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PhD Thesis

Energy retrofits in social housing

Analysis of its thermal behaviour

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Energy retrofits in social housing

Analysis of its thermal behaviour

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Resumen

La presente tesis doctoral trata la evaluación de la rehabilitación energética en edificios, abordando las diferentes partes involucradas en el proceso: la monitorización y adquisición de datos, el tratamiento de los datos (mediante modelos) y el análisis de los resultados obtenidos.

El interés de la tesis nace de la actual situación energética en la que más del 40 % del consumo energético total de la Unión Europea corresponde al sector de la construcción. Además, el consumo energético en la edificación se ha mantenido en constante crecimiento en los últimos años debido al crecimiento de la población y al aumento de la demanda de un ambiente interior saludable y confortable, y un aumento en esos estándares de confort. Así, la reducción de la dependencia de fuentes energéticas es un aspecto crucial en el desarrollo hacia un futuro energético sostenible. Por esta razón, la eficiencia energética en edificios es un objetivo prioritario para la Unión Europea, y esta situación energética y medioambiental exige la mejora del comportamiento energético del parque edificatorio. Observando la antigüedad del parque inmobiliario en la Unión Europea, y concretamente en España, y las bajas exigencias existentes en el pasado en lo referente al comportamiento térmico en edificios, se puede afirmar que para reducir el consumo energético asociado a la edificación, el principal esfuerzo debe ser dirigido en la mejora del parque existente.

Esta situación energética está íntimamente relacionada con las emisiones globales de dióxido de carbono. Es necesario alcanzar una reducción drástica de las emisiones al mismo tiempo que mejoran los estándares de vida de la población global. Sin embargo, el estudio del comportamiento energético en la edificación ha de tener en cuenta otros aspectos. En determinadas áreas y sectores de población, las prioridades económicas inmediatas se anteponen a las preocupaciones ambientales, y la lucha contra el cambio climático por sí solo no es suficiente motivación. En estos casos, debe tenerse en cuenta que la mejora de la eficiencia energética en edificios es también el camino para reducir la llamada pobreza energética. Esto es, la rehabilitación energética de los edificios, además de las implicaciones y beneficios en la reducción de emisiones de dióxido de carbono y ahorro energético, también afecta positivamente a aspectos sociales y

económicos, muy relacionadas entre sí, tales como la reducción y la lucha contra la mencionada pobreza energética.

Así, las metodologías para evaluar de un modo exacto el efecto de diferentes estrategias de rehabilitación posibles son cada vez más demandadas por los distintos agentes que participan en las distintas fases del sector de la rehabilitación de edificios -legisladores, ingenieros o arquitectos-. Para los primeros (los legisladores), de cara a comprobar por una parte si una rehabilitación dada cumple los requisitos mínimos exigidos por la ley; y por otra parte, si un incentivo dado a una actuación concreta se ha invertido de manera efectiva o no. A ingenieros y arquitectos, quienes participan en la ejecución de la rehabilitación, de cara a identificar entre todas las posibles, las actuaciones más adecuadas para un edificio concreto en una zona climática específica.

De esta forma, el desarrollo de esta tesis afronta los pasos necesarios en todo análisis de eficiencia energética en edificios. Comienza con el análisis del parque inmobiliario existente en el País Vasco. Después, se presentan dos metodologías posibles de adquisición de datos, destinadas a obtener resultados de distinta naturaleza: por una parte, la monitorización de una vivienda vacía, para obtener datos que serán utilizados posteriormente especialmente para definir el comportamiento térmico de los elementos constructivos del edificio o vivienda, y del edificio o vivienda en su globalidad; por otra parte, una toma de datos realizada en varias viviendas a lo largo de más de un año que en esta tesis se utilizará posteriormente para obtener información de los comportamientos y perfiles de los ocupantes en el aspecto energético. Los datos obtenidos de ambos estudios se utilizan posteriormente para definir dos tipos de modelos. Finalmente, se presenta de forma detallada la evaluación de resultados obtenidos con esos modelos.

Para presentar el desarrollo de dicho trabajo, esta tesis se ha dividido en 4 bloques diferenciados. La primera, la introducción, incluye los Capítulos 1 y 2, donde se presenta una revisión bibliográfica de los diferentes aspectos tratados a lo largo de la tesis, y se describen los objetivos y la metodología seguida.

El segundo bloque de la tesis describe y detalla la parte experimental llevada a cabo. En primer lugar, en el Capítulo 3 se recoge un estudio de campo de 10 viviendas sociales. Estas viviendas se seleccionan en base a criterios de representatividad de los diferentes tipos de edificación construidas a lo largo del siglo XX en la región. Este estudio proporciona una gran cantidad de datos de gran utilidad para conocer el comportamiento térmico del parque inmobiliario social. Se monitorizan temperaturas y humedad relativa en el interior de cada vivienda durante un año, con una frecuencia de 10 minutos. Con ello, se obtiene información no sólo de confort interior, sino también de las condiciones de operación de cada vivienda y del comportamiento de los usuarios. También se recoge la información de consumos energéticos, utilizando para ello las facturas energéticas (tanto de electricidad, como de gas natural, en su caso). Además, los ocupantes de cada vivienda rellenaron un cuestionario sobre distintos aspectos tales como perfiles de uso y ocupación o concienciación energética entre otras, complementando la información recogida por el resto de fuentes mencionadas. Este estudio ofrece así una panorámica del comportamiento real energético de viviendas sociales, así como una importante referencia para posteriormente definir unas condiciones de operación y perfiles de ocupación representativos de la vivienda social.

El Capítulo 4 se centra en la descripción de una monitorización en detalle de una vivienda representativa. Ésta se selecciona teniendo en cuenta la clasificación realizada previamente en el Capítulo 1. La monitorización cubre dos escenarios: el primero, en el invierno de 2012, y el segundo, en el invierno de 2013, después de una sustitución de ventanas realizada con objeto de obtener una mejora del comportamiento térmico. Se sitúan en torno a 60 sensores de temperatura dentro de la vivienda vacía que toman datos con una cadencia de 1 minuto. Se obtienen así datos suficientes para caracterizar en detalle el comportamiento térmico tanto de los distintos elementos constructivos (ventanas, fachadas, particiones...) como del conjunto de la vivienda.

El tercer bloque de la tesis aborda el desarrollo y definición de dos modelos de simulación, utilizando para ellos los datos experimentales obtenidos previamente, en el bloque anterior. El Capítulo 5 presenta la definición y calibrado de un modelo de la vivienda de "caja blanca", con TRNSYS. El Capítulo 6 define y calibra un modelo de caja gris. Los datos obtenidos en la monitorización en detalle de la vivienda, se utilizan para definir el modelo RC (de caja gris), así como para validar y calibrar tanto el modelo RC como el de TRNSYS. Además, la información obtenida de la monitorización de 10 viviendas se utiliza para posteriormente definir perfiles de ocupación y de operación representativas de la vivienda social que serán incluidos en los modelos desarrollados.

Finalmente, el último bloque de la tesis incluye los capítulos 7 y 8. Se ha centrado en el diseño de la simulación y la evaluación de los resultados obtenidos con dichas simulaciones. En el Capítulo 7, se presentan y evalúan los ahorros energéticos obtenidos tanto mediante posibles mejoras en la envolvente como de los sistemas de calefacción. Para esta evaluación se ha tenido en cuenta criterios económicos, energéticos, medioambientales y de confort. El estudio se ha realizado a escala de vivienda. Las simulaciones muestran primeramente los resultados de 64 posibles combinaciones de medidas de ahorro energético a llevar a cabo sobre la envolvente del edificio. Después de seleccionar una de las combinaciones evaluadas, se presenta el impacto de diferentes estrategias de control de calefacción en el consumo final de energía y confort interior.

En el Capítulo 8 se presenta y evalúa la utilidad del enfoque exegético, donde se expone una breve revisión bibliográfica de la aplicación de este concepto aplicado a la edificación. Se acompaña de dos artículos desarrollados por el autor en la Escuela de Arquitectura de la Universidad Tecnológica de Delft (TU Delft). Estos artículos exploran las posibilidades de este enfoque el análisis de rehabilitaciones energéticas a escala de edificio, usando como caso base e estudio el edificio de referencia de esta tesis.

Como conclusiones del trabajo desarrollado a lo largo de esta tesis, se puede destacar diversos aspectos. Las rehabilitaciones energéticas en edificios presentan un gran potencial para reducir de forma significativa las emisiones de dióxido de carbono asociadas al sector de la edificación. Estas rehabilitaciones energéticas presentan también importantes beneficios económicos y sociales en distintas escalas. Los modelos RC y TRNSYS pueden ser una herramienta útil y adecuada para evaluar el consumo energético en edificios. Finalmente, se remarca la importancia de considerar un enfoque global en la evaluación del consumo energético del parque de edificios, así como el papel que aspectos tales como el comportamiento humano, condiciones de operación (simulaciones presentadas en esta tesis muestran diferencias de alrededor de 50% en el consumo energético dependiendo de las condiciones de operación consideradas) o las estrategias de control juegan en el consumo energético global del edificio o vivienda.

Por último, se identifican las líneas de trabajo a desarrollar en el futuro cercano. Se debe desarrollar la mejora y ajuste del modelo RC, para posteriormente, trabajar en la interacción del modelo RC con el modelo de TRNSYS, y de ambos con la Planta Experimental de Instalaciones Térmicas en Edificios (ubicada en el Laboratorio para el Control de Calidad en la Edificación, del Gobierno Vasco). De esta forma, la línea de trabajo seguida en el grupo de investigación se iniciaría en el estudio de campo de un edificio dado, cuyos datos obtenidos se utilizaran para definir su modelo RC mediante el cálculo de los parámetros característicos. El modelo RC definido se utiliza para calcular demandas de calor, las cuales alimentan al modelo de TRNSYS, que a su vez está conectado con la Planta Experimental de Instalaciones Térmicas en Edificios. Así se pueden evaluar en el laboratorio diferentes sistemas energéticos mediante ensayos semi-virtuales teniendo como referencia demandas definidas en condiciones reales.

Además, el modelo de TRNSYS calibrado en esta tesis, así como los primeros resultados obtenidos de él, y presentados en el bloque 4, son la base para el desarrollo de una guía de rehabilitación energética de edificios, dirigida a los distintos agentes del sector de la construcción. Esta guía, que puede ser desarrollada en colaboración con el Laboratorio para el Control de Calidad en la Edificación del Gobierno Vasco, presentará resultados económicos, energéticos y medioambientales de distintas estrategias de rehabilitación aplicadas en los diferentes tipos de edificios existentes, en diferentes áreas climáticas. Estos resultados estarán basados en simulaciones dinámicas a su vez definidos y alimentados de datos experimentales.

Abstract

This PhD thesis deals with the evaluation of energy renovations in buildings, facing the different parts involved in that process, such as data acquisition and monitoring, data treatment (by means of building models) and analysis of obtained results.

The interest of the thesis was awoken by the current energy situation where the construction sector is responsible of over 40 % of the total energy consumption in the European Union. Besides, building energy consumption has kept rising in the recent years due to several factors, such as a growth in population, an increasing demand for healthy comfortable indoor environment and for higher comfort standards. Hence, reducing the need for energy sources is a key factor in the development towards a sustainable energy future. For that reason, energy efficiency in buildings is a priority goal for the European Union, and this energy and environmental situation requires improving the energy performance of buildings. Taking into account the age of the building stock in the European Union, and specially in Spain, and the low thermal requirements existed in the past, it can be stated that in order to reduce the energy consumption, the main effort must be focused on the challenges of improving the existing stock.

This energy situation is closely related to global CO_2 carbon emissions. A massive decarbonisation of the world economy needs to be achieved while improving the life standards of the global population. However, other aspects must be taken into account when energy issue is treated in buildings. In those areas or population sectors where immediate economic priorities override environmental concerns and climate change alone is often not sufficient, improving energy performance in buildings is also a way driven to alleviate the so called fuel poverty. Implications and benefits of energy renovations thus have consequences not only in the reduction of CO_2 emissions and energy savings but also in financial and social aspects, closely connected amongst them, such as the reduction of mentioned fuel poverty.

Thus, methodologies for evaluating in an accurate way the effect of different energy renovations are needed more and more by the different agents involved on building retrofits. For policy makers it is useful, on the one hand, to check whether a given energy

renovation fulfils the conditions required by law; on the other hand, to check whether a given incentive has been invested in a suitable way or not. As for architects and engineers, to identify the most adequate energy renovations for a specific building and climatic area.

Thus, the development of this thesis faces the different steps given in every analysis on building energy performance. It is started with the analysis of the building stock in this region. Afterwards, two kind of data acquisition are presented: in an empty dwelling, for obtaining data mainly from the passive characteristics of the building; and in several occupied dwellings, more led to obtain data about occupants' behaviour and profiles. Obtained data from both studies are used afterwards to define two different building models. Finally, possibilities of evaluation of results obtained from mentioned building models are described.

For presenting the development of mentioned work, this PhD thesis is divided into 4 different parts. The first one, which is the **introduction**, encompasses Chapter 1 and Chapter 2, where the state of art of the different aspects treated in this thesis are presented, and objectives and methodology are described, respectively.

The second part exhibits the **experimental research** carried out in this thesis. Firstly, a field study of 10 social dwellings is reported in Chapter 3. Ten dwellings are selected to be representative of the different types of buildings built during the 20th century. This study provides a huge amount of data about the current situation of the social building stock. Indoor temperature and relative humidity is logged in each dwelling during a year, obtaining information not only about indoor comfort, but also about operating conditions of each dwelling and occupants' behaviour. Energy consumption information is gathered, by means of energy bills. Additionally, questionnaires are filled in by the occupants, complementing the information obtained by other sources. This study provides an overview of the real energy performance of the social apartments, as well as an important reference for defining later a representative operating condition profiles on social building sector.

Analogously, Chapter 4 is focused on the description of a detailed monitoring of a representative dwelling, selected according to the previously carried out classification. This monitoring covers two scenarios: The first one, carried out in winter 2012, and a second one, carried out in winter 2013, after a thermal improving by means of a windows replacement is executed. Around 60 temperature sensors are placed within the vacant dwelling, obtaining data for characterizing in detail the thermal performance of the constructive elements of the dwelling.

Afterwards, the **treatment of the data** obtained from this experimental part is carried out mainly using two kinds of simulation models. The development of mentioned models is dealt with in the third part. It embraces Chapter 5 (the white box model, TRNSYS) and Chapter 6 (grey box model). Data obtaining in the second monitoring (the detailed monitoring of the selected dwelling) are used for defining the RC Model, and validating and calibrating both the RC Model and TRNSYS model. Meanwhile, information obtained from the monitoring of the ten social apartments is used to define occupation and operating profiles representative of social building apartments.

Finally, the last part of this thesis has focused on the simulation design and **evaluation of results** obtained from the above mentioned simulations. It is explained in two different chapters. Energy savings obtained as a result of improvements both on building envelope and heating systems, is presented and evaluated in Chapter 7, under economic, energy, environmental and comfort criteria. This study is carried out on a dwelling scale. The simulations show firstly the results of 64 possible combinations of energy savings measurements on the building envelope. After choosing one of the evaluated combinations, the impact of the different heating control strategies on the final energy consumption and indoor comfort are presented.

Meanwhile, the exergy approach usefulness is evaluated in Chapter 8, where a brief literature review about this concept in buildings applications is presented, followed by two papers developed in the Faculty of Architecture of TU Delft. These papers explore the possibilities of this approach on the analysis of energy renovations on an entire building scale, using as base case the reference building of this PhD Thesis.

Taking into account the work presented in this PhD Thesis, different aspects can be highlighted. The energy renovations in buildings present a great potential for reducing (in an important manner) the CO_2 emissions of the construction sector, but also present significant social and economic benefits in the different scales. RC models and TRNSYS models can be a very useful and suitable tool in order to evaluate energy consumption in buildings. Finally, the importance of considering a holistic approach when energy consumption the of building stock is evaluated, has also been remarked in this thesis, and the role that aspects such as human behaviour, operating conditions (simulations in this thesis present differences of around 50% on energy consumption depending on the assumed operating conditions) and control strategies play in the global energy consumption is proved.

In the close future, two different lines are identified to develop. The improvement and adjustment of the RC model must be developed, and later, the interaction of the RC model with the TRNSYS model, and both of them with the Energy System Plant (experimental plant for testing different building energy systems) must be explored. This way, a workflow starts on the field study of a given building which is used for defining the RC Model. Defined RC model calculates the energy demands, and that energy demands feeds the TRNSYS model, which is connected to the Energy Systems Plant. Thus, different energy systems are tested in laboratory under real conditions of energy demands.

Moreover, the TRNSYS model calibrated in this PhD Thesis, as well as the first results obtained from it in the last part of this PhD Thesis must be the base to develop a building energy renovations handbook, useful for the different agents of the construction sector. This handbook, which can be developed with the support of the Laboratory for Quality Control in Buildings of the Basque Government (LCCE) will present economic, energy and environmental results of different energy renovation strategies, on different kind of existing buildings, in different climatic area, based on dynamic simulations and experimental data.

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Dice K. Jornet que *"Una cima no es un punto geográfico, una fecha y un crono. Una cima son recuerdos, emociones almacenadas dentro de nosotros, son las personas que nos acompañaban o nos esperaban abajo"* En el fondo, el desarrollo de una tesis se puede asemejar a una ruta de montaña. Y ante su presentación, no puedo olvidarme de las personas que, de una u otra manera, han participado en esta travesía (las que acompañaban, y también las que esperaban abajo). Sirvan estas líneas para expresar y transmitir mi más sincero agradecimiento a todos ellos.

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“The only ecological architecture is the one that is not built”

Frei Otto

"The idea that low energetic consumption buildings are respectful with the environment and that, through the construction of more buildings of this type, we will fulfill the promises done in the Rio de Janeiro Summit in order to reduce the emission of CO_2 for 2005 to a 25 per cent of the existing ones in 1990, is, naturally, a stupidity. A new building never saves energy, but it generates new energetic needs, and the qualification of new land to urbanize is basically anti ecological."

Gunther Moewes

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APPENDICES

Nomenclature and Abbreviations

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BSH	Bilbao Social Housing
CDF	Cumulative distribution functions
CTE	Spanish Technical Building Code (Código Técnico de la Edificación)
DHW	Domestic Hot Water
DPP	Depreciated Payback Period
ESIR	Energy Savings to Investment Ratio
ESM	Energy Savings Measures
EUSTAT	Statistics of the Basque Country
EVE	Basque Energy Agency (Ente Vasco de la Energía)
INE	Spanish Statistical Office (Instituto Nacional de Estadística)
IRR	Internal Return Rate
LCA	Life Cycle Assessment
LCCE	Laboratory for the Quality Control in Buildings (Laboratorio de Control de Calidad en la Edificación)
NG	Natural Gas
NPV	Net Present Value
P.E.	Primary Energy
PLR	Partial load operation
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PRBS	Pseudorandom Binary Sequence
PWF	Present Worth Factor
RH	Relative Humidity
ROLBS	Randomly Ordered Logarithmic distributed Binary Sequence
SIR	Savings to Investment Ratio
TH	Thermo Hygrometer

Nomenclature

A	Area
C	Heat capacity
c	Cost
cp	Isobaric heat capacity
D	Exergy Destruction
E	Electricity
e	Thickness
ED	Energy Demand
En	Energy Consumption
f	Expenses related to operation
F	Exergy Factor
G	Global Irradiation
H	Heating consumption (In Chapter 6, Conductance is also referred as H)
I	Investment
L	Exergy losses
LS	Lifespan
m	Mass
N	Lifetime
n	Time period
P	Power
PEF	Primary Energy Factor
Q	Heat and sensible heat
r	Market discount rate
R	Resistance
S	Savings
T	Temperature
t	Time
U	Heat Transfer Coefficient
V	Volume
Vent	Ventilation
x	Exergy

Greek symbols

Δ	Increment
ε	Emissivity
η	Energy Efficiency
ρ	Density
Φ	Flow
Ψ	Exergy Efficiency
τ	Time constant

Superscripts

BB	Black Body

Subscripts

0	reference
a	Related to air
aft	After
B	Related to Base Case
bef	Before
c	Related to heaters
CHP	Related to co-generation system
conv	Related to convection
del	delivered
dem	demand
e	Related to envelope
E	Related to Electricity
str	Related to structure
exp	exported
ext	Related to external
fi	Related to floor
fs	Related to ceiling
h	Related to horizontal
H	Related to heating system

HR	Related to heat recovery
i	stream
in	Indoor
inf	infiltrations
inl	inlet
Inp	Input
int	internal
m	Related to indoor partitions
max	Maximum
min	Minimum
op	Operative (temperature)
out	Outdoor
outl	outlet
outp	output
p	Related to pillars
rad	Related to radiation
ret	return
s	Related to solar
sol	solar gains
sp	setpoint
ST	Related to Solar thermal
sum	Related to summer
sup	Supply
surf	Related to surface
TES	Related to Thermal energy storage system
TESHT	Related to thermal energy storage system (High temperature)
TESLT	Related to thermal energy storage system (low temperature)
trans	Transmission
vent	ventilation
v	Related to vertical
w	Related to windows
wint	Related to winter
X	related to exergy

PART 1
STATE OF ART

"If Nature had been comfortable, man never would have invented architecture"

Oscar Wilde (1854-1900)

CHAPTER 1

INTRODUCTION

RESUMEN

Éste capítulo presenta la introducción de esta tesis. Incluye una breve referencia a los efectos y las motivaciones de la rehabilitación (no sólo energéticos, sino también sociales y económicos) para después presentar una revisión bibliográfica de diversos elementos que afectan a la rehabilitación energética en edificios: la tecnología disponible actualmente y las estrategias habituales (basadas principalmente en aislamiento térmico y/o inercia térmica); la evaluación de la eficiencia energética en edificios y el efecto de los ocupantes en el consumo energético; el marco legal actual referente a la rehabilitación energética; y finalmente, una panorámica de las características del parque inmobiliario del País Vasco y su clasificación.

ABSTRACT

This chapter presents the introduction of this thesis. It starts a brief mention to the effects and motivations of energy renovations in buildings (not only energy aspects, but also social and economic aspects). Afterwards, a literature review of the different key elements of energy renovations in buildings is presented: available technologies and usual strategies (mainly based on Thermal insulation and/or thermal inertia); evaluation of energy efficiency and the effects of users and occupants on energy consumption; the legal framework on this field; and finally, an overview of the Basque building stock characteristics and its classification.

1 Introduction to energy renovations in buildings

Developing sustainable energy systems is becoming more and more important in today's world due to the depletion of fossil energy resources and the global warming problems related to the use of such resources. Reducing the need for non-renewable energy sources is a key factor in the development towards a sustainable energy future [1]. Energy use reductions can be achieved by minimizing the energy demand, by rational and efficient energy usage and by employing renewable energy sources (from the surroundings: ambient air, ground...).

As a consequence, several policies have been formulated in many countries around the world with the aim of decreasing carbon dioxide emissions, while many countries have also established policies focused on increasing the share of renewable energy utilization.

Buildings play an important role in energy consumption all over the world. Building sector has a significant influence over the total natural resource consumption as well as on the emissions released. Besides, building energy consumption has kept rising in recent years due to growth in population, increasing demand for healthy environment, comfortable and productive indoor environment, global climate changing, etc. Nowadays, the built environment uses more than 40% of the total final energy consumption in the European Union [2].

Retrofitting has become a key aspect in improving the energy efficiency of the buildings. According to data from Spanish Ministry of Public Works, there were more than 26 million dwellings in 2011 [3]. Its average annual growth during the period 2002-2008 was about 2.5 %. However, since this year 2008, this average growth has decreased dramatically, and so in 2010 the Spanish dwelling stock had an average annual growth of just 1.08%.

What is more, the population and dwelling censuses data developed by The National Statistics Institute (year 2011) show that about 56% of the Spanish dwelling stock was built up before 1980, just when the first Spanish thermal regulation (NBE-CT 79) became effective. There is a similar situation in the case of the Basque Country, where more than 70% of the dwelling stock was constructed before 1980 [4]. Therefore, in order to reduce energy consumption, the main effort must be focused on the challenges of the existing stock. Rapid improvement of energy efficiency in existing buildings is essential for a timely reduction in global energy use and promotion of environmental sustainability. Nevertheless, when the investment in existing stock to the total amount of housing investment ratio is compared, Spain still presents one of the lowest values in the U.E. (around 30%), whereas countries such as Sweden or United Kingdom present ratios of 67.9% and 62.1% respectively [5].

Meanwhile, many governments have been making significant efforts towards achieving energy efficiency improvements in existing buildings. At the same time, many researches have been carried out leading to analyse and develop different energy efficiency opportunities to improve energy performance of existing building stock, such as [6,7].

Many studies have shown the benefits that energy renovation in buildings features, but it also presents many challenges. On the one hand, retrofitting of buildings offers the opportunity to improve energy efficiency, reducing maintenance cost and improving indoor thermal comfort. In a greater scale, a good energy renovation strategy may involve an improvement in nation's energy security, reducing exposure to energy price volatility (especially in fossil fuels), and creating job opportunities.

On the other hand, one of the main challenges is the uncertainties (occupation profiles, government policy…), which affect the choice of an energy renovation strategy. The selection of the optimal strategy is also affected by the fact that the subsystems in buildings are interactive, therefore making this selection to become very complex. If there is no financial support from the government, *"Split incentives"* may suppose another challenge in countries where renting is extended, since the cost of retrofitting usually goes to the owner, whereas the benefit flows primarily to the tenants (however, this should not be a great problem in Spain, where a great amount of dwellings are used by the owners). Closely related to this point, financial limitations and other type of barriers constitute obstacles too [8].

Dealing with the above mentioned pros and cons and finding the correct balance between them is essential for any sustainable building renovation project.

2 Social effects of energy renovation in buildings

Implications and benefits of energy renovation have consequences not only in the reduction of CO_2 emissions and energy savings, but also in financial and social aspects. One of them is the reduction of the so called fuel poverty, which involves both financial and social aspects of energy in buildings. A literature review about fuel poverty is presented in Appendix 1.1.

Bearing in mind the fuel poverty, it can be stated that improving the energy efficiency of the existing stock is one of the main strategies, not only for reducing CO_2 emissions, but also for delivering affordable warmth to the fuel poor households. Both, energy savings and improvements in the indoor comfort, have to be taken into account during energy renovation projects. In fact, four objectives of housing renovation policies were identified by Baek and Park [5]: Improvement of physical performance, correspondence to the needs of elderly people, improving energy efficiency and social cohesion and area revitalization. Thus, reduction of P.E. consumption is only one more reason amongst many to promote renovation in buildings, and social issues are usually one of the main motivations for countries and public administrations who actively have conducted renovations during last years.

3 Key elements affecting building retrofits

Based on the selection presented in [8], some key elements of any building renovation are briefly described in this section.

- **Building specific information**

Geographic location, building type, size, age, occupancy schedule, operation and maintenance, energy sources or building fabric, to name but a few. Knowing the building characteristics as far as possible is the first step to define, afterwards, the optimal retrofit solutions.

- **Client resources**

Client expectations, and especially, their resources, will have a strong influence on the project targets. As it will be mentioned afterwards, this thesis will be focused on social building sector. This condition involves a much defined user profile, especially in what it refers to the incomes, as well as to client resources (the users in some cases, public administration, in others).

- **Retrofitting technologies**

Available retrofitting technologies define the scope of the energy renovation. They range from the improvement of the thermal characteristics of the building envelope, better performance of building systems, as well as the use of on-site renewables. The most cost-effective renovation solution is often a combination of energy efficiency and carbon emissions reduction measures. Therefore it is relevant to investigate where the balance point between these two types of measures in a cost/benefit perspective is. A brief summary of this point is presented in section 4 of this chapter.

- **Human factors**

Human factors affect the energy behaviour of buildings in a very important manner. They include comfort requirements, occupancy regimes, management and maintenance, activity. It is necessary to take into account this influence when an energy assessment is carried out, both before and after the renovation. A small review about how human behaviour influences building energy performance is presented in section 5 of this chapter.

- **Policies and regulations**

Policies and regulations present the energy efficiency standards, which set minimum energy efficiency requirements for retrofitting existing buildings. Governments and organizations may sometimes provide financial support and subsidies to promote energy retrofit measures. Some highlights about regulations in Europe are presented in the section 6 of this chapter.

- **Other important issues related to building renovation**

Other issues are also presented in [8]. Taking into account the contents of this thesis, the following ones have been considered the most interesting to be highlighted:

- *Each building is unique with different characteristics. The retrofit measures used in one building may not be suitable in another building.*

This way, a correct assessment of the building before any implementation is a key factor for a successful renovations.

- *The benefit of using multiple Energy Savings Measures (ESM) is not the sum of the benefits of each individual ESM, due to the interactive nature among different building subsystems and ESMs [9]*

Regarding this point, this thesis is carried out under a systemic approach, as presented in chapter 3.

- *The optimisation issue can be developed by using a model -based approach or a model-free approach.*

Thus, this thesis is basically focused on a model-based approach, in the sense that energy simulation models are used to estimate energy saving of different ESMs. After the experimental part of this thesis (Chapters 3 and 4), different energy simulation models were used and compared amongst them (Chapters 5 and 6). Afterwards, in Chapters 7 and 8, the use of one of these models is presented with some suggestions for further analyses.

4 Available technologies and usual strategies

A possible classification of energy renovation measures leading to improve the thermal behaviour of the building is summarized in Table 1. 1. Four different sub-groups are presented. Firstly, energy renovations can be gathered according to their behaviour in the building (passive or active). Besides, another classification can be done. On the one side those leaded to reduce directly the energy demand of the building (avoiding heat losses); on the other side, those that take advantage of the surrounding energy flows using them as "energy inputs" in the building (e.g. increasing properly thermal inertia allows storing thermal energy when there is a surplus, releasing it as "heat input" afterwards).

	Reducing Energy Demand	Using surrounding energy flows
Passive Behaviour	- Building fabric insulation - Windows retrofit - Reducing air tightness	- Thermal Storage (Inertia) - Natural ventilation - Heat Recovery
Active Behaviour	- Energy Efficient services	- Solar Thermal systems - Solar PV systems - Biomass systems - Geothermal power systems

Table 1. 1. Classification of building retrofit technologies

Another possible classification of the building retrofit strategies is based on which element is affected. According to this point of view, three different strategies could be identified: those aimed at improving the opaque envelope of the building, those focused on upgrading the windows characteristics, and those related to the improvement of energy systems. Some highlights about these technologies and strategies are briefly presented in this section.

4.1 Improving the opaque envelope of the building

Two different points can be mentioned in relation to the improvement of opaque envelope. The strategies can be focused either on improving the thermal resistance of the wall by augmenting the thermal insulation or modifying the thermal inertia of the building.

4.1.1 Thermal insulation

Thermal insulation is known to play a critical role in saving energy by reducing the rate of heat transfer, as well as in avoiding other kinds of problems in buildings, such as vapour condensation in walls. Thus, many studies about thermal insulation in buildings have been developed. One example is found in [10], where Papadopoulos presented an interesting state of art of insulation materials, focusing on their characteristics and use in different European countries.

Two aspects could be highlighted about thermal insulation materials: those related to materials themselves and their properties, and those related to the thickness optimization.

4.1.1.1 Thermal insulation materials

Al-Homoud emphasized in [11] the importance of thermal insulation to reduce energy demand (in this case, focusing on hot climates). He also presented an overview of the principles of thermal insulation, and gathered the characteristics of the most common building insulation materials, such as thermal conductivity, fire resistance, durability, cost per value or health risk. Similarly, Lollini et al. examined the effects of insulation on energy and environment [12]. In the first part of their work, they presented a cost analysis of the insulation materials for building applications focusing on the Italian market. Environmental impact assessment of the thermal insulation production processes is also considered in the literature. Papadopoulus and Giama examined the production process of two different insulation materials, based on the Life Cycle Assessment methodology.

Moreover, some studies can be found focusing on the relationship between moisture and thermal conductivity, such as [13], or between temperature and thermal conductivity [14].

4.1.1.2 Optimization

As presented in [15], the more insulation does not always necessarily mean the better. Determining both the type of thermal insulation and the economic thickness in the building envelope are the main subjects of many investigations. The optimized insulation thickness is dependent on the climate, the indoor conditions, the heating cost of the fuel used (which depends on fuel cost and efficiencies of the systems), the cost of the insulation material and its characteristics, the interest rate, the inflation rate and the lifetime considered.

Most studies calculate optimum insulation thickness based on either heating loads or cooling loads, whilst some others take into account both loads.

In most of the references met across, the calculations were carried out estimating the energy requirements by the degree-day concept, which is one of the simplest methods that are applied under steady state conditions [16].

Hasan presented in [17] a systematic approach for optimization and applied it to the conditions in Palestine. In [18], the optimum insulation thickness of the external wall for four climate zones in Turkey was calculated. In both cases, a lifetime of 10 years was considered for calculations. Optimizing insulation thickness, A. Hasan obtained payback periods of 1-1.7 years for rock wool and 1.3-2.3 for polystyrene insulation. Özkan and Onan took into account the effect of the glazing area in the calculation of the optimum insulation thickness [19].

In a small number of publications, dynamic methodologies are applied to compute the heat transfer in a wall. One example can be found in [20], in which dynamic thermal simulation software (Energy Plus) is used.

As far as financial analysis is concerned, three different methods are mainly used to optimize the thermal insulation thickness.

The Simple Payback Period method consists of a simple calculation based on the time required to repay the capital investment with the savings obtained with that investment. The main drawback of this method is that it does not take into account the time value of money.

The most usual method is the Life Cycle Cost analysis. It calculates the cost of a system during its entire lifetime, which can be assumed to be 10 years, 20 years, 25 years or 30 years, depending on the different authors. In this case, energy savings are evaluated by means of the so called present worth factor (PWF), which depends on both the inflation and the discount rates. One example of this is found in [21].

Finally, several studies use the so called P_1-P_2 method, e.g. [22]. The constant P_1 is a present worth factor which depends on the aforementioned lifetime *(n)*, the inflation rate for expenses related to operation *(f)*, typically the rate at which the cost of the fuel inflates, and the market discount rate *(r)*. P_2 is the ratio of the life cycle expenditures because of the additional capital investment to the initial investment. If no additional capital is invested, it can be assumed to be 1 [23].

Other aspects have been deeply studied as well, such as the influence the location the insulation layer has [24]. Further information about financial analysis applied to building renovation in general is given in Chapter 7, where economic aspects of different ESM are evaluated.

4.1.2 Thermal inertia

Thermal inertia also plays an important role in thermal behaviour of buildings. Thermal inertia and thermal insulation are characterized by different phenomena. Whereas thermal insulation reduces the heat flux through the envelope, thermal inertia stores excess heat (from sun, from the internal load of the building…) and releases it in cooler periods.

Even though a detailed study about thermal inertia on buildings is out of the scope of the thesis, it must be taken into account when energy performance of buildings is analyzed. The effects of thermal mass were summarized in [11]. Amongst other aspects, the author highlighted that building thermal mass plays a more significant role in dry climates with large diurnal ranges, whilst insulation is more significant in humid climates with small daily variations.

4.2 Improving windows

Amongst the studies focused on reducing energy consumption in buildings, reducing the heating and cooling loads with energy efficient windows is a topic of great importance. The heat flow through a window can be split into three components: heat conduction, described by the thermal transmittance of the window; solar irradiation gains stated through the *g-value*; and infiltration rates, which reflect the air leakage. Windows can involve high energy losses, as many studies show (some of them are briefly mentioned in the following paragraphs).

Thus, Bojic et al. [25] used energy simulation software to investigate the effects of various glazed units on the energy consumption of two existing flats in China. Similarly, Stegou-Sagia et al. [26] determined the effects of different glazed units, as well as various window to wall ratios of two existing buildings (residential and office building) in Greece, by means of energy simulation software. The effects of shading elements in buildings in hot climates calculated with simulation software can be found in literature too. Ebrahimpour and Maerefat [27] calculated energy consumption with the software Energy Plus, focusing on the effect of overhangs.

The study carried out by Urbikain and Sala [28], where three different methods for estimating energy savings in residential buildings were investigated, and a Windows Energy Rating System (WERS) for residential buildings in the Basque Country was proposed, presents especial interest.

4.3 Improving equipment

Improving energy systems is the other possible strategy to increase the energy efficiency of a building. Numerous studies have been carried out over the years on this issue, under very different approaches and viewpoints, focusing on a specific element of the energy system, or taking into account the whole configuration of the energy system. Some references about this point will be presented in Chapter 8, in a more defined search, paying attention to exergy assessment.

5 Energy efficiency evaluation

Five factors which must be taken into account in energy efficiency evaluation are briefly described in this section. On the one hand, a factor which has a great influence on energy performance of the building is the occupants' behaviour. Somehow, the so called *"rebound effect"* is also related to the occupants' behaviour. This issue is shortly described in subsection 5.2. On the other hand, some ratios which must be taken into consideration when the energy efficiency of a building is evaluated are suggested in literature, and these are presented in section 5.3.

5.1 Occupants' influence

Regarding occupants' influence on the energy consumption in buildings, Annex 53 states that human behaviour could have a great impact, even greater than the building characteristics or other factors [29]. Several studies have pointed out large differences in energy consumption for similar buildings [30,31] due to the occupants' behaviour. Relationships between behavioural patterns, user profiles and energy use are thoroughly analysed in [32].

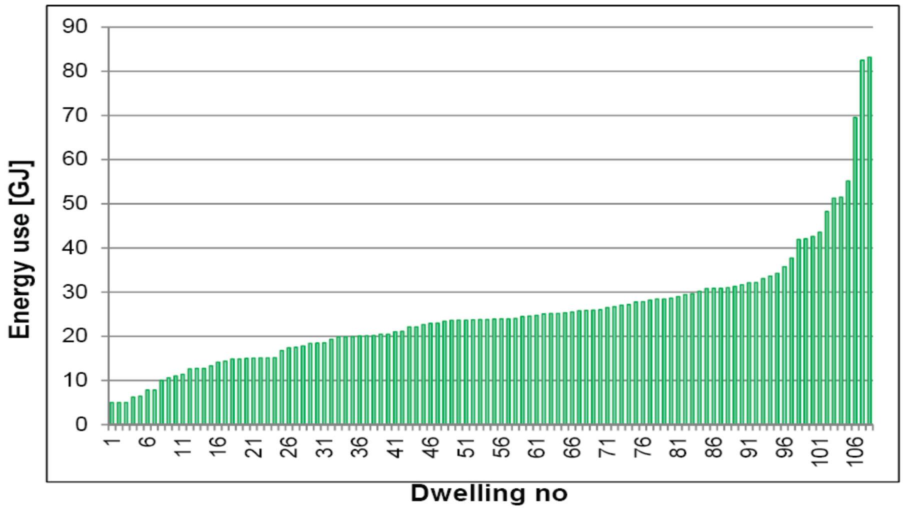


Fig. 1. 1. Energy use [GJ] in 110 similar dwellings

To illustrate this point, a representative graph obtained from [33] is depicted in Fig. 1. 1., where energy use obtained from a field survey in 110 similar dwellings (building characteristics, orientation…) are presented. Energy use of the dwelling with the highest value was 12 times bigger than energy use of the dwelling with the lowest, despite the fact that all dwellings exhibited similar characteristics, except the occupants' behaviour.

Due to this reason, household energy conservation has also been a topic of interest within applied social and environmental psychological research for a number of decades. In the 70s the background was the energy crisis, whereas currently they also are environmental problems such as global warming. Energy use is also related to human behaviour and, consequently, may be reduced through behavioural changes [34].

This effect is even greater when social building sector, target sector in this thesis, is analysed. Interesting considerations about relations amongst low incomes and occupants' behaviour in buildings are presented by Brunner et al. after a survey in Austria. The authors highlighted how whereas *in many spheres of everyday life that the standards of what is considered normal with reference to energy consumption in our society have gradually increased, (e.g. higher room temperatures in recent decades as E. Shove affirmed) many of the low-income households included in the survey react to the burdens they bear with a clear lowering of their living standards, adapting successively to conditions below the level of what would commonly be considered a "normal" lifestyle* [35].

5.2 Rebound effect

Rebound effect [36] is another factor to be considered when effectiveness of energy renovations is evaluated. The rebound effect (also known as take-back effect) was first defined by Daniel Khazzom as the direct increase on demand for an energy service as a result of improvement in technical efficiency in the use of energy (quoted in [37]). The rebound effect is the term used to describe the effect that lower costs of energy services, due to increased energy efficiency, have on consumer behaviour both individually and nationally. It is the amount of energy saving brought about by an efficiency investment that is taken back by consumers in the form of higher consumption, due either to more hours of use or to a higher quality of energy service [38]. So called backfire occurs when fuel use actually increases as a result of that fuel efficiency gain. Detailed definitions of these concepts could be found in [39].

Implications of the rebound effect in building renovations have been widely analysed in several studies such as [40]. An approach for quantifying rebound effect is presented in [41], whereas [42] shows that, in some buildings after renovations, the home energy use did not improve as much as previously had been assumed, in spite of homes had become apparently more efficient. This study affirms that there had been an increase of internal temperatures without occupants demanding it. Some studies as [43] assert that energy efficiency improvements after energy renovations might not achieve the reductions in space heating fuel consumption that were expected, even having taken into account the effect of increased comfort.

5.3 Ratios for evaluating energy efficiency in buildings

Results obtained from renovation works in buildings or dwellings can be evaluated according to different ratios and criteria. Several of the existing ratios related to energy efficiency (as well as other ratios) are presented in the European project called "Energy Efficiency E-Houses" [44]. These ratios can be gathered in four different groups:

- *Technical ratios*, which are important for calculating possible energy savings and therefore measuring the energy efficiency.

- *Environmental ratios,* which, in some way, are closely connected to the technical ones, since they depend on them. That is, the lower the energy consumption is the lower the emissions are.
- *Economic ratios*, which are also directly related to energy consumption and energy costs.
- *Social ratios*, which refer to the "Comfort". It is directly influenced by the general conditions of the building (building techniques, building envelope and indoor design subsystems), and energy systems and its management (occupants and energy systems itself).

The first three types of these ratios can be measured, whereas social ratios can only be rated in a specific way. The following list presented in Table 1. 3. and Table 1. 3 shows the aforementioned ratios. Some of them are only focused on energy savings by comparison of, at least, two different scenarios, but the majority of them can be used not only to assess an energy renovation, but also as indicators of a dwelling thermal performance itself.

Group	Subgroup	Concept	Units
Technical ratios	Heating	Heating consumption per person	[kWh/person]
		Heating consumption per square meter	[kWh/m^2]
		Heating consumption per heating degree days	[kWh/HDD]
		Primary energy consumption per square meter	[kWh$_{PE}$/m^2]
	Cooling	Cooling consumption per person	[kWh/person]
		Cooling consumption per square meter	[kWh/m^2]
		Cooling consumption per cooling degree days	[kWh/CDD]
		Primary energy consumption per square meter	[kWh$_{PE}$/m^2]
	Lighting	Lighting consumption per person	[kWh/person]
		Lighting consumption per square meter	[kWh/m^2]
		Primary energy consumption per square meter	[kWh$_{PE}$/m^2]
	Cooking	Cooking consumption per person	[kWh/person]
		Primary energy consumption per person	[kWh$_{PE}$/person]
	Water	Water consumption per person	[litre/person]
	Solar Thermal DHW	ST DHW consumption per person	[kWh/person]
		Primary energy consumption per person	[kWh$_{PE}$/person]
	Other	Other consumption per person	[kWh/person]
		Other consumption per square meter	[kWh/m^2]
		Renewable energy share in energy	[%]

Table 1. 2. Ratios to assess energy performance in buildings. Technical ratios (based on those proposed in the 3E-Houses European Project)

Group	Subgroup	Concept	Units
Environmental Ratios	HVAC, Lighting	CO_2 emissions per square meter	[CO_2/m^2]
		Avoided CO_2 emissions per square meter	[CO_2/m^2]
	Cooking, DHW	CO_2 emissions per person	[CO_2/person]
		Avoided CO_2 emissions per person	[CO_2/person]
Economic Ratios	All systems	Energy Cost per person	[€/person]
		Energy cost per surface unit	[€/m²]
		Energy cost per person per capita income	[€/person/per capita income]
		Cost per saved kWh of end energy	[€/kWh]
		Profitability (additional cost approach)	[€]
		Profitability (full cost approach)	[€]
		Public funding	[%]
Social Ratios	Comfort	Dry bulb temperature	[ºC]
		Relative humidity	[%]
		Wind velocity	[m/s]
		Predicted Mean Vote index (PMV)	[-]
		Percentage People Dissatisfied (PPD)	[%]

Table 1. 3. Ratios to assess energy performance in buildings. Environmental, economic and social ratios (based on those proposed in the 3E-Houses European Project).

6 Legal Framework. Requirements and Incentives

Legal requirements and incentives in energy renovation play an important role in the energy improvement of the building stock of a country or region. Minimum requirements required on the one hand, and different incentives to energy renovations on the other hand, determine the energy renovations and strategies followed in each place.

In 2012, a renovation policies review was presented by Baek and Park in [5]. Renovation policies in four European countries (France, Germany, Denmark and Sweden) were analysed in detail in this study. They stated that whereas improving physical performance of a building was the main objective of renovations in the past, current policies, designed to deal with the increase of elderly population, are mainly focusing on improving energy efficiency and preventing social segregation.

Two more points are noteworthy in that reference. The first one is related to the financial support for the renovation of existing buildings which varies considerably amongst the four studied countries. Thus, in Denmark welfare of the elderly is valued above other political considerations, and renovation policies are focused from this viewpoint. In Germany the level of support is classified according to the degree of energy performance achieved (as well as in the case of The Netherlands), and improving energy performance is the main objective of those policies. In France, social integration is valued above other renovation purposes. The second point is related to the compulsory controls on existing buildings. The authors affirmed that even though these controls may be highly effective for reducing GHG emissions, some difficulties exist when they try to apply them. Identifying elements where controls can be applied on, as well as organizing a survey system that selects control subjects are the key factors to be successful in this field.

In the first trimester of 2012, an analysis of regulations concerning building renovations was carried out. In this analysis, regulations of four European countries (Germany, France, United Kingdom and Spain) were compared focusing on energy behaviour improvements. The report shows that, in general, thermal requirements in Spain have been quite lower than in the other considered countries, suggesting the high improvement potential of Spanish existing buildings. Moreover, according to the report, it seems that there have been no interest on energy renovations in Spain, and it is only in these last years when this aspect is being taken into consideration, mainly due to the European Directives. This trend seems to have changed in the last years, and the society awareness on this issue seems to have increased significantly. In fact, Spanish Rehabilitation Plan 2009-2012 planed to act over more than 2 million dwellings and 150,000 buildings, with an investment of 25200 € millions (8,400 out of them from public institutions), with the aim of increasing rehabilitation ratio to 35% by 2020.

Like in other EU members, Spanish regulations are strongly affected by European Directives. In short, a relation of European Directives related to energy efficiency in buildings is listed in the left column in Table 1. 4., whilst the corresponding Spanish regulation developed to transpose and implement each directive is shown on the right column.

Finally, in relation to Directive 2010/31/EU, it can be highlighted that it was transposed, with some delay, in mid 2013, through RD 235/2013 on Energy Certification of Existing Buildings. In the Basque Country, this RD 235/2013 is adapted by means of Order of

December 12th 2012 (BOPV 1-22-2013), which stipulates the conditions of external control of Energy Certifications in buildings, and the Order of April 2nd 2013 (BOPV 5-20-2013), where the registration of energy certifications is regulated.

EUROPEAN LEGAL FRAMEWORK		SPANISH FRAMEWORK	
Year	**Name**	**Year**	**Name**
1993	*Council Directive 93/76/EEC*, to limit carbon dioxide emissions by improving energy efficiency (SAVE)	1998	RITE 98
2002	*DIRECTIVE 2002/91/EC* on the energy performance of buildings (EPBD)	2006	CTE (Spanish Technical Building Code)
		2007	RITE 07
		2007	RD 47/2007 Energy Certification of New Buildings
2004	*DIRECTIVE 2004/8/EC* on the promotion of cogeneration based on a useful heat demand in the internal energy market		
2006	*DIRECTIVE 2006/32/EC* on energy end-use efficiency and energy services		
2009	*DIRECTIVE 2009/28/EC* on the promotion of the use of energy from renewable sources and amending		Outstanding
2009	*DIRECTIVE 2009/72/EC* concerning common rules for the internal market in electricity	2012	RD 13/2012
2009	*DIRECTIVE 2009/73/EC* concerning common rules for the internal market in Natural Gas		
2010	*DIRECTIVE 2010/31/EU* on the energy performance of buildings (recast)	2013	RD 240/2011, Energy Certification of New Buildings RD 235/2013, Energy Certification of Existing Buildings
2012	*DIRECTIVE 2012/27/EU* on energy efficiency,		

Table 1. 4. European Directives and its corresponding Spanish regulation

7 Residential building stock in the Basque Country

Building stock in the Basque Country comprises around one million dwellings, with an average dwelling size of around 87 m^2. Traditionally, the majority of the residential building stock in the Basque Country has always been privately owned. 84% of this total are main dwellings (used as usual residence during most of the year), and the 73% of them are located in urban areas. The number of dwellings has increased during the last 20 years more quickly than the population has. As a consequence, the ratio *"persons per dwelling"* has decreased from 2.72 in 1991 to 2.16 in 2010, as depicted in Fig. 1. 2.

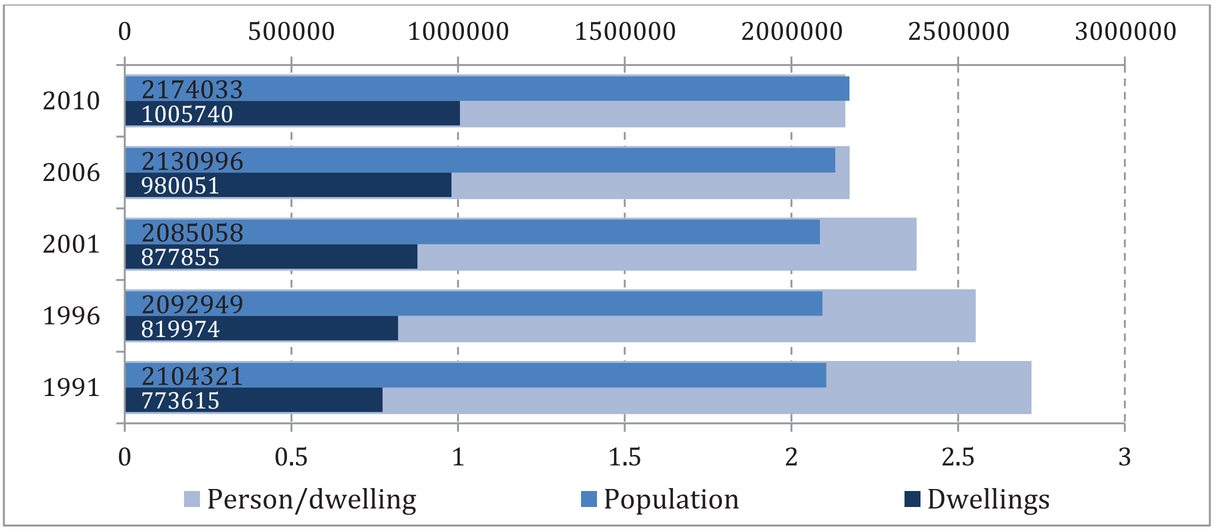


Fig. 1. 2. Number of dwellings Vs population (EVE, EUSTAT)

Two highlights about building stock in the Basque Country must be remarked. The first one is in relation to its age. According to data obtained from EUSTAT, almost 50% of the dwellings in the Basque Country were constructed between 1960 and 1980, and the mean age of the building stock is 39 years. Distribution of the dwellings according to construction year is depicted in Fig. 1. 3.

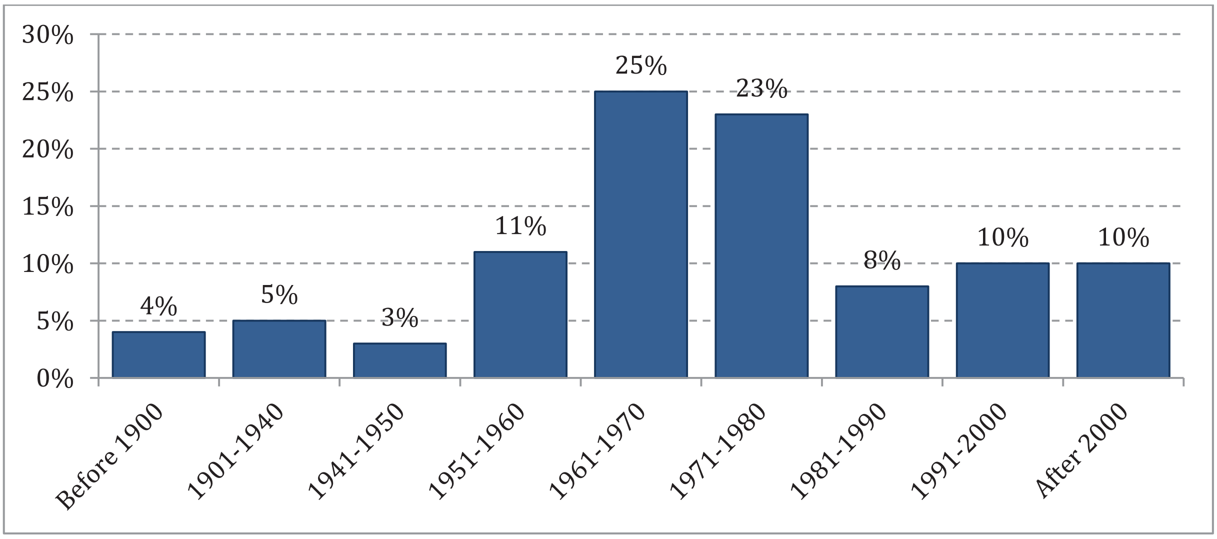


Fig. 1. 3. Amount of dwellings by construction year (EVE, EUSTAT)

Besides, the amount of new dwellings constructed has gone down drastically in the last years. During the 90s, construction sector experienced a strong growth. It reached its highest point in 2002, with 18,200 new dwellings that year. However, since 2005, construction of new buildings is showing a continuous fall (e.g. in 2011 an amount of 11,300 new dwellings were finished). It is also expected that this trend will continue, since between 2009 and 2011 only an annual average of 7500 dwelling were started.

Taking into account these two aspects, building retrofit will have an important role in construction sector in next years, and consequently the opportunity of improving the thermal performance of building stock in the Basque Country. To illustrate this point, an overview of the energy and GHG emissions figures of the building stock in the Basque Country is presented in Appendix 1.2.

7.1 Building Classification Criteria

Knowing the characteristics of the building stock is a key aspect in order to evaluate the improvement potential and, therefore, to face renovation works in a proper way. Like in other countries, building stock in Spain can be characterised by the construction period. Several other factors act upon the building features, like social and financial situations and/or building regulations. In the case of Spain, during the first decades of 20th Century, the first industrialization in some Spanish cities brought on a demographic shift in the population from rural areas to the cities, which led to an increase of building construction in the urban-industrialized areas, like Bilbao.

After the Spanish Civil War (1936-39), there was the Spanish post-war period which reached till the 50s, when the so called *'Desarrollism'* period started. This period was characterized by an industrial boom. As a consequence, during the last 50s and 60s more than 20% of the currently residential building stock in Bilbao was put up.

Nevertheless, that economic model, strongly dependent on heavy industry such as iron and steel or naval industry, collapsed with the 1973 crisis. In the particular case of Bilbao, the industrial crisis was very sharp and leaded to a big reduction in the building construction of those years.

Further on, after the Oil Crisis in the 70s, like in many other European countries, the requirements for insulation were considerably reinforced in Spain. With this aim in mind, the first Spanish thermal regulation was developed and came into force in 1979. Nevertheless, unlike in other European countries, there was no a new Spanish thermal regulation until 2006, when the Spanish Technical Building Code (CTE) [45] came into force.

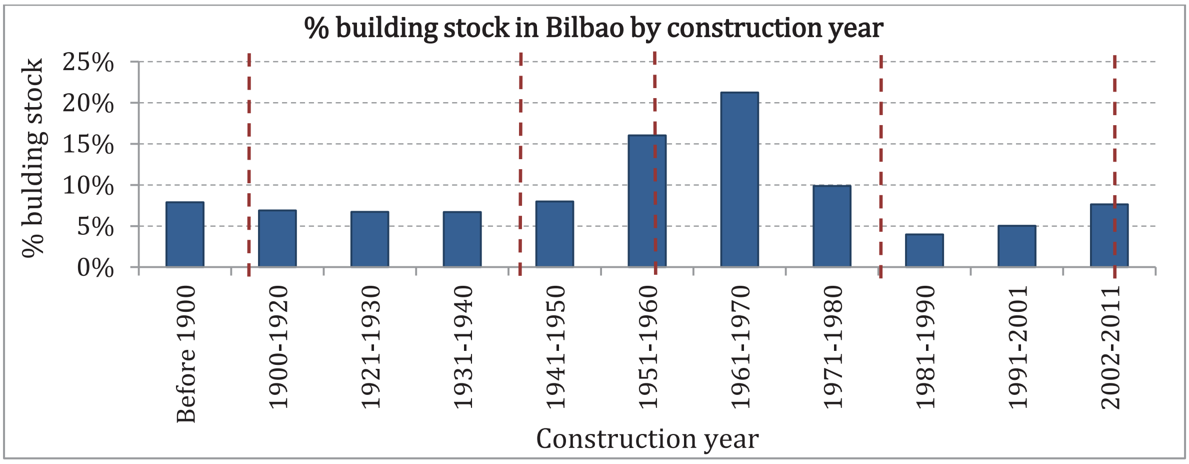


Fig. 1. 4. Building stock in Bilbao in relation to construction year (Building Stock in 2013: 10406, INE 2013)

In order to classify the building stock of the Basque Country, the city of Bilbao is taken as a reference. Detailed data about the Building stock in Bilbao, for different construction periods, is shown in Fig. 1. 4. According to mentioned milestones, as far as construction date is concerned, 5 different periods were identified since 1900, as depicted in Fig. 1. 5. Different representative constructive sections of façades in relation to each period are shown in Table 1. 5. *C* (Heat Capacity) and *U-Value* are calculated as described in Eq. 1 and Eq. 2.

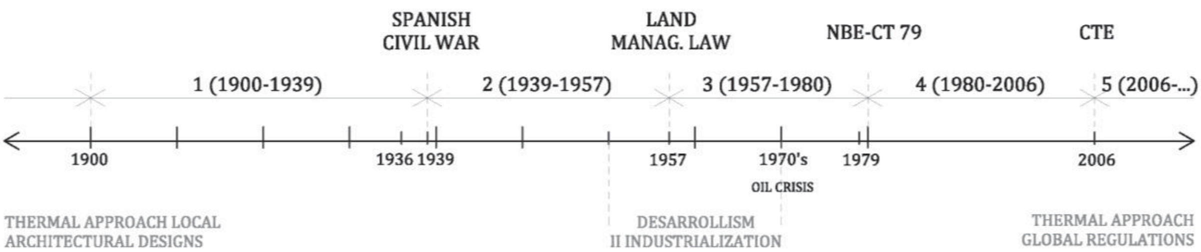


Fig. 1. 5. Construction periods during twentieth century in Bilbao (Spain)

$$U_i = \frac{1}{R_{in} + R_i + R_{out}} \qquad \text{Eq. 1}$$

$$C = \sum \rho_i \times c_{p,i} \times e_i \qquad \text{Eq. 2}$$

where:

- R_{in} is the internal surface thermal resistance (0.13 m^{2}K/W) [46]
- R_i is the surface-to-surface thermal resistance of the construction element
- R_{out} is the external surface thermal resistance (0.04 m^{2}K/W) [46]
- ρ_i is the density of the i layer material
- Cp_i is the specific heat capacity of the i layer material
- e is the thickness of the i layer

The mentioned constructive sections could be gathered into three main groups, depending on the thermal strategy. As affirmed in [47], 3 different wall constructions have been used traditionally for buildings in temperate climates. These wall constructions types are:

- **Capacity:** Traditional buildings with high thermal mass in façade, which acts as heat storage. F.a. 1 belongs to this group. Several authors, such as Dili et al. in [48] or S. Martín et al. in [49] have shown the advantages of this system (see Fig. 1. 6. left).
- **Stratification:** Multilayer envelopes with air cavities whose layers provide a slight thermal resistance, such as F.b and F.c. Many studies have focused on this point, such as K. J. Kontoleon and Bikas [50] (see Fig. 1. 6. right).
- **Resistance:** Insulation materials act as thermal barriers against heat losses. F.d and F.e belong to this group. The efficacy of this strategy has also been demonstrated by several authors such Stazi et al. [51].

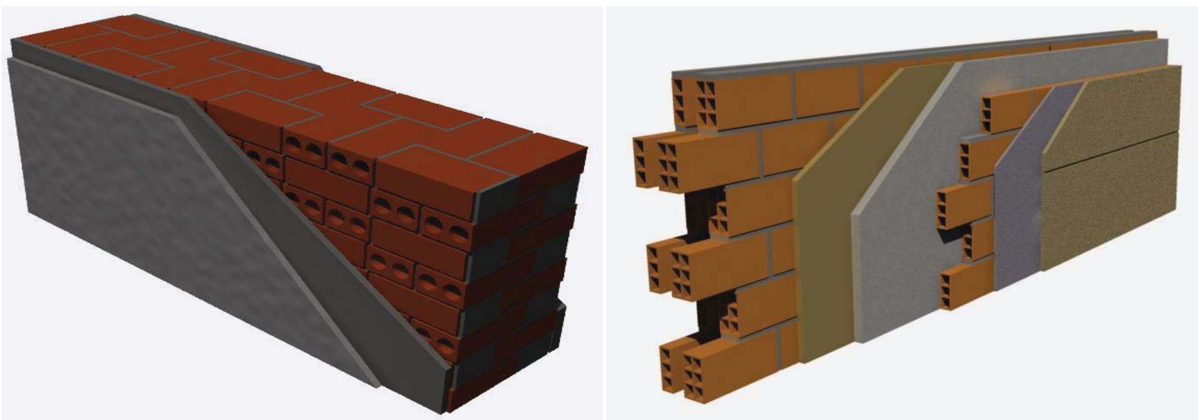
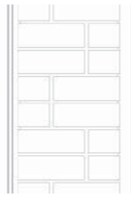
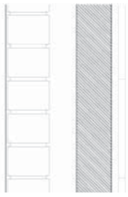
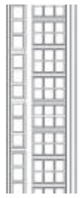
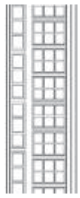
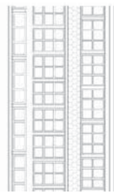
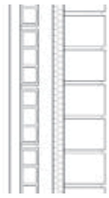
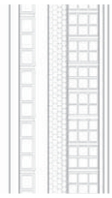


Fig. 1. 6. Two examples of typical façade construction. On the left, a type based on capacity, and on the right, a type based on stratification

Constructive sections of façades						
						
F.a	**F.b**	**F.c**	**F.c.1**	**F.c.2**	**F.d**	**F.e**
From Indoors (left) to Outdoors (right)						

U [w/m².K] C[kJ/ m².K]	Constructive Section (in-out)	Period	U [W/m².K] C[kJ/ m².K]	Constructive Section (in-out)	Period
F.a. **U: 1.11** **C:463.8**	Plaster Perforated Brick (37 cm) Cement Mortar	1	F.b **U: 1.16** **C: 359.8**	Plaster Hollow Brick (12.5 cm) Air gap Concrete Wall (10 cm) Cement Mortar (2cm)	1-2
F.c **U: 1.44** **C: 160.0**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm)	3	F.c.1 **U: 1.27** **C: 180.0**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm) Lighted Cement Mortar (2cm)	3
F.c.2 **U: 0.43** **C: 238.4**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2 cm) Thermal Insulation (4 cm) Hollow brick (9 cm) Lighted Cement Mortar (2 cm)	3	F.d. **U: 0.48** **C: 189.0**	Plaster Hollow Brick (4.5 cm) Thermal Insul. (3 cm) Air gap Perf. Brick (12.5 cm)	4
F.e. **U: 0.41** **C: 162.6**	Plaster Hollow Brick (4.5 cm) Thermal Insulation (6 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm)	4-5			

Table 1. 5. Constructive Sections of Façades (according to data provided by Bilbao Social Housing)

8 Improvement potential in social housing sector

For all the aforementioned reasons, energy efficiency improvements in buildings, and especially in social housing sector, have become a priority goal for the European Union. Due to its characteristics, such as households with low incomes and construction features of the buildings, this sector is one of the most vulnerable to fuel poverty. This way, quantifying the potential energy savings in the social housing stock must become a priority. Characterizing the social building stock is the first step, followed by the thermal behaviour analysis of this building stock.

As it can be deduced from this chapter, the improvement potential evaluation of existing building stock is a complex issue. A global approach is necessary to study the thermal performance of buildings, considering the building as a complex system composed by different subsystems. Thus, after presenting the targets and methodology of this thesis in Chapter 2, a field study of ten occupied apartments which have been assessed under a holistic approach is presented in Chapter 3.

9 Referred appendices

Appendix 1.1. Fuel poverty. Literature Review.

Appendix 1.2. GHG emissions and energy of building stock in the Basque Country in figures.

CHAPTER 2

OBJECTIVES, STRUCTURE & METHODOLOGY

RESUMEN

En este capítulo se presentan los objetivos del trabajo de investigación presentado en esta tesis, así como una breve introducción a la estructura y metodología desarrollados a lo largo de la tesis para alcanzar dichos objetivos.

ABSTRACT

The main objectives of this thesis are presented in this Chapter 2, as well as a brief introduction about the methodology and structure followed to achieving mentioned objectives.

1 Framework of the Thesis

The research developed in this thesis can be considered as a part of the research lines carried out by ENEDI Group (Energy in Buildings Group). A scheme of these research lines and the interactions among them is presented in Fig. 2. 1.

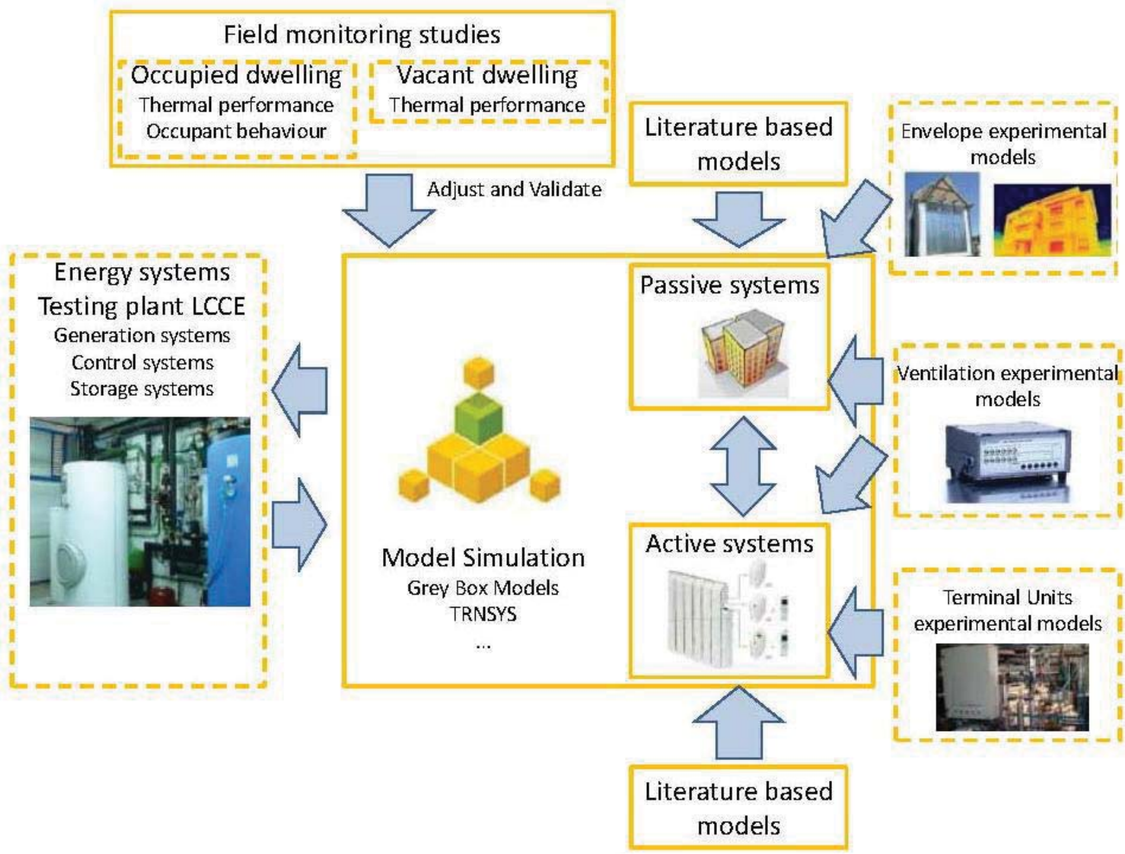


Fig. 2. 1. Scheme of the research lines carried out in ENEDI Group

In short, two different research lines are developed: an experimental one and a model simulation one. The experimental line is encompassed by experimental tests of subsystems (envelope, ventilation…) or whole dwelling by means of building monitoring studies. The experimental research, along with literature based models, allows obtaining data to feed building models and adjusting and calibrating them. On the other hand, calibrated models can interact with the Experimental Plant of Thermal Installations in Buildings of the LCCE (Laboratory for Quality Control in Buildings), carrying out "semi-virtual" tests, where simulations are run in real time, feeding the control system of the experimental plant, and the measurements obtained in the experimental plant feed at the same time the model simulation.

Thus, this research work is integrated in the scheme depicted in Fig. 2. 1. The thesis focuses mainly on two parts of the scheme: the so called "field monitoring studies" and "model simulation" parts. Hence, the experimental part of the thesis deals with monitoring studies, both in occupied and vacant dwellings. Results obtained from the experimental part will be used to feed different kind of building models, and two specifically: a grey box model and a white box model.

It is also a modular scheme. The different parts of the scheme can be used to interact with other parts of the scheme or to obtain specific information of that part. That is, in some cases, the process will be carried out wholly (from obtaining data in experimental tests to interaction between Energy Systems Plant with building models), but other times, simulation or even the experimental study will be enough to achieve the expected targets, being these parts independent themselves.

Taking this point in mind, as far as monitoring studies and building models are concerned, pros and cons of the different possibilities developed will be analyzed in the thesis, according to their goals in each case.

2 Objectives

The overarching goal of this thesis is to deal with the evaluation of energy renovation in buildings. It aims to study the analysis and optimization process of building renovation, which includes:

- Data acquisition and monitoring.
- Data treatment: Building models.
- Analysis of tools, such as exergy approach, to evaluate obtained results and identify potential improvements.

This goal is reached by the development of two different models and applying an exergy approach to the analysis of the different improvement options.

As a result of the mentioned goal, the following objectives are expected to be achieved with this thesis:

- To give an overview of the building stock in the Basque Country, focusing specially on the social building sector. Social buildings in Bilbao are deeply analysed: construction features, as well as indoor environment conditions and energy consumptions. The overall Bilbao Social Housing (BSH)[1] stock is studied and ten representative dwellings are selected and monitored for more than a year to obtain real data in occupied conditions.
- To obtain a detailed picture of the thermal behaviour during a non-occupied period of a representative dwelling from the BSH stock. To get this aim, a thorough monitoring of a representative dwelling is carried out for a period of three months, obtaining numerous data to characterize the thermal behaviour of the dwelling.
- To develop a grey box model, using the data obtained in the detailed monitoring. This model is expected to be useful for assessing the energy savings achieved when considering different renovation options.
- To define a TRNSYS model of a representative building. This TRNSYS model is validated and calibrated using the data obtained in the monitoring. The model is used, amongst other purposes, to obtain different heating demand curves, as well as energy consumption patterns. These demand curves will be useful

[1]As it is defined in its webpage (https://www.bilbao.net/viviendas/), Bilbao Social Housing is a hands-on instrument for implementing the policy on the development of subsidised housing rolled out by the Bilbao City Council, with the aim being to provide, preferably for rent, decent housing for those people who so require. Bilbao Social Housing manages and maintains a property pool made up of 3.994 homes.

in further research for assessing renovation actions in active and passive systems of these buildings.

- To compare the two building models developed: the grey box model, and the white box model (TRNSYS model), identifying the potential uses and analysing pros and cons of each one.
- To evaluate the effect on energy consumption of different control possibilities of the heating system.
- To explore and demonstrate the usefulness of the exergy approach in the assessment and development of energy systems and dwelling/building renovations.

3 Methodology and structure of the thesis

According to Zhenjun Ma et al. [52], five different phases can be mentioned during any building renovation project: (1) Building survey, (2) Energy assessment, (3) Identification of retrofit options, (4) Site implementation, and (5) Assessment of implementation. Four out of the five mentioned phases are explicitly or implicitly considered in this thesis (phases 1, 2, 3 and 5). These phases can be easily identified looking at the structure of the thesis, which can be divided into 4 sections.

The first section encompasses the introduction of the thesis, a state-of-art of the different subjects considered and the global approach of this work. This section includes the previous Chapter 1, and the current Chapter 2. The second section of the thesis develops the experimental work, which is described in Chapters 3 and 4.

An overview of the thermal performance of the social building stock is presented in Chapter 3, by means of a field study of 10 social dwellings in Bilbao. Previously, a thorough analysis of the social housing in Bilbao is carried out, comprising a revision of the different residential sector construction techniques in the region during the last 20th century. The selection of the ten case studies is carried out basing on this study. Results of heating demand and indoor conditions are presented as outcomes.

In Chapter 4, monitoring of a dwelling built in the 60's is described in detail. Two different monitoring periods are depicted in the chapter: the first one is carried out from

January to April 2012, whereas the second one is carried out from December 2012 to February 2013, once windows have been replaced. Results of both monitoring periods, as well as conclusions about methodology and procedure, are obtained from this chapter.

The third section embraces the description of the mathematical models. Two chapters are included in this part: Chapter 5 and 6, devoted to the TRNSYS model assessment and to the grey box model development, respectively.

Chapter 5 is focused on developing a TRNSYS model of the monitored building. This is a physical model and, in this case, data obtained in monitoring periods are not used to define the model itself, but to validate and calibrate it. This model is driven especially to defining possible energy demand curves of a representative building in the Basque Country for the different climate conditions. Moreover, other energy demand curves can be obtained using other constructive features for the building.

The development of a grey box model of a dwelling is shown in Chapter 6, using data gathered in the monitoring tests described in Chapter 4. The developed RC model allows obtaining the heating demand and the thermal behaviour of the studied dwelling under selected operating conditions, as well as studying the effect of several possible improvements on the thermal behaviour of the dwelling. A model of the dwelling before windows replacement is developed, and simulation of the windows replacement is run. This way, by comparison, the efficiency and effectiveness of the improvement under the same conditions can be measured. This chapter shows the usefulness of this method in some specific cases related to building renovations:

- To evaluate the state of the building before any renovation work.
- To look into the different possibilities of thermal improvement, calculating energy savings.
- To evaluate the real effect of any energy renovation, by comparing the previous and after renovation models under the same conditions and leaving out the occupants' behaviour influence.

The fourth section deals with the evaluation of different heating system controls, and the assessment of the exergy approach as a tool for evaluating and developing energy renovation strategies. Thus, in Chapter 7, the TRNSYS model is firstly used to analyse and classify different building energy renovations (passive part) according to their effect on the energy savings, and then, to evaluate different parameters relating to heating systems, such as system temperatures and system control, analysing not only effects on energy efficiency, but also the effect of energy renovation on indoor comfort. The casuistry presented in this chapter may be used in the future for defining different tests in the "semi-virtual" platform.

Afterwards, the exergy analysis of an entire building is described in Chapter 8. It brings forward the work developed in collaboration with S. C. Jansen, carried out during a three months stay at the Faculty of Architecture of TU Delft, and presented in two papers published in *Energy & Buildings* Journal [53,54].

Thus, Chapter 8 explores the usefulness of the exergy approach in the development of energy systems for the built environment, by means of the energy and exergy performance of five different energy systems for the monitored dwelling. The building energy use is considered as a whole, from its envelope to energy generation, and taking into account improvements both in the envelope and in the building systems.

Finally, a summary of the main conclusions of the thesis, followed by contributions and future research objectives are presented in Chapter 9

PART 2
EXPERIMENTAL STUDY

"The experimenter who does not know what he is looking for will not understand what he finds"

Claude Bernard (1813-1878)

CHAPTER 3

FIELD STUDY OF THERMAL BEHAVIOUR IN SOCIAL HOUSING APARTMENTS

RESUMEN

Este capítulo tiene por objetivo describir la metodología desarrollada para el análisis del comportamiento térmico de viviendas y/o edificios desde un enfoque global. Se presenta una visión general del comportamiento térmico de la vivienda social en un clima templado (Bilbao). 10 viviendas representativas del parque fueron seleccionadas, en base a la clasificación presentada en el Capítulo 1. Una monitorización se llevó a cabo durante 10 meses en los que se obtuvieron datos de temperatura, humedad y consumos de las viviendas. Entre otros factores, en este capítulo se muestra la importancia que toma la influencia del ocupante en el comportamiento térmico final de los edificios. Asimismo, el artículo "Field assessment of thermal behaviour of social housing apartaments in Bilbao, northern Spain", publicado en la revista Energy & Buildings en 2013 [55]recoge los datos principales presentados en este capítulo.

ABSTRACT

This chapter aims to describe a methodology for analysing the thermal performance of buildings under a holistic approach. An overview of the thermal performance of the social housing stock in a city with a mild climate (Bilbao) is presented. Ten (10) representative dwellings were selected, based on the classification presented in chapter 1. A field study was performed during 10 months. Results of heating consumption as well as indoor conditions are presented. Amongst other factors, the occupants behaviour influence plays an important role in the final thermal performance of the dwellings. Moreover, the main highlights of this chapter were presented in the paper "Field assessment of thermal behaviour of social housing apartments in Bilbao, northern Spain", published in Energy & Buildings journal in 2013 [55].

1 Introduction

Indoor temperatures and humidity in dwellings are key indicators of the occupant's thermal comfort. Moreover, indoor temperatures also drive energy consumption for space heating relative to external conditions. Many energy models have been developed in the last years to predict changes on energy consumption as a result of energy renovations. As affirmed in [56], the assumptions for the operating conditions are usually based on profiles considered as standard, rather than those obtained from field measurements.

But differences between standards and real conditions of the dwellings can lead to mistaken results of energy consumption being very sensitive to variations of setpoint temperature. For example, in a recently published study of a centrally heated dwelling in the UK, it was found that a 2ºC rise in the heating demand temperature resulted in a 15% increase in energy consumption, even though this relationship is also very strongly influenced by some building characteristics, such as the air infiltration rate, the thermal characteristics of the envelope or the heating system used.

Thus, having performed field measurements on the indoor conditions it is necessary to obtain a more accurate analysis of the energy renovation potential in the social building sector. The fact is that there is a great lack of empirical data on indoor temperatures and its corresponding energy consumption especially in this social building sector.

Hence, in this chapter the study of ten occupied apartments which were assessed under a holistic approach in order to have an overview of their thermal performance is presented. There is no shortage of similar field studies available in the literature to assess thermal comfort and energy consumption in low energy buildings [30], office buildings [57] or vernacular or historical buildings [48,49,58]. Nevertheless, it is not so common to come across this kind of studies applied to the social housing sector. One exception could be the large-scale surveys carried out by aforementioned Warm Front Project [59].

2 Objectives of this chapter

In Chapter 1 an overview of building renovation regulations and general constructive features has been given. However, only taking into account these aspects is not enough, and the global thermal building performance must also be known when building renovation issues are dealt with. Thermal building behaviour has to be understood as a result of interaction of several factors into a complex system.

Thus, a field investigation of architectural and thermal behaviour of Social Housing Stock in Bilbao is presented in this chapter. Along this line, the main aims of this chapter are:

- To present and define a holistic approach to deal with thermal building performance.
- To provide an insight of the thermal performance of Social Housing Stock in Bilbao, Northern Spain, and identify the real energy consumption in social dwellings in a city with mild weather conditions both in winter and summer.
- To identify the potential improvement of the social housing stock.
- To provide the energy consumption and the indoor environment field measurements of these ten dwellings, which can be used in future researches in models fed by operating conditions, not based on standards but on field measurements.
- To provide a comparative and qualitative analysis of thermal building performance of ten selected dwellings, representatives of the social building stock.

This chapter does not only focus on energy consumption itself, but also on assessing thermal comfort in the dwellings. Aspects related to health issues mentioned in Chapter 1, however, are out of scope of the present chapter, although they must be taken into account when benefits of energy renovations are considered.

To accomplish these goals the building stock of social housing in Bilbao was classified according to the criteria described in Chapter 1. Based on this classification, 10 social housing apartments, representatives of the different construction periods of the 20th Century were studied using a holistic approach. Results obtained from this survey provide an important database to quantify the potential benefit of retrofitting the existing social building stock in the Basque Country.

3 Approach

A building's climatic-response is determined by the prevalent exposure conditions (micro-climate) and the ability of the building envelope and building techniques to regulate thermal transmittance (building physics). This ability to passively thermo-regulate indoor thermal comfort is determined by the materials configuring the envelope geometry. At the same time, indoor design, occupants' energy system use and the energy systems themselves will define the global thermal performance of the building.

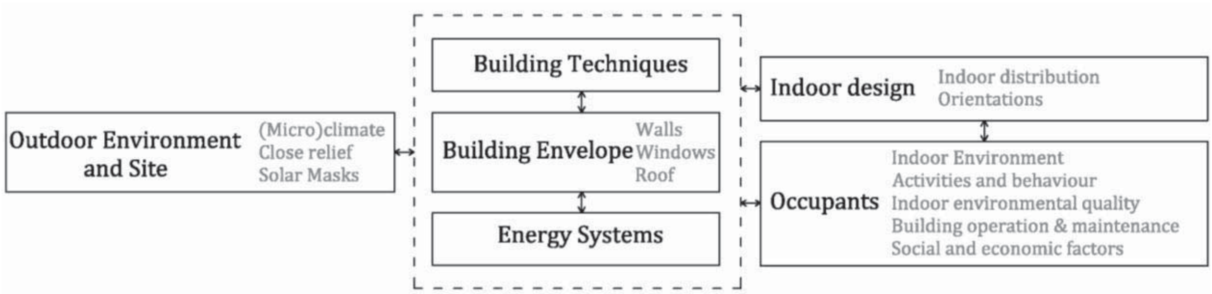


Fig. 3. 1. Subsystems for investigation

To represent all of the aforementioned issues, a holistic approach was applied in this study. In this systemic approach, buildings are treated as open systems considering interactions between them and their environment. Similar approaches are explained and used in [58] with historical buildings and in Annex 53 as well, which states that building energy consumption is mainly influenced by six factors: climate, building envelope, building services and energy systems, building operation and maintenance, occupants' activities and behaviour and indoor environmental quality provided [29]. Similar factors are also mentioned in [60]. The approach used in this chapter is based on these references. The different considered subsystems are shown in Fig. 3. 1.

Building techniques, building envelope and energy systems could be considered as a boundary subsystem, which makes a separation between the outdoor environment and occupants or indoor environment [61]. The combination of all these factors will give the energy performance of the dwelling as a result.

Building renovations are usually focused on the improvement of 3 subsystems: building techniques (such as thermal bridges), building envelope and energy systems. However, although the objective of any improvement in the building energy performance is usually within these subsystems, it is important to take into account the interaction amongst building techniques, building envelope and energy systems, and the other subsystems, and the consequences of these interactions on the overall energy consumption. The study presented in this chapter was carried out bearing this approach in mind.

4 Methodology

This field study was carried out in Bilbao during a period of 10 months, from November 2011 to September 2012. All apartments were occupied during the monitoring period. Due to some municipal housing policies over the last decades, some of the studied dwellings are not property of the city council and rented to the occupants. In fact, three of them belong to the occupants. This point is closely connected to the economical factors, being an indicator of household incomes (the users who are owners have higher incomes than the users who are not), which, as mentioned before, could affect the user behaviour, so it is also taken into account. Different heating systems were used in the selected dwellings: out of the 10 dwellings, 4 are heated by natural gas heating systems, 3 by electric heaters, 1 by kerosene heater, 1 by butane heater and 1 didn't have any kind of heating system. All the studied dwellings had no mechanical ventilation system.

The climate for the studied area (Bilbao), located in latitude 43º N, is oceanic. The proximity to the ocean makes summer and winter temperatures relatively temperate, with low intensity thermal oscillations. The average maximum temperature is between 25 °C and 26 °C during the summer period, while the average minimum in winter can vary between 6 °C and 7 °C.

4.1 Selection of study-cases

The selected sample was composed of ten different dwellings of the Bilbao Social Housing apartment stock (Fig. 3. 2). Each apartment was selected according to features defined in Chapter 1 in "Building Classification Criteria". This way, all aforementioned periods were represented by at least two dwellings. One new dwelling, built in 2005 (only a year before the Spanish Technical Building Code came into force) was also included in this study. The blue dot marks where the meteorological station which provided the climatic data during monitoring period is.

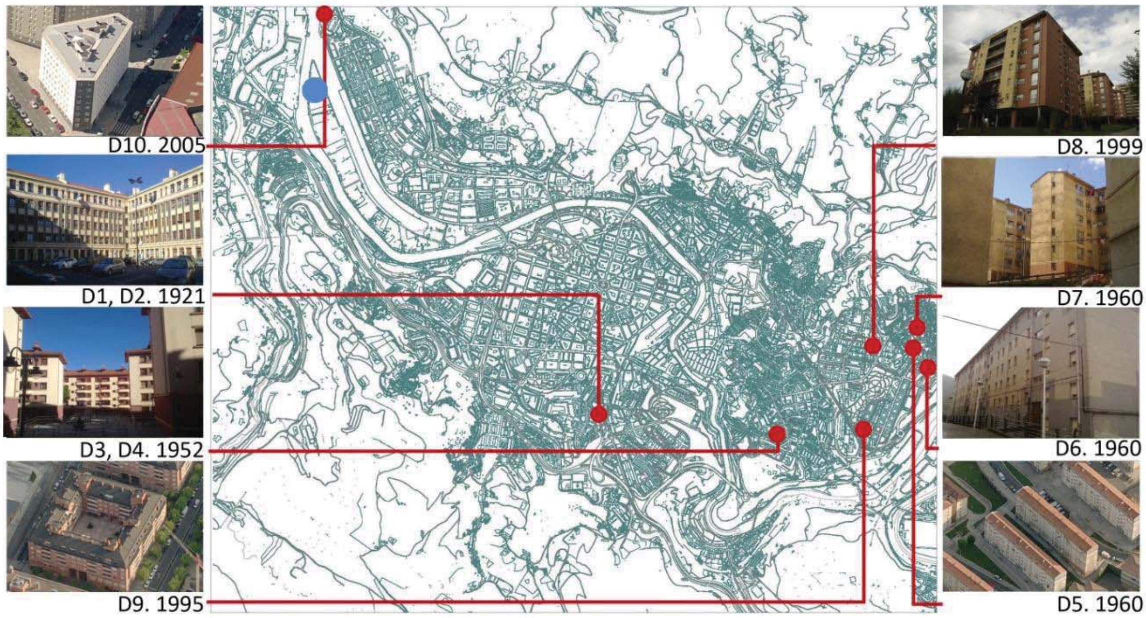


Fig. 3. 2. Location of the ten case-studies

As far as construction features are concerned, these dwellings can be considered representative not only of the social housing in Bilbao, but also of the social housing stock of main urban areas in the region.

Each dwelling is considered as a complex structure which has been modified in some cases in order it to adapt to the different needs of their occupants. Different aspects and features were taken into account for each dwelling, according to the approach described in section 3. Some of these aspects are summarized in Table 3. 1 according to the levels presented in Fig. 3. 1.

The construction year, indoor area of the dwelling (in square meters), façade construction (linked with that classification presented in Chapter 1), calculated U value of the façade, windows characteristics (glass and kind of frame, U value of the window and level of infiltration), used heating system and finally, whether the user is tenant or the owner of the dwelling is shown in this table for each dwelling. Occupation factors, such as occupant age, number of occupants or period of occupation, were considered as well.

		I.E.	Envelope			Windows			E.S.	Occ
Nº	Year	A. (m²)	Sec.	U_{wall} [W/m².K]	C_{wall} [kJ/m².K]	Wind.	U_{win} W/m².K	Inf.	Heating System	Property type
D1	1921	53.33	F.a	1.11	463.8	Wood (f); Gass 6	5.35	High	Butane	Rented
D2	1921	45.68	F.a	1.11	463.8	PVC (f); Glass 4/6/4)	2.38	Low	Elect. heater	Rented
D3	1952	51.5	F.b	1.16	359.8	Al (f); Glass 6 – Wood (f); Glass 6	5.35-5.70	High - Med.	Elect. heater	Rented
D4	1952	51.5	F.b	1.16	359.8	Al (f); Glass 4/6/4)	3.37	High	None	Rented
D5	1960	47.68	F.c.1	1.27	180	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D6	1960	39.7	F.c.2	0.43	238.4	PVC (f); Glass 4/6/4)	2.38	Low	Elect. Heater	Rented
D7	1960	47.65	F.c.1	1.27	180	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D8	1995	68.3	F.d	0.48	189	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Rented
D9	1995	87	F.d	0.48	189	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D10	2005	58.5	F.e	0.41	162.6	PVC (f); Glass 4/6/4)	2.38	Low	Kerosen e	Rented

Table 3. 1. Summary of the characteristics of the studied dwellings, according to the subsystems presented in Fig. 3. 1 (Indoor Environment, Envelope, Windows, Energy Systems and Occupants)

4.2 Field study

Based on the aforementioned systemic approach, a measurement campaign was carried out for each dwelling. The obtained data were combined in six groups according to the six subsystems presented in Fig. 3. 1. Outdoor environment data were collected from field measurements, web data and bibliographical sources. Building techniques data for the building envelope thermal evaluation were obtained by IR techniques. Building components data were collected from bibliography sources and from a visual inspection. Energy systems were evaluated from energy bills and questionnaires filled in by the users. Indoor design data were obtained from plans, field measurements and visual inspections and "occupants" subsystem data were obtained mainly from questionnaires, which were complemented and validated with field measurements data (Table 3.2).

Subsystem	Data	Information sources
Outdoor Environment and Site	Geographical parameters (Lat, Long)	Field measurements, Bibliographical sources
	Climatic area, solar radiation	Field measurements, Bibliographical sources
	Microclimate, outdoor temperature and RH	WEB data, Recorded Data. Visual inspection
Building Techniques	Thermal Bridges	Thermal imaging
Building Envelope	Thermal characteristics of the walls	Bibliographical sources
Energy Systems	Energy Systems, Energy cons.	Questionnaires, Energy bills
Indoor design	Indoor distribution	Plans, field measurements, visual inspection.
Occupants	Indoor Environment: Plans, sections, Façades	Field measurements
	Activities, Behaviour, environmental quality	Questionnaires, Field measurements

Table 3.2. Collected data

4.3 Data collection

4.3.1 Temperature and humidity

Several temperature and humidity monitoring studies can be found in literature. The criteria presented in [62] have been a reference for this study. According to this criterion, detailed measurements of indoor temperature and humidity were collected using Thermo Hygrometers '*Temp-RH Hobo Data loggers*' (HOBO U12-011). Their resolution is 0.03 ºC (25 ºC) for temperature and 0.03 % for relative humidity, and their accuracy is ±0.35 ºC and ±2.5% respectively. They were placed far away from direct heat or humidity sources and windows, and approximately 1 m above the ground. This high was chosen since, in the event of air temperature stratification, air temperature 1 m above the ground can be assumed to be closer to occupants' thermal sensitivity. Moreover, some other studies have chosen this position as well.

The data loggers were programmed to collect data with a 10 min. frequency. Longer time steps can be found in literature, from 20 min. [63] to 2 h. [58]. However, in this study a 10 min. time step was used because it allowed some information about occupant actions, such as heating system activation or ventilation patterns to be had. Temp-RH data loggers had been previously calibrated and validated in the LCCE of the Basque Government. A Thermo Hygrometer (TH) was installed in the most occupied room during a typical day (usually the living room) of each apartment and in some of them another TH was installed in the main bedroom, according to the indoor environment (Fig. 3. 3; all cases are depicted in appendix 3.2.). Similar criteria is followed in other studies, e.g. in [58] or in [43].

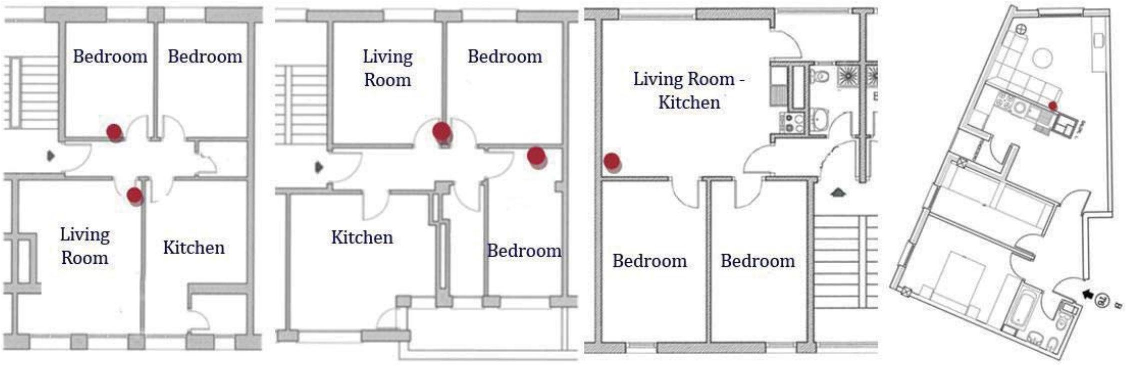


Fig. 3. 3. Layout of some case studies (D1, D3-D4, D6 and D10)

The outdoor temperature and relative humidity were taken from a meteorological station of the Basque Government located in Deusto, Bilbao. This station measures variables such as air temperature, relative humidity, global horizontal irradiation and wind speed, among others, with a sampling frequency of 10-min. Its location in the city is also depicted in Fig. 3. 2, marked with a blue dot.

4.3.2 Energy consumption

Some assumptions were made to estimate heating consumption in winter. The information sources were not the same in all the dwellings: in most of the cases (six of them) energy bills were provided, but in two dwellings, heating consumption data were collected in questionnaires. In the remaining case (D4) no heating system was used. Actually, a small electric heater was used punctually, and its consumption was considered negligible when summer and winter consumptions were compared, so heating consumption was assumed to be 0 kWh/m^2.year. In case D5 some meter readings complemented the information from natural gas bills.

