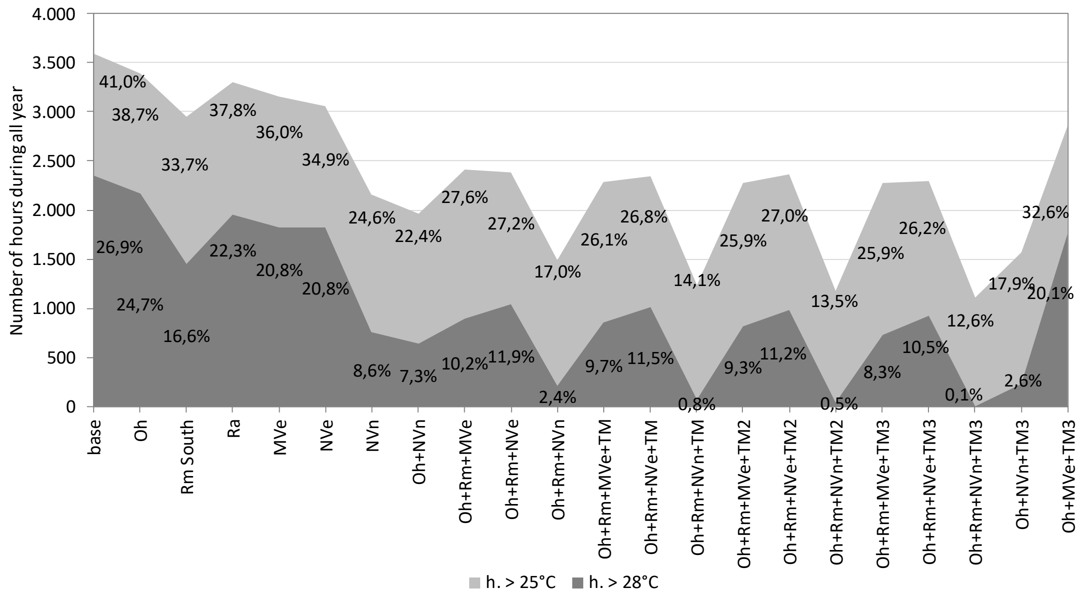


Figure 5.21. Evaluation of all the strategies according to the number of annual warm hours; attached North/South house in Bilbao, Atlantic climate.

The second analysis was focused in thermal comfort with the PMV model and it showed similar results as the assessment for warm hours. This assessment indicates that only night time natural ventilation can reduce the warm discomfort hours below 15% of annual hours, as shown in Figure 5.22. It is important to note that the calculations have been done with a simplified model of indoor air movement and this may not represent the specific conditions of certain rooms. The purpose of these calculations is therefore to be conservative and provide the best indoor environment possible. To solve this question, the adaptive method was used to the indoor conditions with the cooling effect of natural ventilation, see Figure 5.23. This method permitted to identify the improvements obtained with supplementary thermal mass. It also indicates that the use of roof overhangs can contribute considerably to indoor TC. For further details, see the complete results listed in Table 5.14 and Table 5.15 at the end of this Section.

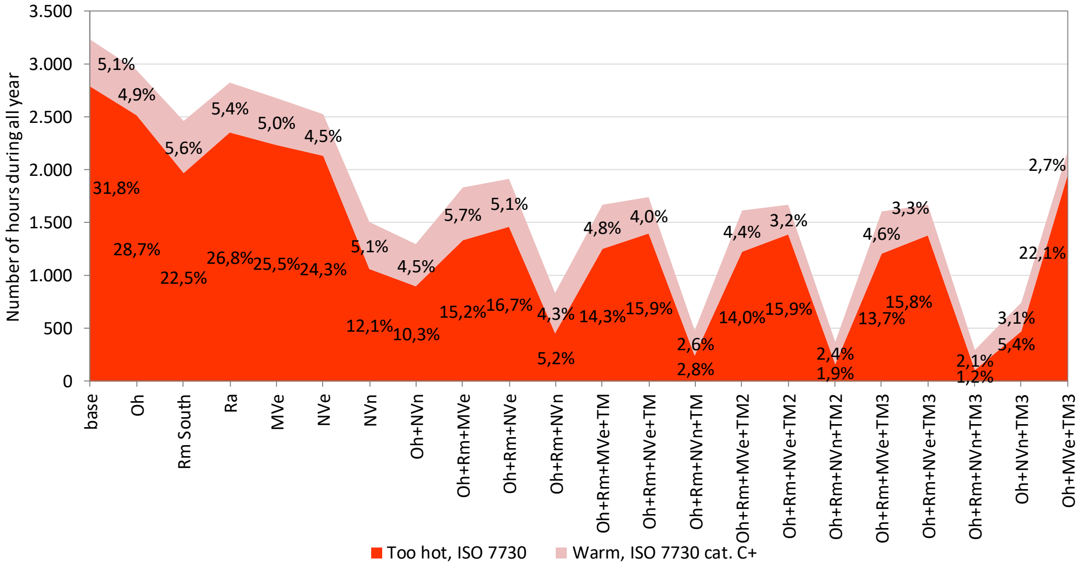


Figure 5.22. Evaluation of all the strategies according to warm discomfort hours calculated with PMV method; attached North/South house in Bilbao, Atlantic climate.

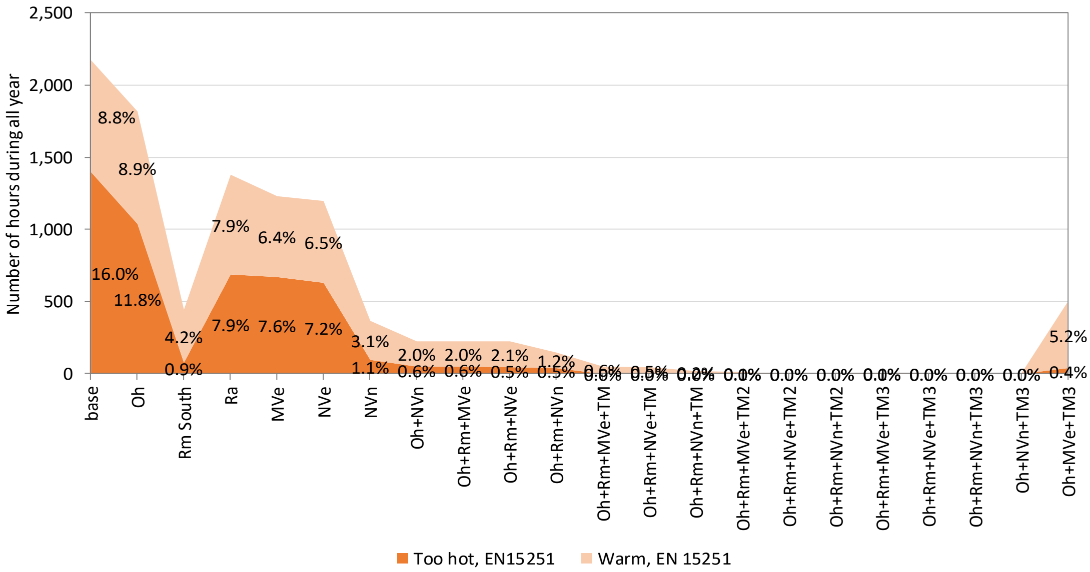


Figure 5.23. Evaluation of all the strategies according to warm discomfort hours calculated with EN 15251 method; attached North/South house in Bilbao, Atlantic climate.

After the general review, the behaviour of some significant strategies was examined in more detail during a hot week in summer. This way, the indoor behaviour with some relevant combinations of ventilative cooling is plotted in Figure 5.24. It indicated that despite the temperate summer of Atlantic climate in Bilbao, the indoor temperatures could overpass 30 °C if no solar shading or natural ventilation is applied. In any case, the indoor temperatures can easily be reduced by 4-5°C with different combinations of ventilation and solar shading.

The use of MVHR with summer bypass enhanced at maximum airflow could have positive effects only in combination with solar shading measures. The use of short natural ventilation in evenings presented a similar capacity as the enhanced MVHR bypass. The use of night natural ventilation presented the best option to keep indoor temperatures cool. Besides, the use of solar shading also demonstrated a clear benefit to reduce the peak temperatures indoors.

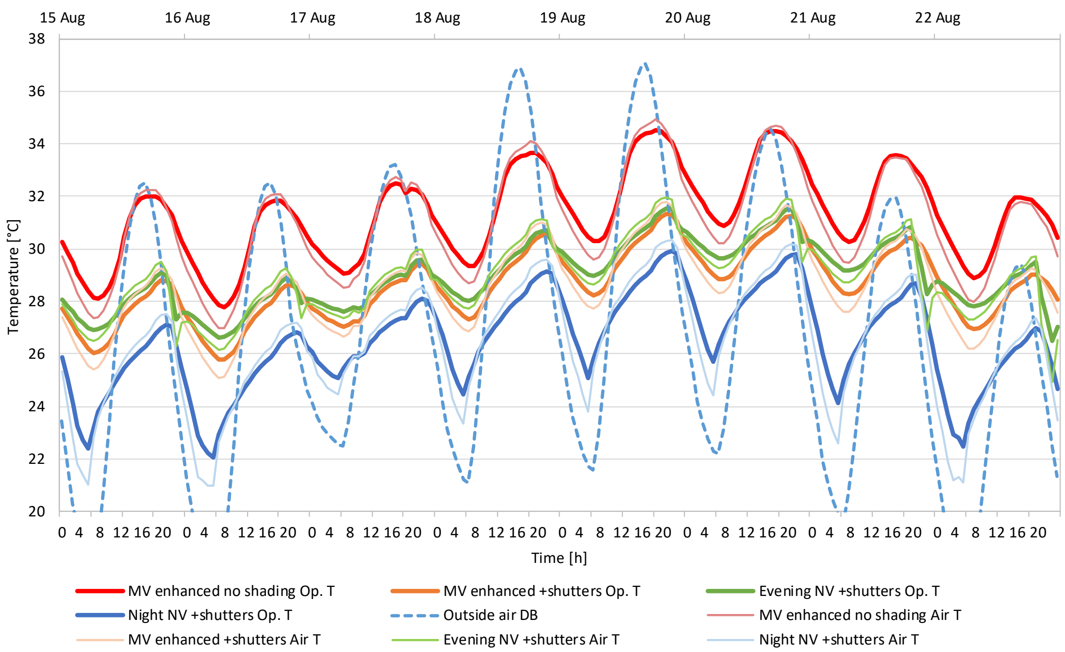


Figure 5.24. Comparison of the main ventilation measures based on the obtained indoor temperatures in summer; attached North/South house in Bilbao, Atlantic climate.

Additionally, this model was characterised by a low thermal mass due to the use of lightweight wooden construction elements. To see the impact of the low thermal mass on this type of constructions, Figure 5.25 presents the results obtained with some supplementary thermal mass based on the same natural ventilation during night-time. It indicates that reductions by 1 °C of the hottest hours are easy with the implementation of TM1 (5 cm of concrete levelling), TM2 (inner 7 cm brick walls) and even more with TM3 (concrete floor slabs).

This way, the use of thermal mass as a supplementary aspect for different types of ventilation could probably eliminate the need of direct solar shading on the windows. This was evaluated in Figure 5.26, which analysed the maximum potential of the MVHR with enhanced summer bypass with the highest feasible thermal mass in this case. The result indicated that the indoor temperatures were considerably flat, but their value seemed to be too high to provide good thermal comfort.

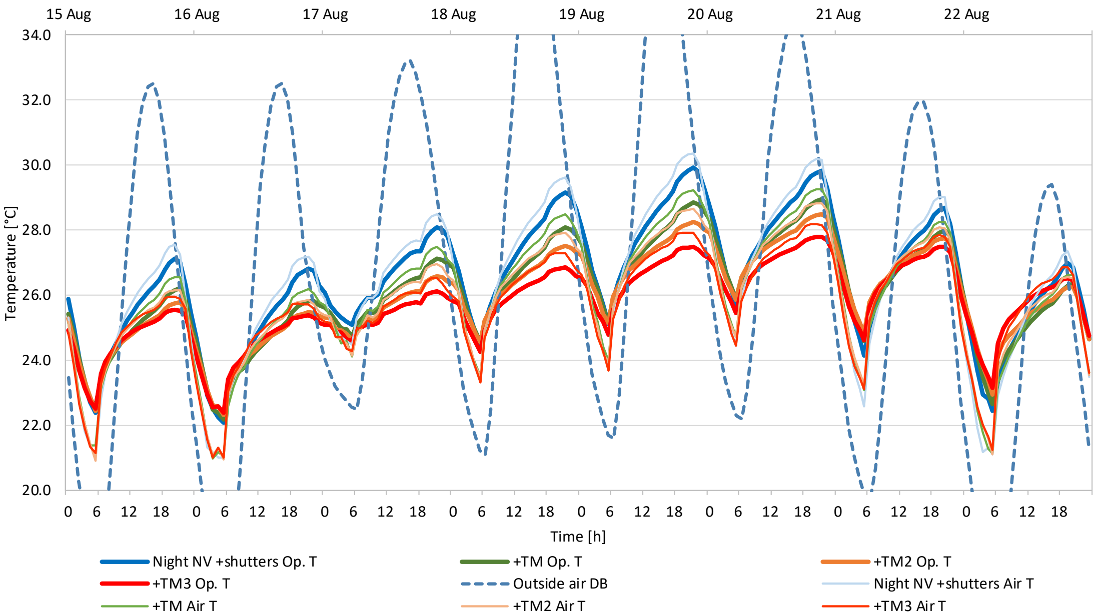


Figure 5.25. Comparison of the thermal mass effect based on the obtained indoor temperatures in summer; attached North/South house in Bilbao, Atlantic climate.

Additionally, the impact of thermal mass with the use of natural ventilation during night hours was considerable. With the same ventilation ratios, the increase of thermal mass had a similar effect as the daily use of roller shutters. This way, with the same operation of ventilation, the roller shutters with enough thermal mass again could be not necessary.

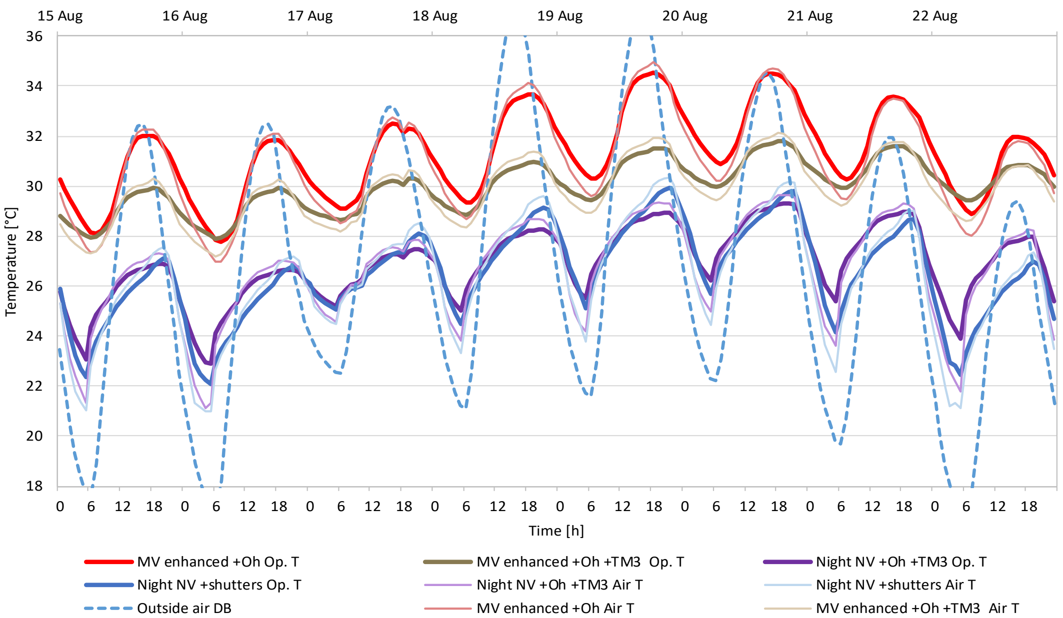


Figure 5.26. Comparison of the main solar shading measures based on the obtained indoor temperatures in summer; attached North/South house in Bilbao, Atlantic climate.

Table 5.14. Annual heating need and summer warm hours of attached house in Atlantic climate, Bilbao.

Summer adaptation models	Annual heating demand (kWh)	Annual solar gains by wind. (kWh)	Heating demand (kWh/ m²y)	Max. daily heating load (W/m²)	Num. hours t >25 °C	Annual hours t >25 °C (%)	Num. hours t >28 °C	Annual hours t >28 °C (%)
Limits PH	2190.0	-	15.0	10.0	876	10.0%	-	-
base	1125.4	5787.1	7.7	7.5	3593	41.0%	2354	26.9%
Oh	1204.6	5217.1	8.3	7.5	3393	38.7%	2168	24.7%
Rm South	1128.5	4216.8	7.7	7.5	2949	33.7%	1453	16.6%
Ra	1127.6	5071.8	7.7	7.5	3307	37.8%	1955	22.3%
MVe	928.2	5787.1	6.4	6.9	3157	36.0%	1826	20.8%
NVe	1203.5	5787.1	8.2	7.5	3054	34.9%	1823	20.8%
NVn	1284.7	5787.1	8.8	7.5	2152	24.6%	756	8.6%
Oh+NVn	1319.5	5217.1	9.0	7.5	1964	22.4%	642	7.3%
Oh+Rm+MVe	991.1	3903.3	6.8	7.0	2416	27.6%	894	10.2%
Oh+Rm+NVe	1262.2	3903.3	8.6	7.5	2385	27.2%	1041	11.9%
Oh+Rm+NVn	1323.5	3903.3	9.1	7.5	1488	17.0%	209	2.4%
Oh+Rm+MVe+TM	908.7	3903.3	6.2	7.1	2287	26.1%	852	9.7%
Oh+Rm+NVe+TM	1170.9	3903.3	8.0	7.6	2345	26.8%	1008	11.5%
Oh+Rm+NVn+TM	1231.9	3903.3	8.4	7.6	1238	14.1%	71	0.8%
Oh+Rm+MVe+TM2	840.0	3903.3	5.8	7.0	2273	25.9%	817	9.3%
Oh+Rm+NVe+TM2	1095.3	3903.3	7.5	7.5	2361	27.0%	985	11.2%
Oh+Rm+NVn+TM2	1164.6	3903.3	8.0	7.5	1182	13.5%	43	0.5%
Oh+Rm+MVe+TM3	742.7	3903.3	5.1	6.1	2273	25.9%	725	8.3%
Oh+Rm+NVe+TM3	993.4	3903.3	6.8	6.6	2293	26.2%	923	10.5%
Oh+Rm+NVn+TM3	1067.5	3903.3	7.3	6.6	1106	12.6%	6	0.1%
Oh+NVn+TM3	1064.6	5217.1	7.3	6.6	1565	17.9%	224	2.6%
Oh+MVe+TM3	742.6	5217.1	5.1	6.1	2856	32.6%	1757	20.1%

The best combinations of measures in relation with the EN 15251 limits are described in more detail in the following plots. The MVHR with enhanced summer bypass with solar shading and supplementary thermal mass (Oh+Rm+MVe+TM3) is presented in Figure 5.27. The potential of natural ventilation during evenings with solar shading and thermal mass (Oh+Rm+NVe+TM3) is presented in Figure 5.28. The capacity of night time natural ventilation together with solar shading and thermal mass (Oh+Rm+NVn+TM3) is patent in Figure 5.29.

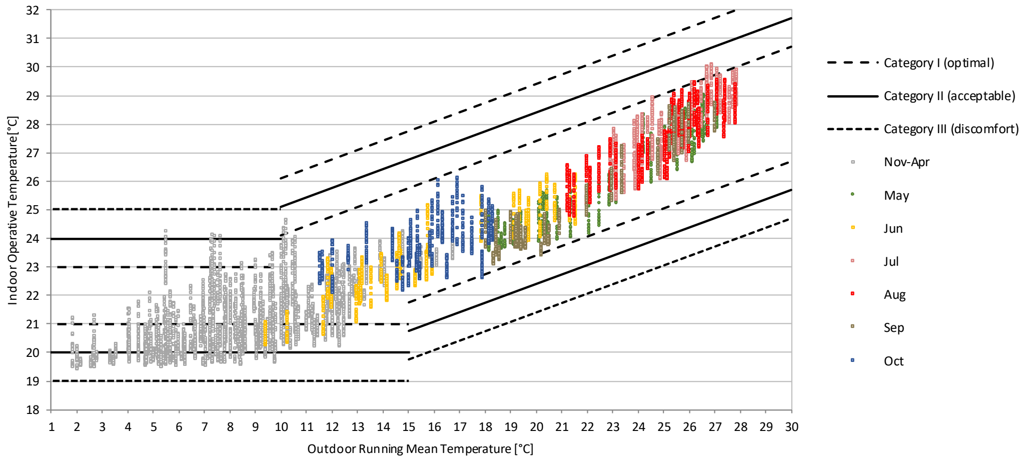


Figure 5.27. MVHR with enhanced summer bypass, roller shutters and supplementary thermal mass in facades and floor slabs, indoor temperatures and limits of EN 15251; attached North/South house in Bilbao, Atlantic climate.

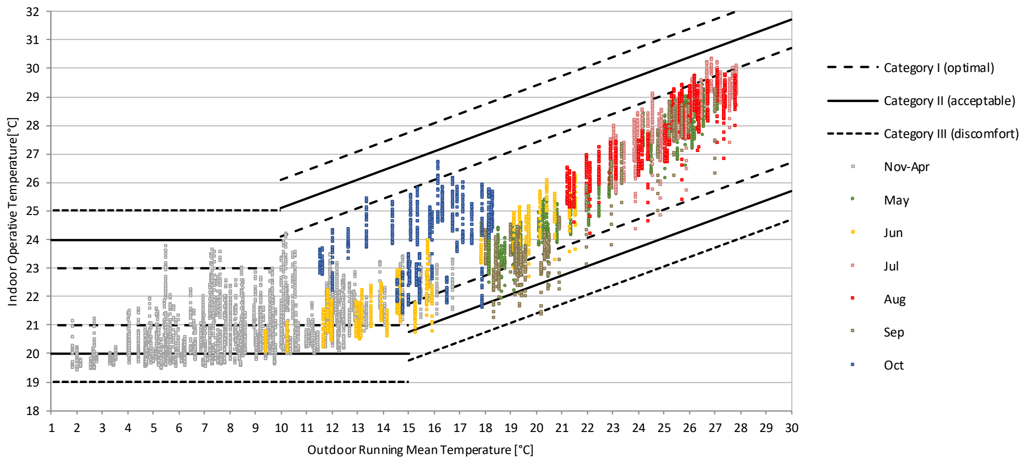


Figure 5.28. Natural ventilation in the evenings, roller shutters and supplementary thermal mass in facades and floor slabs, indoor temperatures and limits of EN 15251; attached North/South house in Bilbao, Atlantic climate.

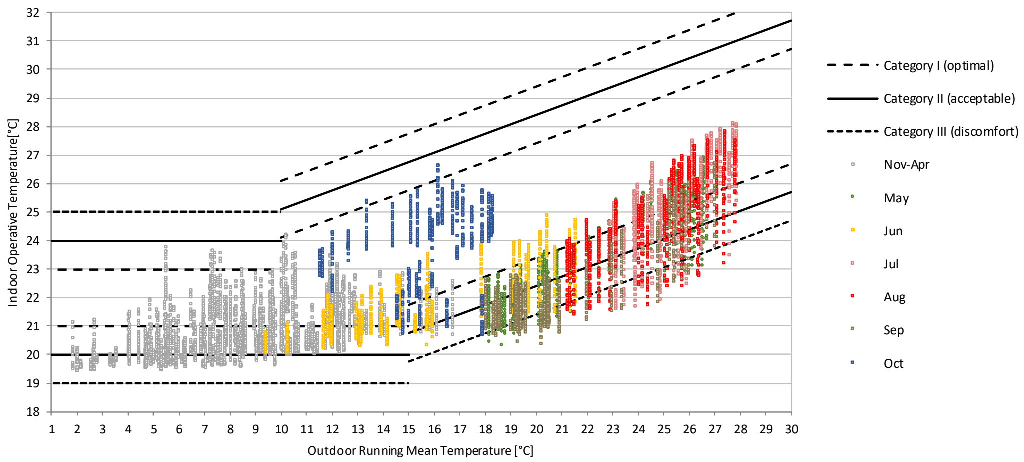


Figure 5.29. Night time natural ventilation, roller shutters and supplementary thermal mass in facades and floor slabs, indoor temperatures and limits of EN 15251; attached North/South house in Bilbao, Atlantic climate.

Table 5.15. Summer thermal comfort summary. Warm discomfort assessed by ISO 7730 and EN 15251; attached house in Atlantic climate, Bilbao.

Summer adaptation models	PMV ISO 7730 Cat. C+		PMV ISO 7730 Too hot		EN 15251 Cat. III +		EN 15251 Too hot	
	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %
base	444	5.1%	2790	31.8%	770	8.8%	1399	16.0%
Oh	429	4.9%	2510	28.7%	780	8.9%	1035	11.8%
Rm South	487	5.6%	1971	22.5%	365	4.2%	77	0.9%
Ra	470	5.4%	2351	26.8%	688	7.9%	688	7.9%
MVe	442	5.0%	2232	25.5%	559	6.4%	670	7.6%
NVe	390	4.5%	2132	24.3%	568	6.5%	632	7.2%
NVn	443	5.1%	1063	12.1%	269	3.1%	96	1.1%
Oh+NVn	392	4.5%	900	10.3%	173	2.0%	50	0.6%
Oh+Rm+MVe	499	5.7%	1332	15.2%	173	2.0%	54	0.6%
Oh+Rm+NVe	451	5.1%	1459	16.7%	186	2.1%	42	0.5%
Oh+Rm+NVn	380	4.3%	454	5.2%	105	1.2%	41	0.5%
Oh+Rm+MVe+TM	419	4.8%	1250	14.3%	52	0.6%	1	0.0%
Oh+Rm+NVe+TM	353	4.0%	1392	15.9%	45	0.5%	0	0.0%
Oh+Rm+NVn+TM	232	2.6%	242	2.8%	19	0.2%	0	0.0%
Oh+Rm+MVe+TM2	385	4.4%	1227	14.0%	11	0.1%	0	0.0%
Oh+Rm+NVe+TM2	282	3.2%	1389	15.9%	1	0.0%	0	0.0%
Oh+Rm+NVn+TM2	207	2.4%	163	1.9%	1	0.0%	0	0.0%
Oh+Rm+MVe+TM3	401	4.6%	1203	13.7%	9	0.1%	0	0.0%
Oh+Rm+NVe+TM3	290	3.3%	1382	15.8%	0	0.0%	0	0.0%
Oh+Rm+NVn+TM3	188	2.1%	105	1.2%	0	0.0%	0	0.0%
Oh+NVn+TM3	270	3.1%	472	5.4%	0	0.0%	0	0.0%
Oh+MVe+TM3	233	2.7%	1939	22.1%	456	5.2%	37	0.4%

5.6.5. Detached single-family house in cold continental climate, Burgos

In an analogous way, this model was also tested with different measures and combinations. The multiple analysis is presented in Figure 5.30, Figure 5.31 and Figure 5.32. The complete details are listed in Table 5.16 and Table 5.17.

The results suggested that the solar shading measures could contribute with passive cooling, but they are insufficient to provide enough thermal comfort during summer. The potential of roof overhang was considerably smaller than the use of direct shading for windows. Note that in this case this was represented by roller shutters on the windows in South, East and West orientations.

Regarding the ventilative cooling measures, the most efficient strategy was the night-time ventilation. It is important to notice that all the ventilative cooling measures (bypass enhancement and natural ventilation in the evenings or night hours) had higher cooling capacity than any of the analysed solar shading measures. However, only night time ventilation can provide proper indoor temperatures without any use of roller shutters on the windows. The best two types of ventilation were tested with supplementary thermal mass and without shutters.

The use of thermal mass is not very effective, because it helps reducing the number of hours over 28°C but it increases the number of hours over 25 °C. In this case, the supplementary thermal mass would be effective only in combination with long hours of natural ventilation, to purge the heat out from these elements, as recommended in (Lewis, 2014).

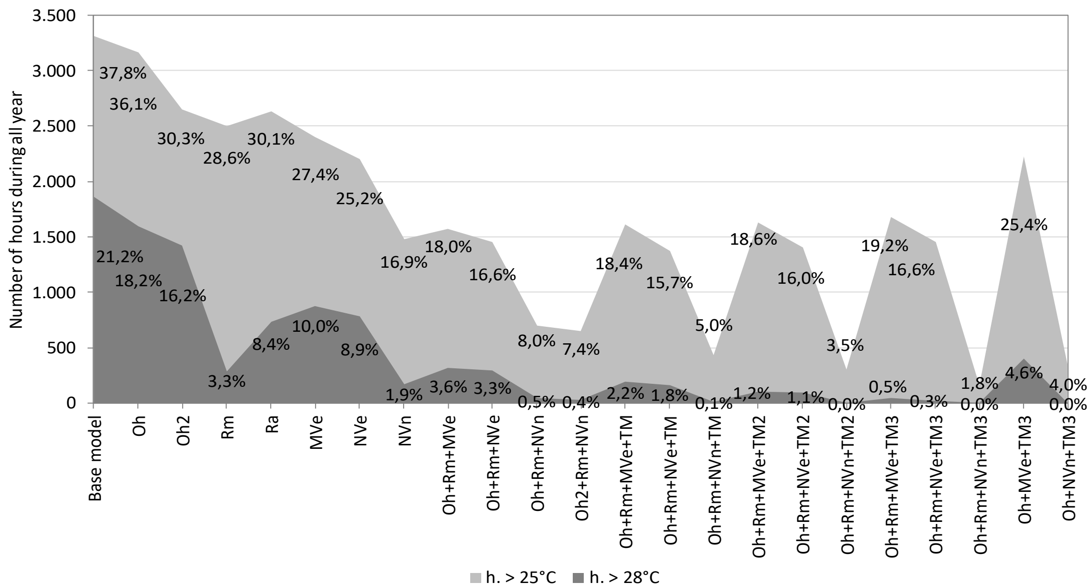


Figure 5.30. Evaluation of all the strategies according to the number of annual warm hours, detached house in Burgos, cold continental climate.

The TC assessment with PMV model presented better results with total warm discomfort below 10% in the majority of the cases with combination of solar shading and ventilation measures. The method of adaptive comfort indicated that majority of the options could achieve an acceptable indoor comfort. All the combinations of solar shading and ventilation measures would reduce the warm discomfort below 1% of annual hours or less. Paradoxically, even some singular measures, such as roller shutters or night time natural ventilation could provide an acceptable range of adaptive comfort by themselves.