Collected data are presented for each dwelling in Table 3. 3, where energy consumptions related to the source during the indicated period is presented. However, it was necessary to standardize these data sets, because some of them were electricity consumption of the whole dwelling and others were natural gas consumption for both Domestic Hot Water (DHW) and the heating system. In all the selected cases, the heating consumption was extrapolated to the same period (1st Dec. – 1st Apr), due to the fact that the heating system was working from the second or third week of December till the last days of March in every dwelling.

$$En_B = \frac{En_{sum}}{n_{sum}} \quad \text{Eq. 3}$$

$$H_{Wint} = En_{Wint} - n_{Wint} \cdot En_B \quad \text{Eq. 4}$$

Eq. 3 and Eq. 4 were used to calculate the estimated heating consumption in winter, where En_B is the base energy consumption per day, En_{sum} is the energy consumption in summertime, En_{wint} is the energy consumption in wintertime, H_{Wint} is the estimated heating consumption in winter, n_{sum} is the evaluated number of days of the summer period and n_{wint} is the evaluated number of days of the winter period. En_B (kWh/day) was calculated considering the energy consumption in summer per day. This method is a good approximation to estimate the heating consumption, especially when heating and DHW is supplied by a natural gas boiler. DHW consumption is assumed to be similar for the whole year, so heating consumption, which only happens in winter, is calculated as natural gas consumption in winter (DHW + Heating) minus natural gas consumption in summer (DHW). This method is also used when the energy supply of the dwelling is purely electrical.

Therefore, the following assumptions were made in order to estimate the heating consumption during the winter period:

1) 159 kWh / Butane Gas Cylinder.
2) Base consumption (without heating) per day is calculated according to data from summer period (Eq. 3). The estimated heating consumption in winter is obtained by means of Eq. 4.

3) In this case, the electrical base consumption is assumed according to IDAE (due to variability of the dwelling energy consumption in summer). The estimated heating consumption in winter is obtained by means of Eq. 4.
4) Using as reference 43,400 kJ/kg for LHV of Kerosene. (9.4 kWh/l)

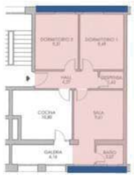
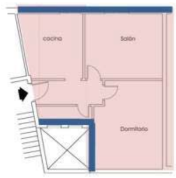
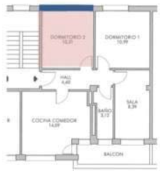
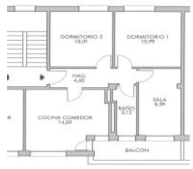
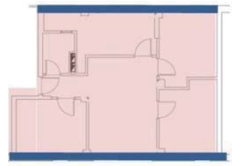
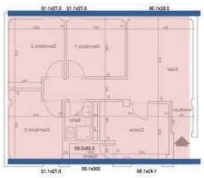
	Collected data			Estimated consumption 1 Dic- 1 Apr
	Source	Period	Consumption	Assumptions
[D1]	Questionnaires	Whole Winter	4 butane gas cylinder	1)
[D2]	Electricity Bills	24 Nov-20 Mar	1840 kWh	3) (Base consumption: 4.16 kWh/day)
[D3]	Electricity Bills	12 Dec-11 Apr	863 kWh	3) (Base consumption: 4.16 kWh/day)
[D4]	N/A	N/A	NEGLIGIBLE	NEGLIGIBLE
[D5]	Natural Gas Bills	18 Dec-17Apr	3600 kWh	2) (Base consumption: 6 kWh/day)
[D6]	Electricity Bill (Annual)	Not enough data available		
[D7]	Natural Gas Bills	15Nov-14Mar	3936 kWh	2) (Base consumption: 6 kWh/day)
[D8]	Natural Gas Bills	15Nov-14Mar	2145 kWh	2) (Base Consumption: 6.7 kWh/day)
[D9]	Natural Gas Bills	15Nov-14Mar	3990 kWh	2) (Base Consumption: 5 kWh/day)
[D10]	Questionnaires	Whole Winter	20 l kerosene	4)

Table 3. 3. Heating consumption data collected

	Estimated consumpt. [kWh]	Heated rooms	m^2 (heated area)	Cons. [kWh/m^2.year]	Corrected Consumpt. [kWh/m^2.y]
[D1]	636	Bedroom (x2), Kitchen	33.87	11.93	18.78
[D2]	1354	Whole dwelling	45.68	29.64	29.64
[D3]	356	Living room	10.31	6.91	34.52
[D4]	NA	NA	NA	NA	NA
[D5]	2880	Whole dwelling	47.65	60.44	60.44
[D6]	Not enough data available				
[D7]	3331	Whole dwelling	47.65	67.37	67.37
[D8]	1335	Whole dwelling	68.3	19.55	19.55
[D9]	3385	Whole dwelling	87	38.91	38.91
[D10]	188	Living room	12.6	3.21	14.92

Table 3. 4. Heating Consumption collected and calculated data

Moreover, the fact that not all rooms were heated in some dwellings was another problem to standardize the heating consumption estimation. As questionnaires and measurements shown, only one or two rooms were heated in some dwellings (D1, D3 and D10, see Table 3. 5). In order to adequate the consumption and having a more representative value of kWh/m^2, a relation between heat consumption and real heated area was also calculated for each case. These values, which were used as a reference to compare the studied dwelling with others, are presented in Table 3. 4.

Geometrical features of the heating area				
				
D1	D2	D3	D4	D5
				
D6	D7	D8	D9	D10

	m^2 façade (of heated area)	EF		m^2 façade (of heated area)	EF
[D1]	*Apartment Façade:* 32.5 (Fachade) 6.5 (Windows; 20%) *Heated Area Façade:* 22.5 (Fachade) 4.5 (Windows; 20%)	1.67	[D6]	*Apartment Façade:* 27.9 (Fachade) 7 (Windows; 25%)	1.43
[D2]	*Apartment Façade:* 29.75 (Fachade) 5.55 (Windows; 20%) *Heated Area Façade:* 29.75 (Fachade) 5.55 (Windows; 20%)	1.51	[D7]	*Apartment Façade:* 41.25 (Fachade) 10.23 (Windows; 25%) *Heated Area Façade:* 41.25 (Fachade) 10.23 (Windows; 25%)	1.16
[D3]	*Apartment Façade:* 35 (Fachade) 8.75 (Windows; 25%) *Heated Area Façade:* 7.5 (Fachade) 1.95 (Windows; 26%)	1.37	[D8]	*Apartment Façade:* 46.8 (Fachade) 11.5 (Windows; 25%) *Heated Area Façade:* 46.8 (Fachade) 11.5 (Windows; 25%)	1.71
[D4]	*Apartment Façade:* 35 (Fachade) 8.75 (Windows; 25%)	N/A	[D9]	*Apartment Façade:* 42.9 (Fachade) 10.7 (Windows; 25%) *Heated Area Façade:* 42.9 (Fachade) 10.7 (Windows; 25%)	1.59
[D5]	*Apartment Façade:* 41.25 (Fachade) 10.23 (Windows; 25%) *Heated Area Façade:* 41.25 (Fachade) 10.23 (Windows; 25%)	1.16	[D10]	*Apartment Façade:* 35.9 (Fachade) 7.7 (Windows;21%) *Heated Area Façade:* 14.95 (Fachade) 2.72 (Windows; 18%)	0.86

Table 3. 5. Geometrical features of the heating area in each dwelling. (EF: Envelope Factor= m^2 heated area /m^2 façade of heated area)

Mentioned information about the heated area in each dwelling, as well as some geometrical features of the envelope are summarised in Table 3. 5, as previously mentioned. In the first lines, the plans of each dwelling are depicted. The heated area is highlighted in red. Below, geometrical values are presented for each dwelling, and an "Envelope Factor" (EF), which is the ratio between heated area and area of the exposed façade of heated area, is calculated.

4.3.3 IR Techniques

A thermal imaging inspection was also carried out during the investigation of two of the aforementioned subsystems: building envelope and building techniques. Infrared radiation is emitted by all objects above absolute zero. The IR camera measures this radiation and gives the surface temperature according to the black body radiation law which have to be corrected with the emissivity for grey bodies.

Thermography allows detecting thermal heterogeneities of the envelope, like thermal bridges, or variations of the U-Value of different areas of the façades. Some aspects which have a strong influence on IR assessment are defined below [64]:

- **Emissivity (ε).** It is the ratio of energy radiated by a surface to energy radiated by a black body (BB) at the same temperature.

  $$\dot{Q}_{rad}^{BB} = 5.67 \times 10^{-8} \times T_{surf}^{4}$$

  Many of the construction materials have an ε from 0.85 to 0.95. Thus, emissivity is usually fixed in 0.9 in an infrared camera. This parameter must be taken into account if a low emissivity material is evaluated, because it could lead to mistakes in the IR Camera readings.

- **Relative Humidity (RH).** IR techniques can not detect presence of mould. However they can identify critical areas where mould could grow. In some cases, Relative Humidity higher than 50% may be enough for its development.

- **ΔT.** It is recommended at least a 10-15 ºC temperature difference between indoors and outdoors when IR analysis is carried out.

- **Solar Radiation.** IR images must be taken avoiding sunny hours, to avoid the effect of the sun on walls. In this way, also thermal inertia of the wall must be taken into account. After the sunset, a façade releases the heat absorbed during the day, and this effect can be misunderstood in the IR images as heat losses.

Other factors, like distance to the measured element, air temperature, air relative humidity, wind or reflected temperature, must be taken into account as well, especially if quantitative analysis is carried out.

According to these parameters, the infrared thermographs were performed with a FLIR infrared Camera Model PS60 which has an accuracy of 2% in temperature measuring. The emissivity used in the calculations was 0.9 because most of building construction materials have high emissivities. The inspection was carried out during two nights: 28th February 2012 (1 am - 4 am) and 2nd March 2012 (0 am - 1 am). During the first night collection, the air temperature was 6.5 ºC and there was a RH of 88%. During the second night, the air temperature was 9 ºC and there was 88% RH. No rains were recorded in the previous days.

4.3.4 Thermal comfort

Special attention was paid in this study to thermal comfort. Thermal comfort and healthy indoor environment are two of the most important targets of any building. In this approach, these aspects were included in “Occupants” subsystem. Different factors determine a comfortable environment, such as air temperature, relative humidity, air movement, human activity and type of clothes, to name some of them. Predicted Mean Vote (PMV) or Predicted Percentage Dissatisfied (PPD) indexes are used to assess thermal comfort. PPD is defined in terms of the PMV. PMV depends on activity, clothing, air temperature, mean radiant temperature, air velocity and humidity [65]. As this long term monitoring study was carried out in occupied dwellings, there were some limitations with the used instrumentation, and all of the above mentioned parameters were not registered during the research. For this reason, a simplified method was used to assess thermal comfort in dwellings, which is described in section 6.6.

4.3.5 Questionnaires

To complete this study, the occupants of each dwelling filled in some questionnaires during the monitoring period. The information supplied by the questionnaires was related to occupant behaviour and awareness, energy consumption, building services, indoor air quality and occupation patterns. The questionnaire template is attached in Appendix 3.1.

4.4 Data analysis

Different analyses of the collected data were made according to different moments of the monitoring period:

- Seasonal values were analyzed for winter (Dec-Jan-Feb-March), tempered season (April-May) and summer (June-July-August).
- The coldest period of 15 days, (1-14 February)
- One period of 15 days in Spring
- The hottest period of 15 days, (8-22 August)
- Short time periods (48h). The hottest (18^{th}-19^{th} August), the coldest (8^{th}-9^{th} February) and a tempered period (24^{th}-25^{th} April).

The following values for each dwelling were provided: maximum and minimum values, average values, standard deviations and correlations between indoor and outdoor temperatures.

5 Results

U-values (Fig. 3. 4) were clearly gathered in two defined ranges. One was the group related to the newest (built after the 80s) or energy renovated buildings, which have their U-values between 0.40-0.50 W/m^2.K. The other group referred to buildings built before the first thermal regulation (1979) with a U-value between 1.10-1.30 W/m^2.K.

As expected there were two clear correlations. First of all, the difference between average outdoor and indoor temperatures is calculated (ΔT). The higher ΔT is, the higher the heat consumption is. As it was also expected, when two dwellings with similar heating consumption are compared, the higher ΔT corresponds to the lower U-value.

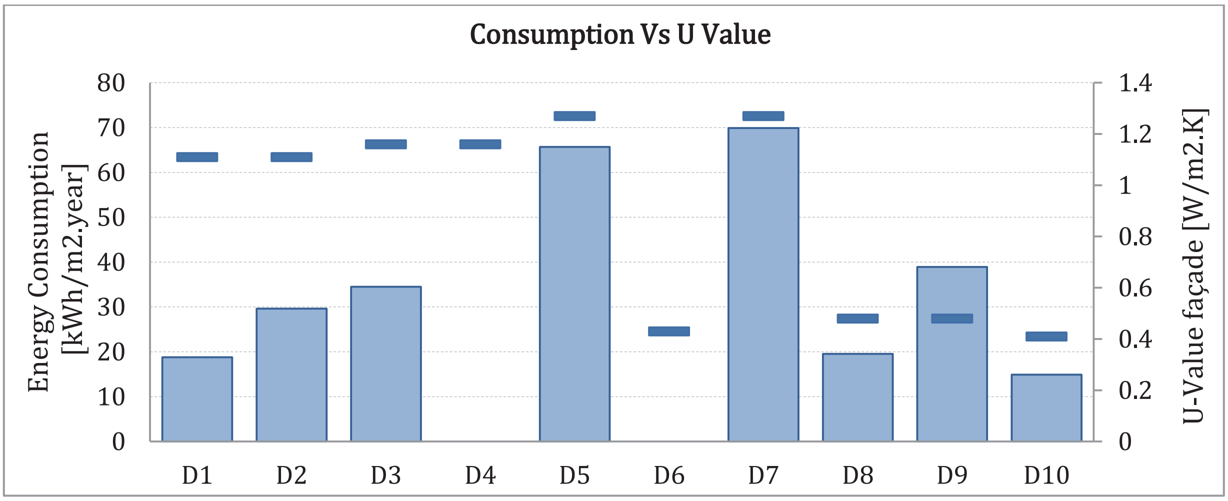


Fig. 3. 4. Relation between energy consumption and U – Value

This trend is clearly shown in the graph depicted in Fig. 3. 5. Even though the comfort zone in winter is defined by ASHRAE in [66] to be between 20 ºC and 24 ºC, the thermal comfort limits were selected according to [49] to be 18 ºC ±2 ºC. ΔT in this graph is the difference of the average indoor and outdoor temperatures in winter. Thus, dotted broken, red lines represent these comfort limits for winter (20 ºC and 16 ºC, which makes 5.83ºC and 9.83ºC of ΔT). The time-constant (τ) was calculated dividing C [J/m^2.K] by U [W/m^2.K], and it is presented in hours [h], according to [67]. This concept was considered useful in this graph since it encompasses both C and U in only one term.

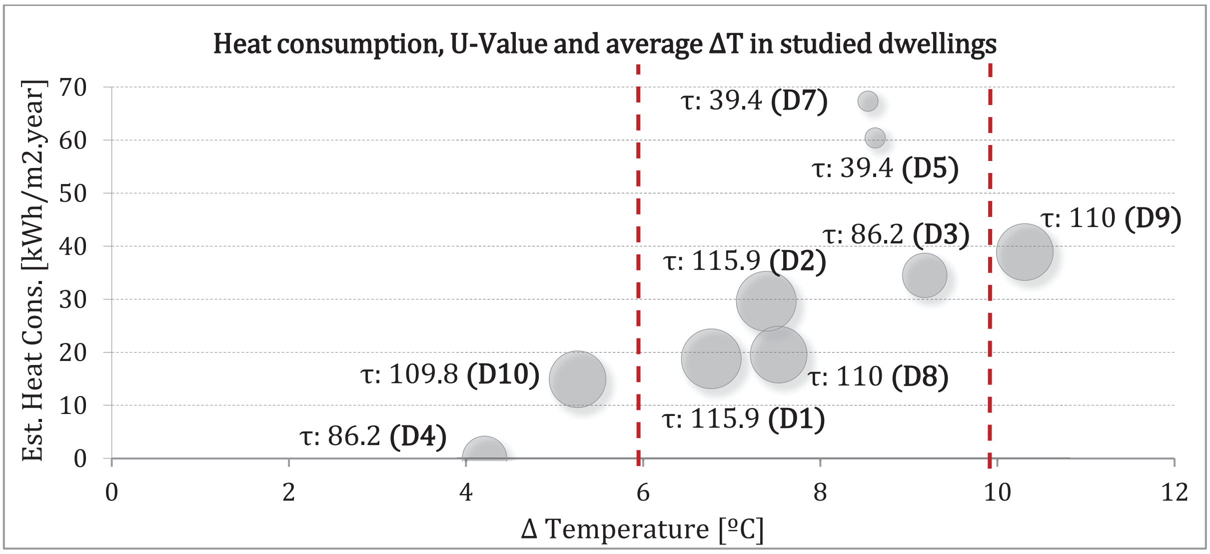


Fig. 3. 5. Relation between energy consumption, time constant and average ΔT. Outdoor Average: 10.17

An unexpected performance of two dwellings can be perceived when looking at this graph: the highest heat consumption in each interval (D5 and D7, respectively) doesn't correspond with the highest ΔT. This point proves that several other factors, such as heat capacity of the façade, user behaviour, ventilation, windows quality and opaque walls to windows ratio or thermal bridges ratio, to name but a few, play an important role in thermal performance in these dwellings. Both dwellings (D5 and D7) exhibit not only a high U-Value (1.27 W/m²K) but also a low heat capacity value in façade (180 kJ/m²K), whilst other dwellings with low U-value in their façades have, however, higher heat capacity (360 kJ/ m²K - 423 kJ/ m²K); Differences between D5 and D7 could be explained when ventilation patterns or user behaviour are taken into consideration.

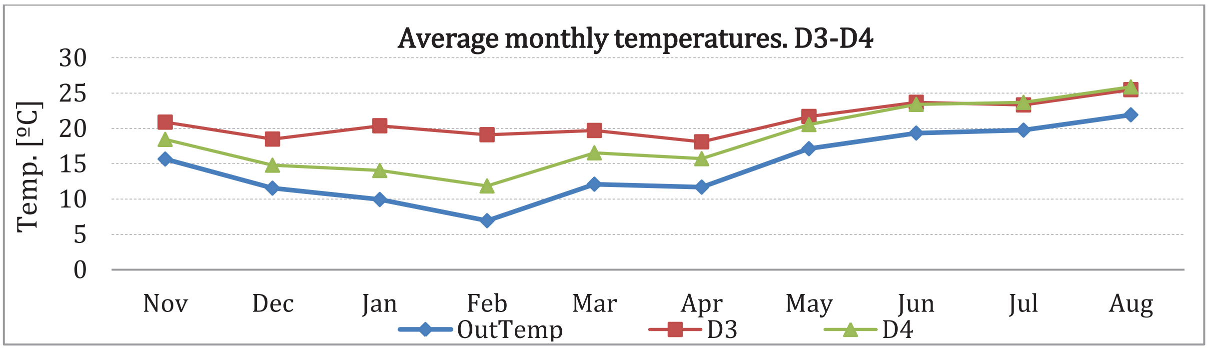


Fig. 3. 6. Evolution of the monthly average temperatures in D3 and D4 (main room)

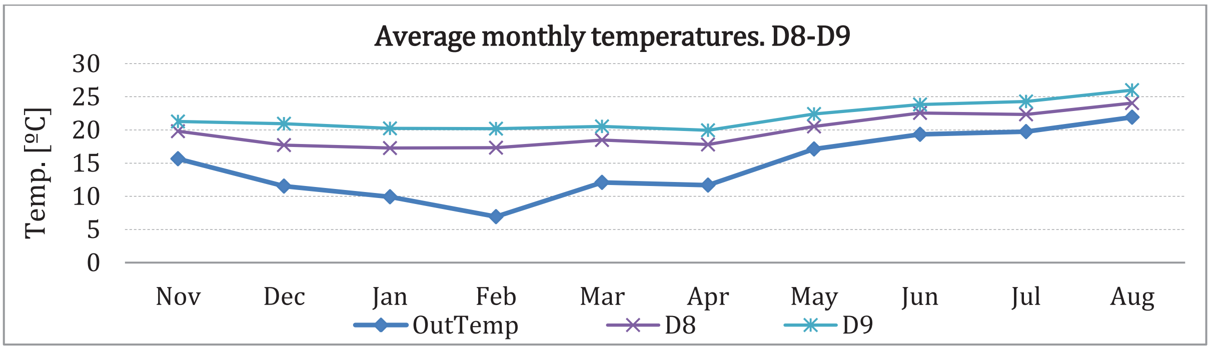


Fig. 3. 7. Evolution of the monthly average temperatures in D8 and D9 (main room)

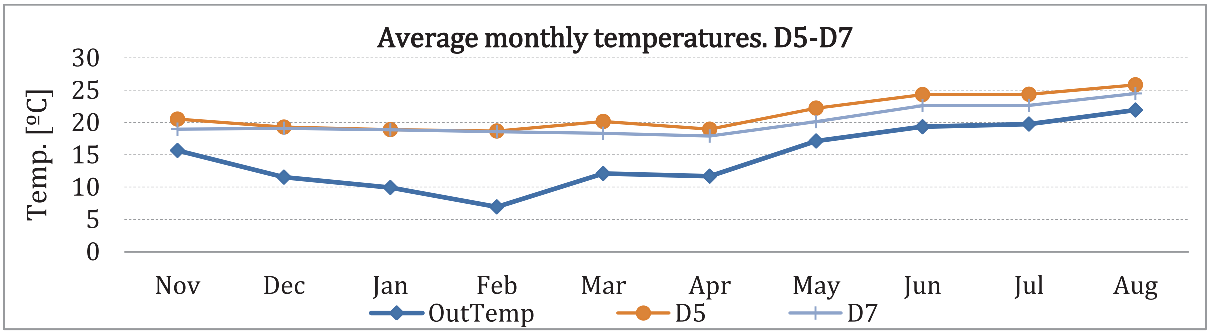


Fig. 3. 8. Evolution of the monthly average temperatures in D5 and D7 (main room)

Thus, these differences in annual energy consumption of each dwelling should be evaluated and explained analysing more parameters. D3 and D4 are quite similarly constructed. Their differences were explained when the heating system was taken into account and when the average monthly indoor temperatures were compared (Fig. 3. 6).

Even using the same heating system i.e. natural gas with high temperature radiators and having very low monthly average temperatures, significant differences were found in heating consumption (about 50%), as Fig. 3. 7 shows for D8 and D9. When D5 and D7 were compared (Fig. 3. 8), with similar average indoor temperatures during the winter period, the slight differences in heating consumption (Fig. 3. 5) were attributed in this case to occupants' behaviour, as previously said.

The kind of heating system, and the way each occupant uses it, also have a strong influence on the global thermal performance of the dwelling, and on the relation between indoor thermal comfort and heating consumption itself, as described in section 6.2.2. in more detail.

6 Analysis of results

6.1 Analysis of annual indoor environment

Social housing sector is a heterogeneous dwelling group when indoor thermal conditions are taken into account. In the studied group, significant differences were found for the average monthly indoor temperatures, especially in winter time, when heating systems were used and consequently, heat consumption was the highest (Fig. 3. 9). This period will be studied in detail later.

As previously said, fluctuations in indoor temperatures were a consequence of several factors, such as the heat capacity of the building structure, the heating system control or ventilation patterns, to name but a few. Diurnal and nocturnal ranges give an idea of the indoor temperature stability. The ratio of internal to external temperature fluctuation ($\Delta t_i/\Delta t_o$) shows correlations between indoor and outdoor temperatures, and it depends on the dwelling features (building techniques, building envelope and energy systems) and, on other factors such as dwelling operation, related to occupant behaviour.

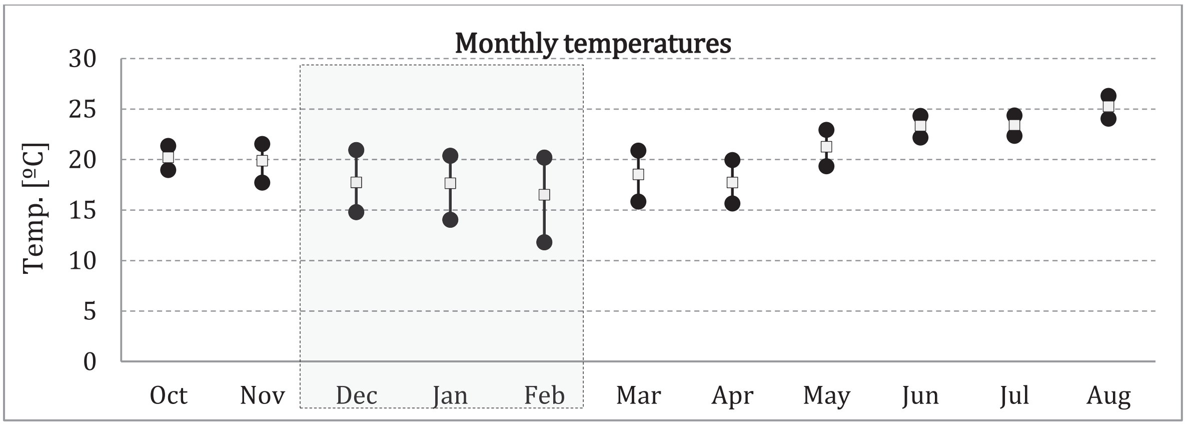


Fig. 3. 9. Maximum, average and minimum indoor monthly temperatures.

Table 3. 6 shows the nocturnal and diurnal ranges by seasons. It is calculated as the difference between the maximum and minimum temperature in each period of the day (nocturnal and diurnal), and seasonal average values are calculated then. The higher diurnal (8 am - 8 pm) and nocturnal (8 pm - 8 am) ranges of indoor temperatures were in winter period, when heating systems were used. Average of diurnal range in this period was between 3.18 (D2) and 1.16 (D6), whilst the average of nocturnal range was between 3.63 (D10) and 0.82 (D6). In summertime, however, these ranges were in general quite smaller, from 3.36 (D2) to about 0.8 (D4 and D6).

		Winter Period (Dec-Mar)		Spring Period (Apr-May)		Summer Period (Jun-Aug)	
	C (kJ/m².K)	Diurnal Range	Nocturnal Range	Diurnal Range	Nocturnal Range	Diurnal Range	Nocturnal Range
(T_o)		5.53	4.01	4.58	4.02	5.19	4.38
D1	463.8	2.14	2.15	1.23	1.33	1.07	0.99
D2	463.8	3.18	2.87	2.53	2.49	3.36	3.68
D3	359.8	3.11	2.99	1.32	1.39	0.91	0.93
D4	359.8	1.19	1.68	1.03	1.46	0.81	1.08
D5	180.0	2.64	2.84	1.98	1.85	2.03	1.80
D6	238.4	1.16	0.82	0.89	0.89	0.79	0.85
D7	180.0	2.98	2.55	1.63	1.33	1.03	0.93
D8	189.0	1.79	1.41	1.64	1.12	1.75	1.38
D9	189.0	2.18	1.92	1.43	1.58	1.17	1.27
D10	162.6	2.02	3.63	1.54	1.56	1.11	1.23
Average of dwellings		2.24	2.29	1.52	1.50	1.40	1.41

Table 3. 6. Ratio of internal to external diurnal and nocturnal temperature fluctuation for the studied dwellings in the studied period (main room data)

Differences were also found when the two monitored rooms of the same dwelling were compared, especially in wintertime. When all rooms of the dwelling were heated by the heating system, nocturnal and diurnal ranges were similar in both rooms (e.g. D5, average diurnal range was 2.64 in the main room and 2.85 in the bedroom; and average nocturnal range was 2.84 in the main room and 2.70 in bedroom) When only some rooms of the dwelling were heated, the differences were significantly bigger: in D3 the average diurnal range was 3.11 in the main room and 1.36 in the bedroom; and the average nocturnal range was 2.99 in the main room and 1.27 in the bedroom.

These results seem to be contradictory to that mentioned in [49], where it is affirmed that fluctuation temperature is closely linked to the heat capacity of the structure. However, this phenomenon can be explained with the fact that both studies were carried out under different conditions. In this case, every monitored dwelling was occupied during monitoring periods, whereas in [49] two dwellings out of the three were vacant.

The way of using the heating system in winter, and ventilation management of the user in summer (both strategies regarding to occupants' behaviour) can increase significantly the indoor temperature range of dwellings. As a matter of fact, this was proved with the values obtained for the diurnal range of temperatures in D4 during the winter period, which was one of the lowest of the sample. Similarly, D6 presented the lowest temperature range and the use of the heating system was very occasional, according to the D6 questionnaire. This hypothesis was proved in summer as well. Dwelling D6, which was also the dwelling with the lowest temperature range in summer, was vacant during this period.

Other factors, such as the ratio of exposed envelope area to dwelling area can complement the explanation of these results. Thus, the high values of D2 are also explained due to its location within the building, directly under the roof and consequently it had a higher ratio of thermal envelope area to indoor area, whereas in D1 the effect of high C in the opaque walls could be counteracted by the low quality of the windows.

Indoor relative humidity (RH) was also analysed. The accepted range of RH for thermal comfort is from 30% to 70% [66]. More than 99% of registered RH data were higher than 30% in all dwellings, as shown Fig. 3. 10. However, the state of affairs changes when the highest limit is observed. In four dwellings, more than 5% of registered data were out of the comfort zone, and two of them gave especially high values: D6 (32.4% of the registered data out of the comfort zone) and D7 (46.9% of the registered data out of the comfort zone).

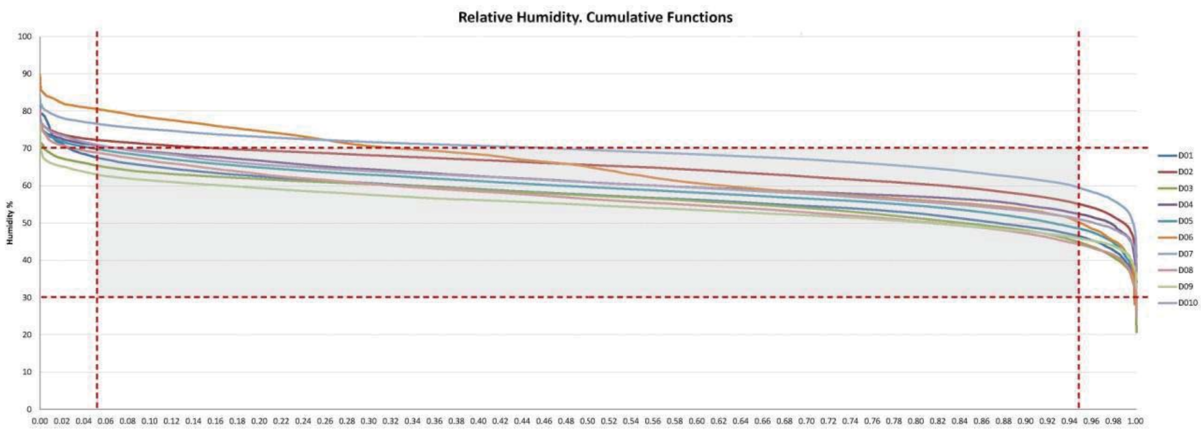


Fig. 3. 10. Relative humidity in the dwellings. Cumulative Distribution Function

Seasonal detailed information is presented in Table 3. 7. The majority of collected data higher than RH 70% correspond to wintertime, except in D7 which had high RH values in every evaluated season.

R.H.	Dec 2011 – Sept 2012		Winter	Tempered season	Summer
	Measures up to 30% (%)	Measures higher than 70% (%)	Measures higher than 70% (%)	Measures higher than 70% (%)	Measures higher than 70% (%)
D1	**0.02%**	**3.7%**	8.1%	0.14%	0.36%
D2	**0.00%**	**16.2%**	27.5%	12.1%	3.9%
D3	**0.06%**	**0.3%**	0.82%	0.00%	0.1%
D4	**0.00%**	**7.2%**	16.2%	0.19%	0.02%
D5	**0.02%**	**4.9%**	9.2%	3.5%	0.02%
D6	**0.2%**	**32.4%**	63.2%	18.6%	0.81%
D7	**0.00%**	**46.9%**	40.6%	58.8%	47.5%
D8	**0.00%**	**3.0%**	0.85%	1.76%	6.9%
D9	**0.00%**	**0.08%**	0.03%	0.00%	0. 2%
D10	**0.00%**	**7.0%**	10.1%	2.3%	6.0%

Table 3. 7. Summary of logged RH (%) during the whole period and by seasons: in Winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and Summer (Jun-Aug 2012)

In occupied dwellings RH was directly affected by natural ventilation as there was no mechanical ventilation in the studied dwellings. Thus, this parameter can also give information about the ventilation rate, whether it was enough or not. Indoor RH is related to outdoors RH, and with indoor humidity sources like cooking or human activity. Too high RH values could mean a low ventilation rate, as well as low indoor temperatures.

6.2 Winter period

6.2.1 Overall analysis

Winter period data (In this study, is assumed between December 2011-March 2012) are presented in this section. Some temperature limits were defined in order to evaluate indoor temperatures in dwellings. For winter time thermal comfort limits were set up around 18 ºC ±2 ºC, based on the research presented in [49]. Moreover, the lowest limit (16 ºC) is used as a reference in other studies for identifying "cold homes" when standardized temperatures are used, such as in [62].

It was found that average indoor temperatures in two dwellings were lower than 16 ºC (D4 and D10) in winter season. For dwellings D1, D2, D6 and D8 average indoor temperatures were also low (Table 3. 8). The reasons of these low temperatures can be several and different in each case, e.g. no dwelling occupancy for some days, poor heating equipment control, building and heating system characteristics, different ventilation patterns, etc.

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	25.80	-0.30	10.17	26.10	3.87
D1	24.46	9.73	16.94	14.73	1.85
D2	22.71	10.79	17.56	11.92	1.32
D3	26.13	14.36	19.35	11.77	1.86
D4	21.27	9.21	14.38	12.06	2.26
D5	23.86	12.94	18.79	10.91	1.59
D6	23.69	13.81	17.67	9.88	1.61
D7	22.39	14.27	18.71	8.13	1.25
D8	22.66	11.13	17.70	11.53	1.20
D9	24.22	13.64	20.48	10.58	1.04
D10	23.28	10.52	15.43	12.76	1.68

Table 3. 8. Summary of logged temperatures (ºC) in Winter (Dec-Jan-Feb-Mar)

Relations between average indoor temperature and heating consumption have already been depicted in Fig. 3. 5. Red lines represent the aforementioned comfort limits in winter. As previously said, it is expected there is a trend, so the bigger the ΔT is, the higher heat consumption is. When heat consumption was similar (e.g. D1 and D8), it was also observed that the bigger the ΔT is, the lower the U- value is. Nevertheless two dwellings (D5 and D7) did not follow this trend. It could be explained due to occupant behaviour, for example, related to ventilation patterns as observed in the 15 day and 48-hour periods. To ascertain this point, the coldest 48-hour period is shown in Fig. 3. 12. Opening windows are highlighted in blue in this figure. Even though the 48-hour period logged was the coldest, an opening windows interval is easily identified for a long time in both days, especially in the bedroom. See the green line that lasts about two hours in February 8th and almost four hours in February 9th.

6.2.2 15-day and 48-hour periods

A 15 day period and a 48-hour period analysis allowed the information gathered by questionnaires to be complemented with real data obtained by the thermo-hygrometers. Measured outdoor temperatures during the 15-day-period are presented in Fig. 3. 11, where the 48 - hour - period assumed is also marked in the graph.

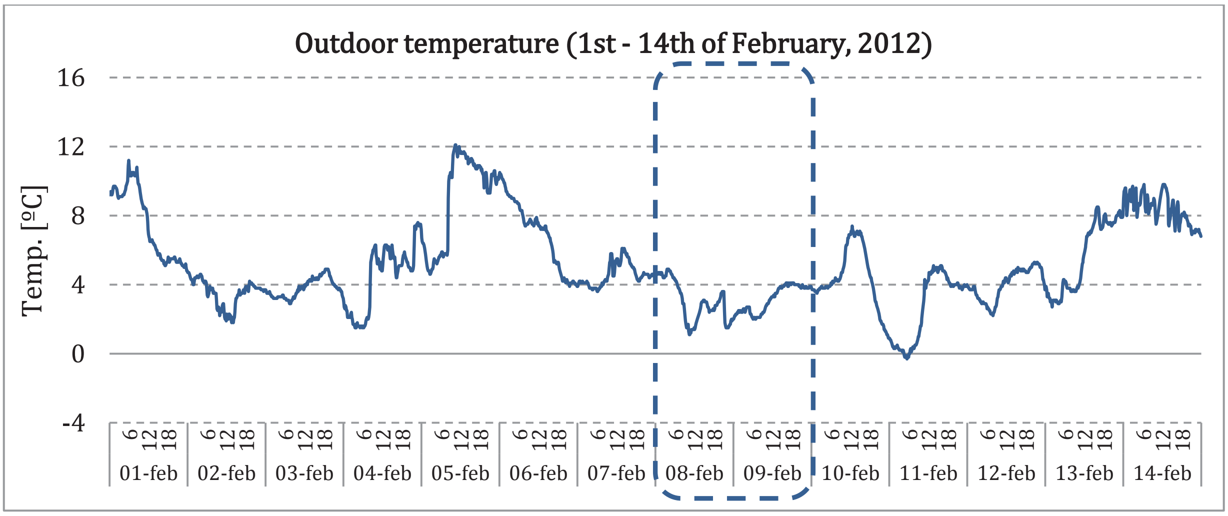


Fig. 3. 11. Outdoor temperature in the 15-day-period studied

Ventilation (opening windows) and heating consumption patterns are easily identified in these analyses. Opening windows in winter are identified in the graphs because RH and temperature drop suddenly. In a similar way, when the heating system is activated, temperature increases and RH drops at the same time. Two examples of this behaviour for dwellings D3 (heating system activation) and D5 (opening windows) are depicted in Fig. 3. 12.

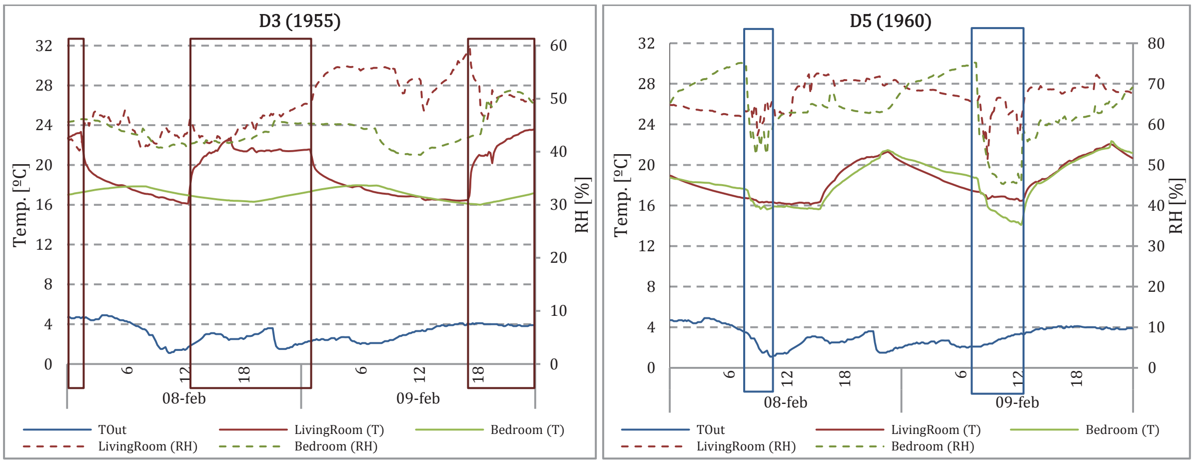


Fig. 3. 12. (left) Identification of heating system activation (D3) and (right) identification of opening windows (D5)

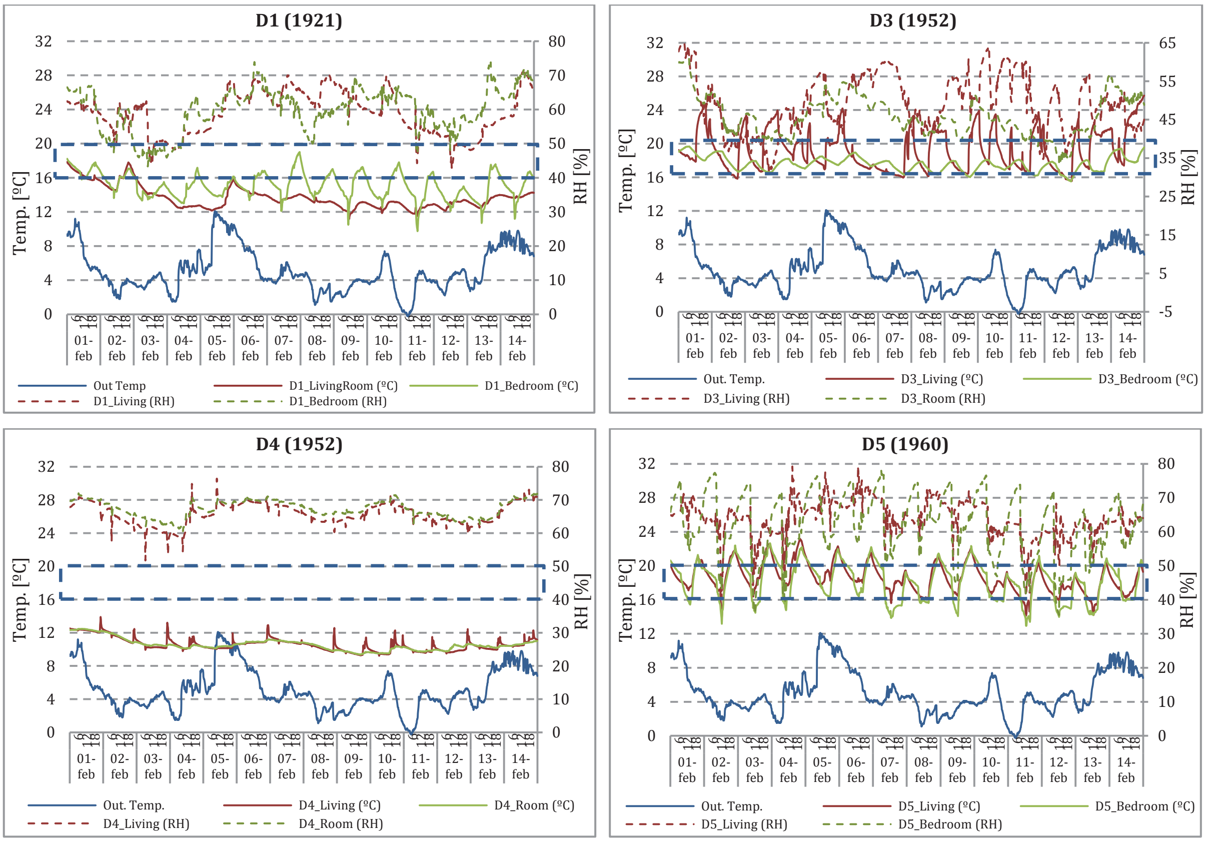


Fig. 3. 13. Indoor temperature [ºC] and RH [%] for D1, D3, D4 and D5

These analyses also allowed different heating systems and the way of using them to be compared. For example, D1 and D3 used heaters only in some rooms of the whole dwelling. However, the results were quite different in each case. Although both dwellings were occupied during the whole day, D1 only had a few peaks over 16 ºC in the heated area and in the 48-hour analysis there was a minimum of 12 ºC corresponding to the moment when windows were open. Meanwhile D3, a dwelling heated by a 2 kW electric heater located in the living room, had a significant amount of logged data over 20 ºC in the heated area. Some of these graphs are depicted in Fig. 3. 13, and all cases are presented in appendix 3.2.

Several differences were also found in the evolution of non-heated area temperatures in these dwellings. D4 (with no heating system) had a very low temperature during the coldest period. The temperature in the whole dwelling was stable and the same in the two measured rooms (studied points). A small peak appeared in the temperature of the main room, due to the use of a small heater, whose consumption was neglected in energy consumption estimations.

The dwellings with natural gas and one radiator in each room showed smaller temperature differences in the whole dwelling during the day. As an example in D5 a natural gas heating system with one heat radiator in each room was used, and a system was commanded with a thermostat located in the living room. Energy consumption for heating was usually higher in these dwellings, but the whole dwelling performs closer to comfort levels. The temperatures were similar in every room, and small variations were due to different ventilation patterns in each room.

	Max. Temp. (ºC)	Min. Temp. (ºC)	Av. Temp. (ºC)	Range (ºC)	Standard Dev.
Outdoors	12.10	-0.30	5.08	12.40	2.54
D1	19.01	9.73	14.38	9.28	1.55
D2	21.10	12.99	16.95	8.11	1.43
D3	25.72	15.51	18.46	10.21	1.99
D4	13.91	9.21	10.57	4.69	0.76
D5	23.16	12.94	18.38	10.22	1.97
D6	17.68	13.81	15.04	3.87	0.84
D7	22.39	14.27	18.86	8.13	1.52
D8	18.60	12.85	16.75	5.76	0.92
D9	24.22	14.96	20.24	9.26	1.01
D10	22.32	10.52	14.81	11.81	1.97

Table 3. 9. Summary of logged temperatures (ºC) in the 15 coldest days (1-14 Feb 2012)

In this analysed 15-day period, the 4 dwellings (D1, D4, D6 and D10) had an average temperature below 16 ºC and only one dwelling (D9) had an average temperature higher than 19 ºC (Table 3. 9).

6.3 Spring period (tempered season)

Tempered season data (April-May 2012) are presented in this section. Similar methodology was followed to analyse these data. In this period, only in one dwelling (D10) was the average indoor temperature lower than 18 ºC. The other dwellings had average temperatures between 18.15 ºC (D4) and 21.19 ºC (D9). Standard deviations were, in general, quite higher than those obtained in wintertime. A summary of the data collected in this period is gathered in Table 3. 10.

Regarding the 15-day and the 48-hour period analysis, although indoor thermal conditions between the dwellings were similar in this period, still several significant differences were found. Some dwellings used the heating system during some days of this period but most didn't.

	Max. Temp. (ºC)	Min. Temp. (ºC)	Av. Temp. (ºC)	Range (ºC)	Standard Dev.
Outdoors	34.80	6.30	14.45	28.50	4.48
D1	28.05	15.03	19.28	13.02	2.67
D2	26.23	11.57	19.48	14.67	2.47
D3	27.21	15.68	20.60	11.53	2.51
D4	28.49	13.55	18.15	14.95	3.19
D5	27.48	15.72	20.21	11.76	2.28
D6	26.06	15.96	20.15	10.10	2.41
D7	23.86	15.06	18.73	8.80	1.53
D8	25.65	14.22	19.18	11.43	1.81
D9	25.57	16.27	21.19	9.30	1.66
D10	23.55	14.03	17.79	9.52	2.06

Table 3. 10. Summary of logged temperatures (ºC) in Spring (April-May)

6.4 Summer period

In order to assess the thermal behaviour of each building without any heating or cooling system, monitoring measurements were carried out in summer as well, from June to August 2012. As expected in this climatic area, indoor thermal comfort was satisfactory without any cooling systems. As shown in Table 3. 11, the indoor average temperatures minus outdoor temperatures range between 6.82 (D7) and 12.34 (D2), with a standard deviation between 1.31 (D7) and 1.86 (D4). These data show the capacity of these dwellings to attenuate the impact of the diurnal summer thermal variations.

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	36.90	12.40	20.35	24.50	3.53
D1	28.64	17.80	23.81	10.85	1.60
D2	29.12	16.77	23.87	12.34	1.70
D3	28.15	20.75	24.06	7.40	1.43
D4	29.99	20.25	24.32	9.75	1.86
D5	30.14	19.75	24.54	10.40	1.43
D6	28.72	20.32	24.62	8.40	1.78
D7	26.97	20.15	23.25	6.82	1.31
D8	29.57	18.89	22.99	10.68	1.38
D9	27.85	20.60	24.72	7.25	1.43
D10	26.72	18.46	23.27	8.26	1.42

Table 3. 11. Summary of logged temperatures (ºC) in Summer (June-August)

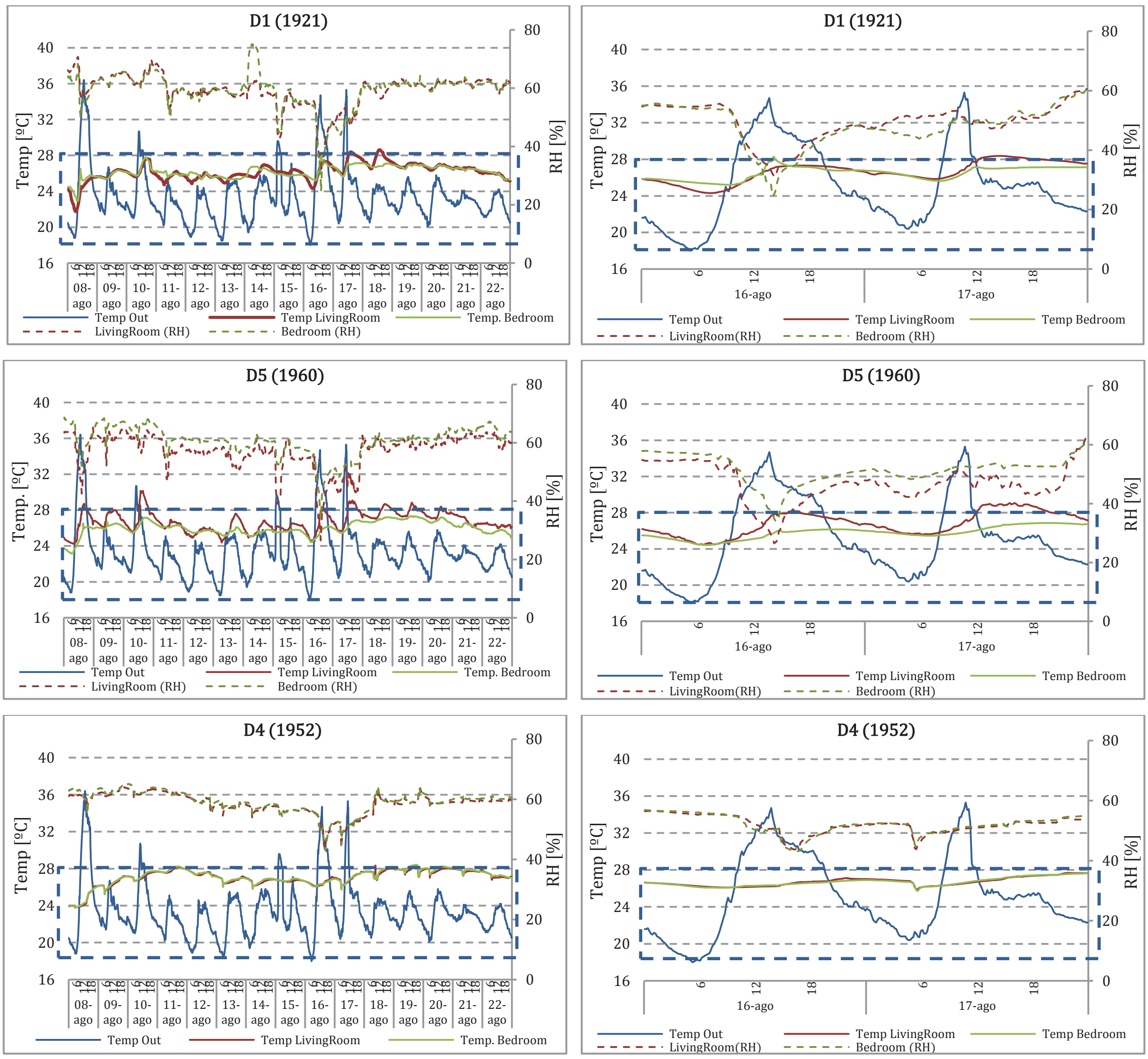


Fig. 3. 14. 15-day and 48-hour period (the hottest period) analyses for D1, D4 and D5 in summer

This behaviour can be explained more deeply if indoor temperatures are evaluated in detail (Fig. 3. 14). For summertime the thermal comfort limits were set up with a maximum value of 28 ºC. Even during the hottest period of the year, a suitable occupants' management (reduction of solar gains during day time and natural cooling at night) ensured a proper thermal regulation. This regulation was achieved thanks to the specific architectural designs of these dwellings, especially because its indoor distribution allowed a cross ventilation and thermal draught created by existing temperature gradients between opposite façades, which allowed adequate natural ventilation.

6.5 Thermal imagining inspection

To analyse the heat consumption of a dwelling, another issue to take into account is the impact of thermal bridges. According to several references, the impact of thermal bridges on heat consumption can vary from 5% [68] (when insulation is at the exterior of the building envelope) to 39% [69] (in many insulated single family houses with bad thermal bridge treatment).

Despite the complexity to carry out an accurate quantitative IR inspection, the temperature profile in the thermal bridge created in the slab face of each building was analysed, as shown in Fig. 3. 15. The minimum temperature (T_{min}) in the external surface of the façade corresponds to a point far away from the thermal bridge, where the heat flux was supposed to be one-dimensional. The difference between the minimum and the maximum temperature (ΔT) indicates the level of the impact of the slab face thermal bridge. The higher the ΔT is, the bigger the thermal bridge impact is.

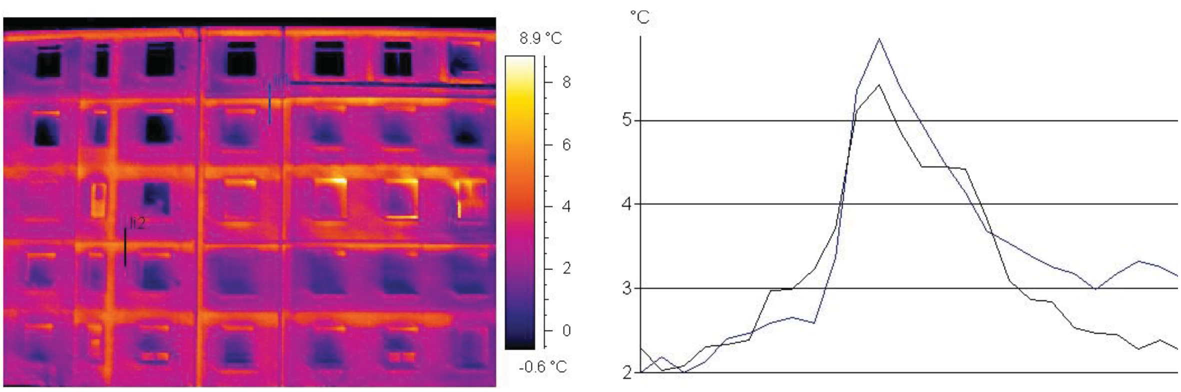
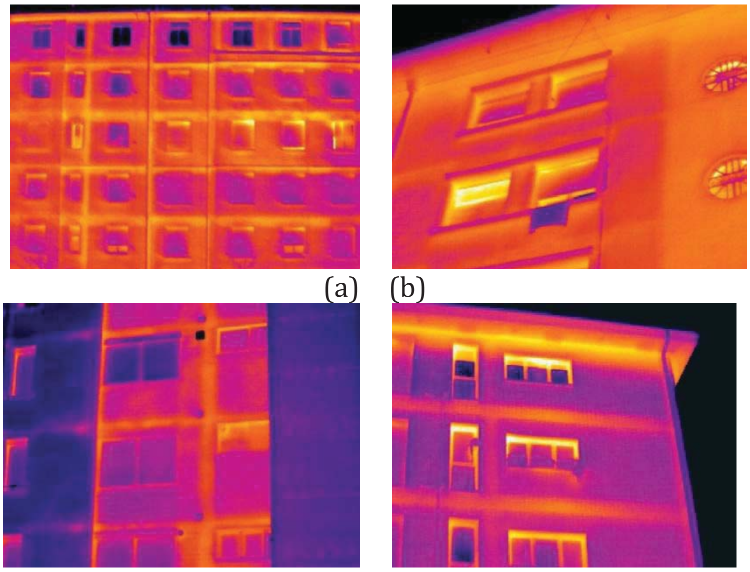


Fig. 3. 15. Temperature profile in the slab face thermal bridge

The lowest difference of surface temperature (ΔT) was found in dwellings D3 and D7 (0.7 ºC), whilst the highest ΔT was registered in the façade of D2 (3.3 ºC). The possible effect of the thermal bridges over the global thermal performance of the dwellings was not very well defined when these results and indoor temperatures or consumption in each dwelling were assessed together. This is due to the fact that the effect of other variables such as opening windows patterns, make the impact of thermal bridges to be negligible. In this case, the fact that the dwellings were occupied during the monitoring period was a handicap to evaluate this effect.



(a) (b) (c) (d)

Fig. 3. 16. Thermographs of some buildings (a) D2; (b) D3; (c) D5; (d) D8

Quantifying the thermal bridges effect on a dwelling requires limiting the effect of human behaviour. This can be achieved by means of simulations or carrying out the monitoring in vacant dwellings, since factors manipulated by the user (such as heating temperature setpoint, ventilation rates or internal gains) have a strong influence on the thermal gradient between indoors and outdoors. This fact can vary the ΔT value of a thermal bridge.

6.6 Indoor thermal comfort and risk of cold homes

Due to the fact that some of the logged temperature data in winter were much lower than expected, an analysis was undertaken, in order to evaluate indoor thermal comfort in winter, and the ensuing risk of cold homes. Thermal comfort is defined by ISO 7730 [65] as the mental condition expressing satisfaction with thermal environment. As previously mentioned, due to the features of this investigation, recording all parameters was not possible. For this reason, an approximation based on statistical analysis was made, following the procedure presented in [49].

Cumulative distribution functions (CDF) were obtained with the series of registered temperatures in the studied dwellings during winter period (from 1st of December 2011 to 1st of April 2012), in order to study thermal comfort (Fig. 3. 17). Significant differences were found when CDF were compared. About 80% of the registered data in D4 in winter were lower than 16ºC. Thus this dwelling could be identified as a cold home. On the other hand, the total amount of registered data below 16ºC in D9 was negligible, being the temperature over 20 ºC almost 70% of the time. This could suggest that reducing the setpoint temperature could diminish energy consumption without decreasing indoor environment comfort levels. CDF of D10, D1, D2 and D5 are also presented in the Fig. 3. 17. CDF of D2 shows a well- balanced indoor temperature, where only less than 5% of the registered data were below 16ºC and less than 5% of the registered data were over 20ºC. CDF of every case are shown in appendix 3.2.

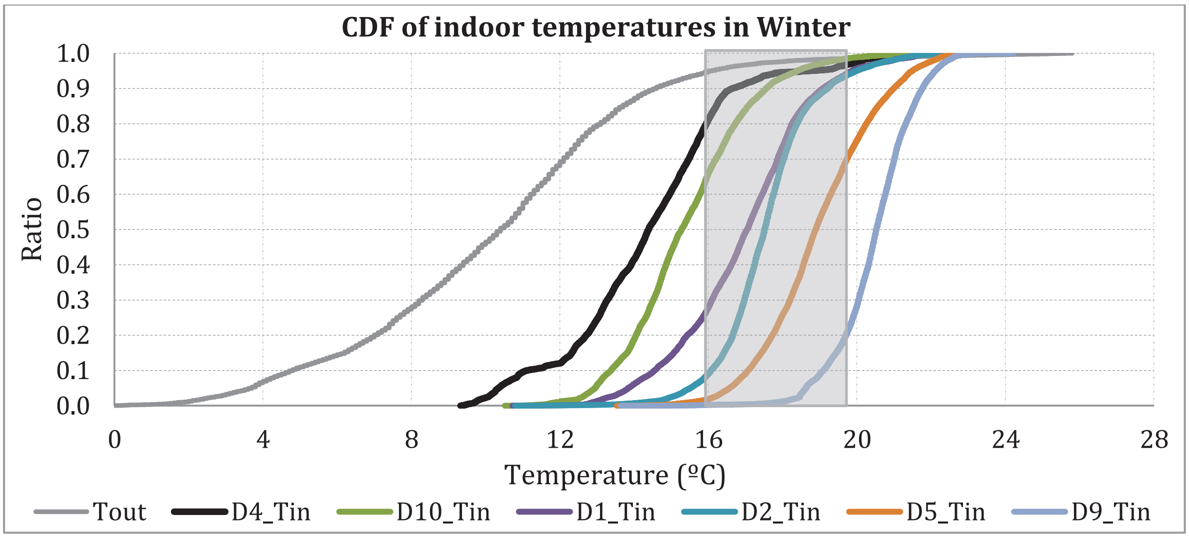


Fig. 3. 17. Cumulative Distribution Function of 6 studied dwellings in Winter (main room)

A summary of logged temperatures according to these criteria is presented in Table 3. 12. The thermal performance of D4 must be highlighted in this table. It was not only the coldest dwelling in winter, but also one of the dwellings with higher temperatures in summer (see Table 3. 11). In D6 high temperatures were logged in summer, but this was due to the fact that the dwelling was empty during that summer period and thus, there was no ventilation. D5 presented higher temperatures over the whole year. Thermal performance of D4 could be explained because of the high U-value of its façade and especially because it is located in the upper floor of the building and the U-Value of its roof is very high.

These CDF analyses give quantitative information, but they don't describe the temperature evolution inside the dwellings. As described in [49], the difference between indoor and outdoor temperatures against outdoor temperature was analyzed (see Fig. 3. 18, and Appendix 3.2). The thermal comfort zone is marked in the graphs (between blue lines), so as to identify which measurements were in the thermal comfort zone and which measures were not. Moreover, the figure also shows the share of measurements which were below 16 ºC. Previously mentioned thermal comfort limits were selected (18 ºC ±2 ºC).

	Winter		Tempered season		Summer	
	Measures below 16 ºC (%)	Measures over 20 ºC (%)	Measures below 16 ºC (%)	Measures over 20 ºC (%)	Measures below 20 ºC (%)	Measures over 28 ºC (%)
OUT	94.67%	1.41%	69.96%	10.43%	52.00%	3.43%
D1	24.6%	5.68 %	11.69%	41.69%	0.20%	0.02%
D2	9.06%	4.94 %	3.13%	39.77%	2.42%	0.17%
D3	0.83%	30.25%	1.15%	49.24%	0.00%	0.00%
D4	81.86%	2.27%	33.15%	29.33%	0.00%	1.36%
D5	0.94%	29.20%	0.00%	52.53%	0.00%	2.33%
D6	12.92%	5.96%	0.14%	46.69%	0.00%	5.07%
D7	1.09%	16.99%	0.31%	26.94%	0.00%	0.00%
D8	5.20%	4.75%	0.92%	30.26%	0.28%	0.03%
D9	0.26%	71.85%	0.00%	76.58%	0.00%	0.00%
D10	65.90%	1.13%	25.41%	18.27%	0.08%	0.00%

Table 3. 12. Summary of logged temperatures in the main room (%) in winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and summer (Jun-Jul-Aug 2012)

The CDF temperature in winter gives an idea of the heating system usage. Differences between D4, (where more than 80% of the measured temperatures are below 16 ºC), and D9, (where more than 99% of measured temperatures are higher than 16 ºC), were apparent. In this case, one of the most influential factors was not the building envelope, the energy system or the building techniques, but the building operation and especially, the way the heating system was used.

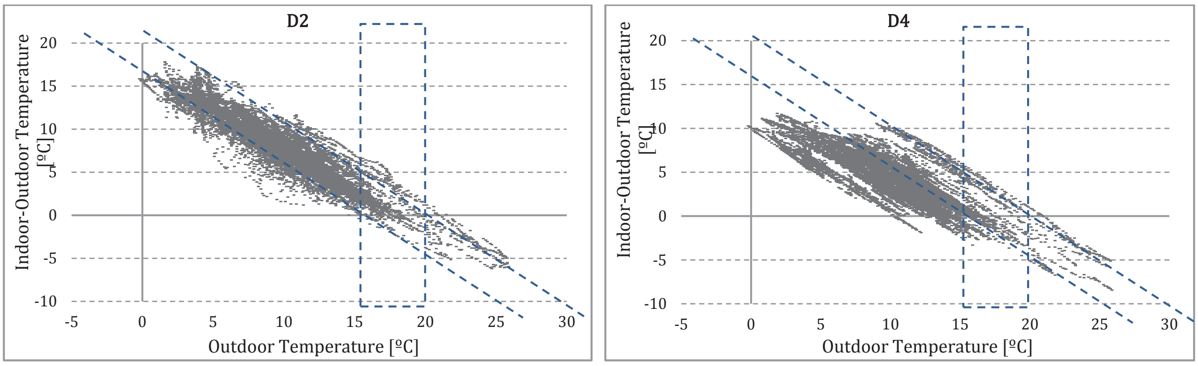


Fig. 3. 18. Indoor-Outdoor temperature against outdoor temperatures in wintertime. (D2 and D4)

7 Discussion

7.1 Overall discussion of the results

Thermal behaviour of dwellings can be explained only when they are studied under a global approach, taking into account the six subsystems mentioned in Fig. 3. 1. In the case of the analyzed dwellings of this chapter, occupants' adaptive behaviour (as affirmed in [70]) played an important role in indoor thermal characteristics, particularly in summertime. In most cases, this adaptive behaviour could ensure a thermal regulation thanks to specific architectural design of the dwellings. A good rooms distribution according to its uses and orientations, allowed natural ventilation to occur, i.e. thermal draughts due to temperature gradients between the two façades of the dwelling.

Following the holistic approach presented in this chapter, the results obtained may be summarized in the following points:

- **Outdoor environment and site.** The dwellings are located in an area with a tempered climate, although sporadically peaks of temperature (both high and low) could be registered.
- **Heating systems.** In the majority of the analysed dwellings the efficiency of the heating system could be improved, especially in rented ones, where the occupants usually decide not to invest in an efficient heating system.
- **Building envelope.** Building envelope of buildings built before 1980 shows high U-values (1.11-1.27 $W/m^2.K$) in its opaque walls, and in its original windows. The

infiltration rates are high too. In many dwellings windows have been replaced at least once, and *"Bilbao Social Housing"* have promoted and developed plans in this way, usually acting not on a building scale, but on a dwelling scale. However, there is still a great number of buildings and dwellings with envelopes displaying a poor thermal performance.

- **Building Techniques.** The effects of thermal bridges were not appreciated due to their low thermal impact compared to other effects, such as ventilation patterns.
- **Indoor design.** In general, studied dwellings present a good indoor design, with crossing indoor distribution, adapted to uses and orientation.
- **Occupants.** Occupation patterns, ventilation patterns or ways of using the heating system will have a high impact on the comfort and on the energy consumption. Therefore strategies for increasing the occupants' awareness are recommended to be developed.

7.2 Indoor comfort

7.2.1 Winter period

Four of the dwellings had an indoor average temperature lower than 16 ºC during the coldest period in winter, and two of them presented an average temperature lower than 16 ºC when the whole winter was analyzed. On the contrary four dwellings had an average temperature over 18 ºC. In three of these four dwellings (D5, D7 and D9), the occupants were the owners. In the fourth one, although the average indoor temperature was higher than 18 ºC, it was quite unstable. These three dwellings were the only ones which had natural gas based heating system, and the household incomes of these dwellings were also the highest of the ten studied cases. Other studies have also demonstrated that amongst other factors, household incomes and energy consumption and therefore, indoor comfort at home, are closely linked [34].

The majority of the analyzed dwellings had lower energy consumption than expected. This is mostly due not to the building thermal performance itself, but to the indoor temperatures which in some cases were very low values.

Improving the thermal performance of the social dwelling stock not only aims at reducing energy consumption, but also (and moreover) at improving indoor comfort.

For that reason, when the effectiveness of a renovation in a social dwelling is evaluated, indoor comfort parameters, such as indoor temperature and RH, must be taken into account. The improvements on the indoor comfort should be considered as essential as energy savings itself. Factors which are out of the scope of our study, such as health and social factors will also be benefitted through a proper renovation of social dwellings.

7.2.2 Summer period

Indoor conditions in summer were also considered in this study. Similar methodology to the one used in section 6.6 to evaluate indoor comfort in winter can be followed to analyse the thermal comfort in summer. It has not been accomplished in this thesis, because the registered indoor temperatures in summer were in general quite comfortable, rarely higher than 28 ºC even during the hottest days of the year, as expected in this climatic area.

8 Conclusions

In order to establish a good energy renovation strategy of the building stock, and to consider different priority criteria, it is necessary to have accurate data on the thermal performance of the building stock. This chapter has shown a methodology for studying thermal performance of social dwellings based on a long term monitoring of 10 dwellings. Collected data have been used to define general trends on energy consumption and thermal performance of social housing sector, as well as to define the operation conditions in social dwellings. Significant differences have been found when comparing standard operation conditions and operation conditions based on gathered measurements. This study also provides qualitative and quantitative characterization of ten reference dwellings, representative of the Social Housing Sector in Bilbao.

The field investigation has shown that energy consumption of these social dwellings was lower than expected. This situation was not due that much to a good thermal performance of the studied dwellings, but to a lowering of the indoor comfort levels. This way, future energy retrofitting strategies will have to bear this aspect in mind when their effectiveness is assessed. That is, sustainability on building renovations does not have to be evaluated only in terms of energy savings, but also under economic and social criteria. The aim of reducing the number of cold homes and the risks they involve therein must be considered as important as energy savings themselves, especially in the social housing sector.

Differences in energy consumption for heating were found amongst the studied dwellings. Those differences could not always be explained by the construction characteristics of the building (e.g. the higher U-value is, the lower the heating consumption is). Especially important is the indoor average temperature required by the occupants in winter, which is usually closely linked to household incomes. As expected, the highest indoor temperatures were found in the dwellings with higher household incomes. These differences on indoor conditions also depended on the heating system and its use. It proves that the heating system influences on indoor thermal comfort, both the kind of heating system itself and the way it is used.

The study also shows that the majority of dwellings had a good design, which could allow thermal regulation by means of the occupants' adaptive behaviour. Energy retrofitting in social dwellings has to be lead mainly to improve energy systems and building envelope, both opaque walls, and windows if necessary.

It is necessary to investigate the different types of social dwellings accurately before any retrofitting intervention, according to the classification previously mentioned. The best retrofitting strategy for improving thermal performance of a building constructed in 1920, with high thermal mass in façade will be different than the best one for a building constructed in 1960 with a light façade.

In short, social dwelling stock is one of the sectors with more risk of energy poverty. Hence, social housing stock, especially that one built before 1980, should be a priority in energy renovation strategies, both due to its improvement potential and the need to fight against the risk of fuel poverty and cold homes. Sustainability of these energy renovations must not only be evaluated in terms of energy savings, but also in terms of social and economical improvements.

Finally, in order to standardize parameters and compare thermal performance of different occupied dwellings, during different period of time and in different climate conditions in a proper way, new strategies and methodologies should be implemented.

Otherwise it would be impossible to create a data base and set the dwellings to be renovated in the first place. Moreover, this methodology would be useful to evaluate a dwelling or building before and after the retrofitting work is performed. Real data of the renovation efficiency should be obtained so as to compare both situations independently of the fact that the occupants' behaviour or outdoor conditions are different during the two monitoring periods. For this reason, the main focus of the next chapters is placed on developing and assessing different models of thermal performance in buildings, and comparing their results.

The next chapter describes the experimental part of this research, the selection of a representative dwelling of the building stock of Bilbao, and the monitoring carried out before and after an energy renovation takes place. This investigation will provide an important amount of data from the dwelling, which will allow the different thermal models developed in chapter 5 and 6 to represent the thermal behaviour of dwellings to be checked. In this way, it will be possible to predict the improvements on energy consumption, indoor comfort, etc, that are involved in different renovation strategies.

9 Referred appendices

Appendix 3.1. Template of presented questionnaire

Appendix 3.2. Detailed data of monitoring

Appendix 3.3. This appendix includes the paper resulted from the research work presented in this chapter:

- "Field assessment of thermal behaviour of social housing apartments in Bilbao, Northern Spain", published in Energy and Buildings, 67 (2013) 118-135.

CHAPTER 4

DETAILED FIELD STUDY OF A SOCIAL DWELLING

RESUMEN

En este capítulo se describe el desarrollo de la parte experimental principal de la Tesis, consistente en la monitorización térmica de una vivienda vacía en el barrio de Otxarkoaga, en Bilbao. La vivienda seleccionada, además de ser representativa, fue rehabilitada en el verano de 2012, llevada a cabo por Viviendas Municipales de Bilbao. Así, dicha monitorización comprenderá dos escenarios distintos: la vivienda antes de ser rehabilitada (invierno de 2012) y la vivienda tras la rehabilitación (invierno de 2013). En la vivienda se colocaron 60 sensores de temperatura así como una pequeña estación meteorológica, que enviaban las mediciones al adquisidor de datos con una frecuencia de 1 minuto. Para ambas monitorizaciones se contó con la colaboración del Área Térmica del LCCE del Gobierno Vasco. Los resultados obtenidos serán la base empleada en los posteriores capítulos de la tesis, para la definición y validación de los modelos de comportamiento térmico de la vivienda o edificio. Además, este capítulo hace un primer análisis de dichos resultados.

ABSTRACT

The main experimental part of the Thesis is described in this chapter. It is a thermal monitoring of a representative social dwelling located in a district of Bilbao. A renovation was carried out in the chosen dwelling during the summer of 2012, driven by Bilbao Social Housing. Thus, this field study covers two different scenarios: the first one in winter 2012, before renovation works, and a second one after renovation works were executed, in winter 2013. Around 60 temperature sensors were placed within the dwelling, as well as a small climate station. Data acquisition system recorded values with a 1 minute frequency. This monitoring was technically supported by the Laboratory for Quality Control in Buildings of the Basque Government. Results obtained from this field study will be used as reference in the following chapters of this thesis, to validate the models of dwellings thermal performance developed in this thesis. Moreover, a first analysis of the obtained results is presented in this chapter.

1 Introduction

This chapter describes the main experimental part of the thesis. On the one hand, measuring the thermal performance of a building before its renovation allows obtaining data to assess the real performance of the building and to identify its potential improvements. On the other hand, when the behaviour of the building is measured after any renovation works, it is possible to check if the renovation strategy that was followed performs as expected, and achieving the expected aims.

As mentioned in the previous chapter, results obtained from a building retrofit are the consequence of multiple interactions amongst different subsystems, and it is a complex issue to deal with. In fact, heat losses are often much higher than those calculated during design phase [71].

As a matter of fact, a large amount of works focused on energy measurement in buildings can be found in literature, leaded both to research and to commercial applications. Two works are mentioned in this section as examples.

As far as research part is concerning, it is noteworthy the work developed by the Danish researchers P. Bacher and H. Madsen. They presented in 2010 a procedure to identify models for the heat dynamics of buildings. An office building called “Flex House” was previously monitored and the results of monitoring and model development were published in [72].

More leaded to commercial usages (ESCOs and similar) is the IPMVP, a protocol of the Office of Energy Efficiency and Renewable Energy developed by the U.S. Department of Energy [73]. It documents the state-of-art and defines common terminology, with the purpose of publishing current good Verification and Measuring practice.

In this chapter the monitoring work carried out in a social dwelling is described. The dwelling was monitored during two different periods. The first one was carried out within the first months of 2012, and the second one the following winter, from November 2012 to February 2013, after a renovation promoted by Bilbao Social Housing was completed.

Useful data to define and validate the models that will be described in next chapters were obtained in this monitoring study. Although the main objective of the monitoring was obtaining enough data to be used in next chapters, it has been considered that the field study carried out is interesting enough for having a chapter devoted to it. Therefore this chapter is dedicated to explain the approach and design of the field studies themselves as well as the results obtained. In fact, several interesting conclusions are found after assessing the obtained results.

It is important to highlight that the monitoring analysis presented in this chapter is focused on the thermal performance of the dwelling related to its construction features. That is, following the system approach described in previous chapters, it is now concerned on defining and evaluating the response of three dwelling subsystems (building techniques, building envelope and indoor design) under specific outdoor conditions. Occupants and energy systems' influence will be considered in next chapters.

1.1 Structure of the chapter

All along the chapter both monitoring periods are displayed, before and after renovation. Once the objectives are presented in section 2, description of the dwelling, in both studied scenarios (before and after renovation) is presented in section 3. Instrumentation used in both monitoring studies, as well as the approach and methodology followed for carrying out them is presented in section 4. Results are presented and analysed in sections 5 and 6. Following the same structure developed in former sections, results are presented and analysed firstly for each scenario, and then, a comparison between both scenarios is performed. Finally, conclusions of the chapter are presented in section 7.

2 Objectives of this chapter

The objectives of the monitoring study presented in this chapter can be shorted in:

- Compiling data about thermal performance of a reference dwelling, and using them to define and validate the thermal performance models in buildings presented in the next chapters of this thesis.
- Obtaining energy consumption values of a reference dwelling before and after being retrofitted and without considering occupation influence (under the same operating conditions).
- Quantifying losses through the different elements of the dwelling: façade, indoor partitions, thermal bridges, windows…
- Comparing and evaluating the effect of the energy renovation in a dwelling (in this case, the windows replacement) on its thermal performance.

3 Case Study

A social dwelling located in a district of Bilbao, called Otxarkoaga, was selected for this field study. Selection was based on classification criteria of the building stock defined in Chapter 1 and 3 of this thesis. It is well known the complexity and heterogeneity of the building stock (as shown in Chapter 3) and the consequent difficulty to define a "standard building" as a model of the total building stock. However, the chosen dwelling is quite representative of a specific construction period of the 20th century, the 60s. It was in this decade when a significant number of today's buildings, especially in industrial cities, were built up. Around 20% of the current building stock was constructed in this decade in the case of Bilbao.

Moreover, Otxarkoaga District (Fig. 4. 1), was entirely built up in barely two years. In 1959 the construction of the area was started, and the 3672 projected dwellings were already set up by 1961.

Fig. 4. 1. General view of Otxarkoaga

3.1 Dwelling description before energy renovation

The studied dwelling is located in a multi-family building built in 1959-1961. The layout of the dwelling is shown in Fig. 4. 2, and some photos are presented in Fig. 4. 3. The net floor area is 52.52 m^2 and the floor to ceiling height is 2.47 m. The considered dwelling has 3 external façades, orientated East, West and South, but only two of them (E and W) have windows.

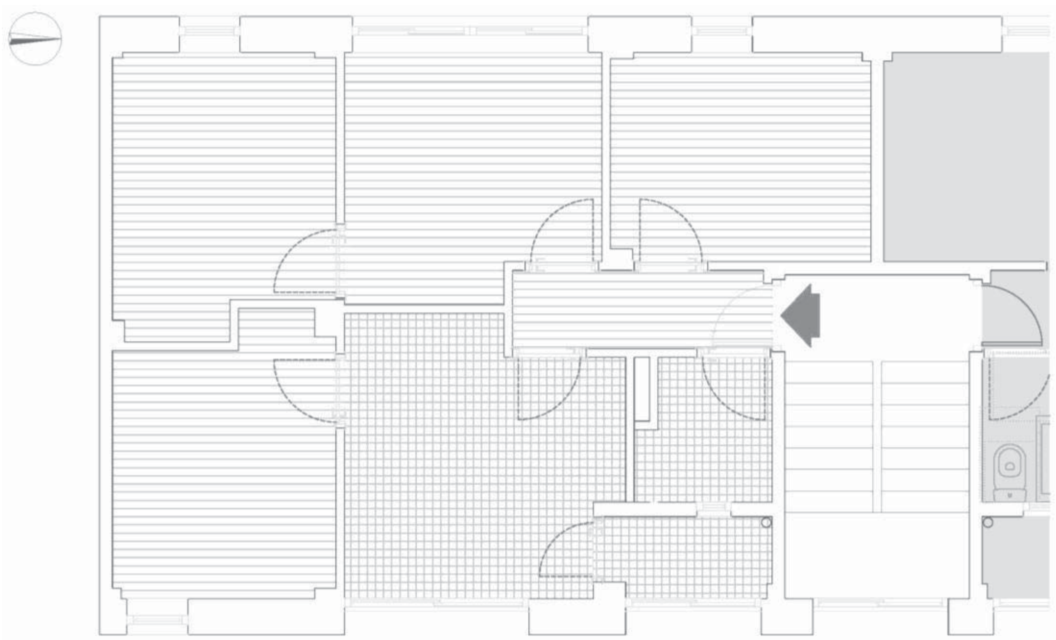
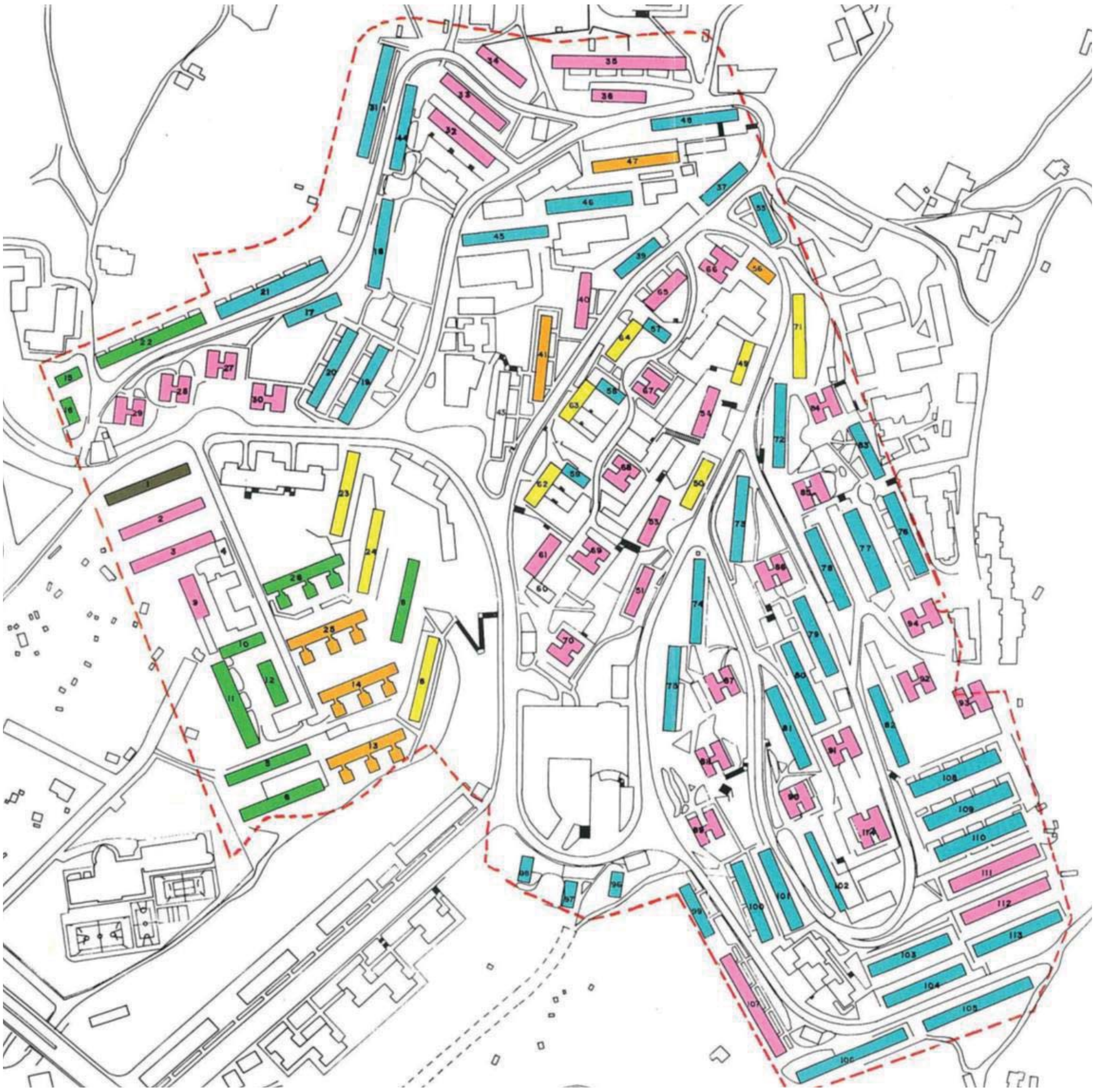


Fig. 4. 2. Layout of the selected dwelling before renovation

Fig. 4. 3. Some external views of the chosen building



Construction systems	
Cement mortar + Coat of paint	Coloured cement mortar
Lightened cement mortar	Addition of new façade and Windows layer
Addition of new façade layer	

Fig. 4. 4. Layout of Otxarkoaga. Buildings are coloured according to performed intervention in 1980's (From Bilbao Social Housing)

3.1.1 Building construction features

In 1980-1989, renovation works were carried out in the district promoted by the city council, by means of different renovation strategies. Some of them involved different levels of thermal upgrading, from the application of a lighted cement mortar in façade to the inclusion of thermal insulation of small thickness in some few cases. Fig. 4. 4 depicts every building of the district coloured in different colours, according to the performed intervention in the building.

Obviously, this was the base case assumed in this chapter. Thus, the following description of the construction features corresponds not to the initial state of the building, but to the state of the dwelling when the first monitoring period was carried out, in the first months of 2012.

3.1.1.1 Façade

According to information provided by Bilbao Social Dwellings, external walls of the dwelling are composed by two layers of hollow bricks separated by an air gap. The indoor surfaces of walls are plaster over gypsum. The external surface is currently the result of renovation works carried out in 1987. According to aforementioned information, an addition of other window and façade layer was executed in the chosen building.

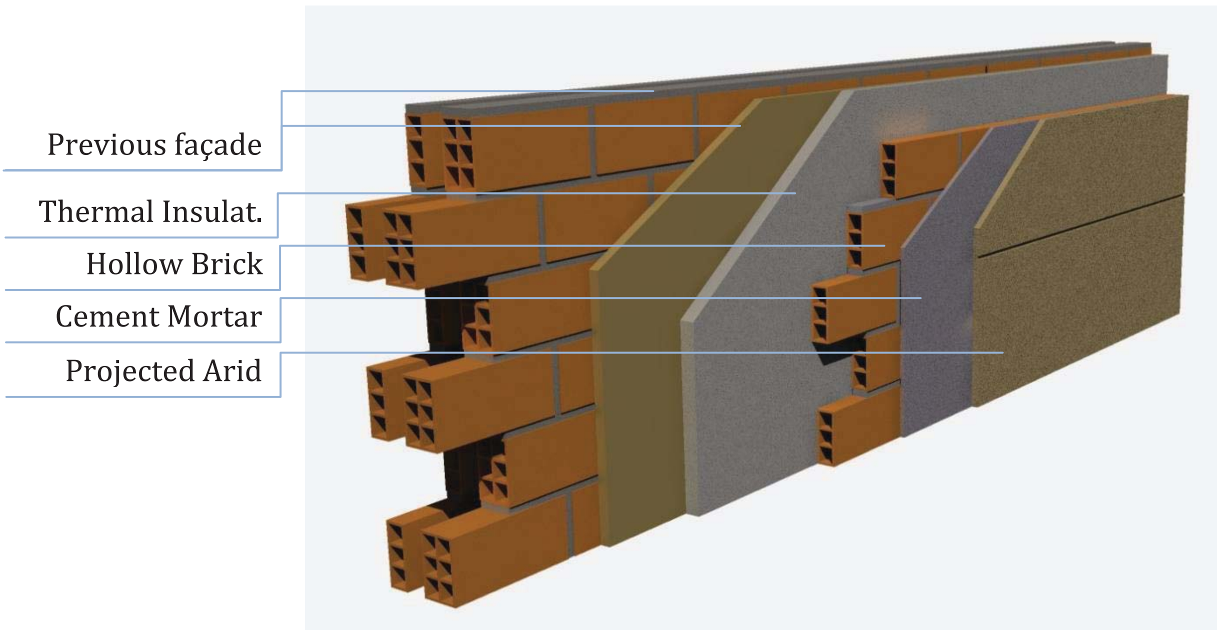


Fig. 4. 5. Façade constructive section (according to Bilbao Social Housing renovation in 1989)

However, no modification in windows was found in the visual inspection of the dwelling. That renovation affected to balconies, which were closed and they become a drying area in each dwelling (currently located behind the bathroom and kitchen). In relation to façades, the assumed addition of a new layer in façade is depicted in Fig. 4. 5, according to a report obtained from Bilbao Social Housing. The thickness of thermal insulation was very small, even negligible in some cases. However, the value of this measure must be compared to the standard at those times, when thermal behaviour in building renovations was not a priority at all in this region.

Detailed section of the façade, as well as indoor partitions (both between two rooms and the dwelling, and other dwelling or staircase) is defined in Table 4. 1.

Kind of wall	Constructive section	U – value (calculated) [W/m²K]
External Walls	Gypsum Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Thermal Insulation (2 cm) Hollow Brick (4.5 cm) Cement Mortar (2cm) Projected arid (1.5 cm)	0.74
Dwelling Partitions	Plaster Hollow Brick (4.5 cm) Plaster	3.59
Dwelling-Staircase/other dwelling	Plaster (1 cm) Hollow Brick (12.5 cm) Plaster (1 cm)	2.26

Table 4. 1. Construction of the main elements of the dwelling envelope

3.1.1.2 Windows

Two different kinds of windows could be found in the dwelling before renovation, both of them with aluminium frame without thermal break, which probably are not the original ones. The window of room 5 (see Fig. 4. 11) was a single glazing window whereas the rest of windows were double glazing.

3.1.1.3 Structure

Like many buildings built up in the region during those years, the building was constructed with reinforced concrete structure. Horizontal structure is composed by hollow-tiled floors, as usual in that construction period.

3.2 Dwelling description after energy renovation

Several renovation works were executed in the dwelling during spring and summer of year 2012. Amongst them, all windows were replaced, which is expected to have a strong influence in the results of the 2nd monitoring period, when improvements on thermal behaviour are assessed. Besides, the layout of the dwelling was slightly modified, as shown in Fig. 4. 6. Hence, bearing in mind a thermal approach, windows are the main change on the dwelling after renovation. Old windows were replaced by PVC double glazed windows.

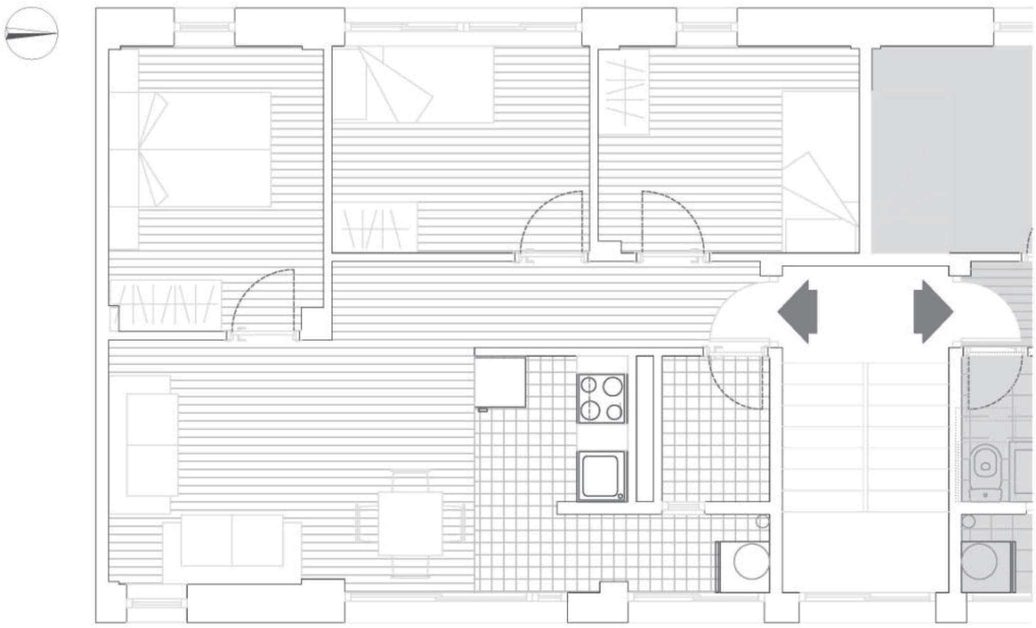


Fig. 4. 6. Layout of the selected dwelling after renovation

4 Methodology

4.1 Monitoring and measurement equipment

Detailed measurements of indoor and outdoor temperatures were collected using 53 platinum resistance thermometers of 100 ohms at 0 ºC (PT100). Four heat flux plates (Ahlborn Instruments) were also used in the study to measure values of the heat flux through façades, floor and ceiling. Values given by these flux meters were used as verification of other collected data.

A meteorological station was installed to measure solar radiation, wind velocity and atmospheric pressure. Five electrical heaters were used for heating the dwelling. Their heat inputs were measured using a SINEAX M561 single phase power meter with an accuracy of 0.2 %.

Function	Range	Resolution	Error
Voltage DC	100 mV	0.1 µV	4 µV
	1 V	1 µV	7 µV
	10 V	0.01 mV	0.05 mV
	100 V	0.1 mV	0.6 mV
	300 V	0.1 mV	9 mV
Intensity DC	10 mA	0.01 µA	2 µA
	100 mA	0.1 µA	5 µA
	1:00 AM	1 µA	100 µA
Resistance	100 kΩ/1mA	0.0005 Ω	0.005 Ω
	1 MΩ/1mA	0.0001 Ω	0.005 Ω
	10 MΩ/100 µA	0.0001 Ω	0.005 Ω

Table 4. 2. Data Acquisition and Switching system specifications

An Agilent 34980A Data Acquisition and Switching system was used for logging measured values, with 34921A channel armature multiplexer and 34921T terminal block. Detailed information about the system is shown in Table 4. 2.

All sensors were previously calibrated and validated in the LCCE of the Basque Government, according to an internal procedure. Detailed information on instruments characteristics is presented in Table 4. 3.

Parameter	Units	Sensor	Uncertainty
Temperature	[°C]	PT100. A class (4 wire)	± 0.2 °C
Heat Flux	[W/m²]	Ahlborn FQA-0801-H	± 5 %
Anemometer	[m/s]	Meteo Multi FMA510	± 0.5 / ± 0.3 m/s
Barometric pressure	[bar]	Meteo Multi FMA510	± 0.5 mbar
Relative humidity	[%]	Meteo Multi FMA510	± 3 %
Solar Irradiation	[W/m²]	Kipp and Zonen CMP11	± 3 %

Table 4. 3.Characteristics of the used sensors

4.2 Methodology

As previously stated, the case-study dwelling is approximately 50 m² divided in five rooms, a toilet, a hall and a drying area. The indoor spaces were numbered 1-8 to distinguish amongst them, as shown in Fig. 4. 11. Data were collected during two different monitoring periods. In the first period, the dwelling was monitored during 4 months (February – May 2012). After the windows replacement, the monitoring was performed during 3 months (November 2012 – February 2013). The dwelling was empty during both monitoring periods.

The heat supply in the monitored dwelling during this field study was purely electrical. Five electrical space heaters were placed in room 1-5 (one heater in each room), and each heater was rated at 400 W (although in situ measurements during monitoring gave a total power of 1800 W, instead 2000 W, as theoretically expected as result of summing the five heaters).

4.2.1 Monitoring approach

In order to design this field study, the heat chain from heater to outdoor air was kept in mind, in a similar way to that used in Annex 49 [74]. In this case, however, due to this monitoring study scale, boundary limits were moved and assessment does not start in primary energy conversion, but in the heater. In this approach, heat chain is also divided into several subsystems. Fig. 4. 7 shows a scheme of described heat chain.

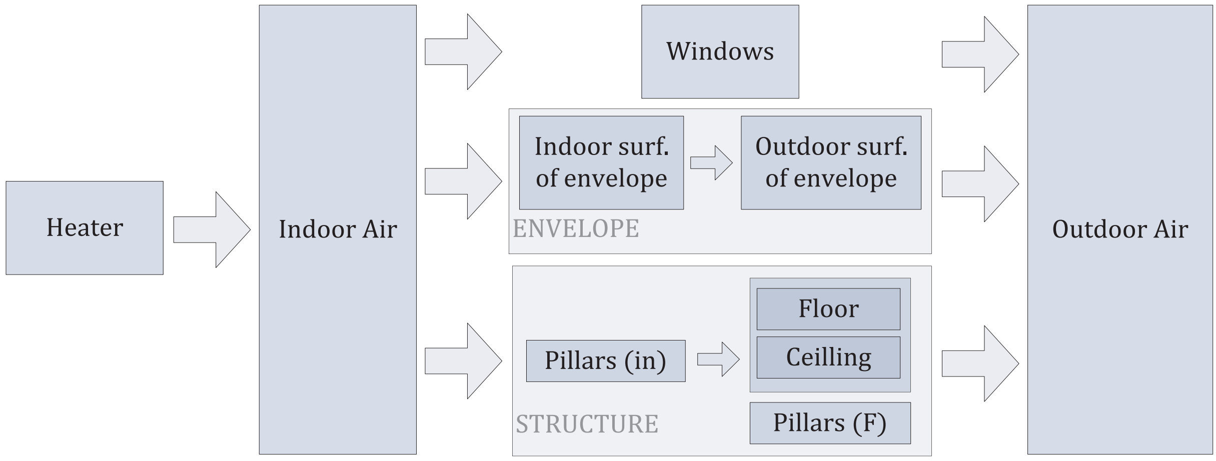


Fig. 4. 7. Heat chain from heater to outdoor environment

Based on this approach, monitoring was designed in order to obtain information about each subsystem during both monitoring periods. Thus, temperature was measured in every subsystem. Moreover, other data were collected in some subsystem, e.g. in heater, where energy consumption was measured, or in outdoor environment, where wind velocity and solar irradiation data were gathered. Fig. 4. 8 depicts in a simplified way the distribution of sensors on the dwelling elements.

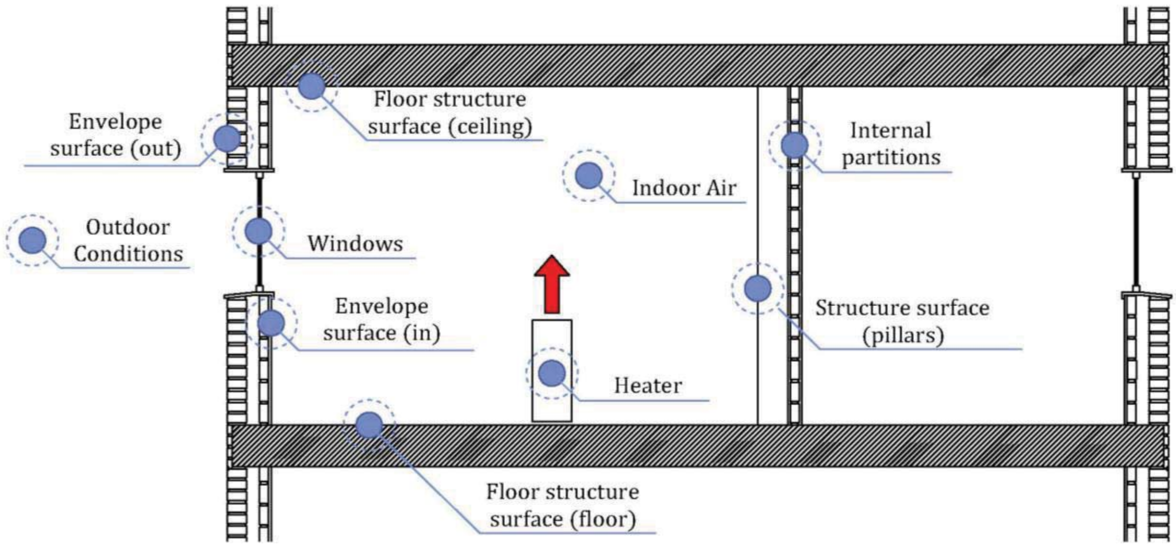


Fig. 4. 8. Subsystems measured during monitoring periods

4.2.2 Data acquisition procedure and data treatment

Measurements were taken with 1 minute frequency. Data acquisition system had an integrated filter. Thus, data were passed through this filter to improve the signal quality.

4.2.2.1 Sampling rate

Sampling rate should be chosen according to the response time of the studied object. In the case of a building, this response time could be assumed in the range of 30-60 minutes. However, as mentioned before, chosen sampling rate for this monitoring study was 1 minute.

The reason of this decision is explained as follows. 1-min. frequency allowed checking the measurements in detail. After this first checking, data were integrated in 10 minute periods (more suitable frequency for buildings), by calculating the average value of each period. This way, the average value contains more accurate information about the 10 minute period than if the representative value for the period is an isolated value. A simplified data set sample is depicted in Fig. 4. 9, to show this explanation clearly. Considering 10 measurements of a data set, average value of those 10 values (depicted in a red dot) is more representative of that period compared than if only one value of the serial is logged. That's to say, following this method, higher accuracy is reached with 10-minute integrated values.

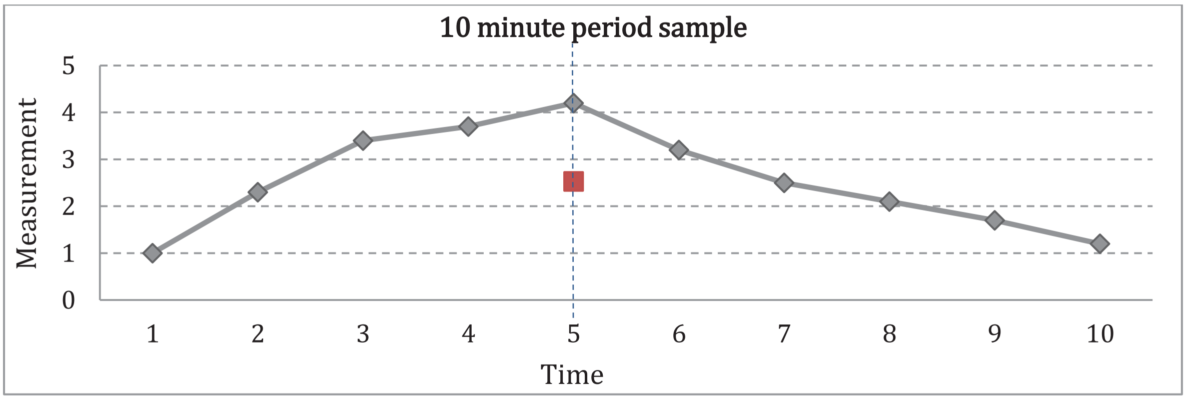


Fig. 4. 9. Example to compare the significance of an average value and a punctual value

4.2.2.2 Assessment of results

Acquisition system generates a data file daily. Each file (raw data) was firstly treated and measurements given by each sensor were passed by calibration factors. These calibration factors were obtained by the aforementioned calibration procedure.

Calibrated results were assessed as follows. First of all, they were studied day-per-day. This procedure allows to identify unexpected behaviour in any sensors, and assessing it in detail or to check if all sensors were measuring and correctly connected, for instance.

Then, they were integrated in ten minute periods as described in the previous section, and average values for each element (indoor air temperature, outdoor surface temperature of façade…) were obtained.

4.2.3 Test-Routine

The controlled heat input was designed as a combination of a Randomly Ordered Logarithmic distributed Binary Sequence (ROLBS, a high frequency routine, with a 30 min. step) and a Pseudorandom Binary Sequence (PRBS, a low frequency routine, with a 60 minute step). The resulted routine, which has no correlations with the other inputs, was designed to excite the heat dynamic at several ranges of frequencies in which the time constant of the building is expected to be [72]. Those time constants varied from 60 minute steps to 12 hour steps. An example of resulted heat input routine for a week is depicted in Fig. 4. 10.

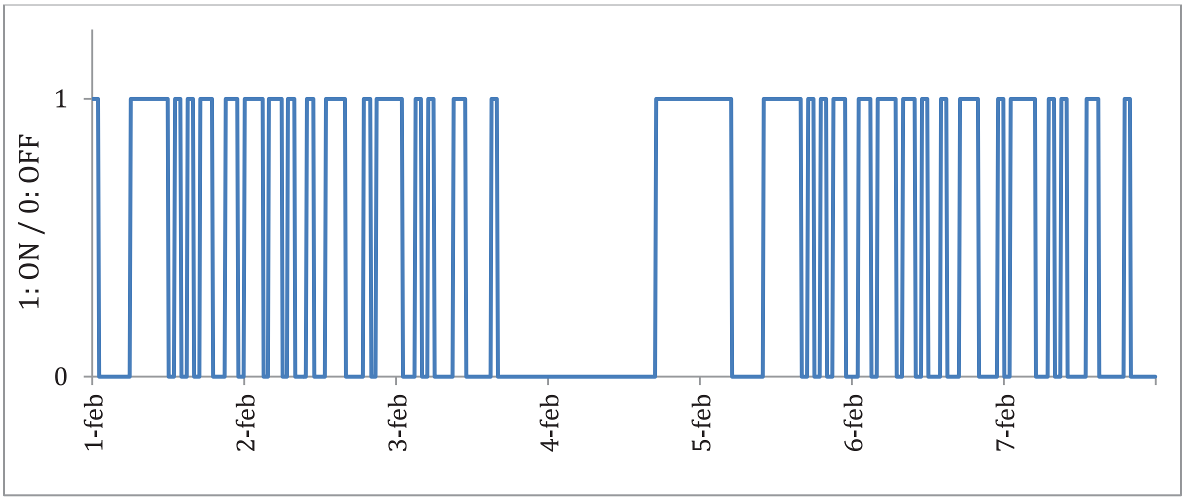


Fig. 4. 10. Heat input control signal in the dwelling from 1st-7th of February

4.2.4 Co-heating method

It was expected as well to use the gathered data to obtain the global transmittance of the envelope based on the procedure of the co-heating method. A co-heating test is a method of measuring a dwelling (unoccupied) heat loss or heat loss coefficient (W/K), both fabric and background ventilation.

It is not a new concept, since it was developed in USA in the late 1970s, and it was used in several occasions in UK in the 1980s. This method involves heating the inside of a dwelling electrically to elevate the indoor mean internal temperature over a specific period of time, typically between 1 to 3 weeks. By measuring the amount of electrical energy the daily heat input to the dwelling can be determined. Then, mentioned heat loss coefficient can be calculated by plotting the daily heat input against the daily difference in temperature between the inside and outside of the dwelling. The resulting slope of the plot gives the heat loss coefficient in W/K. [75], i.e. the heat loss coefficient can be calculated by Eq. 5.

$$UA = \frac{\sum P}{\sum \Delta T} \qquad \text{Eq. 5}$$

On the other hand, it is recommended to obtain a sufficient value of ΔT (difference between indoor and outdoor temperature) in order to maximize the different heat fluxes which take part in the heat transfer, characterizing it more accurately. For that reason, it is advisable to carry out the monitoring studies in the winter months, between November and March, although it will depend on the climate conditions of each place. An added advantage of undertaking the tests during this period is that the effects of solar radiation are also minimised. In this manner, with some small variations, the methodology described in [75] was also borne in mind when this monitoring study was designed.

4.2.5 Scenario 1. Monitoring before energy renovation

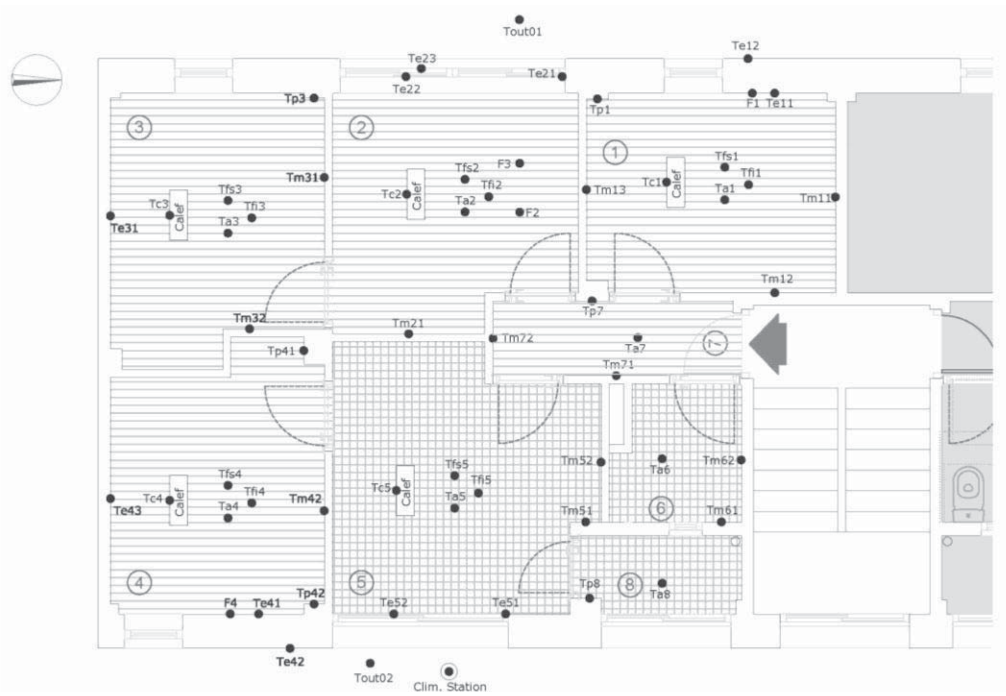


Fig. 4. 11. Layout of the studied dwelling before retrofitting works

A layout of the dwelling can be seen in Fig. 4. 11, where room numbers and sensor positions are also shown, based on the approach described in section 4.2.1.

Collected data group		Number of sensors
Indoor Air Temperature	[Ta]	6
Surface Temperature of opaque walls (envelope)	[Te]	6
- *Indoor surface*		*4*
- *Outdoor surface*		*2*
Surface temperature of windows	[Te]	5
Surface Temperature of Structure	[Tstr]	16
- *Ceiling*	*[Tfs]*	*5*
- *Floor*	*[Tfi]*	*5*
- *Pillars (in)*	*[Tp]*	*2*
- *Pillars (out)*	*[Tp]*	*4*
Heater Temperature	[Tc]	5
Surface Temperature of partitions	[Tm]	13
Outdoor conditions (Air temperature Tout (x2), wind velocity, irradiation)	-	4
Flux meters	[F]	4

Table 4. 4. Highlights of the dwelling for the first scenario

Fig. 4. 12. Some pictures of the first monitoring period

A list of corresponding sensors for the first scenario classified according these data groups is detailed in Table 4. 4: Indoor temperature was measured in 8 points of the dwelling, structure temperature was measured in 16 points, envelope temperature in 9 points (4 in opaque walls and 5 in windows), and outdoor temperature was measured in 2 points. Moreover, indoor wall surface temperatures were measured in 15 points, and 4 flux meters measured data from East and West façade and from floor structure (in floor and ceiling). Air temperature next to each heater was also measured in order to check that all of them were working properly. Likewise, these values can be used to have an approximated value of temperature of the heater resistance. Some pictures of this monitoring period are presented in Fig. 4. 12. A PT100 and a fluximeter placed in the wall are presented in the first picture, the meteorological station, one of the used heaters and the position of the indoor air temperature sensor are shown respectively in the rest of the pictures.

4.2.6 Scenario 2. Monitoring after energy renovation

Several modifications were carried out in the layout of the dwelling. The main thermal improvement was the replacement of all the windows. Sensors were placed in a similar site than in the prior monitoring period, excepting two sensors (T_m42 and T_m72) which had to be removed, since the wall where they were located in the first time was demolished, as depicted in Fig. 4. 13. A list of corresponding sensors for the second scenario, quite similar to the used in the first one, is detailed in Table 4. 5.

Fig. 4. 13. Layout of the studied dwelling after retrofitting works

Furthermore, two different sub-periods can be distinguished in this second monitoring period. The new installed windows have in the frame a ventilation grille. During the first weeks of this monitoring period, until the 28th of December 2012, their regular use was performed. Then the ventilation grilles were sealed (as shown in Fig. 4. 14), and thus a second phase was started. This second phase lasted until 20th of February 2013, when monitoring study was concluded.

Collected data group		Number of sensors
Indoor Air Temperature	[Ta]	6
Surface Temperature of opaque walls (envelope)	[Te]	6
- *Indoor surface*		*4*
- *Outdoor surface*		*2*
Surface temperature of windows	[Te]	5
Surface Temperature of Structure	[Tstr]	16
- *Ceiling*	*[Tfs]*	*5*
- *Floor*	*[Tfi]*	*5*
- *Pillars (in)*	*[Tp]*	*2*
- *Pillars (out)*	*[Tp]*	*4*
Heater Temperature	[Tc]	5
Surface Temperature of partitions	[Tm]	11
Outdoor conditions (Air temp. Ta (x2), wind vel., irradiation)	-	4
Flux meters	[F]	4

Table 4. 5. Highlights of the dwelling for the second scenario

Fig. 4. 14. Sealing of ventilation grilles

Fig. 4. 15. Pictures of the second monitoring period (November 2012-February 2013)

This way, comparing results of both phases allows making a estimation on how much the energy consumption difference is associated to the ventilation performance, since tracer gas monitoring could not be carried out after renovation works. Some pictures of this monitoring period are presented in Fig. 4. 15.

5 Results

Data obtained in this monitoring will be used to define and validate the building models of thermal behaviour in forthcoming chapters. However, even though these results were an intermediate step in order to develop thermal models to obtain final results by simulations, interesting information was found when the results were assessed.

5.1 Experimental data. Results before renovation

As described in section 4.2.2.2, obtained data were assessed following different steps. Firstly, readings in one day data sets were analysed. This way, the coherence of obtained readings is evaluated and possible errors related to sensors, such as a wrong contact or connection mistakes, can be easily detected. Furthermore, detailed analyses are undertaken using these results. As an example, the assessment of data obtained the 1st of February 2012 is presented below. Weather conditions on that day (outdoor air temperature, air velocity and solar irradiation) and heat input control signal are presented in Fig. 4. 16 and Fig. 4. 17, respectively.

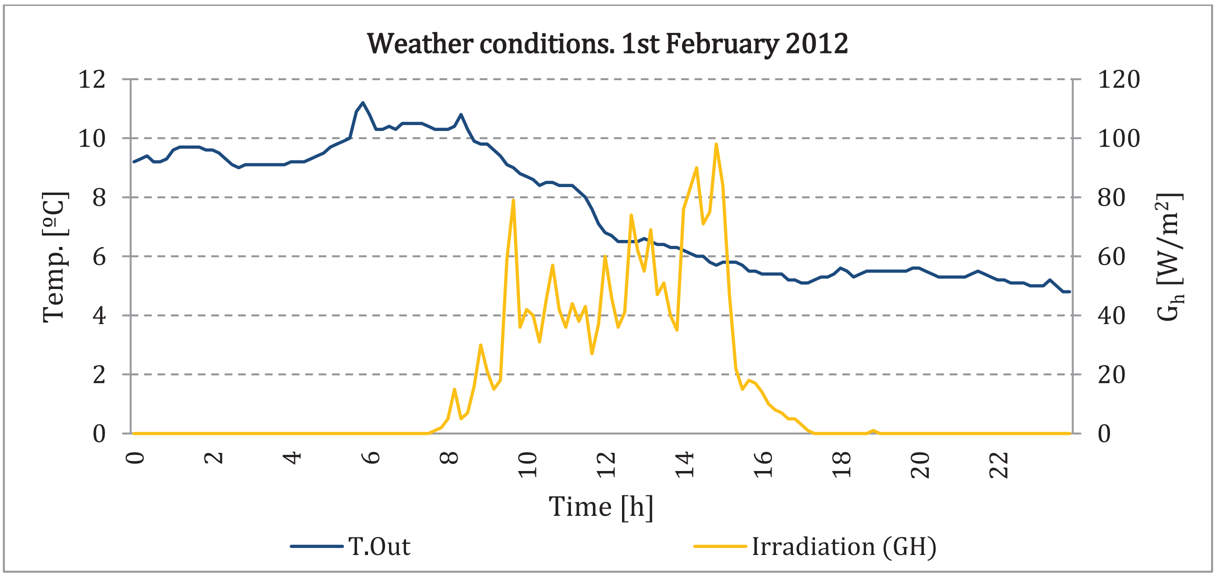


Fig. 4. 16. Measured weather conditions on 1st of February 2012 (Euskalmet)

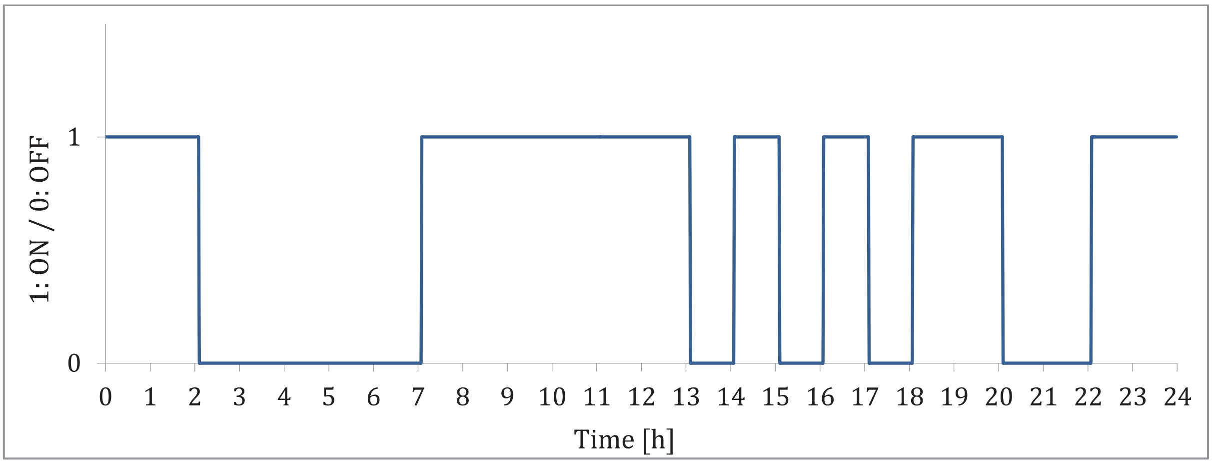


Fig. 4. 17. Heat input routine on 1st of February 2012

5.1.1 Results by systems and subsystems

Daily results gathered by systems and subsystems, in line with the scheme depicted in Fig. 4. 8 (Opaque walls, single glazing window, double glazing window, indoor walls…) were assessed during the monitoring period.

5.1.1.1 Indoor air temperature

Measured temperatures in each room, as well as average temperature and ΔT (difference between maximum and minimum temperature) are depicted in Fig. 4. 18. In the case of indoor temperatures, two set of measurements (T_a6 and T_a8) are quite lower than the others. These indoor temperature differences in mentioned rooms were due to the fact that the measurements appertain to sensors located in the toilet and drying area, where no heater was placed. Temperatures of these two rooms were expected to be lower than those of the other rooms, and temperatures measured in heated rooms (rooms 2-5), as well as room 7, show differences within a range of 0.5 ºC. Meanwhile, temperatures measured in room 1(T_a1) are always about 0.5 ºC below the lowest of mentioned group of rooms. This phenomenon is also detected when daily average values are considered. This fact was observed in the majority of the days of the monitoring period, and it is more noticeable in the coldest days.

It is not an easy task to find a reason to explain it if only data presented so far are taken into account. The size of the room is similar to the others and the heat input is the same (one heater placed in the middle of the room). Even its position in the dwelling is, intuitively, more favourable than in other rooms, such as room 3 or room 4, which have more external façade ratio and, therefore, they are more exposed. Explanation of this phenomenon will be presented later, when more parameters are assessed.

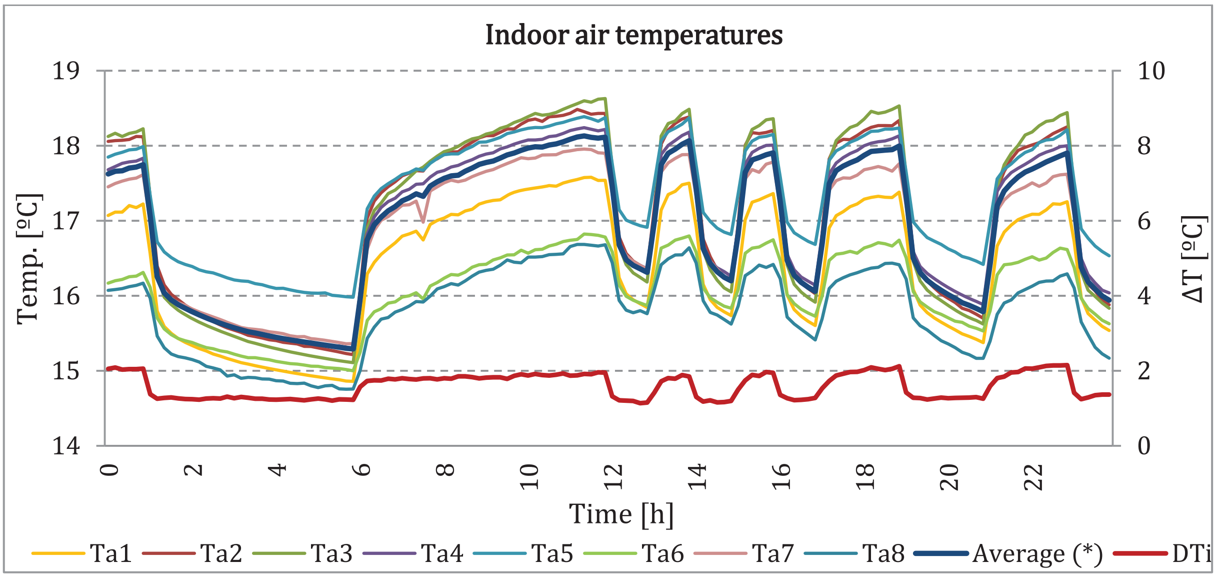


Fig. 4. 18. Indoor air temperatures in 1st of February 2012

5.1.1.2 Temperature of envelope indoor surface

Daily data sets belonging to temperatures of envelope indoor surface are depicted in Fig. 4. 19. All measured indoor surfaces performed in a similar way. In this case, differences amongst measured temperatures were about 0.5 ºC. Again in this case, the lowest temperature was logged in room 1.

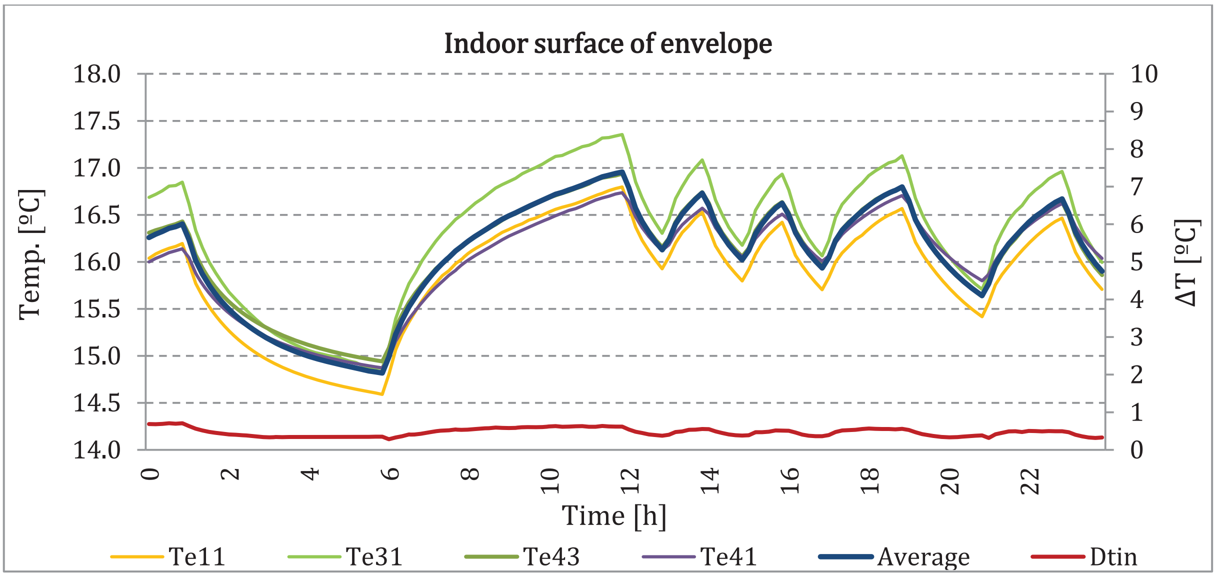


Fig. 4. 19. Temperature of indoor surface of envelope in 1st of February 2012

5.1.1.3 Temperature of envelope outdoor surface

Data obtained from the sensors placed on the outdoor surface of the façade are graphed in Fig. 4. 20. Temperature of the envelope outdoor surface was measured in two different points: one sensor was located in the western façade (T_e12) and the other one in the eastern façade (T_e42). The inclusion of plots related to outdoor temperature and solar irradiation (dotted lines, blue and yellow respectively) has been considered interesting, since envelope outdoor surface is obviously the element more affected by climate conditions.

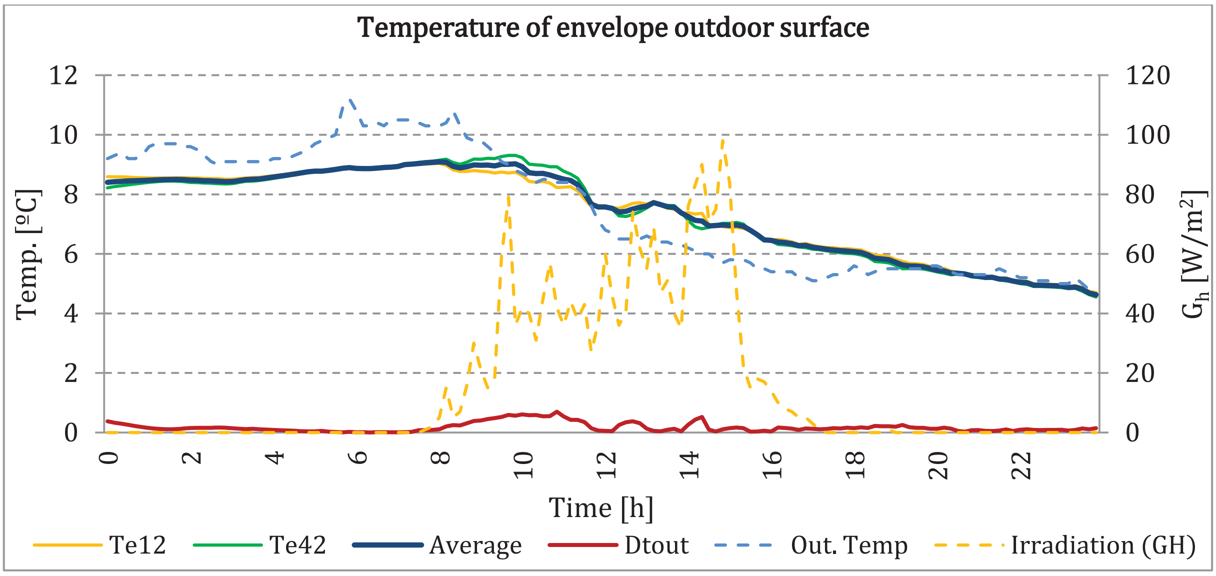


Fig. 4. 20. Temperature of envelope outdoor surface in 1st of February 2012

Two significant aspects can be highlighted assessing the data from envelope outdoor surface. On the one hand, the importance of radiative heat exchange between the outdoor surface of façade and sky, and on the other hand, the influence of solar irradiation over façade.

Concerning the first point, losses by radiative heat exchange with sky are the reason why façade outdoor surface is colder than outdoor air during the night, being the heat flux from indoor to outdoor. That's to say; heat losses caused by radiative exchange between façade and sky at night time in winter are at least as meaningful as those caused by convection between façade surface and outdoor air, and even outdoor surface can achieve a temperature lower than outdoor air due to radiative exchange, which involves a change on the heat flux direction from air to surface, having convection gains.

With reference to the second one, despite the fact that the 1st of February was a cloudy day (there were not measurements of solar irradiation higher than 100 W/m² during this day), differences up to about 0.80 ºC in the morning (eastern façade reach higher temperatures than western one) can be found. Logically, the situation is the opposite in the afternoon: western façade reached temperatures about 0.5 ºC higher than eastern one. After sunset and before sunrise, where there is no solar irradiation, temperature differences between both façades can be deemed negligible.

This effect is more noticeable on sunny days, as it will be described in section 5.1.3.

5.1.1.4 Temperature of floor and ceiling surface

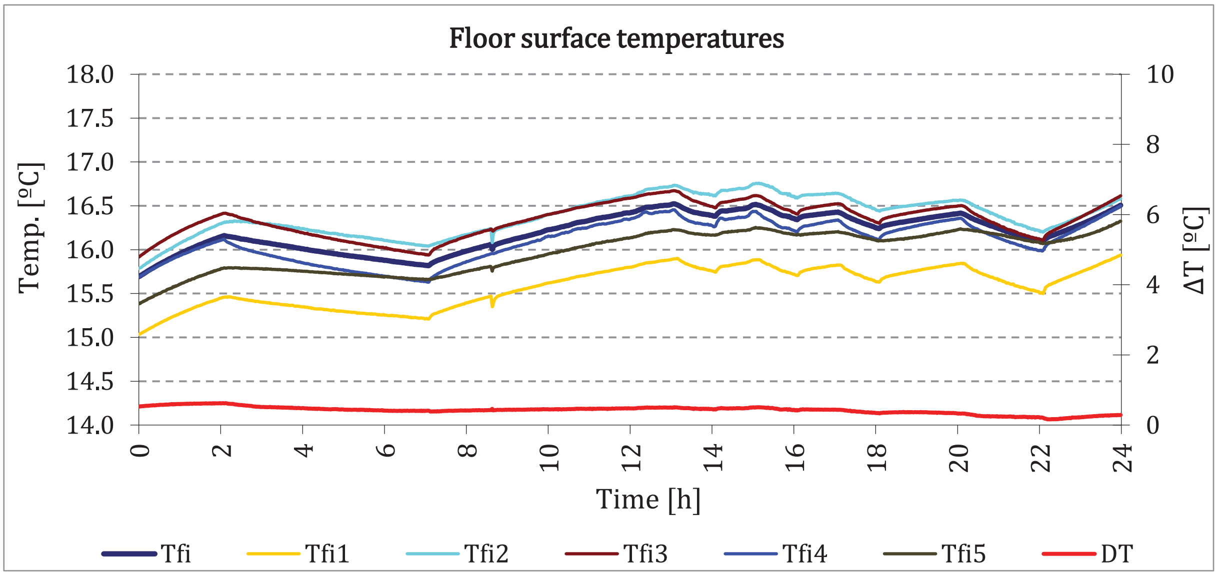


Fig. 4. 21. Floor surface temperatures in 1st of February 2012

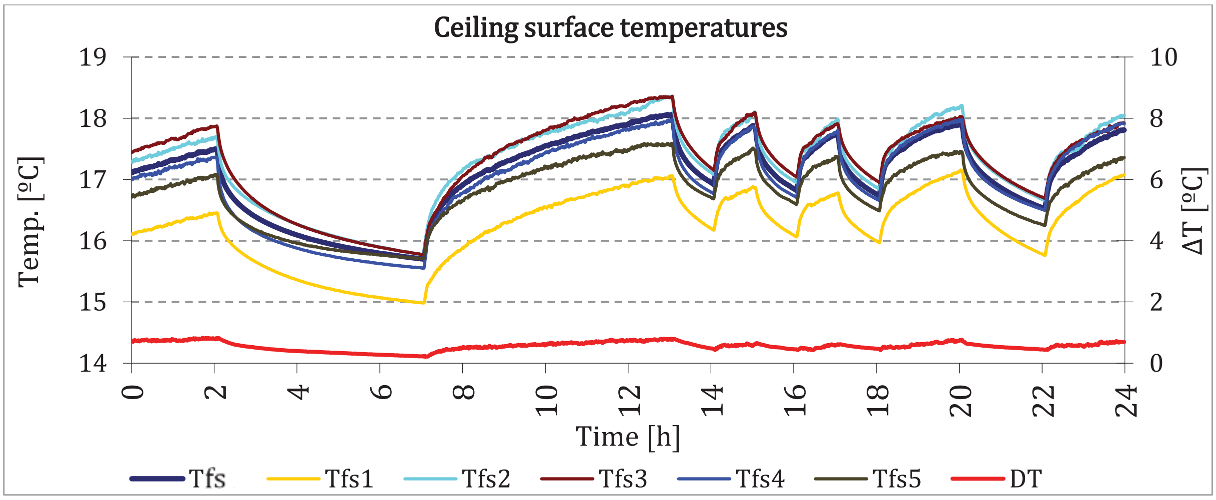


Fig. 4. 22. Ceiling surface temperatures in 1st of February 2012

Temperatures of floor and ceiling surfaces are depicted in Fig. 4. 21 and Fig. 4. 22, respectively. Temperatures measured in room 1 showed also in this case values significantly lower than the others. Average values of ΔT for the other rooms graphed in figures in red line (data set corresponding to room 1 has not been taken into account), were 0.4 ºC in the case of floor surfaces, and 0.6 ºC in the case of ceiling surfaces. Moreover, several appraisals can be done about these data sets.

When floor and ceiling temperatures are compared, thermal air stratification must be taken into account. This means that differences between floor and ceiling surface temperatures in the same room are not only due to different heat losses through each slab. Stratification is clearly observed when heater is connected, even though it is also noticeable (to a lesser extent) when there is no heat input in the dwelling. These differences of temperatures reach more than 2 ºC when heater is switched on, as shown in Fig. 4. 23.

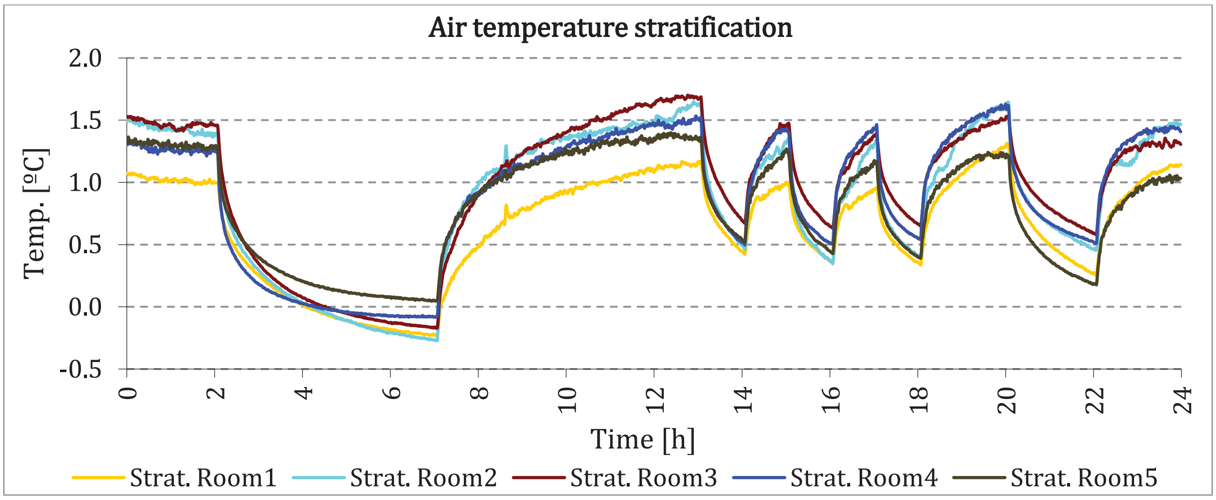


Fig. 4. 23. Air temperature stratification. ΔT (Tfs-Tfi) in 1st of February 2012

As also expected, ceiling surface is more sensible than floor surface to heat input variations, and, in general, to indoor air temperatures, as can be found by looking at Fig. 4. 21 and Fig. 4. 22. This is due to the fact that the aforementioned air stratification is present. Whereas hot air goes up to upper air layers when heater is connected, the lowest air layer temperature is increased more slowly. Due to this stratification, heat losses through ceilings are more marked than those through floors.

The effect is also clearly shown when heat flux measurements by F2 and F3 are observed. When heater was not connected, heat flux in both slabs (floor and ceiling) was nearly zero. This suggests that both sides of the slab (monitoring dwelling and adjacent dwellings) had similar temperatures. However, when heater was switched on and consequently, indoor air temperature increased, losses through ceilings were much bigger than those through floors. It was also observed that when heater was switched on the main heat losses were through the ceiling.

5.1.1.5 Temperature of pillars

Two different behaviours were observed amongst measured temperature in pillars, as shown in the graph depicted in Fig. 4. 24. On the one hand, pillars which are in the middle of the dwelling (T_p41 and T_p7) presented the highest surface temperatures. On the other hand, all the pillars placed in façade (T_p1, T_p3 and T_p8) showed measurements lower than the average values.

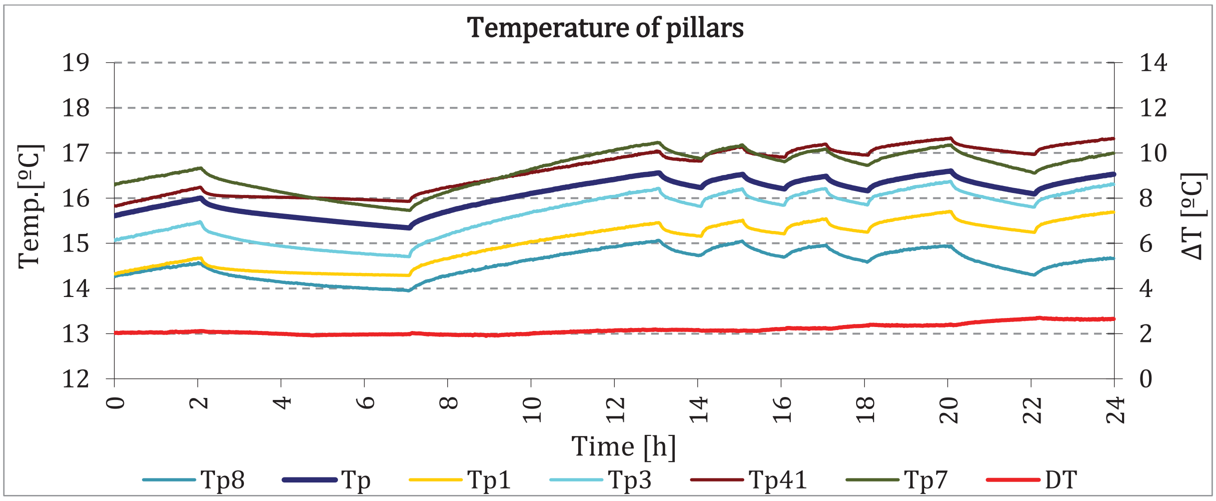


Fig. 4. 24. Measured temperature of pillars in 1st of February 2012

However, while T_p41 and T_p7 did not show great differences and measurements of both pillars were quite similar, measurements obtained from T_p1, T_p3 and T_p8 displayed significant differences. In the case of T_p8, this disparity can be explained because the pillar is placed in a non-heated room. T_p1 measurements should be similar to T_p3, since they both are in the same orientation, and in a heated room. In a similar way to other temperatures measured in room 1 (as shown before), data obtained from this room were about 0.5 ºC lower than those obtained in room 3, which, presumably had similar conditions.

5.1.1.6 Temperature of indoor partitions

When temperatures of indoor partitions are analyzed, it is possible to identify the reason why temperature measurements in room 1 are in general the lowest of those logged in the heated rooms of the dwelling (rooms 1-5).

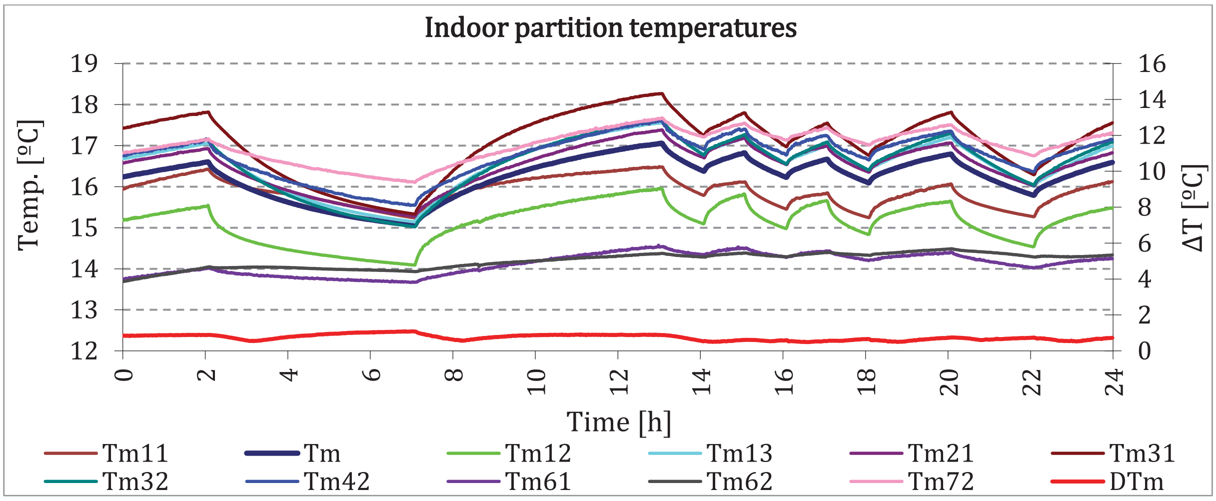


Fig. 4. 25. Temperature of indoor partitions in 1st of February 2012

Surface temperature measurements of indoor partitions for the 1st of February are depicted in Fig. 4. 25. If temperatures corresponding to sensors placed in room 1 (T_m11 and T_m12) and room 6 (T_m61 and T_m62) are not taken into account, ΔT (depicted in Fig. 4. 25 in red line) presented an average value for that day of 0.7 ºC.

But let's focus on data sets whose performance differs from the rest, i.e. mentioned T_m11, T_m12, T_m61 and T_m62. In relation to data collected in room 6, low temperatures registered in T_m61 and T_m62 can be explained mainly since, as previously mentioned, this room has no heat input.

Regarding to data logged in room 1, temperatures measured in this room were lower than the rest of the heated room. However, analyzing in detail these values, one can come to the conclusion that these low values were not as a consequence of the low temperatures of the room, but they were the cause itself because there was a lower temperature than expected in room 1. It was observed that the lowest indoor partition temperatures were logged in T_m11 (this is the wall that separates the dwelling with the contiguous one) and temperature values obtained from T_m12 (this wall separates the dwelling and the staircase) were especially low.

These low temperatures may suggest that there were important heat losses through these walls to contiguous dwelling and, mainly, to staircase. In the first case, a limited use of the heating system (if there were) in the contiguous dwelling can explain the losses through T_m11. Losses through T_m12 are the most significant, as it can be concluded by looking at Fig. 4. 25.

This hypothesis is also reinforced by the fact that the higher differences between heated rooms' temperatures are registered when the heater is switched on (as depicted in Fig. 4. 18) i.e. the higher ΔT was (between room 1 and contiguous dwelling or staircase), the higher heat flux was, and then, the higher heat losses were. That's to say, explained in a simplified way, when two similar rooms have the same heat input (as actually it is), temperature differences between them will be closely linked with the differences on heat outputs, i.e. heat losses.

5.1.1.7 Windows temperatures

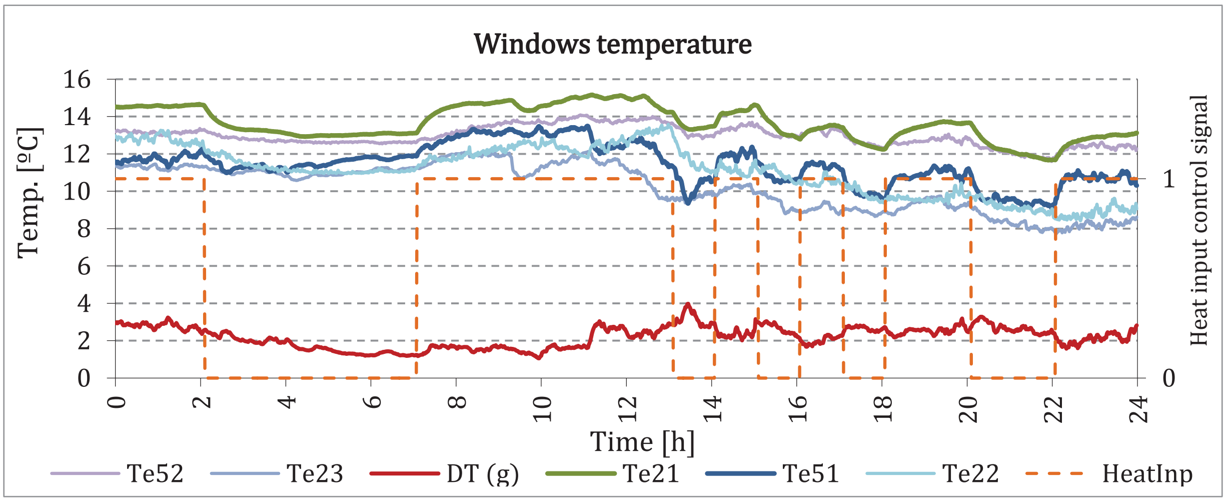


Fig. 4. 26. Window surface temperatures in 1st of February 2012

Five sensors were placed to obtain the temperatures related to windows. As previously said, all windows were double glazing windows, except that located in room 5. Thus, two different types of windows were evaluated, single glazing window, and one double glazing window (in room 2). Temperatures in glazing area and frames were logged during monitoring period. In the case of the double glazing window, temperatures were measured both in the indoor and outdoor surface of the glass, whereas in the single glazing window only indoor surface temperature was logged. Sensors' nomenclature is presented in Table 4. 6.

Element	Surface	Room 2 (Double Glazing)	Room 5 (Single Glazing)
Glass	Indoor surface	Te21	Te51
	Outdoor surface	Te22	-
Frame	Indoor Surface	Te23	Te52

Table 4. 6. Sensor's temperature placed in windows in both monitoring periods

Being both types of windows low thermal quality windows, significant differences were appreciated between single and double glazing (differences of more than 2 ºC were found when indoor surface temperatures were compared). Moreover, T_e22 and T_e51 were similar. It could be assumed that indoor surface temperature of a single glass is almost the same as outdoor surface. T_e52 Temperatures values were a little bit higher than expected, seeing the low quality of the aluminum frame.

5.1.2 Average temperatures

	Initials	Nomenclature	Values taken into account
HEAT.	**Tc**	Reference heater temperature	Tc1
	P	Input heat power	Measured power of the 5 heaters
	Ta	Average ind. air temperature (weighted)	Ta1-Ta8
FAÇADE	**Tfin**	Average ind. surface temperature of façade	Te11, Te31, Te41, Te43
	Tfout	Average outd. surface temperature of façade	Te12, Te42
	Tw	Average surface temperature on windows	Te21, Te51
STRUCTURE	**Tstr**	Average temperature of structure	Tfs1-Tfs5, Tfi1-Tfi5, Tp1, Tp3
	Tfs	*Average temperature of ceiling surfaces*	*Tfs1-Tfs5*
	Tfi	*Average temperature of floor surfaces*	*Tfi1-Tfi5*
	Tp	*Average temperature of pillars surface*	*Tp1, Tp3*
OUT	**Tout**	Outdoor temperature	Web data (Euskalmet)
	Gh	Global horizontal irradiation	Web data (Euskalmet)

Table 4. 7. Groups of data sets

After analyzing the different elements separately (walls, ceilings, windows…), average values were obtained according to data sets presented in Table 4. 7, with the aim of having a representative value for each one. Previously, ΔT (between maximum and minimum logged values in each moment) for each element was studied in order to ensure the representation of every sensor.

Significant differences amongst sensors were found in the case of the heaters. They were since the distance from sensor to resistance surface was not exactly the same for every sensor, and small differences in mentioned distance can involve significant measurement differences when those temperatures (around 150 ºC) are measured. Thus, as Table 4. 7. portrays, measurements obtained in T_c1 were considered as reference values for heater temperatures.

Average indoor air temperature was calculated using measurements obtained with the eight sensors (T_a1-T_a8). Data set of each sensor was weighted using the room area where each sensor was located, as Eq. 6 shows.

$$\overline{T_a} = \frac{\sum T_i \times A_i}{\sum A_i} \qquad \text{Eq. 6}$$

Where

- T_a is the weighted average indoor air temperature
- T_i is the indoor air temperature logged by each sensor
- A_i is the area of each room

This way, calculated values are more representatives, because the problem found when the room area was not taken into account was that the two small rooms without heating (drying area and bathroom) caused an average temperature lower than actually was.

The rest of average ($T_{f,in}$, $T_{f.out}$, T_w, T_{str}, T_{fs}, T_{fi} and T_p) values were obtained using the measurements logged by the sensors pointed out in Table 4. 7. Some sensors were not taken into account when average was calculated. The reason was that some sensors (e.g. T_p42) did not work properly during the studied period.

Despite the fact that a small meteorological station was located in the east façade, finally, climate conditions data were obtained from a meteorological station of the Basque Government located in Deusto, Bilbao, mentioned in the previous chapter, since it was considered that G_h given by mentioned meteorological station was more suitable for study purposes than $G_{v,east}$ given by meteorological station located in the east façade.

This climate station is close enough to Otxarkoaga, and then, those values can be considered as a valid values.

Taken into account the assumptions exposed above, average values for each day were calculated. As a way of example, average values for the same day (1st of February 2012) are presented in Fig. 4. 27.

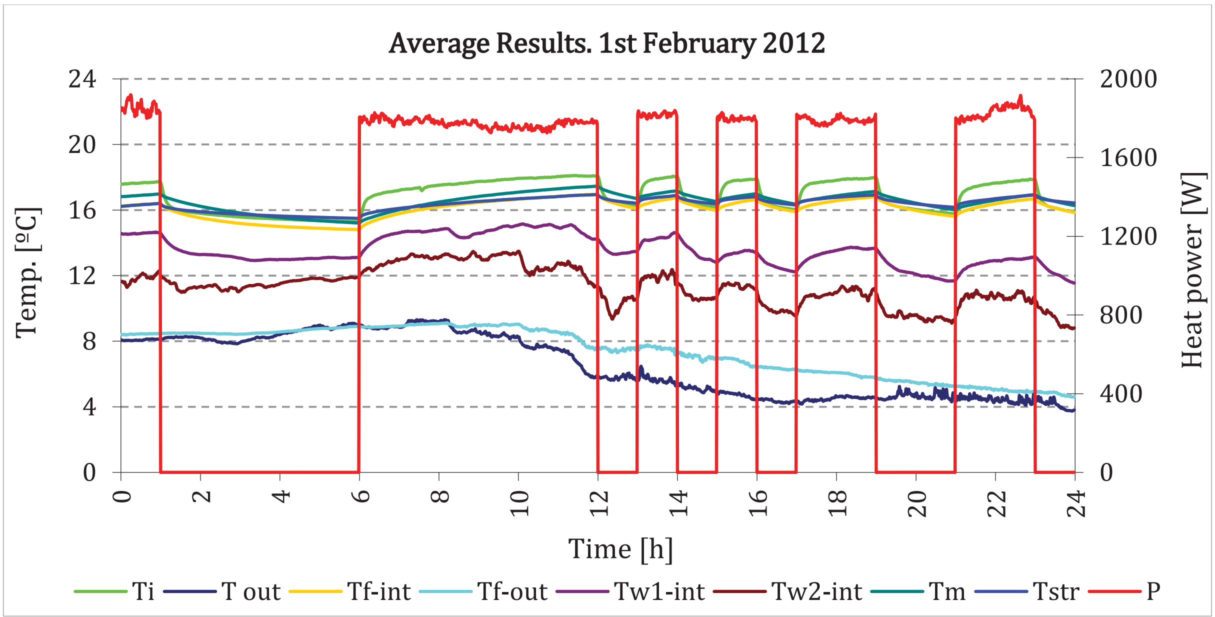


Fig. 4. 27. Results obtained for 1st February 2012

Looking at the graph, some points should be remarked. First of all, the "heat chain" depicted in Fig. 4. 7 is clearly shown in Fig. 4. 27. Heat flows from the hottest point (heater resistance) to the coldest point (outdoor environment). It is shown in the graph, from up to down, especially when heater is running: from heater, heat goes to indoor air, then to indoor partitions, indoor surface of the façade, structure and windows, from indoor surface of façade to outdoor surface of façade, and finally, heat is released to outdoor environment.

Thermal inertia of each element is shown as well in the graph. It can be seen that, when heater is switched on, indoor air temperature presents a fast response, whereas indoor surface of façade, or especially structure temperature (T_{est}) are much more stable.

Influence of heater or outdoor environment in the dwelling can also be explained with this graph. Indoor air temperature and indoor surfaces are, obviously, more sensible to heater influence, especially when it is not a sunny day. Nevertheless, outdoor surface of the façade is not almost affected by indoor variations. Two different performances were shown by windows, depending on their glazing area. Temperatures of indoor surface of the double glazing windows were more dependent on indoor environment, whereas, single glazing window, as expected, was quite more sensible to outdoor variations.

Finally, it must be highlighted the difference in temperatures shown by the windows. Single glazing windows (T_v2, in the graph) presented, in the main, glazing area temperatures about two degrees below the double glazing windows (T_v1).

5.1.3 Other considerations

Data corresponding to 1st February 2012 have been used as an example in order to illustrate the analysis of logged data, and to remark the most significant features of the thermal performance of the dwelling. Even though the majority of the key factors can be explained using as a reference the mentioned day, analysis of the data would be incomplete if the effect of solar irradiation is not taken into account. For that reason, a brief analysis of the elements more affected by solar irradiation in a sunny day is presented in this section.

With this aim in mind, data obtained in 12th of February 2012 have been used by a way of illustration. Data related to climate conditions for this day are depicted in Fig. 4. 28. As this figure shows, it was a relatively sunny day, with low temperatures, even lower than the previously analysed day. Heat input routine is presented in Fig. 4. 29.

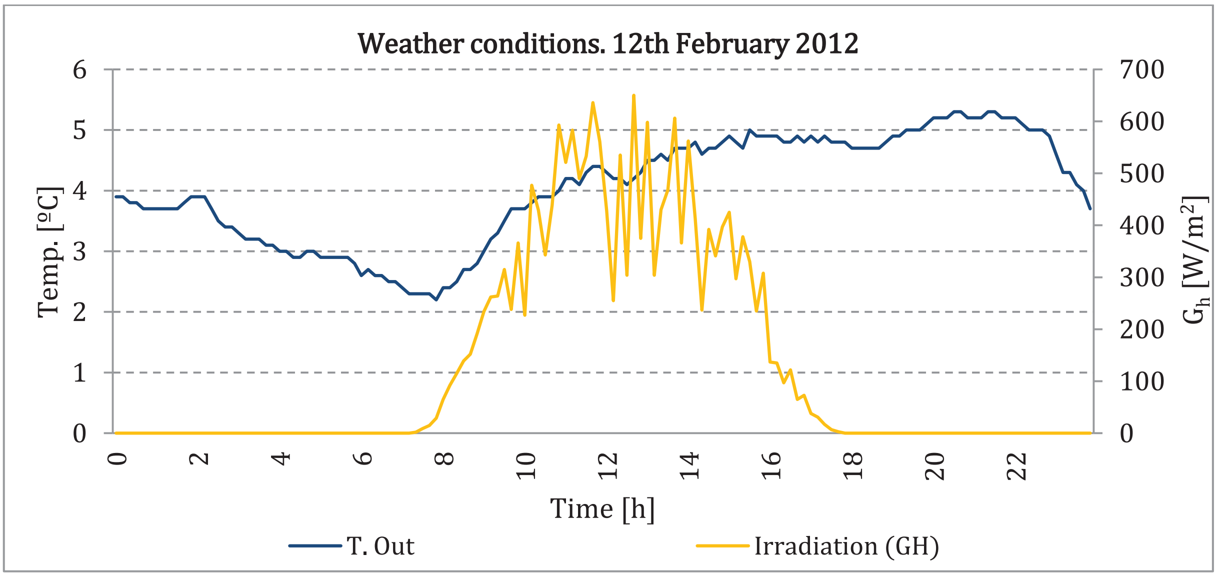


Fig. 4. 28. Measured weather conditions on 12th of February 2012 (Euskalmet)

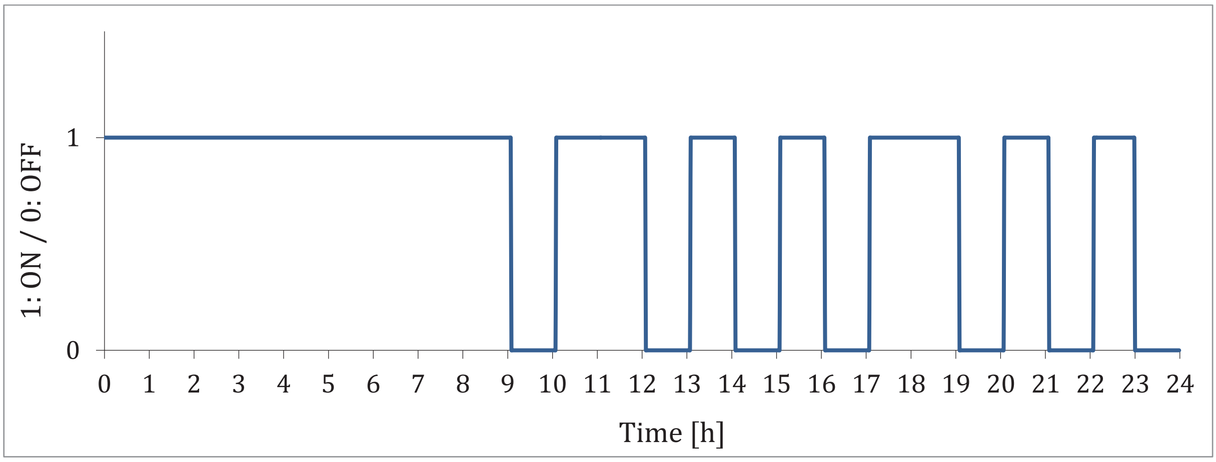


Fig. 4. 29. Heat input control signal on 12th of February 2012

5.1.3.1 *Indoor air temperature*

Indoor air temperatures in 12th of February 2012 are depicted in Fig. 4. 30. T_a4 and especially, T_a5 temperatures increased in the first hours in the morning (more than 2 ºC, in the case of T_a5) when solar irradiations entered through the windows. Similarly, in the rooms in the west façade, T_a1, T_a2 and T_a3 temperatures increased in the afternoon, about 1.5 ºC over the average.

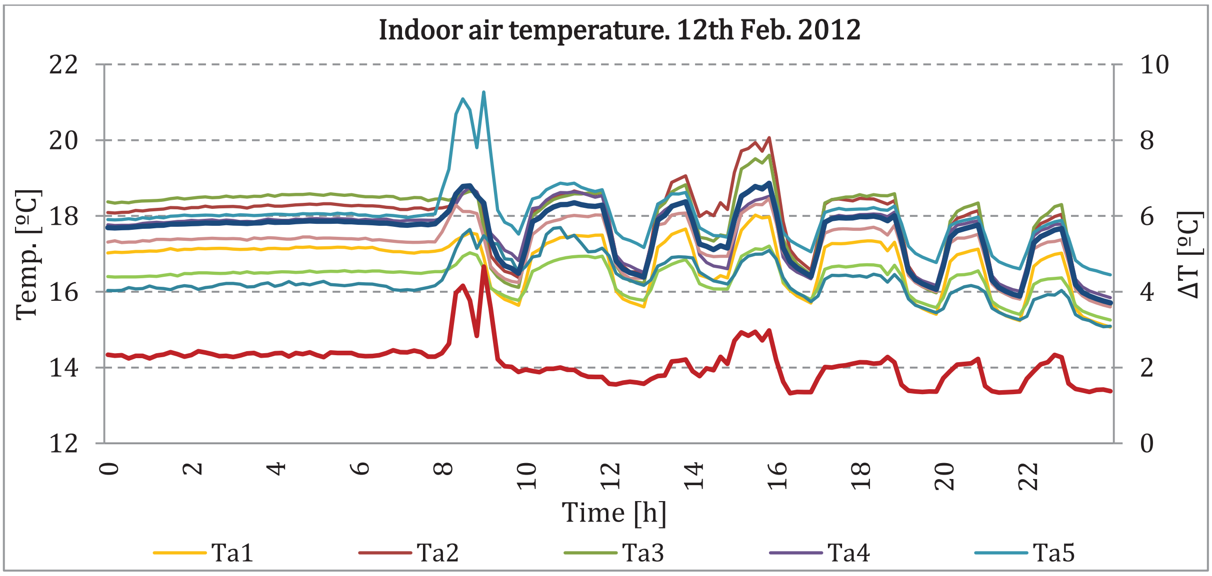


Fig. 4. 30. Indoor air temperatures in 12th of February 2012

5.1.3.2 *Temperature of envelope indoor surface*

Temperature of envelope indoor surface logged in 12th of February 2012 is presented in Fig. 4. 31. No great differences were found with respect to those presented in previous section.

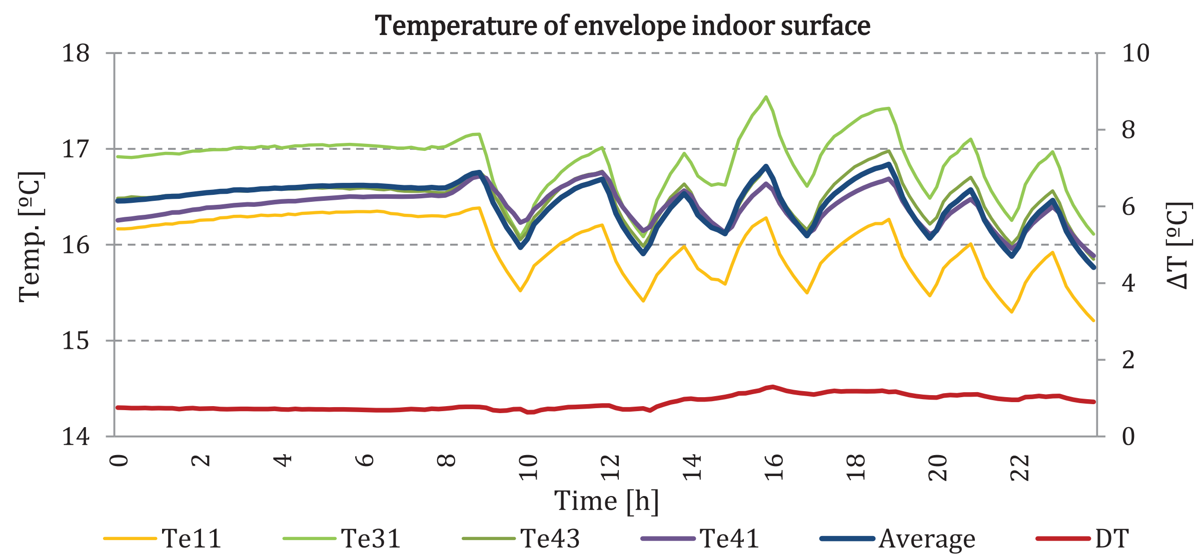


Fig. 4. 31. Temperature of envelope indoor surface in 12th of February 2012

5.1.3.3 Temperature of envelope outdoor surface

When data taken on a sunny day were compared to those obtained on a cloudy day, one of the main differences was found, obviously, in the envelope outdoor surface temperature, as shown in Fig. 4. 32.

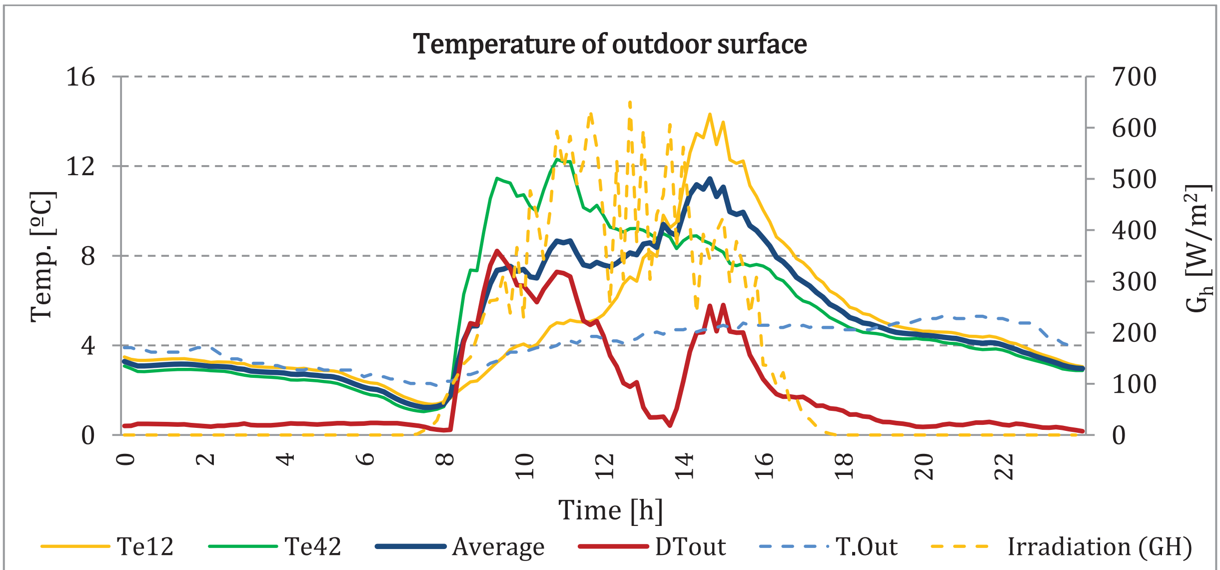


Fig. 4. 32. Temperature of outdoor surface of envelope in 12th of February 2012

Thus, T_e12, placed in the west façade, reached the highest temperature in the afternoon, when it had direct solar irradiation, whereas the highest temperature in the east façade was logged in the morning. The highest difference between façades was reached during the morning, where ΔT values greater than 8 ºC amongst both façades were logged. It is also remarkable the way that the graph shows the influence of solar radiation on outdoor surface temperature. During the night period, both façades had nearly the same temperature, and quite similar to outdoor air temperature, even lower, due to losses by the aforementioned radiative heat exchange between the outdoor surface of façade and sky.

On the contrary, during the daylight period, surface temperature was a little bit higher than outdoor air temperature, when no direct solar irradiation was received in the surface. Looking at the T_e12 values in the first hours of the morning, it can be detected how even the west façade had still received no solar radiation, losses by radiative heat exchange between façade and sky decreased dramatically. When the façade was exposed to solar irradiation, its temperature increased, reaching differences with respect to outdoor air temperature of more than 8 ºC in the case of east façade (green line, T_e42) and almost 10 ºC in the case of west façade (T_e12). This point demonstrates the importance of the gains and losses due to radiative exchanges in the thermal behaviour of the envelope.

Finally, a qualitative evaluation of the heat storage capacity of the façade could be carried out looking at this graph. Despite the fact that east façade seemed to keep for more time higher temperature than outdoor air temperature (about 3.5-4 ºC higher during the afternoon), temperature of both façades decreased in a drastic manner after the sunset (around 6 pm). Based on information presented in Chapter 3, construction typology of this façade is quite similar to F.c.1, whose C (heat capacity) was calculated to be 180 kJ/m^{2}K. It would had been interesting to compare these values with those obtained in a façade with a higher heat capacity, like F.a. (about 460 kJ/m^{2}K), and to assess the differences.

5.1.3.4 Temperature of indoor partitions

No additional information respect to previously presented was found when temperatures of indoor partitions were assessed. Temperatures of indoor partitions for 12th of February 2012 are depicted in Fig. 4. 33.

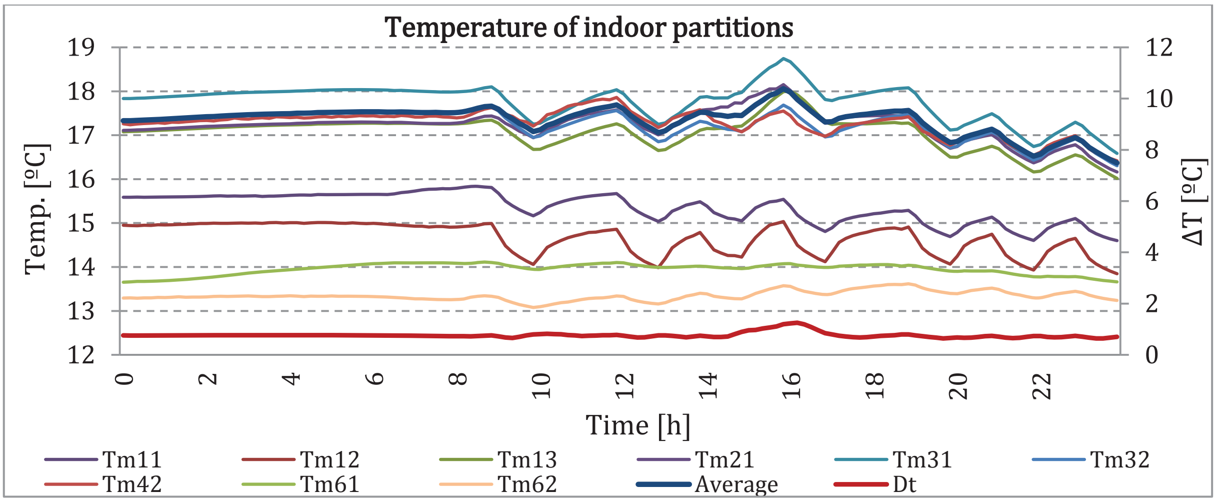


Fig. 4. 33. Temperature of indoor partitions in 12th of February 2012

5.1.3.5 Windows temperatures

At last, window temperatures for the 12th of February 2012 are presented in Fig. 4. 34. These data provide similar information to those obtained with the temperatures of façades outdoor surfaces. Maybe, in this case it is more apparent the effect of radiative heat exchange, since glazing area has practically no heat capacity.

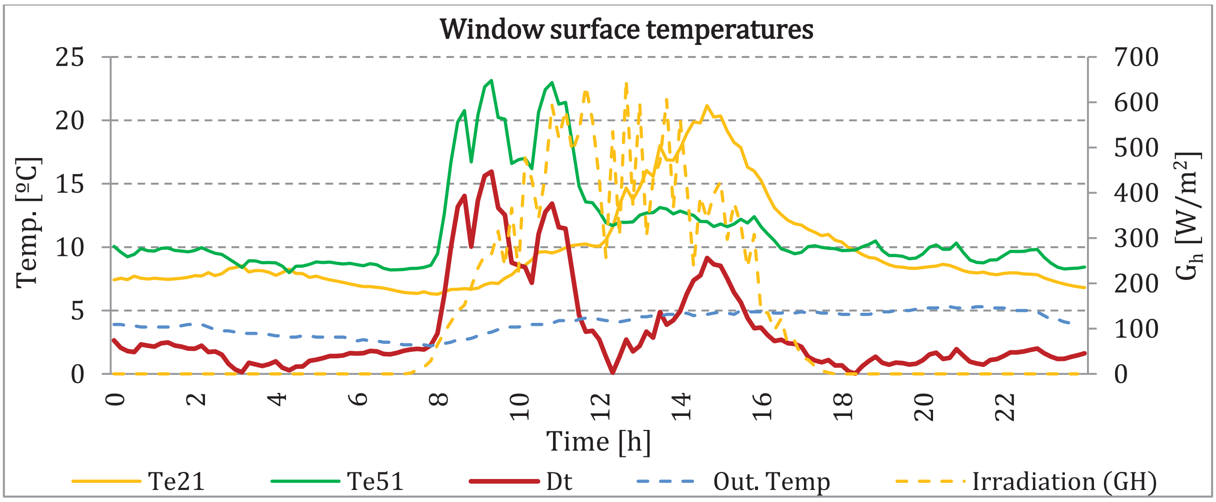


Fig. 4. 34. Window surface temperatures in 12th of February 2012

But if this effect can hardly be detected, in a subtle way, looking at data obtained the 12th of February 2012 and presented in Fig. 4. 34, the effect is clearly shown in Fig. 4. 35, which depicts data of 15th of March 2012. That day, outdoor temperature was about 10 ºC during the whole day. However, it was a sunny day, and G_h reached a maximum of 700 W/m^2. Three different temperature levels could be identified when data of this day are assessed. The three levels are approximately depicted in a dot blue line in Fig. 4. 35.

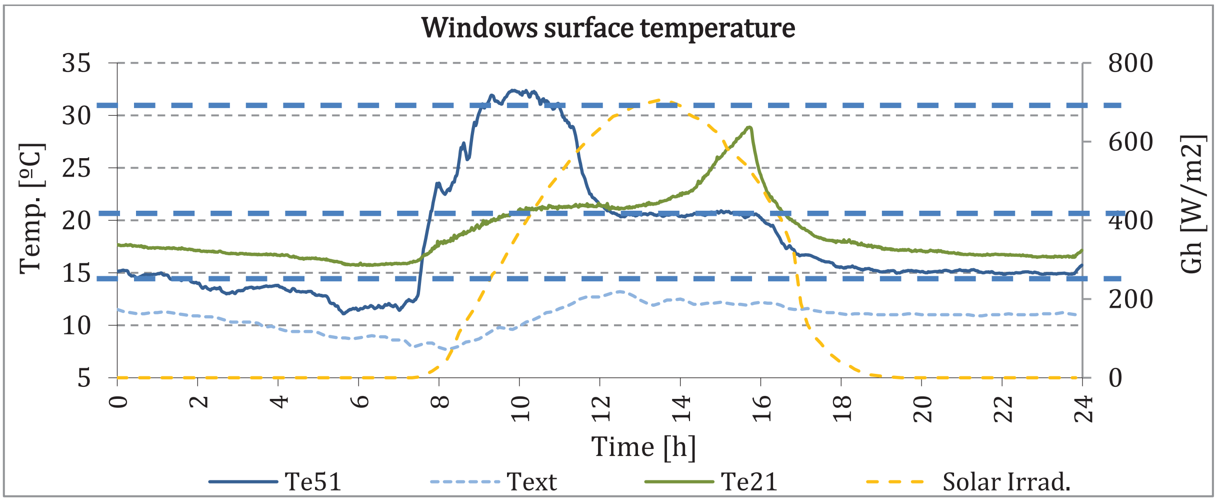


Fig. 4. 35. Window surface temperatures in 15th of March 2012

The first level, around 15 ºC, is the temperature of windows during the night, when losses by radiative heat exchange were higher. The second level, around 20 ºC corresponds to temperature reached by the glazing area during the day, when it received no direct solar irradiation. Finally, a third level could be fixed around 30 ºC, the temperature the windows reached when they received direct solar irradiation. Thus, it was observed how the east oriented window (T_e51) increased drastically its temperature after the sunrise, and in less than two hours, step-up from 12.26 ºC to 31.44 ºC. At around 11 am (time is presented in GMT) it received no radiation anymore, and its temperature decreased in few minutes to around 20 ºC, till the sunset, when its temperature decreased again to 15 ºC.

West oriented windows performed in a similar way. Its temperature increased slower in the morning, when no direct solar radiation was impinging on its outdoor surface but losses by radiative heat exchange between glazing area and sky decreased with the sunrise. Significant temperature increasing happened when it started to receive direct solar radiation in the afternoon, and finally, the temperature fell in the sunset even more dramatically than for the east windows, due the fact that west windows experiment at the same time the increasing of losses by radiative heat exchange, and no gains by direct solar radiation. It is just the opposite situation to the behaviour of east windows in the morning, when losses by radiative heat exchange suddenly decreased with the sunrise, and gains due to direct solar radiation increased.

5.2 Experimental data. Results after renovation

The main data after renovation are presented in this section. It has been considered that presenting the data obtained for every system may result repetitive, and no more significant information would be provided. Thus, the information is focused on indoor air temperature and measurements in windows themselves, which are the two subsystems more affected by the renovation.

In this case, data corresponding to 13th of January 2013 have been selected as example. Climate conditions that day were quite similar to the day chosen as a reference (1st of February 2012) in the former analysis presented in section 5.1.1, as shown in Fig. 4. 36. Heating routine is depicted in Fig. 4. 37.

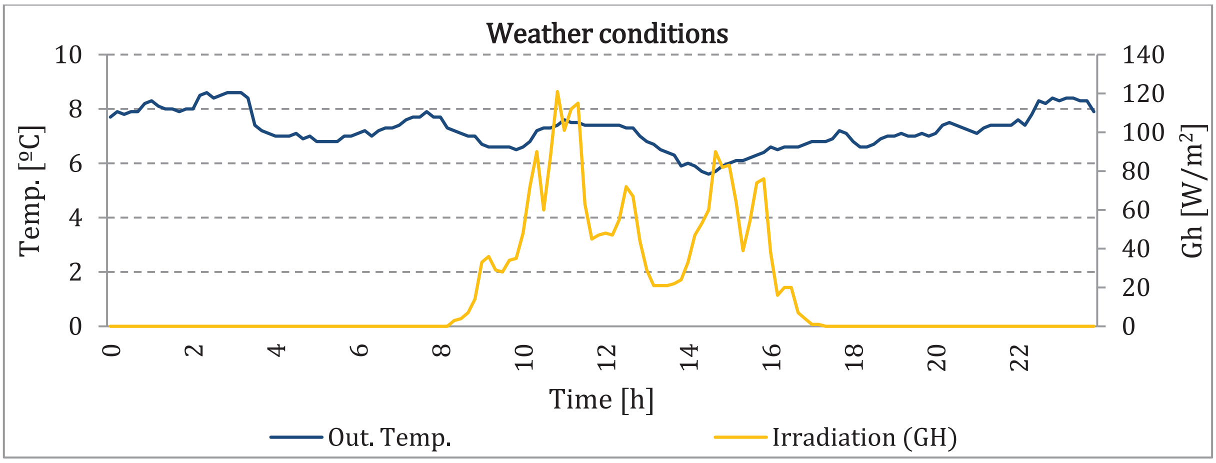


Fig. 4. 36. Measured weather conditions on 13th of January 2013 (Euskalmet)

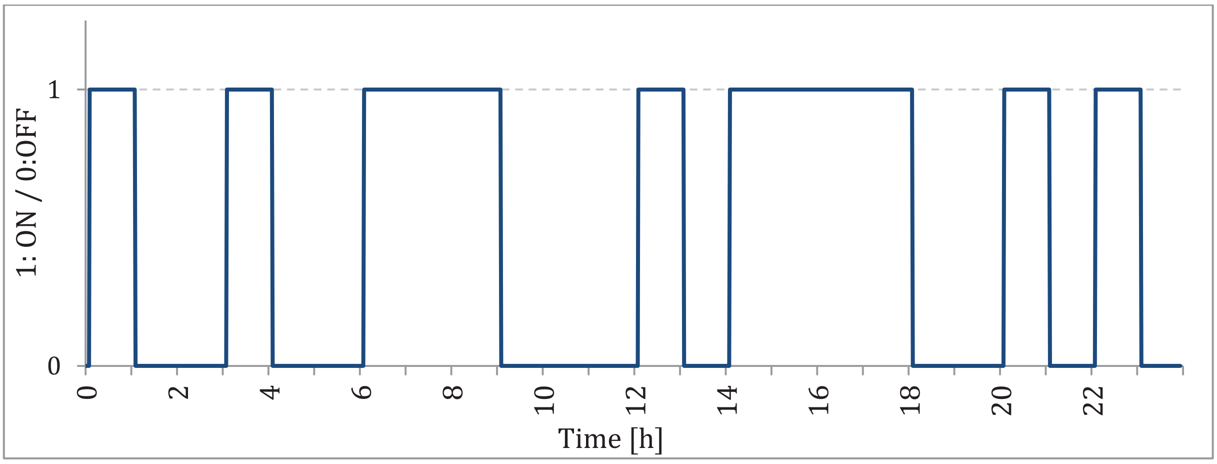


Fig. 4. 37. Heat input control signal on 13th of January 2013

5.2.1 Results by systems and subsystems

5.2.1.1 Indoor air temperature

Indoor air temperature measured in each room is depicted in Fig. 4. 38. In general, indoor temperature was higher than that measured before renovation works. This could be identified as the main attribution of renovation, even though this assertion must be made with caution, since several other factors can influence on indoor temperature, and deeper assessments will be done in next chapters.

Especially noteworthy was the change in the trend of the indoor air temperature in room 1. Unlike measurements taken before renovation works, measurements taken after windows replacement showed that air temperature in room 1 was nearly the average temperature in the dwelling. This is especially remarkable since, bearing in mind the carried out renovation, no significant improvement was expected in this point (no improvement was carried out on walls where T_m12 and T_m11 were located, and important heat losses were supposed). Changes on operation conditions in adjacent dwelling or modifications in ventilation patterns of staircase are two of the several possible explanations to this fact.

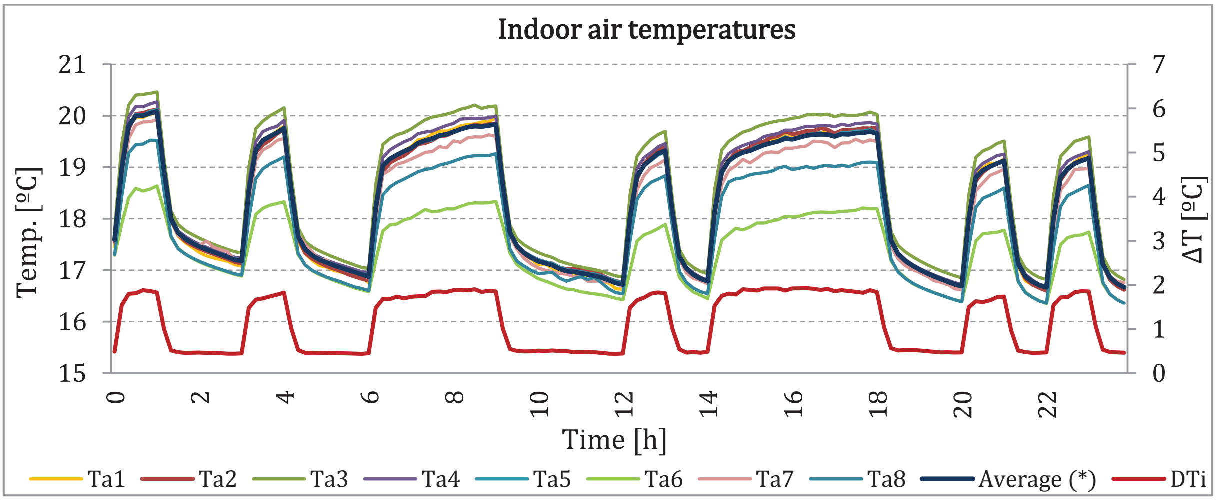


Fig. 4. 38. Indoor air temperatures in 13th of January 2013

5.2.1.2 Windows

The main changes were found evidently in windows. Temperatures in glazing area and new window frames for the selected day are depicted in Fig. 4. 39. Generally, a temperature rising around 1.5 ºC and 2ºC were found in indoor surface of glazing of the new windows, in comparison to the old ones. Furthermore, these variations were more connected to indoor excitements (i.e. heat input) than to outdoor temperature, unlike temperature data obtained before renovation. Finally, data also showed that glazing area presented better thermal performance than window frames even having thermal break, since the frames presented lower temperatures than glazing area. This proves that frames had higher losses per square meter than glazing area (both in frames and in glazing area, temperatures were measured in their indoor surface).

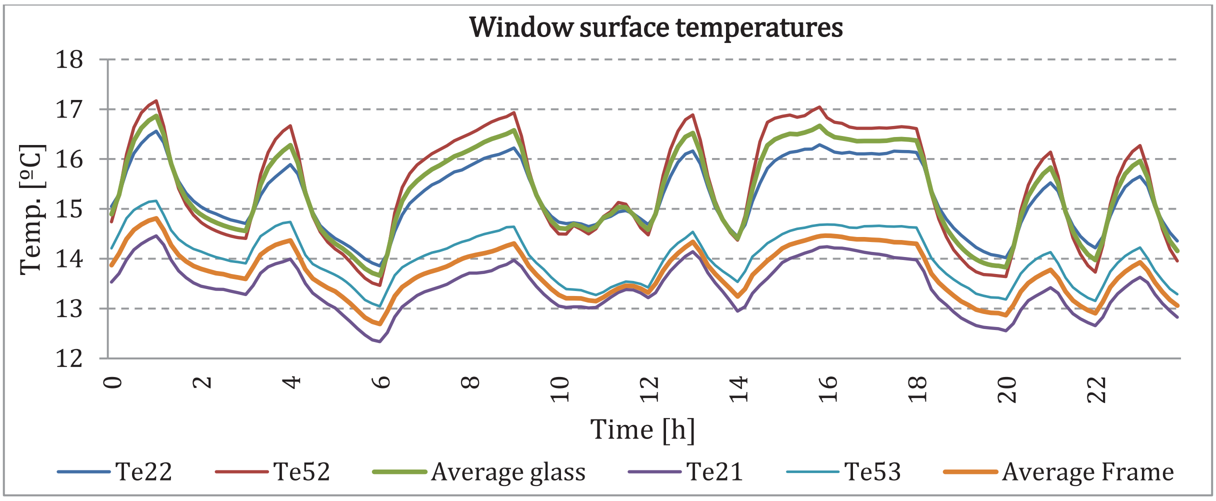


Fig. 4. 39. Window surface temperatures in 13th of January 2013

5.2.2 Average temperatures

In a similar way to the data before renovation, values obtained by monitoring after renovation were integrated in 10 minute periods. Subsequently, average values per element were calculated, as presented in Table 4. 8.

Similar criteria to those kept before renovation works were followed again to obtain these average values. However, since each monitoring study has its peculiarities and special features, some adjustments were made. They can be summarized in the following highlights:

- Despite the fact that this second monitoring period started the last week of November, all initial problems, such as wrong connections, were solved by the 3rd of December. So the analysed data were those obtained from 4th of December 2012 to 20th of February 2013, both included.
- In the case of the air temperature, weighted average values were also calculated in this second monitoring.

- Air temperature values obtained in room 2 were dismissed when weighted average indoor air temperatures were calculated. This point was decided after analysing the values provided for each sensor, because whilst it was observed that sensor placed in room 2 gave similar measurements to those placed in the other heated rooms (i.e. it represents the average value of room temperatures), several exceptions were found for some periods of sunny days when measured temperatures reached peaks which present up to 6 ºC of difference respect to the temperatures measured in the other rooms, as shown as a way of example in Fig. 4. 40.

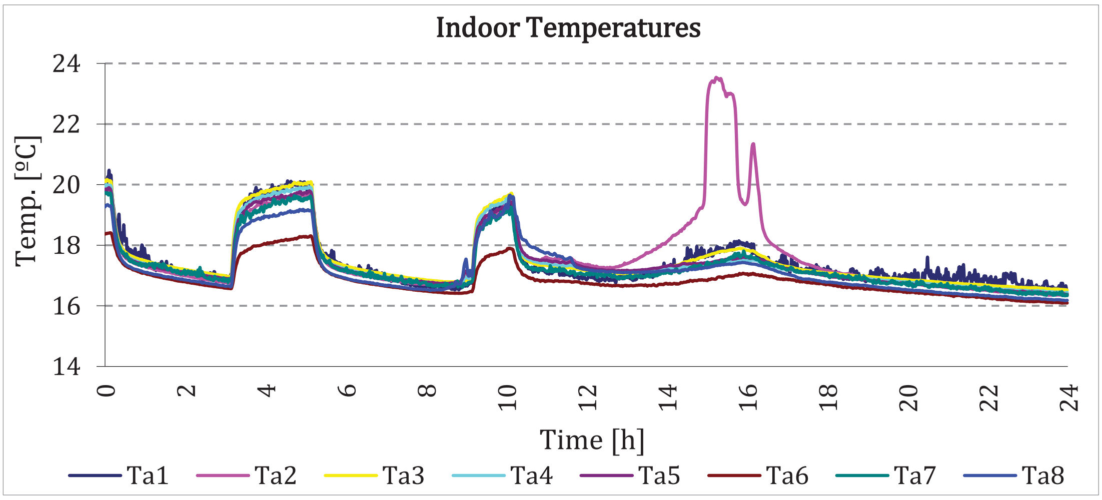


Fig. 4. 40. Indoor temperature results obtained in 28th January 2013

This figure depicts temperatures measured on 28th of January 2013. The peak temperature was reached when the façade and the window of room 2 (west orientation) received direct solar radiation. The hypothesis that the measured temperature is representative of the room was dismissed since the rest of the heated rooms with the same orientation (room 1 and room 3) had no peak time at the same time, even though a small effect of the irradiation can be observed, and their temperatures were quite higher than those obtained in rooms 4-8 during the same time, as shown in Fig. 4. 40. It can be deduced that the peak was caused by direct solar irradiation impinging on the sensor. Thus, even though it would not have a great relevance in the average value, it was decided not considering it. Moreover, in the rest of the hours the other sensors located in heated rooms give a similar behaviour amongst them, especially those placed in room 1 and 3 (also west orientation), and for that reason, they have been representative enough.

	Initials	Nomenclature	Values taken into account
HEAT.	**Tc**	Reference heater temperature	Tc4
	P	Input heat power	Measured power of the 5 heaters
	Ta	Average ind. air temperature (weighted)	Ta1-Ta8
FAÇADE	**Tfin**	Average ind.surface temperature of façade	Te11, Te33, Te41, Te43
	Tfout	Average outd. surface temperature of façade	Te12
	Tw	Average surface temperature on windows	Te22, Te52
STRUCTURE	**Tstr**	Average temperature of structure	Tfs1-Tfs5, Tfi1-Tfi5, Tp1, Tp3, Tp42, Tp8
	Tfs	*Average temperature of ceiling surfaces*	*Tfs1-Tfs5*
	Tfi	*Average temperature of floor surfaces*	*Tfi1-Tfi5*
	Tp	*Average temperature of pillars surface*	*Tp1, Tp3, Tp42, Tp8*
OUT	**Tout**	Outdoor temperature	Web data (Euskalmet)
	Gh	Global horizontal irradiation	Web data (Euskalmet)

Table 4. 8. Groups of data sets in the second scenario

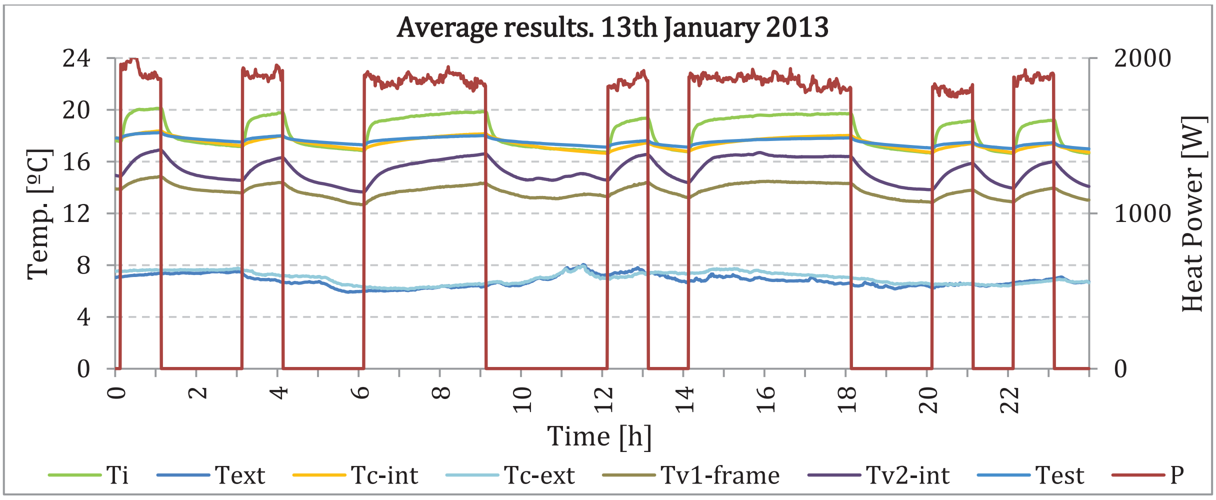


Fig. 4. 41. Results obtained for 13th January 2013

Average values obtained in 13th of January 2013 are presented in Fig. 4. 41. Responses of the structure and of the façade indoor surface were quite similar to results obtained before renovation. However, improvement in windows is clearly shown in the graph, as the indoor surface temperature of the glazing area is more stable and less dependent on the outdoor conditions.