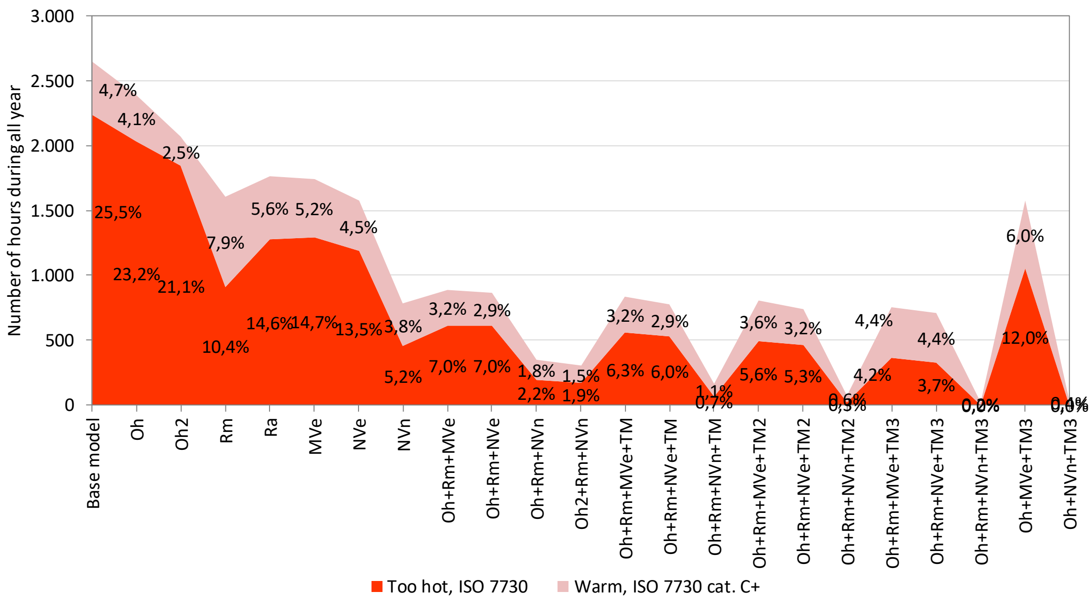


Figure 5.31. Evaluation of all the strategies according to warm discomfort hours calculated with PMV model; detached house in Burgos, cold continental climate.

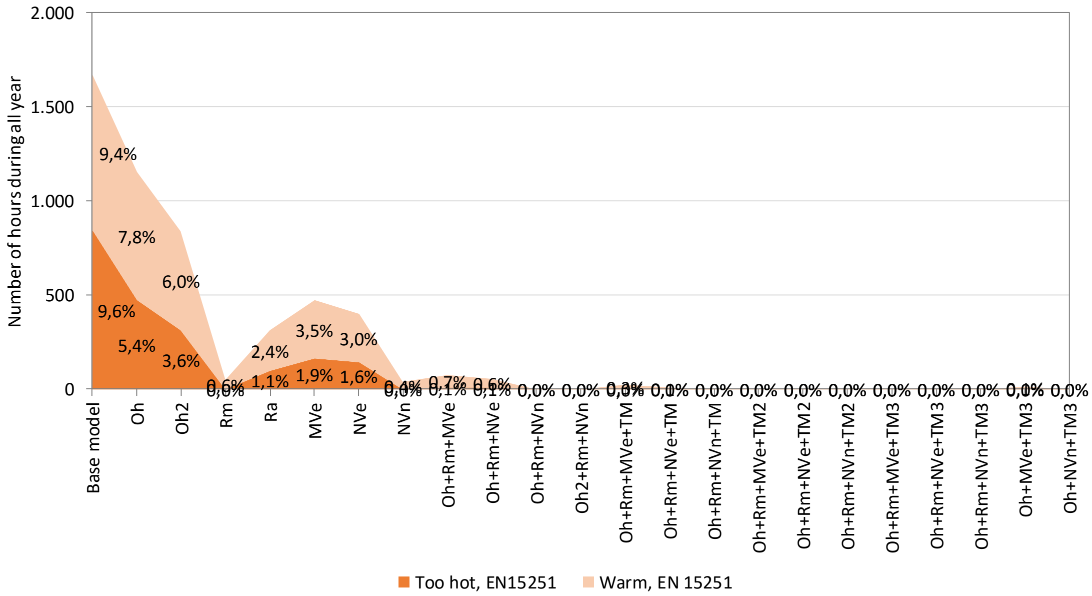


Figure 5.32. Evaluation of all the strategies according to warm discomfort hours calculated with EN 15251 model; detached house in Burgos, cold continental climate.

Probably the best solution for this case would include a certain amount of supplementary thermal mass in combination with natural ventilation, preferably by night, and some devices for solar shading during day time, not necessarily covering the whole window, but certainly reducing the solar gains through the windows.

Taking a closer look at the warm summer week, the indoor temperature differences were smaller than in the case of Bilbao, of Atlantic climate. Regarding the different ventilative cooling strategies, which are illustrated in Figure 5.33, the use of MVHR with enhanced airflow was insufficient without supplementary solar shading. The use of evening natural ventilation of the enhanced MVHR together with roller shutters permitted to maintain the peak temperatures indoors around 30 °C. The best performance corresponds again to the night time natural ventilation, in blue.

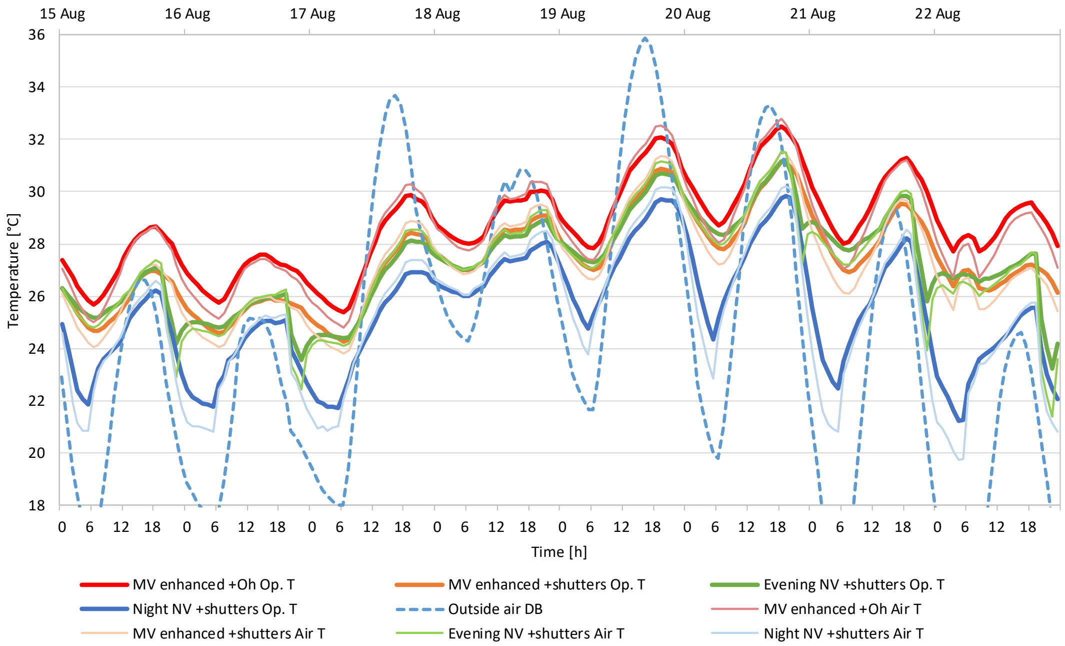


Figure 5.33. Comparison of the main ventilation measures based on the obtained indoor temperatures in summer; detached house in Burgos, cold continental climate.

Afterwards, the potential of thermal mass to reduce the indoor temperatures was assessed (Figure 5.34). It confirmed the benefits of supplementary thermal mass together with natural ventilation. The use of 5 cm of concrete levelling (TM1) could reduce the peak hours by one degree and the use of internal brick walls in the inner facades (TM2) could contribute with a reduction of peak hours by an extra degree. The case of concrete floor slabs (TM3) may be considered too heavy for a full wooden structure, but it could improve very considerably the indoor temperatures in this location. As a result, the warmest hours could be reduced from 28 °C to 26 °C with the use of small heavyweight elements for short time or daily thermal storage.

In order to verify if the potential of thermal mass could substitute the use of direct solar shading of windows, two alternatives for the cases with enhanced MVHR or with night time natural ventilation were compared in Figure 5.35. It showed an important finding for this climate and detached typology: the integration of higher thermal mass than the use of roller shutters, independently from the type of ventilation used appears to be more convenient.

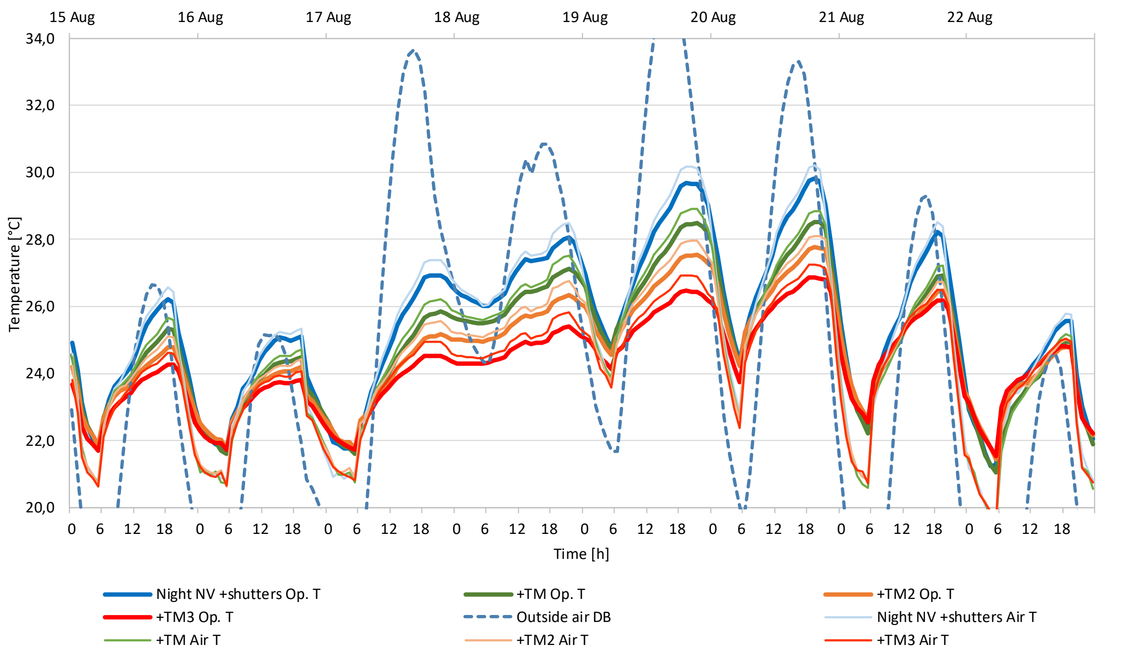


Figure 5.34. Comparison of thermal mass effect based on the obtained indoor temperatures in summer; detached house in Burgos, cold continental climate.

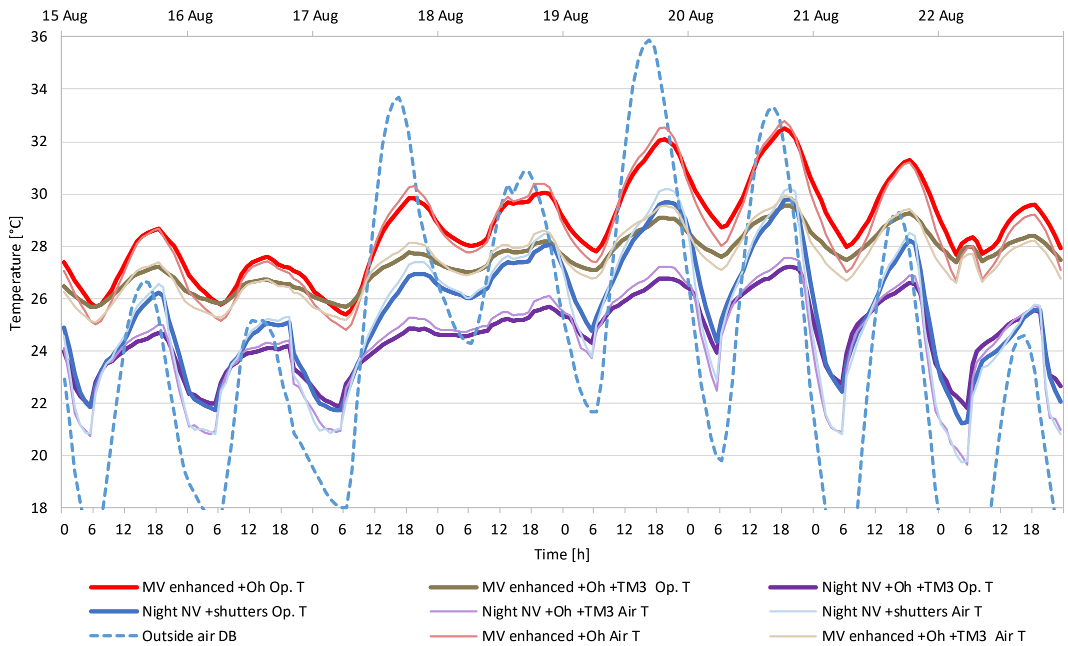


Figure 5.35. Comparison of the main solar shading measures based on the obtained indoor temperatures in summer; detached house in Burgos, cold continental climate.

In this location, the potential of the MVHR unit was significant due to the external cool temperatures. If appropriate solar shading is implemented, the enhanced airflow of the summer bypass should be enough to maintain the indoor environment inside the thermal comfort of the adaptive method. This means using some natural ventilation from time to time. That can be observed in Figure 5.36 with the limits of PMV method and in Figure 5.38 with the adaptive method. The use of MVHR as free-cooling (Rm+MVe+TM) presented many benefits precisely due to its automatic operation and the avoidance of any noise from the outside. However, the capability of this system to cool the indoor space is limited by the airflow of the unit (the maximum airflow of the commonly installed AHU is 350 m³/h) and the lower temperature limit. In this study, the limit was fixed at 23.5 °C to avoid overcooling in summer.

On the other hand, the use of natural ventilation during night-time demonstrated a very large cooling potential in comparison with the aforementioned enhanced MVHR, as shown in Figure 5.37 and Figure 5.39.

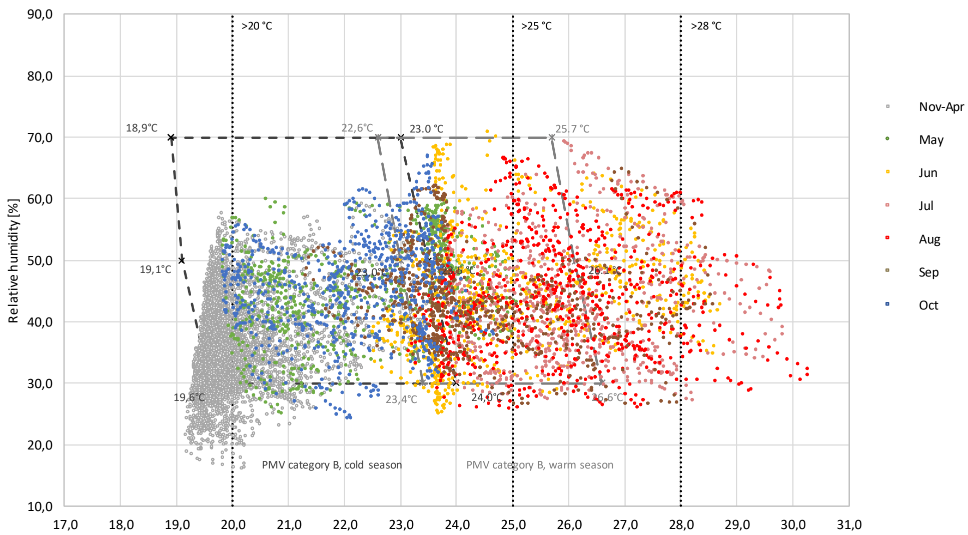


Figure 5.36. MVHR with enhanced summer bypass, roller shutters and supplementary thermal mass as concrete levelling in floors, indoor temperatures and limits of PMV method; attached North/South house in Burgos, cold continental climate.

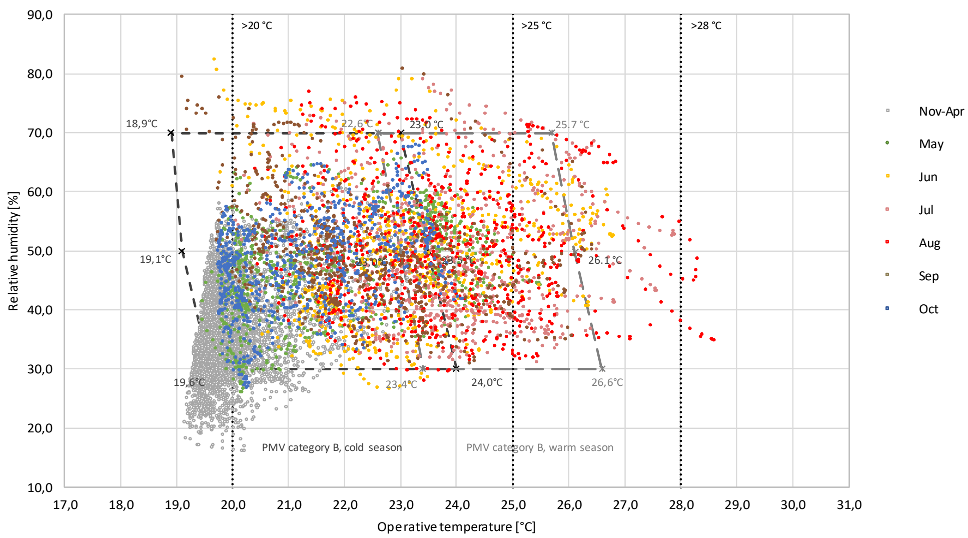


Figure 5.37. Night time natural ventilation, roller shutters and supplementary thermal mass as concrete levelling in floors, indoor temperatures and limits of PMV method, attached North/South house in Burgos, cold continental climate.

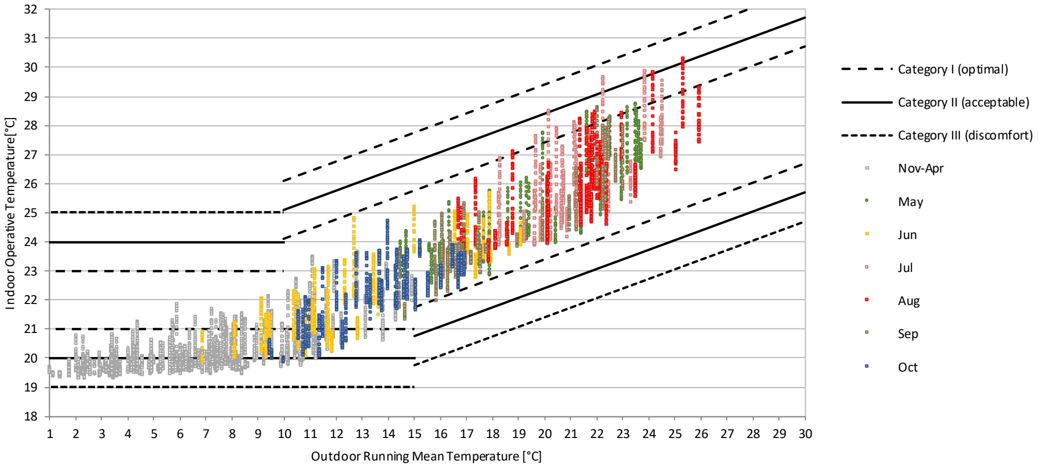


Figure 5.38. MVHR with enhanced summer bypass, roller shutters and supplementary thermal mass as concrete levelling in floors, indoor temperatures and limits of adaptive method; attached North/South house in Burgos, cold continental climate.

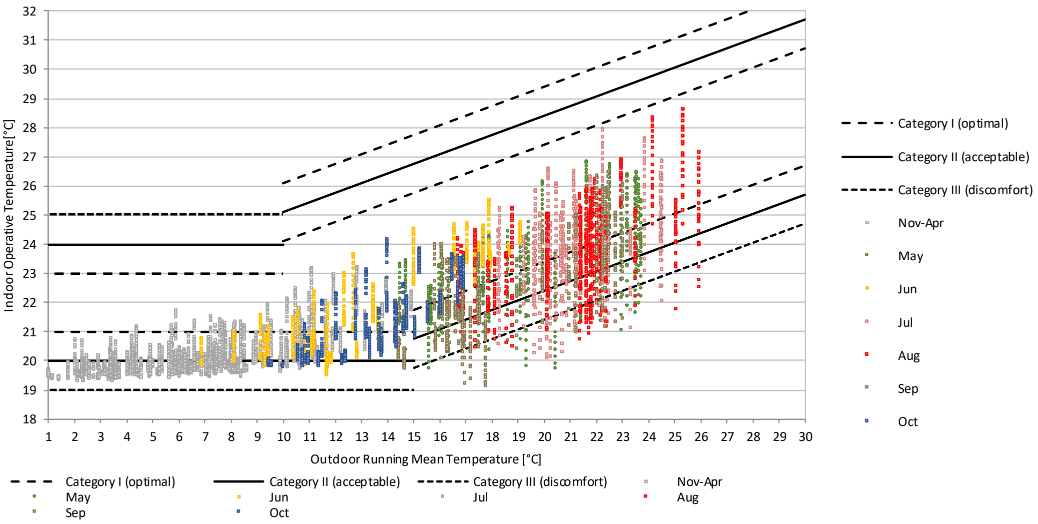


Figure 5.39. Night time natural ventilation, roller shutters and supplementary thermal mass as concrete levelling in floors, indoor temperatures and limits of adaptive method; attached North/South house in Burgos, cold continental climate.

The effect of higher thermal mass can contribute to the considerable reduction of the peak temperatures, as seen in the global assessment. To see this impact in more detial, the three best options from before were improved with a supplementary concrete floor slab of 30 cm (TM3) and were plotted in Figure 5.40, Figure 5.41 and Figure 5.42.

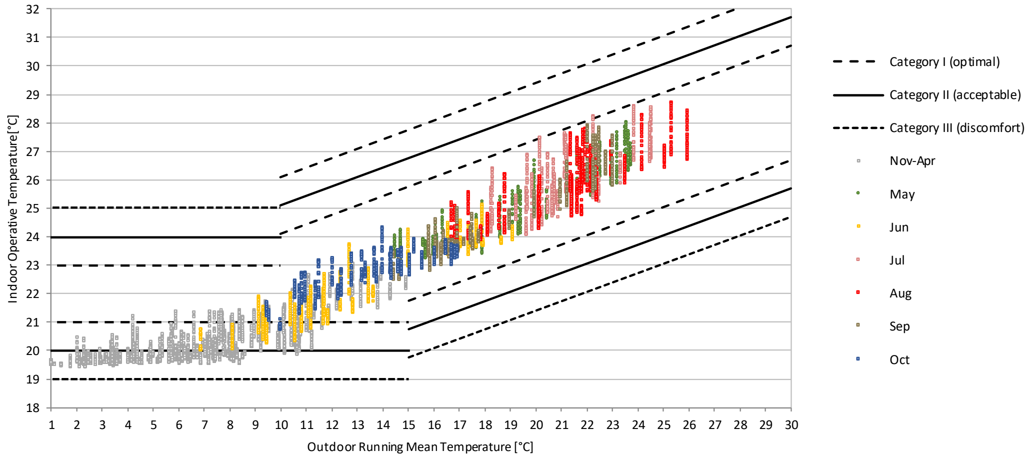


Figure 5.40. High thermal mass impact on enhanced summer bypass MVHR and roller shutters, indoor temperatures and limits of EN 15251; detached house in Burgos, cold continental climate.

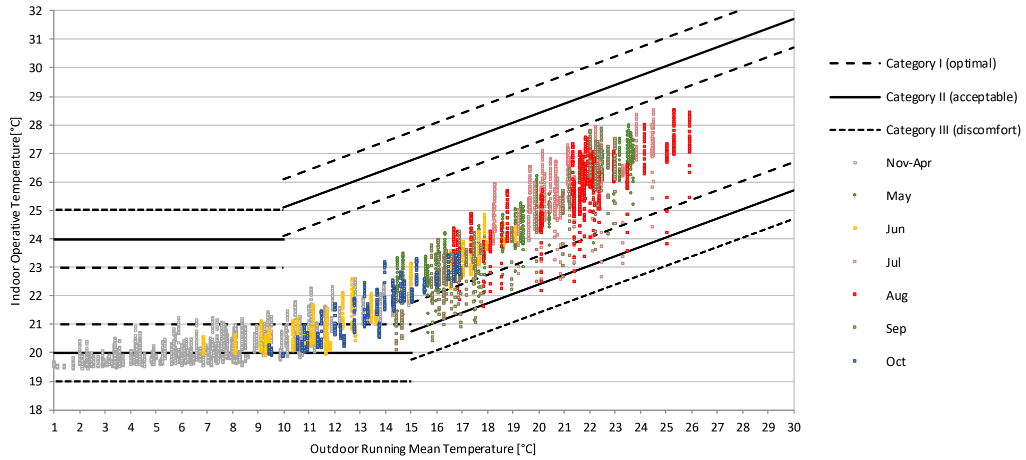


Figure 5.41. High thermal mass impact on natural ventilation in the evenings and roller shutters, indoor temperatures and limits of EN 15251; detached house in Burgos, cold continental climate.

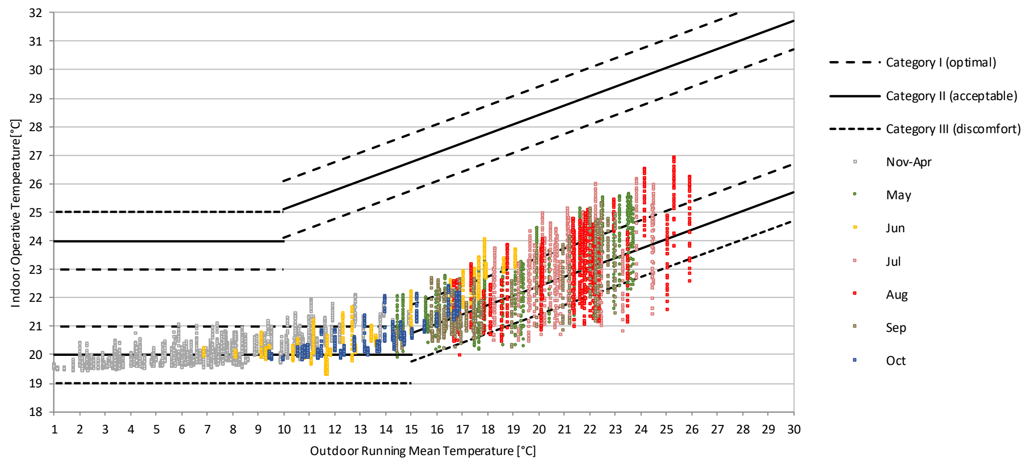


Figure 5.42. High thermal mass impact on night time natural ventilation and roller shutters, indoor temperatures and limits of EN 15251; detached house in Burgos, cold continental climate.

Table 5.16. Annual heating need and summer warm hours of detached housing case in cold continental climate, Burgos.

Summer adaptation models	Annual heating demand (kWh)	Annual solar g. wind. (kWh)	Heating demand (kWh/ m²y)	Max. daily heating load (W/m²)	Num. hours t >25 °C	Annual hours t >25 °C (%)	Num. hours t >28 °C	Annual hours t >28 °C (%)
Limits PH	2190.0	-	15.0	10.0	876	10.0%	-	-
Base model	1922.4	4428.4	13.2	8.7	3313	37.8%	1859	21.2%
Oh	2008.1	4014.3	13.8	8.8	3165	36.1%	1594	18.2%
Oh2	2064.3	3750.2	14.1	8.9	2652	30.3%	1423	16.2%
Rm	1931.1	2947.2	13.2	8.7	2503	28.6%	286	3.3%
Ra	1987.0	3183.9	13.6	8.7	2635	30.1%	734	8.4%
MVe	1663.4	4428.4	11.4	8.2	2399	27.4%	877	10.0%
NVe	1971.2	4428.4	13.5	8.7	2204	25.2%	781	8.9%
NVn	1923.8	4428.4	13.2	8.7	1480	16.9%	169	1.9%
Oh+Rm+MVe	1743.5	3149.6	11.9	8.4	1574	18.0%	316	3.6%
Oh+Rm+NVe	2075.2	3037.3	14.2	8.8	1454	16.6%	289	3.3%
Oh+Rm+NVn	2076.9	3295.9	14.2	8.8	699	8.0%	41	0.5%
Oh2+Rm+NVn	2129.4	3122.8	14.6	8.9	649	7.4%	31	0.4%
Oh+Rm+MVe+TM	1717.9	3184.1	11.8	8.4	1609	18.4%	194	2.2%
Oh+Rm+NVe+TM	2052.6	3103.8	14.1	8.9	1375	15.7%	157	1.8%
Oh+Rm+NVn+TM	2055.8	3447.1	14.1	8.9	434	5.0%	12	0.1%
Oh+Rm+MVe+TM2	1673.6	3183.5	11.5	8.5	1629	18.6%	103	1.2%
Oh+Rm+NVe+TM2	2012.2	3105.0	13.8	9.0	1405	16.0%	94	1.1%
Oh+Rm+NVn+TM2	2019.3	3468.4	13.8	9.0	305	3.5%	0	0.0%
Oh+Rm+MVe+TM3	1616.8	3180.2	11.1	8.6	1679	19.2%	44	0.5%
Oh+Rm+NVe+TM3	1958.9	3092.3	13.4	9.2	1451	16.6%	22	0.3%
Oh+Rm+NVn+TM3	2069.4	3136.9	14.2	9.2	156	1.8%	0	0.0%
Oh+MVe+TM3	1606.1	4014.3	11.0	8.6	2225	25.4%	399	4.6%
Oh+NVn+TM3	1896.6	4014.3	13.0	9.2	349	4.0%	0	0.0%

Table 5.17. Summer thermal comfort summary. Warm discomfort assessed by ISO 7730 and EN 15251; detached housing case in cold continental climate, Burgos.