6 Discussion

Two main points must be highlighted after the first analysis of the obtained data: losses to adjacent spaces of the dwelling (adjacent dwellings and/or staircase) and the radiative heat exchange of the building envelope.

Respect to the first one, significant heat losses to the staircase, and especially to the adjacent dwelling were found, especially in room 1 during the first monitoring period, as already mentioned in this chapter. This kind of losses, which can involve a significant part of the total heat losses in the dwelling, have to be taken into account when thermal behaviour of a dwelling is evaluated. The low quality of the indoor partitions was usual in many construction periods, when the awareness of thermal performance of these indoor partitions was almost nonexistent, since if any awareness existed, it was only about envelope. The indoor environment of the dwelling becomes very dependent of the operation conditions of adjacent dwellings. This situation is even more serious in the case of social housing, where many dwellings have no heating systems, and it increases the amount of losses to the adjacent dwellings which use some kind of heating system.

For similar reasons, losses to staircase were found significant as well. Besides, staircase windows were open almost all day, which worsen the situation, since staircase had not only a similar air temperature to the outdoor air, but also had no solar gains, unlike the façade. So being the stair case in similar conditions to the outdoors (not having into account the wind effect), stair case walls were quite lower thermal quality than façade.

With regard to the radiative heat exchange, data obtained in both monitoring periods showed its impact on the envelope surface temperature, even though its effects are more apparent in the roof.

6.1 Benefits of windows replacement

Despite the fact that the retrofitting carried out on the dwelling was just a windows replacement, some positive effects can be found in the first analysis of the results. As previously said, results showed that indoor surface temperature of the glazing area increased and presented better response to indoor excitements. Likewise, this point also had effect on indoor air temperature, as Table 4. 9 shows.

Prior Renovation (1st-Feb.2012)				After Renovation (13th-Jan.2013)			
	00 m	30m	60m		00 m	30m	60m
6-7 am	15.28 ºC	16.98 ºC	17.20 ºC	**6-7 am**	16.87 ºC	19.12 ºC	19.16 ºC
1-2 pm	16.29 ºC	17.90 ºC	18.05 ºC	**12 am-1 pm**	16.73 ºC	18.95 ºC	19.32 ºC
3-4 pm	16.20 ºC	17.81 ºC	17.90 ºC	**2-3 pm**	16.80 ºC	19.04 ºC	19.29 ºC

Table 4. 9. Increment of temperature during the first hour that heater is switched on

Two similar days were selected to display this effect, one before renovation works (1st-Feb-2012) and the other one after renovation works (13th-Jan-2013). Both days were cloudy. The temperature in 1st of February 2012 was about 8 ºC in the morning, whereas in 13th of January 2013 was about 6 ºC. Even though conditions were not exactly the same, and so it was not possible to make a quantitative comparison directly, conditions were quite similar and qualitative comparison is possible in order to have a first idea of the effect of the window replacement. Further and deeper analyses will be made in next chapters, but a first review of the data collected can give an idea of the above mentioned effect, as explained below.

In Table 4. 9 average temperatures in the first hour after switching the heaters on are presented. In the 1st of February 2012, heaters were running from *6-12 am*, *1-2 pm*, *3-4 pm*, 5-7 pm and 9-11 pm. In 13th of January 2013 heaters were running in the forthcoming periods: 0-1 am, 3-4 am, *6-9 am*, *12 am-1 pm*, *2-6 pm*, 8-9 pm and 10-11 pm. The first hour of the periods marked in italics have been summarized in mentioned Table 4. 9. A ΔT between 1.92, 1.76 and 1.70 ºC can be found in the data collected in February 2012. On the other side, ΔT between 2.29, 2.59 and 2.49 ºC were found when data logged in January 2013 were analyzed.

This influence is clearly depicted in Fig. 4. 42, where ΔT during the first hour after switching on the heater is shown as an example.

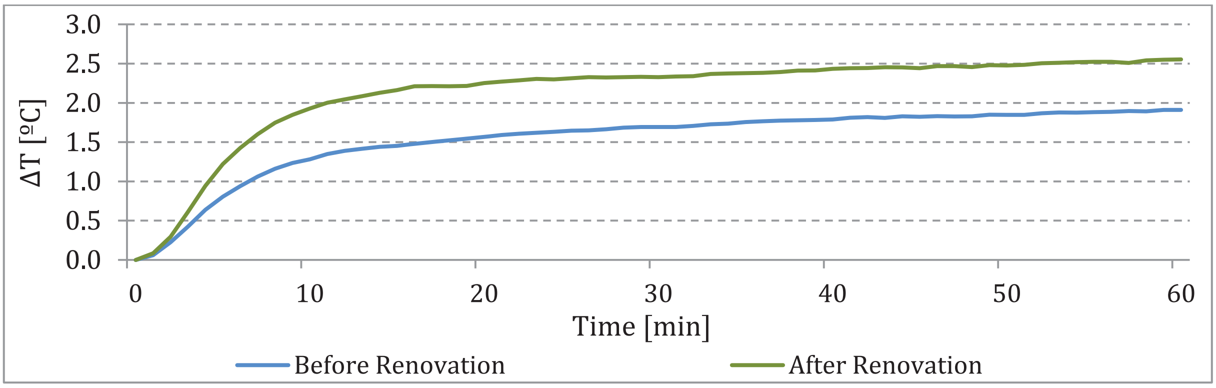


Fig. 4. 42. ΔT of indoor air temperature in the first hour of switching on the heater

ΔT before renovation (blue line) corresponds to the weighted average temperature in 1st of February, 2012 from 6 h to 7 h, whereas ΔT after renovation (green line) represents the weighted average temperature in 13th of January, 2013, from 6 h to 7 h. (Both periods marked in Table 4. 9). When time equals 0 (which corresponds to 6 h. in both periods) heater is activated. The main difference can be found in the first ten minutes. After 10 minutes with heater running, temperature increased 1.28 ºC (from 15.28 ºC to 16.57 ºC) in the case data set logged before renovation, whereas after renovation works, during the same period of time after switching the heaters on, temperature increased 1.93 ºC (from 16.83 ºC to 18.76 ºC). This fact proves that heat transfer coefficient of the envelope was improved. (similar boundary conditions and the same heat input involves a higher increment of indoor temperature, which means that heat losses are lower).

The difference between ΔT before and after renovation works is presented in Fig. 4. 43. As previously mentioned, the main difference between both periods was logged during the first ten minutes. After this period the difference of ΔT before and after renovation was almost stabilized, around 0.65 ºC.

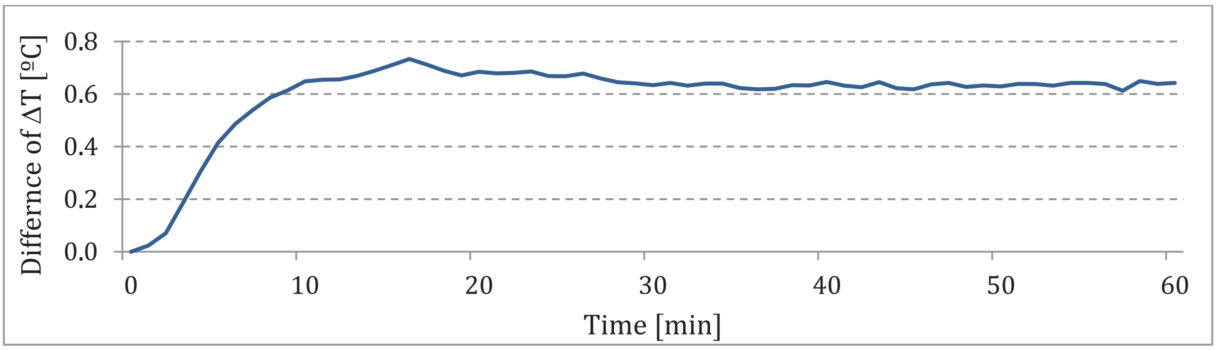


Fig. 4. 43. Difference between ΔT before and after renovation works

6.2 UA-Value calculations

It was considered interesting to carry out a first quantitative analysis of the obtained data. With this aim in mind, a methodology based on co-heating method, previously mentioned in section 4.2.4 of this chapter, was applied using the data obtained from both testing periods.

6.2.1 Expected value

An estimation of the expected improvement of the windows was calculated, by means of obtaining a theoretical UA value reduction after windows replacement. Thus, in Fig. 4. 44 a single scheme for calculating UA is presented. Indoor and outdoor temperatures are depicted in two nodes separated by two thermal resistances in parallel, corresponding to windows (R_{wind}) and the rest of the ways of losses (R_{rest}).

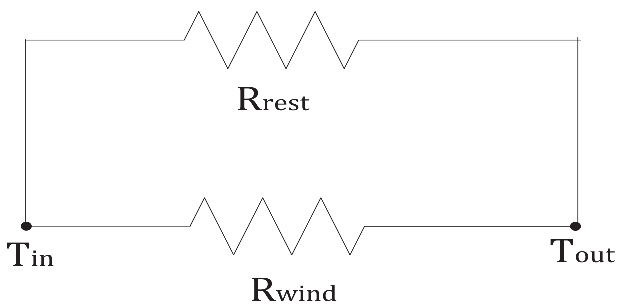


Fig. 4. 44. Single scheme of a RC network of the dwelling

UA_{rest} is the same in both scenarios, since no changes except the windows were performed in the dwelling. Then, estimation can be done following the forthcoming equations:

$$UA_{bef} = UA_{w,bef} + UA_{rest,bef} \quad \text{Eq. 7}$$

$$UA_{aft} = UA_{w,aft} + UA_{rest,aft} \quad \text{Eq. 8}$$

$$UA_{aft} - UA_{bef} = UA_{w,aft} + UA_{w,bef} \quad \text{Eq. 9}$$

For calculating the expected improvement, the U values assumed for old and new windows are presented in the following:

- U windows before renovation: 4.55 W/m^{2}K

- U windows after renovation: 3.09 W/ m^{2}K

Taking into account the fact that the total windows area of the dwelling are 11.5 m^2, it is expected that UA of the whole dwelling, after windows replacement, is improved about 15 W/K.

6.2.2 Obtained value

Some clarifications must be explained before presenting these values. As previously referred, co-heating method consists on heating a dwelling, to maintain a constant internal temperature (around 25°C) over a specified period of time, typically between 1 to 3 weeks. However, experimental part was designed with the aim of characterizing the dynamic behaviour of the building, namely to obtain the characteristic parameters values in the RC model whose development is described in Chapter 6. The main difference between the methodology proposed to carried out the co-heating test and the monitoring presented in this chapter is that co-heating method should be performed using continuous and modulating heating, in order to maintain mentioned constant indoor temperature, whereas in the monitoring presented in this chapter, heating is a non-modulating, discontinuous heater routine, and then, indoor temperature is not as constant as suggested to obtain an adequate UA Value by co-heating method.

Taking into account these limitations, it can be stated that the objective is not to develop and present the results of a co-heating method, but, based on that methodology, obtaining some reference values of the dwelling, before and after windows replacement.

For that reason, only the periods when the heater was switch on were taken into account to the calculation of UA value (They have different length of time, from 1 to 33 h). It must be stated that the in order to achieve a quasi-stationary performance, longer periods are required (for that reason, tests are usually perform over 1 – 3 weeks). Thus, other effects, such as thermal inertia of the building, can affect to the obtained results, and results must be evaluated with caution. Results obtained by this method are presented in Table 4. 10 and Table 4. 11, before and after window replacement, respectively.

These rough calculations present a clear inconsistency (according to these values, energy performance of the dwelling after window replacement presents worse values than those obtained before window replacement). Due to the inconsistency of these first values, a more detailed analysis of the obtained data was carried out.

	Amount of Heating hours	Av. Power	Av. ΔT	UA
FEB 2012	287h 30 min	1780.97	11.06	160.97 W/K
MAR 2012	304h 10 min	1708.16	9.9	172.55 W/K
APR 2012	224h 20 min	1715.05	9.91	173.06 W/K
			AVERAGE UA	**168.61 W/K**

Table 4. 10. Monthly values before windows replacement

	Amount of Heating hours	Av. Power	Av. ΔT	UA
DIC 2012	306 h	1740.32	8.22	211.73 W/K
JAN 2013	342h 10 min	1760.6	9. 58	183.87 W/K
FEB 2013	204h 20 min	1747.28	8.78	198.96 W/K
			AVERAGE UA whole period	**197.49 W/K**
			AVERAGE UA Jan-feb	**189.51 W/K**

Table 4. 11. Monthly values after windows replacement

First of all, the terms which have influence on the UA calculation according to Eq. 5 were analyzed. Let focus on the first month of each monitoring period: February 2012 and January 2013 (Ventilation grilles were not sealed in December 2012). Heating power in both cases was the same (around 1800 W). Indoor average temperatures in those periods when heater was switch on in the first monitoring was 18.34 ºC, whereas in the second monitoring was 19.72 ºC. Outdoor average temperatures were 6.91 ºC and 10.98 ºC respectively. Taking into account the features of the monitoring and the role that ΔT plays in the calculation, the UA vs. outdoor temperature values obtained for each single heating period were evaluated, in order to identify if differences on outdoor temperatures can be affect the UA results. It is depicted in Fig. 4. 45.

It must be highlighted the influence of outdoor temperature on the UA calculations. Comparing the results of each monitoring, a qualitative analysis can be carried out. A correlation between outdoor average temperatures and UA values obtained by that equation is observed, where the higher outdoor temperature, the higher UA value is obtained. Thus, the lower outdoor temperatures registered during the first monitoring cause lower UA values when both monitoring periods are compared (Outdoor temperature average values, as well as UA obtained in both periods are depicted in the graph). In spite of that, a trend where UA values obtained in the second monitoring are slightly lower than those obtained in the first one is appreciated.

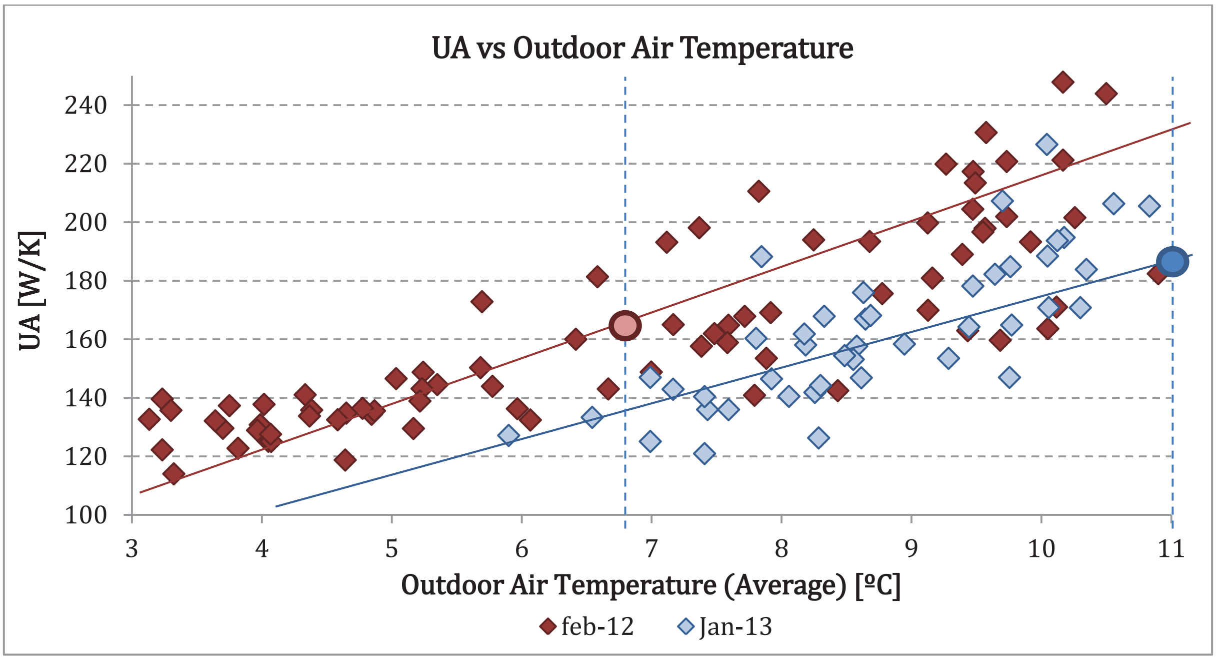


Fig. 4. 45. UA vs. Outdoor air temperature of both monitoring periods

6.2.3 Other aspect to take into account

It must be highlighted the fact that the methodology presented in this subsection is not strictly a co-heating method, but the equation used in co-heating method has been used to obtain several reference values of both monitoring periods. To obtain a correct value by means of co-heating method, studied building requires achieving stable conditions. To do that, maintain an indoor constant temperature for a long period of time is required. Monitoring presented in this chapter, however, due to its characteristics, did not achieve those conditions, and for that reason, correlations can be identified when obtained results are observed. Anyway, some points can be highlighted about these calculations, as presented in the following.

When co-heating method is carried out, the building case study can be understood as a single system, in the way presented in Fig. 4. 46. In this approach, heat input is directly measured, and heat losses through the building envelope are dependent on the global UA- value, which is obtained as previously explained. Thus, any improvement on building envelope (façade, roof, windows…) contributes to reduce the UA of the building, and then, the heat losses through the envelope.

Fig. 4. 46. Sketch of principle of co-heating method

However, when the case study is a dwelling into a building (and not the whole building) new heat inputs and outputs appear in the scheme, as shown in Fig. 4. 47. Actually, solar gains also appear on building scale, and they must be taken into account in order to obtain a more accurate UA of the building envelope, as well as heat losses regarding to infiltration and ventilation rates. But heat flows to/from adjacent dwellings (both through floor and ceiling, and through indoor partitions) can be significant in the energy balance of the dwelling, and different operating conditions in those dwellings can play an important role in the result obtained by co-heating method.

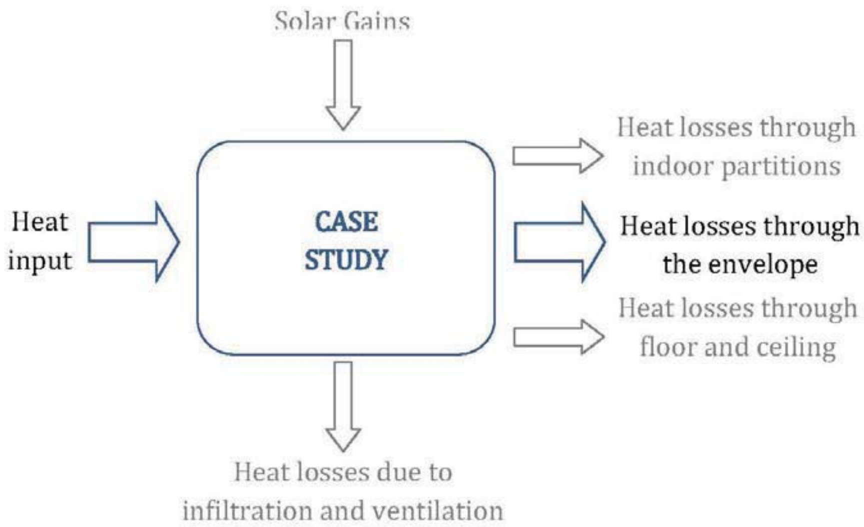


Fig. 4. 47. Modified sketch of principle of the real performance of a dwelling

Based on these sketches, the influence of these points is analyzed in the following paragraph, in order to identify the reason of the results obtained by means of co-heating method.

6.2.3.1 Ventilation losses

Different ventilation patterns can be a strong influence on co-heating tests. However, this aspect was taken into account in both monitoring periods, and all ventilation grilles and channels were sealed, especially in the second period (e. g. see Fig. 4. 14). On the other hand, differences on infiltration values were also dismissed, due to the tests carried out during the first monitoring period showed that infiltration rates were very low values, and windows replacement, in any form, reduces those infiltration rates.

6.2.3.2 Losses to adjacent dwellings

Co-heating method assumes that the whole heat input is lost through its envelope, as explained before. Then, the UA represents the value of the whole "boundary" of the dwelling, i.e. façade and windows, but also indoor partitions with the other dwelling, as well as floor and ceiling. Heat flows through these last elements (indoor partitions, floor and ceiling) are very dependent on the operating conditions of adjacent dwellings. Variations in indoor conditions in an adjacent dwelling can significantly affect the UA results.

6.2.3.3 Variation in solar gains

Solar gains can also have a strong influence in these calculations. In this case, window shutters were opened during both monitoring period (this condition was a requirement in order to define, afterwards, the model presented in the next chapter), and then, solar irradiation entered into the dwelling through the windows.

6.2.4 Highlights about UA calculations

The illogical results firstly obtained for UA values can be explained mainly due to the fact that monitoring was not design with this objective, and methodology is not the most suitable to this method. Three aspects can be remarked when this kind of analysis is performed, as briefly described in the following:

- **Sensitivity to errors in outdoor air temperature measurements:** As previously explained, calculation of UA value based on co-heating method was carried out using Eq. 5. Taking into account the ΔT achieved during both monitoring periods (around 10 ºC), small errors on temperature measurements can involve significant variations in the final U value. Whereas indoor air temperature was obtained by means of 8 temperature sensors (PT 100) and good accuracy is assumed, outdoor air temperature was obtained from a climate station placed close to the dwelling. Small measuring errors could lead to a mistaken result. Increasing ΔT (by means of increasing indoor air temperature) would reduce the impact of the errors of outdoor air temperature measurements on the U value calculation.

- **Influence of solar irradiation:** Influence of solar gains on the dwelling has been also shown. The design of the monitoring was prepared for obtaining data to define the model presented in next chapter. For that reason, it was required to have solar gains. Thus, shutters were not closed during the testing period. However, it is advisable to close the shutters during the monitoring period if co-heating test wants to be carried out.
- **Errors in measurements of heat fluxes to adjacent dwellings:** Even though flux meters were calibrated before both monitoring periods, wrong placement of the flux meters could give wrong values, and these wrong values involve errors in the P_{env}.

7 Conclusions

This chapter has depicted in detail the monitoring study carried out in a social dwelling in Bilbao. Data were collected in two different periods, prior and after renovation works. This field study can be considered the core of the experimental part of this thesis. That is, results presented in this chapter will be used in the next chapters to define and validate different kinds of models.

However, even though the main target of this chapter has been to describe the experimental part and the field study carried out to obtain the above mentioned results, some points can be highlighted in a way of conclusion, both about the methodology and the results themselves.

7.1 Methodology

Two facts must be highlighted in this experimental part. On the one hand, the importance of designing properly the monitoring according to the objective sought has been shown. Once the aim of the monitoring is clear, identifying which data have more sensitivity, and even having a first draft calculation in order to know the magnitude of the data to obtain are advisable in this kind of studies. The problems found to apply the co-heating method to data obtained from a monitoring designed with other targets, i.e. the grey box and black box models defined in the next chapters) are an example of this point.

At the same time, flexibility in the design of monitoring is recommended, if possible. It may happen in this kind of studies that some sensors give wrong measures or environmental conditions are not always the best, to name but a few adverse circumstances. For that reason, it is advisable to foresee these possibilities, and to design the study with enough flexibility (number of sensors, time…)

7.2 Results

The analysis of data obtained in this field study allowed detecting some performances that, in other way, it would have gone unnoticed. Especial relevance had the heat losses detected in room 1 to staircase and adjacent dwelling, more noticeable in the first monitoring period. This point highlights the importance of considering not only the building envelope, but also the indoor partitions of the building when any thermal improvement is considered. Losses through ceilings were found significant. These heat losses can be important especially when the two dwellings display different operating conditions.

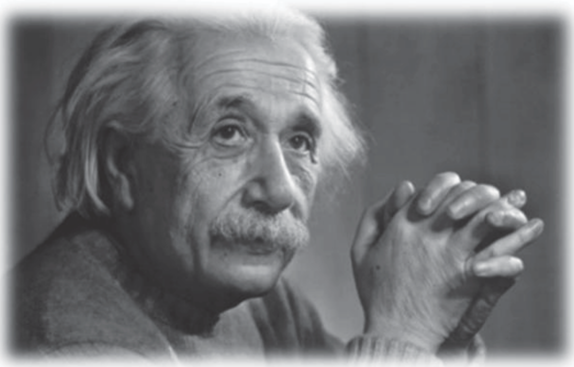
7.3 Next steps

In the next two chapters (Mathematical Models), two different kinds of thermal models will be developed, using as a reference the data obtained in the monitoring study presented in this chapter. By means of these models, the thermal behaviour of the dwelling can be evaluated not only qualitatively, but also quantitatively, and deeper assessment of the thermal behaviour of the dwelling can be achieved. Hence, Chapter 5 deals with the definition and adjustment of a TRNSYS model (i.e. a white box model) for the studied dwelling, whereas a grey box model is developed in Chapter 6.

PART 3
MATHEMATICAL MODELS

"How can it be that mathematics, being after all a product of human thought independent of experience, is so admirably adapted to the objects of reality?"

Albert Einstein (1879-1955)



CHAPTER 5

WHITE BOX MODELS. TRNSYS MODEL DEFINITION

RESUMEN

En este capítulo se presenta la definición de un modelo del edificio presentado en el capítulo 4. Para ello, se definirá el edificio y se utilizarán los datos obtenidos en la primera monitorización de la vivienda para ajustar los parámetros del modelo definido. Posteriormente, se utilizará el modelo para calcular los ahorros obtenidos tras una sustitución de ventanas como la que se llevó a cabo en la vivienda. A su vez ,se consideran dos escenarios para el cálculo: uno con las condiciones de operación y perfiles de uso de acuerdo a los recomendados por la bibliografía existente (concretamente, por el IDAE) y otro escenario en el que dichas condiciones de operación se definen en base a la información obtenida de la monitorización de 10 viviendas ocupadas presentada en el capítulo 3. Finalmente, se evalúan y analizan las diferencias entre los resultados obtenidos en ambos casos.

ABSTRACT

Building model of the dwelling presented in chapter 4 is developed in this chapter. Data obtained in the first monitoring of the dwelling was used to adjust the defined model parameters. Afterwards, the model was used to calculate savings obtained as a result of a windows replacement. Moreover, two different scenarios were assumed to calculate: in the first one, operating conditions were defined according literature (namely, IDAE guidelines); the second one, operating conditions were based on the information obtained by monitoring the 10 dwellings, which has been presented in the Chapter 3 of this Thesis. Finally, the differences on the results of both scenarios were evaluated.

1 Introduction

As mentioned in previous chapters, predicting and evaluating the real performance of a building is a key factor, both to choose the optimal retrofitting solution and evaluate the performance of an implemented retrofitting strategy.

However, several difficulties are found in this way, especially in the case of energy renovations. If the effectiveness of a certain building renovation is being assessed, energy consumptions before and after retrofitting works should be compared. Nevertheless, direct measurements of energy consumption during previous and subsequent occupation periods will not be enough, since energy consumption is influenced by many parameters, such as climate conditions, dwelling operation or rebound effect, to name but a few, which are usually different during different collecting data periods.

For setting an ideal comparison framework, those consumption measurements should be made under the same conditions. Even in the event of monitoring an unoccupied dwelling or building, climate conditions will not be the same, so standardizing the collected data will be necessary to obtain accurate results.

Building model simulations allow comparing different buildings, or different retrofitting strategies in the same building, under the same conditions, being then one of the best ways to check their efficacy.

As it is well known, many kinds of models can be found in order to analyze thermal performance of a dwelling [76]. Amongst them, there are the so called white box models. There are many simulation programs to develop this kind of models, such as TRNSYS [77,78] or Energy Plus [78-80], to name but two of the most known. One of the main advantages of white models is the fact that no experimental data are needed a priori (even though the fact that it is advisable to validate and adjust the model, as shown in this chapter).

Nevertheless, this kind of models requires a great amount of input data to define the building, and sometimes, it can lead to inaccuracies, due both to mistakes or lack of available information. This difficulty is even greater in the case of old buildings, since usually few information about its construction is available. Moreover, even in new buildings where, in principle, project data are available, significant differences which affect to thermal performance of the building can be found when “as projected” and “as actually built” states are compared, as mentioned in Chapter 1. For that reason, it is strongly recommended, even using a white box model, to have some “on field” measurements to validate and adjust the model when a specific building is studied. This is the approach followed in this chapter.

2 Objectives of this chapter

Therefore, the main target of this chapter is to define a TRNSYS model of a representative building built on the 60s. Data obtained from the monitoring study presented in Chapter 4 were used to validate and adjust the model parameters.

The model will be used later to evaluate different renovation strategies. Apart from it, the validated building model will be used in future works as a reference building, since it represents a building typology with features very common in the 60s in this region (a significant part of the building stock was built during those years, as already presented in the Chapter 1 of this thesis) and with a great potential for improvement.

3 Structure of this chapter

Thus, TRNSYS is used in this chapter with two aims. On the one hand, it is used as a tool to evaluate firstly the energy savings achieved by means of implementing the windows replacement. Moreover, it will allow comparing the results with those obtained using the grey box model. On the other hand, this TRNSYS model will be used in the next chapters to evaluate different retrofitting actions, under different approaches, such as energy, economic, environmental, comfort or exergy ones. Taking into account these principles, this chapter is structured as follows.

Firstly, construction features considered as input data for the TRNSYS model (based on information gathered of the building) are described. Secondly, specific operating conditions of 1st – 9th of February, 2012, used to validate the developed model, and its adaptation to the TRNSYS model environment are presented.

Moreover, standard operating conditions based on literature for a typical year for energy demand calculations are presented. At the same time, new operating conditions according to data obtained from monitoring study of ten dwellings presented in chapter 3 are defined. Afterwards, the adjustment and validation of the model is presented.

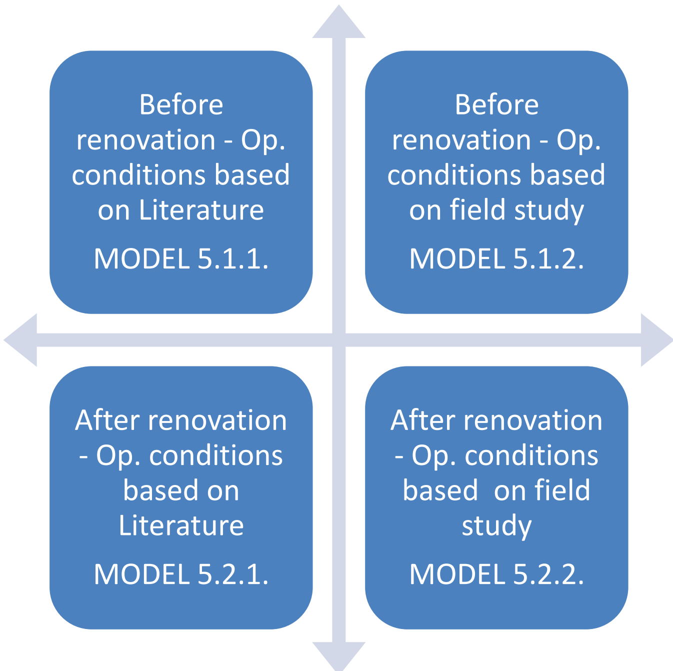


Fig. 5. 1. The four scenarios analyzed by the TRNSYS simulations

First the results on energy demand obtained from the model with standard conditions are presented, before and after renovation works. Energy demand obtained assuming operating conditions based on measured data on the 10 dwellings field study were also calculated with the model.

Finally, both scenarios are compared, as depicted in Fig. 5. 1., and chapter conclusions are presented.

4 TRNSYS model of the selected dwelling

The whole building was geometrically defined using Google Sketch Up with TRNSYS3d plug-in, based on data obtained from plans provided by *Bilbao Social Housing*, and on-site measurements. Two snaps of the model are depicted in Fig. 5.2.

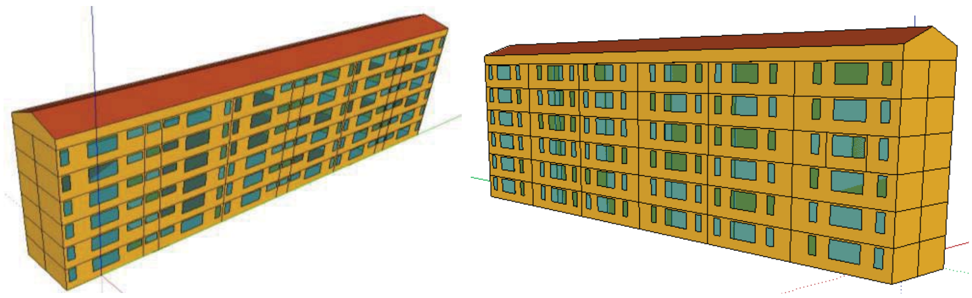


Fig. 5.2. Snaps of the Sketch Up 3D model of the building

4.1 Geometrical and construction data

Dwellings were defined as different thermal areas or air nodes (see Fig. 5.3). Each modelled dwelling encompasses two thermal areas: one of them corresponds to the west side of the dwellings, i.e. the bedrooms; the other one, to the east side which includes living room, kitchen, bathroom and drying area. The importance of selecting the suitable division in thermal areas is shown in literature, such as in [81].

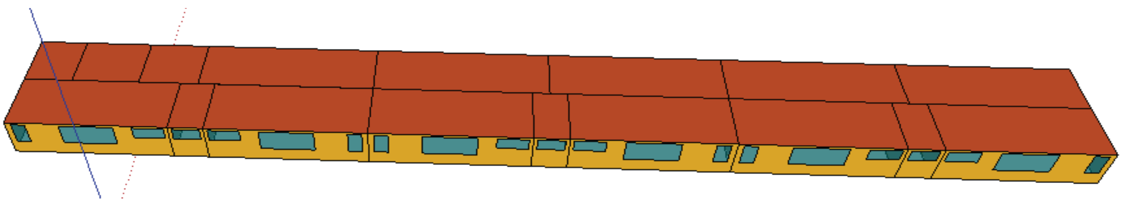


Fig. 5.3. Thermal areas defined in the building model

Similarly, the part of the building model which represents that monitored dwelling was divided more in detail considering four different thermal areas: one per each bedroom and other one which includes living room, kitchen bathroom and drying area. Finally, staircase was considered as an independent thermal area. Thus, the distribution is shown in Fig. 5. 4, where the monitored dwelling (in the left side) and the distribution for the other dwellings (in the right side) are depicted, as well as the staircase.

Fig. 5. 4. Thermal areas defined in the building model in detail

Detailed description of the construction data assumed in the TRNSYS model is presented in the forthcoming Table 5. 1 and Table 5. 2. It is based on data provided by *Bilbao Social Housing*.

	e (cm)	Conductance (kJ/hmK)	Capacitance (kJ/kgK)	Density (kg/m³)	Thermal Resistance
EXT_WALL (Façade)					
Gypsum	1	1.8	1	900	-
Hollow Brick	4.5	1.76	0.9	1200	-
Vertical Air Gap (NoVent)	4	-	-	-	0.047
Hollow Brick	12.5	1.76	0.9	1200	-
Fibre Glass	2	0.144	0.84	12	-
Hollow Brick	4.5	1.76	0.9	1200	-
Cement Mortar	3.5	5.04	1.1	2000	-
Façade U-value	*0.74*				

Table 5. 1. Detailed construction data (part I)

	e (cm)	Conductance (kJ/hmK)	Capacitance (kJ/kgK)	Density (kg/m³)	Thermal Resistance
EXT_ROOF (Roof)					
Cement and sand Mortar	1	3.6	1	1800	-
Hollow Brick	4.5	1.76	0.9	1200	-
Cement and sand Mortar	1	3.6	1	1800	-
Horiz. Air Gap (Lig.Vent)	2	-	-	-	0.022
Roof tile	1	3.6	0.8	2000	-
Roof U-value	*2.7*				
ADJ_WALL (Indoor walls)					
Cement and sand Mortar	1	3.6	1	1800	-
Hollow Brick	12.5	1.76	0.9	1200	-
Cement and sand Mortar	1	3.6	1	1800	-
Adjacent walls U-value	*2.25*				
ADJ_CEILING (Floors and ceilings)					
conifer wood flooring	1	0.504	2.8	600	-
Horiz. Air Gap (NoVent)	1	-	-	-	0.042
Hollow tilled Floor (20+4)	24	3.75	1	1500	-
Gypsum covering	1	1.44	1	1000	-
U-value	*2.27*				

Table 5. 2. Detailed construction data (part II)

Likewise, the main characteristics of the two kind of windows assumed in each scenario are presented in Table 5. 3.

	Frame (30%)	U_{frame} [W/m².K]/[kJ/h.m².K]	Glass	U_{glass} [W/m².K]
Old windows	Metallic without TB	5.7 / 20.52	4/6/4	3.44
New windows	PVC (2 gaps)	2.2 / 7.92	6/12/6	3.0

Table 5. 3. Windows considered in TRNSYS model

4.2 Operation conditions and calculation data for model validation

Data corresponding to the first days of February (from 1st to 9th of February, 2012) obtained by the monitoring study presented in Chapter 4 were used as a reference to calibrate and validate the TRNSYS model.

4.2.1 Weather data

Weather data file (see Fig. 5. 5) was modified to introduce the real outdoor environmental conditions recorded during the monitoring period. Data gathered by the climate station of Euskalmet, located in Deusto (mentioned in the previous chapter) was introduced in the TRNSYS weather data file. Due to the characteristics of the measured data, some assumptions were made, as described as follows.

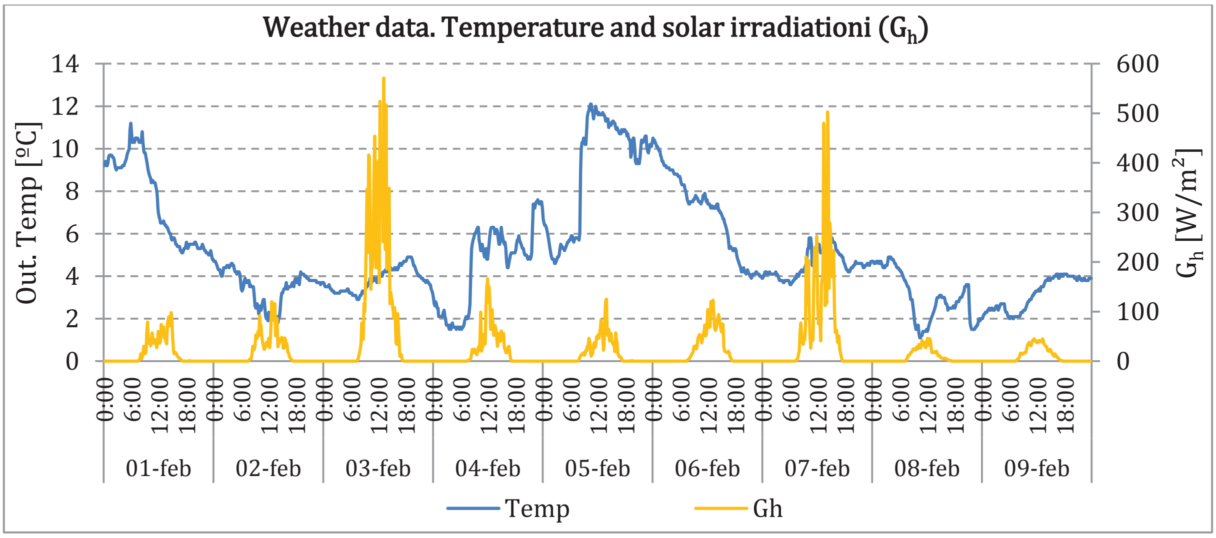


Fig. 5. 5. Outdoor air temperature and solar irradiation (G_h)

The main problem to face was to distinguish between diffuse and direct solar irradiation, since global horizontal radiation is measured in this climate station. Due to weather data file requires including separately direct and diffuse irradiation for more precise calculations, some assumptions had to be made.

In order to reduce as much as possible the difficulty of separating direct and diffuse irradiation from global horizontal irradiation in sunny days (in a cloudy day, almost 100% of the global irradiation is diffuse) a set of consecutive mainly-cloudy days was selected. Normal direct irradiation for the two sunny days of the selected period (3rd and

8th of February) was assumed as 50% during the sunny hours. This value was set based on data obtained from a typical year in Bilbao available from Meteonorm data base.

4.2.2 Heater routine

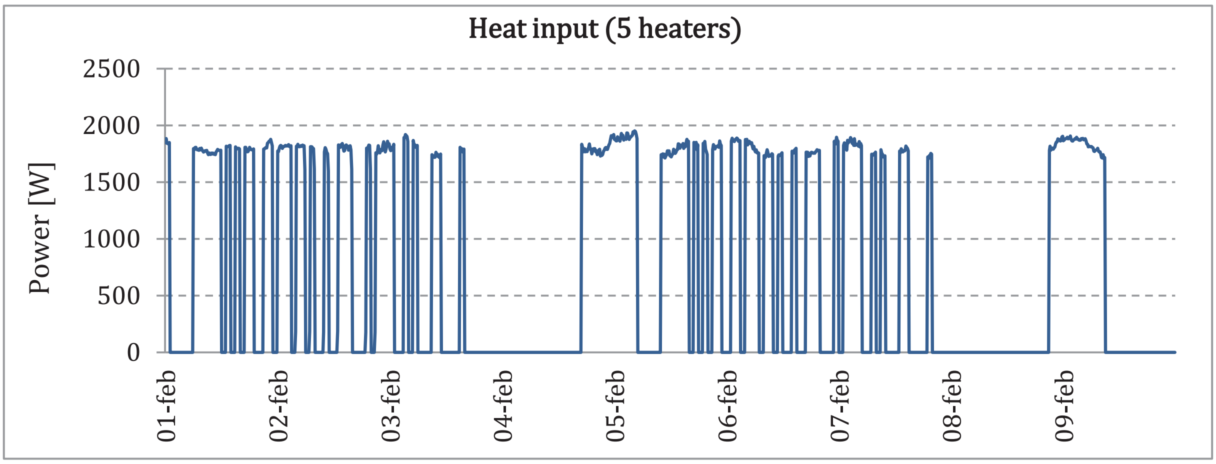


Fig. 5. 6. Total heat input in the dwelling during validation period

Total heat input was measured during the monitoring period. Those data corresponding to the "validation period" (see Fig. 5. 6) were shared out amongst the five radiators, and these gains were included in TRNSYS model validation.

4.2.3 Air infiltration and ventilation

There was no kind of ventilation during both monitoring periods. In fact, even the ventilation system of new windows was sealed during the second monitoring period. Hence, no ventilation rate was considered in the TRNSYS model.

As it was stated in Chapter 4, infiltration rates measured during the first monitoring period were very low. Four different constant infiltration rates were assumed in the different parameter combinations to validate and calibrate the model. These values were: 0.05, 0.1, 0.15 and 0.2 ACH (Air Changes per Hour).

4.2.4 Other significant information about simulation

Other significant data which could play an important role in the simulation, such as capacitance, coupling air flow between different adjacent air nodes, or adjacent dwellings temperatures were fixed and adjusted during the validation, by means of an iterative process, as described in section 6.

5 Operating conditions for reference model

Once validation was carried out and some adjustments to the model were made, the reference model was simulated. The assumed operating conditions and calculation data for the reference model are presented in this section.

Thus, operating conditions (Air infiltration and Ventilation, Internal Gains, Setpoint temperatures, electricity demand, DHW demand and weather data) are presented in each subsection in detail. Some of them (such as electricity demand and DHW) were not used in the calculations of this chapter, but in calculations carried out in Chapter 8. However, it is clearer to present all of them in this section, and in forthcoming chapters just a brief reference is made.

Two different operating conditions are presented. Firstly, a first set of operating conditions is described using the existing bibliography as a reference, mainly criteria given by IDAE (The Institute for Energy Diversification and Savings). Additionally, a new set of operating conditions is defined based on the results obtained from the field study and the indoor conditions monitored in the 10 social housing apartments described in Chapter 3.

5.1 Air infiltration and ventilation

Spanish Technical Building Code sets the ventilation requirements in new buildings. These ventilation requirements are shown in Table 5. 4. These requirements lead to the values described in Table 5. 5.

However, these values are related to the most unfavourable scenario, where all rooms have a constant ventilation rate. Several strategies can be followed in order to increase the energy efficiency of the ventilation system, which lead to less required ventilation rate to obtain the minimum indoor air quality. For that reason, IDAE suggests to assume the value of 1 ACH for ventilation rate (In fact, the tool for energy certification in Spain, CALENER [82], uses this default value), and this value even can decrease if significant reduction of ventilation rate is justified and demonstrated (without affecting negatively the indoor air quality).

Infiltration values are based on the criteria given by IDAE in [83] where a value of 0.24 ACH is given.

	Min. q_v [l/s]		
	Per person	Per m²	Other parameters
Bedroom	5		
Living room	3		
Bathroom and Toilet			15 per room
Kitchen		2	50 per room (*)

Table 5. 4. Min. required ventilation rate according to Technical Building Code

Zones	Net Area	Vol.	According to CTE		ZVH
	m²	m³	dm³/s	m³/h	Vol/h
Room 1 (Bedroom)	7.73	19. 1	5	18	
Room 2 (Living room)	8.06	19.91	9	32.4	
Room 3 (Bedroom)	8.25	20.38	5	18	
Room 4 (Bedroom)	8.25	20.38	5	18	
Room 5 (Kitchen)	9.51	23.49	19.02	68.472	
Room 6 (Bathroom)	2.41	5.95	15	54	
Room 7 (Corridor)	2.82	6.97	-	-	
Room 8 ---	2.04	5.04	-	-	
TOTAL	49.07	121.2		208.9	1.72

Table 5. 5. Values of the reference dwelling according to CTE

5.1.1 Input for the TRNSYS model based on bibliography (scenario 1. Before Renovation)

Ventilation: Since this building was constructed before the Spanish Technical Building Code (CTE) was implemented, there is no mechanical ventilation in the dwelling, so manual ventilation (opening windows) was assumed for an hour (7 am-8 am) with an air change rate of 4 ACH in the dwellings. No ventilation was considered in the staircase.

Infiltration: Infiltration airflow rate in the dwelling can be assumed constant at 0.6 ACH in the dwellings, and 0.9 ACH in the staircase.

5.1.2 Input for the TRNSYS model based on Bibliography (scenario 2. After Renovation)

Minimal requirements described in CTE and IDAE documents [83] should be followed in relation to ventilation and infiltration values for the retrofitted dwelling. No changes were made in staircase assumptions.

Ventilation: IDAE documents leaded to the following given air change rates per zone (ZVH=Zone volume per hour) of 1 ACH, which is the required input in TRNSYS.

Infiltration: A constant value of infiltration is assumed for simulating these case studies. The assumed value is 0.24 ACH. Improvements in infiltration airflow rate are mainly due to windows renovation.

In short, the infiltration and ventilation values based on literature can be assumed as showed in Table 5. 6 .

	Current situation	Retrofitted situations
Ventilation	4 (7-8 am)	1
Infiltration	0.6	0.24

Table 5. 6. General assumed infiltration and ventilation values

5.1.3 Input for the TRNSYS model based on field measurements

Both the data obtained from tracer gas test carried out before the windows replacement and values obtained after the calibration of the TRNSYS model found very similar values of infiltration rates, around 0.15 ACH, pretty lower than expected. Thus, despite the fact that infiltration depends on several conditions (such as outdoor air pressure or wind velocity, to name but a few) a constant value of 0.15 ACH was set as a suitable average infiltration rate for the studied dwelling.

5.1.4 Especial treatment of ventilation and infiltration rates on Chapters 5

Despite the mentioned above, the same ventilation and infiltration rates were considered in all the scenarios. The reason of this assumption is the fact that the aim of this work is to analyze the effect on thermal comfort and energy consumption of different renovation actions. Thus, it was considered better to compare them each other under the same conditions.

Actually, some energy renovations involve a reduction of infiltration rates, for example a windows replacement implies an energy demand reduction, and that improvement must be also assigned to the energy renovation itself, although sometimes the reduction of infiltration rates require a rise of ventilation rates in order not to reduce the indoor air quality. On the other hand, better efficiency in ventilation is usually obtained not only by optimizing that rate, but also by installing a heat recovery in the ventilation systems. In this case, moreover, infiltration test carried out during the first monitoring period showed that infiltration rates before renovation works were low. Anyway, it must be taken into account that this assumption may reduce energy savings.

Therefore, the considered values for both scenarios were finally a constant infiltration rate of 0.1 ACH for the models with field study-based operating conditions, and 0.6 ACH for the models with literature-based operating conditions, In turn, a ventilation rate of 4 ACH from 7am to 8 am is considered for both situations. These values are summarized in Table 5. 7.

	Based on Literature	Based on Field Measurements
Ventilation	4 (7-8 am)	4 (7-8 am)
Infiltration	0.6	0.1

Table 5. 7. Final assumed infiltration and ventilation values

5.2 Internal gains

The internal gains for dwellings given by the IDAE [83] are based on an hourly schedule, as shown in the following section.

- **Occupation gains**

Occupation gains are divided into sensible and latent gains. The convective fraction of occupation gains is defined as 40% of its sensible part. The so defined data are presented in Table 5. 8.

	0-7 am		7 am-3 pm		3-11 pm		11-12 pm	
[W/m²]	Sensible	Latent	Sensible	Latent	Sensible	Latent	Sensible	Latent
Working day	2.15	1.36	0.54	0.34	1.08	0.68	2.15	1.36
Saturday	2.15	1.36	2.15	1.36	2.15	1.36	2.15	1.36
Sunday	2.15	1.36	2.15	1.36	2.15	1.36	2.15	1.36

Table 5. 8. Internal Gains. Occupation

- **Artificial lighting gains**

Artificial lighting gains convective fraction is defined as 20%. The artificial lighting gains schedule is defined as shown in Table 5. 9.

[W/m²]	0-7 pm	7 am-6 pm	6-7 pm	7-11 pm	11-12 pm
Daily	0.44	1.32	2.20	4.40	2.20

Table 5. 9. Internal Gains. Artificial Lighting gains

- **Appliances gains**

For the appliances gains a convective fraction is defined as 30%. The appliances gains schedule is defined for dwelling as shown in Table 5. 10.

[W/m²]	0-7 pm	7 am-6 pm	6-7 pm	7-11 pm	11-12 pm	Average [W/m².h]
Daily	0.44	1.32	2.20	4.40	2.20	1.65

Table 5. 10. Internal Gains. Appliance Gains

As a summary, all of the internal gains are shown in the following Fig. 5. 7.

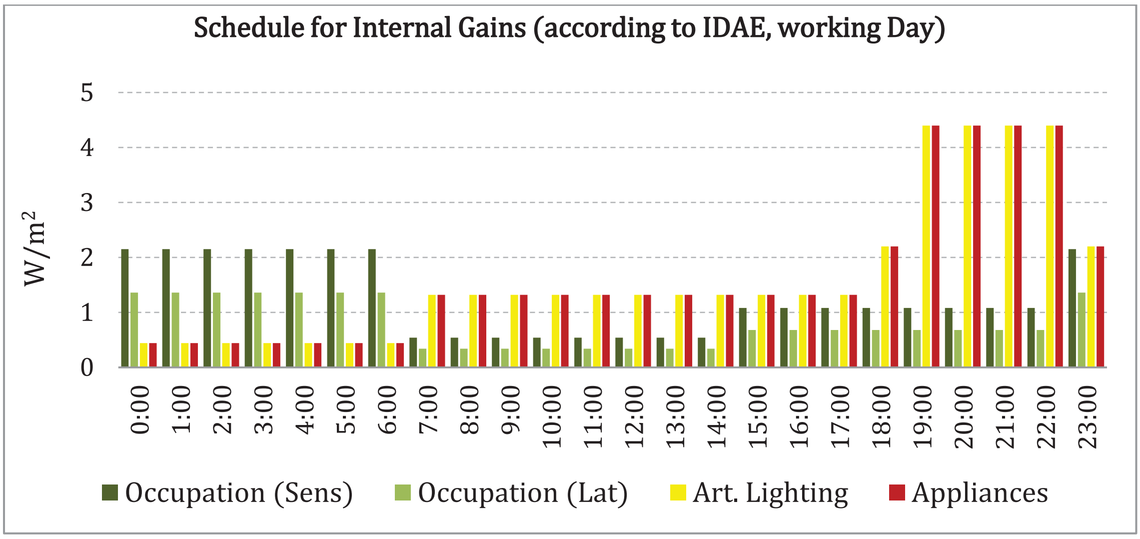


Fig. 5. 7. Schedule for Internal Gains

5.2.1 Input for the TRNSYS model based on bibliography

Based on the mentioned sources, internal gains were modelled according to data presented in Table 5. 11 and Table 5. 12. No difference between weekdays and weekends was assumed; therefore some modifications were made regarding the IDAE values. These values led to the following given internal gains in kJ/h (see Fig. 5. 8) which is the required input in TRNSYS.

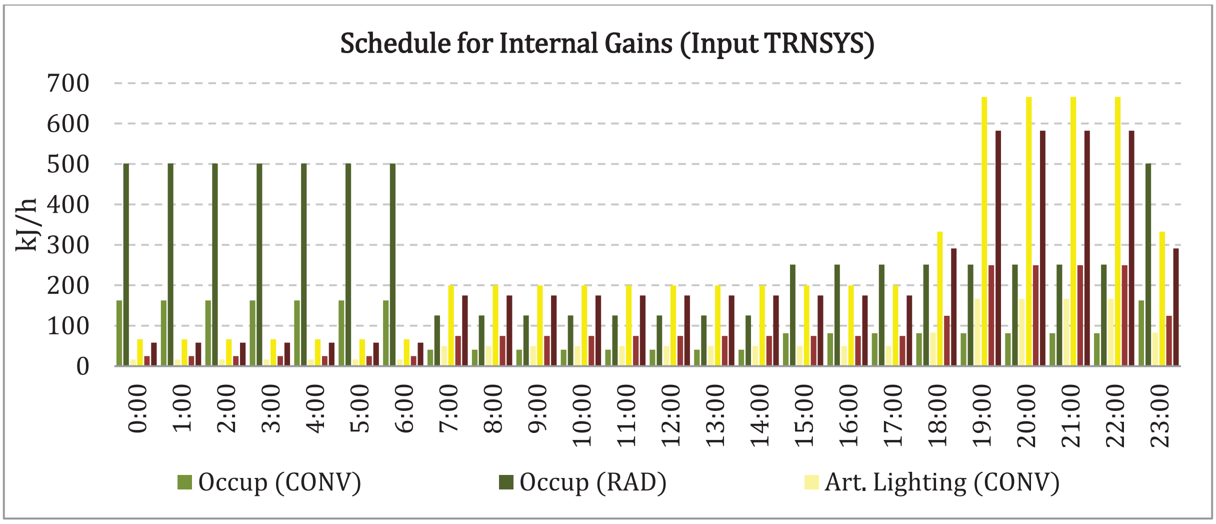


Fig. 5. 8. Internal Gains in the Dwelling. Input TRNSYS [kJ/h.m²]

[kJ/h.m²]	Occup. Gains			Art. Lighting			Appliances		
	Conv.	Rad.	TOT.	Conv.	Rad.	TOT.	Conv.	Rad.	TOT.
0-7 am	3.10	9.54	12.64	0.32	1.27	1.58	0.48	1.11	1.58
7 am-3 pm	0.78	2.39	3.17	0.95	3.8	4.75	1.42	3.33	4.75
3-6 pm	1.56	4.78	6.34	0.95	3.8	4.75	1.42	3.33	4.75
6-7 pm	1.56	4.78	6.34	1.58	6.34	7.92	2.38	5.54	7.92
7-11 pm	1.56	4.78	6.34	3.17	12.67	15.84	4.75	11.09	15.84
11-12 pm	3.10	9.54	12.64	1.58	6.34	7.92	2.38	5.54	7.92

Table 5. 11. Total internal Gains in the Dwelling in TRNSYS model [kJ/h.m²]

[kJ/h]	Occup. Gains		Art. Lighting		Appliances	
	Conv. Part	Radiat. Part	Conv. Part	Radiat. Part	Conv. Part	Radiat. Part
0-7 am	162.63	501.14	16.64	66.57	24.96	58.25
7 am-3 pm	40.85	125.57	49.92	199.70	74.89	174.74
3-6 pm	81.69	251.14	49.92	199.70	74.89	174.74
6-7 pm	81.69	251.14	83.21	332.83	124.81	291.23
7-11 pm	81.69	251.14	166.42	665.66	249.62	582.45
11-12 pm	162.63	501.14	83.21	332.83	124.81	291.23

Table 5. 12. Total internal Gains in the Dwelling in TRNSYS model [kJ/h]

5.2.2 Input for the TRNSYS model based on field measurements

Internal gains were analyzed and considered too high to represent the actual gains of a building of these characteristics resulting into a very conservative assumption. For that reason, new values corresponding to internal gains were set based on the experience of ENEDI Research Group.

In order to define occupation patterns, a dwelling occupied by four people was considered. Taking into account that the dwelling model was divided into the different thermal areas of the dwelling, it was considered, for example, that living room has no occupation during night hours.

Similar criteria were followed when internal gains associated to lighting were defined, where no lighting gains were assumed during sleeping hours, or during daylight hours. Likewise, internal gains related to equipment of the dwelling were defined. Thereby, internal gains assumed for the reference dwelling model are presented in Table 5. 13 (Living represents living room and kitchen, and each room was represented by a single air node).

			Living	Room1	Room2	Room3
Occupation (Number of persons)	M-F	0-7 am	0	2	1	1
		7-9 am	4	0	0	0
		9 am - 6 pm	1	0	0	0
		6-11 pm	2	0	1	1
		11-12 pm	0	2	1	1
	S-S	0-9 am	0	2	1	1
		9 am - 12 pm	4	0	0	0
Lighting (kJ/h)	M-S	0-7 am	0	0	0	0
		7-9 am	108	72	72	72
		9 am - 6 pm	0	0	0	0
		6-11 pm	108	0	72	72
		11-12 pm	0	72	72	72
Equipments (kJ/h)	M-S	0-7 am	36	0	0	0
		7-9 am	144	0	0	0
		9 am - 6 pm	36	0	0	0
		6-11 pm	144	0	36	36
		11-12 pm	36	0	0	0

Table 5. 13. Assumed internal gains based on field study for the reference dwelling

5.3 Set point temperatures

IDAE Annex III [83] defines setpoint temperatures with an hourly time basis for the heating season, every day from January till May and from October to December. The hourly schedule for a winter typical day is defined as follows:

- 0 -7 am: 17 ºC
- 7 am - 11 pm: 20 ºC

- 11-12 pm: 17 ºC

5.3.1 Input for the TRNSYS model based on bibliography

A small modification was applied in comparison to hourly schedule suggested by IDAE. Since a windows opening was assumed from 7 am to 8 am, no setpoint was defined during that hour. Then, the hourly schedule was defined as follows:

- 0-7 am: 17 ºC
- 7- 8 am: -
- 8 am - 11 pm: 20 ºC
- 11-12 pm: 17 ºC

5.3.2 Input for the TRNSYS model based on field measurements

In the field study presented in Chapter 3 it was shown that indoor temperatures were quite lower than those described by IDAE. Even though the setpoint temperature varies significantly depending on the user (as shown in chapter 3) the following standard hourly schedule was set as representative of social housing sector:

- 0-8 am: -
- 8 am -6 pm: 17 ºC
- 6-11 pm: 20 ºC
- 11-12 pm: 17 ºC

The radiative part assumed for the simulation of the terminal units was 0%.

5.4 Electricity Demand

As previously mentioned, these data were not used in this chapter, but they were in next Chapter 8. Definition of electricity demand assumed in the study presented in Chapter 8 are presented in this subsection.

5.4.1 Input for the TRNSYS model based on bibliography

The electricity demand is based on the aforementioned IDAE criteria for internal gains. When subtracting the electricity demand from the total internal gains (since electricity is all converted into internal heat gains within the dwelling), the remainder of the internal gains can be assumed to be generated by the people. This means that the electricity demand can be obtained from IDAE data of lighting and appliances internal gains. According to this criteria, the following profile, presented in Table 5. 14, was assumed in the TRNSYS simulation.

[kJ/h]	W/m²	Tot. W	Tot. kJ/h	Total kJ (Period)
0-7 am	0.88	46.22	166.42	1164.94
7 am-6 pm	2.64	138.68	499.25	5491.75
6-7 pm	4.4	231.13	832.08	832.08
7-11 pm	8.8	462.26	1664.15	6656.6
11-12 pm	4.4	231.132	832.08	832.08
			TOTAL	*14977.45 kJ/day*

Table 5. 14. Electricity demand in each dwelling [kJ/h]

Electricity Demand is 14,977.45 kJ/day, which equals to 4.16 kWh/day (1518.55 kWh/an)

5.4.2 Input for the TRNSYS model based on field measurements

Due to this parameter was not measured in detail in the field monitoring described in Chapter 3, no variations were applied in this aspect to the bibliography based input.

5.5 Domestic Hot Water Demand

Two different possibilities can be taken into account for considering the DHW demand.

- **DHW based on profiles defined in Annex 42 file data profiles**

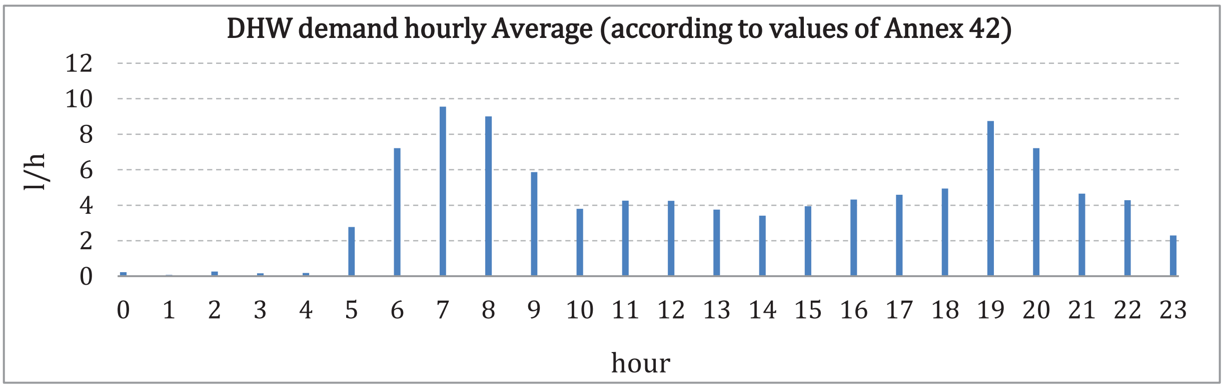


Fig. 5. 9. Hourly Average (According to values of Annex 42)

The 24-h demand profile based on the number of litres of hot water consumption per day and it is considered the same for all days. However, the energy demand for DHW heating differs since it depends on the supply temperature. These DHW demand values are obtained from Annex 42 file data profiles, assuming 100 litres per day. Hourly average for a typical day was calculated (taking as a reference the 15 minute based data for a year described in Annex 42 file data profiles), resulting the averaged DHW consumption profile presented in Fig. 5. 9.

- **DHW based on profiles defined in IDAE**

Based on the total DHW demand defined by IDAE in [83], the profile depicted in Fig. 5. 10 was established.

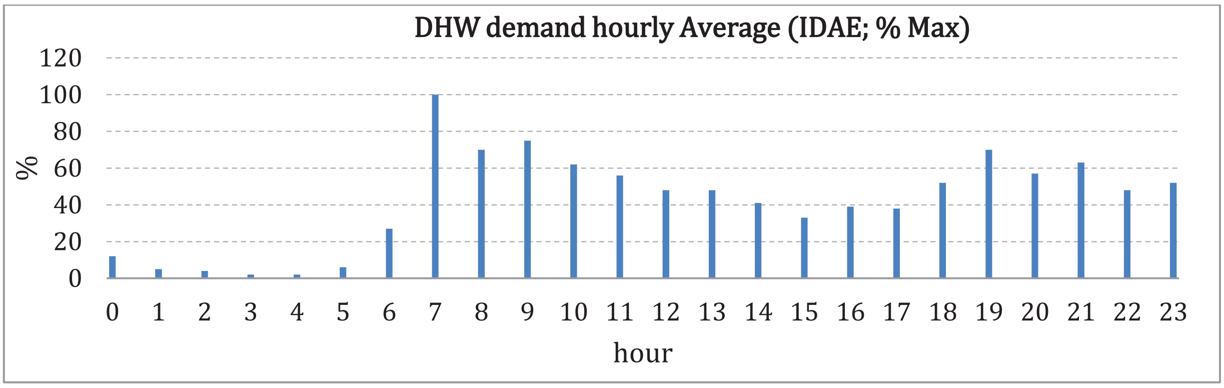


Fig. 5. 10. Hourly Average (IDAE; % Max)

5.5.1 Input for the TRNSYS model based on bibliography

For the TRNSYS model a dynamic but simplified setpoint schedule was used. The daily demand of 101 litres of DHW was assumed. This daily demand is required according to the schedule depicted in Fig. 5. 11.

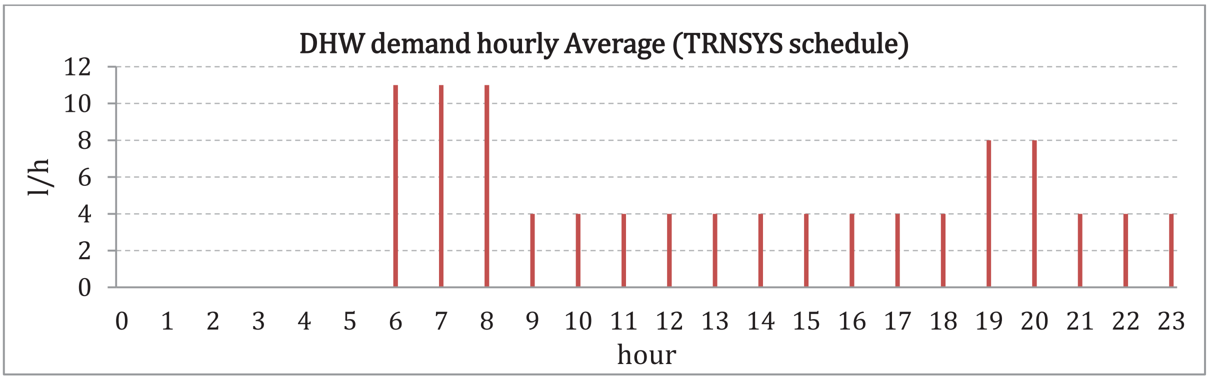


Fig. 5. 11. Hourly Average (TRNSYS schedule)

- 0-6 am: 0
- 6-9 am: 11 litres/hour
- 9 am - 7 pm: 4 litres/hour
- 7-9 pm: 8 litres/hour
- 9-12 pm: 4 litres/hour

The temperature production for the DHW was set at 60 ºC. Annual average supply temperature is 15.4 ºC, according to the measured data by "*Consorcio de Aguas de Bilbao*" in "*Venta Alta*" for the year 2011 (personal communication by mail, April 2012). Taking into account this value, the supply temperature of the DHW is calculated by the approach presented in Eq. 10 (based on the formula described by Jansen in [53]):

- $If\ T_{out} < -5ºC \xrightarrow{then} T_{Supply\_DHW} = 1.8$
- $If\ T_{out} \geq -5ºC \xrightarrow{then} T_{Supply\_DHW} = \frac{(2 \cdot T_{out} + 15.4)}{3}$ Eq. 10

Therefore, the DHW supply temperature follows the outdoor temperature in a tempered way. In addition the minimum temperature is 1.8 ºC and the maximum is 27 ºC whereas the highest outdoor temperature in Bilbao (in the Metenorm data files) for a typical year is 33.7 ºC, as is depicted in Fig. 5. 12.

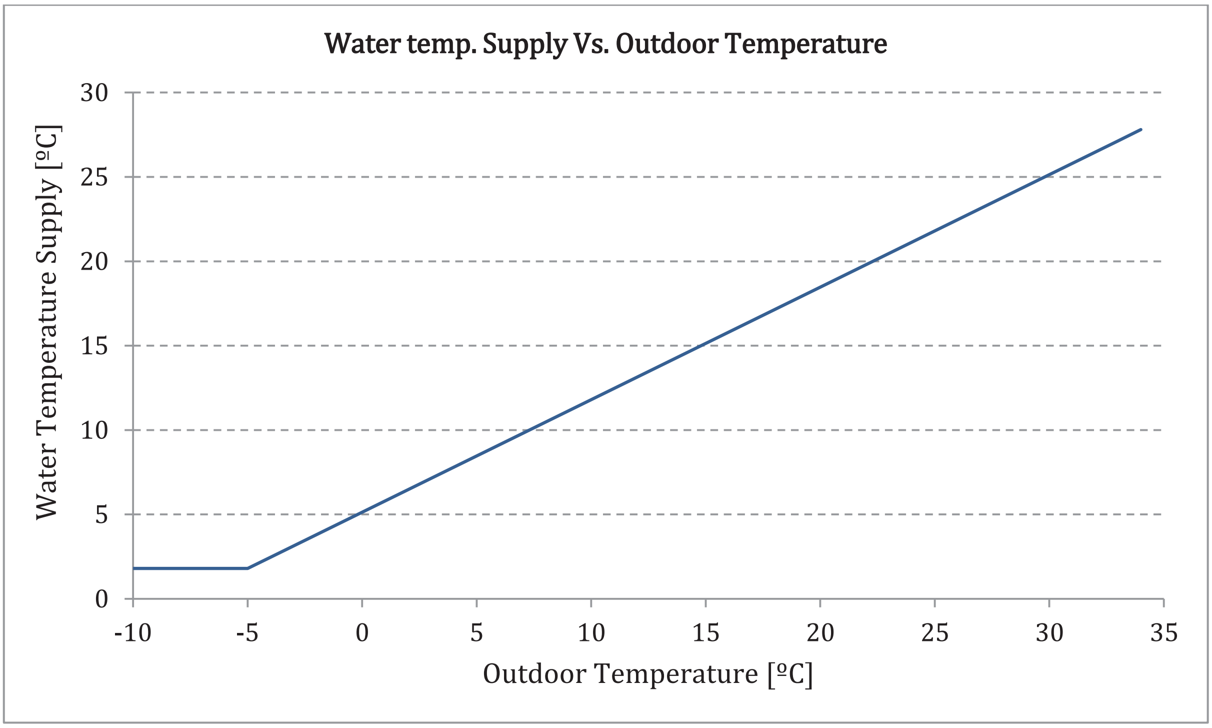


Fig. 5. 12. DHW Supply Temperature Vs Outdoor temperature

5.5.2 Input for the TRNSYS model based on field measurements

As in the case of electricity demand, as this parameter was not measured in detail in the field monitoring study described in chapter 3, the values considered are those aforementioned.

5.6 Weather data

5.6.1 Input for the TRNSYS model

The weather data of Bilbao (Meteonorm Data Base) were used for the simulations. These data files represent a typical meteorological year.

5.7 Other significant information about simulation

Capacitance, coupling air flow between different adjacent air nodes, or adjacent dwellings temperatures were defined for the reference model according to the data obtained from the calibration and validation process. Those values are presented in section 6. The model validation was carried out using a 1h time step in every simulation.

6 Model Validation

Model validation is utilized to determine if a model is an accurate representation of the real system. Validation is achieved through the calibration of the model, an iterative process of comparing the model to actual system behaviour and using the discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is judged to be acceptable.

Besides, validation allows identifying which the most significant parameters in building energy behaviour are.

As previously mentioned, the calibration of the model required:

- Setting up a climate file containing the real outdoor environmental conditions during the period chosen to validate.
- The definition of heat input schedules.

6.1 Parameter combination assumed

To make and adjust this calibration, several parameters were adjusted in the model, modifying them in an iterative process. Mentioned parameters are:

- Capacitance of each air node of the dwelling
- Infiltration value of the dwelling

- Coupling air flows between different air nodes (e.g. living room with bedrooms)

Adjacent dwelling temperatures play a very important role in indoor air temperature of the dwelling. Since it is virtually impossible to known the heat routines in adjacent dwellings (they were not measured) setpoint constant values were assumed in them.

About forty different parameter combinations were simulated in the model. Details about the last of them are presented in Appendix 5.1.

6.2 Analysis of results

Indoor air temperature was used as a reference to compare calculated values by the model and measured data, obtained in the first monitoring period. Model checking described in appendix 5.2 were carried out for indoor air temperatures in each air node of the dwelling, as well as the average value of the whole dwelling. Analysis results for each parameter combination are presented in Appendix 5.2.

6.3 Selected model

According to the described analysis, model MV14 was selected as the most adjusted. Calculated Vs. measured temperature for one room (in this case, room 2) and for the whole dwelling are depicted respectively in Fig. 5. 13 and Fig. 5. 14.

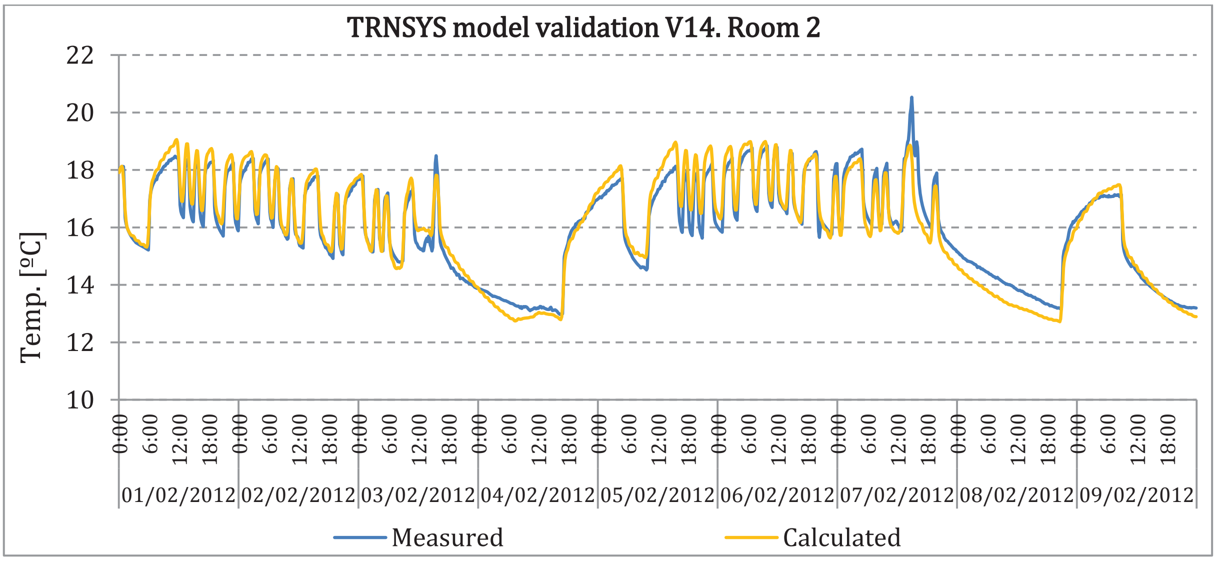


Fig. 5. 13. Comparison between measured data and calculated data in room 2 (Model MV14)

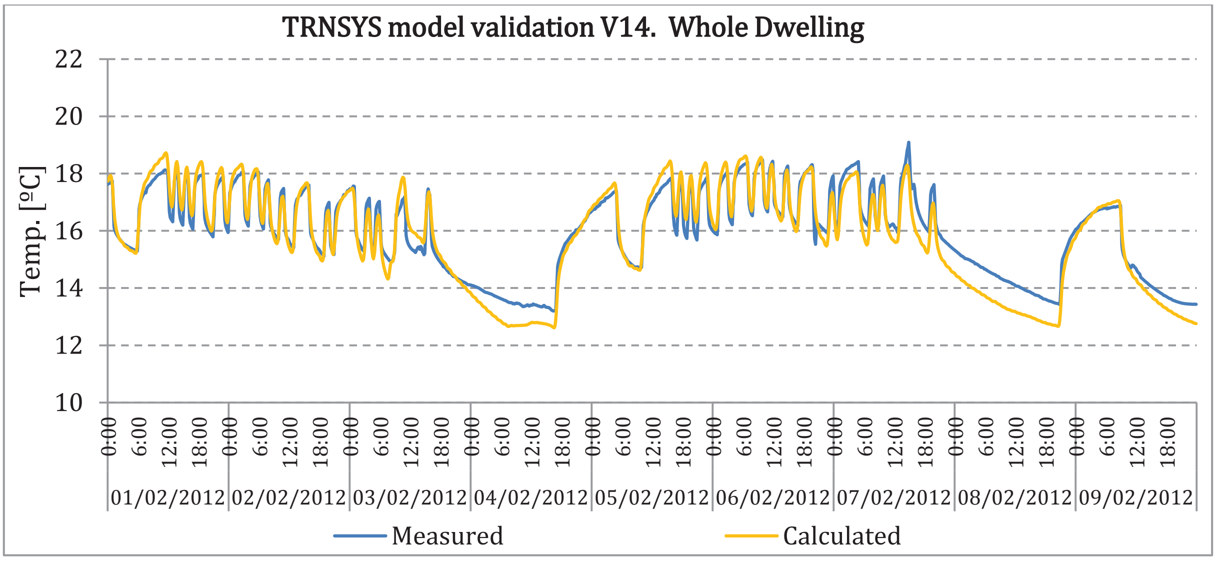


Fig. 5. 14. Measured data Vs calculated data in the studied dwelling (Model MV14)

Analyses of residuals were carried out in the different parameter combinations. As a way of example, residual of the calculated values for room 2 in the selected model is depicted in Fig. 5. 15. Even though residual did not present high values (average residual in room 2 temperatures are 0.34 ºC, and 0.39 ºC for the whole dwelling), some aspects must be clarified.

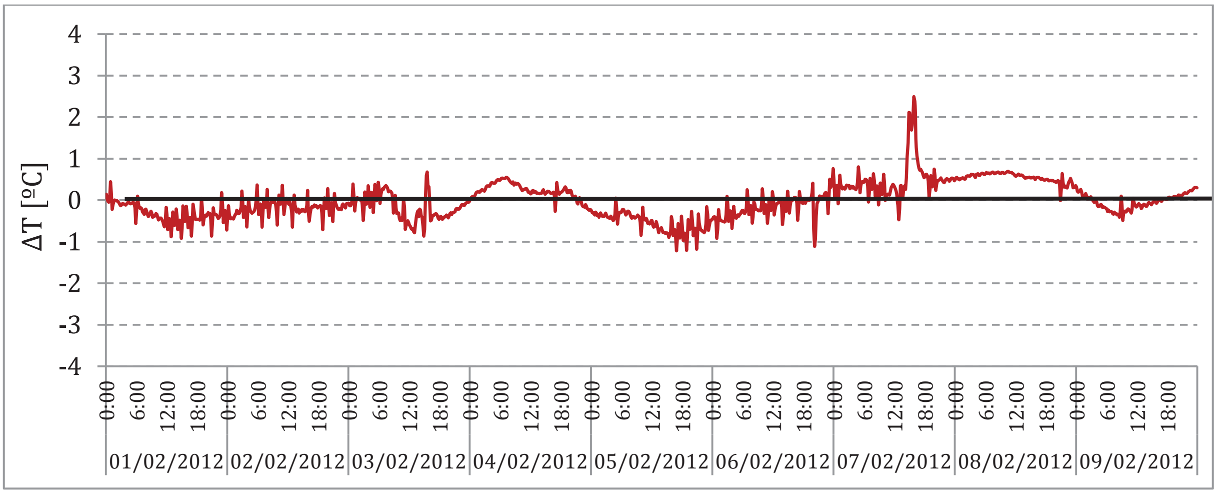


Fig. 5. 15. Residual of chosen model MV14 (average temperature in the Room 2)

On the one hand, the peak in the afternoon of 7th of February coincides with a punctual moment with direct solar radiation in the room. This fact could be related to the fact that assumptions on direct solar irradiation were not accurate enough, and not to the accuracy of the model itself. Apart from this point, residuals follow a trend around 0, but some days seem to have a trend higher than 0 (e.g. 4th of February), and other days, however, the trend of the residual is slightly lower than 0 (e.g. 5th and 6th of February). As previously stated, operating conditions of adjacent dwellings play an important role in thermal performance of the studied dwelling, especially during the winter season, and then, in indoor air temperatures. In fact, those residuals can be lessened if other setpoint temperatures are assumed for adjacent dwellings. In this case, using as a reference the room 2, the setpoint temperatures for upper and downer dwelling were modified, obtaining as a result the adjustment presented in Fig. 5. 16. Residuals are also shown in Fig. 5. 17.

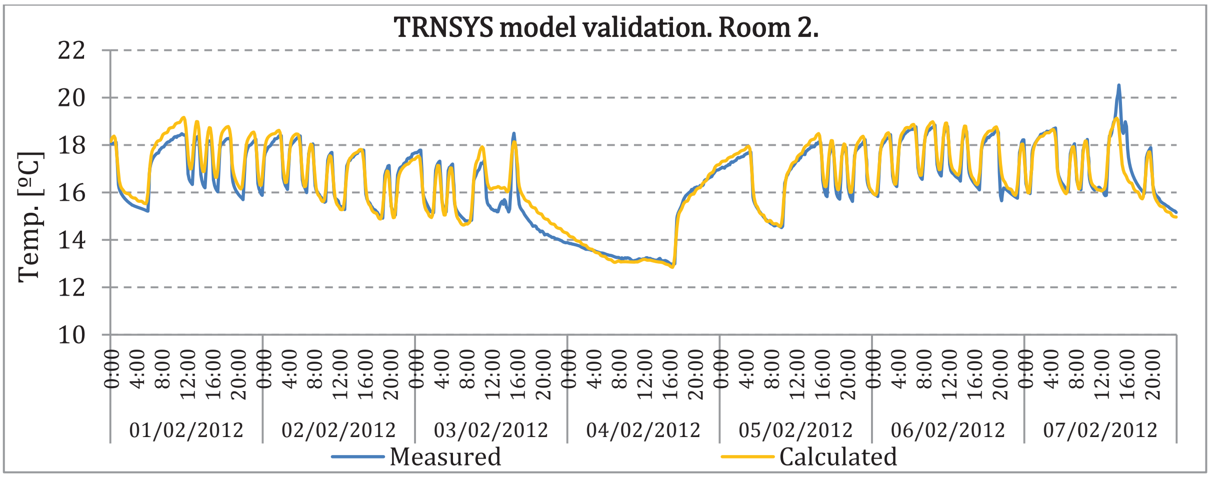


Fig. 5. 16. Calculated Vs Measured data (Room 2), after modifying setpoint in adjacent dwellings

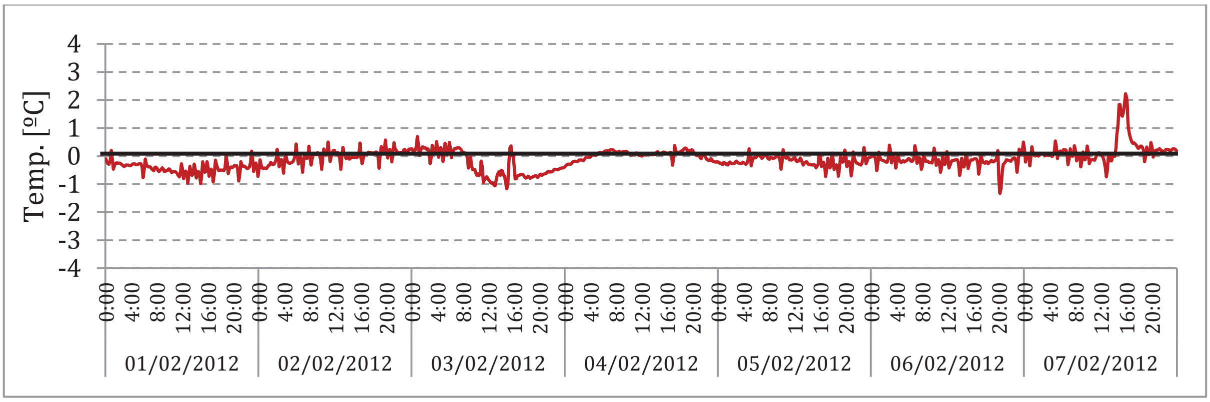


Fig. 5. 17. Residuals of data set presented in Fig. 5. 16

Assumed operating conditions of adjacent dwellings are presented in Table 5. 15.

ºC	Mon.	Tue.	Wed.	Thu.	Fri. [0-8h]	Fri. [8-24h]	Sat.	Sun.
B1P5A	13.6	17.2	16	15.2	15.2	- (12)	16.8	- (12)
B1P3A	14	17.75	16.5	15.7	15.7	- (12.4)	17.3	- (12.4)
B1P4B	No heating system is assumed							

Table 5. 15. Setpoint temperatures assumed in adjacent dwellings

Indoor surface temperatures were also calculated and compared with monitored data. Even though the fitting of them was not as good as that obtained for indoor air temperatures, it can nevertheless be considered a good approximation, as depicted in Fig. 5. 18, whereas residuals are depicted in Fig. 5. 19.

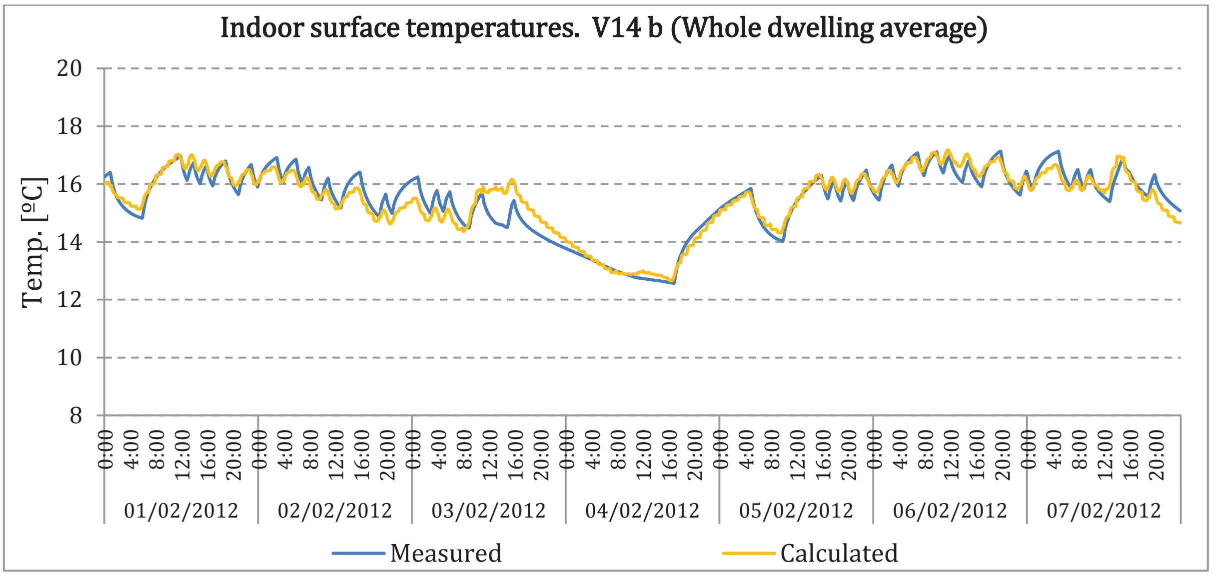


Fig. 5. 18. Indoor surface temperatures. Measured VS Calculated

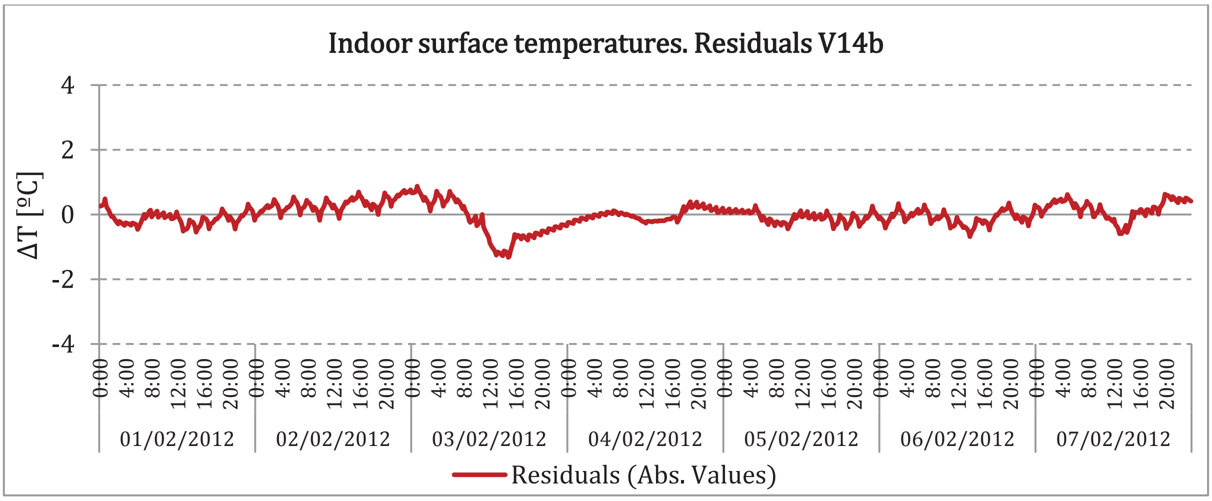


Fig. 5. 19. Indoor surface temperatures. Residuals

Thus, taking into account all mentioned uncertainties and the influence of them on the final performance of the studied dwelling, it can be affirmed that there was a good approximation between the monitored data and the simulation results. Therefore, the main characteristics defined in the model and the accuracy of the results obtained were judged to be acceptable. The final values assumed for the building model are presented in Table 5. 16.

	Room1	Room2	Room3	Living Room	Staircase
Infiltration (from outdoors) [ACH]	0.1	0.1	0.1	0.1	10
Capacity [kJ/K]	100	120	164	650	-
Infiltration (from Staircase) [ACH]	-	-	-	0.26	-
Convective heat transfer coefficient of wall (Façade) [kJ/h.m^2.K]	24				

Table 5. 16. Final parameters assumed in the building model

The rest of the model parameters have been already presented. Hence, assumed construction data have been those presented in section 4.1., ventilation criteria have been presented in section 5.1, internal gains were assumed in section 5.2, setpoint temperatures were defined as described in section 5.3, and electricity and DHW demand were assumed according to 5.4 and 5.5, respectively.

7 Results

Simulations were carried out for the whole building. Dwellings were named according to its position in the building. Thus, as shown in Fig. 5.3, the studied building has 3 staircases, with two dwellings per floor in each one. Dwellings of the first staircase (south part of the building) were called B1, those corresponding to the middle stair case, B2 and those of the third staircase (north part of the building) B3. Dwelling floor is indicated in the next part of the name, where P1 indicates the floor number where the dwelling is placed. Finally, the last letter shows if the dwelling is on the left hand (A) or on the right hand (B). As a way of example, the dwelling B1P4A is that one located in the first staircase, in the 4th floor, and in the left hand.

	Staircase 1 (B1)		Staircase 2 (B2)		Staircase 3 (B3)	
Floor	A	B	A	B	A	B
6	B1P6A	B1P6B	B2P6A	B2P6B	B3P6A	B3P6B
5	B1P5A	B1P5B	B2P5A	B2P5B	B3P5A	B3P5B
4	B1P4A	B1P4B	B2P4A	B2P4B	B3P4A	B3P4B
3	B1P3A	B1P3B	B2P3A	B2P3B	B3P3A	B3P3B
2	B1P2A	B1P2B	B2P2A	B2P2B	B3P2A	B3P2B
1	B1P1A	B1P1B	B2P1A	B2P1B	B3P1A	B3P1B

Table 5. 17. Nomenclature of the 36 dwellings

According to the above nomenclature, the 36 dwellings of the studied building were named as presented in Table 5. 17. This table can be superimposed on the façade elevation represented in Fig. 5.2., where, as previously mentioned, staircase 1 is the south part of the building. In the following subsections 7.1 and 7.2, results correspond to scenario A (operating conditions based on literature) and scenario B (operating conditions based on field measurements) are presented.

7.1 Scenario A. Models 6.1.1. & 6.2.1.

Firstly, heating demands were obtained for the whole building defining operating conditions based on literature. Monthly heating demands for three different dwellings of the building, before and after windows replacement are graphed in Fig. 5. 20 and Fig. 5. 21. These three dwellings were selected according to their relative position into the building. Hence, there is a dwelling in the first plant in the south part (B1P1A), one dwelling in the upper floor of the building, in the north part (B3P6B), and one dwelling placed in the middle of the building (B2P4A). As expected, significant differences on heating demand were seen depending of the placement of each dwelling into the building, e.g. differences around 50% were found when the aforementioned dwelling located in the middle of the building (B2P4A) and a dwelling located in the 6th floor (B3P6B) were compared.

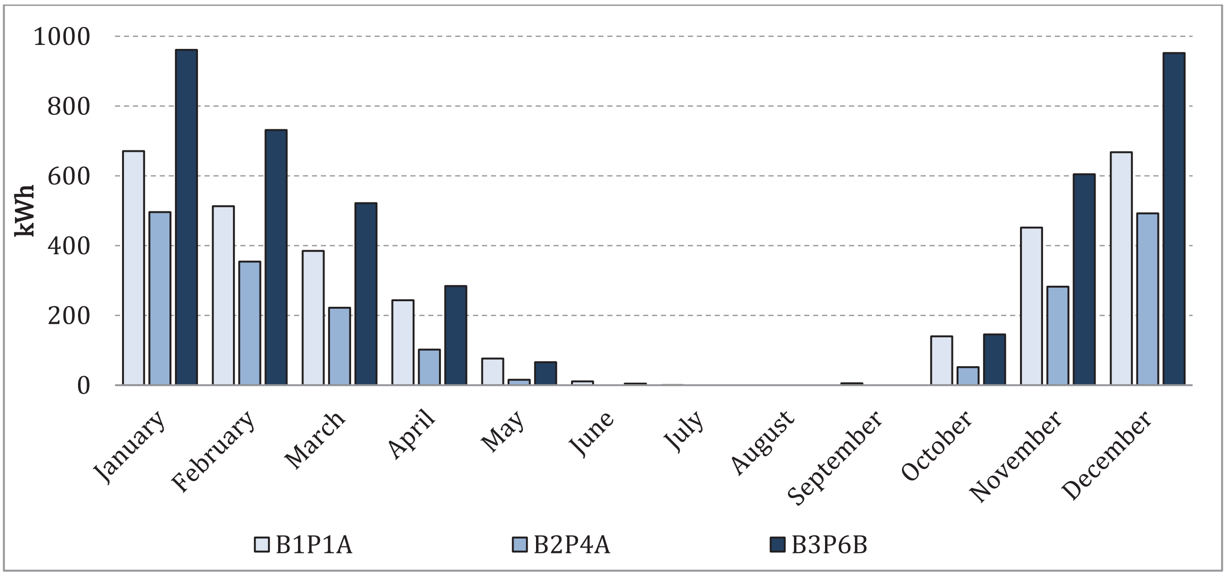


Fig. 5. 20. Monthly heating demands before windows replacement. Literature-based operating conditions (Model 6.1.1.)