Summer adaptation models	PMV ISO 7730 Cat. C+		PMV ISO 7730 Too hot		EN 15251 Cat. III +		EN 15251 Too hot	
	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %
Base model	414	4.7%	2231	25.5%	826	9.4%	843	9.6%
Oh	360	4.1%	2032	23.2%	679	7.8%	474	5.4%
Oh2	222	2.5%	1844	21.1%	527	6.0%	314	3.6%
Rm	696	7.9%	912	10.4%	50	0.6%	0	0.0%
Ra	487	5.6%	1279	14.6%	212	2.4%	100	1.1%
MVe	452	5.2%	1291	14.7%	308	3.5%	164	1.9%
NVe	392	4.5%	1184	13.5%	261	3.0%	142	1.6%
NVn	330	3.8%	452	5.2%	38	0.4%	2	0.0%
Oh+Rm+MVe	276	3.2%	614	7.0%	65	0.7%	12	0.1%
Oh+Rm+NVe	250	2.9%	614	7.0%	49	0.6%	8	0.1%
Oh+Rm+NVn	155	1.8%	192	2.2%	1	0.0%	0	0.0%
Oh2+Rm+NVn	135	1.5%	167	1.9%	0	0.0%	0	0.0%
Oh+Rm+MVe+TM	281	3.2%	556	6.3%	23	0.3%	0	0.0%
Oh+Rm+NVe+TM	252	2.9%	526	6.0%	8	0.1%	0	0.0%
Oh+Rm+NVn+TM	98	1.1%	63	0.7%	0	0.0%	0	0.0%
Oh+Rm+MVe+TM2	313	3.6%	491	5.6%	0	0.0%	0	0.0%
Oh+Rm+NVe+TM2	281	3.2%	460	5.3%	0	0.0%	0	0.0%
Oh+Rm+NVn+TM2	52	0.6%	23	0.3%	0	0.0%	0	0.0%
Oh+Rm+MVe+TM3	388	4.4%	364	4.2%	0	0.0%	0	0.0%
Oh+Rm+NVe+TM3	386	4.4%	324	3.7%	0	0.0%	0	0.0%
Oh+Rm+NVn+TM3	17	0.2%	0	0.0%	0	0.0%	0	0.0%
Oh+MVe+TM3	524	6.0%	1054	12.0%	13	0.1%	0	0.0%
Oh+NVn+TM3	39	0.4%	4	0.0%	0	0.0%	0	0.0%

5.6.6. Attached single-family house in warm continental climate, Madrid

The global analysis of the number of warm temperatures indoors confirmed that this climate presents the warmest conditions and also that the attached houses with East-West orientation have a significantly larger risk of warm discomfort, see Figure 5.43. The indoor temperatures of the base model remained over 25 °C for the 45.8% of annual hours and overpassed 28 °C 36.8% of the time. This means that almost all the hours from May to October are over these limits, because they account for the 50.4% of annual hours.

Regarding the types of ventilation, the use of long hours of natural ventilation during night time is the only way to considerably reduce the indoor temperatures.

The use of thermal mass is only useful in combination with night time natural ventilation. With other types of ventilation it may be even disadvantageous for the indoor environment because it increases the temperatures during the hottest hours.

The use of solar shading on windows was found to be essential to be able to reduce the annual warm hours during summer. The best combination of night natural ventilation with thermal mass and without roller shutter couldn't reduce the warm hours below 23.8%.

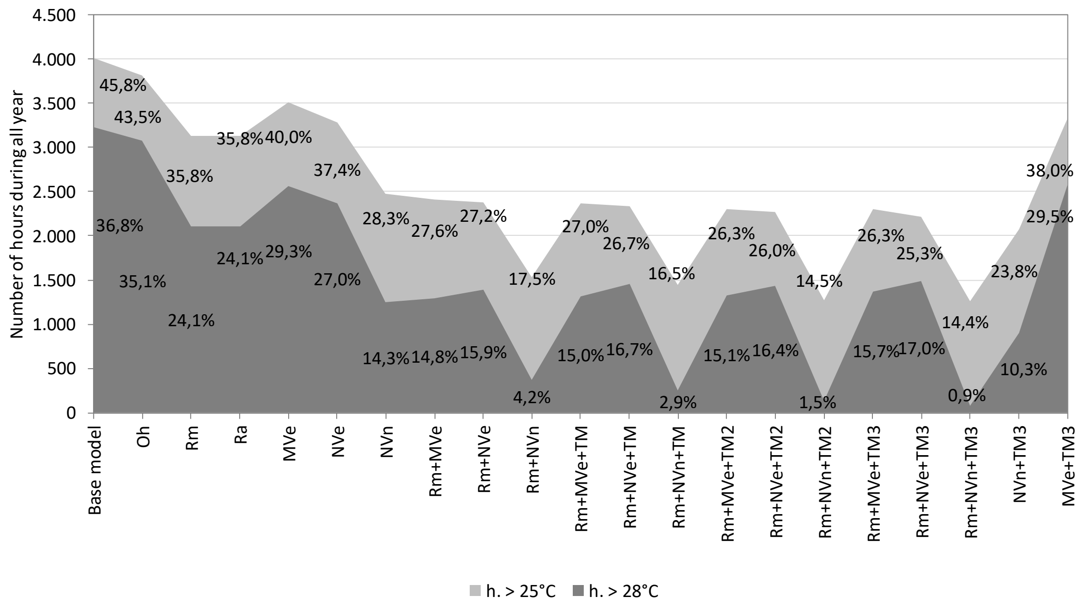


Figure 5.43. Evaluation of all the strategies according to the number of annual warm hours; detached house in Madrid, warm continental climate.

The studies based on TC with PMV method reinforced the bad response of the previous analysis, see Figure 5.44. Only the night time natural ventilation can reduce the discomfort hours significantly, improving the conditions to a range between 10.5% and 6.3% depending on the use of thermal mass. The other alternative of mechanical ventilation of short natural ventilation were inefficient, despite the use of roller shutters.

In the analysis based on the adaptive TC (Figure 5.45), it can be seen that the comfort would be adequate if users could directly use the natural ventilation. In these cases, the use of thermal mass showed a certain improvement and the need of direct solar shading was again confirmed as essential.

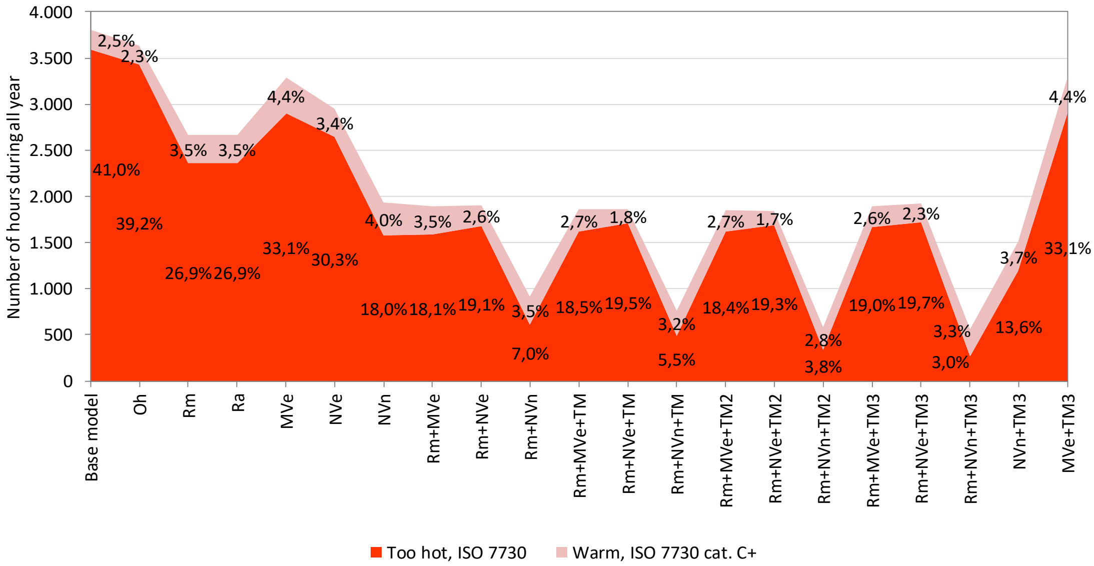


Figure 5.44. Evaluation of all the strategies according to warm discomfort hours calculated with PMV model; detached house in Madrid, warm continental climate.

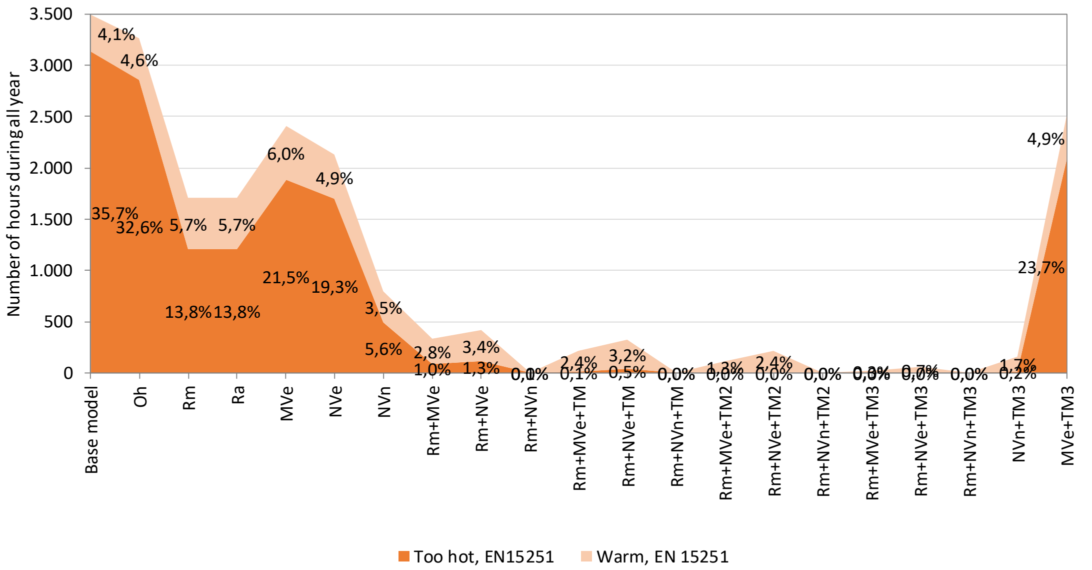


Figure 5.45. Evaluation of all the strategies according to warm discomfort hours calculated with EN 15251 model; detached house in Madrid, warm continental climate.

Taking a closer look at the analysis of the thermal response during a warm summer week, this case presented the highest indoor temperatures of all this study. As shown in Figure 5.46, the lack of solar shading and natural ventilation measures could end in indoor temperatures over 34 °C quite easily. Considering the use of roller shutters, the best strategy would be the long periods of natural ventilation.

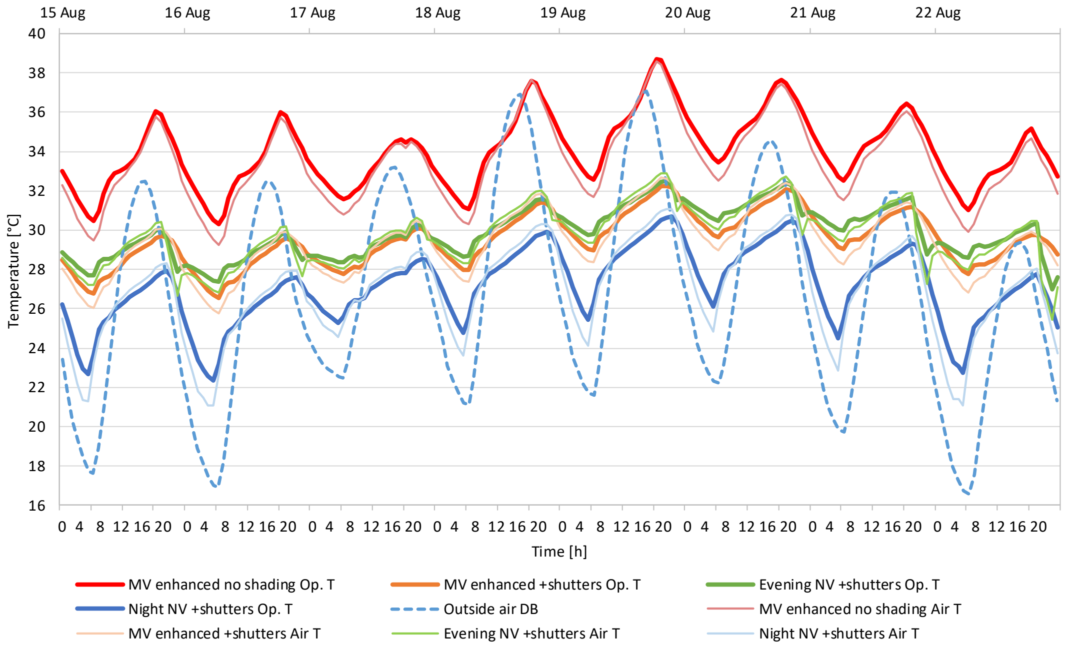


Figure 5.46. Comparison of the main ventilation measures based on the obtained indoor temperatures in summer; detached house in Madrid, warm continental climate.

With respect to the use of thermal mass, it confirmed once again the capacity to reduce the highest temperatures by 2-3 °C. However, it also showed certain limitations to purge the cumulated heat during the night time ventilation, as shown in Figure 5.47. Longer periods of ventilation would be advisory, preferably controlled by automatic systems.

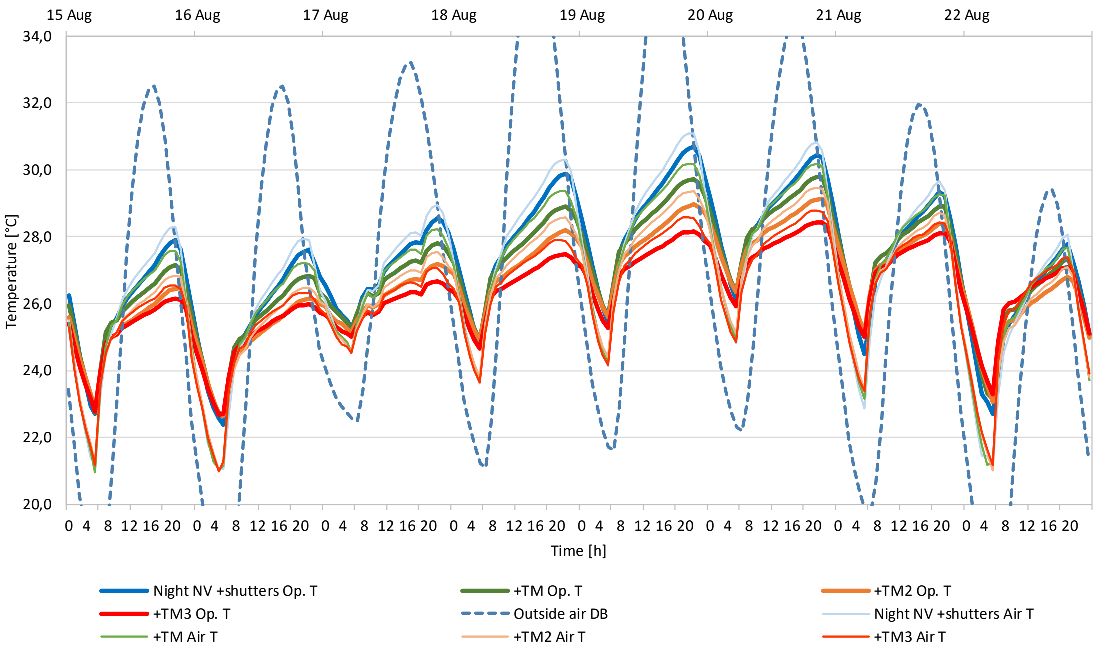


Figure 5.47. Comparison of the thermal mass effect based on the obtained indoor temperatures in summer; detached house in Madrid, warm continental climate.

Regarding the need of solar shading, the temperatures obtained with thermal mass or alternatively with solar shading were compared in Figure 5.48 , and considerable differences were evidenced. So, in this climate and orientation the use of solar shading seemed to be more necessary than in the previous ones. It is worth remembering that the use of solar shading in combination with natural ventilation permitted to avoid all warm discomfort according to adaptive method. The absence of solar shading was directly related with the number of hours over 28 °C. In the cases with night natural ventilation, the difference was very big: from 4.3% to 14.2% without additional thermal mass or from 1.0% to 10.2% in the case of the TM3.

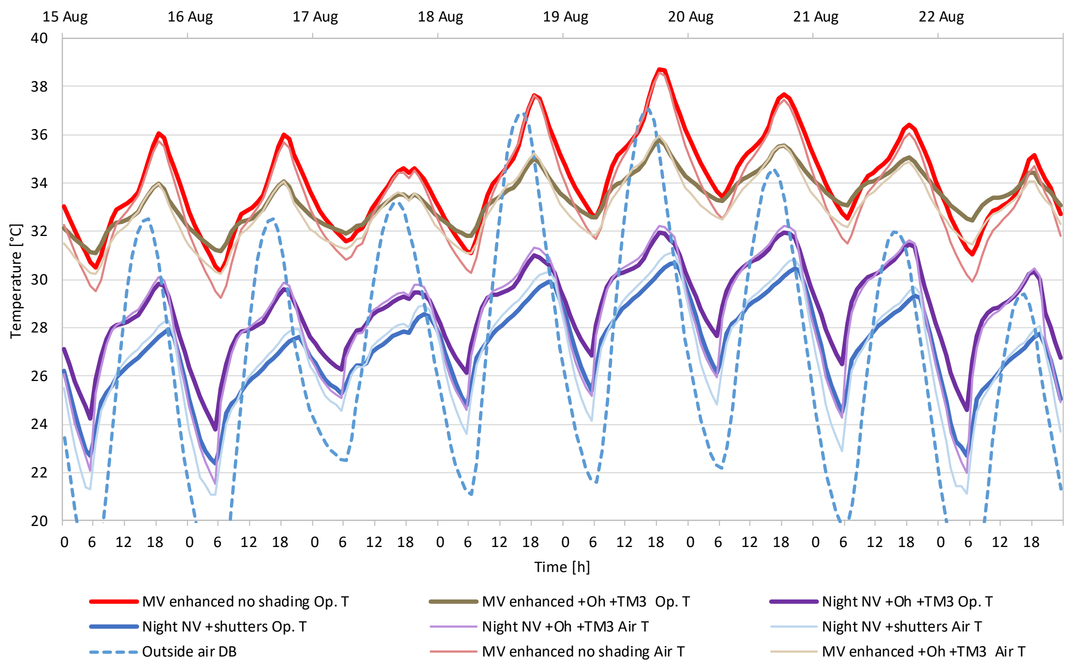


Figure 5.48. Comparison of the main solar shading measures based on the obtained indoor temperatures in summer; detached house in Madrid, warm continental climate.

The best cases of Madrid in relation with the EN 15251 limits are described in more detail in the following plots. For further details of the tested cases, see Table 5.18 and Table 5.19.

The MVHR with enhanced summer bypass with solar shading and supplementary high thermal mass (Rm+MVe+TM3) is presented in Figure 5.52. The potential of natural ventilation during evenings with solar shading and supplementary high thermal mass (Rm+NVe+TM3) is presented in Figure 5.53. The larger capacity to reduce the indoor temperatures with night time natural ventilation, solar shading and supplementary high thermal mass (Rm+NVn+TM3) is shown in Figure 5.54.

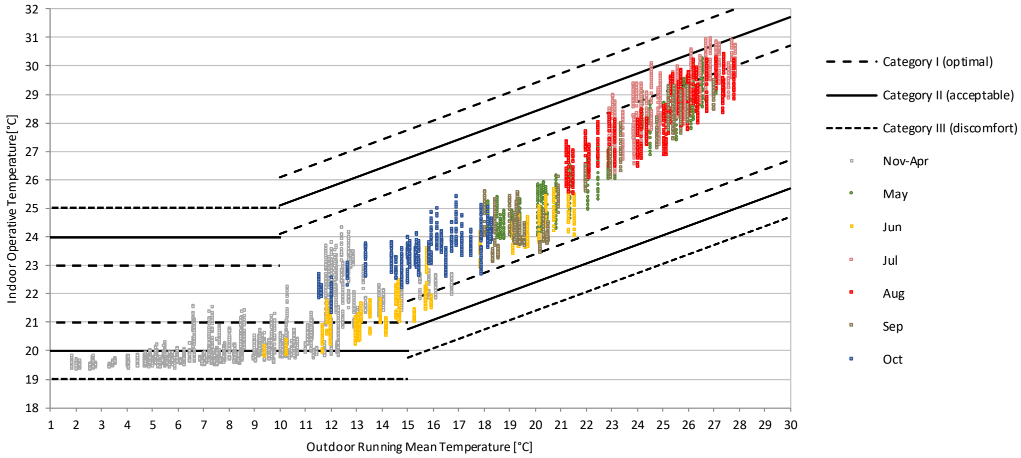


Figure 5.49. MVHR with enhanced summer bypass, roller shutters and supplementary thermal mass in facades and floor slabs, indoor temperatures and limits of EN 15251; attached East/West house in Madrid, warm continental climate.

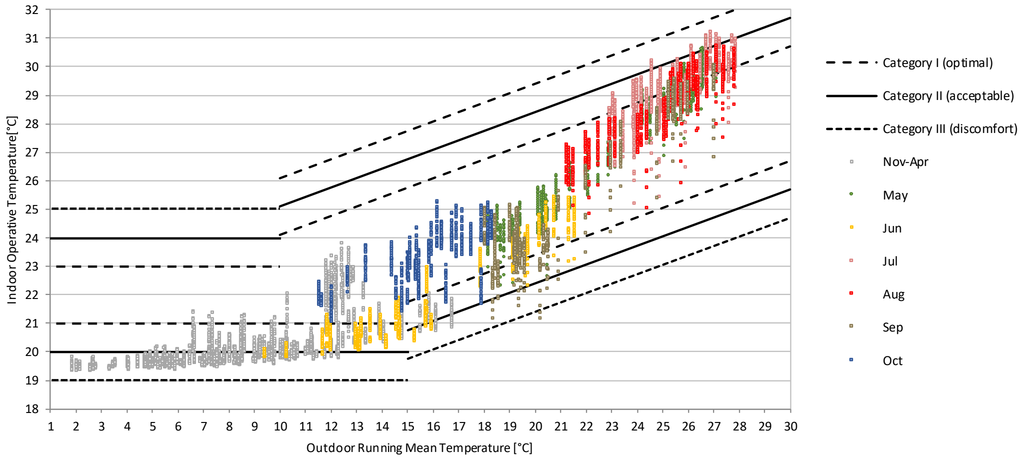


Figure 5.50. Natural ventilation in the evenings, roller shutters and supplementary thermal mass in facades and floor slabs, indoor temperatures and limits of EN 15251; attached East/West house in Madrid, warm continental climate.

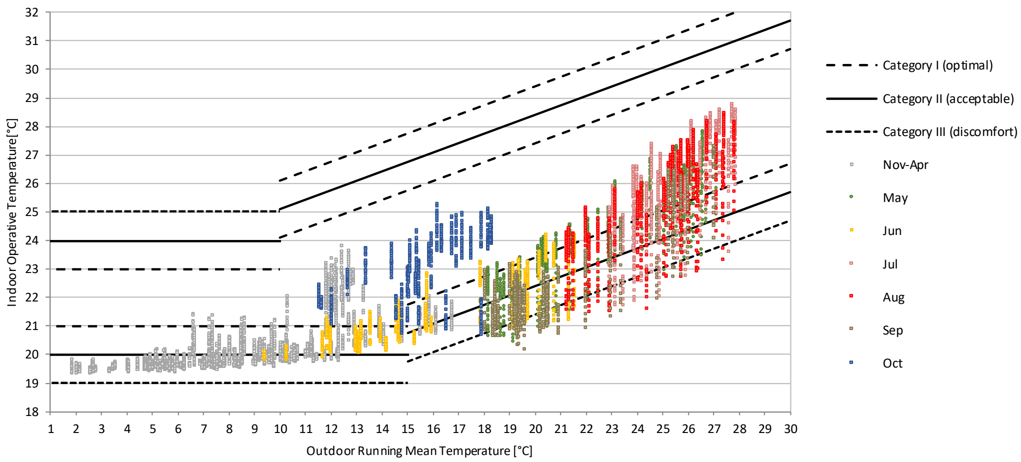


Figure 5.51. Night time natural ventilation, roller shutters and supplementary thermal mass in facades and floor slabs, indoor temperatures and limits of EN 15251; attached East/West house in Madrid, warm continental climate.

Table 5.18. Annual heating need and summer warm hours of the attached case in warm continental climate, Madrid.

Summer adaptation models	Annual heating demand (kWh)	Annual solar g. wind. (kWh)	Heating demand (kWh/ m²y)	Max. daily heating load (W/m²)	Num. hours t >25 °C	Annual hours t >25 °C (%)	Num. hours t >28 °C	Annual hours t >28 °C (%)
Limits PH	2190.0	-	15.0	10.0	876	10.0%	-	-
Base model	1867.4	6186.5	12.8	9.0	4009	45.8%	3226	36.8%
Oh	1933.4	5634.5	13.2	9.0	3813	43.5%	3075	35.1%
Rm	1922.3	3612.8	13.2	9.0	3134	35.8%	2113	24.1%
Ra	1922.3	3612.8	13.2	9.0	3134	35.8%	2113	24.1%
MVe	1843.7	6186.5	12.6	9.1	3505	40.0%	2569	29.3%
NVe	2135.9	6186.5	14.6	9.6	3279	37.4%	2366	27.0%
NVn	2181.1	6186.5	14.9	9.6	2481	28.3%	1253	14.3%
Rm+MVe	1938.7	2675.3	13.3	9.1	2416	27.6%	1294	14.8%
Rm+NVe	2242.6	2675.3	15.4	9.6	2381	27.2%	1395	15.9%
Rm+NVn	2283.6	2675.3	15.6	9.6	1529	17.5%	371	4.2%
Rm+MVe+TM	1904.3	2675.3	13.0	9.0	2364	27.0%	1317	15.0%
Rm+NVe+TM	2209.6	2675.3	15.1	9.4	2335	26.7%	1461	16.7%
Rm+NVn+TM	2248.1	2675.3	15.4	9.4	1442	16.5%	255	2.9%
Rm+MVe+TM2	1889.0	2675.3	12.9	9.0	2304	26.3%	1325	15.1%
Rm+NVe+TM2	2196.5	2675.3	15.0	9.5	2276	26.0%	1435	16.4%
Rm+NVn+TM2	2232.9	2675.3	15.3	9.5	1272	14.5%	134	1.5%
Rm+MVe+TM3	1836.3	2675.3	12.6	8.7	2308	26.3%	1373	15.7%
Rm+NVe+TM3	2142.0	2675.3	14.7	9.2	2220	25.3%	1487	17.0%
Rm+NVn+TM3	2181.1	2675.3	14.9	9.2	1264	14.4%	80	0.9%
NVn+TM3	2122.8	6186.5	14.5	9.2	2081	23.8%	898	10.3%
MVe+TM3	1782.2	6186.5	12.2	8.7	3329	38.0%	2580	29.5%

Table 5.19. Summer thermal comfort summary. Warm discomfort assessed by ISO 7730 and EN 15251; attached case in warm continental climate, Madrid.

Summer adaptation models	**PMV ISO 7730 Cat. C+**		**PMV ISO 7730 Too hot**		**EN 15251 Cat. III +**		**EN 15251 Too hot**	
	Num. hours	**Year %**	**Num. hours**	**Year %**	**Num. hours**	**Year %**	**Num. hours**	**Year %**
Base model	218	2.5%	3589	41.0%	362	4.1%	3130	35.7%
Oh	205	2.3%	3431	39.2%	403	4.6%	2859	32.6%
Rm	308	3.5%	2358	26.9%	499	5.7%	1208	13.8%
Ra	308	3.5%	2358	26.9%	499	5.7%	1208	13.8%
MVe	384	4.4%	2903	33.1%	523	6.0%	1885	21.5%
NVe	301	3.4%	2650	30.3%	431	4.9%	1695	19.3%
NVn	353	4.0%	1576	18.0%	308	3.5%	491	5.6%
Rm+MVe	304	3.5%	1586	18.1%	246	2.8%	88	1.0%
Rm+NVe	226	2.6%	1677	19.1%	297	3.4%	116	1.3%
Rm+NVn	305	3.5%	615	7.0%	5	0.1%	0	0.0%
Rm+MVe+TM	240	2.7%	1619	18.5%	206	2.4%	12	0.1%
Rm+NVe+TM	160	1.8%	1707	19.5%	279	3.2%	42	0.5%
Rm+NVn+TM	282	3.2%	484	5.5%	0	0.0%	0	0.0%
Rm+MVe+TM2	240	2.7%	1615	18.4%	117	1.3%	0	0.0%
Rm+NVe+TM2	151	1.7%	1690	19.3%	214	2.4%	3	0.0%
Rm+NVn+TM2	247	2.8%	333	3.8%	0	0.0%	0	0.0%
Rm+MVe+TM3	226	2.6%	1666	19.0%	26	0.3%	0	0.0%
Rm+NVe+TM3	198	2.3%	1725	19.7%	57	0.7%	0	0.0%
Rm+NVn+TM3	290	3.3%	266	3.0%	0	0.0%	0	0.0%
NVn+TM3	322	3.7%	1187	13.6%	145	1.7%	16	0.2%
MVe+TM3	388	4.4%	2903	33.1%	429	4.9%	2079	23.7%

5.7. Stage III, Overheating evaluation

After the analysis of the indoor environment and the thermal comfort, the cases were also analysed considering the risk of overheating (OH) according to the specific method developed by CIBSE TM52 (CIBSE, 2013a). In the following sections the results of all the cases and combination of passive measures are summarised. These evaluations are complementary to the adaptive comfort study and reflect the major risk to provide sufficient thermal comfort to inhabitants.

5.7.1. Attached single-family house in Atlantic climate, Bilbao

The OH evaluation confirmed that there is a considerable risk of OH in all the cases without roller shutters. The use of thermal mass doesn't substitute the improvements of direct solar shading. The results of (MVe +Oh+TM3) confirmed that it was unable to avoid the exceedance in the warmest days.

An exception would be the use of night time natural ventilation, which great extent could help avoiding the hours of overheating, as shown in Figure 5.52 below. Actually, the solely use of roller shutters may be sufficient regarding the OH risk.

The full details of the assessment can be viewed in Table 5.20.

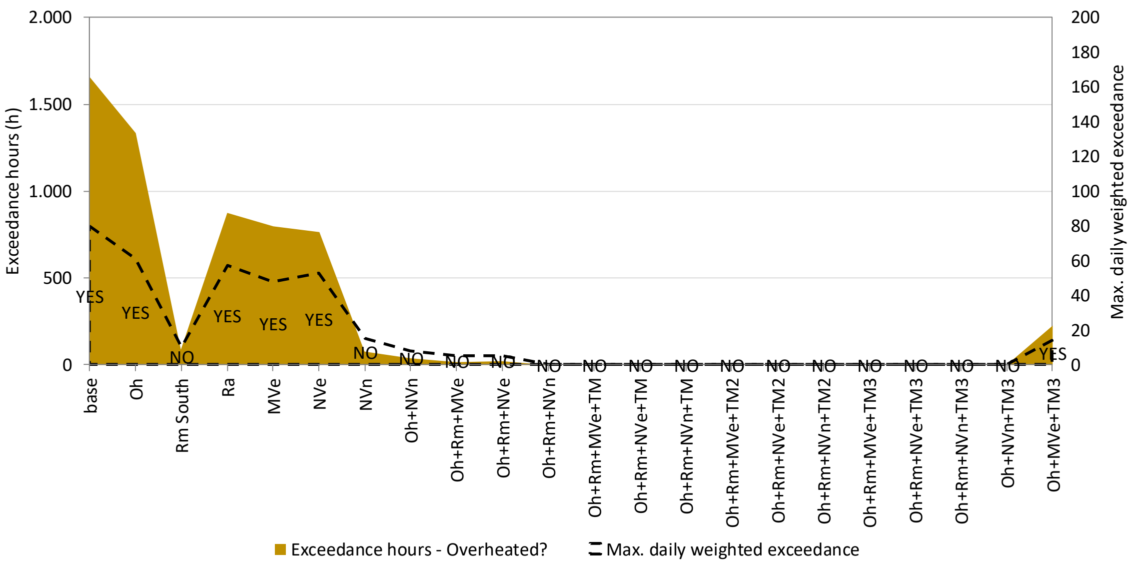


Figure 5.52. Overheating evaluation, including total exceedance hours and maximum daily weighted exceedance; attached North/South house in Bilbao, Atlantic climate.