Savings on annual heating demand achieved by means of windows replacement were calculated and they are presented in Table 5. 18. The highest percentage of energy savings was obtained in the middle floors, where losses through floors and ceilings are very low, and then, losses through windows (as well as through façade) are more significant. The obtained losses, however, are quite similar in all the dwellings when absolute values are compared.

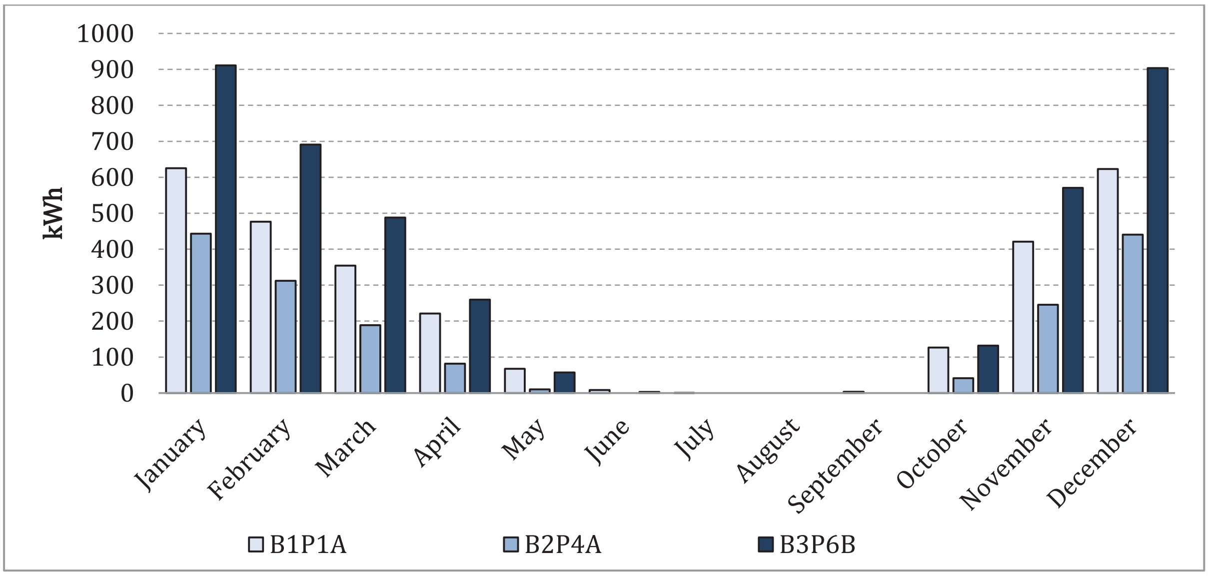


Fig. 5. 21. Monthly heating demands after windows replacement. Literature-based operating conditions (Model 6.2.1.)

[kWh]	B1P1A	B1P4A	B1P6A	B2P1A	B2P4A	B2P6A	B3P1B	B3P4B	B3P6B
6.1.1.	3163.98	2367.54	4181.95	2818.37	2015.98	3893.74	3192.09	2396.08	4269.14
6.2.1.	2926.41	2109.16	3930.07	2578.44	1763.11	3637.58	2954.70	2143.13	4016.41
Savings	237.57	258.38	251.87	239.94	252.87	256.16	237.39	252.96	252.73
%	7.51%	10.91%	6.02%	8.51%	12.54%	6.58%	7.44%	10.56%	5.92%

Table 5. 18. Annual heating demand [kWh] and savings (in demand) per dwelling (Literature based – Operating Conditions)

Finally, monthly energy savings in each dwelling were analyzed with these operating conditions. Two cases of them are presented in Table 5. 19. In general, the main reduction percentage is achieved in March, April and October. It can be also assumed that windows replacement could decrease the number of on switches during these periods. This fact also involves indirectly an additional slightly reduction of energy consumption (energy consumption is assessed in next chapters) since the "on" switch of any heating system usually involves a peak of its energy consumption.

	B2P4A				B3P6B			
	Energy Demand [kWh]		Savings		Energy Demand [kWh]		Savings	
	6.1.1.	6.2.1.	[kWh]	%	6.1.1.	6.2.1.	Savings	%
JANUARY	496.18	442.90	53.28	10.74%	960.87	911.40	49.48	5.15%
FEBRUARY	354.31	312.25	42.05	11.87%	731.08	691.14	39.94	5.46%
MARCH	221.84	188.49	33.35	15.03%	521.56	488.16	33.40	6.40%
APRIL	101.91	81.70	20.21	19.83%	284.00	259.85	24.15	8.51%
MAY	15.50	10.29	5.20	33.57%	65.95	57.29	8.66	13.13%
JUNE	0.00	0.00	NA	NA	4.36	2.86	1.50	34.37%
JULY – SEPT	0.00	0.00	NA	NA	0.00	0.00	NA	NA
OCTOBER	51.72	41.13	10.59	20.47%	145.30	131.61	13.69	9.42%
NOVEMBER	282.08	245.66	36.42	12.91%	604.35	570.53	33.82	5.60%
DECEMBER	492.44	440.67	51.77	10.51%	951.66	903.57	48.08	5.05%

Table 5. 19. Reduction on the monthly heating demand in the dwellings with the highest and lowest energy savings

7.2 Scenario B. Models 6.1.2. & 6.2.2.

Energy simulations were also carried out under operating conditions based on field measurements. For the sake of clarity, however, the case study was not the entire building, but the analysis was focused on the reference dwelling. Although lower heating demands were obtained, savings were found very similar when their relative values were compared, even a little bit higher in the field study – based scenario, as summarized in Table 5. 20.

Howerver, where assumed operating conditions tried to represent in a more faithful way the actual social dwelling operating conditions, calculated energy savings were, in absolute values, quite lower, as shown in Table 5. 20. Energy savings obtained for a typical year with literature based operating conditions were 258.38 kWh, whereas energy saving obtained with Field Study-based operating conditions were 150.1 kWh, which represents a difference about 40% between both criteria. This point shows again the importance of the operating conditions on the energy consumption of the dwelling. Consequently, it must be underlined the importance of defining properly the operating conditions in any building simulation.

Nevertheless, as already mentioned in previous chapters, not only energy savings must be taken into account in energy renovations, but also improvements on indoor comfort, especially in social dwellings, where due to the reasons explained in Chapter 3 of this thesis, energy consumption is lower than usual, and then, impacts of energy renovations are not as significant as in buildings with "standard" operating conditions. In this case, due to specific features of this population sector, energy renovations could seem quite difficult to identify as an opportunity if only economic and/or energy issues are taken into account.

	SCENARIO A				SCENARIO B			
	Energy Demand [kWh]		Savings		Energy Demand [kWh]		Savings	
	6.1.1.	6.2.1.	[kWh]	%	6.1.2.	6.2.2.	[kWh]	%
JANUARY	571.55	517.81	53.74	9.40%	320.56	283.36	37.20	11.60%
FEBRUARY	413.43	370.61	42.82	10.36%	206.23	179.13	27.10	13.14%
MARCH	266.27	232.38	33.89	12.73%	97.89	81.36	16.53	16.89%
APRIL	131.74	110.06	21.69	16.46%	32.60	25.89	6.71	20.59%
MAY	22.85	17.17	5.68	24.84%	0.23	0.00	0.23	100.00%
JUNE	0.04	0.00	0.04	100.00%	0.00	0.00	NA	NA
JULY – SEPT.	0.00	0.00	NA	NA	0.00	0.00	NA	NA
OCTOBER	63.17	51.99	11.18	17.70%	17.67	14.09	3.58	20.27%
NOVEMBER	329.59	292.70	36.89	11.19%	158.27	136.14	22.13	13.98%
DECEMBER	568.89	516.44	52.45	9.22%	325.96	289.34	36.62	11.23%
TOTAL	2367.54	2109.16	258.38	10.91%	1159.40	1009.31	150.09	12.95%

Table 5. 20. Calculated reduction on the monthly heating demand in the reference dwelling (B1P4A), depending on the operating conditions assumed

Moreover, indoor thermal comfort conditions are almost guaranteed when literature based operating conditions are assumed, unlike when field study based operating conditions are assumed. Therefore, if indoor comfort issues must also be taken into account in any energy renovation, even with more reason must be considered in the case of social housing sector.

Thermal comfort was also evaluated when results obtained from building simulation based on field study operating conditions were analyzed, focusing on the reference dwelling (B1P4A). Reasons to fix on 16 ºC the limit temperature were presented on Chapter 3, as well as in the publication based on mentioned chapter [55]. Bearing in mind this value, a comparison between both scenarios (before and after windows replacement) was carried out for the calculated results of the reference dwelling. Monthly values with the amount of hours that the dwelling presented an indoor temperature lower than 16 ºC are summarized in Table 5. 21 and Table 5. 22 (before and after windows replacement respectively)

[amount of hours]	Living Room	Room1	Room2	Room3	Av. dwelling
JANUARY	99	34	64	32	68
FEBRUARY	70	31	42	20	44
MARCH	43	17	32	12	30
APRIL	12	2	12	2	8
MAY	1	0	1	0	0
JUNE - SEPTEMBER	0	0	0	0	0
OCTOBER	2	0	1	0	2
NOVEMBER	44	14	33	9	28
DECEMBER	98	33	57	30	64
TOTAL WINTER (NOV-APRIL)	366	131	240	105	242

Table 5. 21. Amount of hours that dwelling presented an indoor temperature lower than 16 ºC (Scenario 1. Model 6.1.2.)

[amount of hours]	Living Room	Room1	Room2	Room3	Av. dwelling
JANUARY	86	31	49	23	55
FEBRUARY	56	29	36	13	39
MARCH	33	15	30	10	25
APRIL	10	2	7	1	5
MAY	0	0	0	0	0
JUNE - SEPTEMBER	0	0	0	0	0
OCTOBER	2	0	0	0	0
NOVEMBER	36	9	22	5	19
DECEMBER	80	30	46	20	50
TOTAL WINTER (NOV-APRIL)	301	116	190	72	193

Table 5. 22. Amount of hours that dwelling presented an indoor temperature lower than 16 ºC (Scenario 2. Model 6.2.2.)

Other values were also analyzed, such as average and minimum temperature for each month. Those statistical values are presented in Table 5. 23 and Table 5. 24. As it can be observed tinny improvements were found in monthly average temperatures.

	Average Temp	Min. Temp	Standard Deviation	% hours below 16 ºC
JANUARY	17.84	12.16	1.48	9.1%
FEBRUARY	18.09	12.86	1.49	6.5%
MARCH	18.96	13.48	1.72	4.0%
APRIL	20.28	15.00	2.01	1.1%
MAY	23.81	16.22	3.34	0.0%
OCTOBER	22.03	15.80	2.64	0.3%
NOVEMBER	18.45	14.05	1.32	3.9%
DECEMBER	17.84	12.43	1.44	8.6%
TOTAL WINTER (NOV-APRIL)				5.6%

Table 5. 23. Statistical values of temperatures obtained for the dwelling (average) before the windows replacement (Model 6.1.2.)

	Average Temp	Min. Temp	Standard Deviation	% hours below 16 ºC
JANUARY	17.96	12.55	1.43	7.4%
FEBRUARY	18.23	13.27	1.44	5.8%
MARCH	19.16	13.81	1.68	3.4%
APRIL	20.57	15.37	1.98	0.7%
MAY	24.10	16.51	3.31	0.0%
OCTOBER	22.29	16.10	2.60	0.0%
NOVEMBER	18.59	14.36	1.27	2.6%
DECEMBER	17.95	12.79	1.39	6.7%
TOTAL WINTER (NOV-APRIL)				4.4%

Table 5. 24. Statistical values of temperatures obtained for the dwelling (average) after the windows replacement (Model 6.2.2.)

Finally, results obtained under literature based conditions were qualitatively compared with of obtained data under field study operating conditions. It has been working in terms of heating demands, i.e. it is assumed an ideal heating system which supplies in every moment the exact amount of energy required to achieve the temperature fixed as the setpoint. For that reason, when wintertime values are assessed, this analysis only can focus on the period when no setpoint temperature is fixed and the building performs as a free-running building (building does not make any use of mechanical heating or cooling).

The free-running temperature represents the indoor temperature of the building in thermal balance with the outdoor environment when neither heating nor cooling is used. An analysis of the free running temperature in wintertime (i.e. 0-8 am) was carried out. With this aim in mind, a week with low outdoor temperatures was selected to carry out this analysis, namely 13th – 19th of January (Depicted in Fig. 5. 22 and Fig. 5. 23).

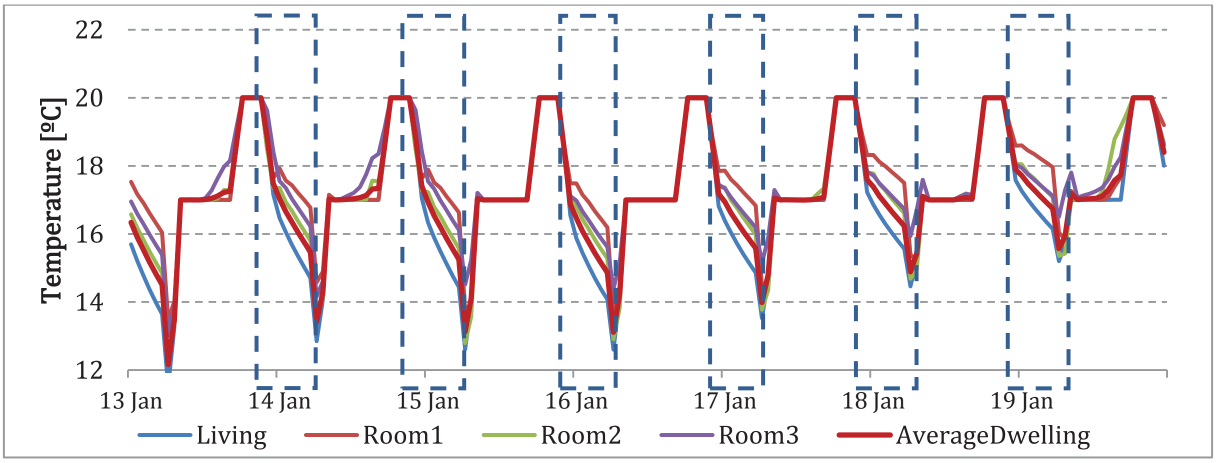


Fig. 5. 22. Indoor air temperatures [ºC] calculated with model 6.1.2.

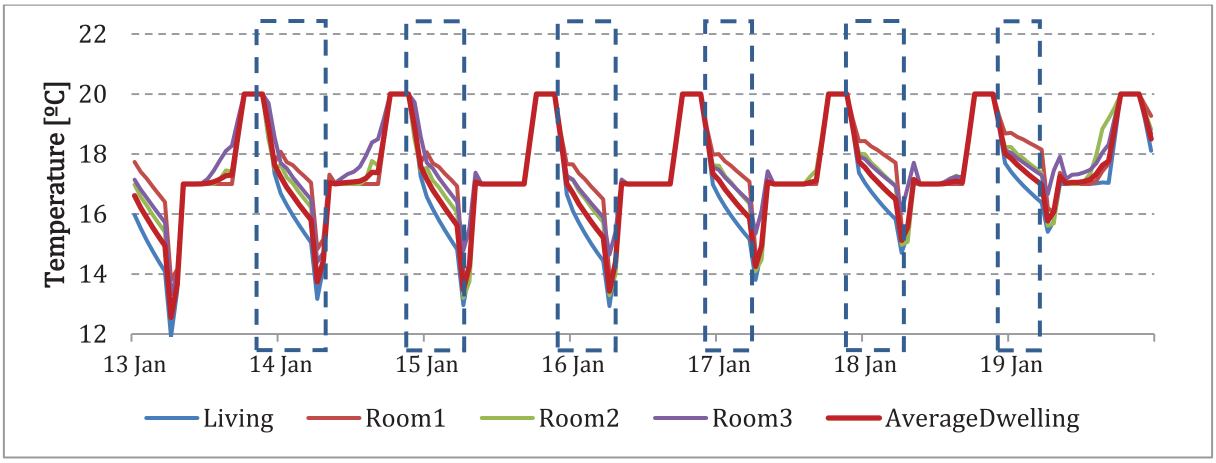


Fig. 5. 23. Indoor air temperatures [ºC] calculated with model 6.2.2.

Two different moments can be identified during the aforementioned period: the first one, from 0 am to 7 am, and the second one, from 7 am to 8 am, when punctual ventilation was assumed. One of the reference points which were evaluated was the indoor temperature at 7 am, just before ventilation starts, and after 7 hours without any use of heating system. In general, temperatures obtained for that hour of day after windows replacement were about 0.5 ºC higher than those obtained before windows replacement.

7.3 Comparison between both scenarios

As mentioned before, the main difference between both scenarios was found when absolute values of heating demand were analyzed. As shown in Table 5. 20, heating demand calculated using field study based operating conditions were about 40% lower than those calculated using operating conditions based on those suggested by IDAE. Heating demand before windows replacement under field study based operating conditions was 57.3% of those obtained under literature based operating conditions; after windows replacement, it was 56%. Similar situation was found when absolute values of energy savings were compared.

On the contrary, when energy savings were compared in relative values, both cases were alike, independently of the operating conditions used (9.22% and 11.23%, as shown in Table 5. 20.)

8 Conclusions

Validation process showed the great influence of the variables which are not controllable when the case study unit is a dwelling, such as operating condition in adjacent dwellings, especially in dwellings where no insulation system is found in its façade and partition walls. This problem is usually reduced, and even becomes negligible when the unit of the case study is the building, and then all boundary conditions are more easily controlled (weather conditions).

It is also noted the influence of the selected operating conditions on the results of the final energy savings, as presented in section 7.3. This aspect is not relevant when the main objective is to compare the effect of different energy renovation strategies, due to the fact that relative values obtained for energy savings were quite similar in both assumptions. However, these differences must be taken into account when absolute values are compared, e.g. for calculating paybacks, or LCA developing. In these cases, assuming operating conditions as close to the real ones as possible is a key factor to obtain more accurate results.

Thus, despite the fact that operating conditions in each dwelling depends on the occupants, and it is not possible to know what will be exactly the user behaviour, it is possible to define some operating condition profiles, according to a group classification of the different occupants' profiles, especially when an specific population sector is studied (in the case of this thesis, social building stock). Even being a small sample (only 10 dwellings), it was shown in Chapter 3 the differences existing between general user behaviour in this sector and the standard profiles proposed by IDAE.

Finally, It must be highlighted the fact that energy savings obtained on Social building stock using field study – based operating conditions (and then, presumably more close to the real occupants' profile) could lead to lower values, as shown in this thesis. This fact, however, must not be seen as an obstacle to carry out energy improvements in social buildings, or to reason out as less interesting any renovation in this field. Quite the opposite. as it has been already mentioned in the first chapters of this thesis, energy renovation must be evaluated under a multi-criteria approach, i.e. not only economical or energy considerations must be taken into account, but also social and healthy aspects, somehow related to indoor comfort.

9 Referred appendices

Appendix 5.1. Combination of model parameters

Appendix 5.2. Analysis of validation model results

CHAPTER 6

GREY BOX MODEL BASED IN RC – NETWORK. MODEL DEFINITION

RESUMEN

En este capítulo se describe el desarrollo de un modelo RC que represente el comportamiento térmico de la vivienda de referencia. El modelo se ha definido a partir de los datos obtenidos en la primera monitorización descrita en el Capítulo 4 de esta tesis, es decir, antes de la sustitución de las ventanas de la vivienda.

Así, en la primera parte del capítulo se presenta una breve introducción sobre el uso de estos modelos RC en edificación, para posteriormente describir el enfoque y diseño del modelo, así como sus bases matemáticas. Posteriormente, se presentan los parámetros característicos obtenidos para el modelo, y una descripción del funcionamiento y los cálculos que realiza el modelo, una vez incluidos en él dichos parámetros característicos. Tras ello, se describe el proceso de validación del modelo y el uso del mismo, simulando el mismo caso que se hacía en el capítulo previo con el modelo de TRNSYS. Se acaba con una comparación entre el modelo TRNSYS definido en el capitulo anterior y este modelo RC, para finalmente presentar las conclusiones, tanto del capítulo como las generales obtenidas de esta parte 3 "Modelos matemáticos", compuesta por los capítulos 5 y 6.

ABSTRACT

The development of a RC model is described in this chapter. This model is led to represent thermal behaviour of the reference dwelling, presented in Chapter 4, and it is developed based on data obtained during the first monitoring described in mentioned chapter, i.e. data corresponding to the reference dwelling before window replacement.

Thus, a brief introduction of the use of RC models in buildings is presented. Secondly, the followed approach and the model design are described, as well as its mathematical bases. Then, characteristic parameters calculated for the model are shown, and the way that model works after including those parameters is defined. Afterwards, validation procedure is presented, and the model is used for simulating the same base case used in the previous chapter. Then, results obtained by both models (TRNSYS and RC) are compared. Conclusions, both of this chapter and of this Part 3 "Mathematical models" are numbered.

1 Grey box models

1.1 Introduction

Different ways to analyse thermal performance of a dwelling or building have already been dealt with in the previous chapters. The field study on occupied dwellings carried out in Bilbao was described in Chapter 3, whereas in Chapter 5 the development of a TRNSYS model to define the thermal behaviour of the dwelling was presented. For that development, data gathered in the monitoring study described in Chapter 4 was used.

Thus, the usefulness of the white models, namely TRNSYS model, has been shown in the previous chapter. However, this kind of models usually requires a significant computational time to perform a yearly simulation. For that reason amongst others, these tools might not be the best option when the user requires running a large number of simulations.

As Ramallo-González et al. refer in [84], some authors have faced this problem using simpler building simulators [85,86]. Some of them were developed in the seventies and are based on linear dynamic models, based on classical heat transfer theory and resistance – capacitance analogues. In fact, the equation of heat transfer through solids could be assumed lineal, and can be represented with the so called electrical analogy. Within this analogy, conductivity of materials is processed as electrical conductivity, and thermal capacity of materials as electrical capacity.

Thus, these models, so called lumped parameter models, simplify the description of the behaviour of spatially distributed physical systems into a model consisting of discrete entities that approximate the behaviour of the distributed system under certain assumptions.

An example of a simulator using this electrical analogy was published by Balcomb et al. in 1977, where the thermal behaviour of a building heated with solar gains was modelled with a simple network of resistors and capacitors (RC network), representing conductivities and capacities of the studied building ([87], quoted by [84]). Another example of one of the first useful approaches for the development of such models is described in [88], which represented component materials in an assembly as an equivalent network of thermal resistances and thermal capacitances.

1.2 Advantages of RC models in building simulations

One of the main advantages of using this kind of models to represent the building performance is therefore the aforementioned low computational cost required in comparison to white box models. As Ramallo-González et al. affirm in [84], RC networks can be mathematically modelled by a set of first order differential equations, also called state-space systems and they provide the temperatures of building elements and zones.

Their mentioned short computational times made these models popular during the seventies when computational resources were limited. However, despite the fact the huge increase of computational resources have reduced this problem nowadays, RC models are still used when quick building simulations are needed [72,85,86,89].

Moreover, the large amount of information required in white box models was already mentioned in the previous chapter. RC models require a smaller quantity of information to be developed, obtaining accurate results of the thermal performance of the building. Besides, required data can be directly obtained from on field measurements. It makes the development of the model easier, when it is possible to carry out a monitoring study of the building or dwelling.

1.3 Steps for the development of a grey box model

In this chapter, the development of a grey box model which represents the thermal performance of the reference dwelling is presented. The eight steps depicted in Fig. 6.1 are followed for that purpose.

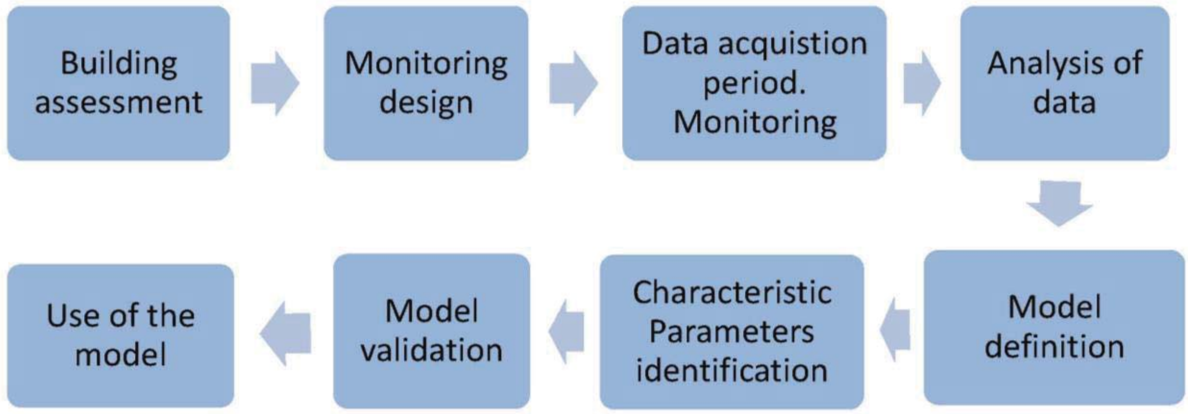


Fig. 6. 1. Steps followed to develop the RC Model of the reference dwelling

As a matter of fact, the four first steps depicted in Fig. 6.1 have already been presented and thoroughly described in previous chapters. Thus, building assessment, monitoring design, monitoring period and analysis of data were dealt with in Chapter 4. The second row depicted in Fig. 6.1. (i.e. RC model definition, the model parameter identification, model validation, and finally, use of the model) is described in this chapter.

Data corresponding to the first monitoring period is used to define the model. Due to the necessity of controlling (amongst other variables) the heat input in the dwelling, as well as monitoring different heating system routines, this methodology is more suitable when it is possible to monitor an unoccupied dwelling, preferably during the winter time.

1.4 Workflows with models

Generally, the data managed by a model are divided into three groups: independent variables (*x*), dependent variables (*y*) and model parameters (*A, B…*), which define *f(x)* Depending on what the unknown values of the model are (and then, the aim of the model), three different workflows can be followed when a model is developed: direct procedure, inverse procedure and composed procedure. An explanatory graph about this point is depicted in Fig. 6. 2. The graph is based on the one presented by C. Ghiaus in Rotterdam during an Annex 53 one-day Forum [29] held in April 2012.

		Known	Unknown	Use
 y=Ax	**Direct:** - Simulation	*x, f(x)*	*y*	Verify
 A=x/y	**Inverse:** - Parameter identification - State estimation - Structure estimation	*x, y*	*f(x)*	Design
 x=y/A	- Control	*f(x), y*	*x*	Control
	Composed: - Detection and diagnosis			

Fig. 6. 2. Workflows to work with models, based on C. Ghiaus presentation

Direct procedure is used when excitements and parameters of the model are known, and results about response of the model to those excitements are looked for. Typical building simulations follow this procedure, where excitements (weather conditions, or outdoor affections) and parameters (which define the building features such as thermal resistance and capacity) are known, and the aim is to obtain the building response (e.g. indoor temperatures or energy consumption).

Inverse procedure is used in two ways. The first one is when the characteristic parameters of the model are unknown, but inputs and response of the model are known and then, they are used to obtain the characteristic parameters. One example of this case is the parameter identification procedure, when experimental data (inputs and responses) are used to define those characteristic parameters. The second way of inverse procedure is when only the parameters and the responses of the model are known, and the unknown part corresponds to the input of the model. This is a typical situation in control models, for instance, where building characteristics are defined, as well as the sought output, and the model calculates the inputs to obtain that defined output (e.g. heat input).

Finally, some occasions require using both direct and inverse procedure, in a so called composed procedure. This is the case developed in this chapter.

1.5 Structure of the Chapter

A thermal behaviour of the reference dwelling is characterised in this chapter, by means of a lumped parameter model development. With this aim in mind, eight steps are followed throughout the chapter. Firstly, a brief introduction about grey box models is presented, and a scheme of the chosen model to develop is defined, using the data obtained from the monitoring study presented in Chapter 4. Secondly, implementation of the collected data in CTSM software is shown. Afterwards, the next part of the chapter is devoted to show the dwelling model definition and its corresponding validation. Then, the use of white box models and grey box models to calculate energy demand are compared, taking into account their pros and cons. Finally, conclusions of the chapter are summarized. A scheme with these steps is depicted in Fig. 6. 3.

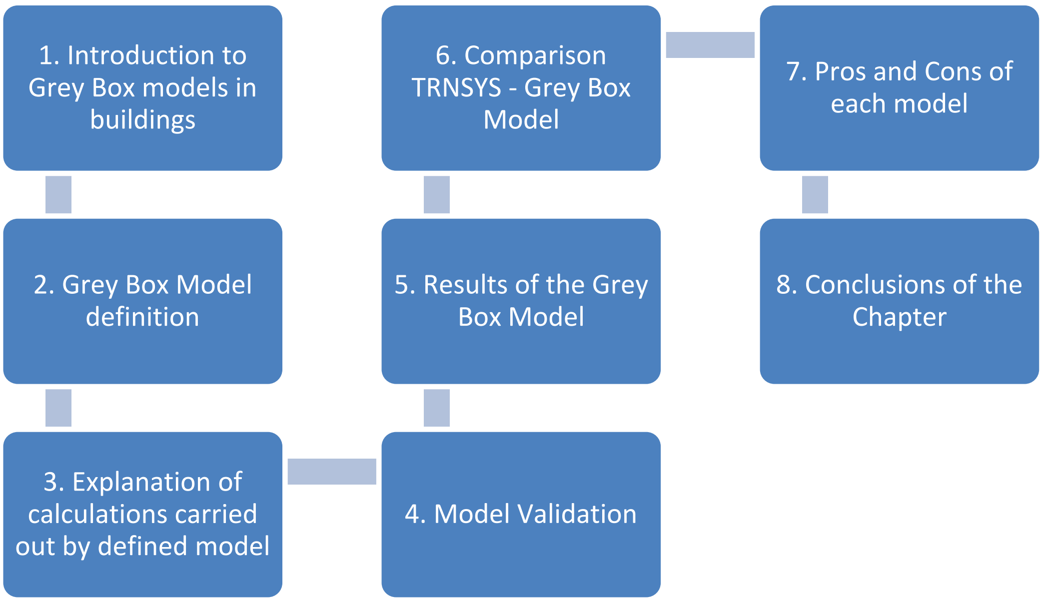


Fig. 6. 3. Structure of the chapter

2 Objectives of this chapter

The main targets of this chapter could be summarized as follows:

- Describing and developing a methodology I order to quantify the heating demand of a dwelling, by developing a grey box model.

- Checking the usefulness of the model to estimate potential savings connected to different energy renovation strategies.
- Comparing the grey box model results with those obtained with TRNSYS model, and identifying the pros and cons of each kind of models for this particular use.

3 Grey box models in buildings

3.1 Approach of the model

Before designing any model, it is necessary to establish which results are wanted to obtain, and which data will be used for developing it. For that, a scheme of the model was previously defined.

Heat fluxes in any building could be represented by an indoor air volume (a) which receives a heat flux from internal gains (b) and, indirectly, solar radiation (which heats the indoor floor, ceilings and walls, and then, by convection, the heat is released to indoor air) (c) in order to maintain given conditions of indoor comfort. That heat is steadily lost through the building envelope to the outdoor environment (d).

Therefore, thermal behaviour in buildings in the winter period could be understood in the way "inputs and outputs" of the indoor air temperature are balanced. As previously mentioned, there are two main sources of heat input, outdoors and indoors respectively. On the one hand, solar gains (outdoors) enter in the buildings indirectly through opaque walls (conduction) and directly through the windows (radiation). On the other hand, there are internal gains, such as occupants, appliances and the heating system itself.

Likewise, there is also a heat output, which is composed by the sum of the losses through opaque walls, roof, windows, structure, ventilation and infiltration. These losses (or gains) are dependent on the difference of temperature between both sides and on the thermal characteristics of those elements. The balance between inputs and outputs maintains a stable indoor air temperature. Thus, the role of the heating system is to increase the heat input in the system (indoor air) in order to equalize heat inputs and heat losses.

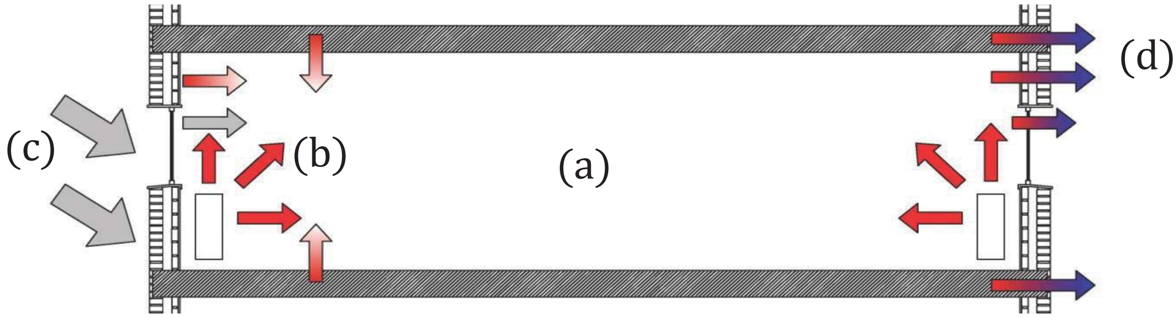


Fig. 6. 4. Single sketch of heat flux in dwellings

A similar approach could be assumed in a dwelling scale, as presented in Fig. 6. 4. A dwelling presents the same heat inputs (solar gains and internal gains including the heating system). Losses in the dwelling occur through opaque walls and windows, and through structure, due to thermal bridges. Moreover, when the boundary is limited to a dwelling, another heat flux can enter from adjacent dwellings when indoor thermal conditions are different to the studied dwelling. Therefore, heat input or output will depend on the conditions of the adjacent dwellings. Hence, this is the general scheme followed for developing the dwelling model.

Furthermore, thermal inertia of the building elements (capacitance) also plays a role in the energy balance. For that reason, the steady-state R-value traditionally used to measure energy performance of a building envelope does not accurately reflect the dynamic thermal behaviour of all complex building envelope systems.

In other words, heat does not flow directly from one point to another. To highlight this point, the case of opaque walls can be used. When solar irradiation heats the wall up, heat does not go immediately to indoor air, but it is stored in the wall and later released, depending on the heat capacitance of the wall. Thus, let's suppose that two different moments, with exactly the same inputs (solar radiation, outdoor temperature, internal gains...) are studied. One moment is in July, and the other one, in February. Clearly, the building response in July, i.e. after a week of high temperatures, will be totally different to the building response in February after a week of low temperatures.

Hence, indoor air temperature, as well as building thermal behaviour in general, is highly dependent, not only on excitements at a given moment, but also on conditions during the previous moments.

3.2 Defining the grey box model

A grey box model was developed to represent the thermal behaviour of a (reference) dwelling. The grey box model was established using a combination of prior physical knowledge and statistics. The prior physical knowledge is formulated by a set of differential equations. The equations describe a lumped model of the heat dynamics of the building. The physical model part is coupled with the data-driven model part with which the information embedded in observed data is used for parameter estimation [72].

Thus, defining building models with these networks involves representing the different elements of the building with resistors and capacitors. Different detail levels can be set. A multilayered construction can be defined just with two resistors, one capacitor and one internal node ([90]quoted by [84]); or two resistors, one capacitor and one internal node can be used to represent each slab of material. Obviously, including all wall layers for all the surfaces of the envelope leads to larger RC-networks, so the detailed level will be set by the author based on the aims of the model and the available information.

Then, the single schemes depicted in previous figures can be represented using electrical analogy, with R and C, to create the model basis. The main calculation principles of these models are based on the calculation of electrical networks. Three ideas about these calculations are briefly presented in the following.

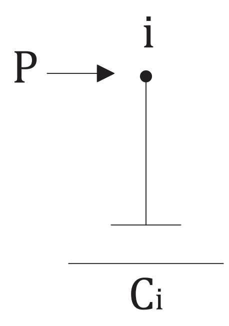


Fig. 6. 5. Single model encompassed by a node I with an excitement P and a capacity C

In any RC model (e.g. Fig. 6. 5), the balance in each node can be carried out as presented in Eq. 11, where P represents the sum of the excitements (heat fluxes) which affect to the node, T is Temperature, t is time, and C is thermal capacity.

$$C_i \cdot \frac{dT_i}{dt} = P \qquad \text{Eq. 11}$$

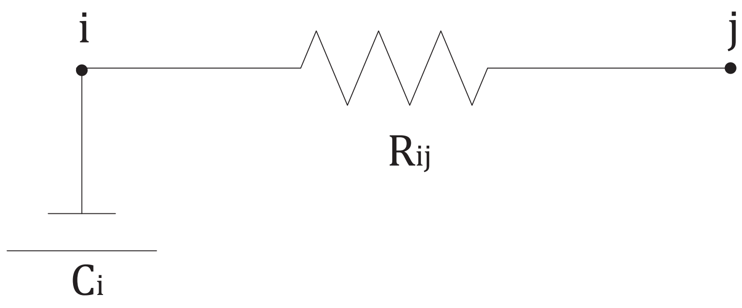


Fig. 6. 6. RC model formed by one resistor and one capacity

When a heat flux flows from other node with different temperature (e.g. Fig. 6. 6), that heat flux through the resistance can be calculated as follows:

$$\phi_{ij} = \left(T_i - T_j\right) \cdot H_{ij} \qquad \text{Eq. 12}$$

$$H_{ij} = \frac{1}{R_{ij}} \qquad \text{Eq. 13}$$

And then:

$$C_i \cdot \frac{dT_i}{dt} = \left(T_i - T_j\right) \cdot H_{ij} \qquad \text{Eq. 14}$$

The indoor air temperature in a building is influenced by different heat fluxes. The lumped parameter model developed in this chapter includes a model of the indoor air connected with the outdoor air through 3 ways: through the opaque walls, through the windows and through the rest of the elements (indoor partitions, structure…). Moreover, the heater is also included in the model. In the following section, each part of the model is defined.

In short, any node of the defined model can be affected by, at the most, 3 different kinds of heat fluxes: that flux consequence of the solar irradiation (whose calculation is explained in the following section), that flux consequence of connection with a node with other temperature, and that flux directly provided by the heater, or internal gains in general.

4 Model definition

4.1 Inputs affecting a node in a building model

Taking into account the aforementioned general basis, these fluxes can be represented in this way. Hence, this section describes those fluxes and their RC representation.

4.1.1 Solar irradiation. Effective area

Firstly, must be noted that solar irradiation has also a strong influence on the thermal performance of the dwelling, both incident solar irradiation that passes through a window and the mentioned incident solar irradiation on the outdoor surfaces of opaque walls. Accordingly, it must be taken into account in the model. However, linear dynamic models are not capable of modelling radiation, and linear approximations must be assumed to include this heat transfer mechanism. To do so, the effective area, both for windows and walls, must be included in equations.

The effective window area ($A_{w\text{-}e}$) is a parameter which considers an average surface exposed factor (f), G-value of the windows (g) and the real area of the window (A_w). Then, $A_{w\text{-}e}$ is obtained by multiplying those three values, f, g and A_w. Thus, the solar flux that passes through windows is calculated as shown in Eq. 15.

$$\phi_s = A_{w-e} \cdot G_h = f \cdot g \cdot A_w \cdot G_h \qquad \text{Eq. 15}$$

Where G_h is the horizontal beam radiation [w/m^2].

Likewise, the effective façade area ($A_{f\text{-}e}$) is a value which considers a surface exposed factor (f), and the real area of the façade (A_f). The inclusion of this term in the governing equations of the developed model is presented in the following (indoor air model and opaque walls model).

4.1.2 Indoor air

Indoor air node was modeled as presented in Fig. 6. 7, based on that explained in Appendix 6.1. Indoor temperature node is composed on a thermal capacity (C_{in}) and a connection with the other elements in contact to indoor air. That connection is represented through a thermal resistance, which represents the thermal resistance between the indoor air and other temperature node *j*. Other direct inputs, such as solar gains, can be included in the node.

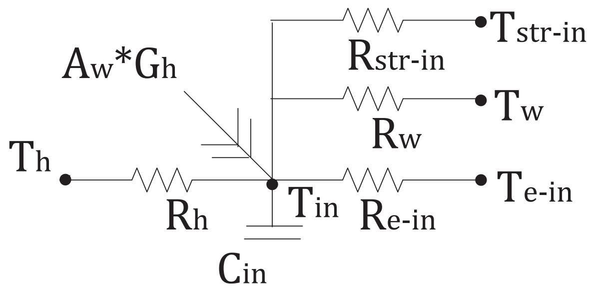


Fig. 6. 7. RC model formed by one resistor and one capacity

Based on that explained in Appendix 6.1. the balance in the air node in the model is connected with Te-in, Tw, Tstr-in and Th. The solar irradiation through the windows also is considered in this node. The resulted equation is presented in the following:

$$C_{in} \cdot \frac{dT_{in}}{dt} = (T_{in} - T_{e-in}) \cdot H_{e-in} + (T_{in} - T_w) \cdot H_{w-in} + (T_{in} - T_{str-in}) \cdot H_{str-in} + (T_{in} - T_h) \cdot H_h + A_w Q_{gh} \qquad \text{Eq. 16}$$

4.1.3 Opaque walls

A representation of the façade branch defined in the RC model is depicted in Fig. 6. 8. It represents the different resistances and capacitances considered through the opaque walls, as well as temperature nodes and other collateral fluxes, such as solar irradiation, which affects the heat flux indirectly, since it heats up the envelope, and it can modify it significantly.

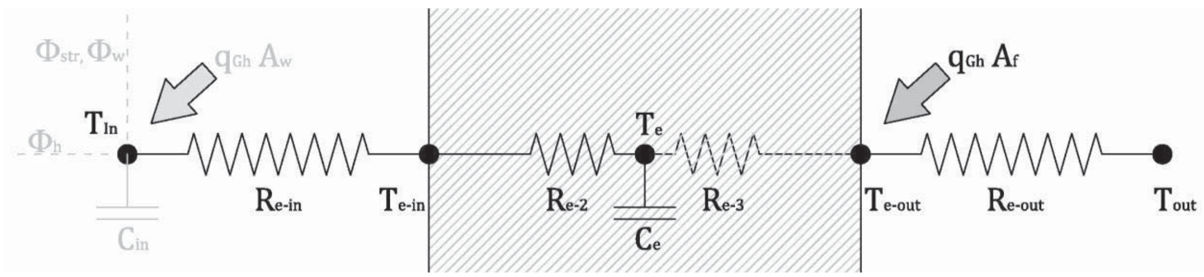


Fig. 6. 8. Façade branch of the developed model

Different thermal resistances in series represent the thermal resistance of the wall, appearing amongst them the temperature of envelope T_e as a new variable. Likewise, a heat capacity of envelope is considered. Thus, the first order dynamics in this subsystem are represented by Eq. 17.

$$dT_e = \frac{1}{C_e}\phi_{e-in} \cdot dt + \frac{1}{C_e}\phi_{e-out} \cdot dt \qquad \text{Eq. 17}$$

Which can be also expressed as presented in the following:

$$C_e \cdot \frac{dT_e}{dt} = (T_{e-in} - T_e) \cdot H_{e-2} + (T_{e-out} - T_e) \cdot H_{e-3} \qquad \text{Eq. 18}$$

Where Φ_{out-e} is the energy flux from outside to the envelope and Φ_{e-in} is the energy flux from envelope to indoor air. Following the same criteria, the balance in each node of the branch can be done. As observed, those heat fluxes depend on the temperatures of each node, and in turn, solar irradiation on the outdoor surface of the façade has a strong influence on T_{e-out}, so it must also be considered, and it was included as an input in this node.

4.1.4 Heat flux through the windows

Heat flux related to the windows (ϕ_w due to heat transfer by conduction and solar irradiation represented by G_hA_w) branch can be handled in an analogous way. A scheme of the window branch is depicted in Fig. 6.9.

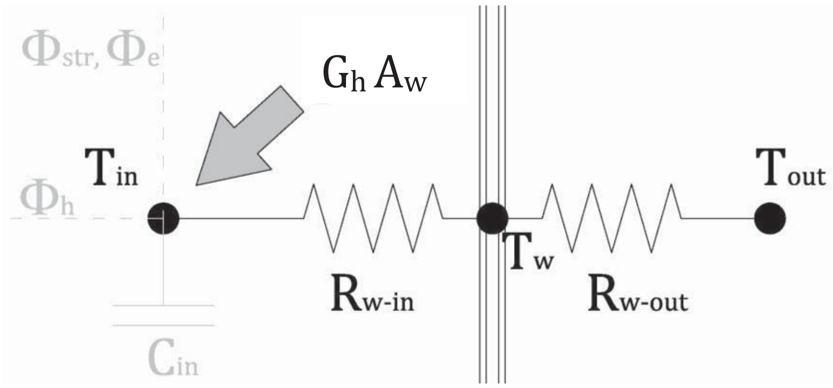


Fig. 6. 9. Windows branch of the developed model

As mentioned, heat losses by conduction through the windows are handled in the same way to that presented in previous subsection, related to opaque walls. Moreover, other energy flux through the windows must be considered, i.e. solar radiation. This flux must also be considered when the balance in the indoor air node is made, using the aforementioned effective area, as presented before.

4.1.5 Heat flux through structure branch

In addition to the mentioned heat fluxes through opaque walls and windows, other heat fluxes (through indoor partitions, thermal bridges…) also occur in a dwelling. These heat fluxes are considered in this structure branch. Heat flux through structure is calculated in the same way. The sketch of the structure branch is depicted in Fig. 6. 10.

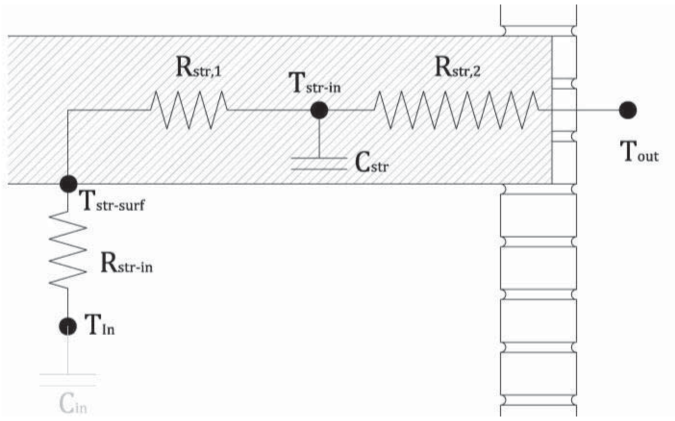


Fig. 6. 10. Structure branch of the developed model

Similar balance to those developed in the case of the opaque walls can be applied to this case. The balance in this case can be expressed as follows:

$$C_{str} \cdot \frac{dT_{str-in}}{dt} = \left(T_{str-surf} - T_{str-in}\right) \cdot H_{str-1} + \left(T_{out} - T_{str-in}\right) \cdot H_{str-2} \qquad \text{Eq. 19}$$

4.1.6 Heat flux from heating system

Heat flux given by the heating system can be treated in the same way as to heat flux through the envelope. It is a more simple system indeed, composed by the heater node itself, a heat capacity of the heater, a power input to the heater and a thermal resistance between the heater and the indoor air temperature, as depicted in Fig. 6. 11.

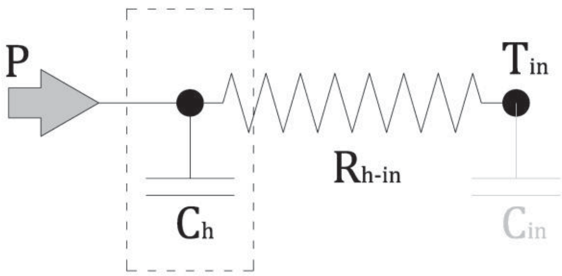


Fig. 6. 11. RC network representing the heat flux from the heating system to indoor air

The balance the heater node can be expressed as follows:

$$C_h \cdot \frac{dT_h}{dt} = (T_{in} - T_h) \cdot H_{h-in} + P$$ Eq. 20

4.1.7 Ventilation

No ventilation happened in the dwelling during the monitoring period. Therefore, it was not represented in the dwelling scheme. However, since ventilation may involve important heat losses in a dwelling during its usage, it will be considered in the model afterwards, as defined later. On its behalf, infiltration rates in the dwelling during the monitoring period were evaluated, giving low values.

4.2 Model coupling

Therefore, heat transfer in the dwelling can be described by means of a lumped parameter model, formulated by a deterministic type, linear continuous time state - space model. Non described effects by mentioned deterministic model are added as a noise, obtaining thus a stochastic model. The mathematical correlations of this kind of model are described in detail in [72,91].

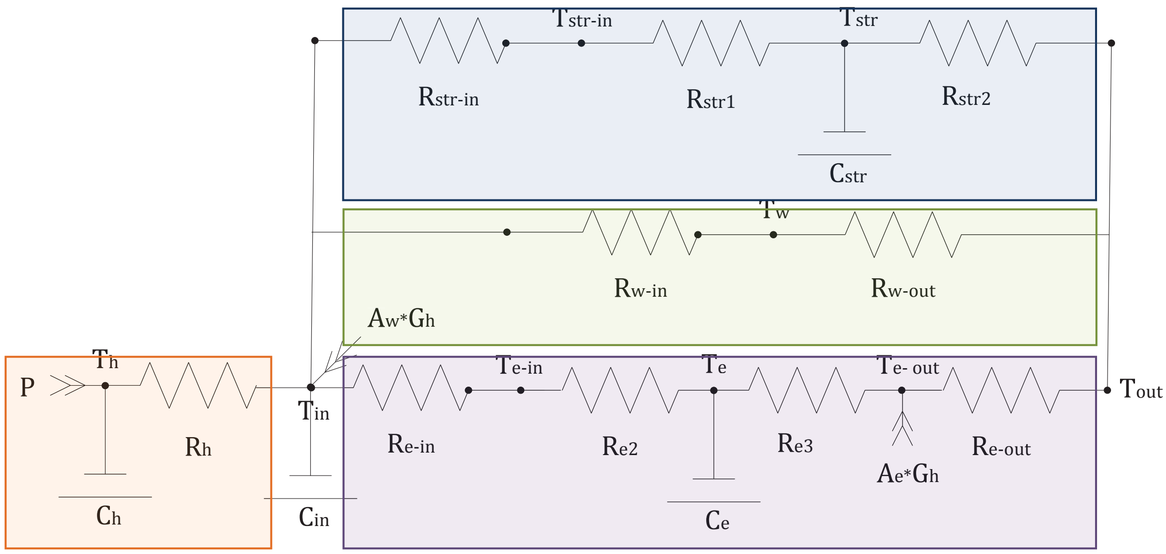


Fig. 6. 12. RC network of the selected model, with the different branches highlighted

Thus, he coupling of the different elements of the model, described in the previously section is presented in the following. The final model was represented with the RC-network depicted in Fig. 6. 12. As shown in that figure, the model was divided in different branches which represent different energy fluxes: energy flux through structure (the upper branch, in blue), through the windows (the middle one, in green), through the façade (in purple) and from heating system (in orange). Also the influence of solar radiation was considered in the model ($A_{in}G_h$ and A_eG_h).

The indoor environment was represented by an indoor air temperature T_{in} and a heat capacity of the indoor air mass C_{in}. This node is also affected by solar gains through semi-transparent elements. It was obtained by taking horizontal global radiation (G_h) weighted with the effective window area factor, as previously mentioned.

Connection with the outdoor environment is through thermal resistances and temperature – capacity nodes. Two different kinds of thermal resistances are presented: those which represent combined heat exchange ($R_{str\text{-}in}$, R_{str2}, R_{w1}, R_{w2}, $R_{e\text{-}in}$ and $R_{e\text{-}out}$); and those which are purely conductive resistance, such as R_{est1}, R_{e2} and R_{e3}. C_{str} represents the heat capacity of the structure, whilst C_e quantifies the envelope heat capacity.

Solar gains on the envelope outdoor surface were also taken into account, in a similar way to solar gains of the indoor air node through semi-transparent elements. No heat capacity was assumed in windows. Heat input from the heaters was not directly included on the indoor air node, but as a small branch which included its thermal resistance and heat capacity.

No infiltration losses were considered in the model. The correct adjustment obtained proves that such losses were negligible. Indoor air renovation tests carried out by means of tracer gas techniques during monitoring period showed that infiltration rate was extremely low, despite the low quality of the windows. Low wind velocities logged during monitoring period could explain this point.

In short, the model took into account thermal capacity of the dwelling and thermal resistance of the envelope. The envelope was divided into the windows component (with the solar gains related to them) and opaque walls component. The influence of the structure on thermal behaviour (heat capacity and thermal bridges) was therefore also considered in the model (upper branch).

5 Parameter identification procedure

5.1 Equation system of the model

Hence, the system is governed by a set of equations of balance based on these mathematical bases. The balance equations are applied on each model node, as described later in detail in section 6.3. This set of equations encompasses a differential equation system which can be represented as shown in Eq. 21 [92].

$$\begin{gathered}\{dT\} = [A]\{T\}dt + [B]\{U\}dt \\ \{Y\} = [C]\{T\} + [D]\{U\}\end{gathered} \qquad \text{Eq. 21}$$

Where [A] is the matrix which contains thermal properties of the model; {T} is a state vector formed by the temperature at each main node (T_{in}, T_h, T_w, T_{str} and T_e); [B] is the matrix which defines the way that excitements affect the model; {U} is the entry vector, formed by excitement variables, such as outdoor temperature, solar irradiation and heat power; {Y} is the measurement vector, formed by registered data, such as measured temperatures and heat fluxes; [C] is the matrix which connects measured variables with state variables; and finally [D], the matrix which connects measured variables with entry variables.

Therefore, a equation system is defined by equations previously defined, applying in each node. In the following, the four equations for the most significant nodes (Indoor temperature, outdoor temperature, temperature of structure and temperature of the envelope) are presented:

$$\begin{aligned} dT_{in} = \frac{1}{C_{in}} A_{in} G_h dt &+ \frac{1}{C_{in}(R_{e-in} + R_{e2})}(T_e - T_{in})dt \\ &+ \frac{1}{C_{in}(R_{w-in} + R_{w-out})}(T_{out} - T_{in})dt \\ &+ \frac{1}{C_{in}(R_{str-in} + R_{str2})}(T_{str} - T_{in})dt + \frac{1}{C_{in} \cdot R_h}(T_h - T_{in})dt \\ &+ \sigma_{in} d\omega_{in} \end{aligned} \qquad \text{Eq. 22}$$

$$dT_e = \frac{1}{C_e(R_{e-in}+R_{e2})}(T_{in}-T_e)dt + \frac{1}{C_e(R_{e-out}+R_{e3})}(T_{out}+A_eG_hR_{e-out}-T_e)dt + \sigma_e d\omega_e \qquad \text{Eq. 23}$$

$$dT_{str} = \frac{1}{C_{str}(R_{str-in}+R_{str1})}(T_{in}-T_{str})dt + \frac{1}{C_{str}R_{str2}}(T_{out}-T_{str})dt + \sigma_{str} d\omega_{str} \qquad \text{Eq. 24}$$

$$dT_h = \frac{1}{C_h}Pdt + \frac{1}{C_hR_h}(T_{in}-T_h)dt + \sigma_h d\omega_h \qquad \text{Eq. 25}$$

Together to these equations, steady state equations are used to calculate intermediate nodes which have no C assumed, based on Eq. 26.

$$\phi_{ij} = \left(T_i - T_j\right)\cdot H_{ij} \qquad \text{Eq. 26}$$

This procedure can be followed to obtain the balance equation in each node, and the equation system of the model would be defined like this. Then, having data of temperatures, R and C values of the model can be obtained. The equation of measurement would be the following:

$$T_{i,k}^{m} = T_{i,k} + e_k \qquad \text{Eq. 27}$$

Where $T_{i,k}^{m}$ is the temperature calculated by the model, $T_{i,k}$ is the measured temperature, and e_k is the error. A maximum error can be fixed, when R and C values are calculated. R and C values are then calculated by assigned different values for the R and C values, and selecting those which the e_k the minimum one.

This parameter identification procedure was carried out by means of the software CTSM. It is a computer program for performing Continuous Time Stochastic Modelling. The program was developed at Informatics and Mathematical Modelling (IMM) at the Technical University of Denmark (DTU) [93]. Initial approximated parameter values must be establish, and the assumed ranges of variation of them. Then, CTSM starts calculations with those and estimates the adjusted parameters of the statistical model by maximum-likelihood estimation (MLE) The software package LORD, which was developed during the PASLINK projects, can also be used with the same aim. It allows the modelling and identification of thermal systems, in particular building components

[94]. In this case, LORD estimates parameters by means of least squares method. More details about the used method can be found in [92].

Briefly explained, CTSM calculated the characteristic parameters of the defined model, by means of minimizing the error. Based on the balance equation previously presented, the software calculates the characteristic parameters (H and C of every element). For it, some input data must be provided to the software. Those data are the data obtained in the monitoring period: heater temperature, Power, indoor temperature, solar radiation, temperature of indoor and outdoor surfaces of the wall and windows, temperature of ceiling and floors and outdoor temperature. These input data is presented in detail in the following section.

5.2 Used data to obtain characteristic parameters

According to the previous description, *x* corresponds to excitements of the system (heat input P, solar irradiation and outdoor temperature); *y* corresponds to system variables (temperatures and heat fluxes) whereas $f_{(x)}$ is associated to the parameters which define the thermal properties of the model (heat capacity and resistance/conductance). They are depicted in Fig. 6. 13, where *x* are marked in a red line, *y* are marked in a blue line and the parameters which define $f_{(x)}$ are marked in green.

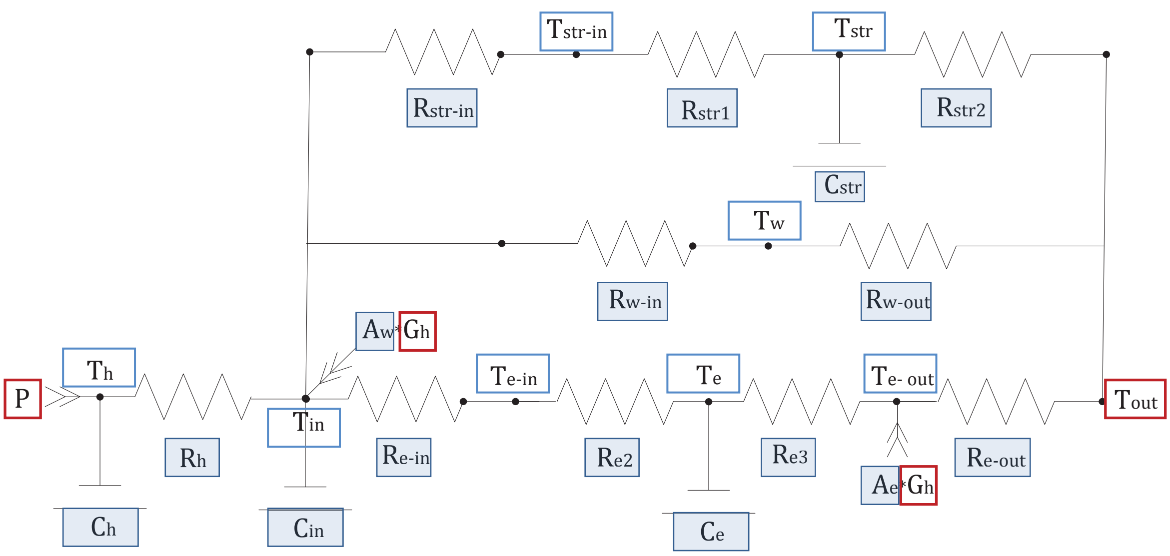


Fig. 6. 13. RC network of the developed model, with different highlights for its *x*, *y* and $f_{(x)}$

It must be noted that the power is marked as an excitement of the system. In fact, it depends on the treatment given to the heat input in the model. There are two possibilities of introducing the heat input into the model. The first one is to introduce the heat power as a predefined value, with a predefined routine. In this case, heat power works as an independent variable. The second one is to introduce it as a dependent variable which depends on the indoor air temperature in the previous time-step (representing a heating system heat point). In this way, heat input acts as a dependent variable which at the same time, affects another independent variable, i.e. indoor air temperature. Both alternatives of treating the heat input are possible within this model.

Based on the schemes depicted in Fig. 6. 2, the followed methodology can be defined as a composed procedure. Thus, parameter identification (inverse procedure) was firstly carried out using measured data. This way, characteristic parameters of the model (thermal capacities and resistances) were obtained, by CTSM. Secondly, once x and $f_{(x)}$ are known, direct use of the model is made to verify the model first, and then to make simulations under different given conditions.

The development of this model was based on data which were collected during a series of experiments carried out in February to May 2012 in a Social dwelling in Bilbao. The study-case monitoring has been thoroughly described in Chapter 4. Specifically, data obtained from 1st of February to 21st of February 2012 were used in the first step to define the model. The following data series were used:

Independent variables x (excitements of the system)

- G_h is the observed irradiation at the climate station
- T_{out} [ºC] represents outdoor temperature
- P [W] represents the power of the heater

Dependent variables y (system variables):

- T_{in} [ºC] is a single value representing indoor temperature which is obtained from the different indoor temperature measurements, measured by PT100 hanging freely in the middle of each room of the dwelling, as explained in Chapter 4. It is the average indoor temperature.

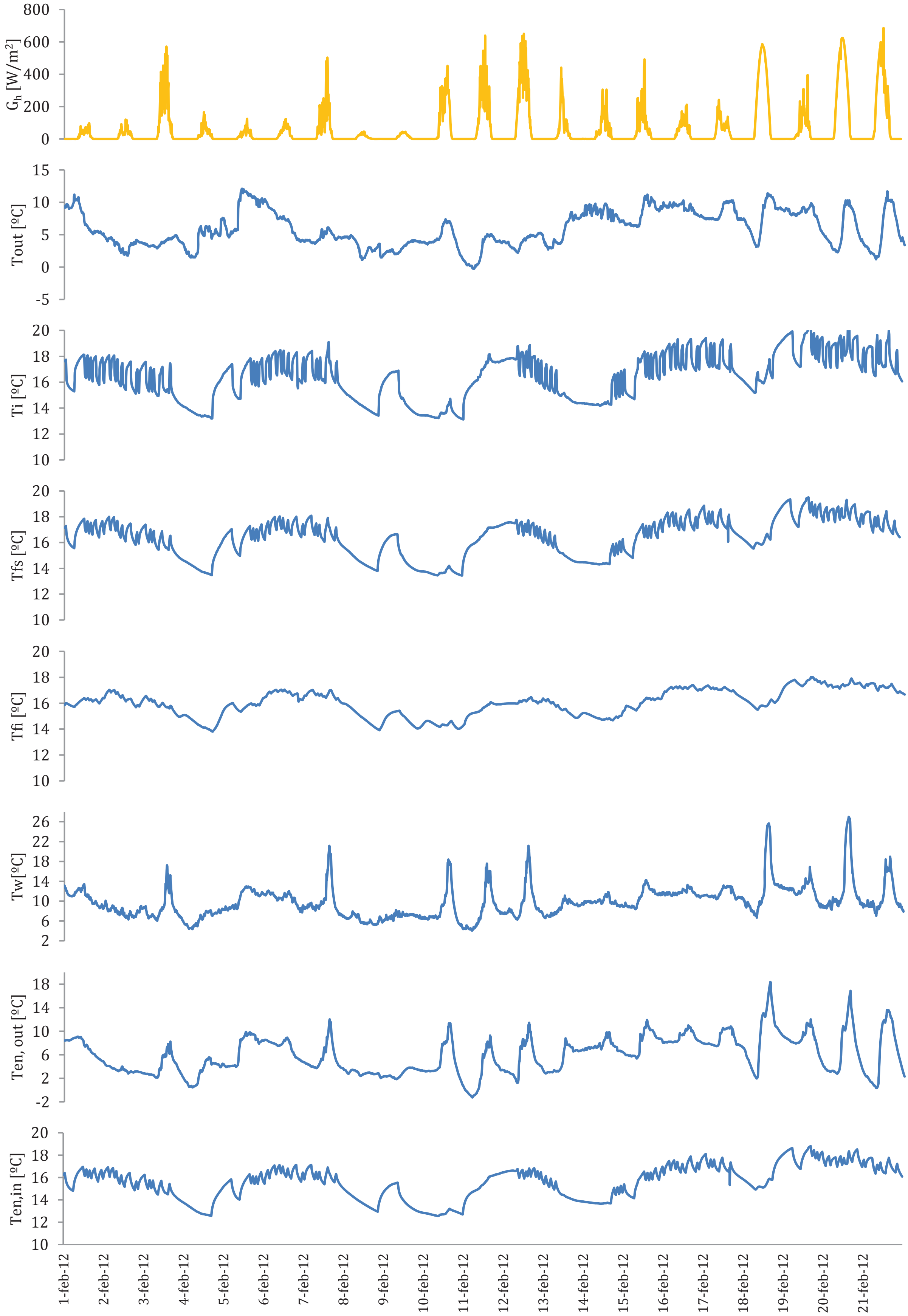


Fig. 6. 14. Some plots of the data used for defining the grey box model (1st -21st Feb 2012)

- $T_{str\text{-}in}$ [ºC] are the average surface temperature of indoor floor, ceiling and pillars.
- T_w [ºC] is the average temperature obtained from temperature sensors placed in windows.
- $T_{e\text{-}in}$ and $T_{e\text{-}out}$ [ºC] is the average temperature obtained from temperature sensors placed in indoor and outdoor surface of façade. Two different averages were calculated, corresponding to the indoor and outdoor surface temperatures.
- T_h [ºC] is the average temperature obtained from temperature sensors placed in the heaters.

Wind velocity was measured as well. However, due to the low values logged during the monitoring period, it was not considered as a significant parameter. Plots of the collected data used to define the model of the building previous to renovation are depicted in Fig. 6. 14.

5.3 Lumped parameters model obtained for studied dwelling

Characteristic parameters obtained by CTSM for the model before windows replacement are presented in Table 6. 1. These characteristic parameters contain information based on physical knowledge and stochastic information of the data measured in the monitoring period. Then, in a certain manner, they can be analysed assigning them a physical meaning. Let's focus on windows, for instance. Windows were represented by two resistors ($R_{w\text{-}in}$ and $R_{w\text{-}out}$). $R_{w\text{-}in}$ equals 0.004 K/W. Taking into account that the total window area in the dwelling is 11.5 m^2, it can be affirmed that that $R_{w\text{-}in}$ equals 0.046 m^{2}K/W. For calculating U-value, standard internal surface thermal resistance value of 0.13 m^{2}K/W and standard external surface thermal resistance value of 0.04 m^{2}K/W are assumed. Its sum equals 0.216 m^{2}K/W, which corresponds to a U-value of 4.62 W/ m^{2}K. Taking into account that this value also "includes" the repercussions of other hidden effects of the dwelling, it can be assumed as logical (In TRNSYS, an U-value of 4.12 W/ m^{2}K was assumed).

However, values obtained in that way are only a reference, and this analysis must be taken with caution, since, as mentioned above, characteristic parameters are not purely based on physical knowledge, but on stochastic methods as well. Therefore it is not possible to share out and distinguish the weight of each part in the value as it depends on the detail level of the model, amongst other factors.

	C [MJ/K]	H [W/K]		R [K/W]		R_{TOTAL} [K/W]
Structure	29.411	Hstr,in	820	Rstr,in	1/820	0.558
		Hstr,1	1191	Rstr,1	1/1191	
		Hstr,2	1.8	Rstr,2	1/1.8	
Windows	-	Hw,in	305	Rw,in	1/305	0.007
		Hw,out	255	Rw,out	1/255	
Opaque walls (envelope)	1.975	He,in	1259	Re,in	1/1259	0.007
		He,2	338	Re,2	1/338	
		He,3	338	Re,3	1/338	
		He,out	1679	Re,out	1/1679	
Heater	0.001	Hh,1	15.5	Rh,1	1/15.5	0.06
Indoor air	0.667	-				
A1: 3.1 m^2 ; A2: 8.66 m^2						

Table 6. 1. Characteristic parameters of the model (before energy renovation)

6 How the model RC works

Once the model parameters have been defined, a model data is implemented, and it is ready for doing simulations. The model was designed to calculate heating consumption, as well as the different element temperatures, depending on the climate conditions, operating conditions, and possible improvements of the model parameters. That is, this RC model can be used with two different aims:

- On the one hand, this model allows the calculation of the monitored dwelling/building under given conditions, and then to modify those conditions (thermal resistance of façade, of windows, thermal capacity…) in order to assess the effects of different possible renovation measurements on the studied dwelling;
- On the other hand, this model allows the calculation of energy savings achieved by a specific energy renovation, by means of a monitoring study before and after renovation works. Characteristic parameters of the two

scenarios can be obtained, and then, by comparing them, it is possible to calculate and obtain the real effect of the renovation which has been carried out. One of the advantages of this methodology is that the model faithfully represents the real building performance of both scenarios, and not only the theoretical improvement, i.e. if windows have been installed incorrectly in a window replacement, and due to this wrong installation, infiltration rate increases, this "hidden" effect will also be considered by the model, giving then the building performance "as built", and not "as projected".

A detailed description of the calculations carried out by the model to obtain the mentioned results is presented in this section.

6.1 Model inputs

Outdoor temperatures and solar irradiation (G_h) for each time step are introduced in the model as inputs. Heat input is now defined not as a fixed value, but as a conditional one depending on indoor temperature. A setpoint temperature must be defined, as well as the heating power. In this way, heating consumption for a year can be obtained for the dwelling in each model.

6.2 Model outputs

As mentioned before, the results obtained for each time step are the average temperatures of the different elements measured during the study, i.e. indoor air temperature, heater temperature, indoor surface temperature of façade, façade temperature, outdoor surface temperature of façade, window temperature, indoor surface temperature of structure. Besides, since heat input from the heater depends on the defined setpoint, and then, on the indoor air temperature, annual heating consumption is also calculated by the model.

6.3 Calculations

From mentioned input data, model calculates the temperature of the eight referent points (see Fig. 6. 12). Governing equations for each point are defined as follows. The first four values (T_{in}, T_h, T_{str}, T_e) are calculated by means of the energy balance in each point for each time step. That is, the sum of the inputs and outputs in a point must be equalled to 0. Then, the other four temperature values ($T_{e\text{-}out}$, $T_{str\text{-}in}$, $T_{e\text{-}in}$, T_W) are calculated as described in the following equations, using as reference Eq. 12.

6.3.1 Indoor air temperature (T_{in})

Indoor air temperature is calculated by means of the energy balance in this node. As observed in Fig. 6. 13, indoor air node is affected by the following heat fluxes: solar gains (A_iG_h), heat flux from the heater, heat flux through the structure, heat flux through the opaque walls and heat flux through the windows. These heat fluxes entail a temperature variation. Thus, energy balance in the indoor air node is defined in Eq. 28.

$$0 = C_{in} \cdot \frac{(T_{in} - T_{in,-1})}{\Delta t} - (T_h - T_{in}) \cdot H_h + (T_{in} - T_{str,in}) \cdot H_{str,(in,1)} + (T_{in} - T_e) \cdot H_{e,(12)} + (T_{in} - T_{out}) \cdot H_w - A_i \cdot G_h + Losses_{Vent} \qquad \text{Eq. 28}$$

The balance presented in Eq. 28 is made up of seven different terms: power associated to temperature variation, heat flux from the heater, heat flux through the structure, heat flux through the opaque envelope, heat flux through the windows, heat flux due to solar gains and ventilation heat losses, respectively.

$H_{str,(in,1)}$ and $H_{e,(12)}$ refer to the result of having two resistances (or H, the inverse of R) in series ($H_{str,in}$ and $H_{str,1}$, and $H_{e,1}$ and $H_{e,2}$, respectively). They are calculated as follows:

$$H_{i,(12)} = \left(\frac{1}{H_{i,1}} + \frac{1}{H_{i,2}}\right)^{-1} \qquad \text{Eq. 29}$$

Ventilation patterns have a great influence in the final heating demand of a dwelling. So, an estimation of ventilation losses was also included in the model as a term of the equation. It is calculated as defined in Eq. 30.

$$Losses_{Vent} = \frac{n}{3600} \cdot V \cdot \rho \cdot C_p \cdot \Delta T_{-1} \qquad \text{Eq. 30}$$

Where $Losses_{Vent}$ are the losses due to ventilation (or gains, if the result is a negative value), n is number of ACH, V is air volume in the dwelling (m^3), ρ is air density (1.225 kg/m^3 is assumed), C_p is the air heat capacity (1007 J/kg.K is assumed) and ΔT_{-1} is the difference between outdoor and indoor temperatures in the previous time step.

6.3.2 Heater temperature (T_h)

Heater temperature is calculated following an analogous method. This node is affected by two fluxes: power (which is an input in the model) and heat flux from the heater to indoor air node. Then, governing equation in the heater node is presented in Eq. 31.

$$0 = C_h \cdot \frac{(T_h - T_{h,-1})}{\Delta t} - P + (T_h - T_{in}) \cdot H_h \quad \text{Eq. 31}$$

6.3.3 Temperature of structure indoor surface (T_{str})

The node which represents the structure indoor surface (T_{str}) is affected by two fluxes: heat flux from the indoor air node and heat flux to outdoor air node. Thus, the balance in this node is presented in Eq. 32.

$$0 = C_{str} \cdot \frac{(T_{str-in} - T_{str-in,-1})}{\Delta t} - (T_{in} - T_{str-in}) \cdot H_{str(in,1)} + (T_{str-in} - T_{out}) \cdot H_{str,2} \quad \text{Eq. 32}$$

6.3.4 Envelope temperature (T_e)

The temperature in the envelope node is also calculated by a balance in the node. Four terms are considered when the balance in this node is calculated: power associated to temperature variation, heat flux from the indoor air node, heat flux to outdoors and heat flux due to solar gains and ventilation heat losses. It is presented in Eq. 33.

$$0 = C_e \cdot \frac{(T_e - T_{e,-1})}{\Delta t} - (T_{in} - T_e) \cdot H_{e,(in,1)} + (T_e - T_{out}) \cdot H_{e,(2,out)} - A_2 \cdot G_h \quad \text{Eq. 33}$$

6.3.5 Temperature of envelope outdoor surface ($T_{e,out}$)

Once the four temperatures previously mentioned have been obtained, the other node temperatures can be calculated from them, as mentioned before. Thus, the temperature of the envelope outdoor surface is calculated by means of Eq. 34, known T_e and T_{out}.

$$T_{e,out} = \frac{(T_e \cdot H_{e3}) + (T_{out} \cdot H_{e-out}) + (A_2 \cdot G_h)}{(H_{e3} + H_{e-out})} \quad \text{Eq. 34}$$

6.3.6 Structure temperature (T_{str})

The same procedure is used to calculate the temperature in this node, as presented in Eq. 35.

$$T_{str} = \frac{(T_{in} \cdot H_{str-in}) + (T_{str-in} \cdot H_{str1})}{(H_{str-in} + H_{str1})} \quad \text{Eq. 35}$$

6.3.7 Temperature of envelope indoor surface ($T_{e,in}$)

$$T_{e,in} = \frac{(T_{in} \cdot H_{e-in}) + (T_e \cdot H_{e2})}{(H_{e-in} + H_{e2})} \quad \text{Eq. 36}$$

6.3.8 Windows temperature (T_w)

$$T_w = \frac{(T_{in} \cdot H_{w,in}) + (T_{out} \cdot H_{w,out})}{(H_{w,in} + H_{w,out})} \quad \text{Eq. 37}$$

6.3.9 Heat power (P)

As mentioned before, heat input is an input of the model. Heat input can be defined in two different ways. On the one hand, a fixed heat power routine can be assumed. Then, the output of the model would be the calculated temperatures at each node and in each time step. On the other hand, heat input can be introduced as a function of indoor air temperature, introducing an hourly schedule with the setpoint temperature.

7 Model validation

As defined amongst others by Whisler et al. in [95], model validation might be defined as a *"comparison of the predictions of a verified model with experimental observation other than those used to build and calibrate the model and identification and correction of errors in the model until it is suitable for its intended purpose"*. Although this definition was actually developed for crop simulation models, it is also applicable to models in general and to building models in particular.

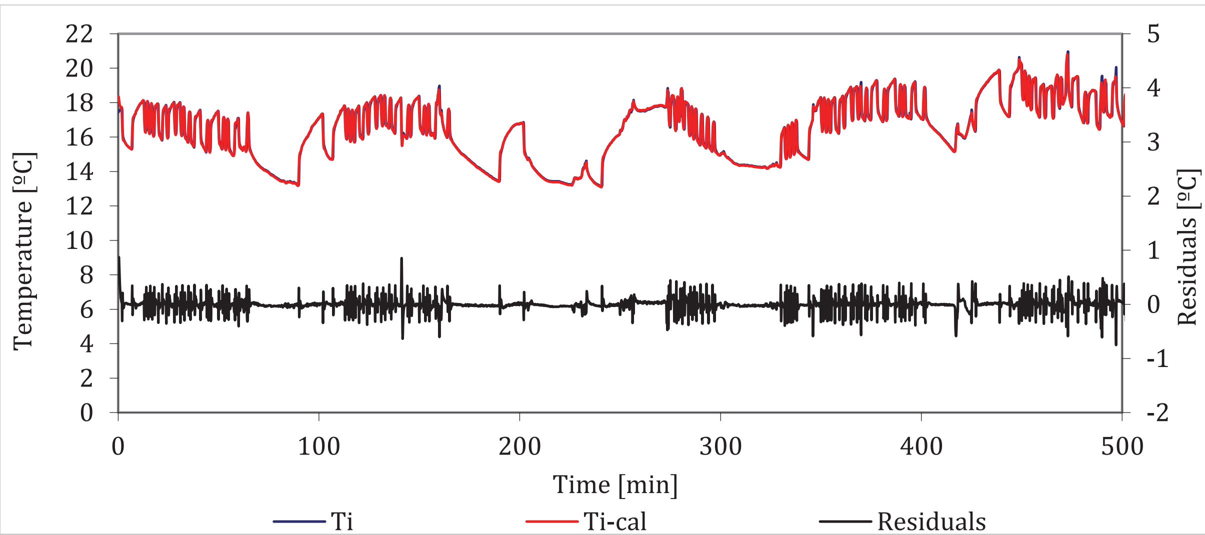


Fig. 6. 15. Indoor temperature calculated (red) Vs. observed (blue), and residuals (black)

Bearing in mind this general definition, a comparison between calculated values of the model and those obtained in the experimental observation was carried out, with the help of C. Escudero (Laboratory for the Quality Control in Buildings, Basque Government). A graph with both sets of data, as well as the residuals is depicted in Fig. 6. 15. As observed in a first sight, obtained residuals were very low values and around zero.

The autocorrelation function (ACF) and integrated periodogram of the residuals were obtained using *Statgraphics* software, in order to verify that residuals presented a random pattern related to white noise of measuring instrumentation. Thus, the analysis of ACF of residuals of indoor air temperature is depicted in Fig. 6. 16. It was evaluated at a maximum lapse of 50 h. Analysis showed that coefficients took low values, close to zero, alternately, without a defined pattern. This performance means the dwelling thermal performance is correctly represented by the model.

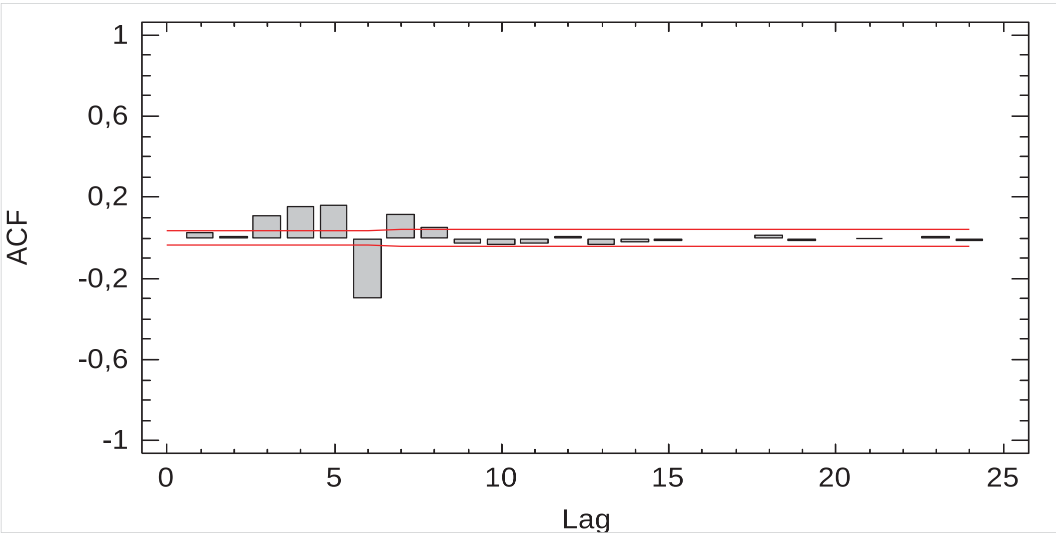


Fig. 6. 16. Autocorrelation Function (ACF) of residuals

Similar conclusions were obtained when the integrated periodogram of residuals shown in Fig. 6. 17 was checked. In this analysis, an ideal time serial purely at random would present cumulative relative amplitudes for each frequency which would draw a diagonal straight line. The Kolmogorov-Smirnov test (K-S test) was used to determinate if both data sets differed significantly. Confidence intervals for 95% and 99% certainties are presented in the aforementioned mentioned graph in red line (inside and outside, respectively). The obtained periodogram showed noticeable deviations from the diagonal line, showing that there was an autocorrelation. However, since it was amongst the confidence intervals, it can be assumed that those correlations were low and therefore they could be neglected.

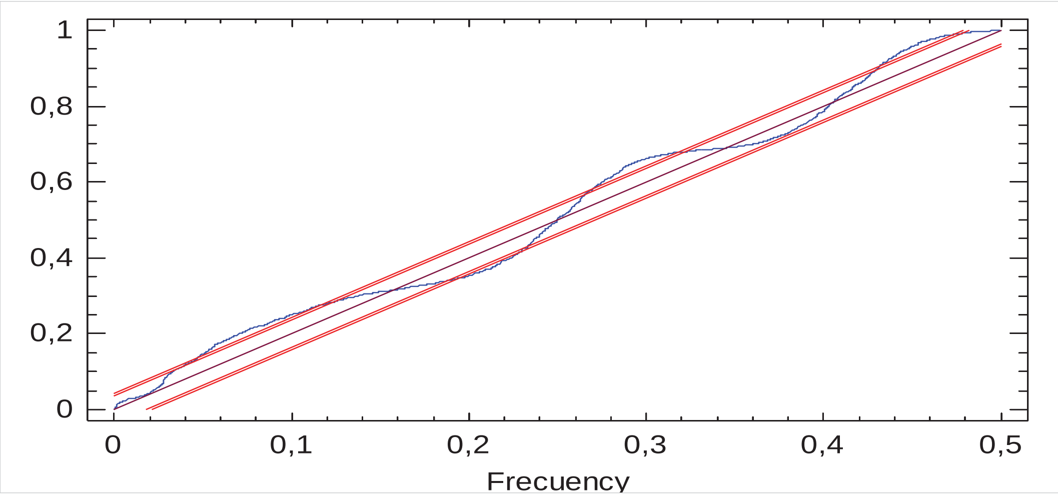


Fig. 6. 17. Cumulated periodogram of residuals

In short, it can be affirmed that the model represent in a proper way the real thermal behaviour of the dwelling. More detailed information about this validation procedure was presented in the 8th National Congress of Engineering Thermodynamics held at Burgos University in June 2013, and it can be found in [92].

8 Results of the model

In this section, the RC model of the dwelling (before renovation) is used as a way of example to obtain the potential energy savings obtained by means of windows replacement, in a similar way to what it has been presented in Chapter 5 with the TRNSYS model. Thus, a comparison between both models and an evaluation of the differences of the obtained results can be carried out.

8.1 Results of the model before carrying out the windows replacement

Even though the RC model presented in this chapter differs significantly to the TRNSYS model developed in the previous one, similar operating conditions were assumed, in order to make the comparison between both models easier. Thus, operating conditions and weather data assumed for this model are presented in this subsection, based on those presented in previous chapter for TRNSYS model.

8.1.1 Operating conditions

8.1.1.1 Ventilation and infiltration

Ventilation rates assumed in this model were the same to those introduced in the TRNSYS model, and specifically presented in section "*5.1. Air Infiltration and Ventilation*". Thus, the assumed schedule for ventilation was a daily ventilation rate of 4 ACH from 7-8 am.

On the other hand, the characteristic parameters of grey box model include, in an implicit way, the infiltration losses existing in the dwelling. For that reason, infiltration rate is not an input in this model.

8.1.1.2 Setpoint temperatures

In a similar way, setpoint temperatures used in field study - based TRNSYS model was used for this model. They are presented in the following:

- 0-8 am: -
- 8 am-6 pm: 17 ºC
- 6-11 pm: 20 ºC
- 11-12 pm: 17 ºC

8.1.1.3 Heating power

Unlike the TRNSYS model, the output of this RC model is not energy demand, but energy consumption. Heat inputs work according to the aforementioned setpoint temperatures. Due to the model definition, it is an on-off system, and no modulation of the heat input is possible. When a given time-step presents an indoor air temperature lower than that set in the setpoint temperatures schedule, heat input is activated, with a previously fixed value. This value was assumed as 3500 W.

8.1.1.4 Internal gains

The developed RC model does not include the possibility of setting internal gains as an input.

8.1.2 Weather data

The only weather data required in this RC model is the outdoor temperature and the global solar irradiation. In order to make the comparison between results of this model and those obtained with TRNSYS model easier, the required weather data were obtained from the weather file of Bilbao (Meteonorm Data Base), which was already used in TRNSYS simulations presented in Chapter 5.

8.2 Modification of the model parameters to evaluate the improvement of the windows replacement

As already mentioned in this chapter, characteristic parameters of the model (R and C values) were calculated using a combination of prior physical knowledge (e.g. equations of heat transfer in solids) and statistics. Therefore, information contained in each parameter is a combination of both physical laws (the part of the model which is known) and statistics (that part of the model which explains and fits the unknown issues). In this way, a physical interpretation can be made of the above mentioned parameters, and consequently, they can be modified in order to evaluate other possible scenarios.

Since this case is addressed to assess the effect of windows replacement, this subsection is only focusing on the windows branch.

As presented in Chapter 5 in table 5.2., old windows presented a U_{frame} equal to 5.7 W/m^2 K and a U_{glass} equal to 3.44 W/m^2 K. Taking into account the fact that the frame represented 30% of the windows total area, $U_{w,1}$ (before renovation) was 4.12 W/m^2 K. Following the same calculations, the value of the new windows ($U_{w,2}$) equalled 2.76 W/m^2 K. That is, windows U-Value improved 1.36 W/m^2 K. Only $H_{w,1}$ was modified to represent the windows replacement in the model. Its modification was calculated as follows.

As explained in section 5.3, H [W/K] is a characteristic parameter and is the inverse of R [K/W]. Mentioned new U-Value of 2.76 W/m^2 K implies a new resistance equal to 0.3623 m^{2}K/W. Bearing in mind the fact that the U-Value is calculated based on the standard internal surface thermal resistance value of 0.13 m^{2}K/W, and the external surface thermal resistance of 0.04 m^{2}K/W, it can be deduced that the global thermal resistance of the windows equal to 0.19231 m^{2}K/W (internal and external surface thermal resistance must be summed to this value). The total windows area of the dwelling is 11.5 m^2, so the total R of the new windows is 0.0167 K/W. Since windows were defined by two resistors ($R_{w,in}$ and $R_{w,out}$) and $R_{w,out}$ was calculated as a characteristic parameter with the value of 0.0033 K/W ($H_{w,out}$=305), the new $R_{w,in}$ equals 0.0134 K/W. Then, new $H_{w,in}$ can be calculated, obtaining a value of 75 K/W.

8.3 Comparison between both models

Results obtained with this model are presented in this section. The analysis of the results was focused mainly on savings percentages obtained after windows replacement.

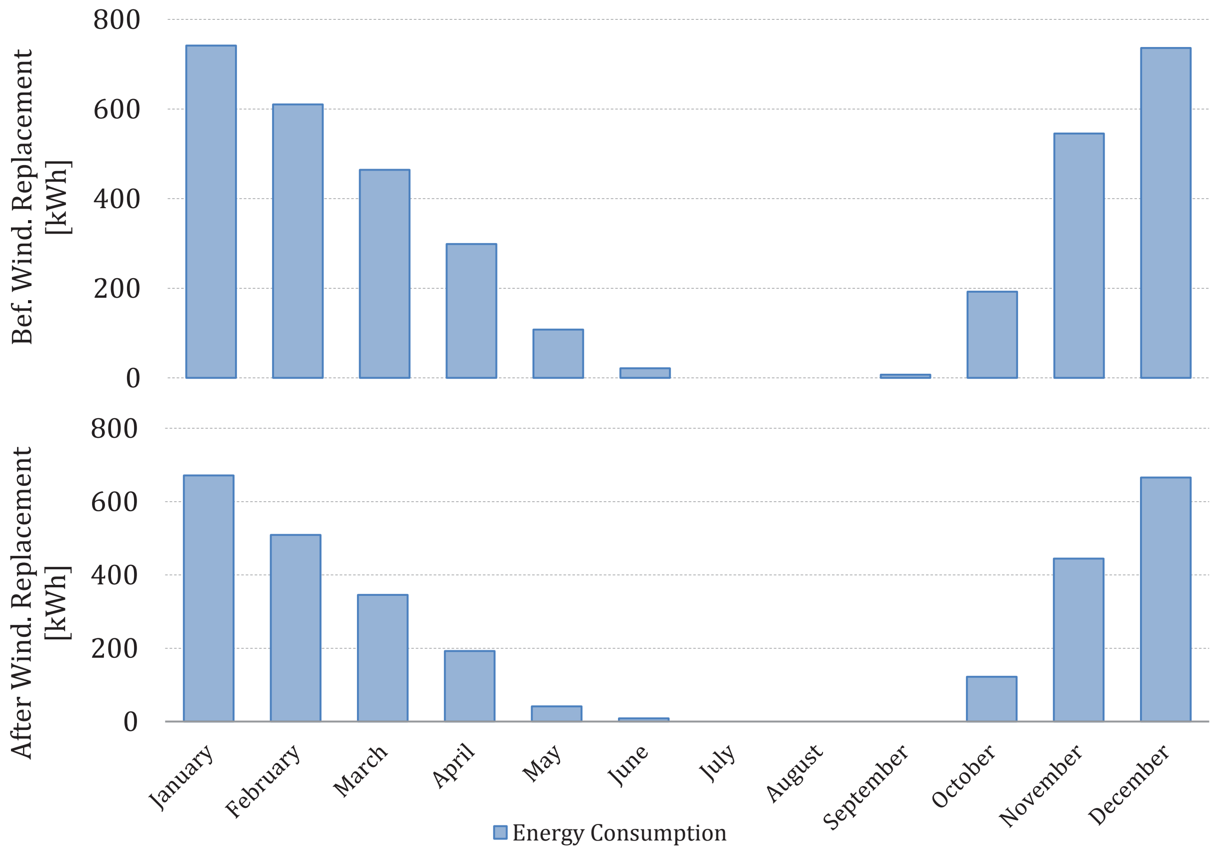


Fig. 6. 18. Energy consumptions obtained by the RC model for both scenarios

As expected, energy consumption results gave significantly higher values than those obtained with the TRNSYS model. This lack of fit between both models is explained mainly due to the following reasons:

- Internal gains were assumed in the TRNSYS model, unlike in the RC Model.
- The TRNSYS model calculated the energy demand of the dwelling, whereas the RC model calculated energy consumption using an specific heating system (a 3500 W electric radiator, not adjustable to intermediate power values,

which was activated every time-step when the indoor air temperature was lower than the setpoint temperature).

- Temperatures assumed in adjacent dwellings also can play an important role in the results. Thus, whereas in the TRNSYS model an assumption of adjacent dwellings temperatures had to be made, the RC model includes implicitly in its definition that statistical information, assuming those patterns (indoor temperatures as function of outdoor temperatures, G_h and heat input, which indirectly includes losses to adjacent dwellings) in its structure.

Although absolute values cannot be directly compared, interesting conclusions were obtained when relative values of energy savings were compared. It was shown in the previous paper that, even though changing operating conditions obviously affected to absolute values of final results, relative values of energy savings were similar. Therefore, this condition was also expected to be fulfilled in this RC model, and similar energy savings relative values were expected to be obtained.

However, relative energy savings obtained with this model were not similar when its yearly values were compared with those obtained by TRNSYS model. For that reason, energy savings were assessed more in detail, and monthly energy saving values obtained by the three carried out simulation sets (one using RC model, two with TRNSYS, assuming two different operating conditions) were analyzed. Thus, the percentages of monthly energy savings obtained by the three mentioned simulation sets are presented in Fig. 6. 19. The figure also graphs in a red line, the difference between monthly results obtained with the RC model and TRNSYS model with field study - based operating conditions.

Analysis of calculated energy savings showed two different trends, as shown in Fig. 6. 19. Obtained results for four months (November, December, January and February) can be assumed as very similar in the three simulations, and especially, in the RC model and TRNSYS model with field study – based operating conditions, both of them defined with similar operating conditions. On the other hand, results obtained with the RC model for the rest of the heating season differed significantly to those obtained with any of the two TRNSYS models.

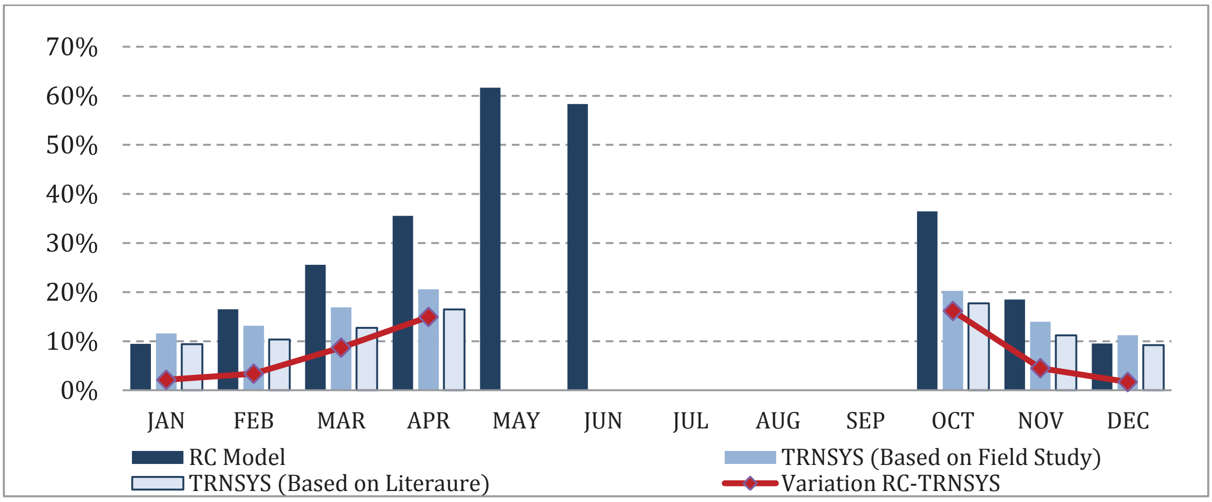


Fig. 6. 19. Percentage of energy saving obtained by the carried out different simulations

This effect is explained by taking into account the way that solar gains are included in the RC model. As mentioned in the first part of this chapter, unlike the equation of heat transfer in solids, equation of radiation is not lineal, and therefore, linear dynamic models are not capable of modelling it, and linear approximations are used to model this heat transfer mechanism. In this model, the so called effective area was used with this aim, as described in section 4.1.1. This term sets a constant value based on the relation between observed G_h and heat gains at the outdoor surface of the façade, as well as solar gains through the windows.

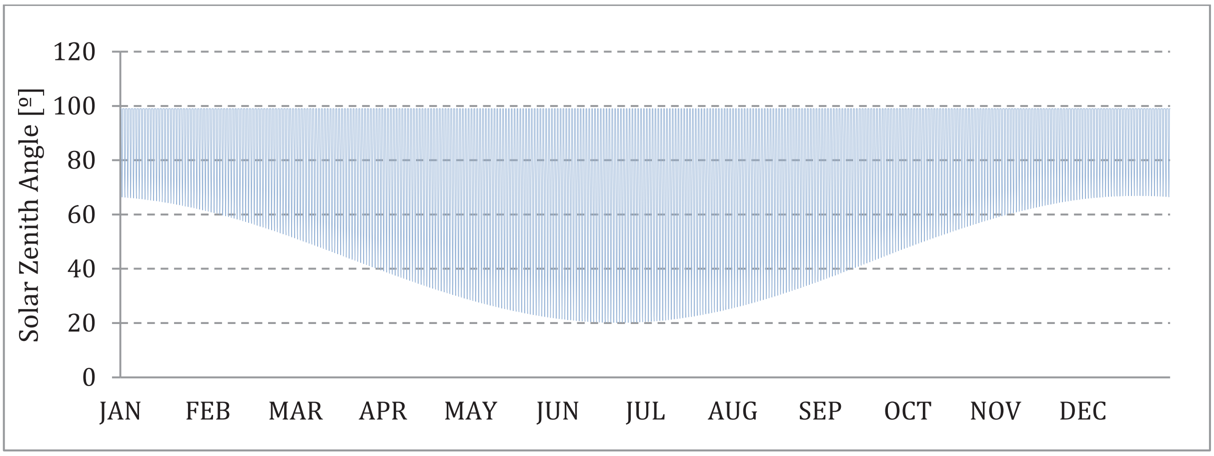


Fig. 6. 20. Solar zenith angle in Bilbao during the whole year

As also explained in this chapter, characteristic parameters of the model (effective window and wall areas, amongst them) were calculated using observed data in February. However, whereas G_h was used as a reference value (since it is usually available), solar gains are directly related to G_v in the case of the reference dwelling, since both façade and windows are vertical, and relation G_h-G_v is not a constant during the whole year, and depends on the solar zenith angle, which varies significantly during the year, as shown in Fig. 6. 20.

This fact is easily shown with an example. Consider two opposite moments of the year, mid day of 21st of December, and mid day of 21st of June. Zenith angles in Bilbao for those hours are 67.39º and 21.78º respectively. Based on these values and by means of a simple trigonometric relation, G_h and G_v of an hypothetical assumed value of 500 W of direct solar irradiation are presented in Table 6. 2.

	Zenith [ºC]	Direct Solar irradiation [W]	Gh [W]	Gv [W]	Gh/Gv [-]
December, 21st	67.39	500	192.23	461.57	0.42
June, 21st	21.78	500	464.31	185.52	2.50

Table 6. 2. Differences on ratio Gh/Gv in winter and summer

The disparity of values explains the lack of fitness between TRNSYS models and RC model results, which in this case, are totally distorted. That is, the RC model gives similar values to the TRNSYS model during the months when the solar zenith angle was similar to the monitoring period of the used data (first weeks of February).This is so because the effective area was calculated based on the ratio G_h-G_v with zenith angles of the monitoring period, and then the effective area is actually a simplification which represents the solar gains effect properly. However, the more the zenith angle varies with respect to the monitoring period, the bigger the differences were found in the results of both models. For that reason, energy saving results obtained by this method must be evaluated in monthly periods, for the closest months to the period which data used to define the model were observed.

9 Discussion

9.1 Grey box model

As mentioned in the introduction of this chapter, one of the main advantages of grey box models is the low computational time required to perform a building simulation, in comparison to white box models.

Moreover, the amount of data required to build the model is significantly lower in the grey box model, and they can be obtained through a monitoring study. In this way uncertainties of data used to feed the model are lower and more controlled. Reduction of required data, however, does not affect the quality of the obtained results, since the RC model represents with a high accuracy the studied building or dwelling, as the validation procedure showed.

On the other hand, the main drawback of this kind of models is its low flexibility. The model represents a given case study with great accuracy, but characteristic parameters are only applicable to that case study. To represent another building, new monitoring and new characteristic parameters must be calculated. Even two buildings with exactly the same construction, will have different characteristic parameters if any tiny change involves any modification of their solar gains, for example. This is due to the fact that solar gains are not governed by a linear equation, and the effects of them are included in the model not based on physical knowledge, but based on statistics.

It has been shown that solar gains can lead to significant mistakes when periods different to the monitored one are evaluated, as shown before.

Besides, if this model can be adequate to evaluate the thermal performance of the building according to its passive elements (envelope, solar gains...), its low flexibility makes it difficult to evaluate complex heating systems.

Thus, based on everything said above, It can be assumed that RC models are suitable when a specific building is studied for a specific period of the year (e.g. winter period), and no complex heating systems are considered.

9.2 TRNSYS model

Flexibility is one of the main pros of the TRNSYS model, both in any kind of tiny modifications in the building (including those which affects to solar gains) and, moreover, in the aspect of the active elements of the building, especially when the heating systems become more complex. Moreover, being a white box model, no experimental data of the case study is required to build the model and data for the different elements encompassed by the model can be fulfilled based on literature and existing databases.

At the same time, this is the main drawback of TRNSYS: the amount of information required to build a model, which usually involves assuming simplified values, which can increase the uncertainty of the model. This aspect can be more or less controlled in the case of systems and installations in general, where their standardized production and tests allow having quite adjusted and accurate values. However, in the case of construction elements, where the "handmade" component still has a strong presence, thermal performance of the envelope not only depends on thermal characteristics of used materials, but also on the way it was built. This issue means that similar construction elements can present significant differences on their thermal performance, depending on the way they were built. This situation is even greater in the case of renovations, since the older a building is, the higher the uncertainty is.

10 Conclusions

This chapter has described the development of a RC model and it has shown its usefulness to represent the thermal performance of the chosen reference building accurately, using experimental data obtained in a previous monitoring study.

It can also be used to calculate reference values of savings related to different energy renovation strategies in the specific building studied, this is done by means of modifying some characteristic parameters properly, based on their physical meaning, such as it has been presented in section 8.2 of this chapter. However, results obtained in this way must be used with caution, since these changes in characteristic parameters can introduce a great level of uncertainty into the model.

Thus, the strongest point of this kind of models is its accuracy to represent the real thermal performance of a specific building when characteristic parameters are obtained from experimental data. Obtained results give information of the building as actually built, taking into account all the interactions and all specific details of the construction, not only based on data “as projected” but on theoretical project data. For that reason, one of the main potential uses of this model is to evaluate the real effectiveness of any energy renovation measure carried out in a given building. It allows obtaining the real energy savings, through the characteristic parameters based on data gathered before and after the carried out energy renovation.

The use of an effective area to introduce solar irradiation is a proper simplification which does not affect the accuracy of results significantly. However, it must be taken into account that the obtained effective area is only representative of the period close to the season when data used to calculate the effective area was gathered. For that reason, working with monthly values instead of yearly values is recommended when the RC model is used.

As far as the detail of results is concerned, the RC model defined in this chapter is a middle way between the Co-heating method (presented in Chapter 4) and TRNSYS model, which is much more detailed.

Besides, in this third part of the thesis, two different kinds of models have been presented and developed to represent the thermal performance of the chosen reference dwelling. Both methods were built and adjusted based on experimental data, and both of them allow the thermal characterization of the reference dwelling to be obtained. Moreover, this aspect allowed the TRNSYS building model and the RC model to be compared.

Thus, this chapter has shown the advantages of each model. As far as the RC model is concerned, it must be noted its lower computational times, and its accuracy to define a dwelling as actually built. The flexibility and its capacity of simulating energy systems more in detail are the main advantages of TRNSYS. Moreover, in the case of the TRNSYS model experimental data is not necessary, and the bibliography and existing databases can provide the required data, even though it would be advisable to use experimental data to validate and adjust the model. Hence, the most suitable model in each case depends on the sought targets and the characteristics of the available information, and it must be chosen according to those criteria

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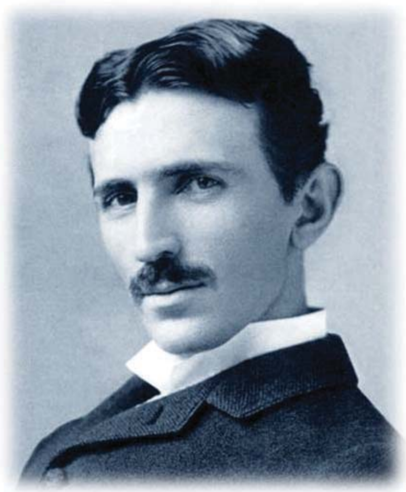
PART 4
SIMULATIONS

"Throughout space there is energy, (...) and it is a mere question of time when men will succeed in attaching their machinery to the very wheelwork of nature."

Nicola Tesla (1856-1943)



CHAPTER 7

DYNAMIC SIMULATIONS. STRATEGIES TO REDUCE ENERGY CONSUMPTION IN BUILDINGS

RESUMEN

En este capítulo se presentan los ahorros energéticos alcanzados a través de posibles mejoras tanto en la envolvente del edificio como en las instalaciones. Las diferentes medidas propuestas son evaluadas bajo criterios económicos, energéticos, medioambientales y de confort. El estudio presentado en este capítulo fue llevado a cabo a escala de vivienda, usando la vivienda de referencia presentada en el capítulo 4 de esta tesis como caso base. En una primera parte, las simulaciones muestran los resultados de 64 posibles combinaciones de medidas de ahorro energético en la envolvente del edificio. Después de elegir una de las combinaciones evaluadas, se presenta el impacto de distintas estrategias de control en el consumo energético y el confort interior.

ABSTRACT

In this chapter, energy savings achieved by means of possible enhancements of both building envelope and heating systems are presented and calculated by TRNSYS simulations. The different proposed measurements are evaluated under economic, energy, environmental and comfort criteria. The study presented in this chapter was carried out in a dwelling scale, using the reference dwelling as a base case. Firstly, the results of 64 possible combinations of energy savings measurements of the building envelope are shown. After choosing one of the evaluated combinations, the impact of different heating control strategies on the final energy consumption and indoor comfort are presented.

1 Introduction

In the previous chapters, the developed models have been presented mainly to check the energy efficiency of certain energy renovation actions. Thus, detailed analysis before and after energy renovation allowed checking the actual improvement.

However, other of the main potentials of building modelling is to evaluate energy renovation possibilities for a specific building and, amongst all of them, selecting the optimal according to some defined criteria (energy, economic, comfort…). According to it, in this chapter the effectiveness of the developed dynamic models (namely, the TRNSYS model) for assessing the effects of several actions to improve energy performance of the building is presented.

Besides, the validated TRNSYS model, along with the simulations presented in this chapter, will be used in a future in the Energy System Plant (mentioned in Chapter 2), which allows testing different systems and control strategies for building installations, combining simulation and experimental procedures.

Energy savings measures (ESM) in existing buildings can be divided into three categories: energy savings owed to the thermal performance of building envelope (it reduces the energy demand), savings by upgrading heating systems (it reduces energy consumption) and energy savings by supplying the total or part of the energy demand by renewable resources (reducing thus P.E. consumption).

This chapter focuses on two of them. The first part of the chapter is devoted to the improvement of the building envelope, and the second part of the chapter studies the savings by heating systems, namely assessing the influence of different control strategies in the operation of condensing boilers.

As far as improvement of the building envelope is concerned, several references are found in literature, many of them related to insulation materials. A state-of-art in thermal insulation materials was presented in [10] or in [11], where the main characteristics and applications of common building thermal insulation materials are gathered. Energy and exergy analyses for three cases of exterior building walls located in three climatic zones in winter conditions was presented in [96].

As already mentioned in Chapter 1, insulation layer optimization thickness has been thoroughly studied and many references are found, such as [12], where an optimization of the opaque wall was evaluated under energy, economic and environmental approach, [18], where optimum insulation thickness in four different climate zones of Turkey was calculated for four different insulation materials, [97], where the effect of the used fuel type on the optimum insulation thickness was evaluated, [47], which defined optimal thermal insulation strategies by means of dynamic simulations after experimental comparison between 3 different wall constructions, or [15], where a review of the economical and optimum thermal insulation thickness for building applications was presented.

Regarding the analysis of heating systems and their control, not many studies are found. As an example, an optimization of different parameters of the heating system taking into account economic and comfort issues was described in [20], which showed, amongst other things, that the supply-water temperature has a big influence not only on comfort, but also on operating costs. Additionally the importance of the control strategies in the energy performance of condensing boilers was demonstrated in a report published by ESRU [98]. The influence of the control was analysed in other heating applications, as for example [99-102].

2 Objectives of the chapter

Thus, the main target of this chapter is to use the TRNSYS model to evaluate the impact of different renovation actions in the envelope and heating system control strategies on the final energy consumption of the dwelling.

With this aim, a variety of ESM in the selected building are proposed and their effect is assessed, taking into account energy, environmental and economic issues. Moreover, the various interventions according to their significance are classified and those which also offer economic benefits are identified.

Hence, the outcomes would be twofold, on the one hand a flexible methodology is presented which can be adapted and applied to any existing building; and on the other hand, qualitative information is given on the main renovation actions to be carried out in the large existing stock of buildings, working as handbook for architects and engineers.

3 Structure of the chapter

In order to fulfil this goal, the following steps were followed.. Firstly, using the TRNSYS model developed in Chapter 5, different ESM on roof, façade and windows are considered along with all the possible combinations amongst them. Economical, environmental and energy results are studied and analyzed. One ESM is selected, in order to study the influence of heating system control strategies on a retrofitted dwelling. A condensing boiler is considered as it is the most common technology being installed nowadays in Spain for heating purposes.

After defining the case study, different control possibilities are presented, regarding the general control strategy, the thermostat setpoint temperature and the boiler setpoint temperature. A set of TRNSYS simulations is carried out, following the same procedure followed in the analysis of the envelope.

Finally, results of all the combinations are presented and evaluated under both energy and comfort criteria.

4 Suggested retrofitting scenarios. Envelope improvement

Different ESM were laid and studied to improve the building envelope elements. These ESM were addressed to improve the thermal behaviour of windows, roof and/or façade. Four scenarios were assumed for each element: scenario 0, when no improvement is carried out; scenario 1, when a typical improvement is carried out (Business As Usual, BAU); scenario 2, when BAU scenario is slightly improved; and finally, scenario 3, when the best solution is assumed. Resulted models were named according to the combinations of the ESM adopted in each case. Thus, Model 7E.1.2.0 represents Chapter 7, improvement of the envelope, façade scenario 1, roof scenario 2, windows scenario 0. This section briefly describes in what the ESMs of each element of the envelope are about.

4.1 Façade

The improvement on façade thermal behaviour was assumed by means of adding an extra thermal insulation layer (EPS). The addition of this layer was added to the existing one which, as presented in Chapter 5, presented a thermal insulation layer of 2 cm.

Some assumptions had to be made in order to define the cost of each ESM. When economic results and their related financial ratios were evaluated, the assigned cost to façade renovation was not the total cost of the renovation, but the cost corresponding to apply the ESM, i.e. the material and workforce cost corresponding to thermal insulation. This assumption was taken due to the variability and amount of possible façade renovations. Thus, it was assumed that façade has to be renovated in any case (and then, the cost of the base renovation is included as maintenance cost of the building during its lifespan) and just the addition of insulation layer was considered when economic evaluations were carried out. Detailed information about assumed conditions for each ESM in façade is presented in the forthcoming subsections.

- **Scenario 0. Base scenario:** The base scenario of the façade is the original façade without any ESM. The U-value of assumed façade in this scenario was 0.74 $W/m^2.K$. Detailed information about the construction data assumed in the TRNSYS model, as well as its main thermal characteristics, has been presented in the Chapter 5 (Table 5.1.).

- **Scenario 1. BAU:** An addition of 4 cm of EPS on the façade outdoor surface was assumed in scenario 1. Therefore, the U-value of the new retrofitted façade in this scenario 1 was 0.43 W/m^2.K.
- **Scenario 2. Improved Scenario:** In this case, an addition of 6 cm of EPS, also on the façade outdoor surface was assumed. So the U-value of the new retrofitted façade in this scenario 2 was reduced to 0.36 W/m^2.K.
- **Scenario 3. Best energy scenario:** An addition of 12 cm of EPS on the façade outdoor surface was assumed in this scenario. The resulting U-value was 0.24 W/m^2.K.

The main data related to façade ESMs presented above are summarized in Table 7. 1 and Table 7. 2. Cost of each ESM (according to data presented by *Institut de Tecnología de la Construcció de Catalunya*, ITEC [103]) is presented in Table 7. 1. Mentioned cost is presented broken down into 3 items: the cost of the insulation material itself, the cost of other materials required for installation, and the cost of the required workforce. As mentioned before, only the additional cost of adding the specific ESM respect to a usual façade refurbishment without ESM was considered.

Insulation	Cost [€/m^2]			
	Insulation Material	Secondary materials	Labour	Total investment
4 cm EPS	3.68	0.63	2.15	6.46
6 cm EPS	5.51	0.75	2.16	8.42
12 cm EPS	11.01	1.23	2.7	14.94

Table 7. 1. Cost of the studied ESM for façade improvement (ITEC)

ESM in Façade	Addition of EPS in façade			
	Currently	BAU	Improved Scenario	Best Scenario
Scenario	0	1	2	3
Thermal ins, thickness [cm]	2 (+0)	6 (+4)	8 (+6)	14 (+12)
U [W/m^2.K]	0.74	0.43	0.36	0.24
Investment [€/m^2]	-	6.46	8.42	14.94

Table 7. 2. Summary of data regarding to ESMs in façade

4.2 Roof

Analogously to the ESM considered in façade, addition of a thermal insulation layer was used to improve the thermal behaviour of the roof, fibreglass solid sheets, in this case. The same assumptions as those presented for the façade case were made to set the cost of each ESM. Detailed information about assumed conditions for each ESM in roof is presented in the following subsections.

- **Scenario 0. Base scenario:** The assumed base scenario for the roof was the original roof without any ESM, with an U-value equal to 2.7 W/m^2.K. More information about the construction data assumed in the TRNSYS model, as well as its main thermal features, has been presented in the Chapter 5 (Table 5.1.)
- **Scenario 1. BAU:** An addition of 6 cm of thermal insulation layer on the roof was assumed in scenario 1. The U-value of the new retrofitted roof in this scenario 1 was 0.53 W/m^2.K.
- **Scenario 2. Improved Scenario:** In this case, an addition of 14 cm of thermal insulation layer was assumed. The U-value of the new retrofitted roof in this scenario 2 was 0.26 W/m^2.K.
- **Scenario 3. Best energy scenario:** Addition of 20 cm of fibreglass was assumed in this scenario. The new U-value was 0.19 W/m^2.K.

Mentioned data about ESM in roof are summarized in Table 7. 3 and Table 7. 4. These data were also obtained from ITEC. Since insulation thickness greater than 12 cm was not available, cost corresponding to 14 cm and 20 cm were assumed as the sum of different thickness (8cm + 6 cm) and (8 cm + 6 cm + 6 cm). Like in the case of façade cases, only the additional cost of adding the specific ESM respect to a usual tilted roof refurbishment without energy performance improvement was considered.

Insulation	Cost [€/m²]			
	Insulation Material	Secondary materials	Labour	Total investment
6 cm Fibreglass	7.14	0.75	2.16	10.05
14 cm Fibreglass	16.43	1.68	2.7	20.81
20 cm Fibreglass	23.57	2.43	3.11	29.11

Table 7. 3. Cost of the studied ESM for roof improvement (ITEC)

ESM in roof	Addition of fibreglass in roof			
	Currently	BAU	Improved Scenario	Best Scenario
Scenario	0	1	2	3
Thermal ins, thickness [cm]	0	6	14	20
U [W/m^2.K]	2.7	0.53	0.26	0.19
Investment [€/m^2]	-	10.05	20.81	29.11

Table 7. 4. Summary of data regarding to ESMs in roof

4.3 Windows

Finally, the improvement of the thermal performance of the envelope by window replacement was also assessed. In the same way as with the roof and façade cases, another four scenarios were considered in the windows case. These four scenarios are presented in Table 7. 5.

Window scenarios	Windows improvement			
	Currently	BAU	Improved Scenario	Best Scenario
Scenario	0	1	2	3
Frame material (30%)	Metal (without TB)	PVC	PVC	PVC
U_{frame} [W/m^2.K]	5.7	2.2	2.2	2.2
Glass	4/6/4	6/12/6	3/12/3 Low-E	4/16/4/16/4
U_{glass} [W/m^2.K]	3.44	3.0	1.76	0.7
U_{wind} [W/m^2.K]	4.12	2.76	1.89	1.15

Table 7. 5. Summary of data regarding to window scenarios

4.4 Combination of the different scenarios

Thus, the 64 possible resulting retrofitting actions resulting from the combination of the presented ESMs (4x4x4) were simulated with TRNSYS software. The reference building model developed in chapter 5 was selected as a reference. The results obtained from these simulations were thoroughly assessed, and one combination was selected to define the retrofitted dwelling.

5 Criteria for evaluating and choosing an ESM

As presented in Chapter 1, evaluation and classification of ESM depends on the chosen criteria. Criteria for evaluating ESM can be classified in five main groups: economic criteria, energy criteria, Life Cycle Assessment (LCA) criteria, environmental criteria and indoor comfort criteria, which present important connections between them.

Economic criteria are one of the most typical used criteria since they present very clear implications. Many studies focusing on examining the economic dimension of ESMs (both in passive and active elements) can be found in literature, such as [104-106], to name but a few. Either macroeconomic scale approach or focusing on the end-user point of view are found amongst these studies.

Energy efficiency is also an usual criteria used for evaluating ESM. Energy efficiency is usually measured by means of energy savings achieved with the ESM. Hence, it is related to economic criteria, since financial benefits on ESM comes through energy savings (yearly avoided costs). However, it is independent to a specific economic situation and it is more valid for different economic scenarios or comparison between different policies. A huge number of studies can be found on this topic, two of them are in [18,107].

Energy efficiency is often presented together with environmental criteria, which in literature is usually referred to as 2E. This is very straightforward since, usually, higher energy savings bring a reduction of the environmental impact of the building during its lifespan. 3E criteria can be also found in literature [108,109], when economic, energy and environmental aspects are taken into account in the evaluation.

Energy and environmental criteria are also connected to LCA. Whereas previously exposed energy criteria are in the majority of the cases mainly focused on the energy use during the lifespan of the building, LCA is a methodology to assess energy and environmental impacts related to all the stages of a case study life from-cradle-to-grave (i.e. from raw material extraction through materials processing manufacture, transport, use, maintenance and disposal or recycling). It is performed by compiling an inventory of relevant inputs and outputs and evaluating the potential environmental impacts associated with those inputs and outputs. However, due to the great level of detail that can be reached by this method, usually is developed for separate building elements, and not for the whole building.

Several works focused on LCA in buildings can be found in the literature, such as [17,110-112]. The author of this thesis took part in a LCA analysis of a modular building element, supposing different values of service life, with the aim of obtaining the environmental hazard associated with the use phase for each case, also considering the influence of rehabilitation systems on durability of buildings [113].

Finally, comfort aspects can also be taken into account in ESM evaluation since the main goal of any building is to obtain suitable comfort conditions for its users. However, this term is not homogeneously used amongst researchers due to its complexity, since overall comfort depends on different factors such as thermal comfort, air quality, acoustic comfort and luminosity [114]. This kind of analysis covers thermal comfort [115] and indoor environmental quality (IEQ), both independently or taking also into account energy issues [47,116].

Of course, other criteria can be used to evaluate ESM, such as functionality [117] or aesthetics, which despite their qualitative nature, are usually used together with the above mentioned criteria(Economic, environmental impact, energy…)

It must be noted that there are also many papers analyzing the effects of ESM under political, healthy or social point of view. However, it can be affirmed that, actually, this approach are assessed implicitly by a combination of the already presented indicators.

Taking into account these criteria, the evaluation of ESM in this chapter is focusing on the followings parameters:

- **Energy issue** is assessed by the energy demand and savings of energy demand. Primary Energy savings is not taking into account. PE is useful when different energy sources are used before and after implementing a specific ESM, and then, it is necessary to unify the values in order to compare them. However, this value does not give additional information in this case, since assumed energy source was the same in all cases, natural gas.
- **Economic and financial parameters** evaluated are the Payback period, NPV, IRR, SIR and ESIR.

- **Environmental issue** is taking into account by means of CO_2 equivalent emissions.

Mentioned values calculated for each criteria group are presented and defined in detail in Appendix 7.1.

6 Simulation of scenarios

6.1 TRNSYS simulation

The base building model used to evaluate mentioned ESM combinations was the one developed in Chapter 5 (it would correspond to model 7.0.0.0.). Geometrical and construction data have been presented in detail in section 4.1 of mentioned chapter, whereas assumed operating conditions were those based on bibliography, described in section 5 of mentioned chapter. The weather data of Bilbao (Meteonorm) were again used. 1 h time step was used in all simulations related to ESM combinations.

6.2 Assumed values for evaluation

6.2.1 Energy values

- Energy performance of assumed heating system: 0.9 [118]
- Natural gas conversion factor to P.E.: 1.07 [119]

6.2.2 Economic values

- Natural gas cost: 5.0 c€/kWh. In January, 2013, the natural gas cost in Spain (tax excluded) was 5.75 c€ for yearly energy consumption lower than 5.000 kWh and 5.08 c€ for yearly energy consumptions higher than 5.000 kWh [120].
- *r*: 4-5-6-7-8 % (based on values used in [104])
- Expected annual increasing of energy costs (natural gas): Three scenarios of increasing were evaluated: 0-4-8%.

6.2.3 Environmental values

- Natural gas emission conversion factor to CO_2 equivalent: 2.34 tCO_2/toe [119].

7 Evaluation of results and selection of a suggested ECM

7.1 Energy results

Regarding to energy issues, energy demand, savings of energy demand and PE savings were assessed, as mentioned before. Energy demand obtained for each of the simulated combination, as well as energy savings achieved in relation to base case (7.0.0.0.) are presented in Fig. 7. 1.

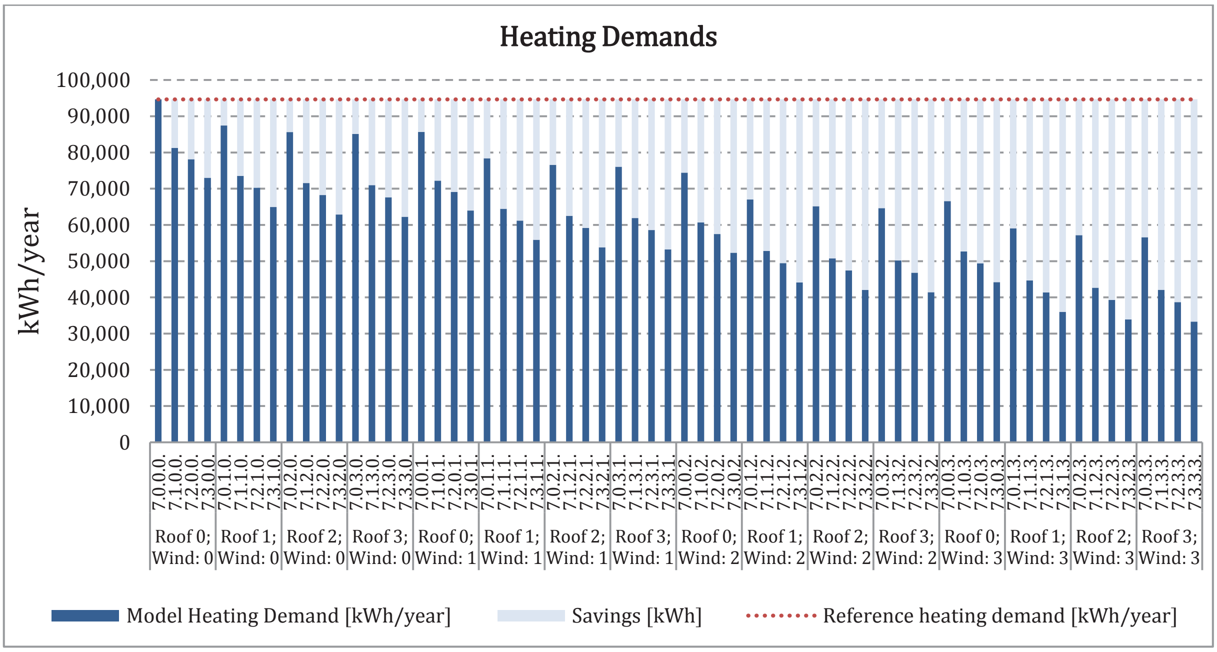


Fig. 7. 1. Yearly heating demands

The best combination scenario (7.3.3.3.) achieved savings of almost 65% respect to the base case. But also significant savings were obtained acting only on one element. Typical windows replacement (7.0.0.1.) achieved savings around 10% (as also shown in previous chapter). The savings obtained by windows replacement were triple with the best windows scenario (7.0.0.3). When the façade is the only improved element, obtained savings on energy demand ranged from 14.15% (7.1.0.0.) to almost 23% (7.3.0.0.)

Effects of roof retrofitting were slightly less significant when the total energy demand of the building was analyzed, from 7.64% (7.0.1.0.) to 10.10% (7.0.3.0.). Savings were obviously more significant in the upper floor, where obtained energy savings reached from 26.31% (7.0.1.0.) to 34.60% (7.0.3.0.).

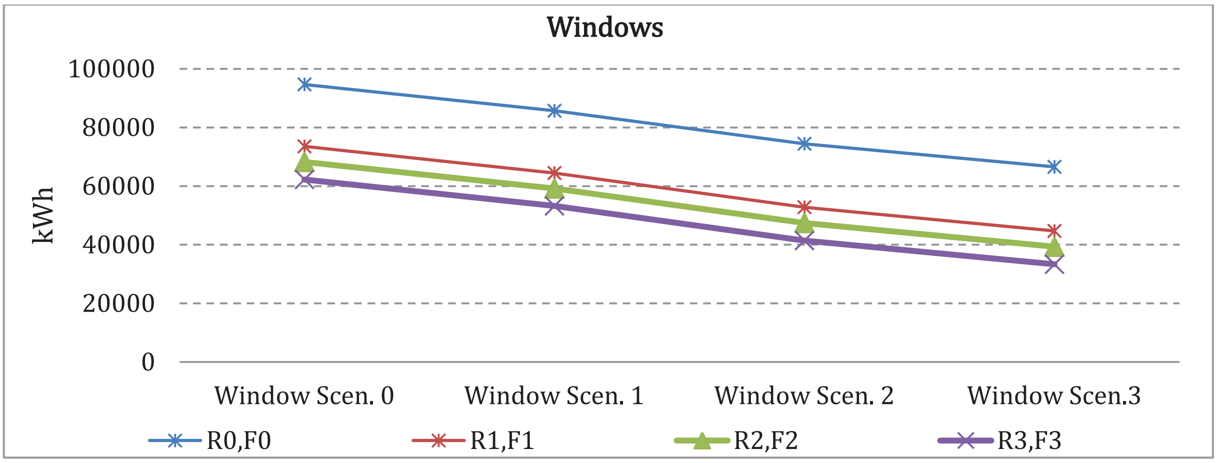


Fig. 7. 2. Energy consumption of scenarios improving windows

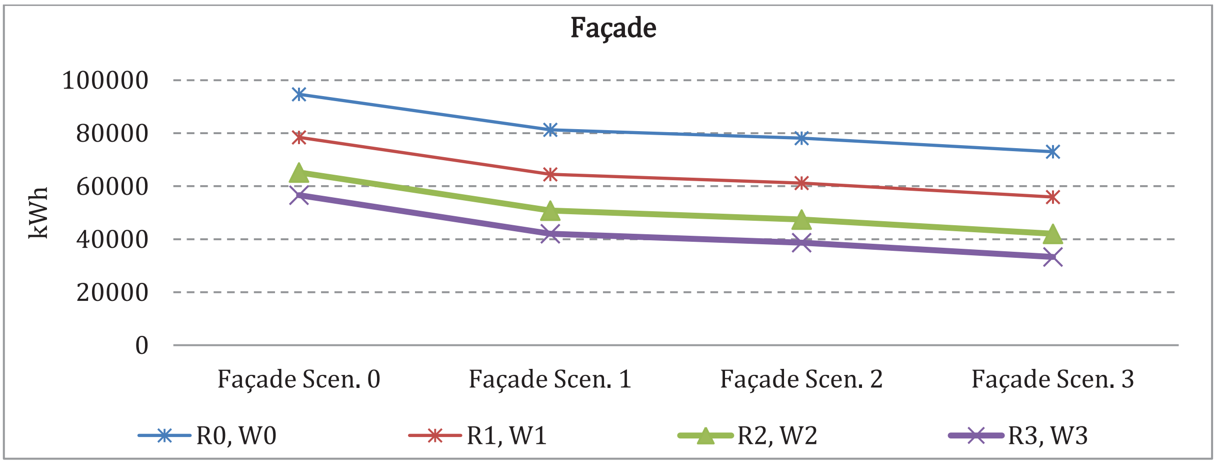


Fig. 7. 3. Energy consumption of scenarios improving façade

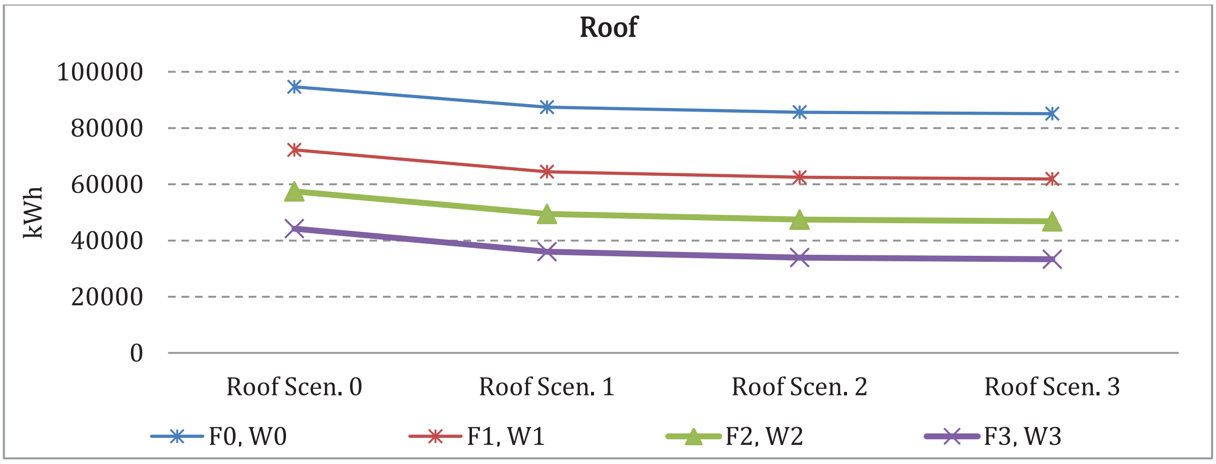


Fig. 7. 4. Energy consumption of scenarios improving roof

Energy demand reductions obtained by each individual element are depicted in Fig. 7. 2, Fig. 7. 3 and Fig. 7. 4, for windows, façade and roof scenarios, respectively. In the case of the window scenarios, energy consumption were steadily reduced from scenario to scenario, whereas both in façade and roof the energy demand reduction from scenario 0 to 1 was greater than from scenario 1 to 2 or 2 to 3. Comparing Fig. 7. 3 and Fig. 7. 4, it can be also appreciated that when energy reduction for the whole building was evaluated, savings were less betrayed in the case of the roof scenarios, as previously observed.

7.2 Economical issues

Hence, the selection of the model bearing in mind only energy use during the building lifespan would be quite direct. For that reason, a brief analysis based on economical parameters was carried out.

Aforementioned parameters (payback period, NPV, IRR, SIR and ESIR) were evaluated for each combination of ESM. Due to the characteristics of the analysis, assessment was carried out in two different parts. Firstly, ESM combinations in roof and façade were evaluated, and afterwards, window replacement were selected independently, since the cost of the windows replacement cannot be shared out like cost associated to roof and façade improvements. Moreover, in the majority of the cases, windows improvement is not only motivated by obtaining a quick payback of the investment, but other aspects, such as thermal and acoustic comfort are appreciated, and as mentioned, it is not possible to shared out the investment corresponding to improving the energy performance and the investment devoted to the other issues, as done for roof and façade improvements.

Financial help and other incentives promoted by different institutions and usual in this case of works, are not considered. Thus, economic results presented below will be better if any kind of economic incentives exists when the energy renovation is carried out.

7.2.1 Façade and roof improvements

Hence, the 15 possible combinations of ESM for roof and façade were economically evaluated using previously mentioned parameters. Different values of r (0, 4, 5, 6, 7, 8) and natural gas cost increment Δc (0, 4%, 8%) were assumed. More detailed data is presented in Appendix 7.2.

Two different trends were observed when NPV of the 15 models were compared. Models where only the thermal characteristics of the roof were improved (7.0.1.0, 7.0.2.0. and 7.0.3.0) presented a lower NPV values than the others. This trend was observed in every r and Δc combination case, with different levels of significance. Two examples of this aspect are depicted in Fig. 7. 5 and Fig. 7. 6.

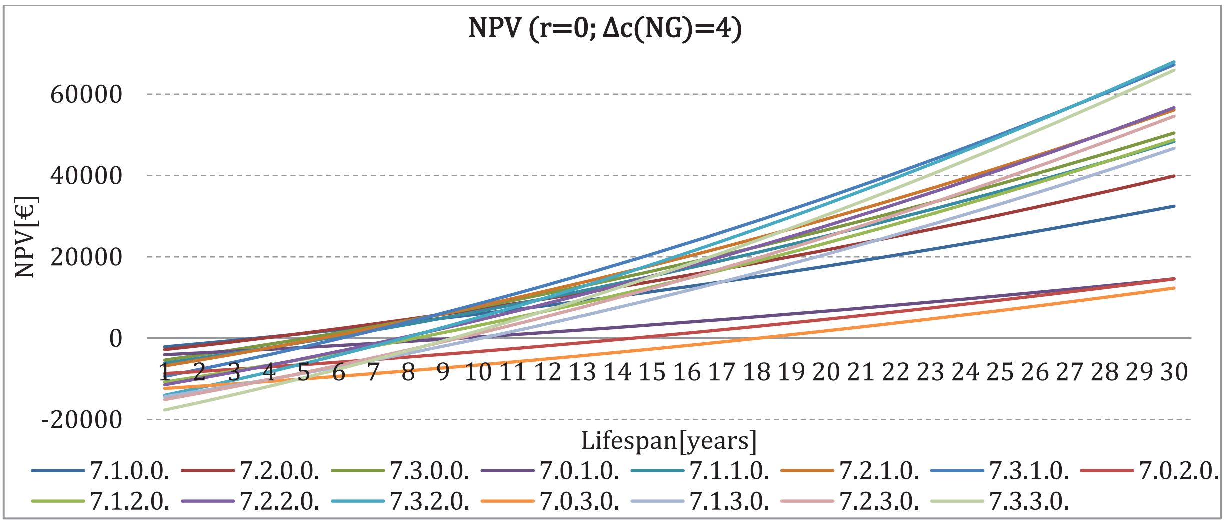


Fig. 7. 5. NPV (r=0, NG Cost increment: 4%)

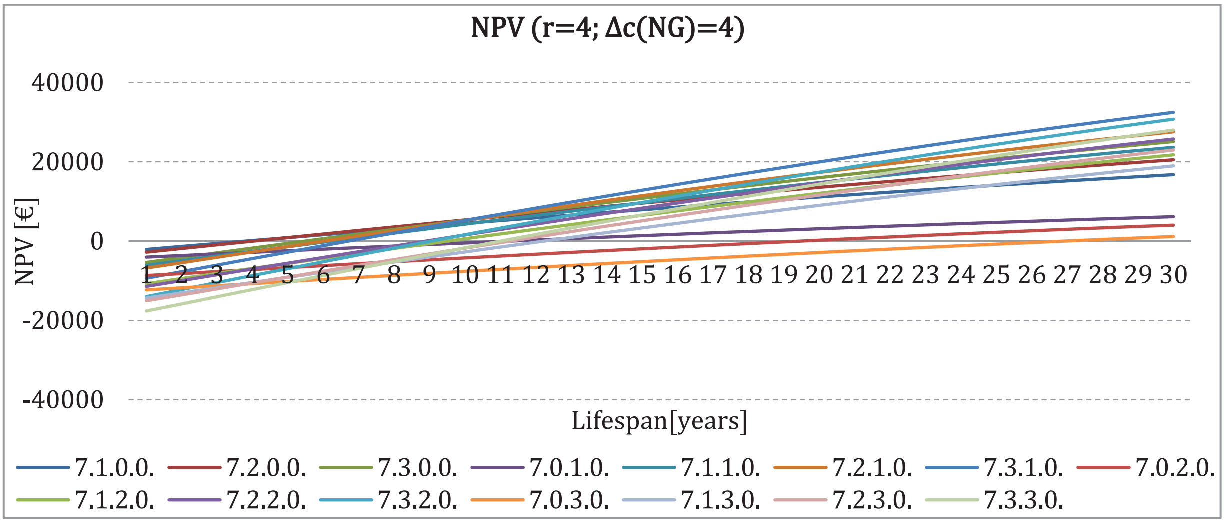


Fig. 7. 6. NPV (r=4%, NG Cost increment: 4%)

Three combinations were pre-selected after the first analysis: 7.1.0.0., which presented the lower payback period and the best IRR; 7.2.0.0., which presented a better NPV than 7.1.0.0. with a slightly higher payback period and similar IRR in every scenario; and 7.3.1.0., which presented the best NPV in a 30 years lifespan. NPV of these combinations assuming an *r*=6%, and three different values of natural gas cost increasing are presented in Fig. 7. 7. Moreover, the graph also represents the depreciated payback period (DPP) of the different scenarios, which is the year when NPV is 0. ESIR and SIR are also depicted for all ESM of façade and roof combinations in Fig. 7. 8.

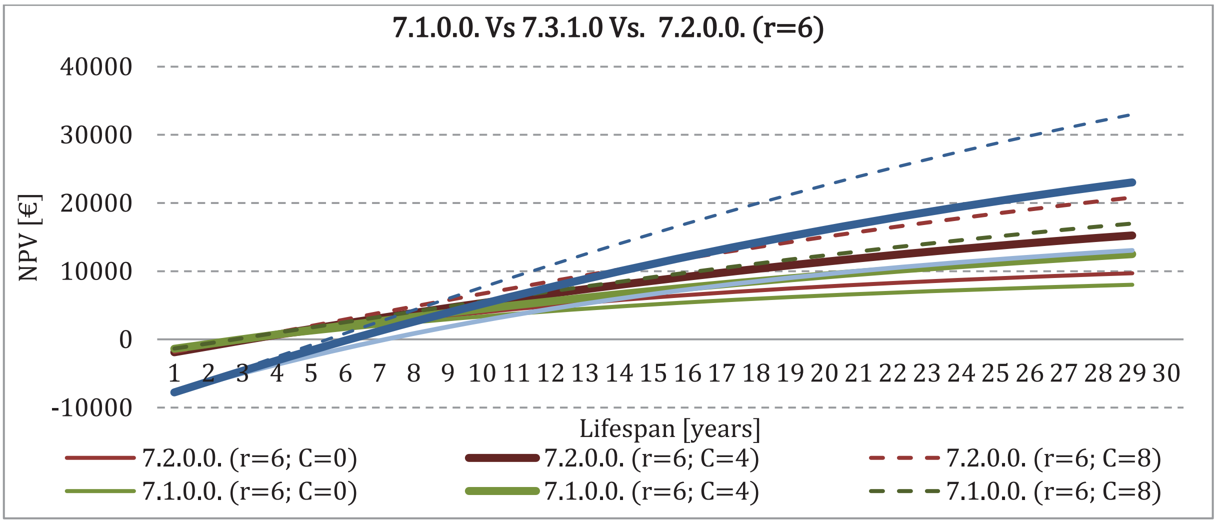


Fig. 7. 7. NPV of the three preselected models

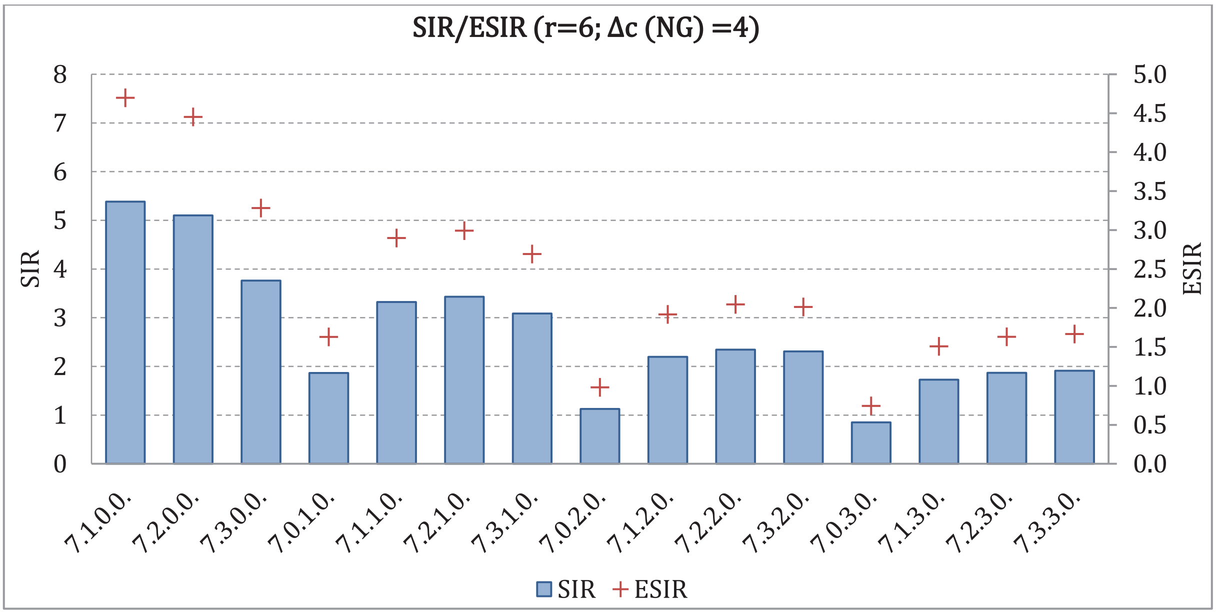


Fig. 7. 8. SIR and ESIR of the ESM of roof and façade combinations (r=6; C=4)

Finally, 7.3.1.0. was selected to be the best option. As mentioned before, it presented the best NPV value, and previously obtained energy savings were quite greater in comparison to 7.1.0.0. and 7.2.0.0. (31.39% in comparison to 14.15% and 17.49% respectively), whereas its payback period was something acceptable for the investment (between 5 and 9 years, depending on the assumed *r* and *c*).

7.2.2 Windows improvements

As far as windows replacement is concerned, Scenario 1 of windows replacement was finally selected. In the case of the climate of Bilbao, no interesting payback periods were obtained when better windows were assumed. For that reason, the most usual solution nowadays (scenario 1) was assumed for the case of the windows.

7.3 Environmental issues

In this case, CO_2 emissions related to energy use during the building lifespan do not give additional information to that given by energy analysis, since conversion factor and assumed heating system energy performance were the same in every case. In any event, CO_2 emissions values are detailed in Appendix 7.2.

7.4 Selected ESM

Therefore, the ESM combination assumed to retrofit the building was finally 7.3.1.1. Its monthly heating demands, as well as the monotonic heat demand for heating of this model are presented in Fig. 7. 9 and Fig. 7. 10, respectively. All data and values mentioned in this section are also summarized in Appendix 7.2.

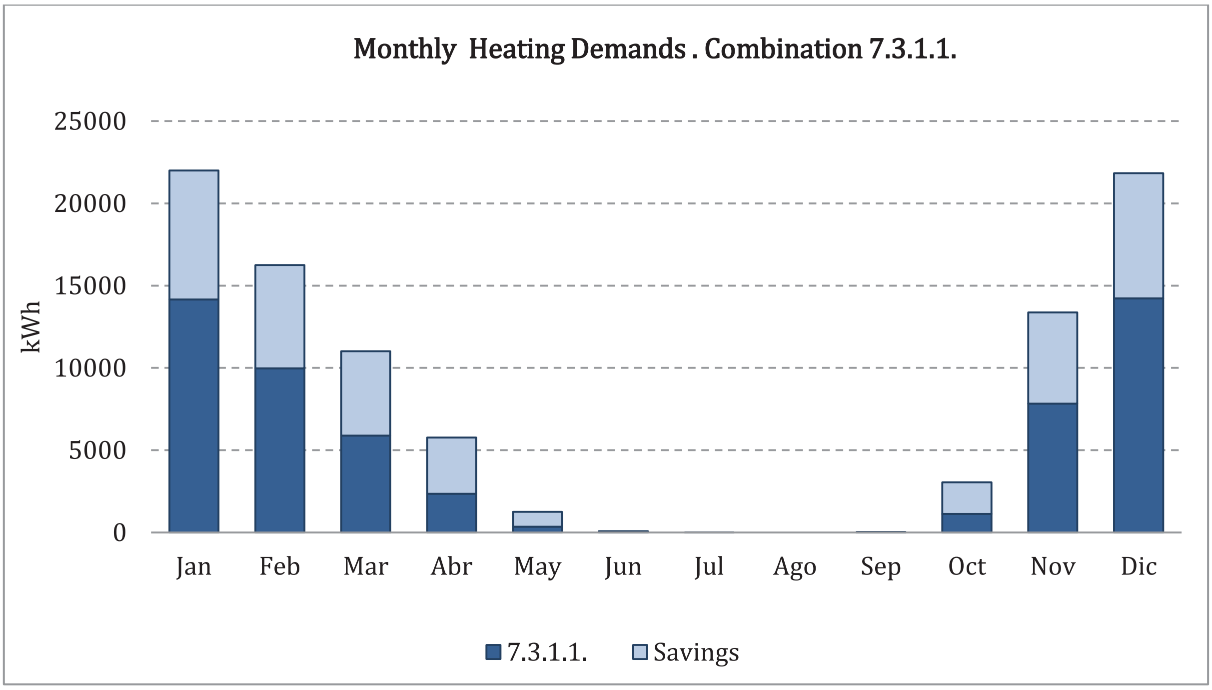


Fig. 7. 9. Monthly heating demands (7.3.1.1.)

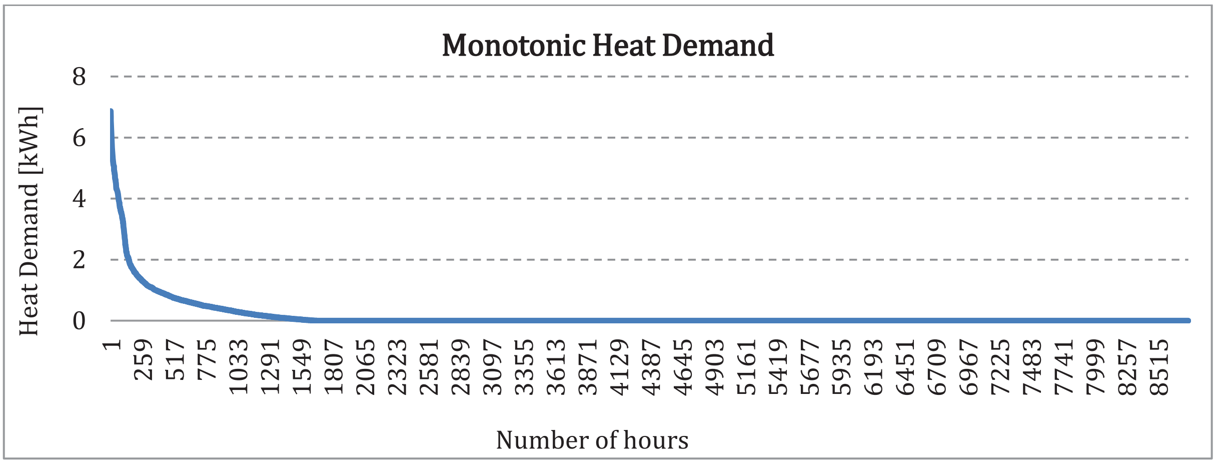


Fig. 7. 10. Monotonic heat demand for 7.3.1.1. (DHW is not considered)

8 Renovation of the heating system

Once a specific ESM was selected, a heating system based on condensing boiler was proposed and several control strategies were evaluated in order to assess the consumption of the renovated building. These strategies focused on the general heating system control definition, boiler temperature setpoint and indoor comfort temperature setpoint.

Additional to the previous definition of the dwelling, during summer months window opening was considered when indoor air temperature was over 22 ºC and outdoor air temperature was cooler than indoor air temperature. This was implemented considering a 4 ACH ventilation rate. A 6 minute time step was used in this case in order to account for the transient nature of the simulated components.

8.1 Definition of the heating system

Details concerning the proposed heating system are covered in this section. A natural gas based heating system, with a condensing boiler and low temperature radiators was assumed. A simple sketch of that system presented over the layout of the dwelling is depicted in Fig. 7. 11.

The main components of the heating loop are the condensing boiler, the circulating pump and a system of four radiators, placed in the living room and in each of the rooms. The installation consists on a closed loop which surrounds the dwelling with the radiators displayed in parallel to the loop by a bypass arrangement, enabling to decouple them from the loop and make the operation more flexible. The boiler is placed in a corner of the kitchen allowing to exhaust the fumes through the external envelope of the building.

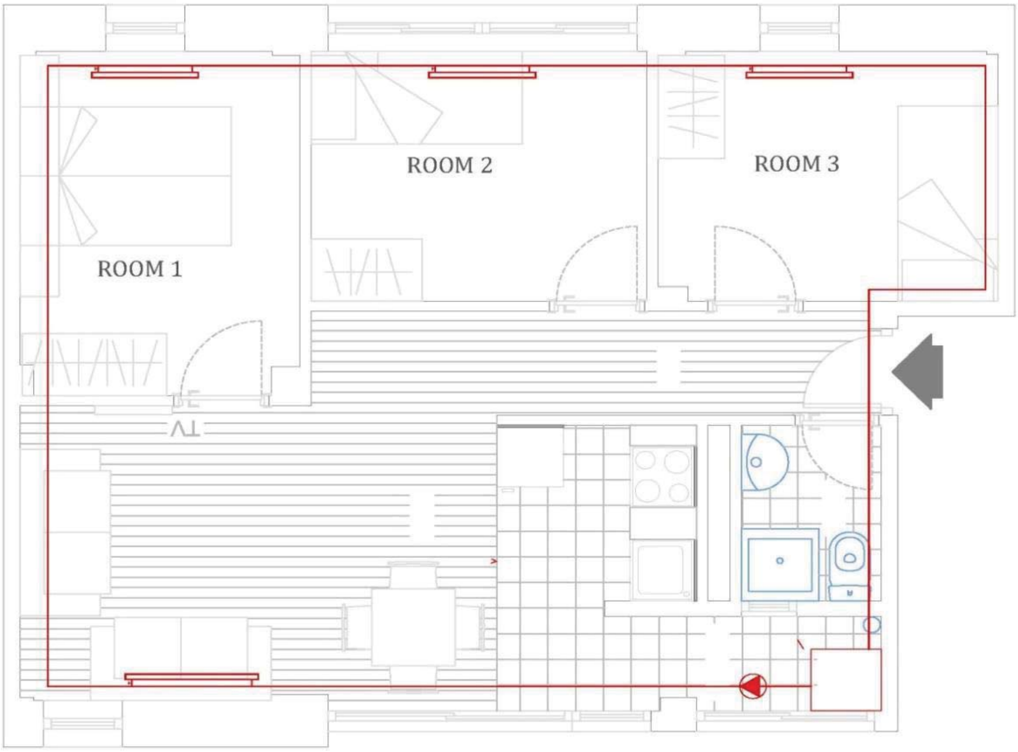


Fig. 7. 11. Sketch of the assumed heating system in the dwelling

Subsequently a brief description of the considered element with their main characteristics is presented. It is also explained the modelling approach followed for their integration in TRNSYS simulation environment.

8.1.1 Condensing Boiler

A generic condensing boiler with a nominal power of 24 kW was chosen, which is the typical boiler capacity used in domestic installations. This boiler uses the lower temperature of the returning water in order to condense part of the water vapour content in the exhausting fumes and recover their latent heat. Then, the lowest the returning temperature the higher the amount of condensing water and the thermal efficiency of the boiler.

The boiler presents load modulation being capable of adapting their instantaneous production to a given temperature setpoint. Both the effects of the temperature of the feed in water and the partial load operation (PLR) on the thermal efficiency are included in the simulation by the relationship in Eq. 38.

$$\eta_{Boiler} = \left(-160.40233 + 26.6297 \cdot T_{in} - 1.06398 \cdot {T_{in}}^2 + 0.02041 \cdot {T_{in}}^3 - 1.90629 \cdot 10^{-4} \cdot {T_{in}}^4 + 6.97436 \cdot 10^{-7} \cdot {T_{in}}^5\right) \cdot \left(1 + \frac{1 - PLR}{10}\right) \quad \text{Eq. 38}$$

This equation was self-tailored considering the efficiency- temperature relation given by the IDAE [82] and the part load operation relationship given by [98]. Owed to the lack of more detailed information the approximation of assuming the direct product between those two expressions was considered accurate enough to represent the actual behaviour of these kinds of boilers for the purpose of this analysis.

This was included in TRNSYS simulation by a direct modification of TYPE 751 by TESS Library [121] which gave rise to the TYPE 751b, where the efficiency expression presented before was implemented within the existing code. These units usually present their own circulating pump inside. The pump was modelled in TRNSYS by TYPE 3b and a flow rate of 6 l/min was chosen according to the proposed design.

8.1.2 Radiators

As terminal units low temperature radiators were chosen. As a reference for their specific definition *"StelRad Elite K2"* radiators are chosen due to the quality of the data given by manufacturers. Their main characteristics are presented in Table 7. 6.

Main characteristics of radiators	
Nominal thermal power per length	1,778 W/m (*)
Effective thermal capacity	1,142 J/kgK
Height of the radiator	0.6 m
(*) Nominal for 75 ºC inlet temperature, 65ºC outlet temperature and comfort temperature of 20ºC	

Table 7. 6. Main characteristics of radiators

The radiator installed in each zone were sized according to the typical installer practice resulting from a simple stationary calculation. This technique is very straightforward to apply once the mathematical model is available. Stationary outdoor temperature of 0ºC was chosen while 20ºC were imposed as the indoor comfort temperature. The heat gain required to maintain these conditions was the radiator power required for each zone.

Considering the radiator characteristics presented in Table 7. 6, the next lengths of radiator were obtained for each zone (Table 7. 7).

	Living Room	Room 1	Room 2	Room 3
Radiator Length [m]	1.1	0.4	0.45	0.35

Table 7. 7. Radiator length per zone

A self-tailored code was developed for modelling the radiator and it was implemented in TRNSYS as TYPE 211. It consists on a lumped capacitance model which couples the heat transfer with the heat transfer fluid and the air node representing a certain thermal zone. Thus, the aforementioned thermophysical properties of the radiator were implemented in such model.

8.2 Operation of the heating system

Once the installation was defined several questions arised on how to run it properly. In this chapter the operation of the heating system is discussed comprising three main issues:

- General control strategy
- Boiler temperature setpoint
- Comfort temperature setpoint

It is considered that these elements present influence on the operation of heating systems, especially when using condensing boilers. However, usually there is no clear information on which operating strategies bring more benefits or how the end user can run optimally this kind of systems getting the whole potential of the installation. Analogously to those presented for the renovation of the envelope a comparative analysis is made between these different strategies. The three considered issues and how they are implemented are subsequently explained in detail.

8.2.1 General control strategy

Four possible heating system control strategies were assessed in this study. They are summarized in Table 7. 8 and briefly described in the next paragraphs.

A simple system consisting of a simple mechanical thermostat in the living room was considered first (**Control A**). In this case the room temperature governed the operation of the whole system and the rest of zones received heat whenever there was a heat demand in the living room.

A modification of the previous system was introduced considering that the radiators in the other rooms had thermostatic valves (**Control B**). These valves allowed flowing the water through the radiator when there was thermal demand (temperature in the room below the comfort temperature setpoint) and bypassed it when there was no need for heating.

In the next case, mechanical thermostats were placed in every zone of the dwelling (**Control C**). So, the system ran when one of the rooms needed heating in any of the zones and it was not only governed by the conditions in the living room. At the same time all the radiators presented thermostatic valves in order to bypass the water when the system was running but there was no need for heating in a specific room.

Finally, the same case presented by Control B is selected but an additional control was set up governing the boiler temperature setpoint by a linear relationship with the outdoor temperature (**Control D**). This control made the boiler generating heat at 65ºC when the temperature was below 15ºC and 50ºC when it was over 20ºC, behaving linearly between these two temperature levels.

Control Number	Control type
1	Living room mechanical thermostat, no thermo-regulated valves
2	Living room mechanical thermostat, thermo-regulated valves in other rooms
3	Living room and non-living zone mechanical thermostat
4	Weather compensation, modulating supply water setpoint. Living room temperature compensation. thermo-regulated valves in other rooms.

Table 7. 8. Control strategies assessed

8.2.2 Boiler temperature setpoint

Boilers allow selecting the temperature level for the heating production. Thus the burner modulated its load to reach the desired temperature. In principle, the lower the boiler setpoint, the lower the temperature returning to the boiler and therefore the thermal efficiency if a condensing boiler is used. However, a low boiler temperature can bring a lower efficiency to the radiators which can lead to problems in meeting the thermal comfort requirements. Three different temperatures were considered as setpoint for the boiler; 55ºC, 60ºC and 65ºC.

8.2.3 Comfort temperature setpoint

The main purpose of a heating system is to provide good thermal comfort conditions to the users of the building. In domestic applications thermal comfort is identified by the temperature of the air and the whole installation is run to meet a specified temperature which is known as comfort temperature setpoint. Different temperatures can be selected as comfort temperature setpoint being the lowers the ones which imply a lower energy consumption. However, as in the case of the boiler temperature setpoint, too low comfort temperature setpoint will affect the thermal comfort of the users. In the carried out analysis, three temperature levels were used: 19, 20 and 21ºC. It should be considered that, while the comfort temperature setpoint is just a temperature objective it is the actual running of the system which allows satisfying it at every time instant.

8.3 Simulation cases

From the combination of the aforementioned issues 30 simulation models arised. Specifically, there were 9 models for the **Control A**, **B** and **C** and 3 cases for **Control D** since the boiler temperature setpoint cannot be a variable in that case.

Resulted simulation models were named according to the combinations adopted in each case. Thus, for instance, **Model 7S.a.b.C** would represent setpoint temperature **a** (19ºC); setpoint of the boiler **b** (60 ºC) and **Control C** configuration.

8.4 Evaluation criteria

As previously mentioned in regard to evaluation and classification of ESM on envelope, different kind of evaluations can be made on the operation of the heating system depending on the evaluation criteria. Amongst the available alternatives, energy and comfort issues were selected for evaluating the above defined control scenarios.

8.4.1 Energy Criteria

Yearly and monthly energy consumption for each model, as well as average seasonal performance values for the different control parameter combinations were considered when energy aspects were evaluated.

8.4.2 Comfort criteria

Unlike previous evaluation of the ESMs, it was interesting to evaluate comfort aspects because, apart from the energy performance, a certain heating system should provide good comfort conditions to the users. A certain heating system could provide a low energy consumption but a complete analysis should evaluate its actual capacity in providing good thermal conditions. This is the reason to consider this issue in the evaluation of the heating system.

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" ([122] quoted by [123]). It is a result of a combination of parameters related to the environment and the human body itself. Fanger, who developed the first heat balance thermal comfort model, formulated an expression for optimal thermal comfort which can be deduced from the metabolic rate, clothing insulation and environmental conditions. Fanger proposed a method to predict the actual thermal sensation of persons in an arbitrary climate where the variables might not satisfy the equation: the Predicted Mean Vote (PMV). According to Fanger, the sensation of thermal comfort was quantified by a scale with values ranging from -3 (cold) over 0 (neutral) to +3 (hot). Thus, the International Standard ISO 7730 [65] uses these PMV indices (and PPD, predicted percentage of dissatisfied, which is related to PMV) to predict the thermal sensation of people exposed to moderate thermal environment, as well as to specify acceptable thermal environmental conditions for comfort.

In any case, these data must be assessed taken into account the fact that in residential buildings, conditions are not quite comparable to those during the experiments for calibration of the PMV equations. That is, domestic scene is a very dynamic state: activity level, as well as clothing can vary within small timescales, and fluctuating internal gains can rapidly affect the indoor temperature. Moreover, there are many forms of adaptations in the case of residential buildings, such as changing activity, adapting clothing or opening windows, to name but a few. The range is thus wider than what is generally the case for other building uses, e.g. office buildings.

PMV was calculated by TRNSYS. Input parameters were assumed constant and the same for the four thermal zones. Defined input parameters were:

- Metabolic Rate: 1 met
- Clothing Index: 1 clo
- Air speed: 0.1 m/s

So, PMV values were obtained by TRNSYS at every time step. Analysis was focussed only in the cold season of the year when the comfort was provided by heating (September – April).

8.5 Results

Results obtained by the simulations of the defined cases are presented in this section. However, the amount of obtained results was quite significant and it is expected to analyze them in detail in future works.

Quantitative and qualitative analyses of the obtained results were carried out, taking into account energy and comfort issues. Regarding the energy results, yearly and seasonal final energy consumption, as well as average seasonal performance was evaluated in each model. Analogously, the comfort was evaluated by the NPV.

8.5.1 Energy Results

While the demand can be an interesting factor to evaluate the performance of the envelope, the effectiveness of the installations are better understood when the final energy consumption is considered, since it involves also the performance of the whole system. In this case, energy consumption is brought by the natural gas used to feed the condensing boilers. The overall consumption for each of the cases resulting for the combination of cases is presented in Fig. 7. 12. Moreover, in orange, the average seasonal performance for each model is depicted in the graph, which is calculated as the relation between energy output from the radiators and energy input into the boiler.

As stated in chapter 5, these results showed the influence that indoor air setpoint temperature has on yearly energy consumption. In fact, models with a 19 ºC indoor air setpoint temperature (In blue) gave yearly energy consumption values nearly to 35 % respect to the same model (same temperature in the boiler, the same control strategy) with a setpoint temperature of 21ºC (in red). This result emphasizes the famous fact of reducing the temperature setpoint in the thermostat leads to an important reduction in the energy consumption. However the other issues, general control strategy and boiler temperature setpoint offer not so clear reductions in the energy consumption. Understanding this effect seems clearer when analyzing how the different issues affect the energy consumption.

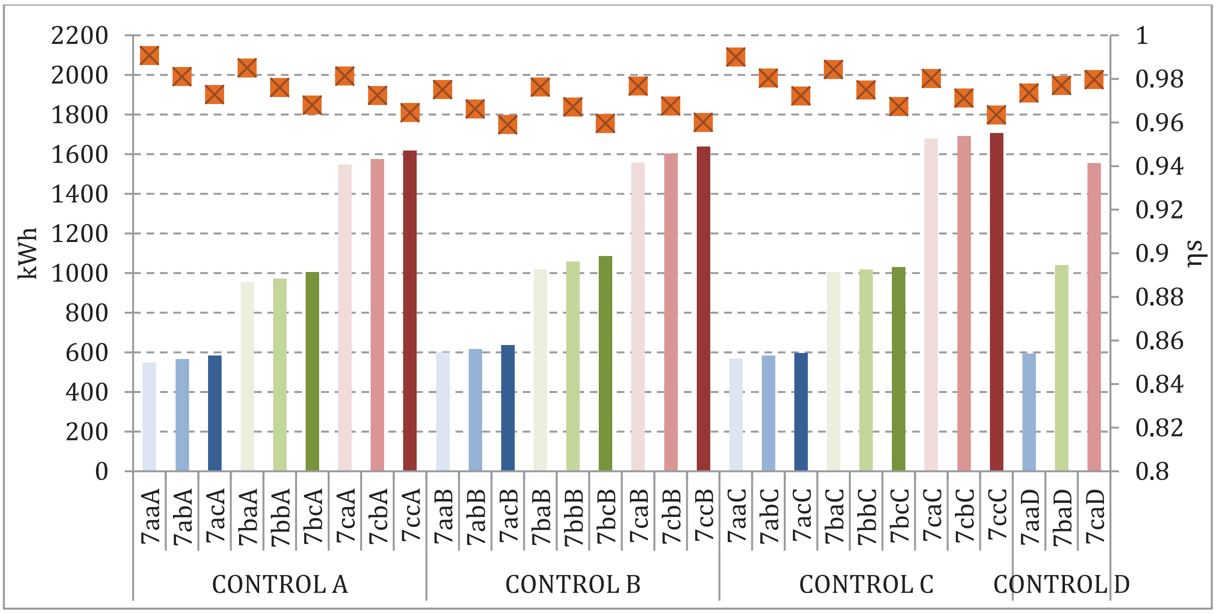


Fig. 7. 12. Yearly boiler energy consumption for each model

It was seen that the boiler temperature slightly affected the energy consumption. When it is reduced the returning temperature is also reduced enabling the condensing of the boiler as it is seen by analyzing the seasonal performance of the boiler. However, it can be stated that although the condensation reducing the boiler temperature setpoint can be increased, the increase of the performance was not very big with this kind of wall radiators. As shown in Fig. 7. 12, average seasonal performance ranges between 0.96 and 0.99.

Finally it is difficult to find clear relationships between the general control strategy and the energy consumption and no clear statement can be made. This is owed to two facts:

- All the radiators were sized to its optimal as previously calculated and there are no imbalance
- All the zones were heated at the same temperature setpoint at every moment.

These facts do not allow to take advantager of the control strategies and it is expected to get better results when selective heating is applied to the different zones of the dwelling. Taking into account the imposed constraints it can be said that the Control A, simple mechanical thermostat in the living room, offers slightly lower consumption than the others, probably due to the fact that releasing more heat to the zones reduces the return temperature and then, increase the condensation in the boiler.

To carry on with the analysis, the distribution of the energy consumption in winter and spring/autumn when 60ºC was considered as the boiler temperature setpoint and 20ºC as the comfort temperature setpoint, is presented in Fig. 7. 13. It is observed that the major part of the consumption occurs during the winter and again not significant trend is seen amongst the control options.

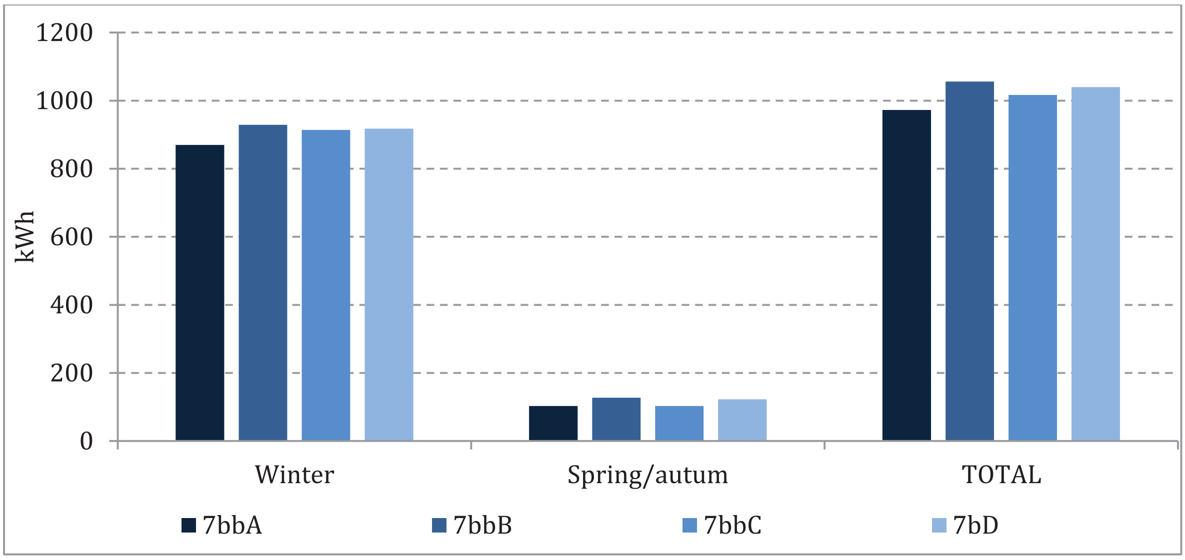


Fig. 7. 13. Seasonal boiler energy consumption for models "bb"

8.5.2 Comfort Results

Up to now, only energy issues have been considered and it could happen that some of the cases could lead to discomfort situations. According to the previous section 8.4.2, average PMV was evaluated in each thermal zone (Fig. 7. 14). Even though PMV values were in general similar in the different thermal zones for each model, small differences were found. Thus, in every model room 2 was the zone with the best average PMV values, followed by room 3. The worst PMV values, instead, were obtained in every case for room 1. Differences are not higher than 0.05 in any case, which suggests that it can be corrected adjusting the sizing of radiators, for example.

Nevertheless, if average values were considered as important indicators in order to assess the indoor thermal comfort, the stability of PMV also must be taken into account when comfort issues are evaluated. With this aim in mind, standard deviation of every data set was also evaluated. The results of the comfort analysis by means of PMV are subsequently presented in Fig. 7. 15. There, the PMV average values along with its standard deviation and the minimum and maximum are synthesized in a pareto chart.

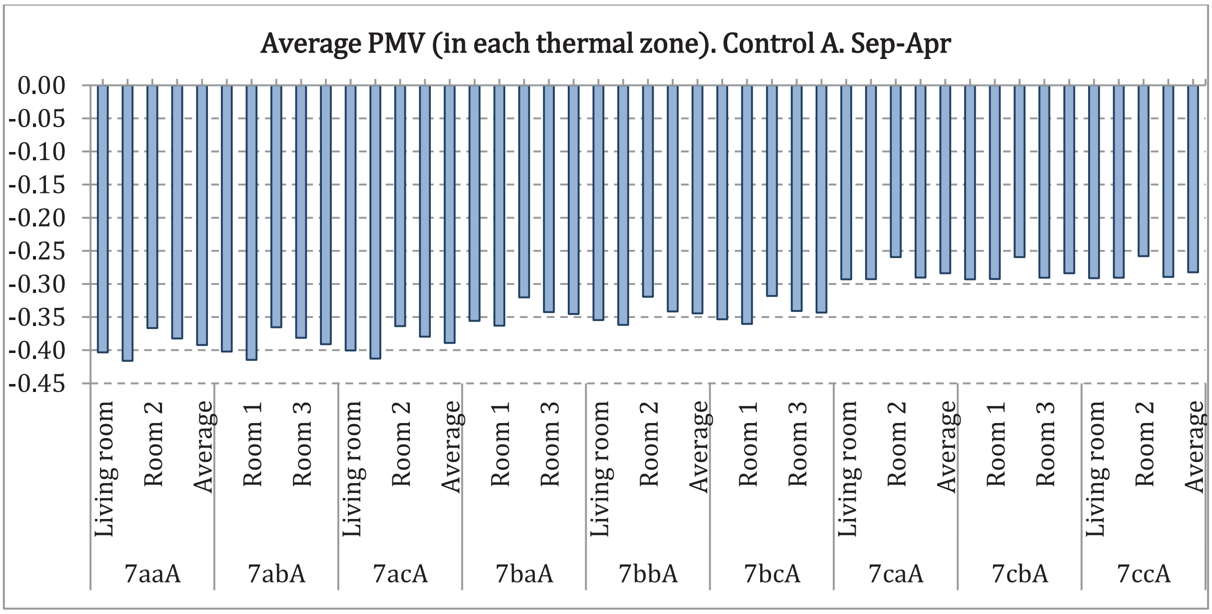


Fig. 7. 14. Average PMV in each thermal zone: living room, room 1, room 2, room 3 and dwelling average (Control A, Sep-Apr)

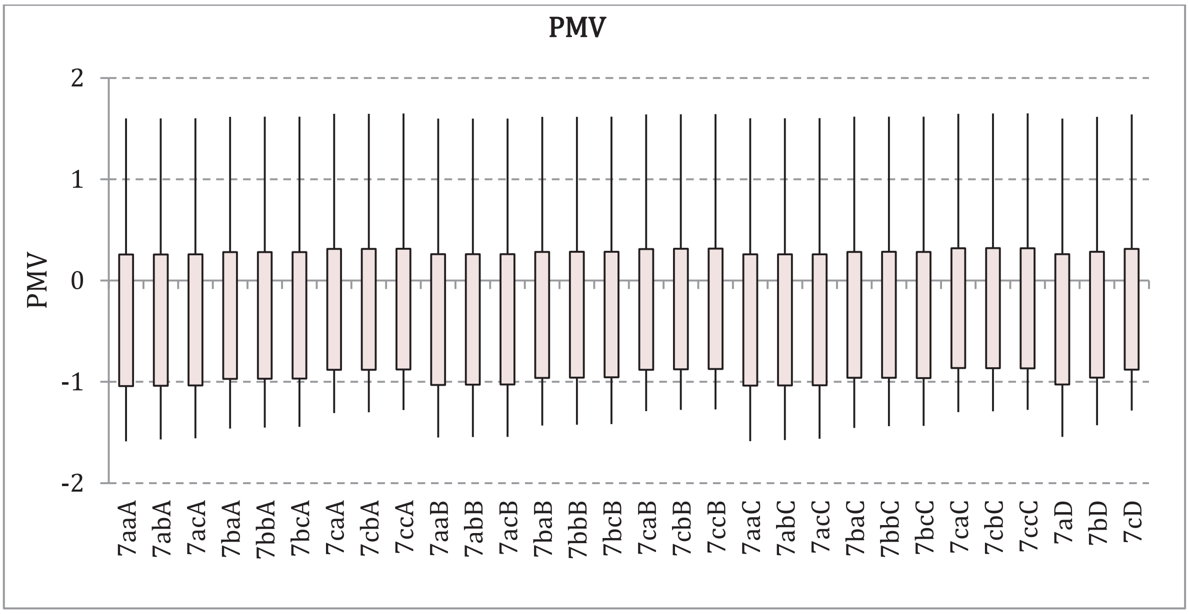


Fig. 7. 15. PMV in each combination (Average values from September to April)

It is seen that all cases offered similar comfort conditions which were just slightly lower when the temperature setpoint was diminished. However this reduction is almost negligible. Moreover, according to mentioned results, it is concluded that the general trend of all models was slightly cool as shown by graphs, where no average value was greater than 0 but always within -1 and 1, which can be easily adjusted changing the clothing factor. It must be also noted the fact that the positive peaks are not related to the heating system itself, but to other external circumstances.

In any case, it must be highlighted the all mentioned before about thermal comfort in residential buildings, and the fact that these comfort values can be improved just by increasing some tenths the clothing factor. Thus, the main strength of obtained PMV results is not to define if the system achieves an expected thermal comfort (which is just a matter of small adjustments on radiator sizing and comfort parameters such as clothing factor and metabolic rate) but the fact that these values are a useful indicator to compare the indoor comfort amongst models under the same conditions.

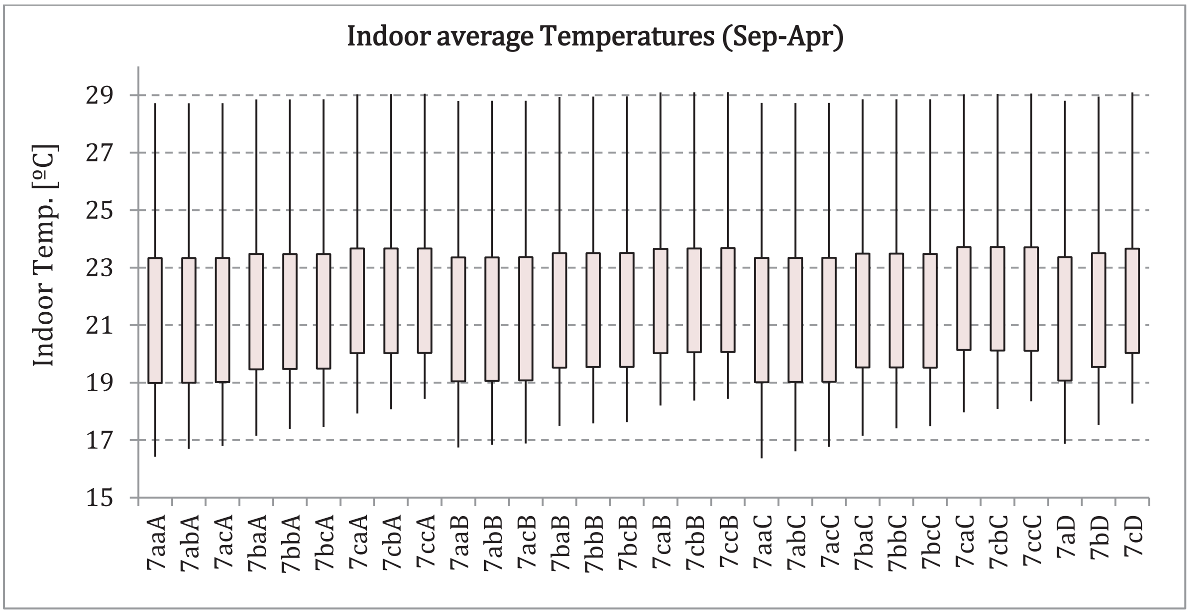


Fig. 7. 16. Indoor average temperatures for each model

For that reason, indoor temperatures were also evaluated in order to have a better picture of the indoor thermal comfort in each model. Moreover, comfort information by means of temperature terms are usually easier to understand by the average user. Thus, indoor temperatures during winter period (Dec-April) were firstly evaluated. These data are presented in the next Fig. 7. 16 by means of other pareto chart.

Indoor temperature values were assessed taking into account average, minimum, maximum and standard deviation temperatures for the selected cold period

(September-April) and, in a similar way to the study presented in Chapter 3 of this thesis, values corresponding to the coldest week of the year were also obtained.

		Average Temp [ºC]	Min. Temp [ºC]	Max. Temp [ºC]	Standard Deviation
CONTROL A	7.b.a.A	21.47	17.15	28.85	2.01
	7.b.b.A	21.47	17.38	28.85	2.00
	7.b.c.A	21.48	17.45	28.86	1.99
CONTROL B	7.b.a.B	21.51	17.49	28.94	1.99
	7.b.b.B	21.52	17.58	28.95	1.98
	7.b.c.B	21.53	17.62	28.96	1.98
CONTROL C	7.b.a.C	21.51	17.15	28.86	1.98
	7.b.b.C	21.51	17.41	28.86	1.98
	7.b.c.C	21.50	17.48	28.86	1.98
CONTROL D	7.b.D	21.52	17.52	28.95	1.98

Table 7. 9. Temperature values for September-April period

Besides, as a way of example, mentioned values for the models with a setpoint temperature of 20 ºC are presented in Table 7. 9. Analogously to PMV values, indoor temperature values were virtually equal in every model, and differences found amongst them can be considered negligible.

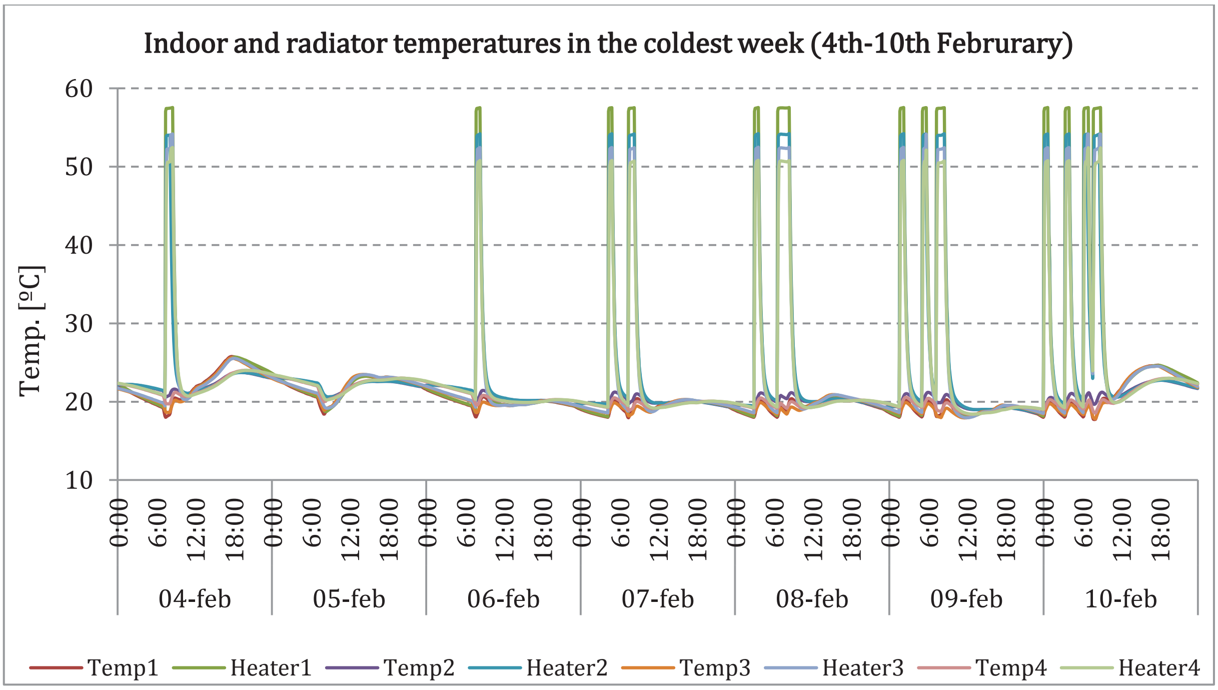


Fig. 7. 17. Indoor temperature and radiator temperature in the coldest week (7.b.b.B.)

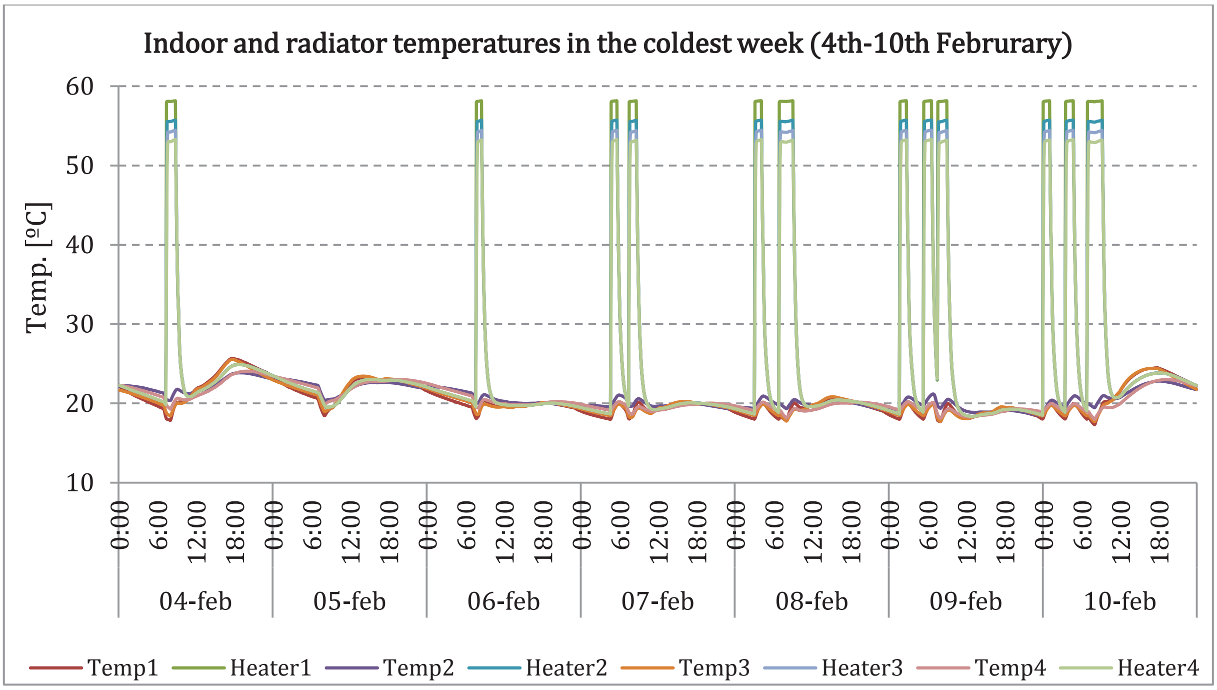


Fig. 7. 18. Indoor temperature and radiator temperature in the coldest week (7.b.b.A.)

In order to evaluate the indoor conditions more in detail when heating system is working, the same process was carried out taking data related to the coldest week of the year, in this case, 4th -10th February. Two examples (combinations 7.b.b.B. and 7.b.b.A.) are depicted in Fig. 7. 17 and Fig. 7. 18.

MODEL	19-21 ºC	18-22 ºC	Lower than 18 ºC	Higher than 22 ºC
7baA	55.15 %	76.92%	0.24%	22.84%
7bbA	54.67%	77.86%	0	22.14%
7bcA	56.16%	76.86%	0	23.14%
7baB	57.41%	76.98%	0	23.02 %
7bbB	57.82%	76.86%	0	23.14%
7bcB	58.30%	76.68%	0	23.32%
7baC	59.37%	76.20%	0.12%	23.08%
7bbC	54.31%	76.62%	0	23.38%
7bcC	59.37%	76.74%	0	23.26%
7bD	58.18%	76.74%	0	23.26%

Table 7. 10. Frequency of Temperatures during the coldest week (4th – 10th February)

Frequency of temperatures in the different models during that period was also evaluated. Those related to models with a setpoint temperature of 20 ºC are presented in Table 7. 10. Like in the other indicators previously presented, differences of temperature results amongst the different models were negligible, which proved that indoor comfort was achieved in similar levels in every model, independent on the used control strategy.

8.6 Discussion

As mentioned below, every control strategies combination simulated in this chapter achieve similar comfort levels, so the focus could be placed on the energy consumption. As far as energy consumption is concerned, the highest differences amongst control were found around 8%, being Control A the most favourable of the evaluated control strategies.

However, further analysis of these control strategies would be recommended. Control B, for example, presents a higher flexibility level than Control A, and it allows adapting the heating system to heat only the rooms which are occupied in each moment, since assumed thermostatic valves allow to the occupants activate or not each radiator according to their necessity. In this case, simulations were programmed to activate each radiator if room temperature were lower than the setpoint temperature. Then, the Control B simulations present a significant improvement potential. Defining different and more detailed occupation profiles per zones, and simulating each radiator not as a function of room temperature, but of room occupancy would give results better fitted to its real use. Finally one can identify what kind of occupation profiles are the most suitable for this kind of control.

In a similar manner Control D can be referred to. In this case, a better adjustment of the correlation boiler setpoint temperature and living room could lead to more optimal use of the system, and then, to a lower energy consumption of it.

9 Conclusions

This chapter has shown the possibilities and flexibility of a validated TRNSYS model to evaluate different strategies to improve the energy performance of a residential building. Results of 64 possible combinations of ESM focusing on passive elements of the building have been firstly presented. Not only energy results, but also economic and environmental results were thoroughly assessed, and they have been presented in this chapter. Results show that in the majority of the cases thermal improvement of roof and façade is not only beneficial under environmental, energy or social approach, but also under an economic approach. Obtained economic indicators were clearly favourable, even under conservative assumptions (assumed natural gas cost was lower than the real cost in January 2013, no kind of financial or economic incentives were considered…)

Afterwards, an ESM combination was selected and the TRNSYS model was used for evaluating the impact of the different heating system control strategies on the final energy consumption of the dwelling. It has been shown that control strategy of the heating system can play a significant role in reducing the energy consumption of a dwelling. It is especially important the effect of the set point (as it has been mentioned in previous chapters, such in Chapter 5), although other points, such as boiler temperature or control strategies must be taken into account when a heating system is designed. On the other hand, average seasonal performance has been similar in all of the assessed model. It ranges, depending on the cases, between 0.96 and 0.99.

10 Referred Appendices

Appendix 7.1. Energy, economic and environmental criteria definition.

Appendix 7.2. Energy economic and environmental values of evaluated ESM combinations.

CHAPTER 8

DETAILED BUILDING-SCALE ANALYSIS. EXERGY APPROACH

RESUMEN

Este capítulo evalúa el uso del concepto de Exergía como una herramienta útil para la evaluación de diferentes medidas de rehabilitación energética en edificios. Incluye una breve revisión bibliográfica sobre el enfoque exergético en edificios en los últimos años, así como el trabajo llevado a cabo con Sabine Jansen en la "Faculty of Architecture" de la TU Delft (Países Bajos) durante el segundo trimestre de 2012.

ABSTRACT

This chapter of the thesis deals with the use of exergy as a fruitful tool for evaluating different energy renovation strategies. It encompasses a brief literature review about exergy approach in buildings, as well as the work carried out with Sabine Jansen in the Faculty of Architecture of the TU Delft, in The Netherlands during the second trimester of 2012.

1 Introduction

As mentioned in the first chapters, the work developed in this thesis tries to include the whole process of renovation works. Thus, a data collection procedure has been presented in the first chapters of the thesis: an overview of the building stock has been described in the first chapter, whereas a field study of ten occupied dwellings has been presented in Chapter 3, as well as the detailed monitoring study presented in Chapter 4 of a vacant dwelling. Chapter 5 and 6 have described the modelling developments in order to assess and explain building performance, using the data collected to adjust the model. An analysis of different actions in dwelling scale has been presented in Chapter 7. And finally, in this chapter 8, different energy renovation strategies are evaluated, in this case under a building scale approach, instead the dwelling scale approach used in the previous chapter.

2 Exergy in Buildings

2.1 Introduction to exergy concept

Energy demand in buildings has various quality levels. One part of that energy demand is electricity ("high quality" energy) for supplying the different electrical appliances and lighting. However, an important part of the energy demand (more than 60% of the overall energy demand in buildings) includes DHW and energy for heating and cooling.

Energy demand for heating and cooling in the built environment is mainly a demand for "low quality" energy, due to associated temperatures required. Exergy is a thermodynamic concept which can be regarded as the quality of a form of energy, by expressing the maximum theoretical work that can be ideally obtained from it in a given reference environment. The first law of thermodynamics states that energy cannot be destroyed. However, exergy, according to the second law, can be destroyed. Gong and Wall explained the differences between energy and exergy in their work [124], as presented in Table 1. 6. Explanations of the exergy theory can be found in many textbooks on thermodynamics, such as [125,126].