Table 5.20. Overheating assessment of the attached case in Bilbao, Atlantic climate.

Models to analyse summer behaviour	Passive House Annual data		CIBSE TM52 May - September				
	Hours >25 °C (%)	OH?	Exceedance hours May-Sep (h)	Exceedance (%)	Max. daily weighted exceedance	Upper limit t.	OH?
Limits	10.0	-	-	3.0%	6	4	-
base	41.0%	Yes	1658	45.2%	80	5	Yes
Oh	38.7%	Yes	1334	36.3%	61	4	Yes
Rm South	33.7%	Yes	86	2.3%	10	1	No
Ra	37.8%	Yes	876	23.9%	57	4	Yes
MVe	36.0%	Yes	797	21.7%	48	4	Yes
NVe	34.9%	Yes	761	20.7%	53	4	Yes
NVn	24.6%	Yes	75	2.0%	15	2	No
Oh+NVn	22.4%	Yes	38	1.0%	8	1	No
Oh+Rm+MVe	27.6%	Yes	16	0.4%	5	1	No
Oh+Rm+NVe	27.2%	Yes	24	0.7%	5	1	No
Oh+Rm+NVn	17.0%	Yes	0	0.0%	0	0	No
Oh+Rm+MVe+TM	26.1%	Yes	0	0.0%	0	0	No
Oh+Rm+NVe+TM	26.8%	Yes	0	0.0%	0	0	No
Oh+Rm+NVn+TM	14.1%	Yes	0	0.0%	0	0	No
Oh+Rm+MVe+TM2	25.9%	Yes	0	0.0%	0	0	No
Oh+Rm+NVe+TM2	27.0%	Yes	0	0.0%	0	0	No
Oh+Rm+NVn+TM2	13.5%	Yes	0	0.0%	0	0	No
Oh+Rm+MVe+TM3	25.9%	Yes	0	0.0%	0	0	No
Oh+Rm+NVe+TM3	26.2%	Yes	0	0.0%	0	0	No
Oh+Rm+NVn+TM3	12.6%	Yes	0	0.0%	0	0	No
Oh+NVn+TM3	17.9%	Yes	0	0.0%	0	0	No
Oh+MVe+TM3	32.6%	Yes	224	6.1%	14	1	Yes

5.7.2. Detached single-family house in cold continental climate, Burgos

The studied overheating case of Burgos is summarised in Figure 5.53. Evidence was found that in this case the potential of thermal mass can substitute the need of direct solar shading on windows. If the majority of the measures couldn’t avoid OH, all the combination of measures seemed to be able to prevent the OH risk.

The full details of the assessment are listed in Table 5.21.

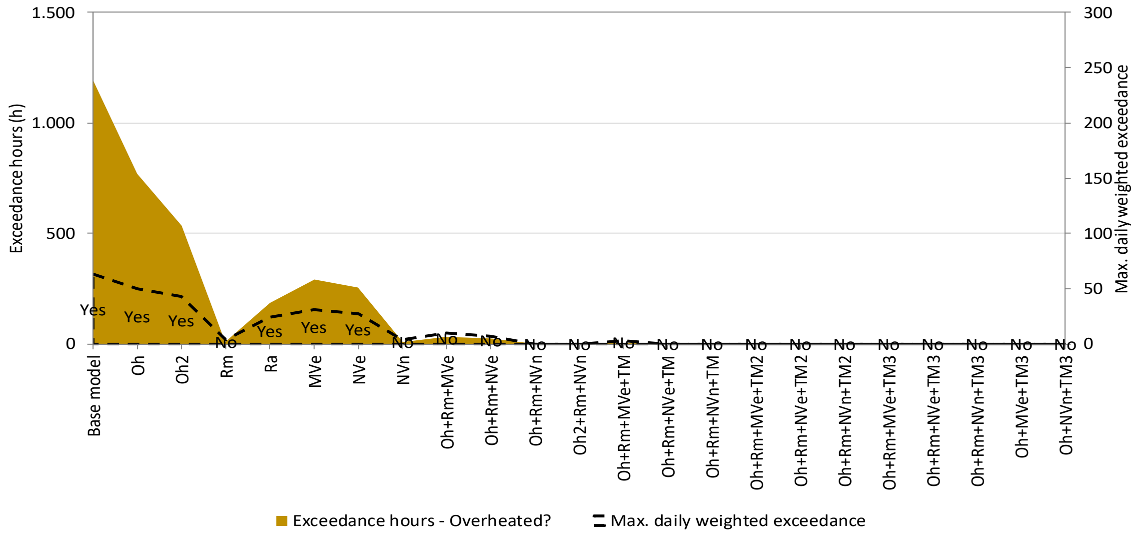


Figure 5.53. Overheating evaluation, including total exceedance hours and maximum daily weighted exceedance; attached North/South house in Burgos, cold continental climate.

Table 5.21. Overheating assessment of the attached case in Burgos, cold continental climate.

Models to analyse summer behaviour	Passive House Annual data		CIBSE TM52 May - September				
	Hours >25 °C (%)	OH?	Exceedance hours (h)	Exceed. (%)	Max. day weighted exceed.	Upper limit t.	OH?
Limits	10.0	-	-	3.0%	6	4	-
Base model	1189	32.4%	63	4	Yes	1189	32.4%
Oh	768	20.9%	50	4	Yes	768	20.9%
Oh2	535	14.6%	43	3	Yes	535	14.6%
Rm	10	0.3%	4	1	No	10	0.3%
Ra	184	5.0%	24	3	Yes	184	5.0%
MVe	291	7.9%	31	3	Yes	291	7.9%
NVe	255	6.9%	27	3	Yes	255	6.9%
NVn	8	0.2%	4	1	No	8	0.2%
Oh+Rm+MVe	30	0.8%	10	2	No	30	0.8%
Oh+Rm+NVe	25	0.7%	7	1	No	25	0.7%
Oh+Rm+NVn	0	0.0%	0	0	No	0	0.0%
Oh2+Rm+NVn	0	0.0%	0	0	No	0	0.0%
Oh+Rm+MVe+TM	3	0.1%	3	1	No	3	0.1%
Oh+Rm+NVe+TM	0	0.0%	0	0	No	0	0.0%
Oh+Rm+NVn+TM	0	0.0%	0	0	No	0	0.0%
Oh+Rm+MVe+TM2	0	0.0%	0	0	No	0	0.0%
Oh+Rm+NVe+TM2	0	0.0%	0	0	No	0	0.0%
Oh+Rm+NVn+TM2	0	0.0%	0	0	No	0	0.0%
Oh+Rm+MVe+TM3	0	0.0%	0	0	No	0	0.0%
Oh+Rm+NVe+TM3	0	0.0%	0	0	No	0	0.0%
Oh+Rm+NVn+TM3	0	0.0%	0	0	No	0	0.0%
Oh+MVe+TM3	0	0.0%	0	0	No	0	0.0%
Oh+NVn+TM3	0	0.0%	0	0	No	0	0.0%

5.7.3. Attached single-family house in warm continental climate, Madrid

The simulated cases in Madrid presented the highest warm discomfort ratios. Regarding the OH detection, the exceedance hours and the maximum daily weighted exceedance are plotted in Figure 5.54. Many cases were found to be with a considerable risk of OH.

The use of roller shutters was essential - almost none of the cases without solar shading could avoid OH. Only the use of natural ventilation with the highest thermal mass (TM3) could compensate the lack of direct solar shading.

The types of ventilation followed the trends identified in previous sections, showing that the best option to prevent the overheating would be the night time natural ventilation. The use of MVHR with enhanced summer bypass (MVe) or the short use of natural ventilation during evenings (NVe) presented similar results, with a slightly better performance for the bypass, when used with certain supplementary thermal mass.

The use of thermal mass seemed to be especially helpful in the cases with MVHR with enhanced summer bypass and, to a smaller degree, in the cases with short natural ventilation in the evenings.

The full details of the case study are listed in Table 5.22.

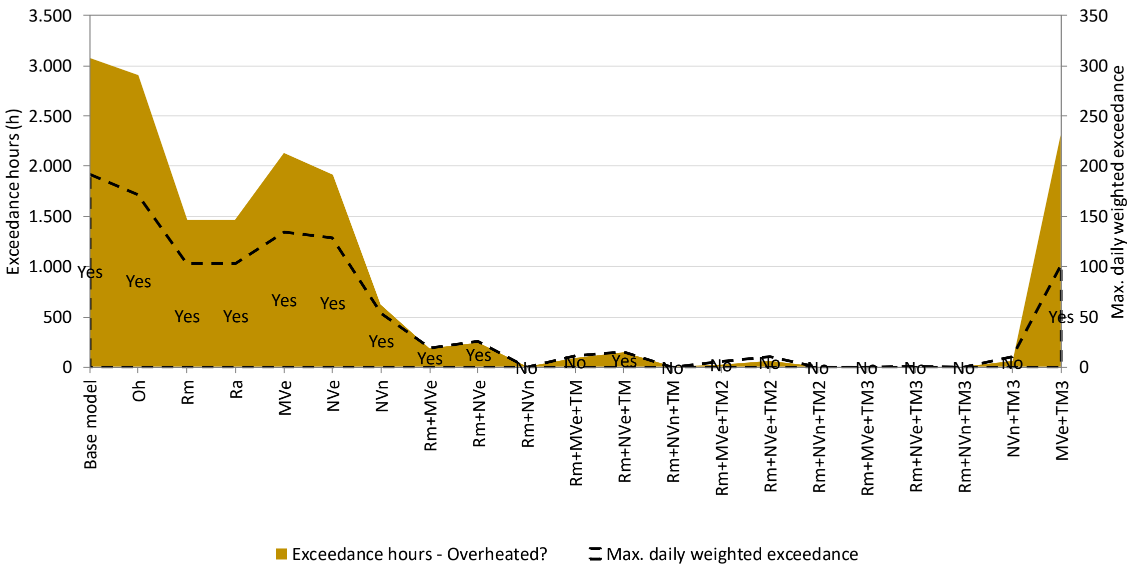


Figure 5.54. Overheating evaluation, including total exceedance hours and maximum daily weighted exceedance; attached North/South house in Madrid, warm continental climate.

Table 5.22. Overheating assessment of the attached case in Madrid, warm continental climate.

Models to analyse summer behaviour	**Passive House Annual data**		**CIBSE TM52 May - September**				
	Hours >25 °C (%)	**OH?**	**Exceedance hours May-Sep (h)**	**Exceedance (%)**	**Max. daily weighted exceedance**	**Upper limit t.**	**OH?**
Limits	10.0	-	-	3.0%	6	4	-
Base model	45.8%	Yes	3081	83.9%	192	11	Yes
Oh	43.5%	Yes	2909	79.2%	172	10	Yes
Rm	35.8%	Yes	1460	39.8%	103	7	Yes
Ra	35.8%	Yes	1460	39.8%	103	7	Yes
MVe	40.0%	Yes	2132	58.1%	135	9	Yes
NVe	37.4%	Yes	1910	52.0%	129	9	Yes
NVn	28.3%	Yes	629	17.1%	53	6	Yes
Rm+MVe	27.6%	Yes	188	5.1%	19	2	Yes
Rm+NVe	27.2%	Yes	246	6.7%	26	2	Yes
Rm+NVn	17.5%	Yes	0	0.0%	0	0	No
Rm+MVe+TM	27.0%	Yes	88	2.4%	11	1	No
Rm+NVe+TM	26.7%	Yes	152	4.1%	15	2	Yes
Rm+NVn+TM	16.5%	Yes	0	0.0%	0	0	No
Rm+MVe+TM2	26.3%	Yes	21	0.6%	6	1	No
Rm+NVe+TM2	26.0%	Yes	66	1.8%	10	1	No
Rm+NVn+TM2	14.5%	Yes	0	0.0%	0	0	No
Rm+MVe+TM3	26.3%	Yes	0	0.0%	0	0	No
Rm+NVe+TM3	25.3%	Yes	1	0.0%	1	1	No
Rm+NVn+TM3	14.4%	Yes	0	0.0%	0	0	No
NVn+TM3	23.8%	Yes	63	1.7%	10	2	No
MVe+TM3	38.0%	Yes	2310	62.9%	102	6	Yes

5.8. Stage III, building resilience in future climate change scenarios

Already in 2006 the PH guide in UK warned about the risks of overheating considering the global warming scenario: "*In the light of climate change predictions designers are recommended to achieve a figure of 5% overheating frequency or less (using current day data) and to make provision for additional seasonal shading devices to combat future overheating risks*." (BRE, 2006).

This section analyses the upcoming problems in a local context with an expected increase of temperatures. The studied scenarios cover the low (B1), medium (A1B) and high emissions (A2) as different hypothesis for an uncertain world, which are supported by a number of studies, as shown in the Chapter 2. These scenarios permit having a clearer idea of the future requirements, which designers should start considering today when making the present deign decisions.

For this analysis, the three most relevant cases were selected, considering the importance of understanding that mild summers like in Burgos might likely require more careful summer design and also how the present best options for Madrid could be at risk in a close future.

The three selected cases were:

- Detached house in Burgos with MVHR and enhanced summer bypass (MVe), manual roller shutters (Rm) and supplementary thermal mass in structure and walls (TM3).
- Detached house in Burgos with night time natural ventilation (NVn), manual roller shutters (Rm) and supplementary thermal mass in structure and walls (TM3).
- Attached East-West house in Madrid with night time natural operation (NVn), manual roller shutters (Rm) and supplementary thermal mass in structure and walls (TM3).

5.8.1. Detached single-family house in cold continental climate, Burgos

The assessment was done following the same methodology as in the present climate. This way, the indoor warm temperatures were analysed first, as presented in Figure 5.55. The plot includes the results of the two models in Burgos: one with night natural ventilation (NVn) and the other with the MVHR with enhanced summer bypass (MVe).

The results for 2040 don't change significantly. The use of natural ventilation showed a good capacity to reduce indoor temperatures below 25 °C and the use of enhanced MVHR indicated certain improvement with a decrease of 3-5% of the number of hours over 25 °C.

In 2080 the situation changes considerably and both systems perform much worse than in the present. Considering the medium CO_2 emissions scenario (A1B), the increase would be from 1.8% to 7.0% with natural ventilation and from 19.2% to 23.9% with enhanced MVHR. In both cases there would be an expected increase of around 5%.

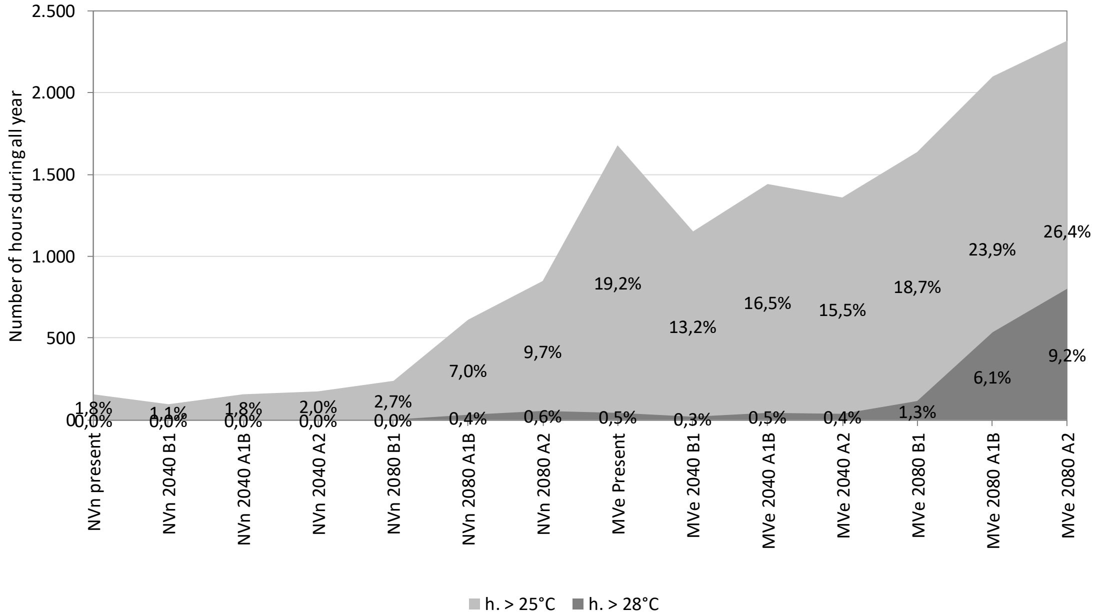


Figure 5.55. Evaluation of the future indoor temperatures in detached house model, based on IPCC climates of 2040 and 2080 in Burgos, cold continental climate.

With respect to the TC, the situation was analogous. Figure 5.56 summarises the results with PMV method of both models for 2040 and 2080. The outcomes suggested that the use of enhanced MVHR may be enough for 2040 but rather insufficient to maintain the acceptable indoor comfort in 2080 scenarios.

The study with adaptive method, summarised in Figure 5.57, indicated that the house may be always inside acceptable comfort if the principles of natural ventilation, lower activity levels, clothing adaptation and etcetera were followed (EN-15251, 2007).

However, this method presented some problems of application in the future climates of 2080. Keeping in mind that the range of application of the adaptive standard is limited to outdoor running mean temperatures up to 30 °C, the climate scenarios of 2080 present several days over this value and so they would require a further study of the user's maximum limits for those days.

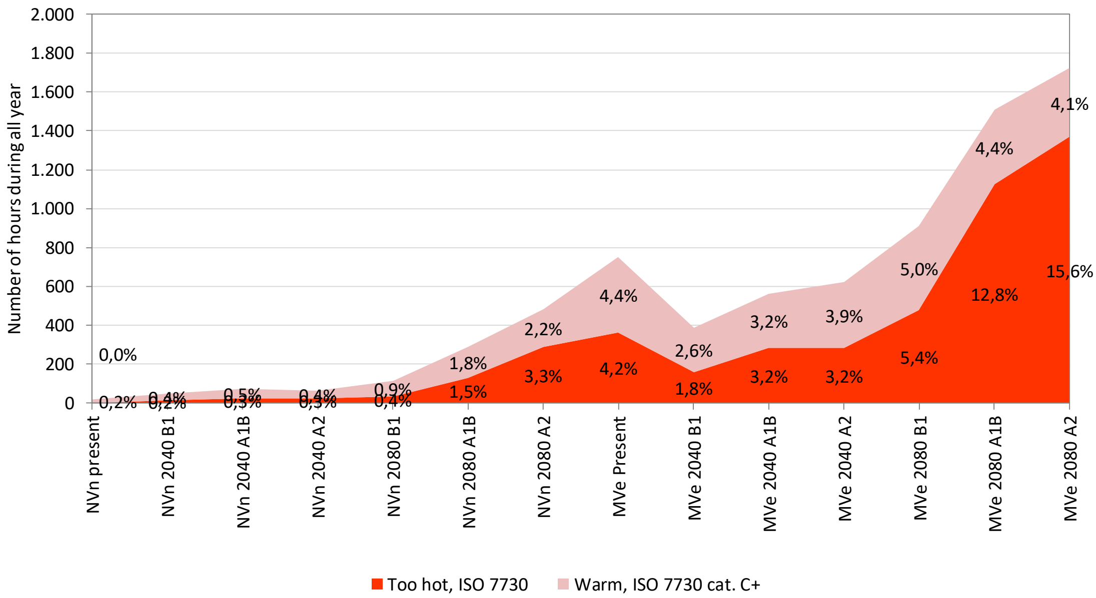


Figure 5.56. Evaluation of the future thermal comfort based on PMV method in a detached house model;
IPCC climates of 2040 and 2080 in Burgos, cold continental climate.

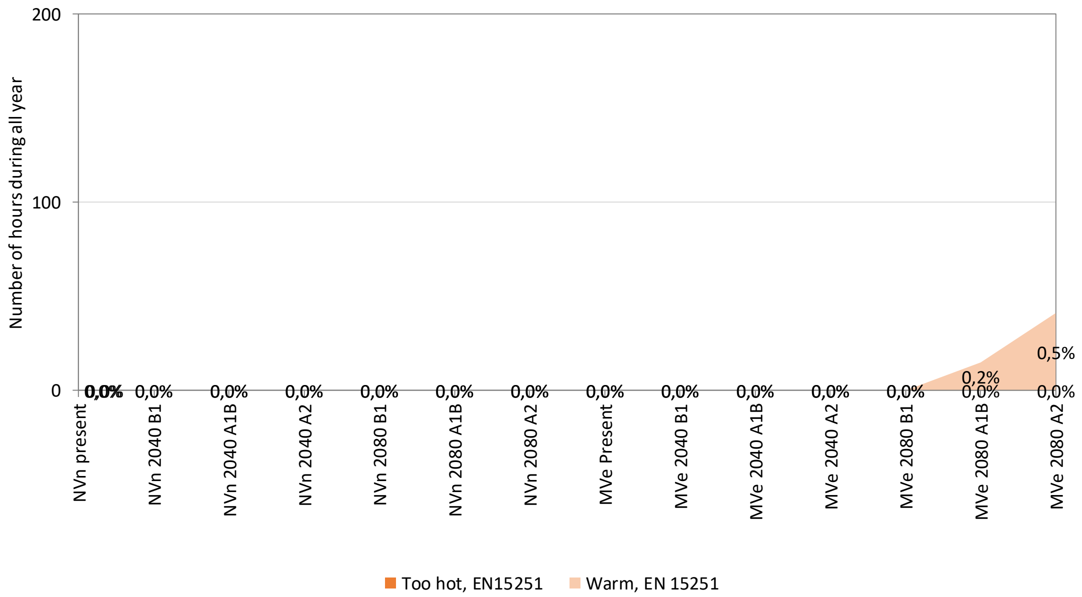


Figure 5.57. Evaluation of the future thermal comfort based on EN 15251 method in a detached house;
IPCC climates of 2040 and 2080 in Burgos, cold continental climate.

For further details of indoor temperatures and thermal comfort of each case for the future climate scenarios, see Table 5.23 and Table 5.24, respectively.

Table 5.23. Future changes in indoor temperatures due to global warming in Burgos. Annual heating need and summer warm hours of detached house in Atlantic climate.

Summer adaptation models	Annual heating demand (kWh)	Annual solar g. wind. (kWh)	Heating demand (kWh/ m²y)	Max. daily heating load (W/m²)	Num. hours t >25 °C	Annual hours t >25 °C (%)	Num. hours t >28 °C	Annual hours t >28 °C (%)
Limits PH	2190.0	-	15.0	10.0	876	10.0%	-	-
NVn present	2069.4	3136.9	14.2	9.2	156	1.8%	0	0.0%
NVn 2040 B1	2018.1	3396.4	13.8	9.1	97	1.1%	0	0.0%
NVn 2040 A1B	1801.6	3399.1	12.3	9.0	155	1.8%	0	0.0%
NVn 2040 A2	1858.1	3434.8	12.7	7.7	172	2.0%	0	0.0%
NVn 2080 B1	1776.9	3375.1	12.2	8.7	237	2.7%	3	0.0%
NVn 2080 A1B	1429.5	3418.5	9.8	7.6	613	7.0%	31	0.4%
NVn 2080 A2	1275.4	3428.3	8.7	7.2	847	9.7%	54	0.6%
MVe Present	1616.8	3180.2	11.1	8.6	1679	19.2%	44	0.5%
MVe 2040 B1	1648.0	3222.7	11.3	8.6	1152	13.2%	22	0.3%
MVe 2040 A1B	1443.9	3196.1	9.9	8.5	1443	16.5%	45	0.5%
MVe 2040 A2	1496.2	3242.6	10.2	7.2	1356	15.5%	38	0.4%
MVe 2080 B1	1430.7	3195.4	9.8	8.2	1639	18.7%	112	1.3%
MVe 2080 A1B	1157.3	3186.3	7.9	7.1	2098	23.9%	533	6.1%
MVe 2080 A2	1014.6	3201.9	6.9	6.7	2317	26.4%	804	9.2%

Table 5.24. Future changes due to global warming in Burgos. Summer thermal comfort summary, warm discomfort assessed by ISO 7730 and EN 15251; detached housing case in cold continental climate.

Summer adaptation models	PMV ISO 7730 Cat. C+		PMV ISO 7730 Too hot		EN 15251 Cat. III +		EN 15251 Too hot	
	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %
NVn present	17	0.2%	0	0.0%	0	0.0%	0	0.0%
NVn 2040 B1	32	0.4%	14	0.2%	0	0.0%	0	0.0%
NVn 2040 A1B	48	0.5%	24	0.3%	0	0.0%	0	0.0%
NVn 2040 A2	38	0.4%	24	0.3%	0	0.0%	0	0.0%
NVn 2080 B1	80	0.9%	33	0.4%	0	0.0%	0	0.0%
NVn 2080 A1B	159	1.8%	129	1.5%	0	0.0%	0	0.0%
NVn 2080 A2	195	2.2%	286	3.3%	0	0.0%	0	0.0%
MVe Present	388	4.4%	364	4.2%	0	0.0%	0	0.0%
MVe 2040 B1	231	2.6%	158	1.8%	0	0.0%	0	0.0%
MVe 2040 A1B	278	3.2%	284	3.2%	0	0.0%	0	0.0%
MVe 2040 A2	339	3.9%	284	3.2%	0	0.0%	0	0.0%
MVe 2080 B1	437	5.0%	475	5.4%	0	0.0%	0	0.0%
MVe 2080 A1B	387	4.4%	1124	12.8%	15	0.2%	0	0.0%
MVe 2080 A2	357	4.1%	1368	15.6%	41	0.5%	0	0.0%

To understand better the future changes, the main cases were analysed for a typical summer week, comparing the present thermal response with the forecasted future scenarios.

Firstly, the model with night time natural ventilation in the scenarios of 2040 evidenced small differences among them, see Figure 5.58. In 2080, all the scenarios showed an increase and the forecasted differences could be around 2 °C for warm days, as presented in Figure 5.59.

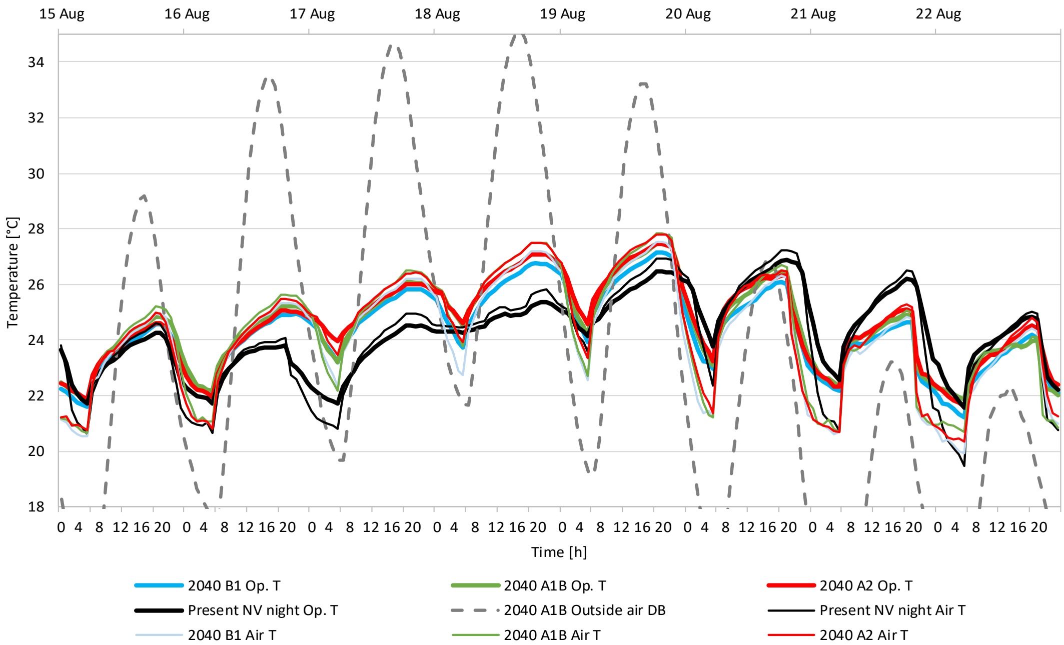


Figure 5.58. Comparison between future scenarios of 2040 and present indoor temperatures with night time natural ventilation; detached house in Burgos, cold continental climate.

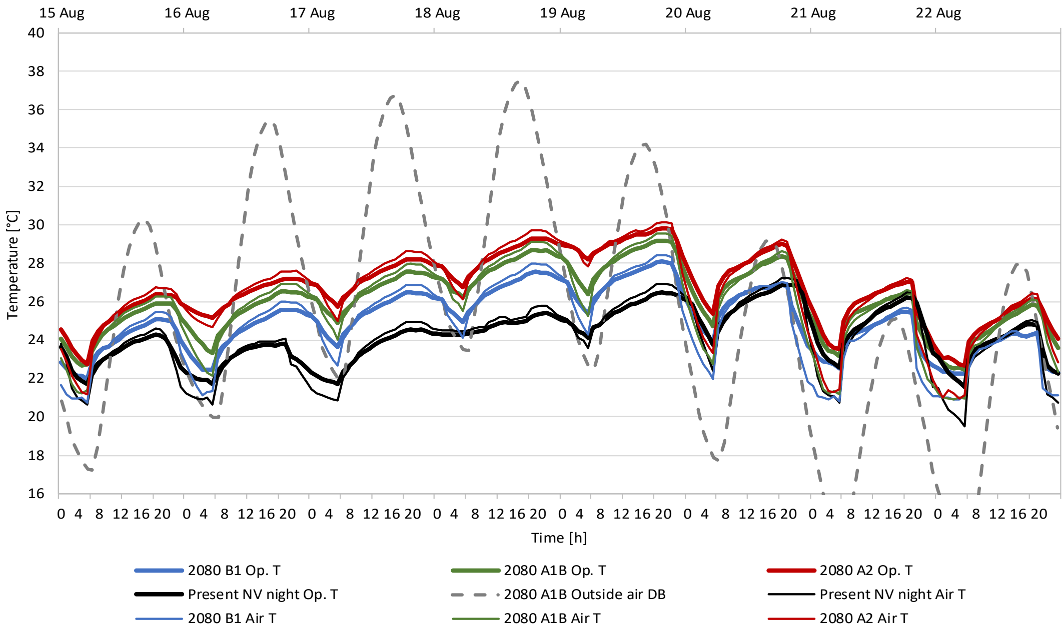


Figure 5.59. Comparison between future scenarios of 2080 and present indoor temperatures with night time natural ventilation; detached house in Burgos, cold continental climate.