Energy	Exergy
The first law of Thermodynamics	The second law of Thermodynamics
Nothing disappears	Everything disperse
Energy is motion or ability to produce motion	Exergy is work or ability to produce work
$\Delta Q=\Delta U+\Delta W$ Where: ΔQ is the total heat supplied to the system, ΔU is the total increase in the internal energy U of the system, ΔW is the total increase in the external energy of the system or the total work done by the system.	$\boldsymbol{E = T_0(S_{eq}^{tot} - S^{tot})}$ Where: E is exergy, T_0 is the temperature of the environment, S_{eq}^{tot} is the entropy of the total system, i.e. the system and the environment when the system is in equilibrium with the environment, S^{tot} is the entropy of the total system at a certain appropriate deviation from equilibrium.
Energy and matter is "the same thing". Everything is energy	Exergy and information is "the same thing". Contrast is energy
Energy is always conserved. It can be neither produced nor consumed.	Exergy is partly consumed in irreversible process (i.e. real process). Exergy is never in balance for a real process
Energy is a measure of quantity	Exergy is a measure of quantity and quality

Table 1. 6. Energy Vs Exergy (based on table presented in [124])

2.2 Exergy definitions

The exergy concept is based on the early classical thermodynamics of the 19th century, as Sciubba and Wall affirmed and documented in [127]. The word "exergy" was introduced in mid 20th century, and, since then, several exergy definitions can be found in literature, as gathered in [128]. Even though some subtle differences can be found amongst these definitions, the majority of the quoted references by A. Hepbasli mentioned "maximum theoretical work", whereas only three authors made mention of "the quality of an energy source". According to those definitions, exergy can be defined as "the maximum theoretical useful work that can be extracted from a system or may be done by a certain quantity of energy, expressing the quality of an energy source".

Thermodynamic ideal processes are reversible, which means no exergy is destroyed and the original situation can be re-obtained. In real processes, however, exergy is always destroyed, often even in large amounts. The exergy destruction of a process indicates the ideal thermodynamic improvement potential of this process. This improvement potential is not shown in an energy analysis; exergy analysis can therefore add more information for the evaluation of the performance and improvement potential of a system. Hence, exergy may be a more rational measure of the performance of an energy conversion process than energy [129]. Due to this potential to identify and quantify consumption of useful energy as well as irreversibilities and losses (destruction of exergy associated to mentioned irreversibilities) and consequently, to highlight the areas of improvement of a system, exergy analysis has been extensively discussed and applied to a wide variety of energy conversion systems.

Analogously to energy, exergy can be classified according to the nature of its origin (i.e. potential, kinetic, or from material stream, electrical, etc.). Several authors have proposed different classifications for exergy. A proposal for classification and decomposition is presented in [130]. The proposal is divided into three levels: the first one, based on the type of carrier (energy streams or material streams); the second one is based on the exergy ratio of energy, also known as level of exergy (cases where the exergy equals the energy content or cases where the exergy is less than the energy content). Finally, the third level refers to the origin of the exergy (chemical, thermo-mechanical, electrical…)

2.3 Reference State

As already stated, exergy measures the potential to cause a change a system or material has. Thus, it is closely linked to the imbalance between a given system and its environment. Therefore, it must always be formulated in relation to a reference environment, and then, the state of the environment will play an important role in the mentioned potential. The correct definition of that reference environment may have a strong influence on the result obtained from an exergy analysis, especially in building assessments, where that influence is even higher, due to differences between some "products" (e.g. energy for heating and cooling) and environment are quite lower than those in other industrial processes, as later explained in section 2.5.3.

2.4 Applications of exergy analysis

Originally, the concept was primarily applied to chemical processes and thermal plant analysis [127], with the aim of finding the most rational use of energy. An extensive number of studies have been carried out in the last decades in this field, such as [131-133].

2.5 Building Exergy Assessment

As mentioned before, the “low exergy” heating and cooling demands in the built environment are generally met with “high exergy” energy sources, such as gas or electricity and, as a consequence, a lot of exergy is usually destroyed in these systems. In other words, heating and cooling systems are driven to maintain indoor comfort temperatures at around 20 ºC. Due to this temperature level, the energy demand for heating and cooling in the built environment is mainly a demand for “low quality” energy. However, this demand is usually met by aforementioned high quality energy carriers. The building sector has a high potential for improving the quality match between energy supply and demand and, thereby, reducing the required input of high quality energy sources. It can be affirmed that there is much room for improvement.

Nevertheless, the exergy approach in the built environment is relatively new and may be considered an emerging field of science. Exergy is often perceived as a highly complex concept, and some engineers have simply disbelieved exergy methods to lead tangible direct results. Therefore, as P. Sakulpipatsin states in his Thesis [134], specific examples of exergy analyses for the built environment are needed to make the concept "more familiar and usable to the building profession".

Although M. Shukuya and Nishikawa can be considered as the pioneers of exergy application in built environment during the decade 90s, it can be affirmed that exergy concept in buildings has been significantly spread since the first years of the 21st century, thanks to several international research projects, such as IEA ECBCS Annex 37 [135] and Annex 49 [74].

As a result, many studies related to the built environment can be found in the last years in different levels, some of which are presented in section 2.5.7.

2.5.1 Exergy approach in built environment

A global exergy analysis in buildings should be based on a holistic framework, assessing the whole energy chain for supplying energy demands in a building. Energy supply chain is depicted in Fig. 8. 1. Although optimization of single components is required, the influence of optimizing one component on the performance of the following and previous ones should also be regarded. That is, focusing only on optimizing single components might decrease the performance of the system as a whole, and for that reason, optimization of the integral system must be taken into account.

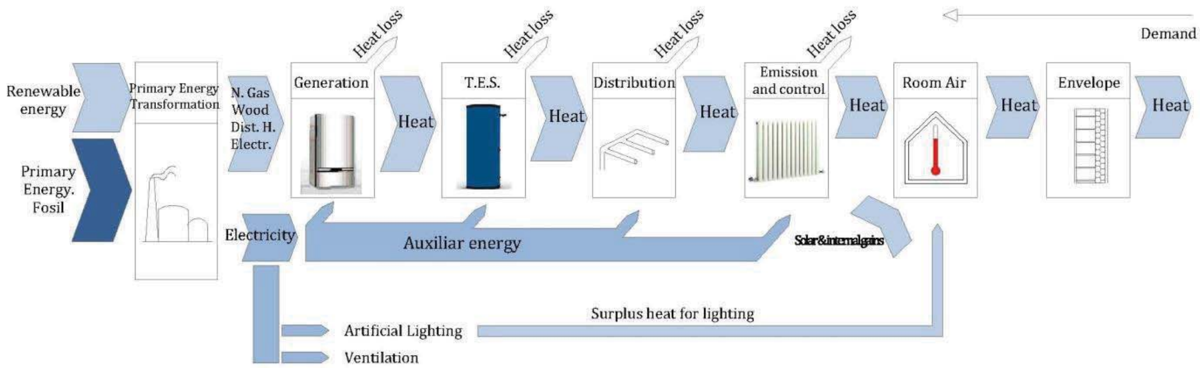


Fig. 8. 1. Energy supply chain for space heating in buildings (Adapted from [136])

Hence, one of the first steps in the exergy analysis is the estimation of the energy demand of the building. Firstly, heat demand of the building must be obtained. Heat demand is a key figure in the analysis, since it corresponds to the building's exergy load. Then, energy and exergy requirements of the service equipment are calculated.

2.5.2 Steady state exergy analyses

Most exergy studies in the built environment are based on steady state calculations. Steady state energy and exergy analysis can be performed using an excel tool based on that developed within the framework of the aforementioned IEA ECBCS Annex 37. The calculation approach follows the method developed by D. Schmidt, which divides all the processes into several subsystems, as previously shown in Fig. 8. 1. An input-output approach is used in these calculations. This modular approach focusing a better understanding of the processes involved in each subsystem, and makes it easier to compare results between different building systems. Detailed information about methodology and governing equations can be found in [136].

2.5.3 Dynamic exergy analysis

Steady state calculations might lead to inaccurate values. Several aspects, such as thermal inertia or reference environment variations, may play an important role in the building behaviour, and dynamic state must be considered in order to take them into account. Thus, accurate estimations of the exergy demands and flows in buildings are necessarily dynamic or, at least, quasi–steady.

Regarding to the reference environment selection, Rosen and Dincer carried out a sensitivity analysis on the results for different definitions of reference environment, based on temperature and humidity. They proved that, when properties of the system are close to those of the reference state (the case of exergy analysis of space heating and cooling in buildings), results from exergy analysis presented strong variations depending on the definition of the reference environment [137].

A quantification of inaccuracies is presented by P. Sakulpipatsin in [134], where exergy analyses in buildings using various reference environments (annual average value state, dynamic reference state, taking into account air humidity or not…) in different climates (The Netherlands, Bangkok and Portugal) are presented. Results depended on the climate, but errors over 90% were obtained in the case of the hot humid climate of Bangkok. For the temperate sea climate in Portugal (namely Lisbon), using average annual indoor and outdoor air temperatures led to underestimations of 44% on exergy flows. These underestimations are quite noteworthy in this Thesis, since Portugal is, amongst the three studied countries by Sakulpipatsin, the closest to Spanish climatic conditions,

At the same time, Angelotti and Caputo [138] evaluated the difference between steady state and dynamic analysis for a heating and cooling system in two representative Italian climates (Milano and Palermo). Although they only focused on the dynamic versus steady state issue whilst Sakulpipatsin also considered the effects of air humidity on the reference state, both studies recommended dynamic exergy analyses whenever HVAC systems operate in temperatures very close environmental temperature.

Nevertheless, despite the above mentioned, dynamic exergy analyses in buildings are not widespread yet due to several reasons. One of them is that there is no tool for dynamic exergy assessment implemented in the most usual building energy simulation programs, as mentioned by S. Jansen in [139].

One dynamic exergy analysis example can be found in the study carried out by Nishikawa and Shukuya [140] in 1999, where a method for calculating “cold” and “warm” exergy stored by building envelopes is described. A case study is made to examine the combined effects of shading and natural ventilation on making better use of the walls heat capacity for passive cooling in Tokyo.

2.5.4 Key parameters for performance assessment and comparison

One of the problems to evaluate the results obtained in any exergy analysis is the exergy performance definition. As D. Marmolejo-Correa and T. Gundersen affirmed in [130], the characterization of the exergetic performance is often open for individual interpretations, which may lead to confusion when processes are compared under different exergy efficiency metrics. For that reason, having unique exergy efficiency for all cases has been discussed in the literature since the beginning of the exergy concept. In the aforementioned reference, they classified the six most used exergy efficiency definitions into two main groups: *input-output* efficiencies and *consumed-produced* efficiencies.

Like any other efficiency, exergy efficiencies are defined as the ratio between the obtained output and the input required to produce it. However, as previously said, several differences amongst definitions can be found in literature.

Firstly, depending on if the exergy efficiency is referred to a single component or process, or to all processes and components integrating the system. This leads to defining the so called “single” and “overall” exergy efficiencies.

Moreover, depending on the exergy output used to calculate the exergy efficiency (exergy output in general, or *desired exergy* output), different types of exergy efficiency will be obtained. Thus, H. Torio et al. mentioned in [141] two main types of exergy efficiencies, which are presented below.

2.5.4.1 Simple or universal exergy efficiency

It is an unambiguous definition that works when all the components of the incoming exergy flow are transformed into some kind of useful output. It would be included into the group of *input-output* efficiencies. Its mathematical expression is shown in the following equation:

$$\psi_{simple} = \frac{Ex_{out}}{Ex_{in}} \quad \text{Eq. 39}$$

2.5.4.2 Rational or functional exergy efficiency

In some systems, part of the exergy input does not constitute a useful output. Rational exergy efficiency can be more suitable in those cases, where the desired exergy output is only considered instead the total exergy output. It is defined as follows.

$$\psi_{rat} = \frac{Ex_{des,out}}{Ex_{in}} \quad \text{Eq. 40}$$

2.5.4.3 Exergy expenditure figure

Exergy expenditure figure was defined by Schmidt et al. [142] for characterizing the exergy supply in buildings. As shown in Eq. **41** for a general component *i* of an energy system, this parameter is calculated as the ratio of the exergy input required for supplying a given energy demand (effort) and the provided energy demand (use). It gives an idea of the quality factor of the studied energy process, i.e. the exergy to energy ratio. Exergy expenditure figure is calculated as follows:

$$\psi_{rat} = \frac{Ex_{in}}{En_{out,i}} = \frac{F_{q,in,i}}{\eta_i} \quad \text{Eq. 41}$$

Thus, exergy expenditure figure expresses the matching between quality levels of the demanded and supplied energy.

2.5.4.4 Transit exergy

Some mentions to transit exergy can be also found in literature, i.e. unaffected exergy after passing through the system. However, transit exergy is barely used in building assessments. The exergy efficiency can be then calculated as follows:

$$\psi_{(tr)} = \frac{Ex_{out} - Ex_{tr}}{Ex_{in} - Ex_{tr}}$$ Eq. 42

2.5.5 Other performance indices

Hepbasili, in its literature review presented in [128], gathered other performance indices, such as exergetic renewability ratio ($R_{R,ex}$). This term is defined as the *"useful renewable exergy supplied to the building to the total exergy input to the system"* ratio. It is expressed as follows:

$$R_{R_{Ex}} = \frac{Ex_{usf}}{Ex_{tot}}$$ Eq. 43

2.5.6 Indexes of exergy quality

As stated before, exergy expresses the energy quality, and accordingly, the amount of energy of a system that can be transformed into useful energy. Having the exergy quality indexes of the different energy carriers is essential in any exergy assessment. Wall introduced in 1977 the exergy quality indexes presented in Table 1. 7.

Form of energy	Quality index (% of exergy)
Potential energy	100
Kinetic energy	100
Electrical energy	100
Chemical energy	About 100
Nuclear energy	95
Sunlight	93
Hot stream	60
District heating	30
Waste heat	5
Heat radiation from earth	0

Table 1. 7. Exergy quality indexes of different forms of energy (From [143])

2.5.7 Review of LowEx studies

As already mentioned, a growing number of studies about exergy in buildings can be found in literature. Several examples are presented next.

Starting with general issues related to environment and sustainability in building environment, many references are found in literature. Four of them are presented in the following as a way of example. Thus, in [144] the exergy concept is reviewed as a tool for resource accounting, defining conversions of energy and material resources in Italian society in terms of exergy. In [145] and [146] exergy is presented as a useful ecological indicator, and sustainability is evaluated with relation to exergy flows of earth. Similar conclusions are reached in [147], where M. A. Rosen and I. Dincer suggested that exergy provides the basis for an effective measurement of the potential of a substance or energy form to impact the environment.

Continuing with the urban scale, the research project with the name "Synergies between Regional Planning and Exergy" funded by the Dutch Agency for Innovation and Sustainable Development can be stood out. It explored and proposed an amount of exergy-conscious design principles applied to the planning and design of sustainable landscapes. In [148], S. Stremke, A. van den Dobbelsten and J. Koh presented the results of that research.

Regarding to exergy demand evaluation in buildings, some tools have been developed in the last years. The pre-design tool presented by Schmidt in [136] is noteworthy. It is led to exergy assessment (in steady state) of heating and DHW systems for buildings.

Focusing on specific parts of the aforementioned energy/exergy chain, some studies focused on quantifying the exergy demand in relation to the thermal characteristics of the building envelope are found. As an example, Dovjak [96] evaluated the effects of the thermal improvement of the building envelope and boiler efficiency on the thermal behaviour of the building.

The influence of the occupants on the final energy consumption and energy performance of a building has been already mentioned in this thesis. Exergy analyses taking into account this point can be also found in literature, as that carried out by M. Schweiker and M. Shukuya in [149], where adaptive comfort is evaluated with an exergy approach of human body consumption. On the other hand, exergy is used in [150], where the strong influence that operation and control strategies have on energy consumption of a building is demonstrated. Furthermore, several studies focused on human metabolism from an exergy point of view can be found in literature, such as [151-154].

Nevertheless, it can be affirmed that energy systems in buildings are one of the most extensive fields related to buildings where the exergy concept has been applied in the last years. Some examples are: [155] and [156] on thermal storage systems; [157] focused on low temperature radiant heating systems; and [158] on HVAC. Several studies on heat pumps, solar systems and heat exchangers (both separately or interacting amongst them) are also found, such as [159-162].

The literature review presented in this chapter indicates that applying the exergy approach for energy renovation issues from a global point of view, taking into account the actions both on the envelope and heating systems and assessing their influence is a suitable tool. However, no study on global energy renovations of existing stock has been found so far. Thus, in the following section two publications, resulting as a consequence of the work developed in TU Delft by the author of this thesis together S. Jansen are included. In them, the fruitfulness of the exergy approach to evaluate different energy renovation strategies of the reference building of this thesis is assessed.

3 Referred Appendices

The appendix of this chapter (Appendix 8.1) includes the two mentioned papers:

- *"The exergy approach for evaluating and developing an energy system for a social dwelling",* published in Energy and Buildings in December 2012 (Vol 55, pag 693-703) [53]
- *"Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement",* published in Energy and Buildings in September 2013 (Vol. 64, pag 359-371) [54]

CHAPTER 9

CONCLUSIONS, CONTRIBUTIONS & FUTURE WORKS

RESUMEN

Éste último capítulo recoge las principales conclusiones de esta Tesis, así como sus contribuciones y una propuesta de líneas de trabajo futuras y la forma de llevarlas a cabo. Todo esto viene acompañado también del plan de difusión, es decir, la lista de publicaciones actualmente disponibles que han resultado del trabajo de esta tesis, así como de aquellas que actualmente están en proceso de preparación.

ABSTRACT

This last chapter gathers the main conclusions of this PhD Thesis. Its contributions and a proposal of future works which are identified are also presented, as well as the means to proceed with them. This is accompanied by the dissemination plan, i.e. list of publications which are currently available (and which are a result of the work presented in the Thesis) as well as those which are currently under preparation.

1 Main contributions

The overarching goal of this PhD Thesis has been to deal with the evaluation of energy renovation in buildings, face the different parts involved in that process, such as data acquisition and monitoring, data treatment (by means of building models) and analysis of obtained results. The most relevant contributions of this PhD Thesis, classified in three different groups are listed in the following.

1.1 Characterization of social dwellings in the region

This PhD Thesis has provided an overview of the thermal characteristics of the Social Housing sector in Bilbao. It has been deeply analysed, both its construction features and indoor environment conditions. This overview has been developed based on data obtained both from literature reviews and field studies, developed with the support of Bilbao Social Housing.

Data of indoor thermal conditions and energy use logged during a year in ten occupied, representative social dwellings have been obtained. These data allow obtaining information regarding not only energy and comfort aspects in these dwellings, but also occupants behaviour and operating conditions, being a reference in future simulations for defining an occupant’s profile in this sector.

Detailed monitoring data of a representative dwelling have been also provided. These data afford the possibility of using as a reference for validating and calibrating different simulation models.

1.2 Models definition

The development, calibration and validation of two kinds of models (a grey box model and a TRNSYS model) of the reference dwelling have been provided in this thesis. These models can be used in the future to simulate different elements and as a reference model for test carried out by Energy System Testing Plant, as it is described later.

A comparison between both models have been performed, identifying the main strengths and weaknesses of each one.

At the same time, the models resulted from the combination of different renovation strategies can be used in the future to obtain the yearly energy demand, for different levels of energy renovation in different climatic areas. These demand curves, obtained by a validated model of a representative dwelling, will be useful in future analysis of the different heating systems, carried out by Enedi Research Group.

1.3 Energy and exergy analysis

A detailed analysis of the effects on improving thermal behaviour of a dwelling by means of different combinations of ESM has been presented in this thesis. Economic, energy, environmental and comfort data have been considered for different envelope refurbishment scenarios. Therefore, the advantages of each ESM combination have been evaluated, allowing to identify the best options for places with weather conditions similar to Bilbao.

Analogously to ESM on the building envelope, several improvements on energy systems have been simulated and evaluated. Combinatory presented for these cases, as well as the first conclusions, can be used as a reference for defining different tests in Energy System Plant.

The usefulness of the exergy approach for evaluating different thermal performance improvements has been also treated in this thesis. Dynamic analyses in a building scale have been presented, assuming different renovation strategies under a holistic approach, considering the entire energy supply chain for space heating and cooling in buildings.

2 Main conclusions

Partial conclusions have been presented in every chapter related to that chapter. For that reason, in this section the conclusions are summarized, and the most significant ones are highlighted.

One of the main challenges of the current society is to reduce the E.P. consumption. Building sector plays an important role in this regard, and presents a huge potential for improvement. This thesis has highlighted the importance of having a holistic approach when building energy consumption is evaluated.

Four aspects must be faced when energy consumption optimization is sought in buildings:

- Firstly, reducing the building energy demand, by means of improving the thermal characteristics of the passive elements of the building. Some examples have been presented in the first part of the Chapter 7.
- Improving the heating (and cooling) system efficiency. This involves supplying the same energy demand with less P.E. consumption.
- A good control strategy of the heating systems also allows a more efficient usage of the energy systems, as presented in Chapter 7. The influence of the occupant's adaptive behaviour has been also shown in different parts of the thesis, such as in Chapter 5, Chapter 6 and Chapter 7.
- Using renewable resources and surrounding energy flows for supplying a part of the demand. A brief evaluation of some examples has been presented in Chapter 8.

Hence, the main conclusions are summarized in the following:

- Energy efficiency in buildings is a priority goal for the European Union. In the case of Bilbao, more than 80% of the residential building stock was built before 80s and in the majority of the cases, it presents a great improvement potential, especially the part related to heating the building.
- As a result, European Directives and the consequently implementation of them on Spanish legal framework are increasing energy requirements in buildings, not only the new ones, but more and more, also existing buildings. At the same time, some

governments and institutions offer incentives to improve the thermal behaviour of buildings or dwellings. Thus, the development of tools to evaluate, in an accurate way, effects of energy renovations is needed in order to, on the one hand, check if the energy renovation fulfils the conditions required by law, and on the other hand, identify the most adequate energy renovations, and whether a given incentive has been invested in a suitable way or not.

- Energy consumption of the studied social dwellings has been, in general, lower than expected. This situation is not due so much to a good thermal performance, but to a low indoor temperatures in winter and hence, to poor indoor comfort levels.
- Sustainability on building renovations, and especially in social hosing sector, does not have to be evaluated only in terms of energy savings but also under economic and social criteria. The aim is to reduce cold homes and energy poverty, and in this way, the risks they involve.
- Cold homes and the risk of energy poverty is a real problem in Spain, which can be aggravated in the near future, due to the current economic recession and the increment of fuel costs. Social housing sector is one of the main risk groups, and for that reason, the improvement of its thermal performance must be considered as a priority.
- The majority of the studied social dwellings present, however, a good indoor design, which can make the occupants' adaptive behaviour easier. This issue highlights the interest of making the efforts on improving the thermal performance of the buildings by means of updating energy systems and enhancing building envelope.
- This PhD Thesis has also demonstrated the influence of the occupants' behaviour and on energy consumption and indoor comfort. Chapter 3 has presented how many aspects which are strongly dependent on the occupants (such as heating system usage, ventilation patterns setpoint temperatures or closing the windows shutters at night) involve great variations on the final energy consumption of a building. Differences around 30% on energy consumption have been presented in Chapter 7 when comfort temperature setpoint varies 2 ºC, and differences in other operating conditions (such as ventilation patterns or internal gains) have been evaluated in Chapter 7, where differences around 50% between models (field study conditions Vs literature operating conditions) have been found.

- When an energy evaluation is carried out at a dwelling scale, it must be taken into account not only those factors related to the evaluated dwelling itself, but also to adjacent dwellings, especially when no insulation system is found in its partition walls, which is usual in buildings constructed before 80s.
- Although great differences on energy consumptions (and then, on energy savings, when a given energy renovation is being evaluated) have been found when absolute values were compared, relative values on energy savings have been found similar when they are calculated under the same operating conditions in both scenarios (before and after retrofitting works). Hence, relative values are quite less dependent on a given operating conditions.
- Mentioned conclusions led to highlight the necessity of defining adequate operating conditions, taking into account the possible user profiles of the building, when a specific study case is evaluated.
- Monitoring studies allow obtaining information on the thermal performance of the building as actually built, identifying “hidden” effects that in a simulation based on project data would be missing.
- The correct monitoring design plays an important role on the subsequent success of the study, and it must be defined according to sought targets. Monitoring carried out with the objective of defining an RC model may not be the same to that aimed to carry out a co-heating test.
- Variables such as operating conditions on adjacent dwellings can influence significantly on the thermal performance of the building. This aspect affects not only simulations, but also monitoring studies. For that reason, logged data led to obtain information for defining them in a more accurate way and then, to reduce this effect, is recommended.
- The main strengths on TRNSYS models on this field of energy renovations are basically its flexibility, and the fact that no previous monitoring study is required for its definitions (even though it would be advisable to validate the model). That is, it is useful especially when data are obtained from a project and the building (or the energy renovation) has not been constructed yet.
- The main advantages of the RC model are its lower computational times, as well as its accuracy to represent the thermal behaviour of the dwelling “as built”, and not “as

projected". Thus, it is quite useful to evaluate the real savings of a specific energy renovation.

- Solar gains in RC models must be carefully considered. The effective area methodology, followed in this Thesis, is a useful way to include these gains in the model. However, in this case, model results are only applicable to the months that are close to the periods in which data used to define the model were obtained.
- RC models are quite useful when the thermal performance of a particular building or dwelling is evaluated, whereas TRNSYS model presents more flexibility when different strategies are evaluated, especially on energy systems.
- Thermal improvements on roof, and especially, on façade have given good payback periods in the majority of the assessed scenarios, amortizable in acceptable periods (2-15 years in the majority of the cases, depending on the assumed financial conditions r and ΔC)
- Control strategy of the heating system can play a significant role. Parameters such as boiler temperature slightly affects the energy consumption. Reducing it, the returning temperature is also reduced, enabling the condensing of the boiler, and then, increasing the seasonal performance of the boiler. In all studied cases, the thermal performance ranged between 0.96 and 0.99, depending on the combination of control parameters.
- Economic results are quite sensitive to several values difficult to predict accurately, such as the yearly increase of fuel costs. Similarly, not only environmental, but also exergy results, are very sensitive to the P.E. factor of the electricity production.
- The exergy concept is a useful tool to assess thermal performance in buildings under a holistic approach. It complements and gives a more rational analysis than an analysis solely based on the energy approach.
- Most exergy losses in the case study presented in chapter 8 cannot be identified using energy analysis such as the exergy losses of heating systems based on combustion or electrical resistance, losses between the energy demand and the energy supplied by the emission system (depending on emission system, differences on exergy efficiency varies from 0.12, using an electric heater to 0.52 using very low temperature floor heating).

- Exergy analysis can support the development of improved systems with reduced exergy losses and thus reduced high quality energy input. It identifies which components of a given system are more responsible for the losses, and hence, more responsible for the required input or resources.

3 Diffusion of the results

Even though some results have been already published, the diffusion of the results is, at the time of writing these lines, under process. The main relevant contributions to the dissemination of the results at international and national level so far are subsequently listed.

3.1.1 International Journals

- J. Terés-Zubiaga, K. Martin, A. Erkoreka, J.M. Sala, Field assessment of thermal behaviour of social housing apartments in Bilbao, Northern Spain, *Energy and Buildings*, 67 (2013) 118-135.
- J. Terés-Zubiaga, S.C. Jansen, P. Luscuere, J.M. Sala, Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement, *Energy and Buildings*, 64 (2013) 359-371.
- S.C. Jansen, J. Terés Zubiaga, P.G. Luscuere, The exergy approach for evaluating and developing an energy system for a social dwelling", *Energy & Buildings*, 55 (2012) 693-703.
- V. J. Del Campo Díaz, J. Terés Zubiaga, "Experimental Investigation of Demand Controlled Ventilation Systems: a Suitable Alternative for Controlling Ventilation in Dwellings." *Journal of Energy and Power Engineering*, 6 - 10 (2012). Pag. 1553-1559.

3.1.2 National Journals

- J. Terés Zubiaga, L. Arrien Elguezabal, J. M. Sala Lizarraga "Panorámica de la rehabilitación en Europa. Normativa e incentivos en 4 países de la U.E.: Inglaterra, Alemania, Francia y España". *Revista de Edificación*. (2011) (Accepted).
- V. J. Del Campo Díaz, J. Terés Zubiaga, (2010) "Ventilación en Viviendas: El reto de una ventilación eficaz y Eficiente". *Revista de Edificación*. N 39-40. Pag: 120-128.

3.1.3 International Conferences

- J. Terés Zubiaga, Iker González Pino, Álvaro Campos Celador, Estibaliz Pérez Iribarren, José María Sala Lizarraga. "An Exergy Application for Assessment of Dwellings Renovation." III European Conference on Energy Efficiency and Sustainability in Architecture and Planning. San Sebastián, (2012).
- J. Terés Zubiaga, A. Campos Celador, E. Pérez Iribarren, I. González Pino, J. M. Sala Lizarraga "PCM Possibilities in the Restoration of Public Housing" II European Conference on Energy Efficiency and Sustainability in Architecture and Planing. San Sebastián, (2011).
- E. Pérez Iribarren, L.A. del Portillo Valdés, J.M. Sala Lizarraga, J. Terés Zubiaga, "Influence of durability on a modular building life cycle" XII DBMC. International Conference on Durability of Building Materials and Components, Porto, (2011).

3.1.4 National Conferences

- Carlos García-Gafaro, César Escudero-Revilla, Gonzalo Diarce Belloso, Jon Terés Zubiaga, Moisés Odriozola Maritorena. "Caracterización Térmica de Viviendas a Partir de Monitorización e Identificación de Parámetros" VIII Congreso Nacional de Ingeniería Termodinámica, Burgos, (2013).
- Jon Terés Zubiaga. "Thermal Characterization of retrofiting systems. Monitoring." III Jornadas de Rehabilitación de Edificios. Bilbao, (2012).
- J. Terés Zubiaga, E. Pérez Iribarren, A. Campos Celador, J.M. Sala Lizarraga, M. Olaizola Maritorena, "Estudio de la Aplicación de Materiales de Cambio de Fase en Rehabilitación de Edificios de Viviendas" VII Congreso Nacional de Ingeniería Termodinámica, Bilbao, (2011).
- E. Pérez Iribarren, J. Terés Zubiaga, L.A. del Portillo Valdés, M. Olaizola Maritorena, A. Campos Celador, "Aplicación de la Exergía como indicador Ambiental de los edificios." VII Congreso Nacional de Ingeniería Termodinámica, Bilbao, (2011).

3 more papers are currently under preparation for their publication in several International Journals.

4 Future directions

Although this PhD Thesis finishes here, the research work is still in progress. Different directions have been identified to carry on with it in the future. Thus, this thesis sets up the bases for future works, i.e. adjusted and validated models, a huge data base from field studies or a defined methodology. All of these bases can be integrated on the research lines that the Energy System Plant of the L.C.C.E. (see Fig. 2.1. in Chapter 2) will be carried out in the future.

Thus, following mentioned picture, field monitoring studies have been described in Chapter 3 and 4, where a huge amount of data has been obtained. In chapter 5 a validated TRNSYS model, which can be used as reference model in this plant, has been developed. Several combinations of actions on passive and active systems have been developed in Chapter 7, which can be used as a reference in future tests of the plant. Exergy approach has been proved in Chapter 8 as a useful tool to evaluate different energy performance in buildings.

4.1 Future works

4.1.1 Related to experimental part

Related to Chapter 3, it could be interesting to carry out further research about the influence of the occupants on energy consumption and indoor comfort. Many aspects which are strongly dependent on the occupants, such as the heating system usage, ventilation patterns, setpoint temperatures or window shutters closing at night, involve great variations on the final energy consumption of the building.

A sample of ten different dwellings was studied in Chapter 3. Some of them presented a low U- value in façade, some of them presented a high C-value in façade, and two of them presented a high U -value and a low C- value in façade at the same time. However, none of them had a façade with both low U-Value and high C- value. It could be interesting to study the thermal behaviour of a dwelling with these features in further research.

Obtaining accurate data on energy consumption was one of the main problems met during that field study. Energy bills which are available every two months were the main source of uncertainty. In most cases, they don't disaggregate between energy consumption for DHW and heating or other uses. For this reason, some assumptions had to be made. However, given that temperature and humidity data were taken with a 10 min time step, trying to get consumption data in similar time steps would be recommended in order to obtain more accurate analysis.

Thus, increasing the amount of dwellings to be monitored, or collecting data in other dwellings during shorter periods of time, would be useful in order to have more accurate information about the Social Dwelling Sector.

The risk of cold homes in Spain is a factor to be taken into account. Although this problem could be only linked to northern countries, this research has shown that, at least in the social housing sector, cold homes can become a real problem. This problem will be aggravated in the near future due to the economic crisis and the steady increment of the energy prices. Even though this field is out of the scope of this thesis, the interest of studies in this field should be highlighted when further research is carried out.

Problems related to Co-heating test must be checked in detail. Even though some hypothesis has been presented in Chapter 4, it should be interesting to compare results obtained in this dwelling to results obtained from other dwelling, and identify which was exactly the problem.

4.1.2 Related to building models

Some ideas for future works can be deduced from this part of the thesis, which has been devoted to describing the developed mathematical models. Thus, one of the main challenges of the works identified with the end of this PhD Thesis is those related to building models, and specifically, to the interaction amongst both building models and the Energy System Testing Plant of the LCCE.

First of all, it would be interesting to calculate the characteristic parameters based on data collected after windows replacement. This way, a real and very accurate value of energy saving attributed to windows replacement would be obtained for the winter period. Besides, this value can help to identify and clarify the problems found with the co-heating test, using sets of data from both monitoring periods, presented in the Chapter 4 of this thesis.

The RC model can be improved, by modifying the calculations to obtain energy demand instead of energy consumption. This variation will involve introducing a modular heat input (instead an on-off heat input) as a function of indoor air temperature, and not as a previously fixed value (on-off) as currently does. Including the possibility of adding a schedule of internal gains must also be part of the model improvement. In this way, a schedule of internal gains will be assumed, which will make a more flexible model available.

Once the RC model is improved, results of the RC model would be in the same conditions of those obtained by the TRNSYS model, and comparison of absolute values results would be easier. Moreover, the RC model will increase its capability of simulating with operating conditions closer to the real use of the dwelling or building, and so, obtaining absolute values of consumptions more adjusted to those the case study will have during its lifespan.

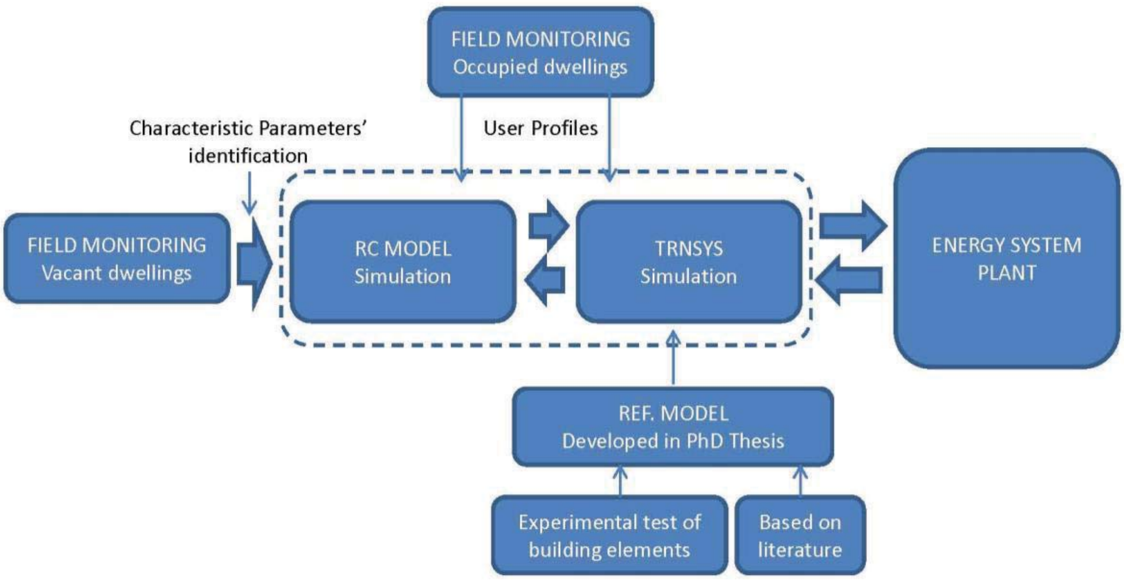


Fig. 9. 1. Interaction of monitoring studies, simulations and Energy System Plant

Moreover, this fact would make the aforementioned interaction between the TRNSYS model and the RC model easier. The possibility of making it easy to work with the interaction of both models must be studied. I.e. using the RC model to represent the passive elements of the building, and TRNSYS to represent the active part (energy systems) of the building, interacting both models with each other, in order to take advantage of the benefits of both models. This interaction would integrate the work flow with the Energy System Plant, linking the three lines of the mentioned plant (Field studies, Laboratory experimental data and simulations). The proposed interaction amongst the different parts is shown in Fig. 9. 1.

There would be two different ways of working, depending on the sources of data and the aim of the work carried out by the plant:

- One of them is when the study case is not a specific building, but the energy system. In this case, reference building model is the TRNSYS model defined in this thesis, which can be run assuming different energy renovation levels, based on the different combinations presented in Chapter 7. Moreover, thermal characteristics of different retrofitting solutions can be tested in laboratory, for obtaining their thermal characteristics (which define the solution behaviour under dynamic conditions) and including them in a TRNSYS model. Thus, model can also simulate new construction elements and retrofitting solutions tested in Laboratory, in order to assess how the tested energy system would work with a specific renovation measure. The workflow scheme is depicted in Fig. 9. 2.

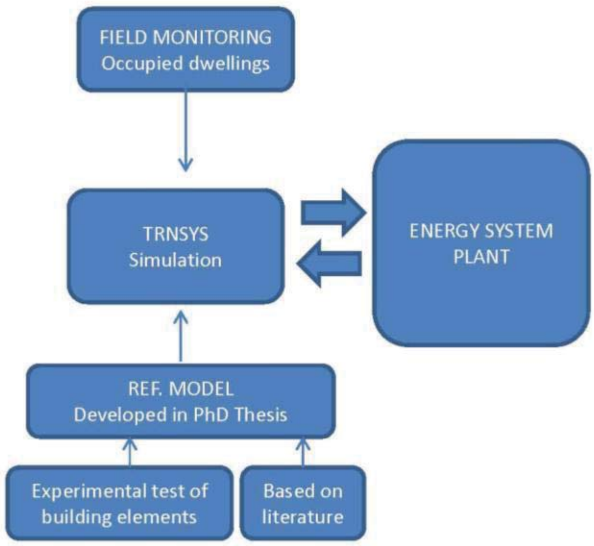


Fig. 9. 2. Workflow when the object of the test is the energy system itself

- The other one is when the tested heating system is wanted to be applied to a specific dwelling or building. In this case, TRNSYS model energy demands are not fed by TYPE 56, but by the RC model, whose characteristics parameters are obtained previously by a monitoring. The workflow scheme in this case is depicted in Fig. 9. 3.

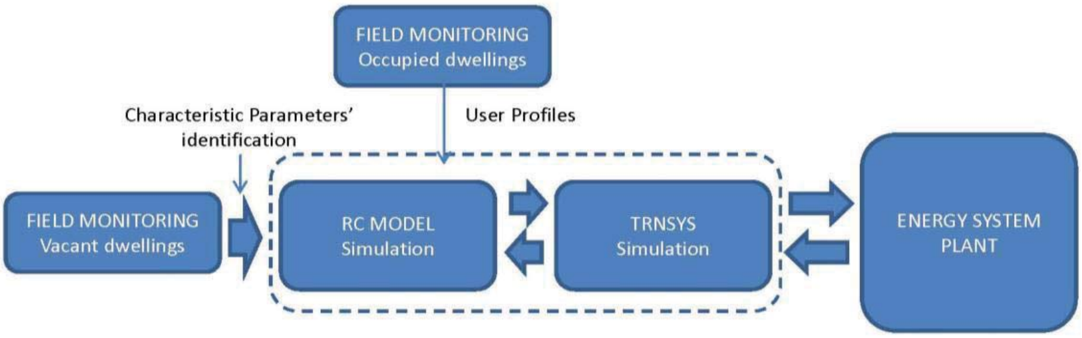


Fig. 9. 3. Workflow when the object of the test is the interaction between the energy system and a given building

Taking into account these workflows, it would be interesting to carry out experimental tests under dynamic conditions of different façade solutions (with and without ESM) in order to create a data base which can be useful for feeding the TRNSYS model, as well as for being as a reference for other research lines.

4.1.3 Related to simulations

The TRNSYS model developed for the selected building gives a huge amount of possibilities on studying the influence of many factors on the energy performance of the dwelling. Simulations presented in Chapter 7 are only a small example of the capabilities of the model. Hence, some ideas of future works using the developed model are presented in the following:

4.1.3.1 Passive elements

Exploring the effects of different insulation thickness and the optimal thickness on all the climatic areas in Spain could be an interesting work to develop in the future research, as well as keeping on looking for the best ESM combinations in each climatic area. In this way, the most suitable solutions for each climatic area would be identified.

Mentioned assessment can be carried out under a multi-criteria analysis, using the decision tree methodology. It would be recommended to define a set of criteria by means of identifying the most significant parameters to be evaluated, and weighting them according to its relative importance. Developing this methodology would allow to compare different measurement combinations under different aspects such as economic, energy, environmental, comfort issues, obtaining a global indicator to compare different renovation strategies.

4.1.3.2 Energy system

Only one heating system has been assessed in this chapter (Natural gas condensing boiler with high temperature radiators). More possibilities on heating systems are recommended to evaluate in further analysis, so to explore the differences on energy consumption. Comparing condensing and typical boiler combined with floor heating, low temperature radiators, or differences in these systems with a central or individual boiler, as well as the so called adaptive control, are possibilities to analyise in further analysis.

Moreover, several small adjustments can be done in the models. As an example, Control B can be adjusted to represent in a more accurate way the flexibility of the thermostatic valves of room radiators.

The developed models have been defined to evaluate the thermal performance of a building in a temperate climate on winter conditions. For that reason, no especial attention has been paid to define with accuracy adaptive behaviour in summer. For further analysis, however, defining in a better way those conditions (such as ventilation rates or window shutters operation) is advisable, especially if cooling systems, thermal performance of building in summer, and other climatic areas are studied with this model.

4.1.3.3 Other issues

Finally, developing a simplified methodology for evaluating thermal comfort based mainly on indoor temperature (and then, avoiding to define parameters such as clothing factor and metabolic rate) would be interesting. That methodology must fix the comfort limits (19-21, 20-22) and a discomfort value would be obtained as a result of the product of temperature difference to those limits and the duration of the period out of comfort limits.

A handbook which gathers effects of different energy renovations on different building types taking into account economic, energy and environmental issues will be developed, obtained from the combination of experimental tests and simulations.

When economic aspects of ESM were assessed, the great influence of some variables such as r and c (expected yearly increasing natural gas cost) was shown. A sensitivity analysis on the influence of mentioned parameters, as well as other such as the used fuel type, on economic availability of energy renovations is recommended in further analysis.

Input parameters for calculating comfort (clothing factor, metabolic rate…) can be more representative. More detailed schedules, adjusted to the room, season, and the hour of the day can be defined in order to obtain a more accurate analysis. Similarly, adjustments in assumed parameters and function for modelling the different control strategies can be carried out.

Further analysis both on the influence of the control parameters (boiler temperature, radiators temperature...) must be carried out in the future. Even thought involved savings are not very high, slight savings can be achieved just modifying those parameters to the optimal ones, making the optimal operation of the heating system and its elements easier.

Analogously, optimization studies of the different parameters in different circumstances (climate areas, buildings constructed in different periods…) must be carried out based on the developed work in this chapter. Energy consumption results could be classified by references buildings and references profiles, for obtaining representative energy consumption values by areas, allowing to detect renovation priority areas.

APPENDICES

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Appendix 1.1. Fuel Poverty. Literature review

The fuel poverty is mainly a consequence of the combination of three causes: poor energy efficiency of housing, high energy prices and low household incomes. According to this, three different indicators can be used to evaluate fuel poverty [163]:

- Households with difficulties to pay for energy bills
- Low thermal quality of the accommodation
- Winter over mortality rate, as a consequence of under heated homes

The first and second indicators can be defined as "causes of fuel poverty", whereas the third one is a consequence of it.

Similar terms are used by other authors, such as [164], who highlight that "*fuel poverty is different to poverty. Poverty can be eradicated through income support, whereas the eradication of fuel poverty requires not just income subsidisation but* ***also crucial investment in the capital stock (i.e. the household)****, as fuel poverty is caused by a complex interaction between low income and domestic energy inefficiency*"

1 Defining fuel poverty

However, before any kind of definition, the use of terms requires some discussion. At the EU level, there is a conflicting use of the terms *Energy Poverty* and *Fuel Poverty,* as D. Ürge-Vorsatz and S. Tirado Herrrero noted in [165]. On the one hand, *fuel poverty* is the most commonly used in English-speaking nations as the UK (e.g. [166], where the concept originated, and Ireland [167]. On the other hand, other references from Central and Eastern Europe [168] refer the same concept as *energy poverty*. Nevertheless, some authors speak of *energy poverty* referring to the lack of access of quality energy carriers [169].

In the original definitions that are currently prevalent in UK, fuel poverty is described as a household's inability to ensure an adequate thermal regime in its living space. D. Ürge-Vorsatz and S. Tirado Herrero give a broader definition of *energy poverty*, which encompasses the various sorts of affordability-related challenges of the provision of adequate energy services to the domestic space. Thus, it represents situations in which households with access to modern energy carriers cannot comfortably satisfy their energy service needs, be it because of their inability to afford sufficient energy services and/or because of the disproportional costs they have to bear for those energy services [165]

Due to the scope of this thesis, focusing on thermal performance of buildings, the concept of *fuel poverty* is used in this work, *energy poverty* instead.

Nevertheless, despite of the fact of a huge amount of references can be found in literature focusing on fuel poverty, in 2013, only three EU member states had an official definition of fuel poverty (the United Kingdom, Republic of Ireland and France), as presented in [170].

The Irish government defines fuel poverty as "the inability to afford adequate warmth in a home, or the inability to achieve adequate warmth because of the energy inefficiency of the home" [171].

In France, a person is considered fuel poor "if he encounters particular difficulties in his accommodation in terms of energy supply related to the satisfaction of elementary needs, this being due to the inadequacy of financial resources or housing conditions" [172] (quoted by [170]).

In UK a fuel poor household is "one that cannot afford to keep adequately warm at reasonable cost. The most widely accepted definition of a fuel poor household is one which needs to spend more than 10% of its income on all fuel use and to heat its home to an adequate standard of warmth" [173].

2 Consequences of fuel poverty

As mentioned below quoting [164] fuel poverty is not synonymous with poverty. However, as [170] state, the two do certainly exacerbate each other; a low household income can cause households to restrict their use of heating, whilst high fuel costs, (perhaps resulting form an energy inefficient property), can put pressure on household budgets, leading to households relinquish other essential items. According to this, consequences of fuel poverty can be summarised in two main groups: the consequences related to economic factors as aforementioned giving up of other essential items such as food, and those ones related to the lowering of indoor temperatures (cold homes). Regarding to the first group, Christine Liddell found that children in fuel poor homes have been found to have poorer weight gain and lower levels of adequate nutritional intake, the so called "heat-or-eat" effect [174].

The major part of the three groups of consequences gathered in [170] could be actually included as a consequence of cold homes: health consequences, consequences on mental wellbeing and social contact and the most extreme consequence of fuel poverty, excess winter mortality (EWM).

Health consequences of belonging to a fuel poor household are wide ranging, from an increased likelihood of suffering from illnesses to an increased risk of suffering from asthma. There is also an increased likelihood of the use of health services by people living in cold homes. Some studies about this issue are referred in [170]

Mental wellbeing and social contact also are affected by living in cold homes. B. Harrington et al. presented in [175] effects such as depression, social isolation and constraints on mobility as consequences of living in a cold home.

But the phenomenon of excess winter mortality is without doubt, the most extreme consequence of cold homes. Low winter indoor temperatures are an important factor contributing to cold related morbidity and mortality [176]. Increased rates of mortality during cold weather were first noted almost a century ago (e.g. [177]), and they have been confirmed by an amount of studies "excess winter mortality". As affirmed in [178], cold indoor temperatures are strongly implicated in this effect, in that risks are especially great for residents of poorly insulated homes [179]

Thus, EWM is defined as "the surplus number of deaths occurring during the winter season (from December to March inclusive) compared with the average of the non-winter seasons" [180]. In his study of EWM across the EU14 from 1988 to 1997, Healy found that Portugal and Spain suffered from the highest levels of EWM, despite the general perception is that southern European countries are not affected by EWM (and indeed fuel poverty) due to their milder climates. In Table 2. 1 results of the analysis of EWM in EU-14 described by J. D. Healy are presented. The results showed that Portugal, Spain and Ireland had the highest seasonal variation in mortality in Europe. In the case of Spain presented an increase of some 21% (19.000 deaths).

	CSVM	95% CI		CSVM	95% CI
Austria	0.14	0.12 to 0.16	Ireland	0.21	0.18 to 0.24
Belgium	0.13	0.09 to 0.17	Italy	0.16	0.14 to 0.18
Denmark	0.12	0.10 to 0.14	Luxembourg	0.12	0.08 to 0.16
Finland	0.10	0.07 to 0.13	Netherlands	0.11	0.09 to 0.13
France	0.13	0.11 to 0.15	Portugal	0.28	0.25 to 0.31
Germany	0.11	0.09 to 0.13	Spain	0.21	0.19 to 0.23
Greece	0.18	0.15 to 0.21	UK	0.18	0.16 to 0.20
Mean	*0.16*	*0.14 to 0.18*			

Table 2. 1. Coefficient of seasonal variation in mortality (CSVM) in EU-14 (mean 1988-97)

This situation can be attributed to poor thermal efficiency standards, and suggests an improvement in standards could reduce the levels of excess deaths. In a paper where results of a survey carried out in Vienna during 2009 and 2010, K.M. Brunner et al, affirmed, in fact, that limit financial resources are not only evident in the indoor standards and operation conditions of the dwelling. They are also evident in the state of the dwelling (only a small share of people with low incomes live in thermally improved energy efficient flats, and many of them live in badly insulated buildings with leaking windows). And finally, income does not only limit the choice of dwelling and its maintenance, but is frequently also reflected in household equipment and appliances [35].

Thus, adaptation of buildings is therefore the key factor to reducing the levels of mortality resulting from cold winter temperatures (and hot summer temperatures as well), and energy efficiency measures may be able to address both issues.

3 Energy renovations to tackling fuel poverty

Until few years ago (and still nowadays), tackling fuel poverty has been one of the main incentives (sometimes, even more than ecological reasons) to carry out energy renovations in buildings.

Hence, many studies about energy efficiency and the suitability of energy renovations under the perspective of tackling the fuel poverty can be found in literature, such as in [62] where it is investigated possible improvements in the methodology for identification of cold homes; In [181], where explanatory factors for persistent cold temperatures in home which have received heating improvements are investigated, the concept of a comfortable and healthy home is called into question by the behaviour of occupants who prefer a cooler home, even when this preference involves temperatures low enough to present a risk to health. Thus, the necessity of conveying the range of tolerable living-conditions to the most vulnerable sections of the population is set up by the authors of this reference.

4 Large-scale Studies about fuel poverty

As previously mentioned, many studies about fuel poverty have been undertaken in the last years. In [178], the five main studies published between 2000 and 2009 focusing on the impacts of cold housing in human health are deeply analysed. Amongst these five studies, the British Warm Front project can be found, which are briefly described below.

Several of aforementioned studies have been developed into the so called Warm Front Program. Warm Front (WF) is a UK government's programme for tackling fuel poverty in English households, providing grant-funded packages of insulation and heating improvements. Through the scheme has significantly raised average indoor temperatures in UK [176]. Based on the results presented in [182], at 16.5 ºC (the current estimated temperature of housing in Great Britain), 30% of the potential energy saving will be taken as an increase in the comfort temperature, and the rest, as energy savings. It is not until temperatures are around 19 ºC that 80% is taken as an energy saving.

The other four studies mentioned in that review are listed below. They are:

- CHP: Scottish Central Heating Program (UK)
- HIHS & HHHS: Housing, Insulation and Health Study & Housing, Heating and Health Study (New Zeland)
- NATCEN (UK)

- C-SNAP (US)

Interesting analysis of the results of these five programs on human health can be found in [178]

5 The extent of fuel poverty in the EU. The case of Spain

Concerns about fuel poverty at the EU level have increased during last years. The European Fuel Poverty and Energy Efficiency (EPEE) project, which ran from 2006 to 2009, was carried out to assess fuel poverty policy in United Kingdom, Spain, Italy Belgium and France, and significant differences were found across these five member states. Unlike the United Kingdom, which was found to have the greatest level of knowledge and understanding of fuel poverty, in Spain "fuel poverty is not recognised at any significant level… there is no perception of fuel poverty as a compelling social problem" [183]. The lack of awareness about fuel poverty is alarming taking into account the evidence indicates that southern European countries, (and also eastern European countries with Bulgaria, Cyprus and Romania) suffer from the highest levels of fuel poverty in Europe according to the three indicators presented by H. Thomson and C. Snell and previously mentioned (Ability to pay to keep the home adequately warm, arrears on utility bills and the presence of leaking roof, damp walls or rotten windows).

Besides, as can deduced from data previously presented in Table 2. 1, one of the direct consequences of fuel poverty, the aforementioned EWM was already high in Spain years ago, in the last 90's, showing that it is not a recent problem in Spain.

Reinforcing this point, a study [184] was recently conducted aimed at exploring and raising awareness about the dual relationship between fuel poverty and unemployment. It also shows the increase of this problem in Spain in the last years and highlights building retrofitting as one of the most effective ways to tackle fuel poverty.

Appendix 1.2. GHG emissions and energy of building stock in the Basque Country

1 Residential building stock. GHG Emissions

Regarding GHG (Greenhouse gas) emissions of residential building stock in the Basque Country, some values are presented in this section. In Fig. 2. 2, distribution of GHG emissions by sectors in 2010 is depicted.

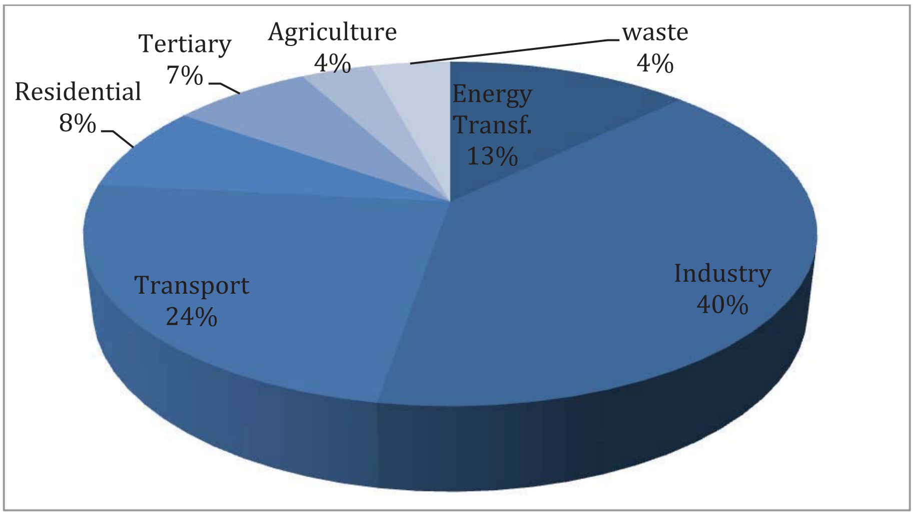


Fig. 2. 2. GHG emissions by sectors in the Basque Country in 2010 (EUSTAT, 2011)

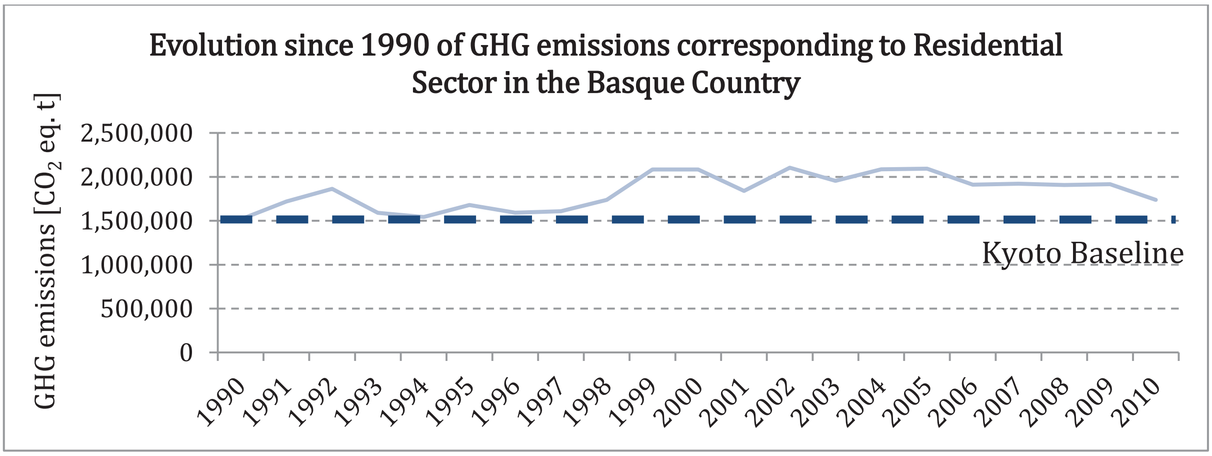


Fig. 2. 3. GHG emissions corresponding to Basque residential sector (EUSTAT, 2011)

The marked industrial profile of the region influences significantly the distribution. As far as construction sector is concerned, it was responsible of about 15% of the total GHG emissions, 8% of which corresponded to residential sector and 7% to tertiary sector.

Evolution of GHG emissions since 1990 for the residential sector in the Basque Country is presented in Fig. 2. 3.

As shown in Fig. 2. 3., between 2000-2006 annual GHG emissions were about 25% higher than the baseline fixed by Kyoto protocol. Despite the fact that the trend has changed in the last years, residential sector emissions are still far away from the 20/20/20 targets, i.e., a 20% reduction in EU greenhouse gas emissions from 1990 levels.

Thus, two strategies must be followed to achieve the mentioned targets. On the one hand, all new buildings should be low energy consumers, even nearly zero - energy buildings. But that achievement is not enough, because the major challenge is in the existing building stock. Potential of thermal improvements in existing buildings is the key strategy in the way to 20/20/20 targets. Likewise, energy efficiency measures implementation, both in new and existing buildings, must take into account the reduction of energy demand and the inclusion of renewable energy sources.

2 Energy use in Basque dwellings

According to data presented by EVE, mean consumption per dwelling in the Basque Country is about 0.69 TOE per year, being annual electricity consumption 3370 kWh/dwelling and natural gas consumption 5930 kWh/dwelling. Renewable energy is spreading out steadily, but it still represents about the 5% of the whole energy use, according to the same source.

Energy consumption in the Basque Country presents similar distribution to the average Spanish values. The main energy consumption in dwellings corresponds to heating systems, which represent about 40% in the Northern Atlantic Area in Spain (where the Basque Country is located) and 47% in Spain, according to IDAE data. Distribution of energy consumption in Northern Atlantic Spain is depicted in Fig. 2. 4.

Looking at these data, a quickly introduction of policies leaded to burst energy efficiency and renewable energy in building sector should be expected, in a similar way to other sectors (Industry and transport). However, the result in building sector has been slower than in the other cases. IDAE gives some reasons of this delay:

- Sector dispersal
- Long life of buildings and building services
- Very dispersed energy consumption
- Energy costs are not usually paid by the building developer, but by the user.
- Energy issues have not been taken into account in the purchase of a building This situation may change from now on with the buildings energy certification.

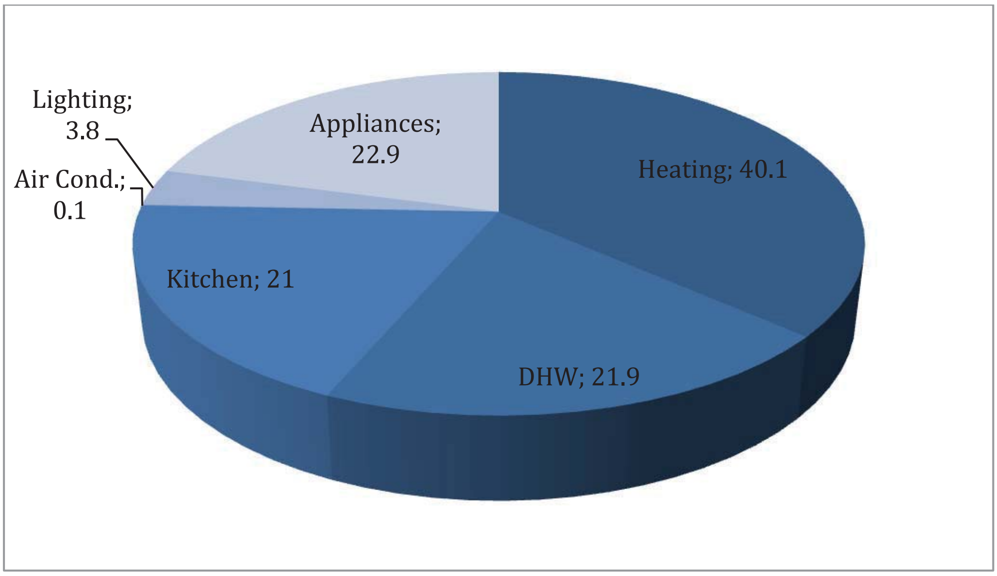


Fig. 2. 4. Reparto Atlántico Norte (Análisis del consume energético del sector residencial en España 2011 IDAE)

2.1 Heating and cooling systems

Let's focus on heating and cooling systems, whose energy consumption is closely linked to the thermal performance of buildings. As deduced from Fig. 2. 4, the use of air conditioning systems in dwellings is negligible in the Basque Country. On the contrary, heating systems are responsible of more than 40% of energy consumption in residential buildings. Almost the total of the Basque dwellings (91%, according to data obtained from EUSTAT) have some kind of heating system, and its mean annual use is 4.6 months. In its survey, EUSTAT identified three different kinds of heating systems:

- Central heating, when the same heating system is shared by different dwellings in one or several buildings.
- Individual system, when heating corresponds only to one dwelling.
- Punctual system, if only a device, (fixed or mobile) is used to heat one or several rooms of the dwelling.

In the coastal climate area, even though it is not the majority of the cases, an important share of punctual systems can be found in dwellings (34%). The most used type is individual system (47%), and only a 19% of the dwellings present central system.

Shares change in continental climate area. The use of punctual systems is almost negligible (6%), and central heating systems are more widespread (34%). However, the majority of the systems are also individual (60%)

A brief comment about the commonly used fuel is presented next. The share of heating systems according to the used fuel is depicted in Fig. 2. 5. Some years ago, when there was a bet for natural gas, a great effort to develop gas infrastructures was carried out. As a result, gas (usually natural gas, but also propane in some cases) is used in a majority of the houses (55%). Besides, electricity use for heating is not negligible at all, since 21% of the dwellings used it.

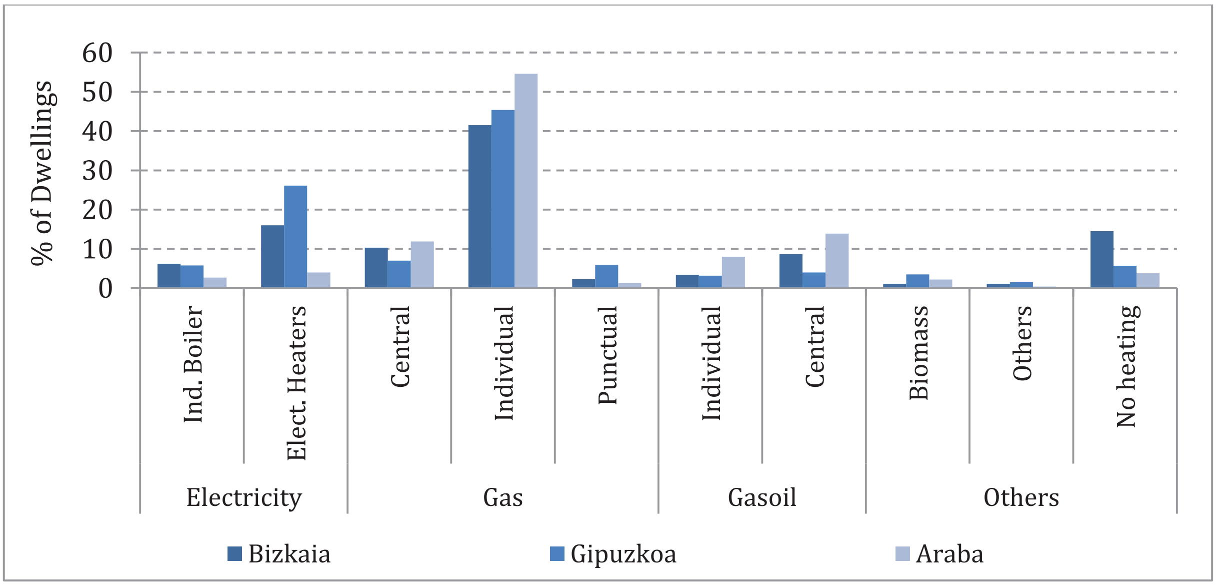


Fig. 2. 5. Heating systems (according to fuel) used in Basque dwellings (EUSTAT 2008)

However, in Social Dwelling. although natural gas-based heating systems are the most common in dwellings of the Basque Country, many Social Housing apartments have no natural gas heating installation. This can be explained because, even though the use of this kind of heating systems is not especially expensive, it requires an important first investment in installation. As a consequence, other heating systems, usually less inefficient and more expensive during their lifespan, such as electric heaters, are used. Due to the combination of high energy bills (e.g. electricity) and low thermal quality of some buildings, heating is not performed with usual comfort standards in a significant amount of social dwellings. In fact this combination leads to logged indoor temperatures lower than standard, and as a result, to the aforementioned situations of cold homes and fuel poverty.

2.2 Energy consumption in dwellings according to their age

A study on energy consumption in buildings in the Basque Country was carried out by EVE (Basque Energy Agency) in 2012. This study was performed by means of model simulations and took into account the climatic area and the building construction year. Two different climatic areas were defined for the Basque Country: a coastal and a continental climatic area. A reference building defined according to the Spanish Technical Building Code (CTE) requirements was taken into consideration. This reference building is, in short, a building with the same conditions as the studied one, but reaching the minimal energy requirements laid down by the CTE. As shown in Table 2. 2, the energy consumption for buildings constructed before 1979 is, on average, two times to the energy consumption of the reference building in a continental climate, and 78% more in the case of buildings in coastal climate area.

Construction year	Energy Consumption (CTE req. = 1)	
	Coast	Continental
Before 1979	1.78	2.01
1979-1985	1.39	1.59
1986-2007	1.18	1.35
After 2007	0.64	0.73

Table 2. 2. Energy consumption of the building stock in relation to minimal requirements of CTE (EVE)

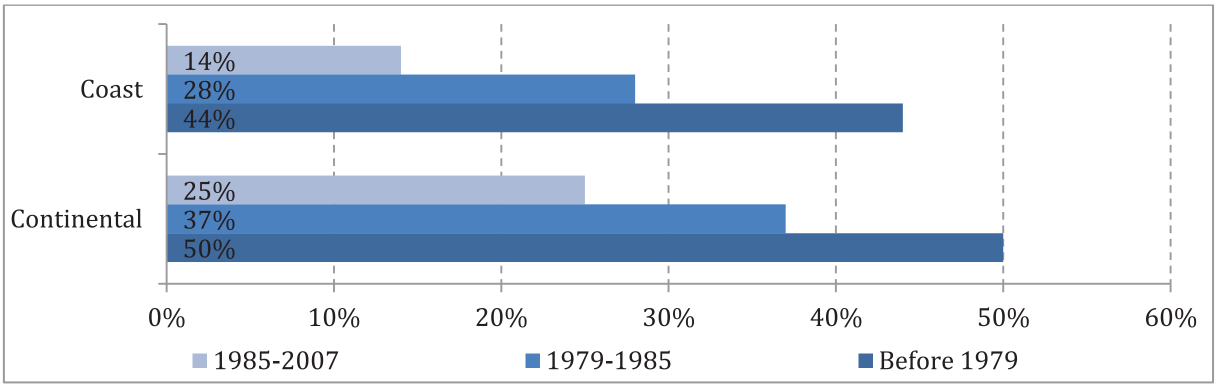


Fig. 2. 6 (Energy consumption in dwellings by construction year, 2012, EVE)

It can also be observed that the newest buildings (built after 2007) have a mean energy consumption of almost a third of those constructed before 1979. These data reinforce the idea presented previously: the high potential of energy improvement that Basque building stock has. In aforementioned study, the Basque Energy Agency calculated the potential of energy improvement in buildings constructed before 2007. Potential energy savings for heating was estimated to be around 40% of current heating consumption in those dwellings. Some of the results obtained in that work are depicted in Fig. 2. 6.

2.3 Economic issues

Finally, economic aftermaths of the energy use in dwellings are dealt with in this section. Energy bills, as it will be mentioned in the next chapter, can play an important role in social aspects, especially in some sectors of the population.

According to data obtained from the Basque Energy Agency, electricity cost in dwellings reached a total value of 582 M€ in year 2011 (with a mean cost of 20.3 c€/kWh), whereas natural gas cost in the same year reached the figure of 203 M€ (with a mean cost of 6.7 c€/kWh). This means that the average energy expense per dwelling was 1008€ (686 € electricity, 322 € natural gas). This figure amounted the 2.4% of household incomes. However, it must be noted that this expense in energy has increased meaningfully in the last years, due to the increase of both electricity and natural gas prices. That increment can be clearly noticed in Fig. 2. 7, where the evolution of the energy bill per year is depicted, based on data obtained from EVE.

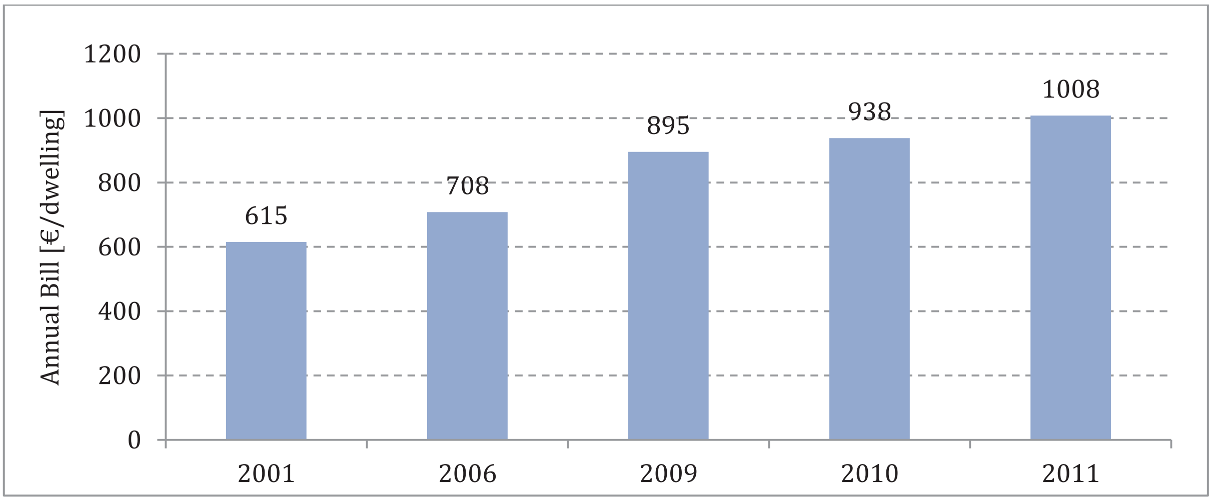


Fig. 2. 7. Annual energy expenses per dwelling (2012, EVE)

Appendix 3.1. Occupants' questionnaire

Bilbao Viviendas Etxebizitzak

enedi

CUESTIONARIO USUARIOS. ESTUDIO EFICIENCIA ENERGÍETICA ETXEBIZITZAK.

A) Comportamiento del usuario y concienciación

01. ¿qué importancia tiene el coste de la energía comparado con otros costes en la vivienda en la determinación del uso de su vivienda?

Muy importante – Importante – Ni importante ni no importante – Poco importante – nada importante – NS/NC

02. ¿Considera su vivienda más eficiente energéticamente que las demás?

Si – No – NS/NC

03. En caso de haber respondido SI la pregunta 02, ¿Cuáles de las siguientes características cres que hacen tu vivienda más eficiente que otras (seleccione todas las que considere)?

Diseño o características estructurales (Orientaciones, sombras...) – Comportamiento de la envolvente (aislantes, ventanas...) – Sistema de calefacción

04. ¿Suele dejar equipos en "Stand By" cuando no los está usando?

Nunca – Raramente – A veces – Habitualmente – Prácticamente siempre – No se aplica

05. ¿Suele apagar la televisión u otros equipamientos eléctricos cuando nadie está en la habitación durante más de 15 minutos?

Nunca – Raramente – A veces – Habitualmente – Prácticamente siempre – No se aplica

06. ¿Cuándo adquiere un nuevo electrodoméstico, considera importante su clase energética?

Nunca – Raramente – A veces – Habitualmente – Prácticamente siempre – No se aplica

07. ¿Cuál es su patrón de ventilación? ¿Durante cuánto tiempo tiene las ventanas abiertas? ¿En qué momento del día lo hace?

B) Consumo de energía.

08. Consumo anual de energía

Tipo	Cantidad	Unidades	Coste	
Electricidad		kW*h		€
Diesel		l		€
Butano		l		€
Gas Natural		m^3		€

09. Fuente

Facturas – Medidor – Otras

10. ¿Podría indicar, al menos aproximadamente, el consumo de energía mensual dedicado a calefacción durante el periodo de monitorización?

	E	F	M	A	M	J	J	A	S	O	N	D
Gas												
Elect												
Otras												

C) Descripción de la vivienda e instalaciones

Descripción de la vivienda

11. ¿Dispone de sistemas de sombreamiento?

Si – No

12. ¿Qué tipo de ventanas tiene la vivienda?

Marco
Vidrio
Grado de infiltración

13. ¿Cómo suele utilizar habitualmente las persianas (cuándo las baja)?

	Al anochecer	Al acostarse	Nunca
Salón			
Cocina			
Habitación 1			
Habitación 2			
Baño			

14. ¿Ha percibido en su vivienda problemas de humedad?

Si – No

15. Si ha respondido SI a la pregunta 13, ¿Dónde?

	Paredes	Techos	Suelos
Salón			
Cocina			
Habitación 1			
Habitación 2			
Baño			

Sistemas energéticos

Calefacción

16. ¿Tiene sistema de calefacción centralizado?

Si – No

17. ¿Tiene sistema de calefacción en la vivienda?

Si – No

18. **En caso de haber respondido sí a la pregunta 16, indique, aproximadamente, el uso típico de este sistema.**

Operación Mensual

	E	F	M	A	M	J	J	A	S	O	N	D
Operación sistema												

Operación diaria

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
L																								
M																								
X																								
J																								
V																								
S																								
D																								

19. **¿Tiene el sistema control de temperatura?**

Sí – No

20. **En caso de haber respondido SI la pregunta 18, indique cual es la temperatura de consigna. _**

21. **En caso de haberlos, ¿Purga los radiadores anualmente?**

Sí – No

22. **¿Utiliza otros aparatos de calefacción?**

Sí – No

23. **En caso de haber respondido si la pregunta 20, indique por favor qué tipo de estos aparatos emplea en su casa.**

	Número de unidades
Radiador eléctrico portable	
Calentador de aire	
Estufas de combustible	
Otros	

24. **¿Cuándo los utiliza (Ej: todas las tardes de invierno, algunas mañanas de invierno...)?**

25. **¿Se encuentran los emisores de calor (en caso de haberlos) libres de obstáculos?**

Sí – No

26. **En caso de existir, ¿Conoce el funcionamiento de la caldera?**

Sí – No

27. **Otras consideraciones al respecto del sistema de calor (Tipo de caldera, antigüedad...)**

Ventilación

28. **¿Tiene sistema de ventilación en la vivienda?**

Si – No

29. **Si es así, ¿Es centralizado?**

Si – No

30. **En caso de haber respondido sí a la pregunta 24, indique, aproximadamente, el uso típico de este sistema.**

Operación Mensual

	E	F	M	A	M	J	J	A	S	O	N	D
Operación sistema												

Operación diaria

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
L																								
M																								
X																								
J																								
V																								
S																								
D																								

31. **Otros comentarios referidos al sistema de ventilación.**

D) Calidad de Aire Interior

32. **¿Cómo describiría la temperatura típica de su vivienda en verano?**

Demasiado calurosa – Algo calurosa – Confortable – Algo fría – Muy fría

33. **¿Cómo definiría la estabilidad de la temperatura en su vivienda en verano, si 1 es "muy estable", y 5 es "muy variable"?**

1 – 2 – 3- 4 - 5

34. **¿Cómo se siente con la temperatura de su vivienda en verano?**

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

Bilbao Viviendas Etxebizitzak

35. ¿Cómo describiría la temperatura típica de su vivienda en invierno?

Demasiado calurosa – Algo calurosa – Confortable – Algo fría – Muy fría

36. ¿Cómo definiría la estabilidad de la temperatura en su vivienda en invierno, si 1 es "muy estable", y 5 es "muy variable"?

1 – 2 – 3- 4 - 5

37. ¿Cómo se siente con la temperatura de su vivienda en invierno?

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

38. Otros comentarios referentes a la temperatura

39. ¿Cómo definiría el movimiento de aire en su vivienda en verano, si 1 es "sin corriente", y 5 es "mucha corriente"?

1 – 2 – 3- 4 - 5

40. ¿Cómo se siente con el movimiento de aire de su vivienda en verano?

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

41. ¿Cómo definiría el movimiento de aire en su vivienda en invierno, si 1 es "muy estable", y 5 es "mucha corriente"?

1 – 2 – 3- 4 - 5

42. ¿Cómo se siente con el movimiento de aire de su vivienda en invierno?

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

43. Otros comentarios referentes a la temperatura

44. ¿Cómo definiría la calidad de aire interior en su vivienda durante el verano?

(Cargado) 1 – 2 – 3 – 4 – 5 (Fresco)
(Seco) 1 – 2 – 3 – 4 – 5 (Húmedo)
(sin olores) 1 – 2 – 3 – 4 – 5 (olores)

45. ¿Cómo se siente con la calidad de aire de su vivienda en verano?

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

46. ¿Cómo definiría la calidad de aire interior en su vivienda durante el invierno?

(Cargado) 1 – 2 – 3 – 4 – 5 (Fresco)
(Seco) 1 – 2 – 3 – 4 – 5 (Húmedo)
(Sin olores) 1 – 2 – 3 – 4 – 5 (olores)

47. ¿Cómo se siente con la calidad de aire de su vivienda en invierno?

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

48. Otros comentarios referentes a la Calidad de Aire

49. ¿Cómo definiría la cantidad de luz natural que entra en su vivienda por lo general?

Demasiada – Adecuada – Poca

50. ¿Experimenta brillos y deslumbramientos por el sol en algún sitio durante el día en su casa?

Sí – No

51. ¿Cómo se siente con la cantidad de luz natural que entra en su casa?

Muy contento – Contento – ni contento ni descontento – Descontento – Muy descontento

E Información Personal

52. ¿Cuánto tiempo lleva viviendo en esta vivienda?

53. Número de ocupantes permanentes en la vivienda.

54. Para cada uno de los ocupantes, completar la siguiente tabla:

Ocupante	Edad	Sexo (M/F)	Estatus (*)	Ocupación Aprox. de vivienda
1				
2				
3				
4				
5				

(*) 1: Trabajador a tiempo completo/ 2: Trabajador a tiempo parcial/ 3: Trabajo desde casa/ 4: Pensionista/ 5: Estudiante / 6:Parado

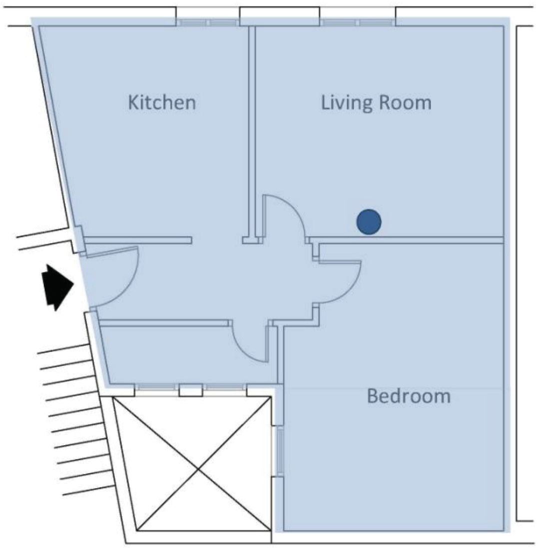
55. ¿Cómo cree que puede mejorarse el confort interior de su vivienda?

Appendix 3.2. Detailed data of monitoring

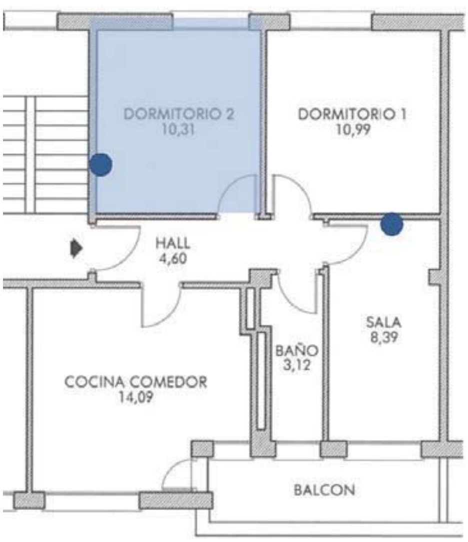
1 Geometric details of the dwellings and TH location

In this section 1 of the appendix, the geometrical features of the heating area of each dwelling, as well as the location of the TH, are presented.

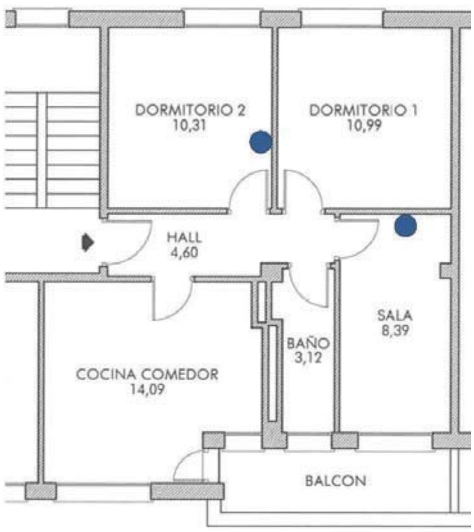
D1



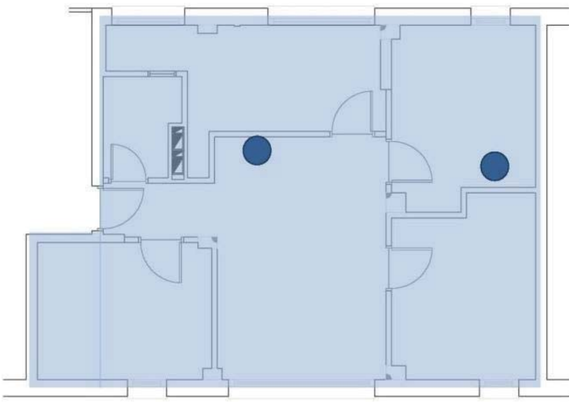
D2



D3

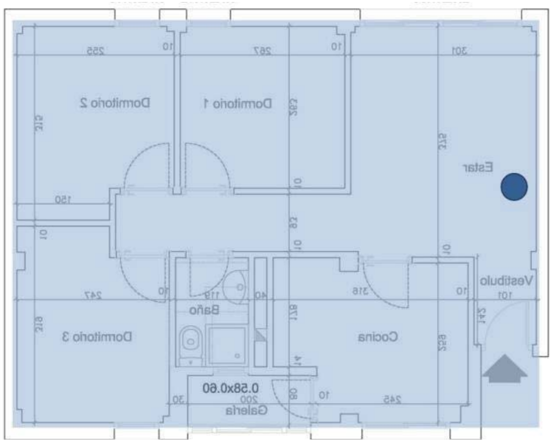


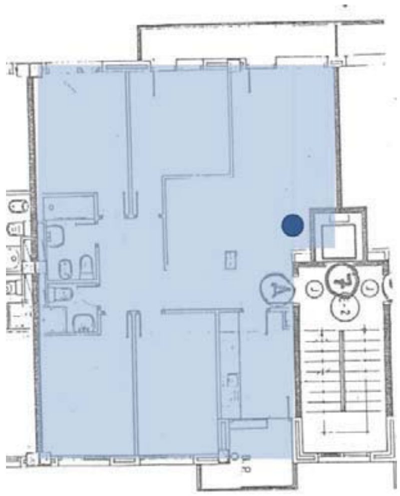
D4



D5

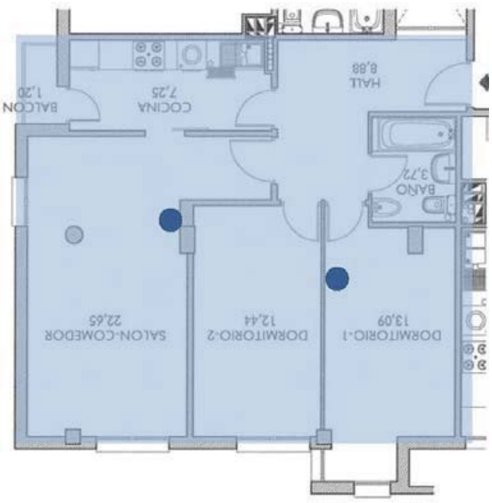
D6

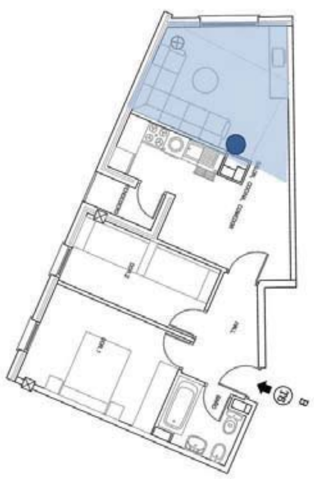




D7

D8



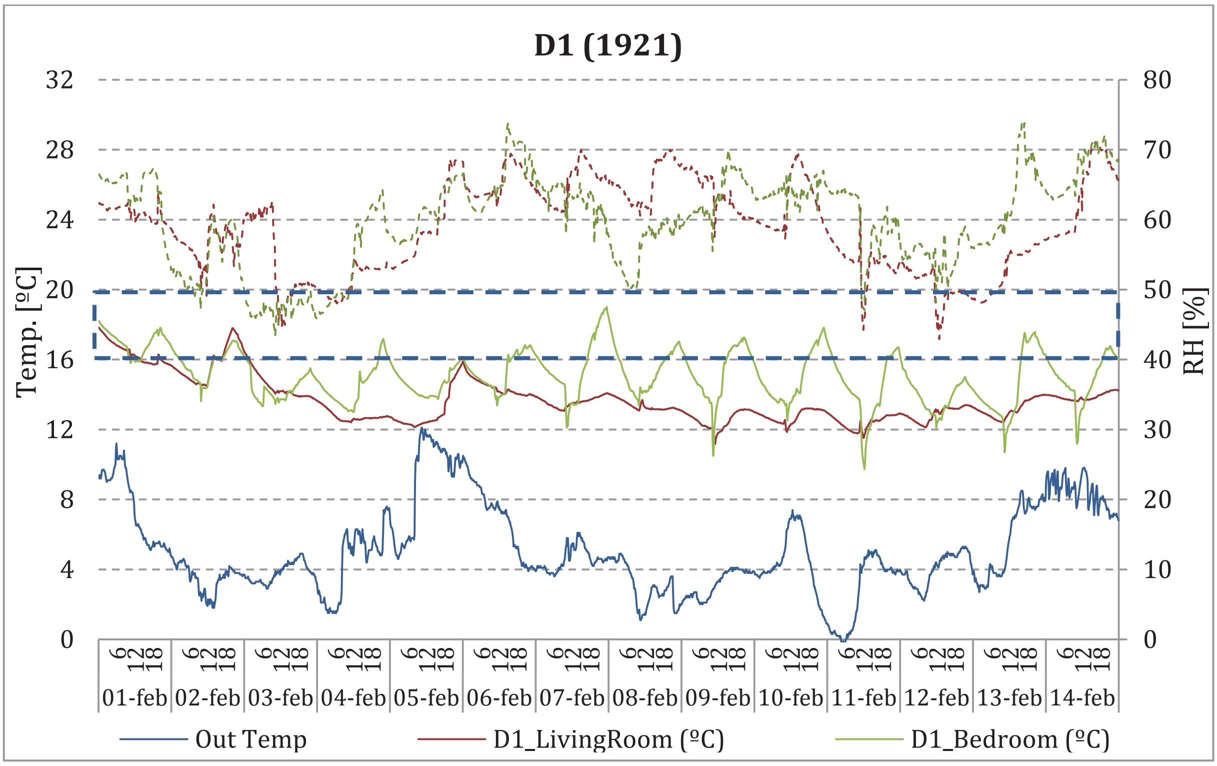


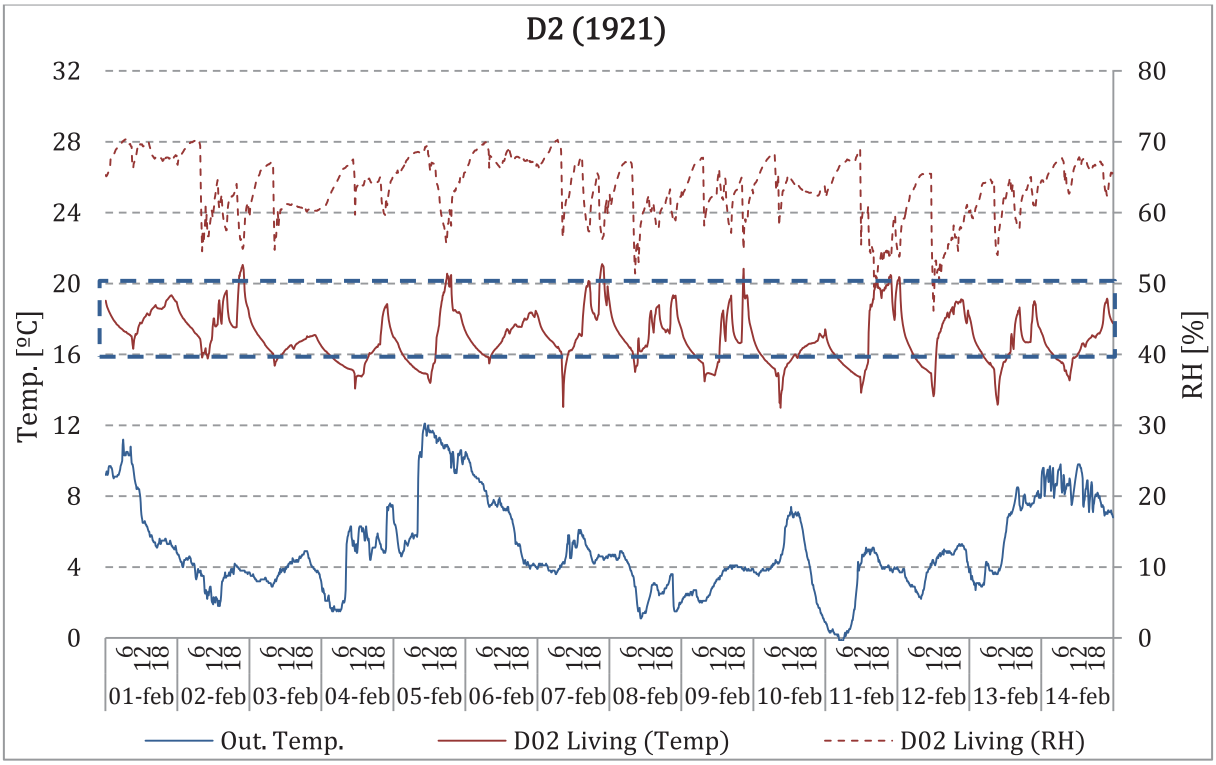
D9

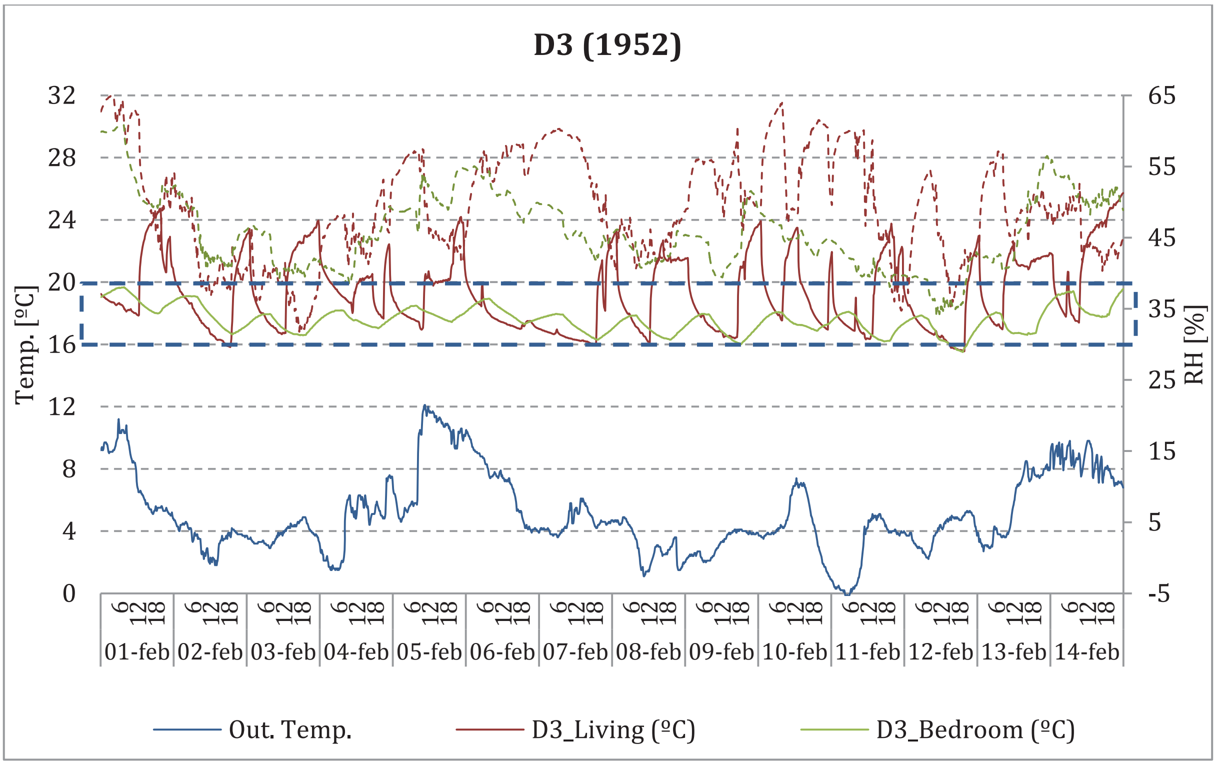
D10

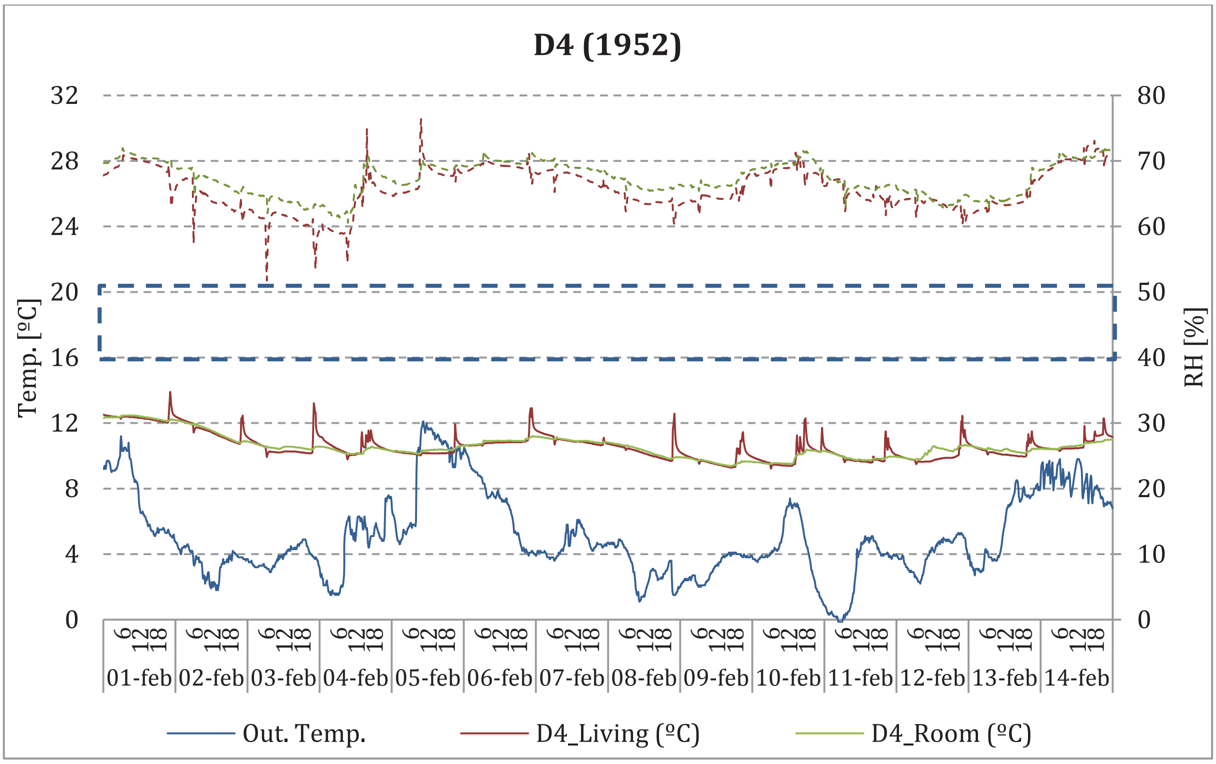
2 Winter graphs

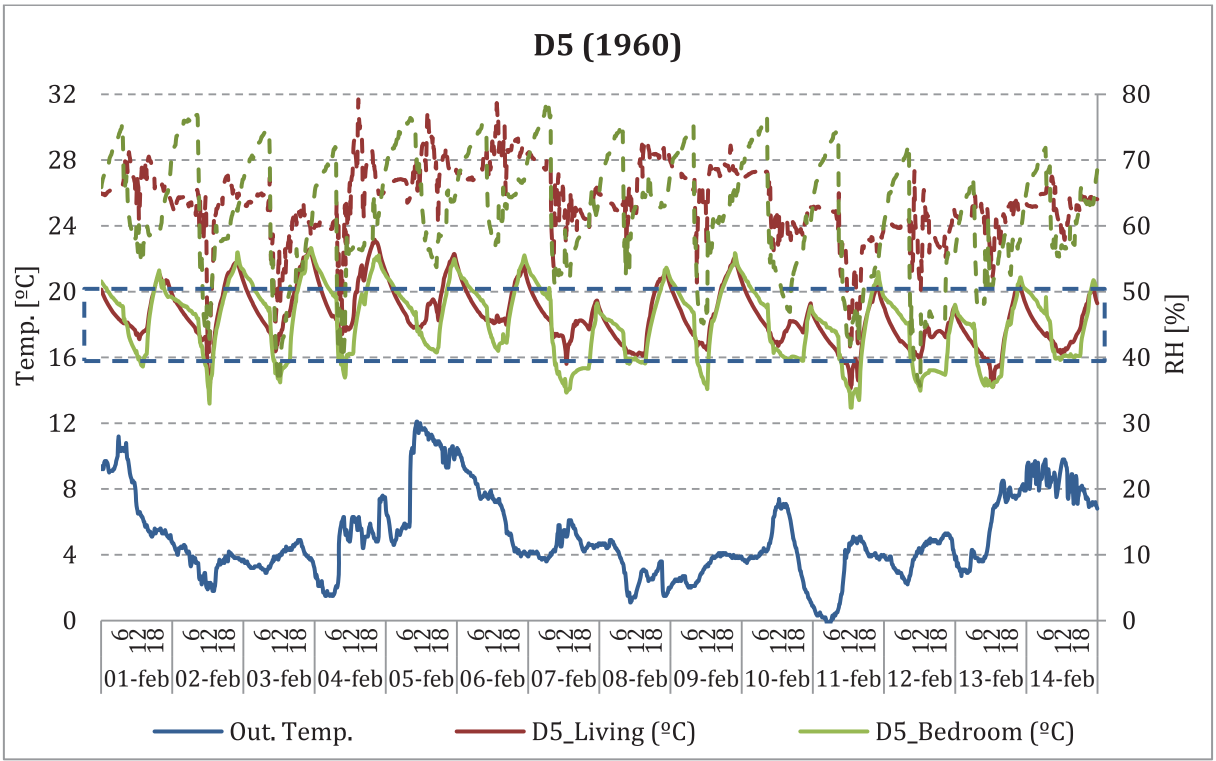
In this section, 15 day analysis for each studied dwelling are presented.