Regarding the second model, with MVHR and enhanced summer bypass operation, the behaviour of the solution is less effective. Figure 5.60 presents the comparison between the scenarios of 2040 and also includes the scenario of the present as a reference. The plot reinforced the findings of the global assessment and indicated that the capacity of cooling of this ventilation type appears to be less efficient than these scenarios of the close future, in 2040. The situation in 2080 seems to be considerably worse and increases of indoor temperatures by about 2-4 °C could be expected, as shown in Figure 5.61.

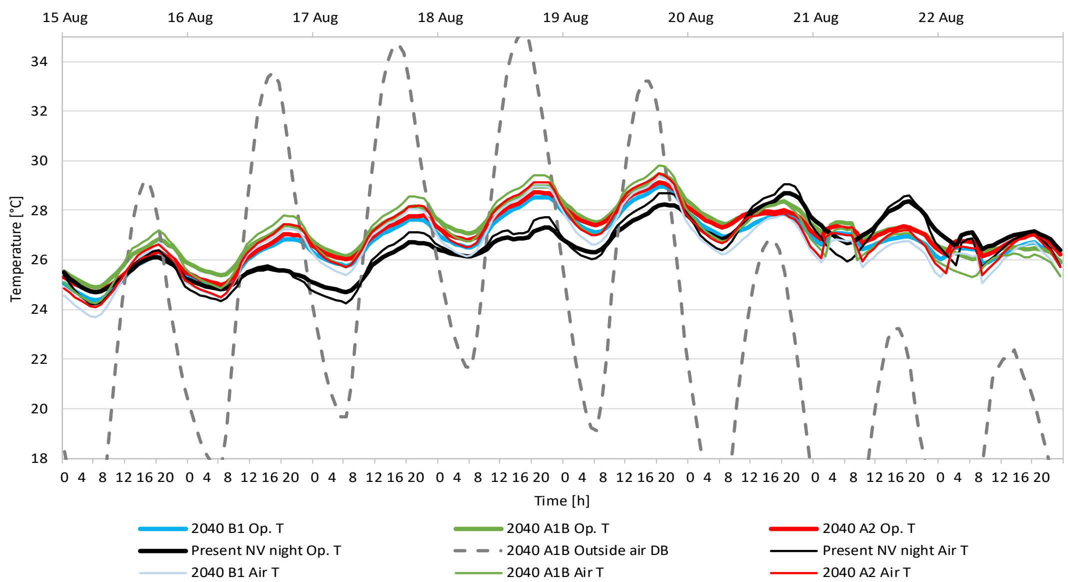


Figure 5.60. Comparison between scenarios of 2040 and present indoor temperatures with MVHR and enhanced summer bypass; detached house in Burgos, cold continental climate.

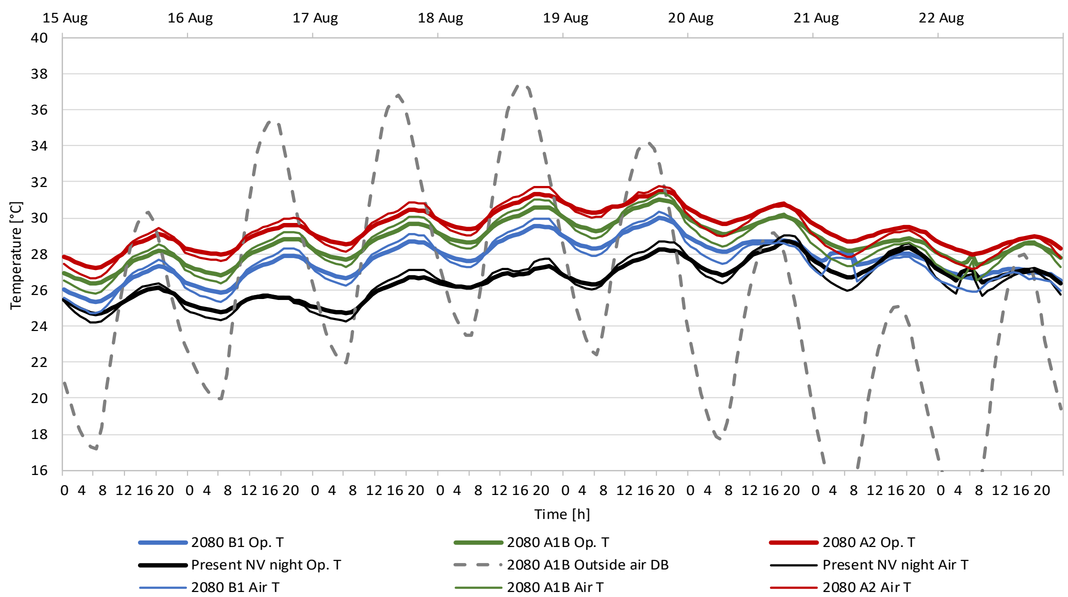


Figure 5.61. Comparison between scenarios of 2080 and present indoor temperatures with MVHR and enhanced summer bypass; detached house in Burgos, cold continental climate.

The details of the studied scenarios are presented in Figure 5.62 and Table 5.25 .

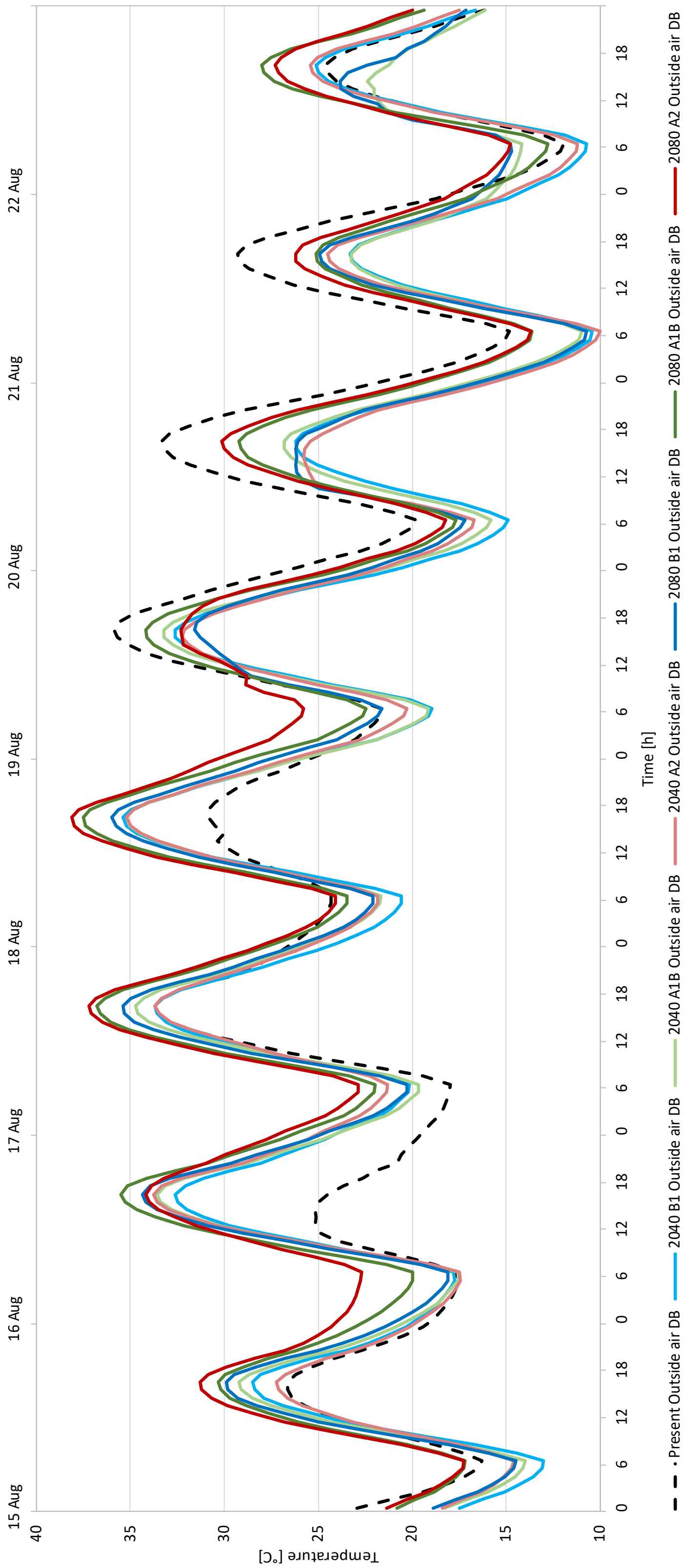


Figure 5 erent
future climate scenarios in Burgos, cold continental climate (data source IPCC and Meteonorm).

Table 5.25. Monthly summary of future climate scenarios in Burgos, cold continental climate (data source IPCC and Meteonorm).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Present BURGOS													
Monthly average DB temperature	3.6	4.9	8.2	10.1	14.6	19.6	21.7	21.2	17.3	12.9	6.8	4.0	12.1
Min. daily average DB temperature	-3.2	-0.9	0.8	4.2	7.0	12.1	14.8	14.8	11.3	6.7	0.9	-2.5	-3.2
Max. daily average DB temperature	9.5	11.0	14.4	16.8	23.1	27.0	27.8	28.8	24.1	19.2	12.7	10.0	28.8
Monthly average Relative Humidity	76.6	67.7	63.7	60.8	60.3	51.7	44.4	45.8	53.5	65.2	72.2	75.2	61.4
Global horizontal solar radiation	98.6	109.3	174.4	209.2	256.0	297.1	328.0	286.7	229.4	152.5	102.9	92.3	2336.5
HDD (18.3)	456	375	313	248	128	27	10	12	56	170	347	443	2585
CDD (25.0)	0	0	0	0	0	3	8	9	0	0	0	0	20
2040 B1													
Monthly average DB temperature	3.6	4.4	6.8	8.7	12.6	16.4	20.3	20.5	17.4	12.6	6.9	4.4	11.2
Min. daily average DB temperature	-3.3	-1.1	-0.8	2.8	5.1	8.8	13.4	14.1	11.6	6.5	0.9	-2.1	-3.3
Max. daily average DB temperature	9.4	10.6	13.0	15.6	20.9	23.8	26.4	28.0	24.3	18.9	12.8	10.3	28.0
Monthly average Relative Humidity	90.9	86.7	77.4	76.3	73.3	70.8	60.0	62.6	69.1	79.4	87.6	90.1	77.0
Global horizontal solar radiation	101.1	109.3	178.9	216.3	262.6	306.7	334.8	295.8	229.5	163.0	99.6	92.6	2390.3
HDD (18.3)	457	390	357	289	181	79	20	18	54	177	344	432	2798
CDD (25.0)	0	0	0	0	0	0	2	6	0	0	0	0	8
2040 A1B													
Monthly average DB temperature	3.9	4.7	7.1	9.0	13.0	16.8	20.8	20.9	18.1	13.1	7.2	4.6	11.6
Min. daily average DB temperature	-2.8	-0.7	-0.5	3.0	5.5	9.2	14.0	14.5	12.2	6.8	1.3	-2.0	-2.8
Max. daily average DB temperature	9.8	10.8	13.2	15.8	21.6	24.1	26.9	28.5	24.9	19.3	13.1	10.5	28.5
Monthly average Relative Humidity	90.6	86.1	77.0	76.5	73.2	70.2	60.5	62.3	69.9	80.1	87.3	90.7	77.0
Global horizontal solar radiation	101.1	100.6	187.7	214.8	263.1	300.7	339.5	297.3	233.0	167.8	110.1	93.9	2409.6
HDD (18.3)	447	382	348	281	169	72	15	15	41	164	334	427	2695
CDD (25.0)	0	0	0	0	0	0	4	8	0	0	0	0	12
2040 A2													
Monthly average DB temperature	3.8	4.6	7.0	9.0	12.9	16.6	20.7	20.9	18.0	12.9	7.1	4.5	11.5
Min. daily average DB temperature	-3.0	-0.8	-0.7	3.1	5.3	9.1	13.9	14.5	12.2	6.7	1.2	-2.1	-3.0
Max. daily average DB temperature	9.6	10.2	13.2	15.9	20.9	23.9	26.9	28.5	24.9	19.2	13.0	10.4	28.5
Monthly average Relative Humidity	90.8	87.4	77.4	76.2	73.4	70.9	60.2	62.8	69.4	79.9	87.7	90.8	77.2
Global horizontal solar radiation	95.2	115.6	186.1	215.8	268.3	302.2	340.2	301.0	233.2	166.1	108.5	98.0	2430.3
HDD (18.3)	449	384	351	281	174	75	16	15	42	170	337	430	2724
CDD (25.0)	0	0	0	0	0	0	4	8	0	0	0	0	11
2080 B1													
Monthly average DB temperature	4.1	4.8	7.3	9.2	13.6	17.3	21.3	21.5	18.5	13.3	7.4	4.9	11.9
Min. daily average DB temperature	-2.7	-0.6	-0.3	3.3	6.0	9.8	14.5	15.1	12.6	7.1	1.5	-1.7	-2.7
Max. daily average DB temperature	9.9	10.4	13.5	16.1	21.9	24.6	27.4	29.1	25.3	19.5	13.3	10.7	29.1
Monthly average Relative Humidity	91.3	87.7	78.2	77.2	73.2	70.5	60.5	62.3	69.7	80.4	88.4	91.1	77.5
Global horizontal solar radiation	102.1	112.5	183.0	220.8	271.0	305.8	342.0	303.0	237.4	171.4	104.8	88.1	2442.0
HDD (18.3)	441	379	341	273	153	61	12	10	35	158	327	418	2607
CDD (25.0)	0	0	0	0	0	0	6	11	0	0	0	0	17
2080 A1B													
Monthly average DB temperature	4.9	5.6	8.1	10.2	14.7	18.6	22.9	23.0	19.8	14.6	8.3	5.6	13.0
Min. daily average DB temperature	-1.9	0.3	0.5	4.4	7.1	11.2	16.0	16.6	14.0	8.4	2.3	-1.0	-1.9
Max. daily average DB temperature	10.7	11.8	14.3	17.2	23.1	26.0	28.9	30.6	26.7	20.9	14.2	11.5	30.6
Monthly average Relative Humidity	91.3	87.6	78.7	76.8	73.2	70.8	60.2	62.3	69.2	80.4	88.1	91.1	77.5
Global horizontal solar radiation	95.8	106.8	186.3	220.3	275.9	312.4	348.0	309.6	243.2	174.1	111.1	98.1	2481.4
HDD (18.3)	416	355	317	243	124	39	5	3	17	120	301	394	2334
CDD (25.0)	0	0	0	0	0	1	16	22	2	0	0	0	41
2080 A2													
Monthly average DB temperature	5.0	5.7	8.3	10.6	15.1	19.3	23.5	23.6	20.4	14.9	8.5	5.6	13.4
Min. daily average DB temperature	-1.7	0.2	0.7	4.6	7.3	11.8	16.7	17.2	14.6	8.7	2.6	-0.9	-1.7
Max. daily average DB temperature	10.9	11.4	14.4	17.5	23.4	26.6	29.6	31.2	27.3	21.2	14.5	11.5	31.2
Monthly average Relative Humidity	91.4	87.9	78.8	77.0	73.2	71.0	60.2	61.4	69.9	79.5	88.6	91.0	77.5
Global horizontal solar radiation	107.5	113.3	190.8	219.7	283.2	314.9	349.5	309.8	248.6	174.7	109.4	90.3	2511.5
HDD (18.3)	413	354	310	232	114	30	2	1	12	111	294	394	2268
CDD (25.0)	0	0	0	0	0	2	23	28	4	0	0	0	57

5.8.2. Attached single-family house in warm continental climate, Madrid

The third and the last model analysed in the future climate change scenarios corresponds to the typology of attached single family houses with East West orientation. This case required the combination of all the solutions to provide good comfort without active cooling systems, as seen in Section 5.6.6. In this section, the expected future behaviour of this case is analysed in order to understand if in the future these typologies will be able to adapt to the predicted warmer climate.

Firstly, the assessment of the number of warm indoor hours indicated that in the future the house will present considerably warmer conditions. This happened in all the climate change scenarios, including the optimistic calculations (B1 scenario) which stated increases of the number of hours over 25 °C and over 28 °C for 2040 and 2080. The warmest scenario (A2) indicated a very remarkable double number of warm hours and ten times more hours over 28 °C, as shown in Figure 5.63.

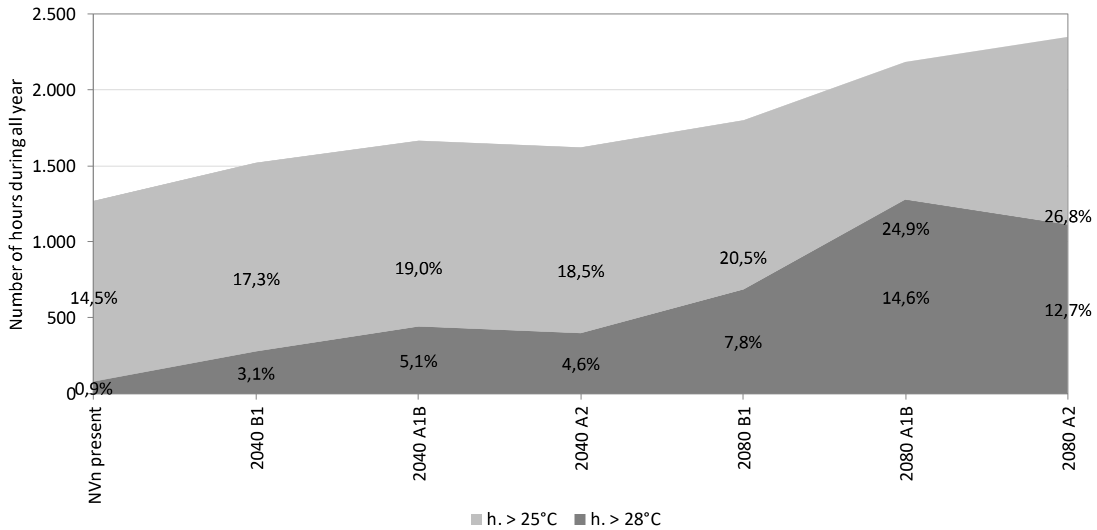


Figure 5.63. Evaluation of the future indoor temperatures in detached house model, based on IPCC climates of 2040 and 2080 in Burgos, cold continental climate.

The study of thermal comfort by the PMV method suggested similar results with three times more discomfort in 2040 and five times more discomfort in 2080 in the average scenarios (A1B), see Figure 5.64.

The study with adaptive comfort is again limited by the presence of the number of days with outdoor running mean temperatures over 30 °C. Further studies shall be done to understand the applicability of this method beyond this limit. For now, by extending the formulas of adaptive comfort beyond that limit, the observed indoor temperatures could be considered within the adaptive limits, as shown in Figure 5.65.

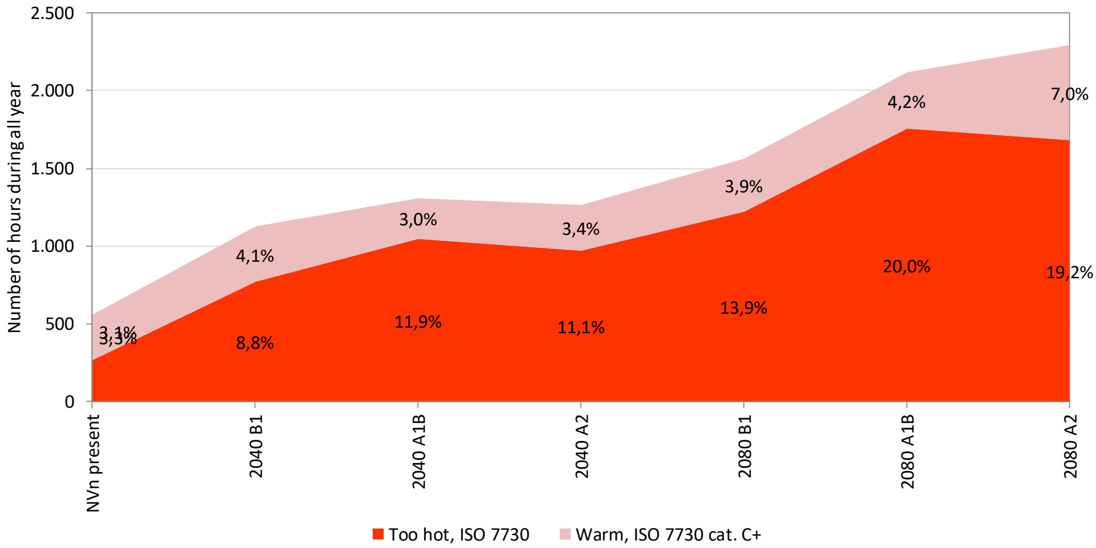


Figure 5.64. Evaluation of the future thermal comfort based on PMV method in detached house model, IPCC climates of 2040 and 2080 in Burgos, cold continental climate.

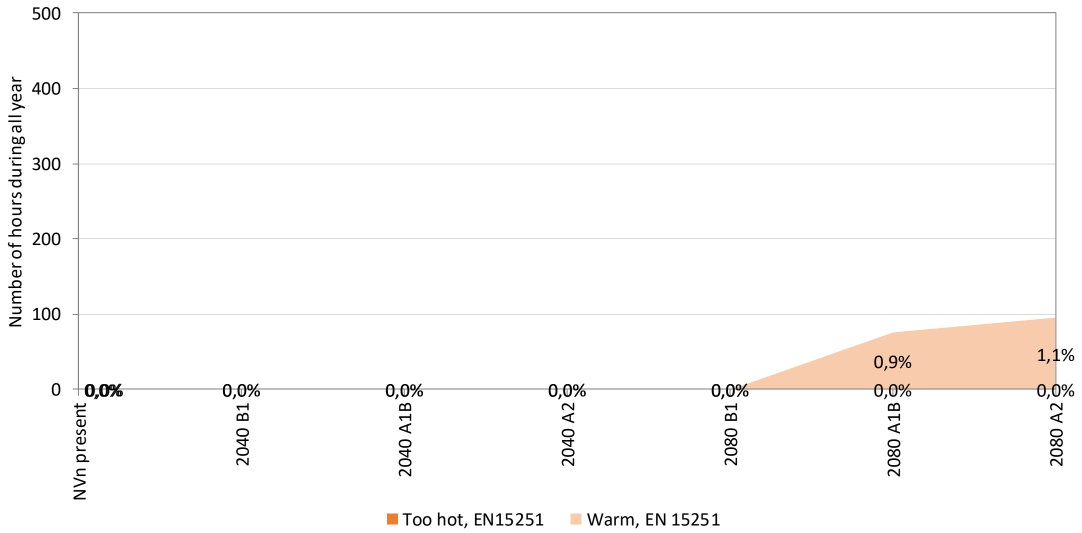


Figure 5.65. Evaluation of the future thermal comfort based on EN 15251 method applied for a detached house;
IPCC climates of 2040 and 2080 in Burgos, cold continental climate.

For more details, the results of indoor temperatures and thermal comfort are summarised in Table 5.26 and Table 5.27, respectively.

Table 5.26. Future changes due to global warming in Madrid; annual heating need and summer warm hours of detached case in warm continental climate.

Summer adaptation models	Annual heating demand (kWh)	Annual solar g. wind. (kWh)	Heating demand (kWh/ m²y)	Max. daily heating load (W/m²)	Num. hours t >25 °C	Annual hours t >25 °C (%)	Num. hours t >28 °C	Annual hours t >28 °C (%)
Limits PH	2190.0	-	15.0	10.0	876	10.0%	-	-
NVn present	2251.7	2675.3	15.4	9.2	1272	14.5%	80	0.9%
2040 B1	1989.0	2712.9	13.6	8.5	1519	17.3%	275	3.1%
2040 A1B	1813.9	2702.0	12.4	8.1	1664	19.0%	443	5.1%
2040 A2	1886.0	2731.4	12.9	8.5	1623	18.5%	400	4.6%
2080 B1	1755.2	2711.9	12.0	7.9	1799	20.5%	687	7.8%
2080 A1B	1356.7	2778.3	9.3	7.3	2182	24.9%	1277	14.6%
2080 A2	1232.2	2793.4	8.4	6.6	2349	26.8%	1115	12.7%

Table 5.27. Future changes due to global warming in Madrid. Summer thermal comfort summary. Warm discomfort assessed by ISO 7730 and EN 15251; detached case in warm continental climate.

Summer adaptation models	PMV ISO 7730 Cat. C+		PMV ISO 7730 Too hot		EN 15251 Cat. III +		EN 15251 Too hot	
	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %	Num. hours	Year %
NVn present	287	3.3%	269	3.1%	0	0.0%	0	0.0%
2040 B1	356	4.1%	768	8.8%	0	0.0%	0	0.0%
2040 A1B	264	3.0%	1046	11.9%	0	0.0%	0	0.0%
2040 A2	294	3.4%	972	11.1%	0	0.0%	0	0.0%
2080 B1	341	3.9%	1220	13.9%	0	0.0%	0	0.0%
2080 A1B	365	4.2%	1753	20.0%	76	0.9%	0	0.0%
2080 A2	614	7.0%	1679	19.2%	95	1.1%	0	0.0%

After the global assessments, the case of Madrid was analysed for a typical summer week, comparing the present thermal response with the forecasted future scenarios.

The near future scenarios of 2040 were compared in Figure 5.66, including the reference of one of the warmest weeks of the present summer. The values show small deviation from one scenario to another, and the differences are below 1 °C.

The situation in 2080 is expected to become more varied, depending on the ratio of global CO_2 emissions. According to these scenarios, the indoor temperatures might increase between 1 °C in the most optimistic scenario and 5 °C in the worst one. In the worst case, the cooling capacity during night hours is significantly reduced, as shows the Figure 5.67.

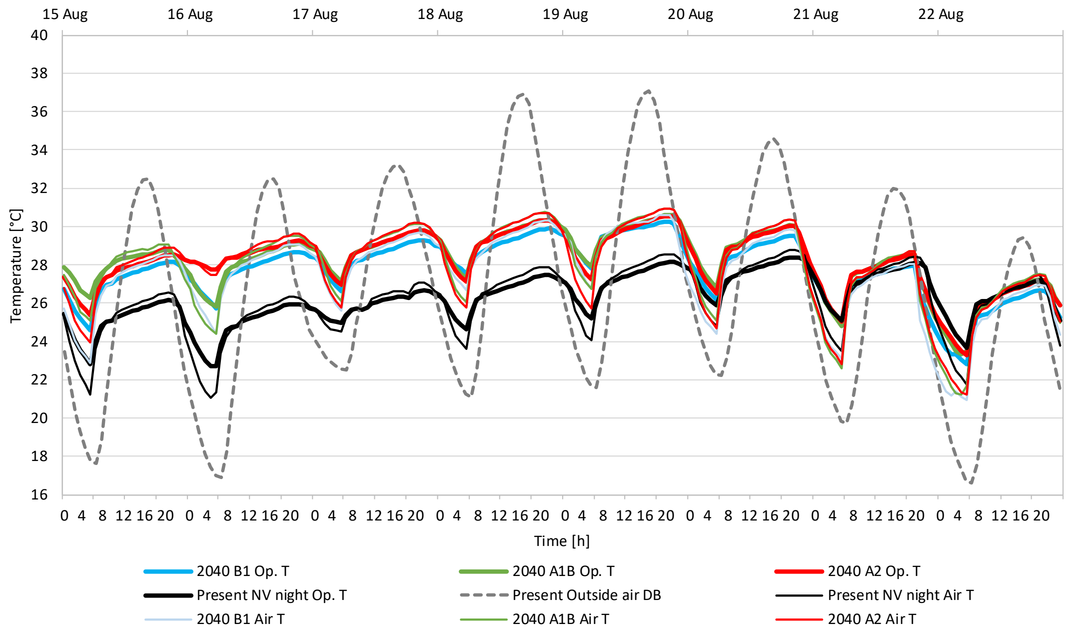


Figure 5.66. Comparison between scenarios of 2040 and present indoor temperatures with MVHR and enhanced summer bypass; detached house in Burgos, cold continental climate.

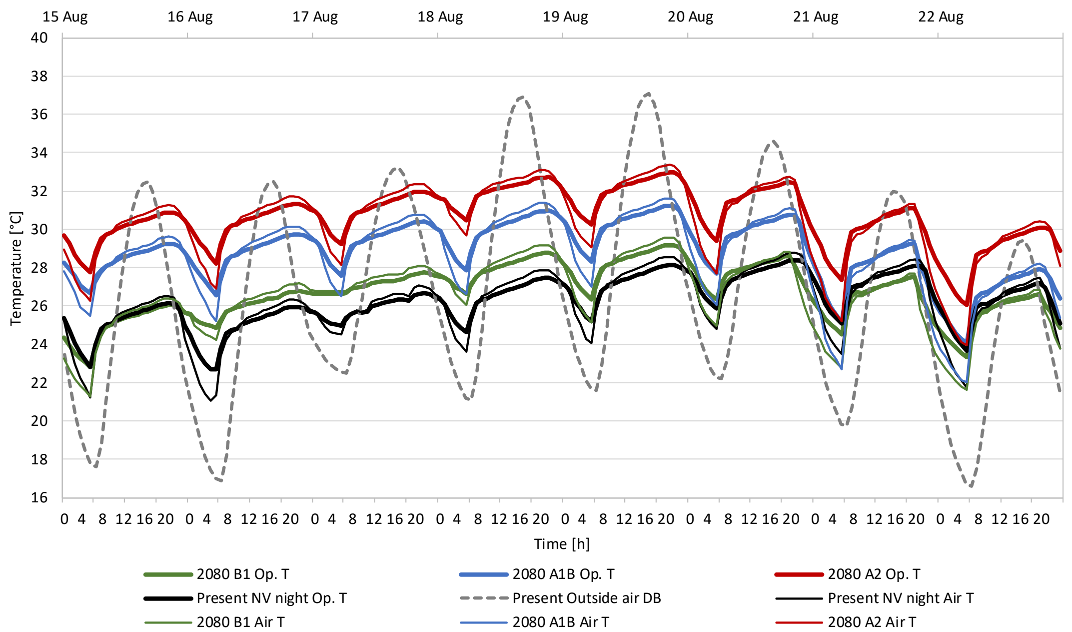


Figure 5.67. Comparison between scenarios of 2080 and present indoor temperatures with MVHR and enhanced summer bypass; detached house in Burgos, cold continental climate.

Additionally, a typical summer week of the different scenarios was plotted in Figure 5.68 and the monthly climate details can be viewed in Table 5.28.

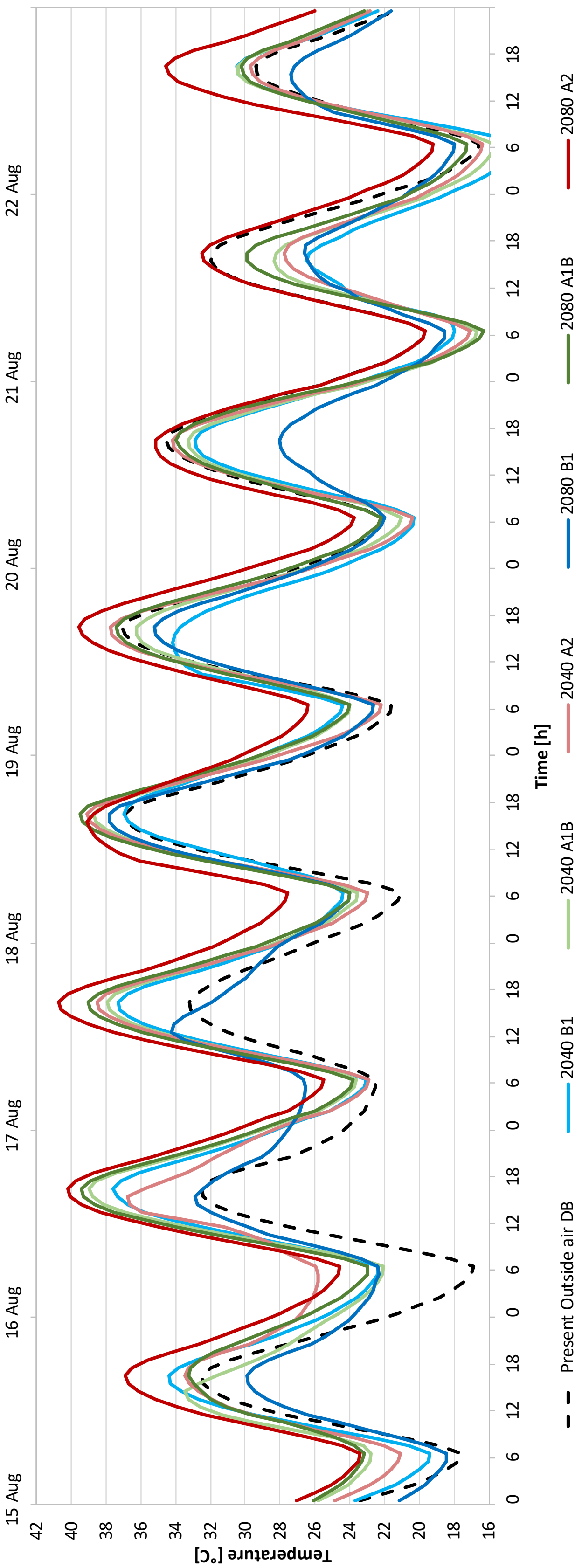


Figure 5.68. Example of outdoors temperatures in summer days based on different future climate scenarios in Madrid, warm continental climate (data source IPCC and Meteonorm).

Table 5.28. Monthly summary of future climate scenarios in Madrid, warm continental climate (data source IPCC and Meteonorm).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Present MADRID													
Monthly average DB temperature	5.2	6.7	10.3	12.2	17.0	22.9	25.7	24.9	20.0	14.8	8.5	5.5	14.5
Min. daily average DB temperature	-0.7	2.4	3.8	7.1	9.6	16.3	19.8	19.4	14.1	9.0	3.0	-0.8	-0.8
Max. daily average DB temperature	10.6	11.2	14.9	18.4	24.6	28.5	30.0	29.3	26.2	19.9	13.9	11.2	30.0
Monthly average Relative Humidity	5.2	6.7	10.3	12.2	17.0	22.9	25.7	24.9	20.0	14.8	8.5	5.5	14.5
Global horizontal solar radiation	132.6	138.3	205.8	234.5	261.8	291.2	321.9	286.4	227.3	163.6	125.7	101.1	2490.1
HDD (18.3)	407	325	249	185	71	4	0	0	15	113	294	398	2060
CDD (25.0)	0	0	0	0	0	17	46	32	1	0	0	0	96
2040 B1													
Monthly average DB temperature	6.4	7.5	10.4	12.6	17.3	22.0	26.6	26.1	21.7	16.1	9.8	7.1	15.3
Min. daily average DB temperature	0.6	0.2	3.9	7.5	9.9	15.4	20.7	20.6	16.1	10.5	4.3	0.8	0.2
Max. daily average DB temperature	11.8	11.5	15.0	18.7	25.0	27.7	30.9	30.5	28.0	21.3	15.1	12.9	30.9
Monthly average Relative Humidity	77.4	74.8	67.5	69.9	66.2	63.0	53.0	55.0	62.4	69.9	76.3	79.0	67.9
Global horizontal solar radiation	136.4	125.1	224.7	210.9	286.0	310.5	318.0	286.3	228.0	171.0	116.9	93.4	2507.5
HDD (18.3)	369	304	244	172	65	7	0	0	5	75	256	347	1846
CDD (25.0)	0	0	0	0	0	11	64	54	7	0	0	0	135
2040 A1B													
Monthly average DB temperature	6.7	7.8	10.7	12.9	17.7	22.4	27.3	26.7	22.4	16.6	10.2	7.4	15.7
Min. daily average DB temperature	0.8	0.3	4.2	7.9	10.2	15.9	21.4	21.2	16.7	11.1	4.7	1.1	0.3
Max. daily average DB temperature	12.1	12.1	15.3	19.1	25.4	28.1	31.7	31.1	28.7	21.7	15.7	13.2	31.7
Monthly average Relative Humidity	77.9	75.7	67.6	69.6	65.9	62.7	52.9	54.5	62.4	70.3	77.0	78.9	68.0
Global horizontal solar radiation	129.2	121.2	227.0	207.8	289.3	308.7	319.2	284.2	234.5	180.1	117.7	83.4	2502.2
HDD (18.3)	360	295	235	163	58	6	0	0	3	63	244	340	1768
CDD (25.0)	0	0	0	0	0	14	81	66	11	0	0	0	171
2040 A2													
Monthly average DB temperature	6.8	7.7	10.7	12.9	17.5	22.3	27.2	26.6	22.3	16.4	10.0	7.2	15.6
Min. daily average DB temperature	0.9	0.2	4.2	7.8	10.2	15.7	21.2	21.1	16.6	10.8	4.5	0.9	0.2
Max. daily average DB temperature	12.1	11.6	15.2	19.1	25.2	27.9	31.5	31.0	28.6	21.6	15.5	12.9	31.5
Monthly average Relative Humidity	78.1	76.0	67.4	70.4	66.1	62.3	52.7	54.4	63.1	70.0	77.0	79.4	68.1
Global horizontal solar radiation	138.4	122.6	228.1	215.5	288.9	311.4	317.9	286.4	228.6	176.9	119.3	90.9	2524.9
HDD (18.3)	359	298	236	164	62	6	0	0	3	68	249	345	1788
CDD (25.0)	0	0	0	0	0	12	78	64	10	0	0	0	165
2080 B1													
Monthly average DB temperature	7.0	7.9	11.0	13.1	18.3	23.0	27.8	27.3	22.9	16.9	10.4	7.7	16.1
Min. daily average DB temperature	1.1	0.6	4.5	8.1	11.0	16.5	21.9	21.8	17.2	11.4	4.9	1.4	0.6
Max. daily average DB temperature	12.4	11.8	15.6	19.4	25.9	28.7	32.2	31.8	29.2	22.1	15.8	13.3	32.2
Monthly average Relative Humidity	77.9	75.5	67.6	70.2	65.9	62.3	52.5	54.5	63.0	70.5	76.8	78.7	68.0
Global horizontal solar radiation	129.7	119.5	224.7	210.4	293.8	315.4	319.7	292.8	234.0	184.9	113.5	92.3	2530.6
HDD (18.3)	352	292	228	157	48	3	0	0	2	57	239	331	1709
CDD (25.0)	0	0	0	0	1	18	94	82	14	0	0	0	210
2080 A1B													
Monthly average DB temperature	7.7	8.8	11.8	14.2	19.6	24.5	29.5	29.1	24.4	18.3	11.3	8.5	17.3
Min. daily average DB temperature	1.9	1.4	5.3	9.2	12.2	18.0	23.6	23.5	18.7	12.8	5.9	2.2	1.4
Max. daily average DB temperature	13.2	13.7	16.3	20.5	27.2	30.2	33.9	33.5	30.7	23.4	16.7	14.3	33.9
Monthly average Relative Humidity	77.9	74.9	67.8	69.8	65.6	62.4	52.6	54.4	62.9	70.2	77.1	79.2	67.9
Global horizontal solar radiation	129.3	126.8	228.8	218.5	297.7	323.5	326.6	292.4	237.7	183.4	120.2	97.5	2582.3
HDD (18.3)	328	266	203	127	31	0	0	0	0	33	210	306	1503
CDD (25.0)	0	0	0	0	3	34	143	128	27	0	0	0	335
2080 A2													
Monthly average DB temperature	7.6	9.1	11.9	14.7	20.6	25.3	30.6	29.9	25.1	18.8	11.6	8.4	17.8
Min. daily average DB temperature	1.8	1.4	5.3	9.5	12.8	18.5	24.5	24.2	19.2	13.2	6.0	2.2	1.4
Max. daily average DB temperature	12.9	14.1	16.5	21.1	28.6	31.1	35.1	34.5	31.6	24.1	17.1	14.2	35.1
Monthly average Relative Humidity	80.2	76.7	69.1	71.4	66.4	63.0	53.1	55.0	63.6	70.7	77.3	79.3	68.8
Global horizontal solar radiation	133.4	125.6	231.3	218.7	298.7	322.6	326.4	295.5	238.2	185.1	117.4	95.4	2588
HDD (18.3)	334	258	201	123	29	0	0	0	0	32	205	308	1491
CDD (25.0)	0	0	0	0	3	35	148	132	27	0	0	0	346

5.9. Conclusions

The **average models of Spanish single-family passive houses were defined** (**objective 5.1**) through the details obtained in the review of the single-family passive houses in the country up to date. Three main cases were identified and during the tests a number of passive measures were implemented, including solar shading, orientation of the building and thermal mass.

The **analysis of the climatic areas showed large differences in the severities of winter and summer** in Spain (Álvarez & Molina, 2016) (Royal Decree 314/2006, 2006). As the present study was centred on the regions where the heating need is a driving force for building design, the Mediterranean climate was not considered in the study. In order to be able to represent such a wide range of local conditions between the Atlantic coast and the continental areas, the coldest, the warmest and an intermediate locations were selected (**objective 5.2**). This way, the study was focused on: (i) **Bilbao**, as a coastal area with Atlantic climate, (ii) **Burgos**, as a cold area with cold continental climate and (iii) **Madrid**, as a city with a considerable heating need and also a significant presence of cooling need.

The **winter performance** of the three models was evaluated with 5 different levels of thermal insulation of the envelope, using balanced thermal transmittance for the opaque elements, windows and thermal bridging. The results indicated that the requirements of passive house standard can be fulfilled in medium severity climates with approximately 15 cm in detached housing and 10 cm in attached housings. In the coldest area, these values would need a slight increase and would need 20 cm for detached housing and 15 cm for attached housing. This way, both the requirements for the heating demand and the heating load could be met with an average design (**objective 5.3**).

The summer performance of the selected models was improved with the implementation of several passive measures (**objective 5.4**). The results confirmed that **all the cases in the studied climates could completely avoid the use of active cooling**, if the proper combination of measures is selected.

The measures based on **ventilation** proved to have the highest capacity for passive cooling in all the locations. The best type of ventilation was found to be the use of long periods of natural ventilation during night hours. In combination with roof overhangs and certain amount of thermal mass, the natural ventilation could be sufficient in the three locations without the need for additional shading on windows. The use of the MVHR unit with enhanced airflow during summer bypass could be beneficious in certain locations as well, but due to its limited cooling capacity it always needed to be combined with solar shading measures on the windows. In a similar way, the use of short periods of natural ventilation was very limited. These two types of ventilation were insufficient to regulate the comfort for the hottest weeks and so they should be considered as a complementary measure in combination with other passive cooling elements, like solar shading or thermal mass.

The use of **solar shading** demonstrated to be critical in Madrid and Bilbao, which are in the intermediate and warm locations. Only in Burgos, according to the PMV method, solar shading was found possible to be removed while maintaining the warm discomfort hours below 3% of annual hours.. The passive cooling potential of roof overhangs was limited, but they proved to be useful in combination with thermal mass and natural ventilation strategies in all the locations. The use of automatic control for roller shutters didn't show a clear benefit in the studied models and for the purpose of the study they were finally considered all the day-time closed at 80% of global solar reflectance.

The use of **thermal mass** proved to be very useful to reduce the temperatures for the peak hours, reducing the too hot hours in combination with ventilation measures. However, the capacity to reduce the general trend of the indoor temperatures was very limited unless it was combined with long hours of night natural ventilation as a heat purge. In any case, the analysed increases of thermal mass were beneficious for all the tested present scenarios.

The assessment done with the **adaptive model** of EN 15251 confirmed the large advantages of natural ventilation and showed how the majority of the combinations of measures could provide an optimal thermal comfort 100% of the time following the adaptation principles suggested by the standard (direct access to windows, activity adjustment, clothing and so on). These aspects shall be more clearly stated for the future users of passive houses, which often apply only reduced natural ventilation ratios and rely mainly on the MVHR operation. This was also seen in the monitored performance of the passive house of the present study, presented and analysed in Chapter 3.

Regarding the **overheating detection** method of CIBSE TM52, Bilbao and Burgos presented similar results and low overheating risk, while Madrid presented considerably higher risk (**objective 5.5**). In these locations, the OH absence was considerably easy to achieve and it would be sufficient with the use of either natural night ventilation, roller shutters or any combination of the measures. In Madrid, the situation was found to be more complex, and to avoid the OH risk, the combination of several measures would be necessary. Thus, apart from the combination of solar shading and ventilation, it would also be necessary to implement a considerable thermal mass in the outer walls and in the floor levelling to control the peak hot hours.

Finally, with respect to the **future climate**, the selected cases confirmed a trend to increase the indoor temperatures in summer by about 1-2 °C by 2040 and around 2-5 °C by 2080. These increases can provoke considerable deterioration of the indoor environment and all the new designs should be aware of this reality, especially in warm continental areas like Madrid.

Based on the findings of the present study, there is evidence that single-family houses in Burgos and Madrid will likely have to implement additional measures or active cooling systems in the upcoming years. Unless these climate scenarios are applied in the early building design, frequent indoor temperatures over 30 °C may be faced in the continental climate.

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6. Conclusions and future work

This work presents a complete review of the adaptation possibilities of single-family passive houses to the cool-temperate climates of Spain. The study monitored an on-use passive house for more than a year, in order to quantify the potential and limitations of passive design in this climate. As several summer performance issues were detected, a number of feasible improvements of ventilation and solar shading were tested in a calibrated building energy performance simulation model (BEPS).

Later, these possible issues of local climate adaptation were analysed in some general cases extracted from the average features of Spanish passive houses built in recent years. The cases were analysed so that they would meet the principal passive house requirements and provide an excellent thermal comfort during all year, avoiding any risk of overheating. To reinforce the importance of this adaptation, the cases were tested again under the future climates of 2040 and 2080, and the capacity of the proposed measures was compared with the present results.

6.1. Research findings

To achieve the goal of the study and to fulfil the objectives, the following questions were raised and answered.

How can passive house design adapt to the cool-temperate climates in Spain, minimising the energy need and providing optimal comfort also in summer?

The results of the study indicate that in order to adapt to the studied climates, present passive house designs should rely on more detailed solar gain calculations and implement solar shading devices as a primary safety measure.

The use of natural ventilation should be encouraged, especially in the constructions with high thermal mass, because they need larger periods of heat purge. According to the results of the conducted simulations, the cooling capacity of the MVHR units with summer bypass in housing buildings is too low for the studied climates.

Is the performance of the passive house as good as it was expected, considering the heating operation, the performance of the thermal envelope, the operation of ventilation and the thermal comfort?

The overall performance of the monitored passive house was positive. The measurements proved a very low energy demand of 17.6 kWh/m² with a slightly higher consumption than the PH limit. The initial heating system based on the pellet stove caused a gradient of temperatures among the rooms, especially in those ones which were farther away from the heat source. This problem was solved after the monitored period with the installation of supplementary electric heaters in the opposite side of the house.

The study of the thermal envelope verified a high level of thermal insulation and a good quality of construction. The heat losses were quantified with direct measurements and the infrared thermography survey permitted the identification of moderate thermal bridges located mainly in the ground contact of the building walls.

The MVHR unit demonstrated a good performance with good air distribution and a high recovery ratio of 86% of the sensible heat. The operation of the bypass was able to provide enough free-cooling during the majority of summer days.

The full-year thermal comfort assessment based on PMV model indicated that 95.9% of annual hours the house was in acceptable values of temperature and RH. On the contrary, 3.7% of the hours the house was too warm, in other words, for 13 summer days. The assessment based on the adaptive method of EN 15251 showed some hours close to the upper limit, but the recorded temperatures didn’t mean any relevant discomfort. Thus, the occasional natural ventilation periods applied by the inhabitants to cool down the indoor was advantageous but insufficient to decrease significantly the indoor temperatures inside the PMV range.

Would it be possible to implement non-invasive measures in the monitored passive house in order to reach an optimal thermal comfort during winter and summer without increasing the energy demand?

The implementation of additional solar shading and ventilation measures demonstrated to be sufficient to provide an optimal thermal comfort during all the year.

The tested ventilation improvements indicated that the best option would be to apply natural ventilation during the night-time. The use of the MVHR with enhanced summer bypass at higher airflow would be insufficient to decrease the indoor temperatures due to its limited airflow, and the use of short periods of natural ventilation only during evenings would be also insufficient to cool down the house during the hottest days.

The use of supplementary lightweight solar shading devices outside the windows could contribute to a significant reduction of the too-hot hours, but it would still need additional ventilation measures during the majority of the summer. This is probably related with the high thermal mass of this case study, which required considerable periods of ventilation to reduce the indoor temperatures.

Which passive cooling measures would be more appropriate to be installed in this housing typology to reach an optimal thermal comfort during winter and summer in the cool-temperate regions of Spain?

The measures based on ventilation proved to have the highest capacity for passive cooling in all the locations. The implementation of the most common passive measures into average typologies indicated that the PH limit of 10% of the hours above 25 °C is only reachable in the cold continental climate (e.g. Burgos). The other climates, namely warm continental climate (e.g. Madrid) and Atlantic climate (e.g. Bilbao), have considerably more difficulties to reduce the indoor temperatures and would require additional design changes.

Regarding the typologies, the houses with their main openings to South wouldn't need any solar shading measures on the windows and they could achieve the optimal thermal comfort only with night-time natural ventilation, roof overhangs and a small amount of thermal mass in the floors. On the contrary, the cases with significant openings in the West side of the house or the ones with low thermal mass would always require the solar shading of windows to be able to maintain the indoor comfort conditions. In many cases and locations, the use of high thermal mass could substitute the need of supplementary shading, but it could also maintain the indoor high temperatures if the users don't use the natural ventilation frequently enough.

The study also determined the minimum levels of insulation. In the Atlantic areas and the warm continental areas they were determined as 10 cm and 15 cm for the attached and detached houses respectively, while in the cold continental areas they were calculated as 15 cm and 20 cm respectively. On the other hand, the higher insulation levels showed subtle increases of the cooling need when increasing the thermal insulation together with double glazing. However, the cooling need was again reduced with the use of triple glazing which proved to cut down significantly the solar gains through the windows.

The simulations with future climates evidenced a very significant increase of indoor temperatures by about 1-2 °C in 2040 and by 2-5 °C in 2080. Therefore, the present designs should be calculated with a larger margin of security to be able to adapt to the upcoming climate.

6.2. Future work

The future work arising out of this research is discussed by topics:

Regarding the **thermal comfort**:

- Compare the differences between the methods to identify the cold and warm seasons depending on the type of building, considering the type of use and the level of thermal insulation.
- Conduct an enquiry among the inhabitants of passive houses, to investigate the habits of internal activity and the possible local adaptation to warm conditions with running mean temperatures over 30 °C.
- Analyse the impact of lower internal gains in the future designs.

Regarding the **ventilative cooling**:

- Quantify the ventilative cooling potential for all regions in Spain, applying the methods outlined in (Kolokotroni & Heiselberg, 2015).
- Evaluate the cooling effect by different possibilities of window openings as a guide for inhabitants about how to apply effective ventilation routines.
- Study the cost-benefit of implementing automatic controls for the natural ventilation.
- Study the existing models for real thermal mass activation in low energy houses.

Regarding the **solar shading**:

- Analyse the potential of advanced solar shading measures to improve TC, such as venetian blinds with programmable angles.
- Calculate the impact of solar shading operation schedules on indoor environment in a low energy demand housing with average features and indoor activity levels.

Regarding the **passive design**:

- Calculate the potential of the porch to harvest additional solar gains with an automatic control.

Regarding the **active systems**:

- Investigate the cost-efficient heating systems which can adapt better to the needs and features of this typology.

Regarding the **building monitoring**:

- Analyse the measured data to provide guidelines about the minimum number of sensors necessary in the future low energy housing monitoring.

Nomenclature, list of abbreviations and acronyms

ACH	Air Changes per Hour
BDT	Blower Door Test
BEPS	Building Energy Performance Simulation
CCP	Climatic Cooling Potential
CDD	Heating Degree Days (base temperature of 25.0 °C)
CHTC	Convective heat transfer coefficient
CNV	Controlled Natural Ventilation
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DHW	Domestic Hot Water
DRT	Dry-Resultant Temperature
EPC	Energy Performance Certificate
GSHP	Ground Source Heat Pump
g-value	% of solar radiation transmittance through glazings
HDD	Heating Degree Days (base temperature of 18.3 °C)
HPSU	Heat Pump Solar Unit
HR	Heat recovery
IEQ	Indoor Environment Quality
MBE	Mean Bias Error
MVHR	Mechanic Ventilation with Heat Recovery
NV	Natural Ventilation
OH	Overheating
PE	Primary Energy
PHI	Passive House Institutw
PHPP	Passive House Planning Package
PMV	Predicted Mean Vote (Fanger method of ISO 7730)
POE	Post-Occupancy Evaluation
PPD	Percentage of Dissatisfied (Fanger method of ISO 7730)
PVC	Passive Ventilative Cooling
RH	Relative Humidity
RMT	Running mean temperature (EN 15251)

SAP	Standard Assessment Procedure
SBEM	Standard Building Energy Model
TC	Thermal Comfort
TRM	Running mean outside temperatures (adaptive method of EN 15251)
U	Thermal transmittance
VC	Ventilative Cooling
Ψ	Linear thermal transmittance of thermal bridges

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APPENDICES

Appendix I. Extended file of the monitored data

Additional climate data of the location of the case study between 2012 and 2015:

Years	Average daily method		ASHRAE method		EUROSTAT method	
	HDD 18.33	CDD 18.33	HDD65	CDD65	HDD	CDD
2012	2666.88	171.66	2590.83	227.97	2404.55	227.97
2013	2695.73	138.49	2633.49	174.67	2462.88	174.67
2014	2263.76	82.99	2261.64	133.47	2073.04	133.47
2015	2516.53	176.47	2399.88	220.88	2195.30	220.88

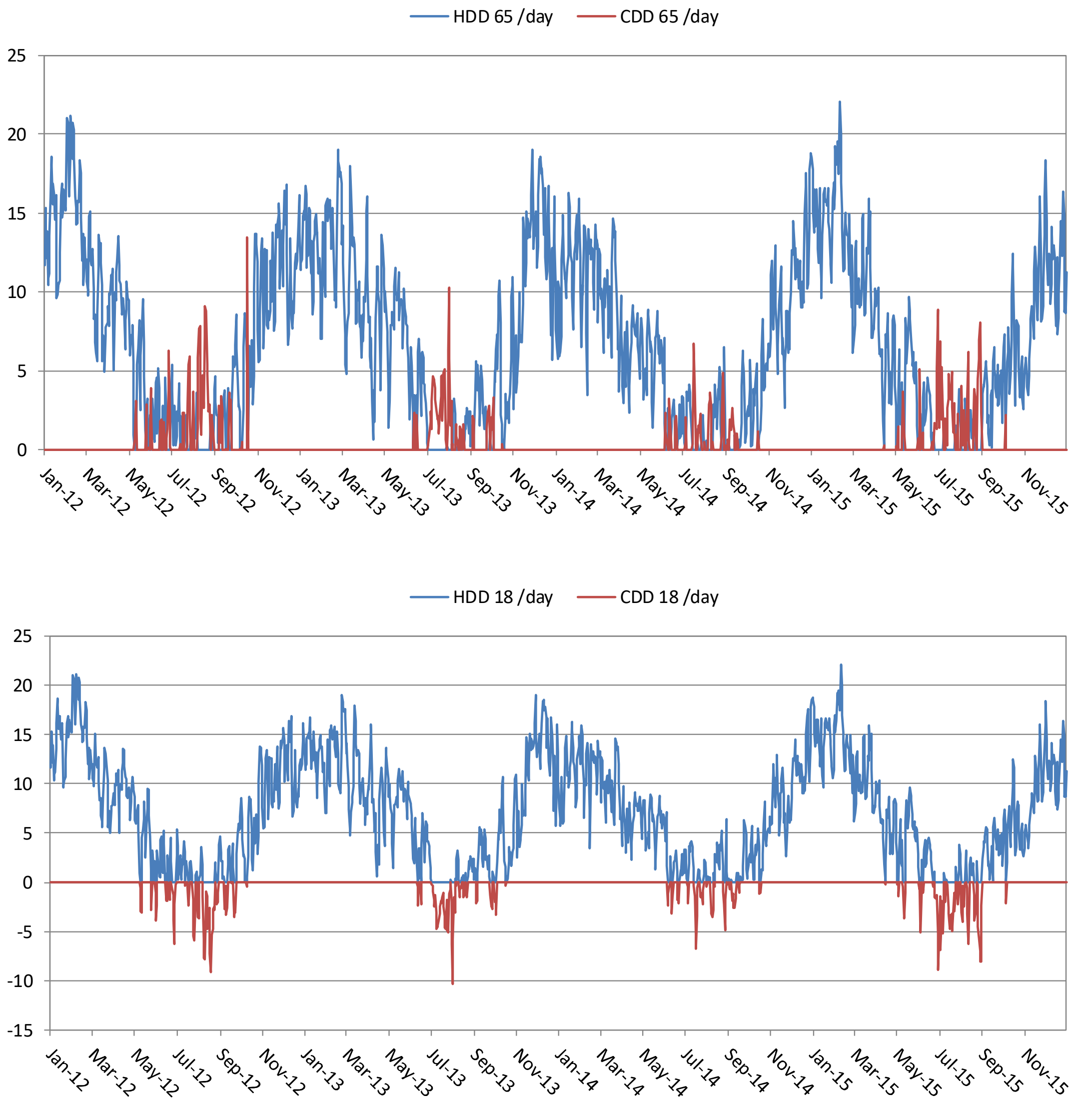

Figure I. 1. Daily HDD and CDD of the location of the case study.

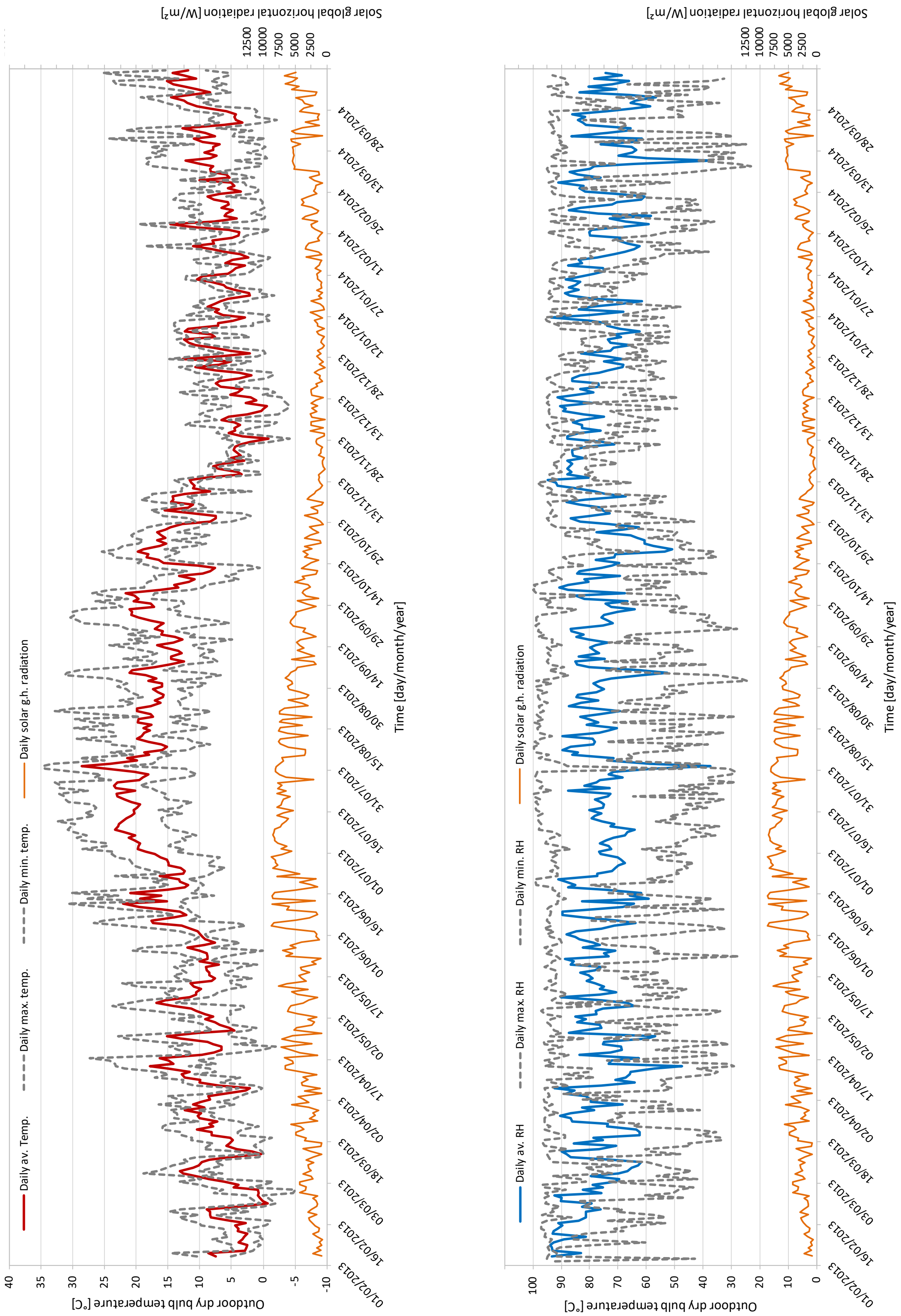

Figure I. 2. Measured outdoor air conditions and solar global horizontal radiation, air dry bulb temperature (left side) and relative humidity (right side).

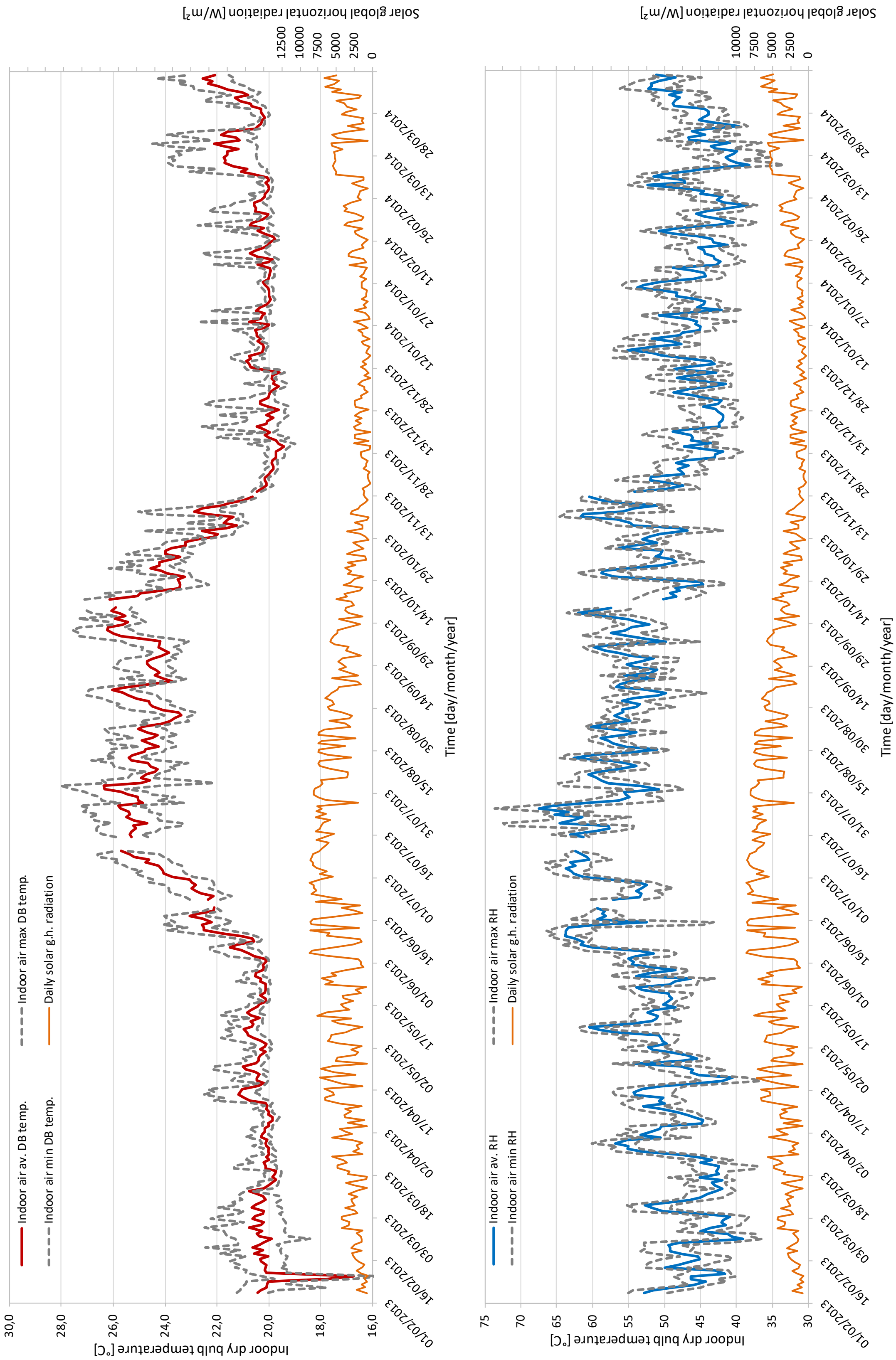

Figure I. 3. Measured indoor air conditions of the case study,
average air dry bulb temperatures (left side) and average relative humidity (right side).

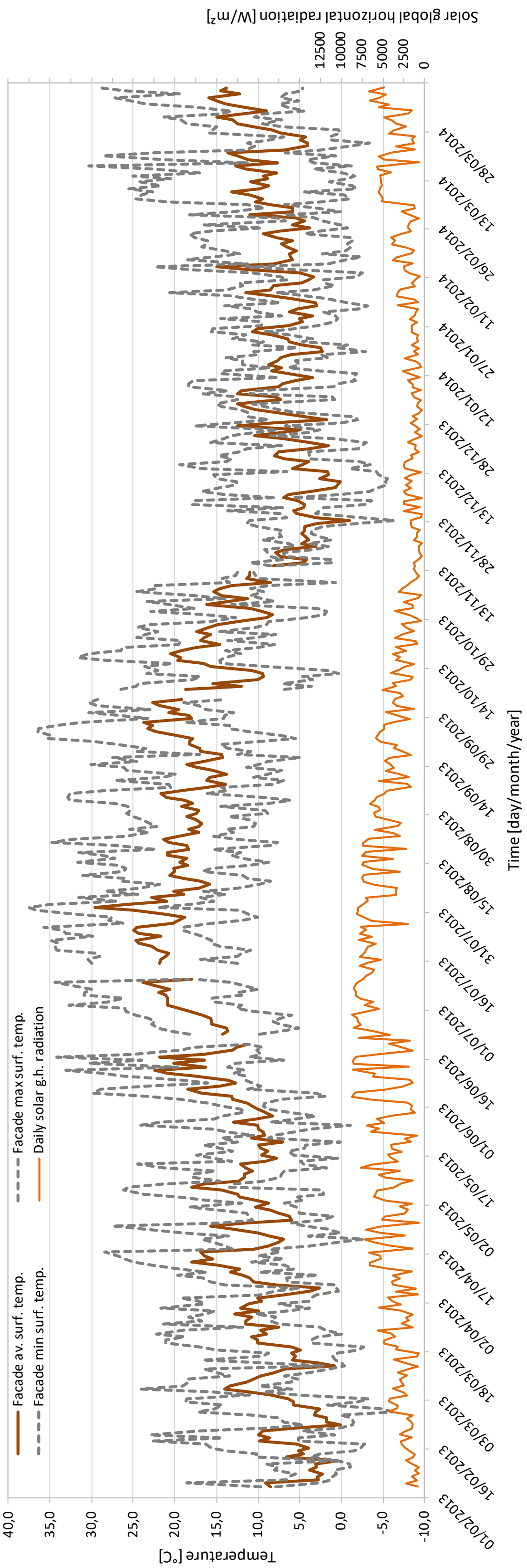

Figure I. 4. Measured façade outside surface temperatures, average of North, South, East and West facades.

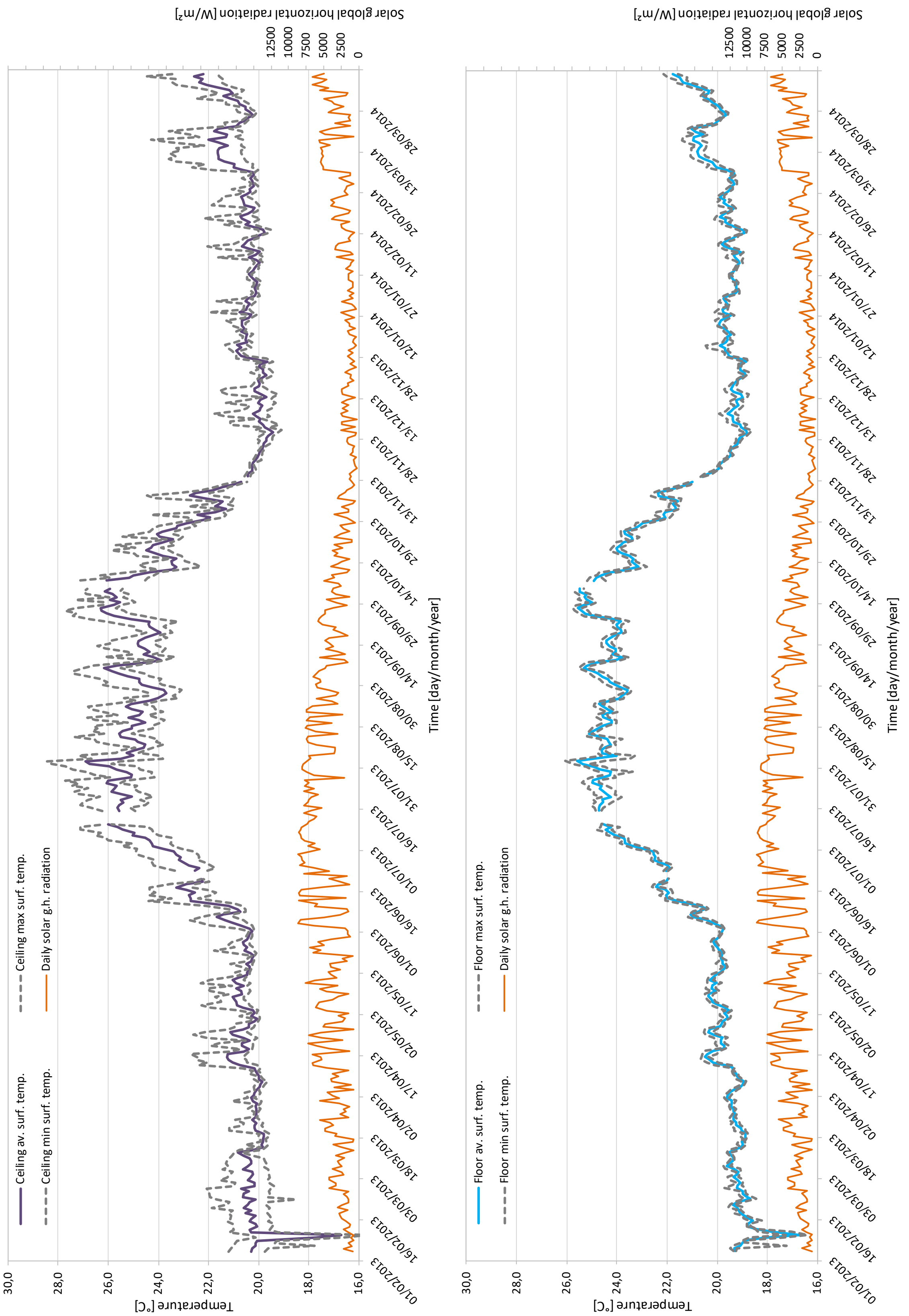

Figure I. 5. Measured ceiling surface average temperatures (left side)
and floor surface average temperatures (right side).

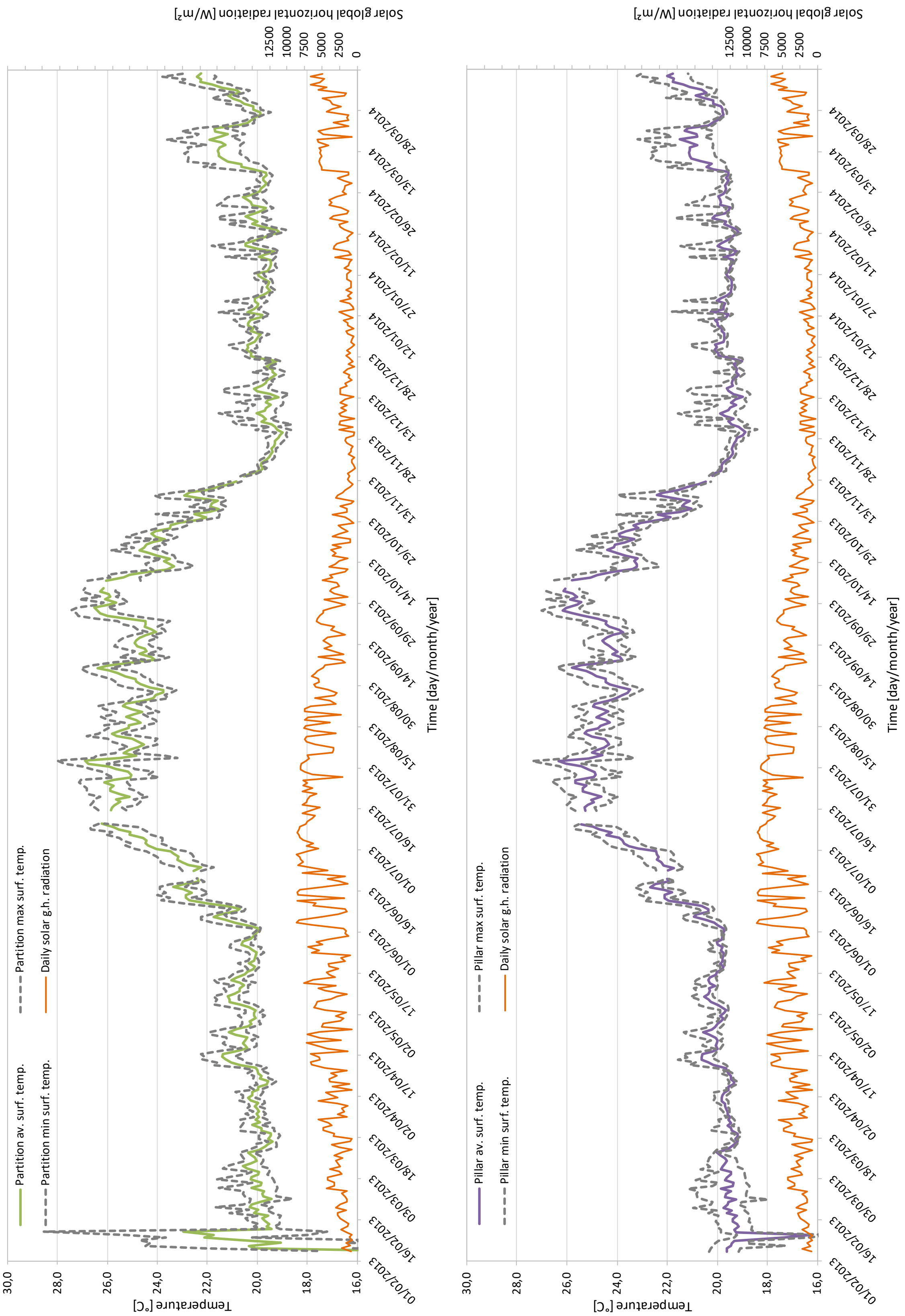

Figure I. 6. Measured partitions surface average temperatures (left side) and columns or pillars surface average temperatures (right side).

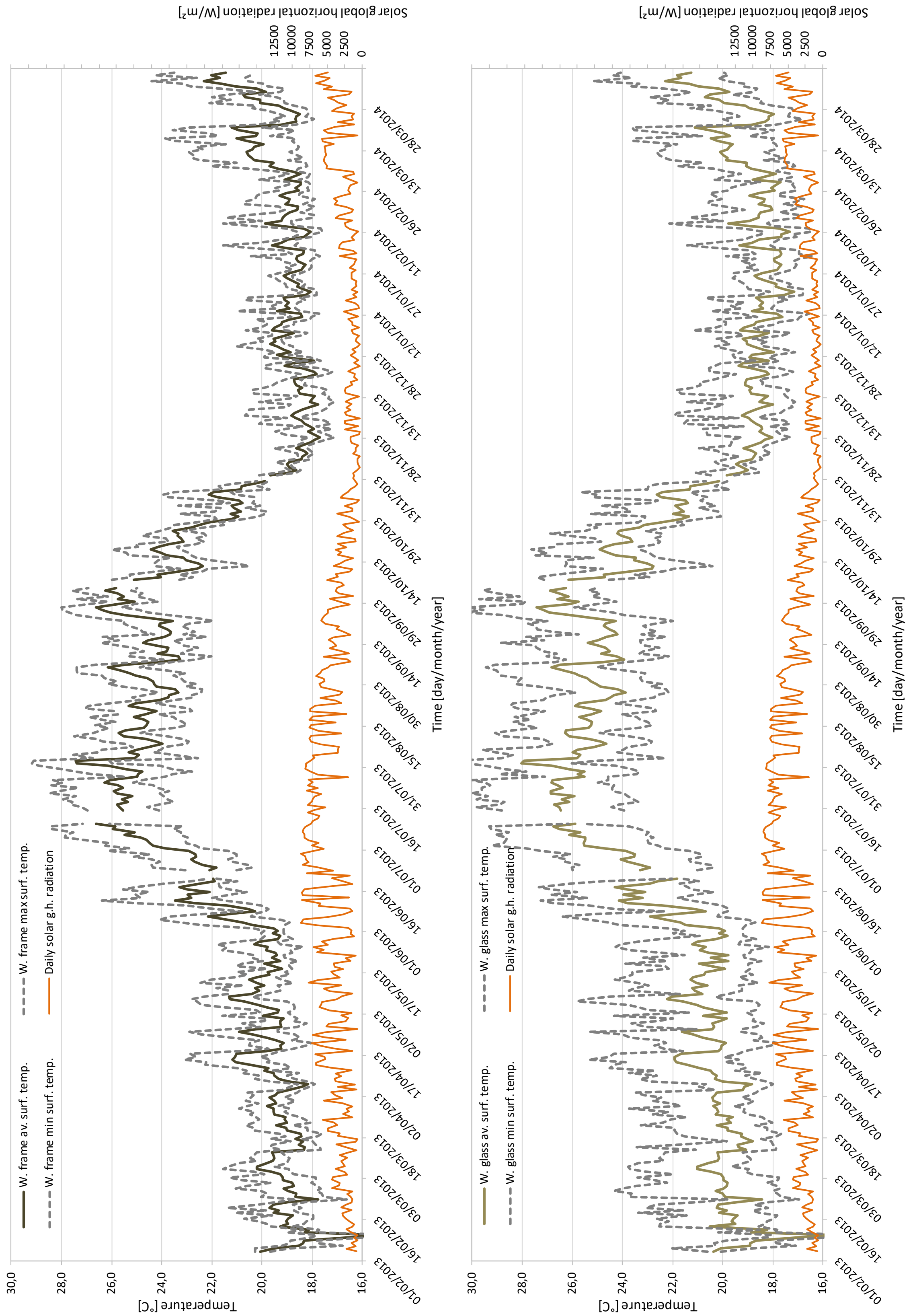

Figure I. 7. Measured north window frames surface average temperatures (left side) and window north glass surface average temperatures (right side).

Heater systems comparison:

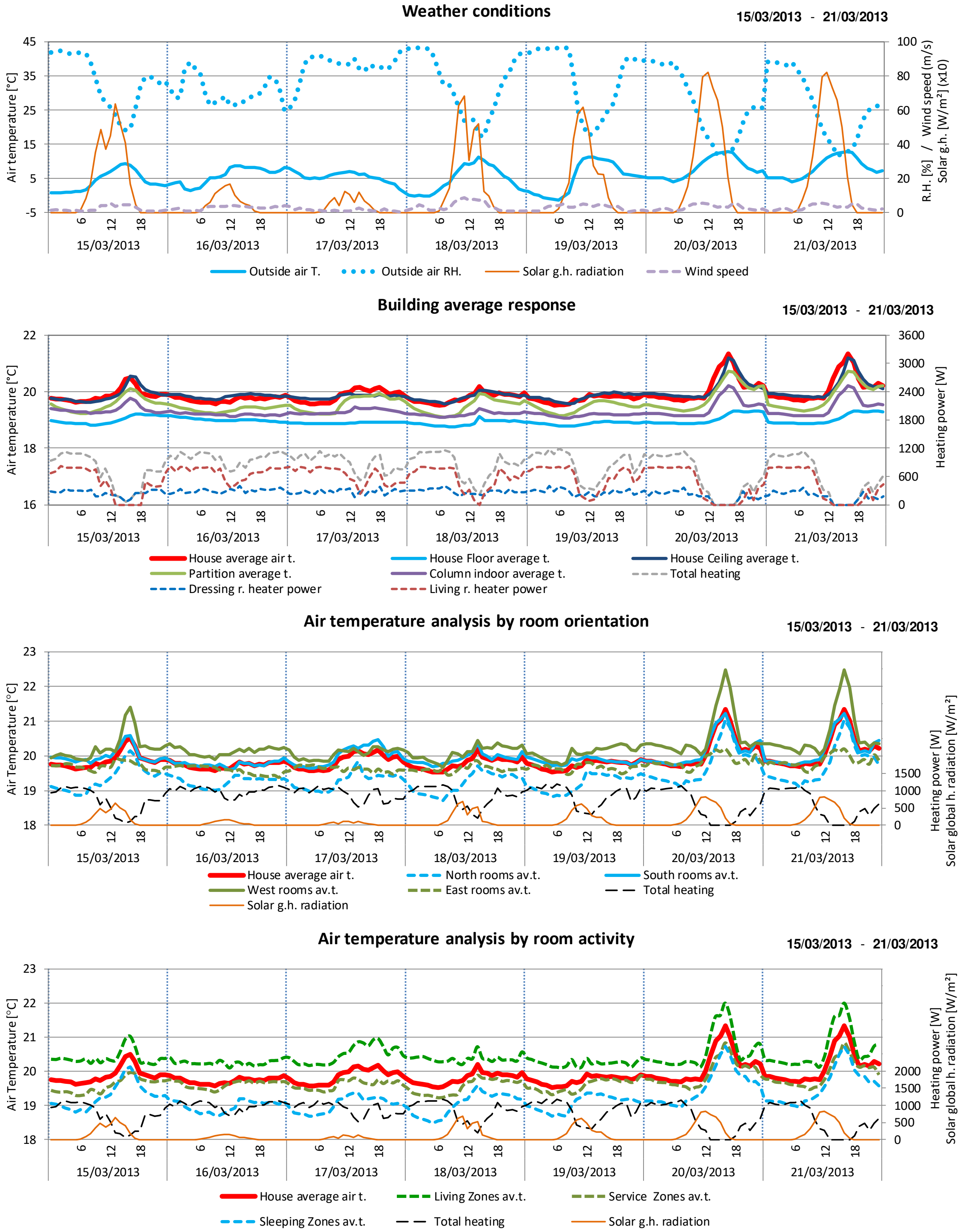

Figure I. 8. Measured thermal response of the house with distributed electric heaters.

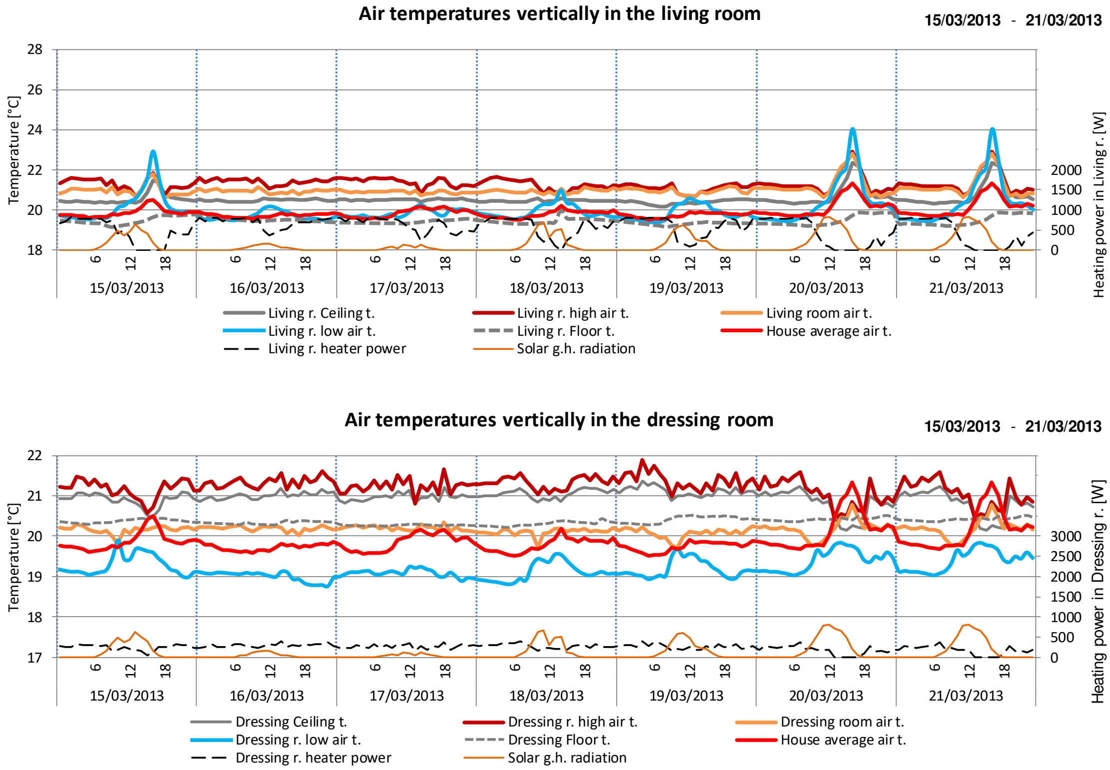

Figure I. 9. Measured air stratification with distributed electric heaters.

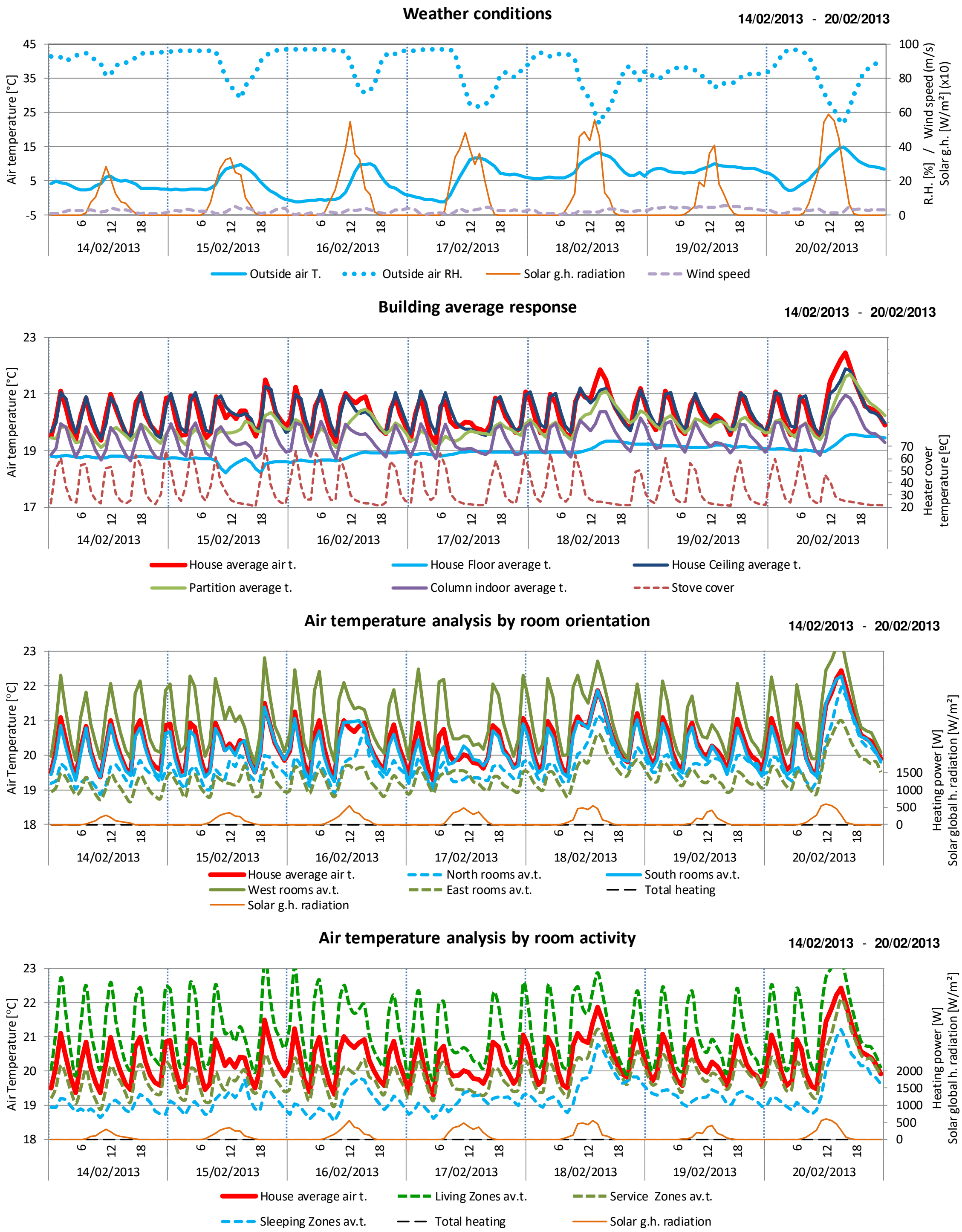

Figure I. 10. Measured thermal response of the house with pellet stove heating.

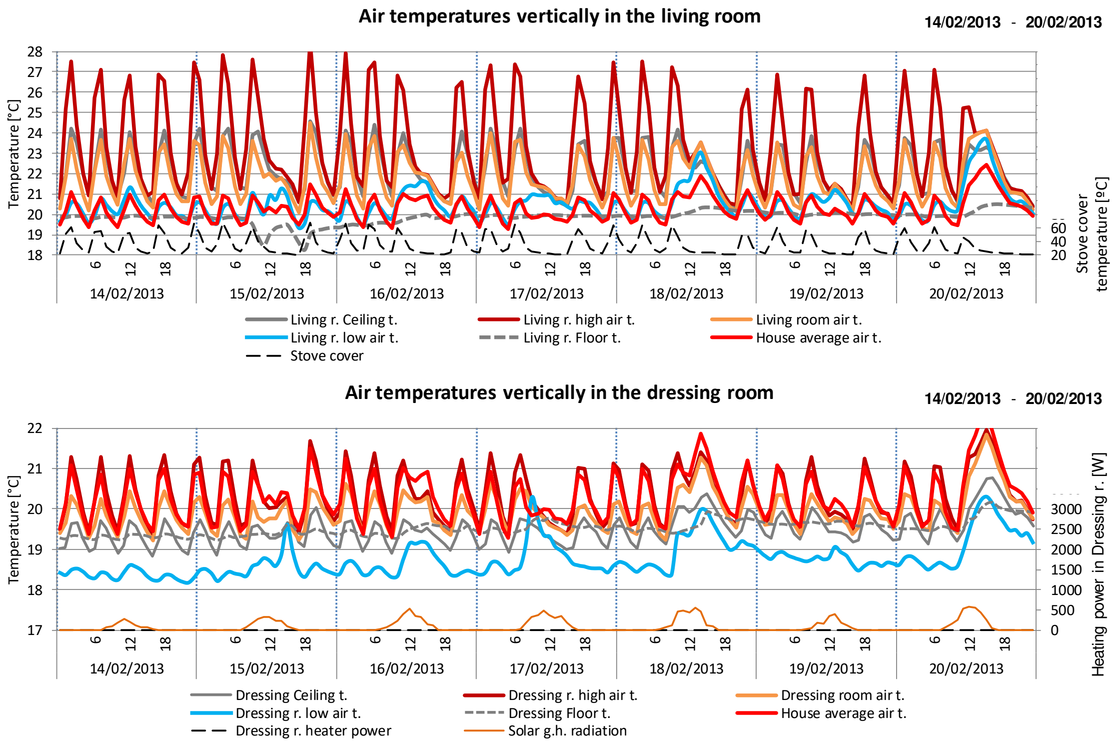

Figure I. 11. Measured air stratification with pellet stove heating.

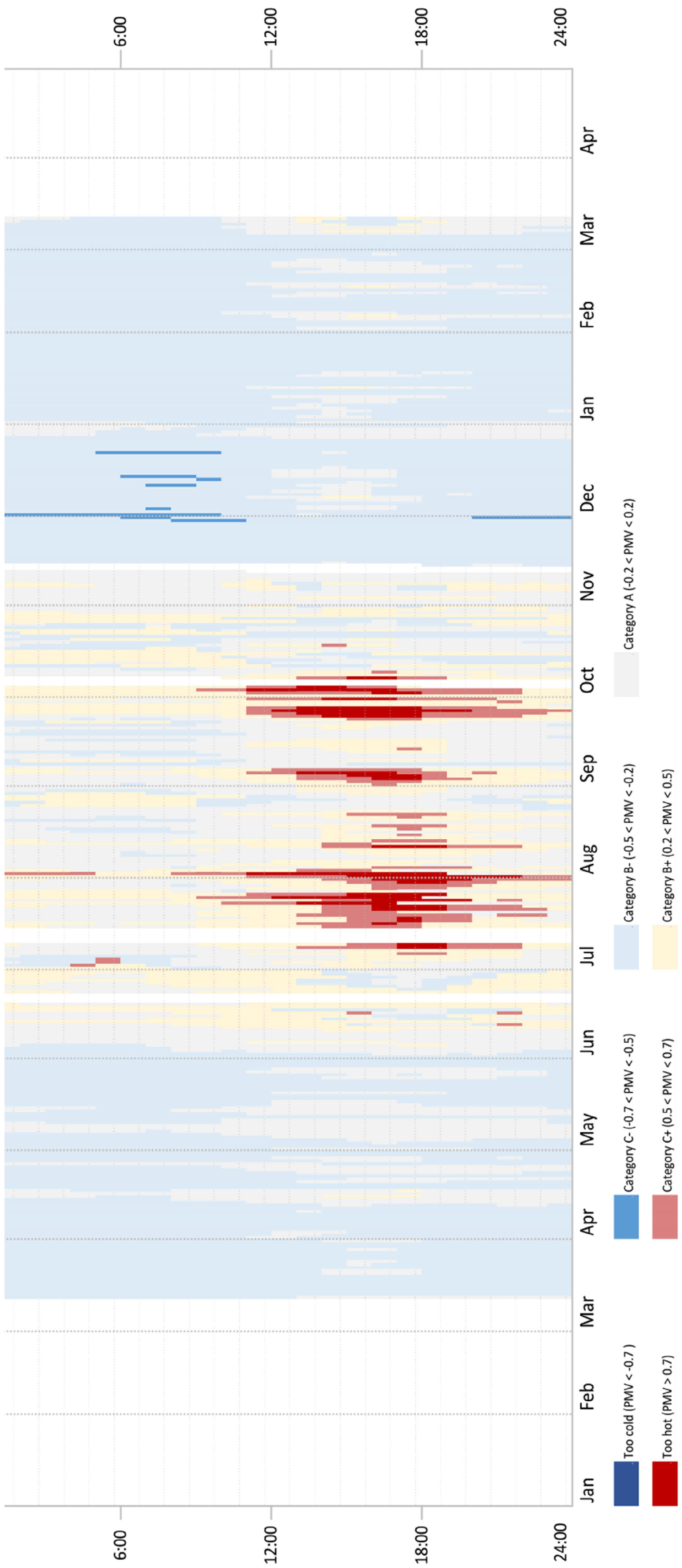

Figure I. 12. Monitored year of thermal comfort in average house, hourly diagram of PMV method.

Additional images of the case study and the installation of the sensors:

Figure I. 13. Monitored house view of the Northwest corner.

Figure I. 14. Monitored house view of the Southeast corner.

Figure I. 15. Detail the pellet stove heating on-use (right side).

Figure I. 16. Detail of the meteorological station used during the monitoring.

Figure I. 17. Details of the monitoring installation process, living room air sensors.

Figure I. 18. Details of the monitoring installation process.

Appendix II. List of single-family passive houses built in Spain

Table II. 1. List of single-family PH dwellings in Spain, part 1 of 4 (data source PEP & PHI, 2017)

House name	Vivienda ASSYCE-Ecoholística 1	House in Lleida	Casa Bunyesc Arboretum	Prototype ASSYCE-Ecoholistic 2	Casa Farhaus AF1	Casa Eficient MZ	Rehabilitación La Floresta	Casa Arias	Casa Jade y 2 más	Casa EntreEncinas	Villa ana	Casa Arcones	Larixhaus
Year of construction	2009	2009	2009	2010	2010	2011	2011	2011	2012	2012	2012	2013	2013
Location	Moraleda de Zafayona, Granada	Lleida	Lleida	Escuzar, Granada	Castellterçol, Barcelona	Barcelona	San Cugat del Vallés, Barcelona	Roncal, Navarra	Jungitu, Álava	Villanueva de Pría, Asturias	Santiago de Compostela, A Coruña	Arcones, Segovia	Collsuspina, Barcelona
Elevation	616	167	167	866	726	13	124	720	518	< 100	260	1151	901
Climate zone (Spanish CTE classes)	C3	D3	D3	D3	D1	C2	C2	E1	D1 - E1	C1	D1	D2	E1
Passive House Institute ID	1690	1998	2116	2300	2780	2650	2412	2055	2620	2413	4056	3794	3874
Description	First Spanish PH certified building. Built with recycled ISO containers	Biomaterials, positive CO2 balance, PV panels, price below 1000 €/m2	Biomaterials, positive CO2 balance, PV panels, price below 1000 €/m2	Prototype home recycling ISO containers	PEFC wood materials, preconstructed components, positive CO2 balance	First Spanish Rehabilitated PH certificate. 10 factor rehabilitation	Refurbishment and extension of a traditional masonry house	traditional style, wooden structure clad with stone	Conventional materials and concrete structural solutions	Bioconstruction design, wooden CLT panels	Mixed structure with wood walls and concrete slabs. BREEAM certified	Renovation and enlargement of old construction from 1888, EnerPhit	First Spanish prefabricated straw bale passive house
Typology	detached	semi-detached	detached	Detached	detached	semi-detached	detached	detached	detached	detached	detached	semi-detached	detached
Number of floors	2	2	2	1	2	1	3	2	1	2	2	2	2
Net floor area [m²]	98	250 (2 apartments)	176	61	125	68	247	185	176	133	675	156	92
Structure materials	Steel, concrete	Wood	Wood	Mixed	Wood	ısonry, wood, concr	Wood	Wood	Masonry, concrete	Wood	Concrete, wood	ısonry, wood, concr	Wood
Type of construction	New	New	New	New	New	Renovated	Renovated	New	New	New	New	Renovated	New
Passivhaus certified	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	No	No	Yes
Thermal mass	Medium	Low	Low	Low	Low	Medium	Medium	Low	High	Low	Medium	High	Low
U wall [W/(m²K)]	0,090	0,200	0,22	0,127	0,124 - 0,156	0,195	0,218	0,170	0,140	0,200	0,225	0,142	0,146
U ground [W/(m²K)]	0,185	0,370	0,35	0,237	0,250	0,371	0,349	0,200	0,160	0,240	0,186	0,178	0,164
U roof [W/(m²K)]	0,100	0,150	0,15	0,144	0,146	0,159	0,152	0,230	0,110	0,190	0,163	0,118	0,147
Window U [W/(m²K)]	1,030	1,650	1,65	0,880	1,100	1,400	1,400	1,040	0,900	1,270	0,820	0,800	1,090
Frame U [W/(m²K)]	-	1,400	-	-	1,000	1,060	-	-	1,070	1,300	1,200	-	1,240
Glass U [W/(m²K)]	0,750	1,200	1,2	0,700	1,100	1,100	0,500	0,700	0,600	1,100	0,500	0,800	0,600
Window g-value	0,5	0,22	0,65	0,50	0,52	58,0%	0,49	0,51	0,50	0,58	0,45	0,70	0,47
Window frame material	PVC	Wood	Wood	Wood	Wood	Wood	Wood	Wood	Wood-aluminium	Wood	Aluminium	-	Wood
ACH 50 Pa [h⁻¹]	0,59	1,00	1,00	0,43	0,60	2,10	1,50	0,36	0,21	0,39	-	-	0,32
MV maximum air flow (m3/h)	250	150	150	150	370	200	150	250	300	370	950	-	370
HR sensible eff. [%]	92%	-	-	90%	90%	95%	-	92%	95%	90%	92%	-	90%
HR PHI method [%]	83%	85%	85%	86%	80%	88%	85%	83%	89%	84%	67%	-	79%
Bypass	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes
Heating systems	HP	Radiant floor	Radiant floor	HP	Air HP	Air post-heater	Radiant floor, radiators in bathrooms	Air, GSHP	Stand-alone pellet stove	Air post-heater and stand-alone wood stove	GSHP, radiant floor	Radiant floor, radiators in bathrooms	electric radiators, biomass stove
Cooling systems	HP	No	No	HP	-	No	No	No	No	No	No	No	No
DHW generation	HP, thermal 70%	Storage heater, solar	condensing gas boiler, solar	electric, 86 % solar	HP	Solar	condensing gas boiler, solar	GSHP	HP SU	solar thermal 100%	GSHP and solar panels	biomass boiler, solar thermal	HP
Heating thermal power [kW]	-	-	-	-	4,5	-	-	-	2,4 - 9	-	-	-	3,6
Hot water storage [l]	300	-	-	300	150	-	-	170	300	500	-	-	300
Solar harvesting	thermal 4,4 m²	thermal panels	thermal 6 m²	thermal 4,9 m²	No	thermal 2,4 m²	thermal 4,5 m²	No	thermal 2,4 m²	6,9 m2 solar collectors	Solar thermal panels	thermal panels	No
Other devices	-	Canadian well	-	-	-	-	-	-	-	-	-	-	-
Annual heating demand [kWh/m²a]	3,0	8,5	7,0	-	13,0	18,0	9,0	14,0	13,0	12,0	22,0	33,0	15,0
Heating load, daily average [W/m²]	11,4	12,0	13,0	-	12,0	17,0	15,0	12,0	9,0	11,0	10,0	18,0	11,0
Annual cooling demand [kWh/m²a]	1,0	0,0	0,0	-	0,0	15,0	0,0	0,0	0,0	0,0	-	11,0	0,0
Cooling load, daily average [W/m²]	3,0	0,0	0,0	-	0,0	12,0	0,0	4,0	0,0	0,0	12,0	4,0	0,0
Primary Energy annual use [kWh/m²a]	68,0	25,0	52,0	-	107,0	81,0	51,0	81,0	67,0	116,0	119,0	82,0	95,0
Construction costs / treated floor	-	1100,0	1100,0	-	1200,0	1204,0	-	-	-	-	-	-	1083,0

Table II. 2. List of single-family PH dwellings in Spain, part 2 of 4 (data source PEP & PHI, 2017)

House name	Casa Arkarats	SBAY house	Casa Centón	House in Sevilla	Casa José Luis	Casa El Plantío	Casa 100x100madera	PassivPalau	House in Grañén	Casa La Vega	Casa MM	Casa Passivhaus en Agoncillo	Proyecto Tierra
Year of construction	2013	2014	2014	2014	2014	2014	2014	2014	2014	2014	2014	2014	2014
Location	Azcona, Navarra	Trokoniz, Álava	Santander, Cantabria	Sevilla	Guadalix de la sierra, Madrid	Carrión de los Condes, Palencia	Guadalix de la sierra, Madrid	Palau-Solità i Plegamans, Barcelona	Grañén, Huesca	Vega de Poja, Asturias	Génova, Islas Baleares	Agoncillo, La Rioja	Llucmajor, Islas Baleares
Elevation	621	634	8	11	832	838	832	140	332	269	120	346	151
Climate zone (Spanish CTE classes)	E1	E1	C1	B4	D3	D1	D3	C2	D3	D1	B3	D2	B3
Passive House Institute ID	4791	4763	4118	4162	4238	2910	4264	4378	4454	4441	4459	4500	4717
Description	Traditional design with a canadian ground air exchanger	Traditional design with timber construction and CLT panels	Renovation by stages with conventional materials, it is a Case Study building in EuroPHit project.	Andalusian traditional terraced-patio, greenhouse and evaporative cooling	Prefabricated CLT components, 56 days of construction	CLT walls, prefabricated elements	Timber frame construction, bioconstruction, based on Kuusamo design	Prefabricated wood walls with external insulation	Constructed with conventional heavyweight materials	Prefabricated timber framing construction, north-south solar design	Traditional concrete and brick construction, awarded by the festival World Architecture 2016	Prefabricated concrete facade modules	Traditional mediterranean design, bioconstruction materials and bioclimatic strategies
Typology	Detached	Detached	semi-detached	mi-detached (terrac	detached	semi-detached	Detached	Detached	Detached	Detached	Detached	Semi-detached	Detached
Number of floors	2	1	2	3	2	2	1	1	1	2	1	2	2
Net floor area [m²]	92	150	76	211	96	282	103	106	117	136	136	70	143
Structure materials	Wood	Wood, concrete	Masonry, wood	Masonry	Wood	Wood	Wood	Wood	Masonry, concrete	Wood	Masonry, concrete	Masonry, concrete	mpressed-earth blo
Type of construction	New	New	Renovated	New	New	New	New	New	New	New	New	New	New
Passivhaus certified	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes, Premium
Thermal mass	Low	Medium	Medium	High	Low	Low	Low	Low	High	Low	High	High	High
U wall [W/(m²K)]	0,136	0,166	0,198	0,220	0,158	0,155	0,135	0,146	0,144	0,159 - 0,186	0,233 - 0,262	0,121	0,183
U ground [W/(m²K)]	0,131	0,193	0,340	0,530	0,174	0,229	0,164	0,372	0,171	0,208	0,369	0,106	0,450
U roof [W/(m²K)]	0,150	0,147	0,145	0,200	0,124	0,153	0,138	0,115	0,116	0,148	0,221	0,099	0,227
Window U [W/(m²K)]	1,230	0,770	0,800	1,250	0,950	0,730	0,850	1,250	0,910	1,130	1,370	1,020	1,260
Frame U [W/(m²K)]	-	1,000	-	1,500	1,200	0,970	1,140	-	1,040	1,500	1,350	1,100	-
Glass U [W/(m²K)]	0,70 - 1,10	0,500	0,500	1,100	0,500	0,500	0,650	1,100	0,540	0,500	1,640	0,600	1,150
Window g-value	0,51 - 0,62	0,53	0,44	0,59	0,53	0,53	0,46	0,50	0,53	0,53	0,73	0,50	0,60
Window frame material	Wood	Wood-aluminium	PVC	Wood-aluminium	Wood-aluminium	Wood-aluminium	Wood	Wood	Wood-aluminium	Wood-aluminium	Wood	Wood	Wood
ACH 50 Pa [h⁻¹]	0,22	0,40	1,00	0,60	-	0,40	0,55	0,21	0,28	0,49	-	0,50	0,22
MV maximum air flow (m3/h)	200	370	200	450	300	400	300	370	200	300	350	300	370
HR sensible eff. [%]	95%	90%	95%	-	95%	-	-	90%	95%	94%	80%	94%	90%
HR PHI method [%]	88%	84%	83%	89%	82%	83%	84%	84%	83%	86%	78%	86%	84%
Bypass	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heating systems	lellet stove, GSHP	Pellet stove, electric heaters	No (in future, bathroom heaters)	Active slabs	Biomass boiler, towel rails	Wood stove, post-heater HP, towel heaters	Radiant floor	Stand-alone stove	Air HP, towel heaters	Stand-alone pellet stove, radiant floor	HP	Pellet stove, post-heater HP	No
Cooling systems	GSHP	No	No	Active slabs	No	No	Radiant floor	No	No	No	-	No	No
DHW generation	lellet stove, GSHP	HP	Electric (in future, pellet boiler)	HP	Biomass boiler	HP	Pellet boiler, HP	HP	HP	HP	HP	HP	HP
Heating thermal power [kW]	10 (stove)	-	-	-	4	8	6,5	5	-	2,4 - 9	-	8	2
Hot water storage [l]	Yes	-	-	200	-	-	200	110	200	300	-	300	200
Solar harvesting	No	No	No (in future, PV panels)	thermal 5,0 m²	No	No	No	No	-	No	thermal 1,0 m²	No	No
Other devices	-	-	-	› with winter/summ	-	-	-	-	-	-	-	-	-
Annual heating demand [kWh/m²a]	14,0	13,0	24,0	13,0	14,0	13,0	11,7	9,0	13,0	9,0	14,0	18,0	8,0
Heating load, daily average [W/m²]	10,0	13,0	11,0	11,0	13,0	12,0	13,0	9,0	11,0	10,0	20,0	20,0	12,0
Annual cooling demand [kWh/m²a]	-	-	0,0	-	0,0	0,0	14,5	17,0	3,0	0,0	26,0	-	15,0
Cooling load, daily average [W/m²]	-	-	0,0	-	0,0	0,0	12,0	10,0	5,0	0,0	21,0	-	9,0
Primary Energy annual use [kWh/m²a]	97,0	83,0	84,0	95,0	98,0	92,0	108,0	117,0	115,0	93,0	111,0	55,0	54,0
Construction costs / treated floor	1800,0	-	-	840,0	1100,0	1180,0	1100,0	1200,0	1500,0	1150,0	-	-	-

Table II. 3. List of single-family PH dwellings in Spain, part 3 of 4 (data source PEP & PHI, 2017)

House name	Tossa de Mar	House in Alzina	Rivas Passivhaus	Casa Muros	Cagical Passivhaus	Casa "Sol y Viento" en Mijas	Vivienda en Tenerife	Casa Mikeleiz	House in Alicante	Passivhaus en el Plantío	Atalaya house	Casa "Hulohaus"	Passiv Etxea 1
Year of construction	2014 2015	2014-2016	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015 - 2016	2016
Location	Tossa de Mar, Girona	Alzina de Ribelles, Lleida	Rivas Vaciamadrid, Madrid	Muros de Nalón, Asturias	Vitoria-Gasteiz, Alava	Mijas, Málaga	Granadilla de Abona, Santa Cruz de Tenerife	Ezkaroz, Navarra	Alicante	Madrid	Cudillero, Asturias	Cerdanyola del Vallès, Barcelona	Ibero, Navarra
Elevation	6	875	563	131	539	428	640	742	5	657	785	32	395
Climate zone (Spanish CTE classes)	C2	E1	D3	D1	D1 - E1	C3	A2	E1	C3	D3	E1	C2	D1
Passive House Institute ID	5114	5192	4483	4596	4718	4477	4418	4792	4764	4599	4634	4668	4863
Description	Mediterranean house based on PH principles	Expansion over an existing building with prefabricated wood facades	Prefabricated timber frame construction	Prefabricated timber frame construction	Conventional materials and concrete structural solutions	Reinforced concrete slabs and celular block walls	Reinforced concrete construction with external themoacoustic mortar	Traditional design, wooden structure.	Traditional mediterranean construction, BREEAM certification	Frist PH certified house in Madrid. High thermal mass with honeycomb clay block walls	Prefabricated timber frame construction	Prefabricated timber construction	Renovated stone wall house, masonry and CLT construction
Typology	Detached	Detached	Detached	Detached	Detached	Detached	Detached	Detached	Detached	Detached	Detached	Detached	Semi-detached
Number of floors	2	1	3	2	1	2	2	2	2	2	1	2	3
Net floor area [m²]	144	104	241	170	214	403 (2 apartments)	140	134	262	248	116	133	265
Structure materials	Concrete, wood	Wood	Wood-concrete	Wood	Masonry, concrete	Masonry, concrete	Masonry, concrete	Wood	Masonry, wood	Masonry, concrete	Wood	Wood	Masonry, wood
Type of construction	New	New	New	New	New	New	New	New	New	New	New	New	Renovated
Passivhaus certified	No	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	No	Yes
Thermal mass	Medium	Medium	Low	Low	High	High	High	Low	High	High	Low	Low	Medium
U wall [W/(m²K)]	0,150	0,162	0,145	0,176	0,117	0,22 and 0,27	1,640	0,133	0,281	0,160	0,182	0,179	rom 0,166 to 0,19
U ground [W/(m²K)]	0,504	0,253	0,396	0,187	0,157	0,235	1,767	0,133	1,128	0,290	0,259	0,183	0,159
U roof [W/(m²K)]	0,163	0,139	0,124	0,181	0,110	0,230	0,227	0,199	0,293	0,170	0,199	0,176	0,223
Window U [W/(m²K)]	2,380	0,920	0,960	1,200	0,760	1,320	1,400	0,890	1,730	0,980	0,800	1,160	0,950
Frame U [W/(m²K)]	-	1,240	1,050	1,540	1,000	-	1,500	1,030	1,440	1,000	0,970	1,120	0,930
Glass U [W/(m²K)]	1,600	0,600	0,621	0,800	0,540	1,000	1,000	0,600	1,000	0,840	0,500	0,690	0,520
Window g-value	0,70	0,49	0,61	0,50	0,50	0,60	0,35	0,61	0,39	0,57	0,53	0,62	0,50
Window frame material	Wood	Wood	PVC	Wood	PVC	Wood-aluminium	Wood	Wood	Wood	PVC	Wood-aluminium	Wood	Wood-aluminium
ACH 50 Pa [h⁻¹]	2,00	0,40	0,59	0,46	0,57	0,47	0,59	0,20	0,57	0,44	0,60	1,70	0,60
MV maximum air flow (m3/h)	370	250	550	400	370	285	300	200	370	550	300	370	550
HR sensible eff. [%]	90%	90%	95%	95%	90%	-	95%	95%	90%	95%	95%	90%	95%
HR PHI method [%]	84%	-	83%	84%	79%	85%	82%	88%	84%	83%	82%	84%	83%
Bypass	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heating systems	Post-heater HPSU	Post-heater HP	Electric post-heater, 3 bath heaters	Stand-alone pellet stove	Pellewt stove and bathroom heaters	HP	No	Pellet stove, bathroom heater	Post-heater HP	Post-heater HP	Wood stove, air post-heater, towel heater	Electric post-heater	Post-heater HPSU
Cooling systems	Post-cooler HP	Post-cooler HP	No	No	No	Automatic blind operation	No	No	No	Post-cooler HP	No	No	No
DHW generation	HPSU	HP	HP	HP	HP	HP	HP	Pellet stove	HP	Hot water storage with HP	HP	solar 87%, electric	HP SU
Heating thermal power [kW]	-	4,5	2	2,4 - 8	-	-	-	10	-	-	3	-	-
Hot water storage [l]	-	-	-	270	-	-	-	150	-	-	150	200	300
Solar harvesting	thermal panels	-	thermal panels	-	No	5 thermal and PV panels	-	No	No	No	No	vacuum panels (CPC)	thermal panels
Other devices	-	ainwater harvestin	-	-	-	canadian dwell	-	-	-	-	-	Automatic shutters	-
Annual heating demand [kWh/m²a]	39,0	12,0	14,0	14,9	15,0	8,8	0,0	16,0	13,0	10,8	14,0	1,0	18,8
Heating load, daily average [W/m²]	29,0	19,0	11,0	12,7	10,6	10,1	5,0	9,0	12,0	11,3	13,0	10,0	9,3
Annual cooling demand [kWh/m²a]	13,0	-	8,0	-	-	5,0	15,0	-	-	6,9	-	14,0	-
Cooling load, daily average [W/m²]	16,0	-	8,0	-	-	9,0	16,0	-	-	9,2	-	9,0	-
Primary Energy annual use [kWh/m²a]	124,0	92,0	117,0	99,0	77,0	78,0	75,0	97,0	77,0	97,0	81,0	-	86,0
Construction costs / treated floor	1184,0	1250,0	1100,0	1200,0	-	-	1100,0	1750,0	-	-	-	1600,0	1200,0

Table II. 4. List of single-family PH dwellings in Spain, part 4 of 4 (data source PEP & PHI, 2017)

House name	Passiv Etxea 2	Esencia Mediterránea	Yellow House	PH off grid	Cadavedo house	Casa piloto Zorzano	Casa Zabala	Cármenes	Matadepera	Zaratán house	Casa Estrella dels vents	House in Vitoria	House in Gironella
Year of construction	2016	2016	2016	2016	2016	2016	2016	2016	2016	2016	2016	2016	2017
Location	Ibero, Navarra	Castelldefels, Barcelona	Santander, Cantabria	Llanera, Asturias	Villademoros, Asturias	Arrúbal, La Rioja	Moaña, Pontevedra	Cármenes, Leon	Matadepera, Barcelona	Zaratan, Valladolid	Cantonigros, Barcelona	Vitoria-Gasteiz, Alava	Gironella, Barcelona
Elevation	395	3	8	200	<100	356	3	1167	423	755	693	539	469
Climate zone (Spanish CTE classes)	D1	C2	C1	D1	D1	D2	C1	E1	D2	D2	D1	D1 - E1	D1
Passive House Institute ID	4864	5067	4331	4832	5155	5183	4572	5229	5191	5226	5241	5245	5189
Description	Traditional design, concrete structure and wood components	Traditional mediterranean design, focused in comfort and summer protection	Renovation of a house from 1920	Passive house Plus, off grid with PV panels, two separated volumes	Prefabricated timber frame elements	Prefabricated concrete facades, the house is a showroom and it is tested	Renovation of existing summer cabin to permanent residence	Prefabricated timber and CLT components	Prefabricated timber structure with concrete basement	Bioclimatic design, concrete basement and woof upper floors	Prefabricated wood and straw construction elements	Traditional masonry and concrete construction	Prefabricated wood facades
Typology	Semi-detached	Detached	Semi-detached	Detached	Detached	Semi-detached	Detached	Detached	Detached	Detached	Detached	Detached	Detached
Number of floors	3	2	2	1	2	1	1	1	2	2	2	1	2
Net floor area [m²]	203	165	92	149	183	104	83	94	191	121	215	161	125
Structure materials	Wood, concrete	Wood	Masonry, wood	Wood	Wood	Concrete, wood	Masonry	Wood	Concrete, wood	Concrete, wood	Wood and straw	Masonry, concrete	Wood
Type of construction	New	New	Renovation	New	New	New	Renovated	New	New	New	New	New	New
Passivhaus certified	Yes	Yes	No	No	No	Yes	No	No	No	No	Yes	No	No
Thermal mass	Medium	Medium	High	Low	Low	Medium	High	Low	Medium	Medium	Low	High	Light
U wall [W/(m²K)]	rom 0,159 to 0,19	0,160	0,142	0,149	0,158 - 0,202	0,142	0,170	0,147	0,138 - 0,166	0,145	0,127	0,121	0,138 - 0,166
U ground [W/(m²K)]	0,146	0,260	0,123	0,194	0,306	0,123	0,180	0,140	0,197	0,209	0,100	0,133	0,131
U roof [W/(m²K)]	0,111	0,154	0,122	0,198	0,176	0,122	0,738	0,137	0,118	0,091	0,086	0,128	0,118
Window U [W/(m²K)]	0,960	1,490	1,237	1,170	0,980	1,320	0,910	0,900	1,200	0,850	0,850	0,860	0,850
Frame U [W/(m²K)]	0,925	1,400	0,970	1,200	1,087	1,040	1,140	1,087	1,300	0,970	0,920	0,970	0,920
Glass U [W/(m²K)]	0,520	1,100	1,100	0,800	0,500	0,640	0,600	0,500	0,850	0,500	0,600	0,520	0,600
Window g-value	0,50	0,36	0,61	0,50	0,53	0,49	0,54	0,53	0,60	0,53	0,59	0,50	0,47
Window frame material	Wood-aluminium	Wood	Wood-aluminium	Wood-aluminium	Wood-aluminium	PVC	Wood	Wood-aluminium	PVC	Wood-aluminium	Wood	Wood-aluminium	Wood
ACH 50 Pa [h⁻¹]	0,60	0,40	0,52	0,60	0,54	0,40	0,60	0,50	-	0,20	0,60	0,60	-
MV maximum air flow (m3/h)	550	550	200	300	300	370	200	300	550	300	370	370	370
HR sensible eff. [%]	96%	96%	95%	95%	95%	90%	95%	95%	96%	94%	90%	90%	90%
HR PHI method [%]	83%	83%	88%	82%	79%	84%	88%	82%	83%	86%	82%	84%	82%
Bypass	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heating systems	Post-heater HPSU	Stand-alone pellet stove	2 towel rails	Pellet boiler and room heaters	Pellet stove, post-heater electric	Pellet stove	earth-air exchanger, post-heater electric	Post-heater Pellet boiler	Post-heater HPSU	Pellet stove, post-heater electric	Electric heaters	Pellet stand-alone stove, 2 towel h., 3 elec. heaters bedr.	Post-heater HPSU
Cooling systems	No	HPSU	No	No	No	No	No	No	Post-cooler HP	No	-	No	Post-cooler HPSU
DHW generation	HPSU	HPSU	HP	Pellet boiler	HP	Solar, electric	solar, electric	Solar thermal and electric	HPSU	HP	HP, PV support	HP	HPSU
Heating thermal power [kW]	-	6	-	12	3	12	1	2,5 - 8	-	ectric battery 1,5 kV	-	6, pellet stove	6 pellet stove
Hot water storage [l]	300	500	200	-	300	200	100	250	-	300	-	-	500
Solar harvesting	thermal panels	thermal panels	No	PV panels	No	PV panels	1 thermal panel	thermal 5,0 m²	thermal panels	-	PV panels	No	thermal panels
Other devices	-	Automatic shutters	-	inwater for irrigatic	-	-	h-to-air heat exchar	-	-	-heating canadian v	-	-	-
Annual heating demand [kWh/m²a]	14,6	14,5	13,0	9,0	12,0	14,0	7,0	15,0	14,0	12,0	13,0	15,0	13,0
Heating load, daily average [W/m²]	8,6	13,0	9,0	10,0	10,0	13,0	9,0	15,0	9,0	10,0	13,0	11,0	15,0
Annual cooling demand [kWh/m²a]	-	17,3	-	-	-	-	-	-	-	-	-	-	-
Cooling load, daily average [W/m²]	-	9,2	-	-	-	-	-	-	-	-	-	-	-
Primary Energy annual use [kWh/m²a]	93,0	110,9	109,0	54,0	68,0	78,0	96,0	79,0	113,0	72,0	51,0	84,0	84,0
Construction costs / treated floor	1200,0	1119,0	800,0	-	-	-	-	-	-	-	-	1552,0	-

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