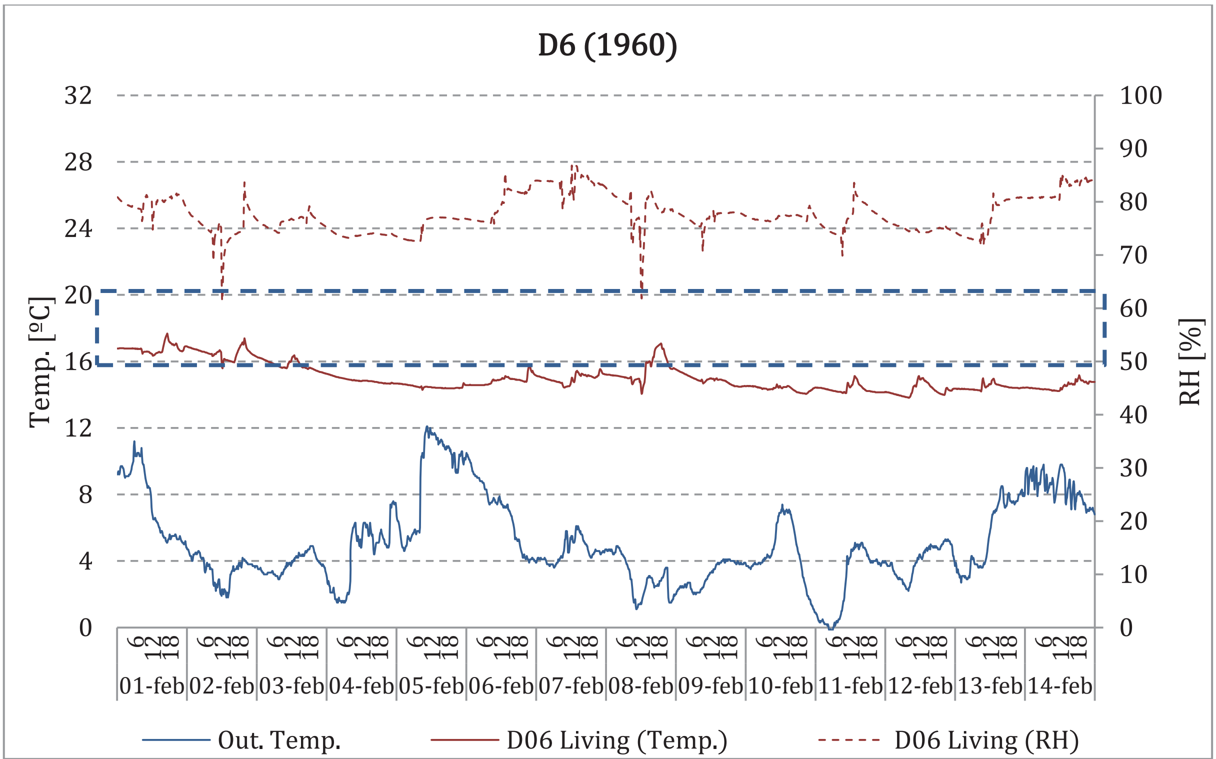


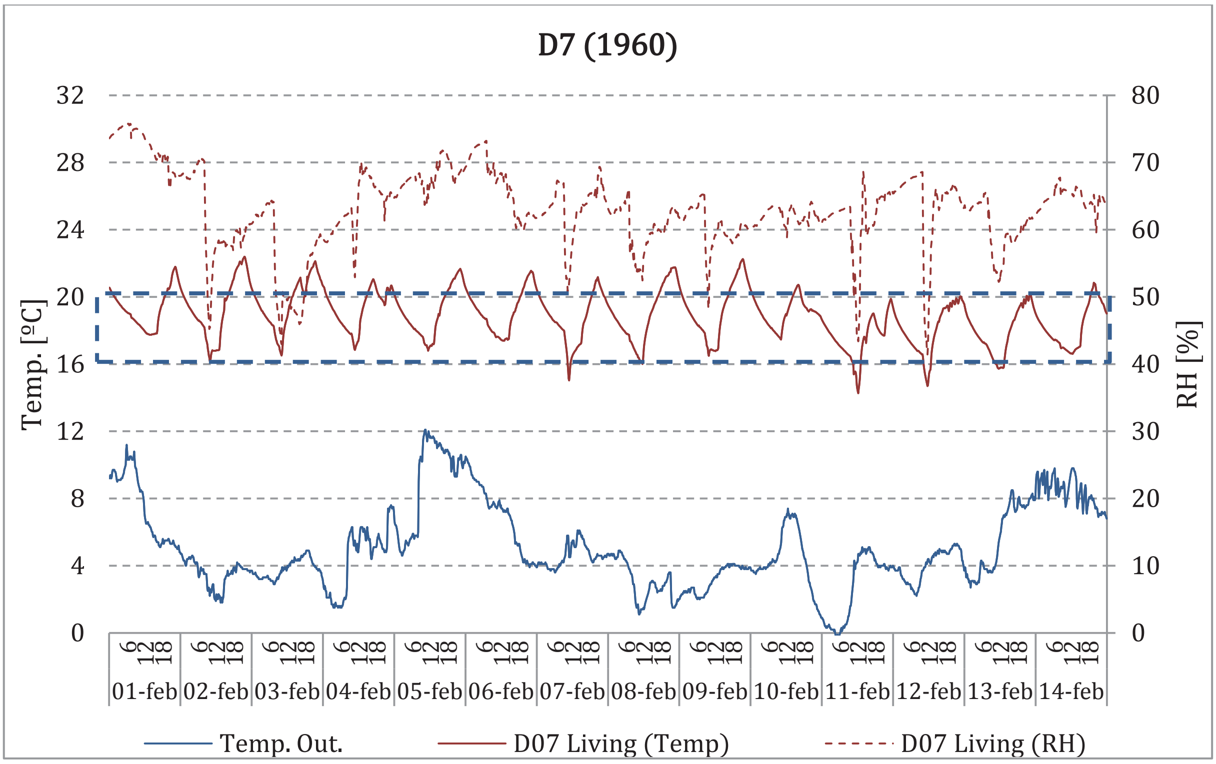


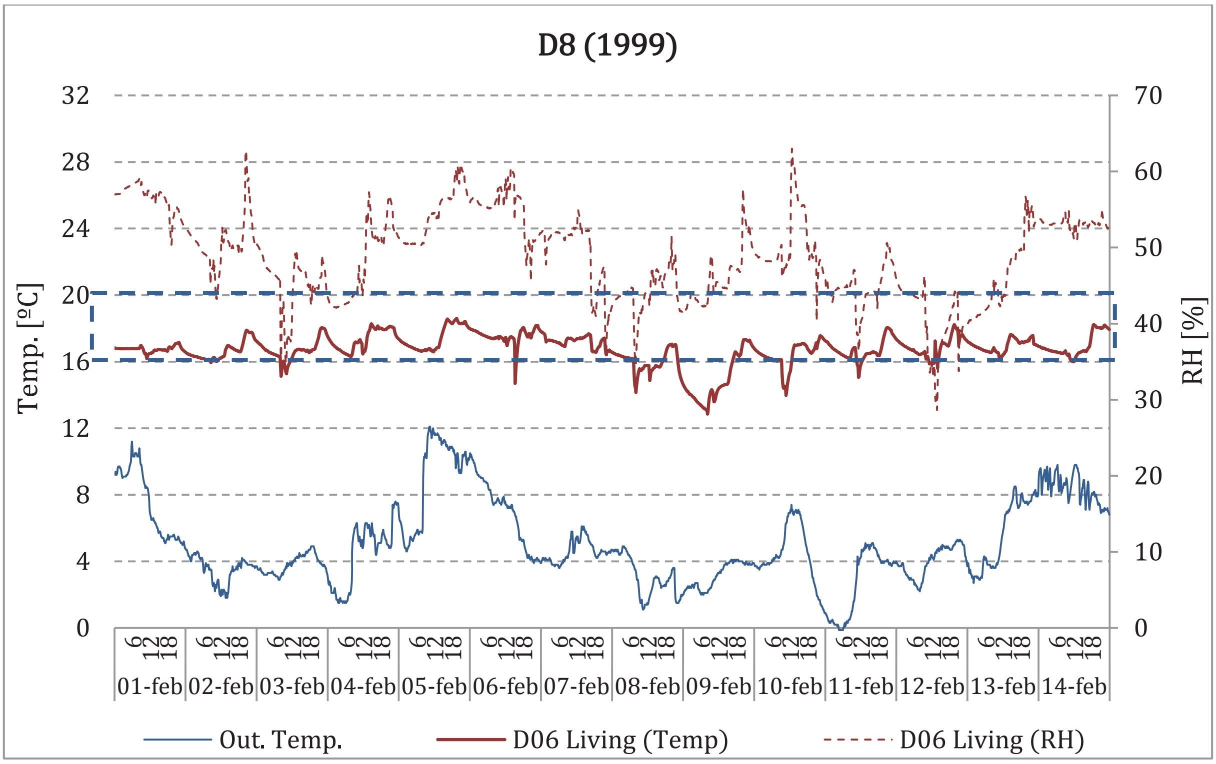

D3 (1952)
Temp. [ºC]
RH [%]
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D3_Living (ºC)
D3_Bedroom (ºC)

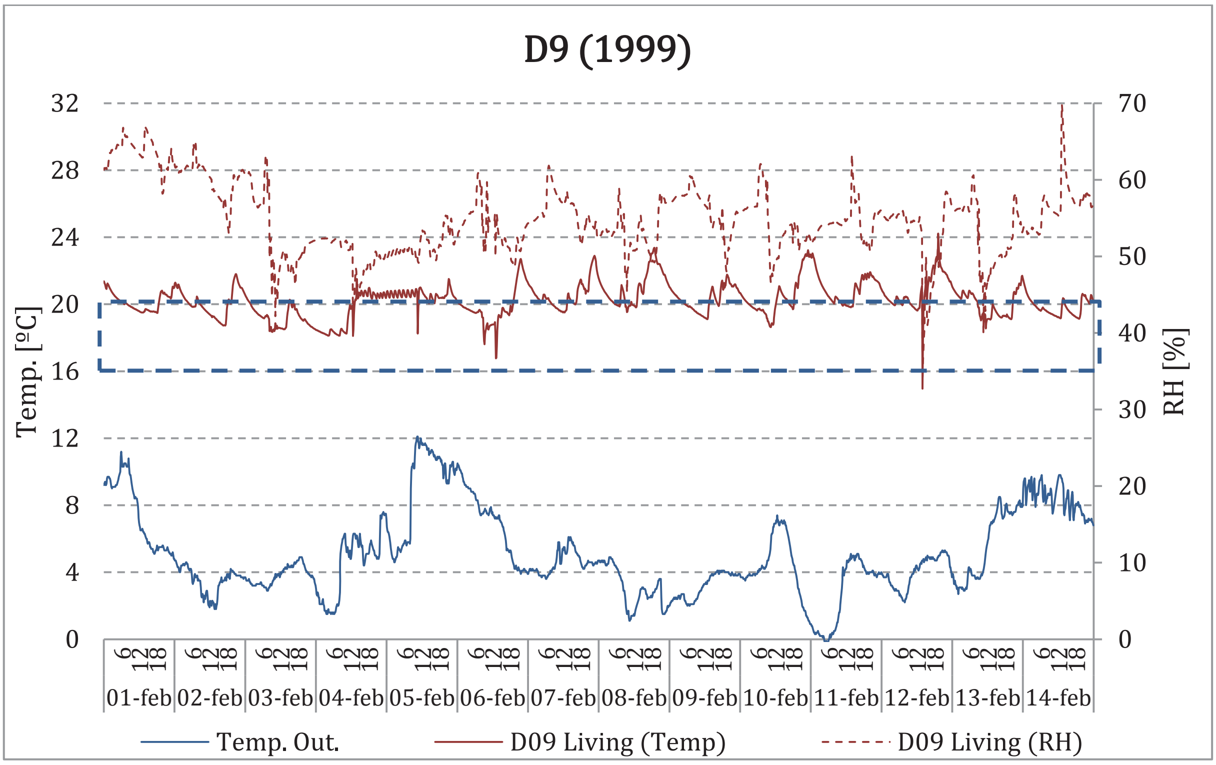

D4 (1952)
Temp. [ºC]
RH [%]
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D4_Living (ºC)
D4_Room (ºC)

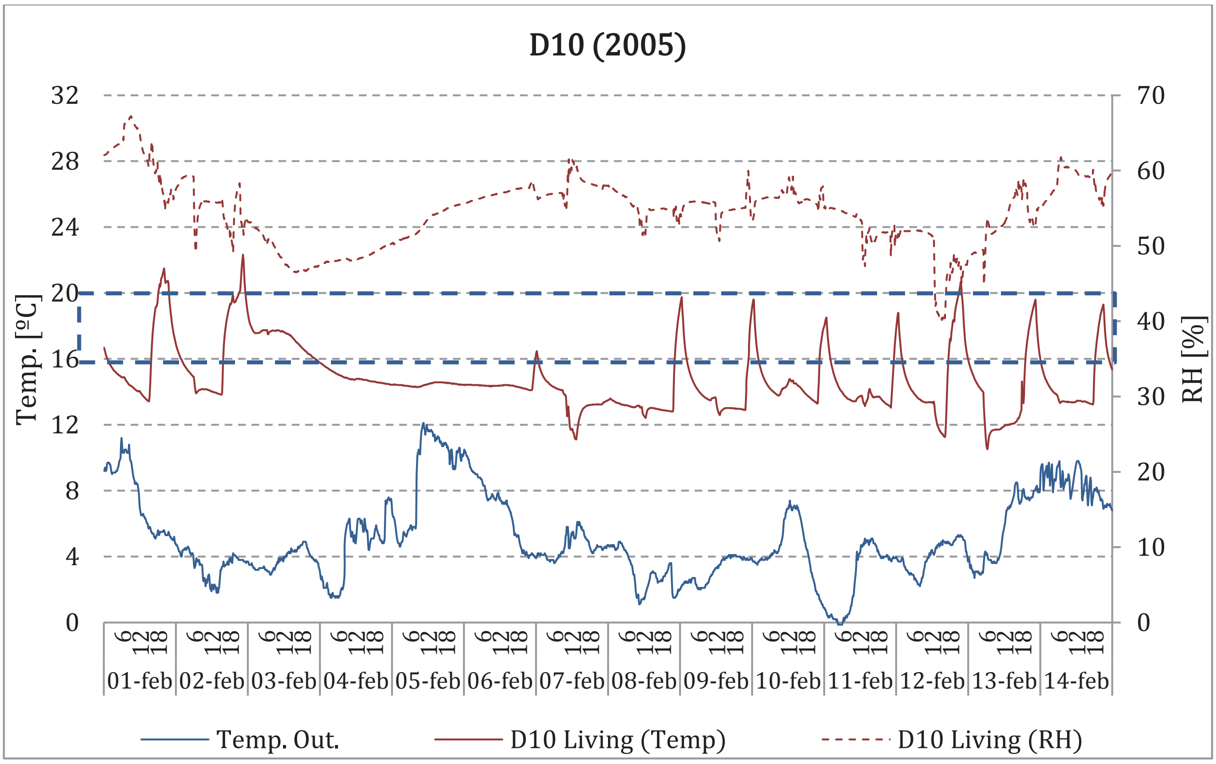

D5 (1960)
Temp. [ºC]
RH [%]
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D5_Living (ºC)
D5_Bedroom (ºC)


D6 (1960)
Temp. [ºC]
RH [%]
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D06 Living (Temp.)
D06 Living (RH)


D7 (1960)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
80
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Temp. Out.
D07 Living (Temp)
D07 Living (RH)

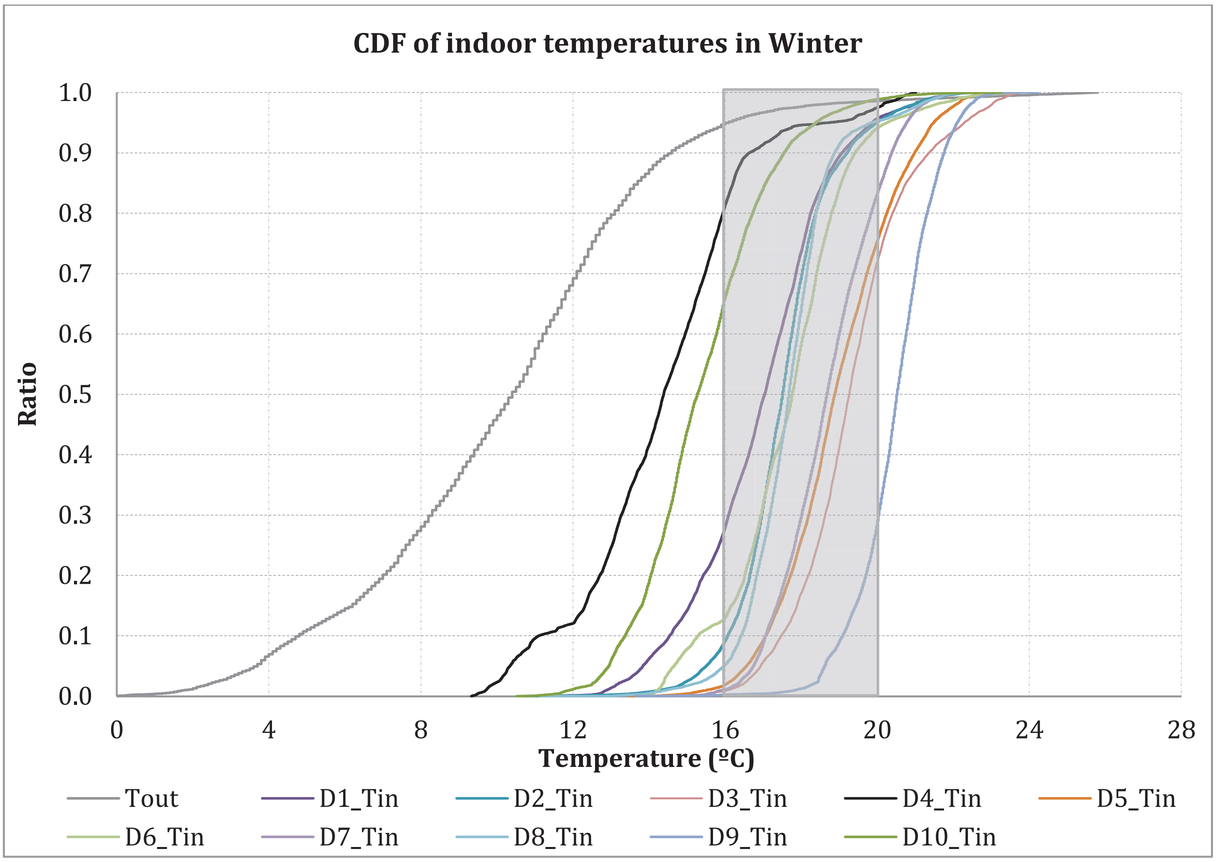

D8 (1999)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D06 Living (Temp)
D06 Living (RH)


D9 (1999)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Temp. Out.
D09 Living (Temp)
D09 Living (RH)


D10 (2005)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Temp. Out.
D10 Living (Temp)
D10 Living (RH)

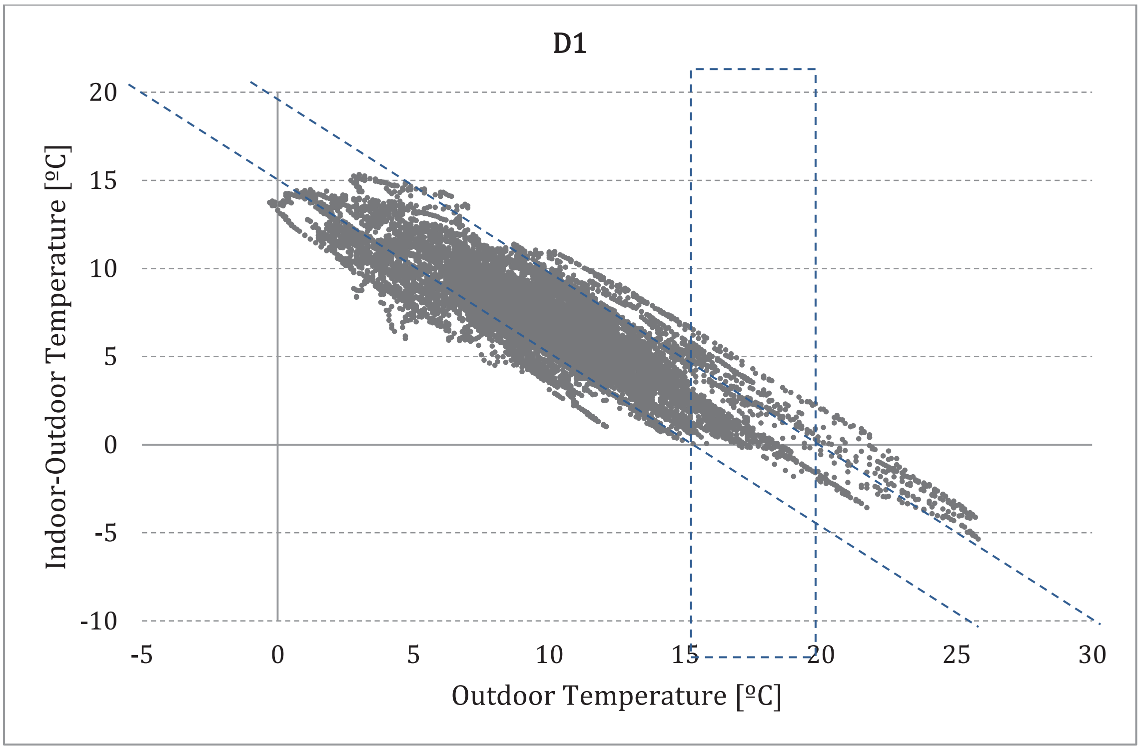
3 CDF of indoor temperatures in winter

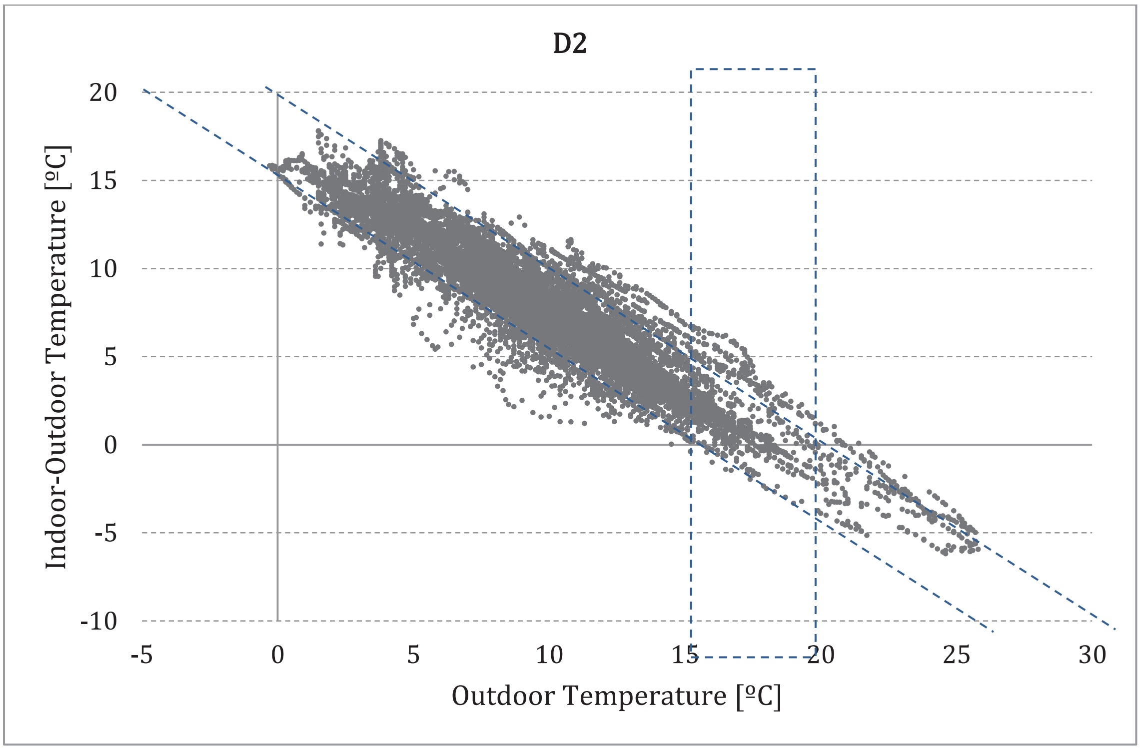
Cumulative distribution function (CDF) corresponding to the series of registered temperature in each dwelling are presented in the following graph.

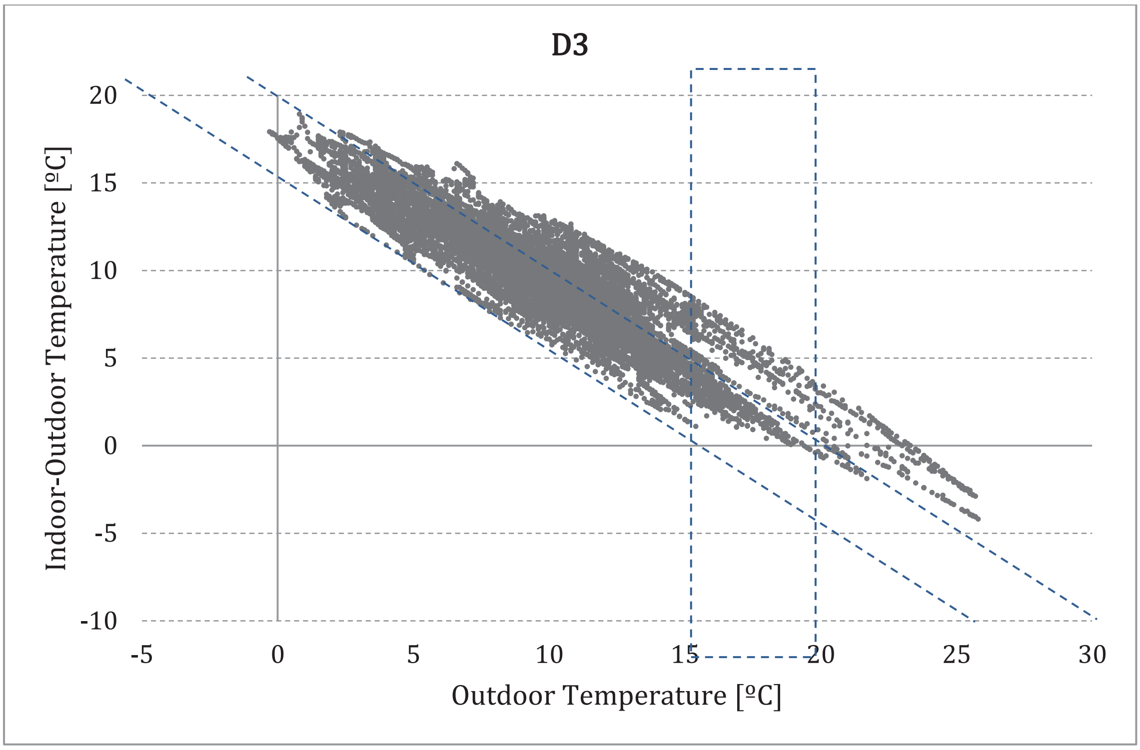


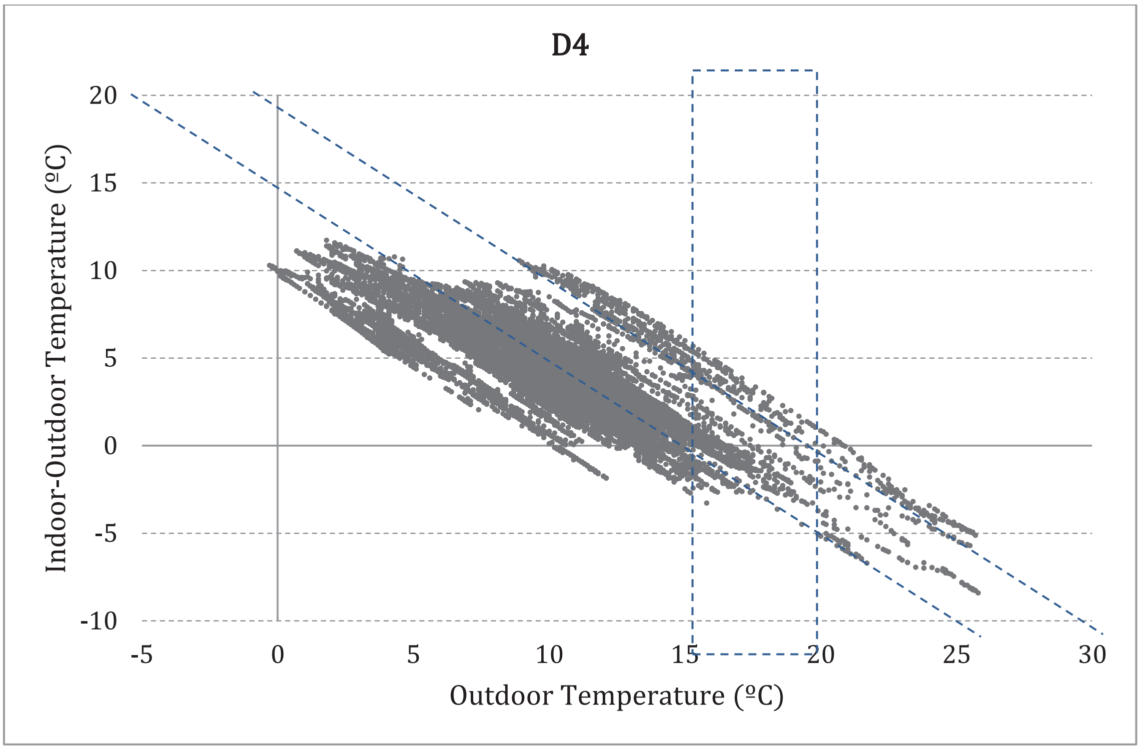
4 Indoor-outdoor Vs outdoor temperature in winter

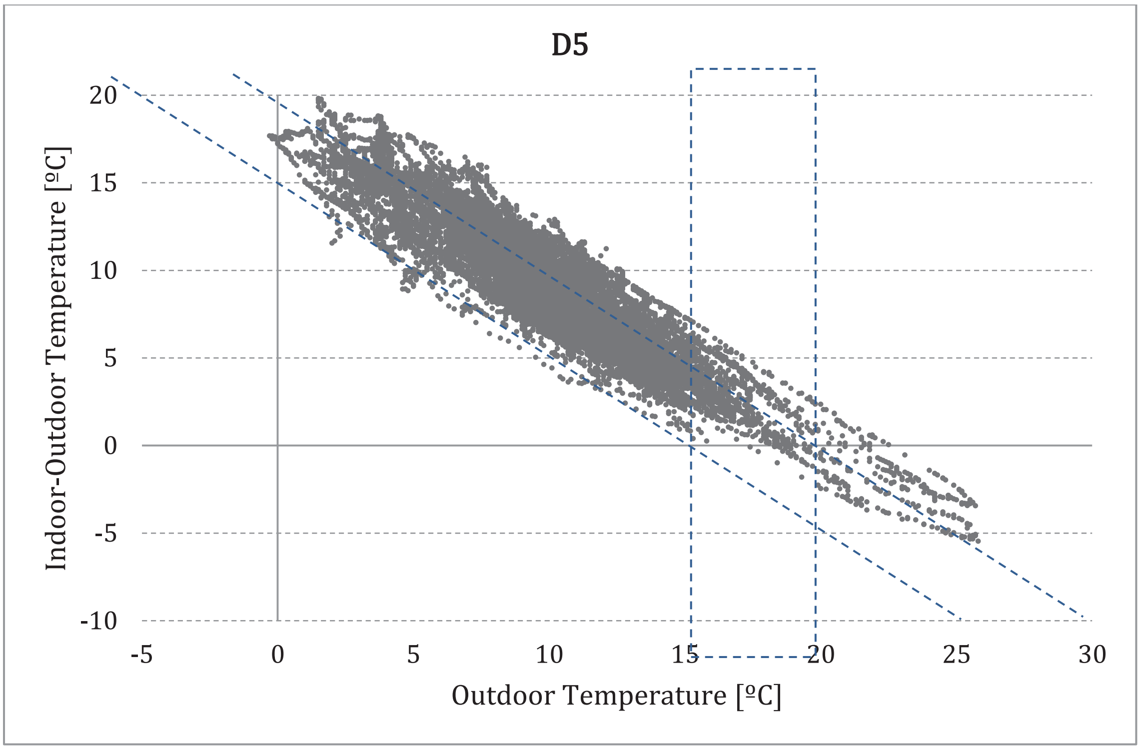
In the following graphs, the difference between indoor and outdoor temperatures against outdoor temperature is presented for each dwelling.

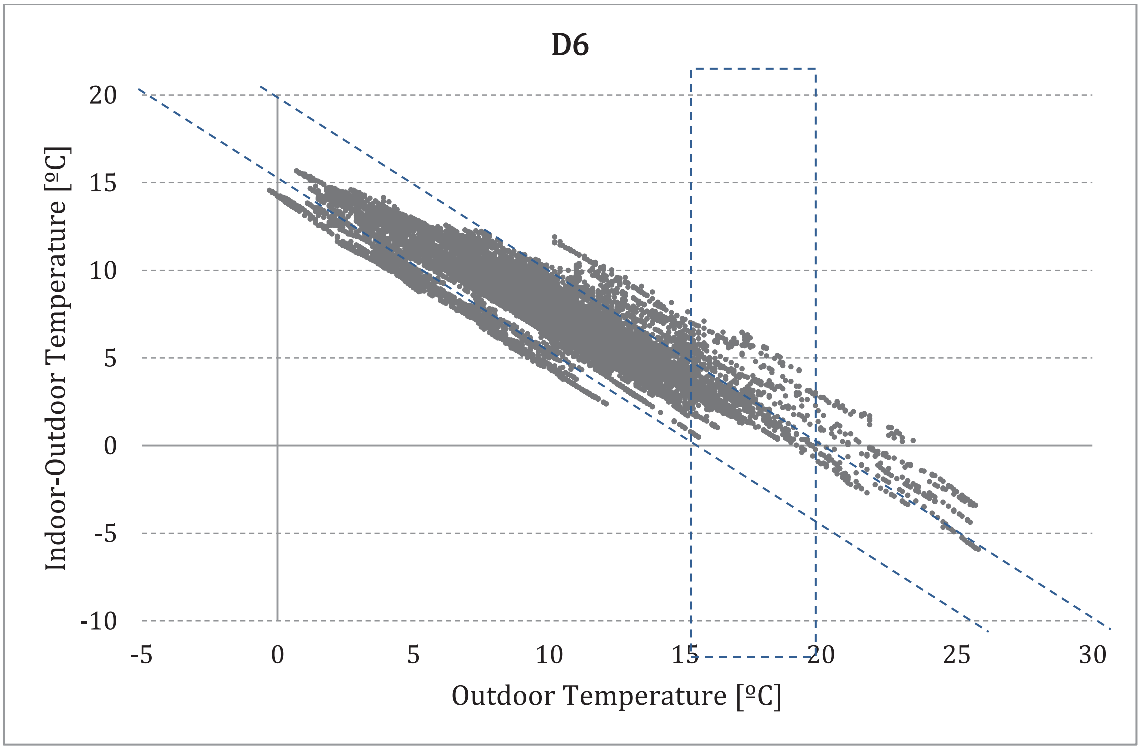


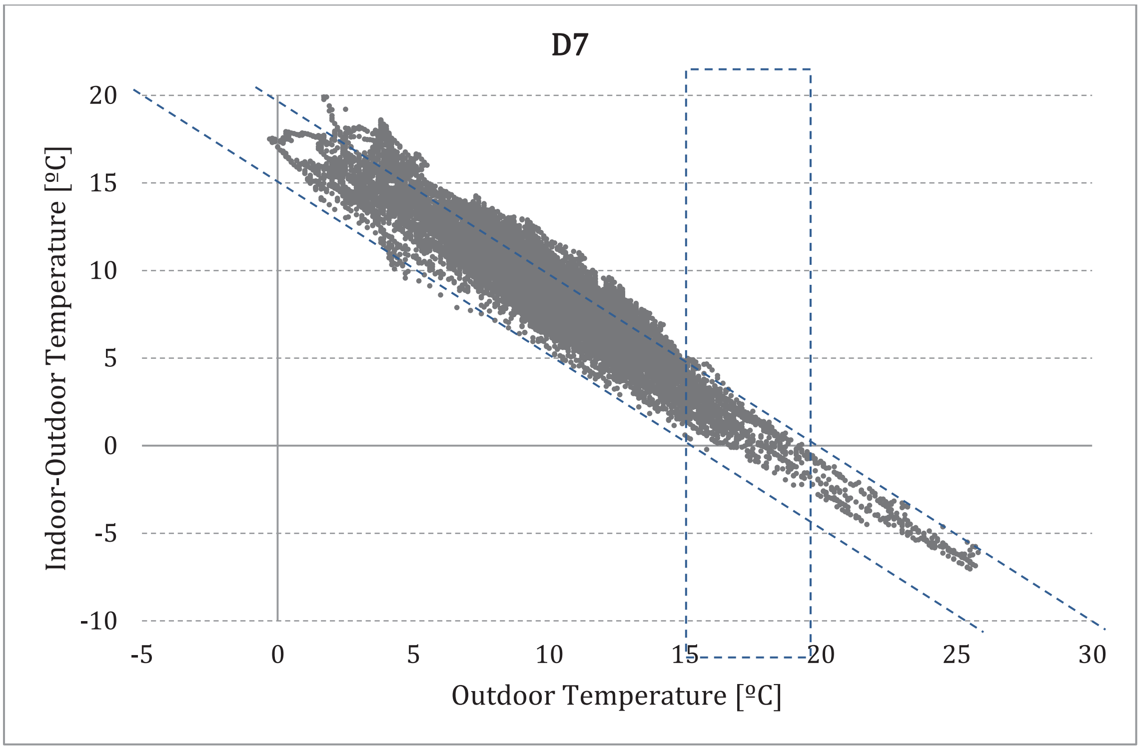


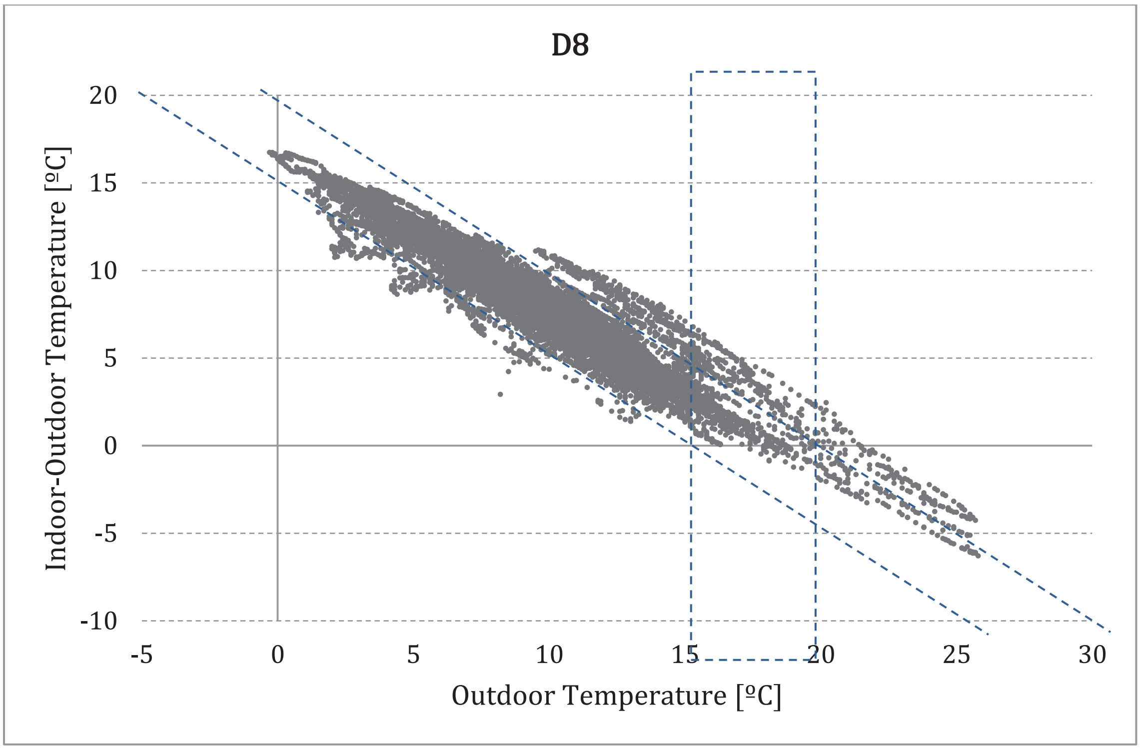

D3
Indoor-Outdoor Temperature [ºC]
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Outdoor Temperature [ºC]

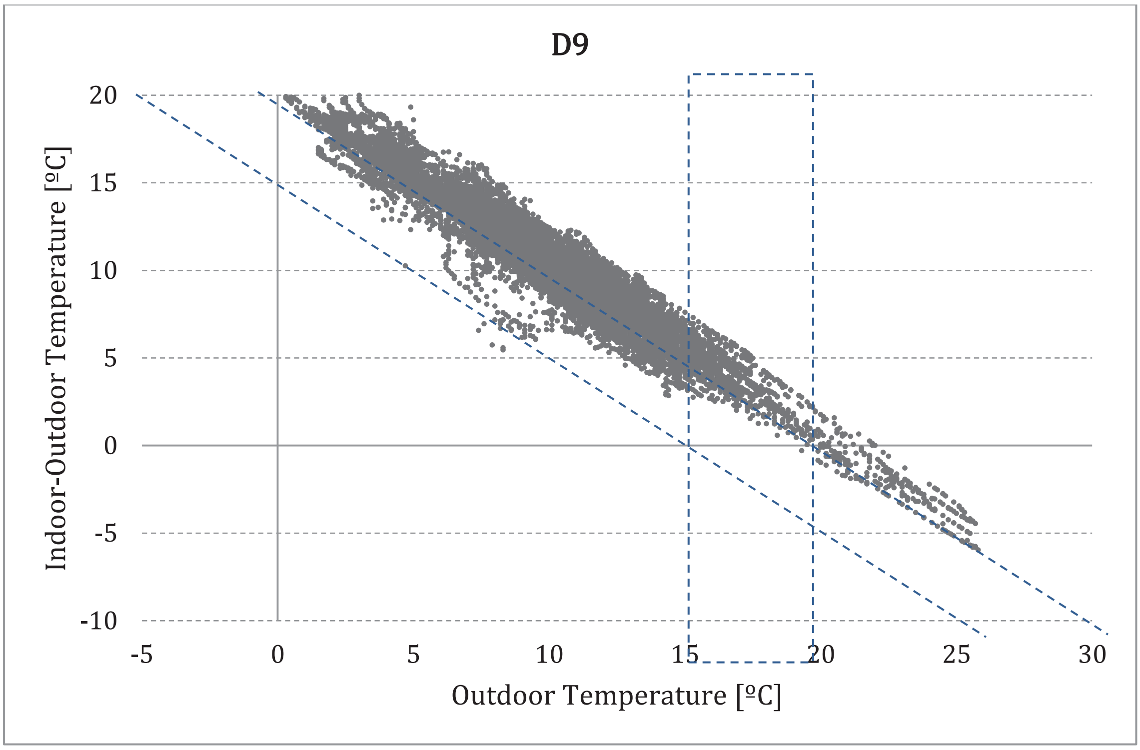

D4
Indoor-Outdoor Temperature (ºC)
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Outdoor Temperature (ºC)

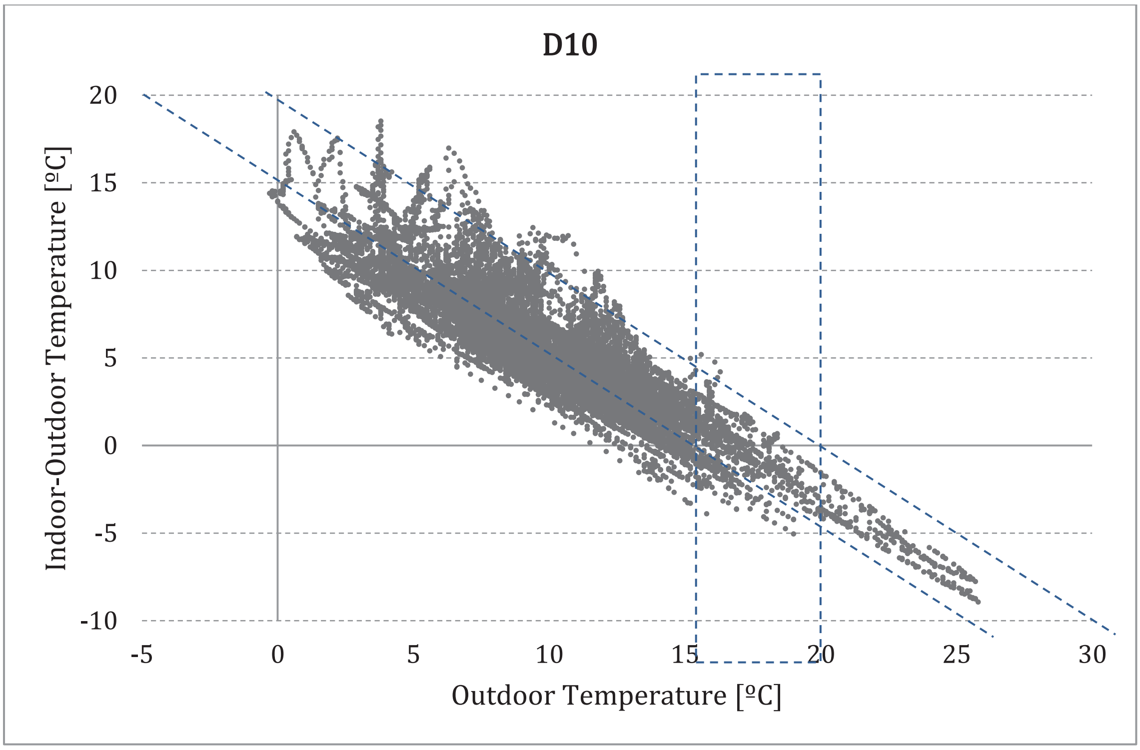

D5
Indoor-Outdoor Temperature [ºC]
Outdoor Temperature [ºC]
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30


D6
Indoor-Outdoor Temperature [ºC]
Outdoor Temperature [ºC]
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30


D7
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Indoor-Outdoor Temperature [ºC]
Outdoor Temperature [ºC]


D8
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Indoor-Outdoor Temperature [ºC]
Outdoor Temperature [ºC]


D9
Indoor-Outdoor Temperature [ºC]
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Outdoor Temperature [ºC]


D10
Indoor-Outdoor Temperature [ºC]
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Outdoor Temperature [ºC]

Appendix 3.3. Assessment of thermal behaviour of social housing apartments

- J. Terés-Zubiaga, K. Martín, A. Erkoreka, J.M. Sala, Field assessment of thermal behaviour of social housing apartments in Bilbao, Northern Spain, Energy and Buildings 67 (2013) 118-135.

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Field assessment of thermal behaviour of Social Housing apartments in Bilbao, Northern Spain

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Abstract

A field study of 10 social housing dwellings in the north of Spain is presented in this paper. Knowing the building stock is the first step to set up priorities in a global strategy to improve the energy efficiency of the existing building stock. Moreover, improving the energy efficiency of buildings is one of the most effective ways to tackle fuel poverty, which is increasing in Spain in the last years, being social housing one of the most vulnerable sectors of being at risk of fuel poverty.

The aim of this research is to describe a methodology for analysing the thermal performance of buildings under a holistic approach. An overview of the thermal performance of the social housing stock in a city with mild climate in Spain is presented. Social housing stock in Bilbao is classified by means of selecting 10 representative dwellings. A field study was performed during 10 months. Results of heating consumption as well as indoor conditions are presented. Results show that energy consumption in winter is not as high as expected, due to the low indoor temperatures. Amongst other factors, the influence of the occupants plays an important role in the final thermal performance of dwellings.

Keywords: *Thermal performance, holistic approach, energy renovation, social housing, fuel poverty*

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1 Introduction

Currently the energy consumption of the construction sector is estimated to be over 40% of the total energy consumption in the European Union. Thus, the energy and environmental situation requires improving the energy performance of buildings. The National Statistics Institute (year 2001) data shows that about 67% of the Spanish dwelling stock was built before 1980, just when the first Spanish thermal regulation (NBE-CT 79) became effective. There is a similar situation in the case of the Basque Country (a region located in Northern Spain) where more than 75% of the dwelling stock was constructed before 1980 [1]. Therefore, to reduce the energy consumption, the main effort must be focused on the challenges of the existing stock.

The implications and benefits of energy renovations have consequences not only in the reduction of CO_2 emissions and energy savings, but also in financial and social aspects. One of them is the so called fuel poverty, which is mainly a consequence of a combination of three causes: poor energy efficiency of housing, high energy prices and low household incomes. [2]. Poor energy efficiency can be responsible of low winter indoor temperatures and in some countries it is an important factor contributing to cold related morbidity and mortality as well [3]. Some other studies about energy efficiency, fuel poverty and the suitability of energy renovations have been carried out, such as in [4][5][6]. This problem is increasing in the last years in Spain, as shown in [7]. Thus, improving the energy efficiency of the existing stock is one of the main strategies, not only for reducing CO_2 emissions, but also for delivering affordable warmth to the fuel poor households. Both, energy savings and improvement on the indoor comfort, have to be taken into account during energy renovations projects.

Regarding occupants influence on the energy consumption in buildings, Annex 53 states that human behaviour could have a great impact, even greater than building characteristics or other factors. Several studies have pointed out large differences in energy consumption for similar buildings [8,9] thereby suggesting to the occupant's behaviour a strong influence. In [10] relationships between behavioural patterns, user profiles and energy use are thoroughly analysed. Related to this approach, rebound effect [11] is another factor to be considered when effectiveness of energy renovations is evaluated, as shown in several studies such as in [12][13][14][15][16][17].

Because of all the above reasons, energy efficiency improvements in buildings, and especially in social housing sector, have become a priority goal for the European Union. Due to its characteristics (such as households with low incomes and construction features of the buildings), this sector is one of the most vulnerable to fuel poverty. This way, quantifying the potential energy savings in the Social housing stock must become a priority. Characterizing the social building stock is the first step to be taken, followed by the thermal behaviour analysis of this building stock. Moreover, many energy models have been developed in the last years to predict changes on energy consumption as a result of energy renovations. As affirmed in [18], the assumptions for the operating conditions are usually based on profiles considered as standard, rather than those from field measurements. Thus, having field measurements on the indoor conditions in social dwellings is necessary to obtain a more accurate analysis of the energy renovation potential in the social building sector.

A global approach is necessary to study the thermal performance of buildings, considering the building as a complex system composed by different subsystems. With this aim in mind, in this work ten occupied apartments have been studied under a holistic approach to have an overview of their thermal performance. There is no shortage of similar field studies available in the literature to assess thermal comfort and energy consumption in low energy buildings [8], office buildings [19] or vernacular or historical buildings [20][21][22]. Nevertheless, it is not so prevalent to come across with this kind of studies applied to the Social Housing Sector. One exception could be found in the large-scale surveys carried out by Warm Front Project [23].

2 Objectives

In order to define optimal strategies in building renovations, its thermal behaviour must be known. Thus, architectural and thermal behaviour of Social Housing Stock in Bilbao is assessed in a field study. Along this line, the main aims of this paper are:

(a) Provide an insight of the thermal performance of Social Housing Stock in Bilbao, Northern Spain, and identify the real energy consumption in social dwellings in a city with mild weather conditions both in winter and summer; (b) Identify the potential improvement of the social housing stock; (c) Provide energy consumption and indoor environment field measurements of these ten dwellings, which can be used in future researches and models to set up operating conditions not based on standards, but on field measurements; and (d) Provide a comparative and qualitative analysis of thermal building performance of ten selected dwellings, representatives of the social building stock.

This study is not only focusing on energy consumption itself, but also on assessing thermal comfort in the dwellings. Previously mentioned aspects related to health issues, however, are out of scope of the present study, although they must be taken into account when energy retrofitting benefits are considered.

To accomplish with these goals the building stock of social housing in Bilbao has been classified according to the criteria described in section 4. Based on this classification, 10 social housing apartments, representatives of the different construction periods of the 20th Century have been studied using a holistic approach. Results obtained from this survey provide an important database to quantify the potential benefit of retrofitting the existing social building stock in the Basque Country.

3 Approach

A holistic approach is applied in this study. In this systemic approach, buildings are treated as open systems considering interactions between them and their environment. Similar approaches are explained and used in [20] with historical buildings, in Annex 53 [24] or in [25]. The approach used in this paper is based on these references. The different considered subsystems are shown in Fig. 1.

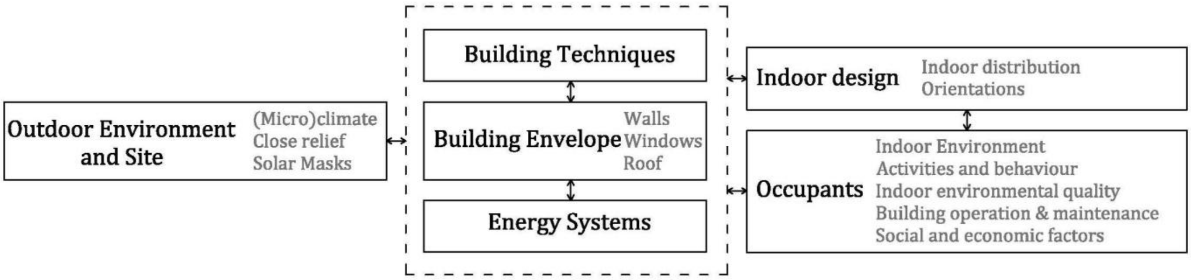


Fig. 1. Subsystems for investigation.

Building techniques, building envelope and energy systems could be considered as a boundary subsystem, which makes a separation between outdoor environment and occupants or indoor environment [26]. The combination of all these factors will give as a result the energy performance of the dwelling.

Building renovations are usually focused on the improvement of 3 subsystems: building techniques (such as thermal bridges), building envelope and energy systems. However, although the objective of any improvement in the building energy performance is usually within these subsystems, it is important to take into account the interaction amongst building techniques, building envelope and energy systems, and the other subsystems, and the consequences of these interactions on the overall energy consumption. The study presented in this paper has been carried out bearing in mind this approach.

4 Choice of buildings

This field study has been carried out in Bilbao from November 2011 to September 2012. All apartments have been occupied during the monitoring period. Different heating systems are used in the selected dwellings: out of the 10 dwellings, 4 are heated by natural gas heating systems, 3 by electric heaters, 1 by kerosene heater, 1 by butane heater and 1 has not a heating system whatsoever. All the studied dwellings have no mechanical ventilation system. The climate for the studied area (Bilbao), located in latitude 43º N, is oceanic. The proximity to the ocean makes summer and winter temperatures relatively temperate, with low intensity thermal oscillations. Average maximum temperature is between 25 °C and 26 °C during summer period, while the average minimum in winter can vary between 6 °C and 7 °C.

4.1 Building stock classification criteria

Building stock of Bilbao is characterised by the construction period in this study. Several factors act upon construction features, like social and financial situations and/or building regulations. As far as thermal requirements are concerned, after the Oil Crisis in the 70's, in Spain, like in many European countries, the requirements for insulation of buildings were considerably reinforced. With this aim in mind, the first thermal regulation was developed and came into force in 1979. Unlike in other European countries, there was no new Spanish thermal regulation till 2006, when the Spanish Technical Building Code (CTE) [27] came into force. Detailed data about the Building stock in Bilbao, based on Population and Housing Censuses developed by National Statistics Institute in 2001, by construction year, is shown in Fig. 2.

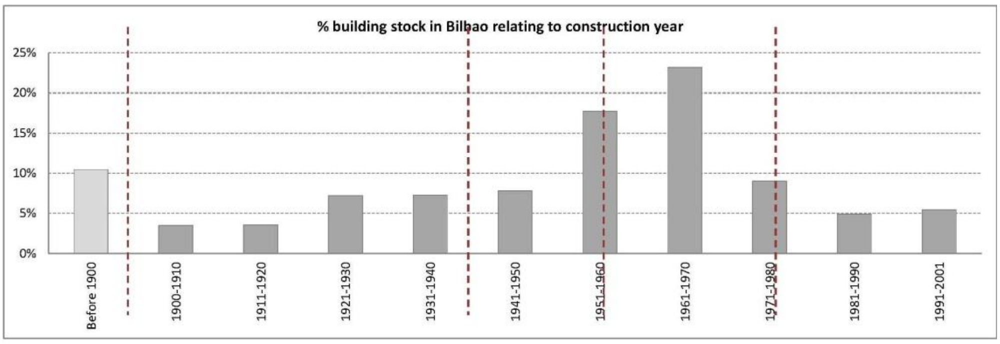


Fig. 2. Building stock in Bilbao in relation to construction year (Building Stock: 10044, year 2001, INE)

Based on the mentioned facts, 5 different periods have been identified since 1900, as depicted in Fig. 3 (Periods are numbered from 1 to 5). Different representative constructive sections of façades in relation with each period are shown in Table 1. *C* (Heat Capacity) and *U-Value* are calculated as described in eq. 1 and eq. 2

$$U_i = \frac{1}{R_{in} + R_i + R_{out}}$$	**eq. 1**
$$C = \sum \rho_i \cdot c_{p,i} \cdot e_i$$	**eq. 2**

Where:

R_{in}: is the internal surface thermal resistance (0.13 m²K/W) [28]
R_i: is the surface to surface thermal resistance of the construction element
R_{out}: is the external surface thermal resistance (0.04 m²K/W) [28]
ρ_i: is the density of the *i* layer material.
$c_{p,i}$: is the specific heat capacity of the *i* layer material
e: is the thickness of the *i* layer

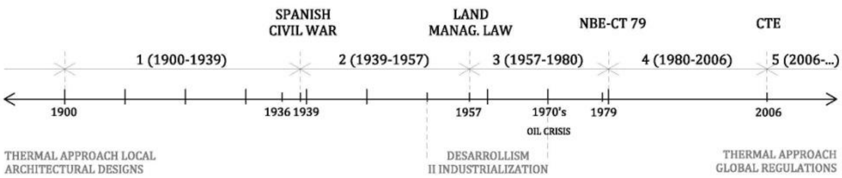
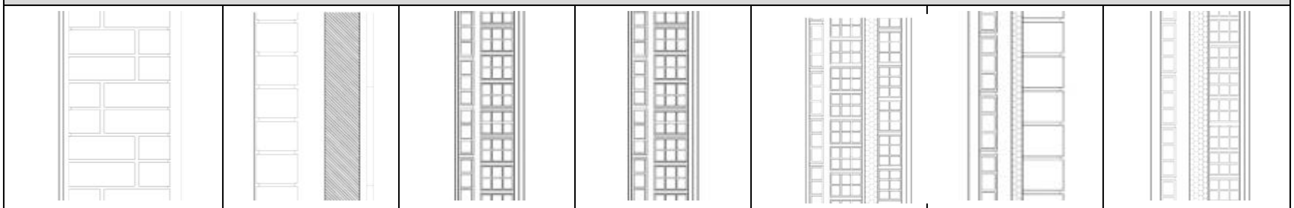


Fig. 3. Construction periods during twentieth century in Bilbao (Spain)

Geometrical features of the heating area						
						
F.a	**F.b**	**F.c**	**F.c.1**	**F.c.2**	**F.d**	**F.e**

From Indoors (left) to Outdoors (right)					
U [w/m².K] C[kJ/ m².K]	**Constructive Section (in-out)**	**Period**	**U [w/m².K] C[kJ/ m².K]**	**Constructive Section (in-out)**	**Period**
F.a. U: 1.11 C:463.8	Plaster Perforated Brick (37 cm) Cement Mortar	1	**F.b U: 1.16 C: 359.8**	Plaster Hollow Brick (12.5 cm) Air gap Concrete Wall (10 cm) Cement Mortar (2cm)	1-2
F.c U: 1.44 C: 160.0	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm)	3	**F.c.1 U: 1.27 C: 180.0**	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm) Lightened Cement Mortar (2cm)	3
F.c.2 U: 0.43 C: 238.4	Plaster Hollow Brick (4.5 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2 cm) Thermal Insulation (4 cm) Hollow brick (9 cm) Lightened Cement Mortar (2 cm)	3	**F.d. U: 0.48 C: 189.0**	Plaster Hollow Brick (4.5 cm) Thermal Insulation (3 cm) Air gap Perforated Brick (12.5 cm)	4
F.e. U: 0.41 C: 162.6	Plaster Hollow Brick (4.5 cm) Thermal Insulation (6 cm) Air gap Hollow Brick (12.5 cm) Cement Mortar (2cm)	4-5			

Table 1. Constructive Sections of Façades (according to data provided by Bilbao Social Housing)

4.2 Selection of study-cases

Each apartment of the sample (Fig. 4) was selected according to features defined in section 4.1. This way, all aforementioned periods are represented by at least two dwellings. One new dwelling, built in 2005 (only a year before the Spanish Technical Building Code came to force) is also included in this study.

		Indoor Environm	Envelope			Windows			En. Syst	Occ
Nº	Year	A. (m^2)	Sec.	U_{wall} [W/m².k] (calc)	C_{wall} [kJ/m².K] (calc)	Wind.	U_{win} (calc)	Infiltr.	Heating System	Property type
D1	1921	53.33	F.a	1.11	463.8	Wood (f); Gass 6	5.35	High	Butane	Rented
D2	1921	45.68	F.a	1.11	463.8	PVC (f); Glass 4/6/4)	2.38	Low	Elect. heater	Rented
D3	1952	51.5	F.b	1.16	359.8	Al (f); Glass 6 – Wood (f); Gass 6	5.35-5.70	High - Med.	Elect. heater	Rented
D4	1952	51.5	F.b	1.16	359.8	Al (f); Glass 4/6/4)	3.37	High	None	Rented
D5	1960	47.68	F.c.1	1.27	180	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D6	1960	39.7	F.c.2	0.43	238.4	PVC (f); Glass 4/6/4)	2.38	Low	Elect. Heater	Rented
D7	1960	47.65	F.c.1	1.27	180	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D8	1995	68.3	F.d	0.48	189	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Rented
D9	1995	87	F.d	0.48	189	PVC (f); Glass 4/6/4)	2.38	Low	Nat. Gas	Owner
D10	2005	58.5	F.e	0.41	162.6	PVC (f); Glass 4/6/4)	2.38	Low	Kerosene	Rented

Table 2. Summary of the characteristics of the studied dwellings, according to the subsystems presented in Fig. 1 (Indoor Environment, Envelope, Windows, Energy Systems and Occupants)

Fig. 4. Location of the ten case-studies.

As far as construction features are concerned, these dwellings can be considered representative not only of the social housing in Bilbao, but also of the social housing stock of the main urban areas in the region. Different aspects and features are taken into account for each dwelling, according to the approach described in section 3. Some of these aspects are summarized in Table 2. Occupation factors, such as occupant age, number of occupants or period of occupation, have been considered as well.

4.3 Field study

Based on aforementioned systemic approach, each dwelling is analyzed in situ. The data are combined in six groups based on the aforementioned six subsystems, as summarized in Table 3.

Subsystem	Data	Information sources
Outdoor Environment and Site	Geographical parameters (Lat, Long)	Field measurements, Bibliographical sources
	Climatic area, solar radiation	Field measurements, Bibliographical sources
	Microclimate, outdoor temperature and RH	WEB Data, Recorded Data. Visual inspection
Building Techniques	Thermal Bridges	Thermal imaging
Building Envelope	Thermal characteristics of the walls	Bibliographical sources
Energy Systems	Energy Systems, Energy consumption	Questionnaires, Energy bills
Indoor design	Indoor distribution	Plans, field measurements, visual inspection.
Occupants	Indoor Environment: Plans, sections, Façades	Field measurements
	Activities, Behaviour, environmental quality	Questionnaires, Field measurements

Table 3. Collected data

4.4 Data collection

4.4.1 Temperature and humidity

Several temperature and humidity monitoring studies can be found in literature. The criteria presented in [4] have been a reference for this study. According to this criterion, detailed measurements of temperature and humidity were collected using Temp-RH Hobo Data loggers (HOBO U12-011). Their resolution is 0.03 ºC (25 ºC) for temperature and 0.03 % for relative humidity, and their accuracy is $\pm$0.35 ºC and $\pm$2.5 % respectively. They were placed far away from direct heat or humidity sources and windows and approximately 1 m above the ground. These data loggers are programmed to collect data with a 10 min. frequency. Although longer time steps can be found in literature (from 20 min. [29] to 2 h. [20]), 10 min. time step has been used because it allows having information about some occupant actions, such as heating system activation or ventilation patterns. Temp-RH data loggers were previously calibrated and validated in the Laboratory for the Quality Control in Buildings (LCCE) of the Basque Government.

A TH (Thermo Hygrometer) was installed in the living room of each apartment and in some of them another TH was installed in the main bedroom, according to the indoor environment (Fig. 5). Similar criteria have been followed in other studies, e.g. in [17] or in [20]

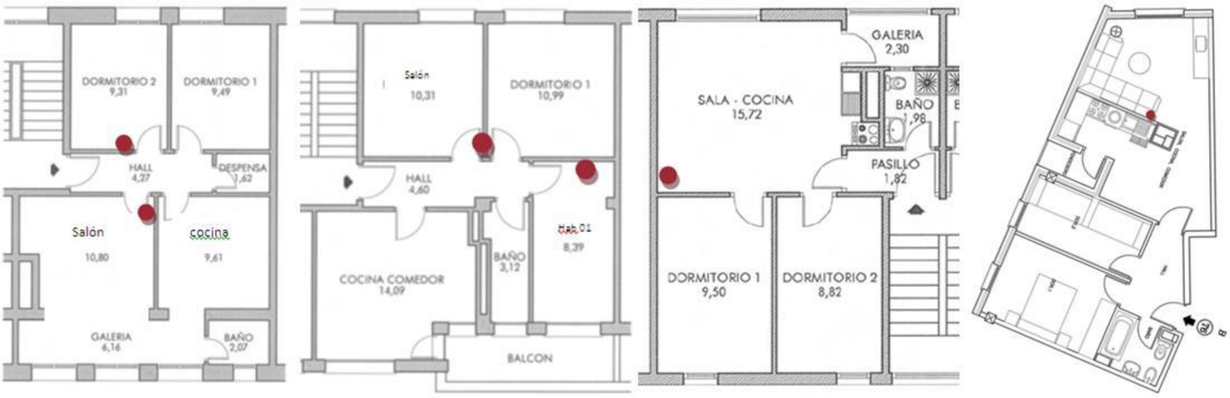


Fig. 5. Layout of some case studies (D1, D3-D4, D6 and D10).

Outdoor temperature and relative humidity were taken from a meteorological station of the Basque Government located in Deusto, Bilbao. This station measures variables such as air temperature, relative humidity, global horizontal irradiation and wind speed, among others, with a sampling frequency of 10-min.

4.4.2 Energy Consumption

Some assumptions have been made to estimate heating consumption in winter. The information sources are not the same in all the dwellings. In most of the cases (six of them) energy bills have been provided, but in two dwellings, heating consumption data have been collected in questionnaires. In the last case (D4) no heating system is used. Actually, a small electric heater is used punctually but its consumption has been considered negligible when summer and winter consumption are compared. In case D5 some meter readings have complemented the information from natural gas bills.

Collected data are presented for each dwelling in Table 4, where energy consumption related to the source during the indicated period is presented. However, it is necessary to standardize these data sets, because some of them are electricity consumption of the whole dwelling and others are natural gas consumption for Domestic Hot Water (DHW) and the heating system. In all the selected cases, this heating consumption has been extrapolated to the same period (1st Dec. – 1st Apr), due to the fact that the heating system has been working from the second or third week of December till the last days of March in every dwelling.

$$\mathrm{E_B} = \frac{\mathrm{E_S}}{n_s}$$	**eq. 3**
$$\mathrm{H_w} = E_w - n_w \cdot E_B$$	**eq. 4**

Eq. 3 and Eq. 4 are used to calculate the estimated heating consumption in winter, where E_B is the base energy consumption per day, E_S is the energy consumption in summertime, E_w is the energy consumption in wintertime, H_W is the estimated heating consumption in winter, n_s is the evaluated number of days of the summer period and n_w is the evaluated number of days of the winter period. E_B (kWh/day) is calculated considering the energy consumption in summer per day. This method is a good approximation to estimate the heating consumption, especially when heating and DHW is supplied by a natural gas boiler. DHW consumption is assumed to be similar for the whole year, so heating consumption, which only happens in winter, is calculated as natural gas consumption in winter (DHW + Heating) minus natural gas consumption in summer (DHW). This method is also used when the energy supply of the dwelling is purely electrical.

Therefore, the following assumptions have been made in order to estimate the heating consumption during winter period: *1)* 159 kWh / Butane Gas Cylinder; *2)* Base consumption (without heating) per day is calculated according to data from summer period, eq. 3. The estimated heating consumption in winter is obtained by means of eq. 4.; *3)* In this case, the base consumption is assumed according to IDAE[30] (due to variability of the dwelling energy consumption in summer). The estimated heating consumption in winter is obtained using eq. 4.; *4)* Using as reference 43400 kJ/kg for LHV of Kerosene. (9.4 kWh/l)

		Data collected		Estimated consumption 1 Dic- 1 April
	Source	Period	Consumption	Assumptions
[D1]	Questionnaires	Whole Winter	4 butane gas cylinder	1)
[D2]	Electricity Bills	24 Nov-20 Mar	1840 kWh	3) (Base consumption: 4,16 kWh/day)
[D3]	Electricity Bills	12 Dec-11 Apr	863 kWh	3) (Base consumption: 4,16 kWh/day)
[D4]	N/A	N/A	NEGLIGIBLE	NEGLIGIBLE
[D5]	Natural Gas Bills	18 Dec-17Apr	3600 kWh	2) (Base consumption: 6 kWh/day)
[D6]	Electricity Bill	Not enough data available		
[D7]	Natural Gas Bills	15Nov-14Mar	3936 kWh	2) (Base Consumption: 6 kWh/day)
[D8]	Natural Gas Bills	15Nov-14Mar	2145 kWh	2) (Base Consumption: 6.7 kWh/day)
[D9]	Natural Gas Bills	15Nov-14Mar	3990 kWh	2) (Base Consumption: 5 kWh/day)
[D10]	Questionnaires	Whole Winter	20 l kerosene	4)

Table 4. Heating Consumption data collected

Moreover, the fact that not all rooms are heated in some dwellings is another problem to standardize the heating consumption estimation. As questionnaires and measurements show, in some dwellings only one or two rooms are heated (D1, D3 and D10, as summarized in the appendix). In order to adequate the consumption and having a more representative value of kWh/m^2, a relation between heat consumption and real heated area has also been calculated. These values, which are used as a reference to compare the studied dwelling with others, are presented in Table 5.

	Estimated consump. [kWh]	Heated rooms	m² (heated area)	Consumpt. [kWh/m².year]	Corrected Consumpt. [kWh/m².year]
[D1]	636	Bedroom (x2), Kitchen	33.87	11.93	18.78
[D2]	1354	Whole dwelling	45.68	29.64	29.64
[D3]	356	Living room	10.31	6.91	34.52
[D4]	NA	NA	NA	NA	NA
[D5]	2880	Whole dwelling	47.65	60.44	60.44
[D6]	Not enough data available				
[D7]	3210	Whole dwelling	47.65	67.37	67.37
[D8]	1335	Whole dwelling	68.3	19.55	19.55
[D9]	3385	Whole dwelling	87	38.91	38.91
[D10]	188	Living room	12.6	3.21	14.92

Table 5. Heating Consumption collected and calculation data

4.4.3 IR techniques

Thermal imaging inspection was also carried out during the investigation of two aforementioned subsystems: Envelope and Building Techniques. Infrared radiation is emitted by all objects above absolute zero. The IR camera measures this radiation and gives the surface temperature according to the black body radiation law which have to be corrected with the emissivity for grey bodies.

Thermography allows detecting thermal heterogeneities of the envelope, like thermal bridges, or variations of the U-Value of different areas of the façades (see Fig. 14). Some aspects which have a strong influence in IR assessment are [31]: Emissivity (ε), Relative Humidity (RH).ΔT (It is recommended at least a 10-15 ºC temperature difference between indoors to outdoors when IR analysis is carried out) and Solar Radiation. IR images must be taken avoiding sunny hours, to avoid the effect of the sun on the walls. In this way, also the thermal inertia of the walls must be taken into account. Other factors, like distance of the measured element, air temperature, air relative humidity, wind or reflected temperature have to be considered as well, especially if quantitative analysis is carried out.

According to these parameters, the infrared thermographs were performed with a FLIR infrared Camera Model PS60 which has an accuracy of 2% in temperature measuring. The emissivity used in the calculations has been 0.9 because most of building construction materials has high emissivities, The inspection was carried out during 2 nights: 28th February 2012 (01.00-04.00 AM) and 2nd March 2012 (00.00-01.00 AM). During the first night collection, the air temperature was 6,5 ºC and there was a RH of 88%. During the second night, the air temperature was 9 ºC and there was a RH of 88%. No rains were recorded in the previous days.

4.4.4 Thermal comfort

Special attention has been paid in this study to the thermal comfort. Thermal comfort and healthy indoor environment are two of the most important targets of any construction. In this approach, these aspects have been included in "Occupants" subsystem. Different factors determine a comfortable environment, such as air temperature, relative humidity, air movement, human activity and type of clothes, to name some of them. Predicted Mean Vote (PMV) or Predicted Percentage Dissatisfied (PPD) indexes are used to assess thermal comfort. PPD is defined in terms of the PMV. PMV depends on activity, clothing, air temperature, mean radiant temperature, air velocity and humidity [32]. As this long term monitoring study was carried out in occupied dwellings, there were some limitations with the used instrumentation, and all of the above mentioned parameters were not registered during the research. For this reason, a simplified method has been used to assess thermal comfort in dwellings, which is described in section 6.6.

4.4.5 Questionnaires

To complete this study, the occupants of each dwelling filled in some questionnaires during the monitoring period. The information supplied by the questionnaires is related to occupant behaviour and awareness, energy consumption, building services, indoor air quality and occupation patterns.

4.5 Data Analysis

Different analyses of the collected data were made according to different moments of the monitoring period:

- Seasonal values were analyzed for winter (Dec-Mar), tempered season (Apr-May) and summer (Jun-Aug).
- The coldest period of 15 days, (1-14 February)
- One period of 15 days in Spring.
- The hottest period of 15 days, (8-22 August)
- Short time periods (48h). The hottest (18th-19th August), the coldest (8th-9th February) and tempered (24th-25th April) short periods.

These values for each dwelling are provided: maximum and minimum values, average values, standard deviations and correlations between indoors and outdoors air temperatures.

5 Results

U-values of dwellings are clearly gathered in two defined ranges. One is the group related to the newest (Built after 80's) or energy renovated buildings, which have an U-value between 0.40-0.50 W/m^2.K. The other group refers to buildings built before the first thermal regulation (1979) with a U-value between 1.10-1.30 W/m^{2}K.

As expected there are two clear correlations. First of all the higher ΔT, the higher the heat consumption. As it was also expected, when two dwellings with similar heating consumption are compared, the higher ΔT corresponds to the lower U-value. This trend is clearly shown in the graph depicted in Fig. 6. A comfort zone has been assumed to this study. Even though comfort zone in winter is defined between 20 ºC and 24 ºC by ASHRAE in [33], the thermal comfort limits are selected according to [22] (18 ºC ±2 ºC) Thus, red lines represent these comfort limits for winter, which makes 5.83ºC and 9.83ºC of ΔT). ΔT in this graph is the difference of the average indoor and outdoor temperatures in winter (see Fig. 8). The time-constant (τ) has been calculated dividing C [J/m^2.K] by U [W/m^2.K], so τ is presented in hours [h], according to [34]. This concept is considered useful in this graph since it encompasses both C and U in only one term.

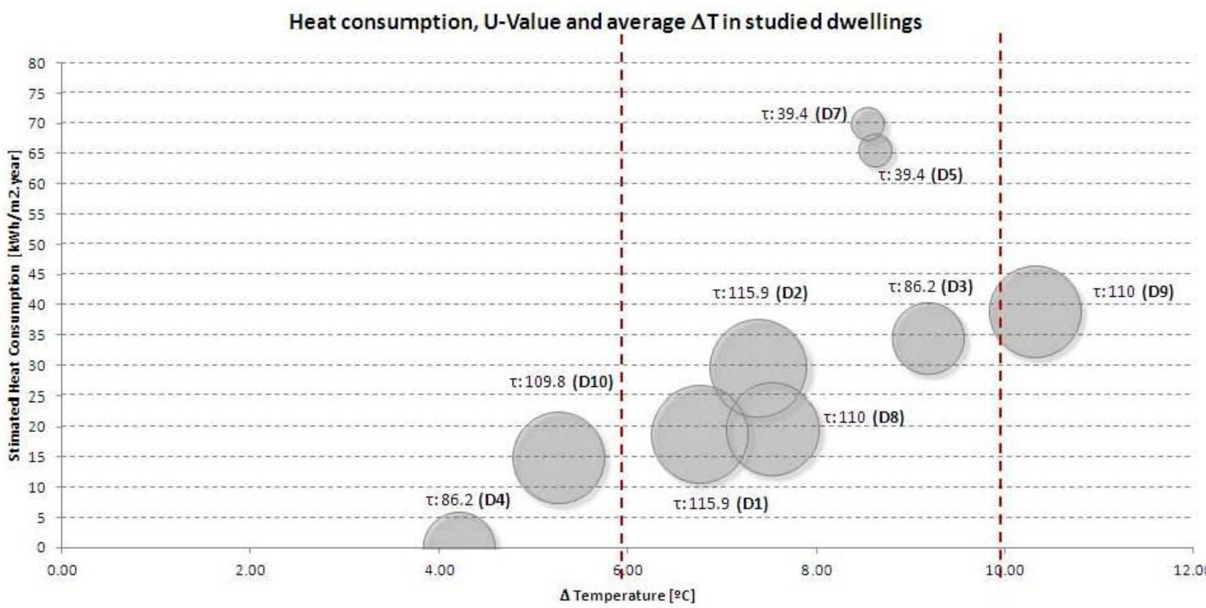


Fig. 6. Energy performance of the dwellings. Relation between yearly energy consumption per square meter of heated area, time constant and average ΔT. (Non available heating consumption data in D6) Outdoor Average: 10.17

However, if only these aspects are taken into account, an unexpected performance of two dwellings could be deduced looking at this graph: the highest heat consumption in each interval (D5 and D7, respectively) doesn't correspond with the highest ΔT. This point proves that other aspects, such as heat capacity of the façade, user behaviour, ventilation, windows quality and opaque walls and windows ratio or thermal bridges, to name but a few, play an important role in thermal performance in these dwellings. Both dwellings (D5 and D7) present not only a high U-Value (1.27 W/m^{2}K) but also a low heat capacity value in façade (180 kJ/m^{2}K), whilst other studied dwellings with low U value in their façades have, however higher heat capacity (360 kJ/ m^{2}K - 423 kJ/ m^{2}K); Differences between D5 and D7 could be explained when ventilation patterns are born in mind or user behaviour, in general.

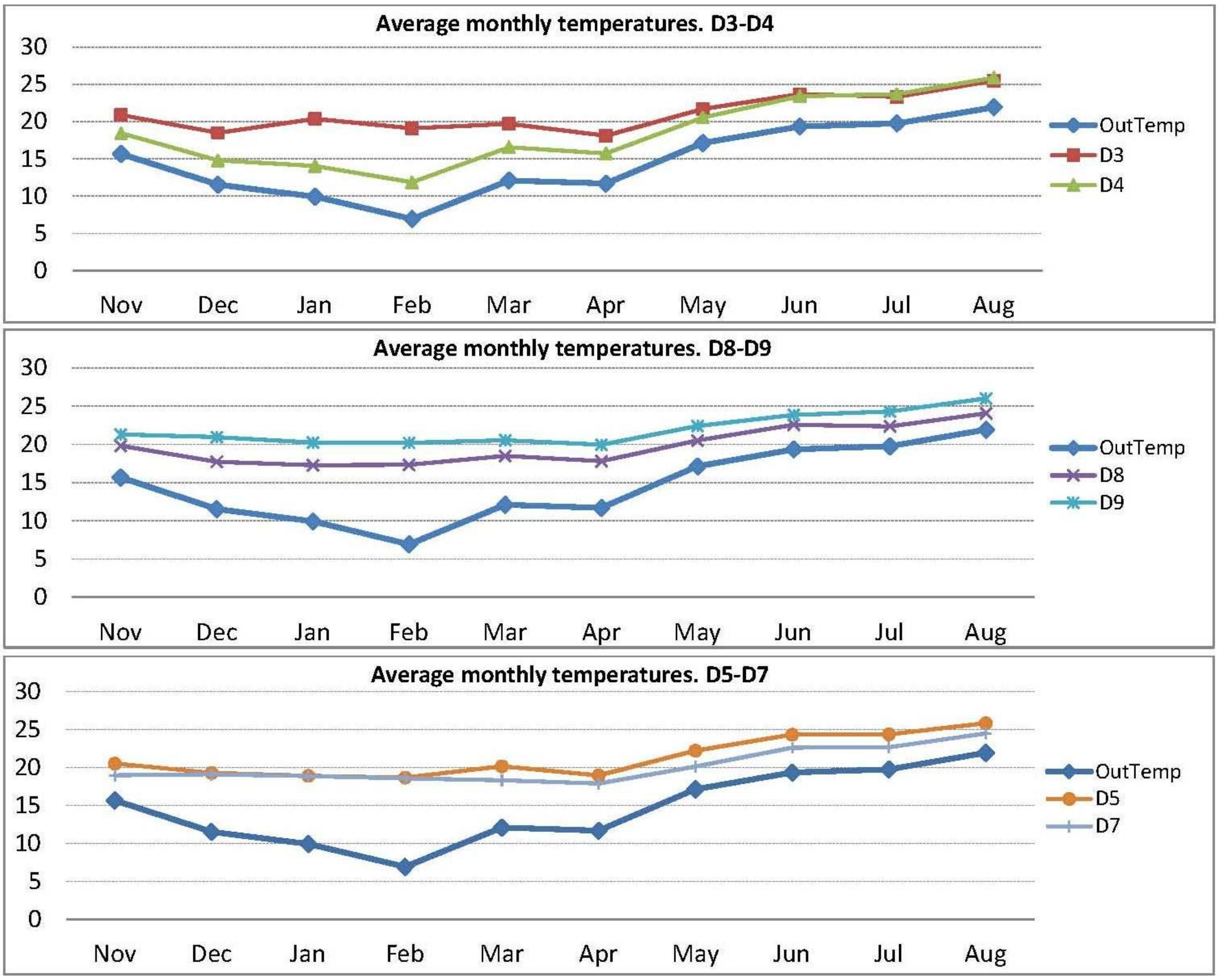


Fig. 7. Comparison of the monthly average temperatures in some studied dwellings.

Thus, these consumption differences should be evaluated and explained analysing more parameters. D3 and D4 are quite similarly constructed. Their differences can be explained when the used heating system is taken into account (D4 has no heating system) and when comparing the average monthly indoor temperatures (Fig. 7). Even using the same heating system (natural gas with high temperature radiators), significant differences can be found in heating consumption (about 50%), as Fig. 7 shows in graphs for D8 and D9. When D5 and D7 are compared, with similar average indoor temperatures during winter period, differences in heating consumption (Fig. 6) can be attributed in this case to occupants behaviour, as previously said.

6 Analysis of results

6.1 Analysis of annual indoor environment

Social housing sector is a heterogeneous dwelling group when indoor thermal conditions are taken into account. In the studied group, significant differences are found for the average monthly indoor temperatures, especially in winter time, when heating systems are used and consequently, heat consumption is the highest (Fig. 8). This period will be studied in detail later.

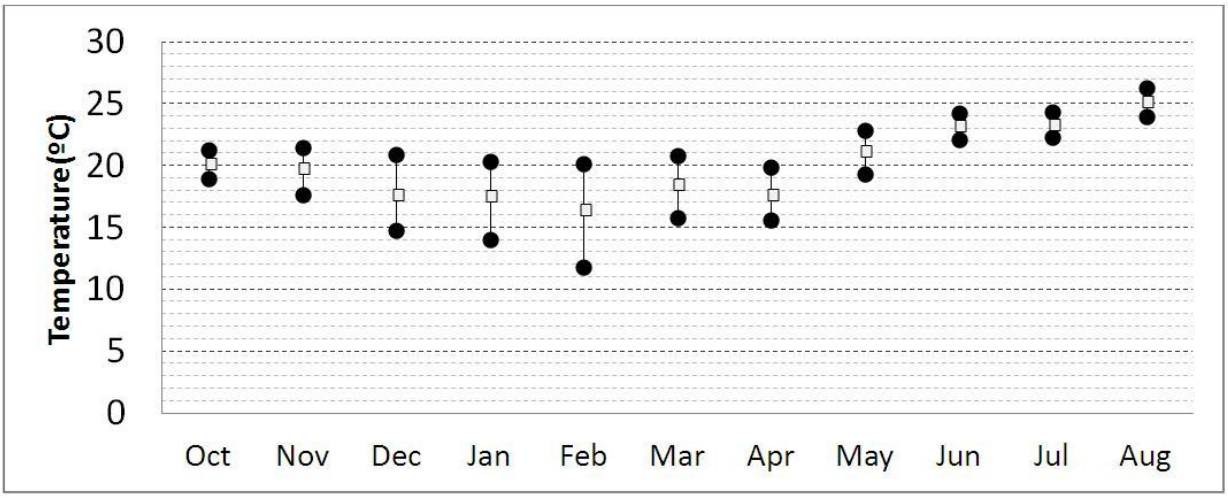


Fig. 8.Maximum, average and minimum monthly indoor temperatures for the 10 studied dwellings.

Fluctuations in indoor temperature are a consequence of several factors, such as the heat capacity of the building structure, the heating system control or ventilation patterns, to name but a few. Diurnal and Nocturnal Ranges give an idea of the indoor temperature stability. The ratio of internal to external temperature fluctuation ($\Delta t_i/\Delta t_o$) shows correlations between indoor and outdoor temperatures, and it will depend on the dwelling features (Building Techniques, Building Envelope and Energy Systems) and, on the other hand, on dwelling services and dwelling operation, related to occupant behaviour.

Table 6 shows the nocturnal and diurnal ranges by seasons. The higher diurnal and nocturnal ranges of indoor temperatures are in winter period, when heating systems are used. The average of diurnal range in this period is between 3.18 (D2) and 1.16 (D6), whilst the average of nocturnal range is between 3.63 (D10) and 0.82 (D6). In summertime, instead, these ranges are in general quite smaller, from 3.36 (D2) to about 0.8 (D4 and D6).

	C (kJ/ m²K)	Winter Period (Dec-Mar) Diurnal Range (8-20h) (Δti)	Winter Period (Dec-Mar) Nocturnal Range (20-8h) (Δti)	Spring Period (Apr-May) Diurnal Range (8-20h) (Δti)	Spring Period (Apr-May) Nocturnal Range (20-8h) (Δti)	Summer Period (Jun-Aug) Diurnal Range (8-20h) (Δti)	Summer Period (Jun-Aug) Nocturnal Range (20-8h) (Δti)
(T_o)		5.53	4.01	4.58	4.02	5.19	4.38
D1	*463.8*	2.14	2.15	1.23	1.33	1.07	0.99
D2	*463.8*	3.18	2.87	2.53	2.49	3.36	3.68
D3	*359.8*	3.11	2.99	1.32	1.39	0.91	0.93
D4	*359.8*	1.19	1.68	1.03	1.46	0.81	1.08
D5	*180.0*	2.64	2.84	1.98	1.85	2.03	1.80
D6	*238.4*	1.16	0.82	0.89	0.89	0.79	0.85
D7	*180.0*	2.98	2.55	1.63	1.33	1.03	0.93
D8	*189.0*	1.79	1.41	1.64	1.12	1.75	1.38
D9	*189.0*	2.18	1.92	1.43	1.58	1.17	1.27
D10	*162.6*	2.02	3.63	1.54	1.56	1.11	1.23
Average of dwellings		2.24	2.29	1.52	1.50	1.40	1.41

Table 6. Ratio of internal to external diurnal and nocturnal temperature fluctuation for the studied dwellings (main room data)

Differences can also be found when the two monitored rooms of the same dwelling are compared, especially in wintertime. If all rooms of the dwelling are heated by the heating system, nocturnal and diurnal ranges are similar in both rooms (e.g. D5, average diurnal range is 2.64 in the main room and 2.85 in the bedroom; and average nocturnal range is 2.84 in the main room and 2.70 in bedroom) When only some rooms of the dwelling are heated, the differences are quite bigger: in D3 the average diurnal range is 3.11 in the main room and 1.36 in the bedroom; and the average nocturnal range is 2.99 in the main room and 1.27 in the bedroom.

These results seem to be contradictory with that mentioned in [22], where it is affirmed that fluctuation temperature is closely linked to the heat capacity of the structure. However, this phenomenon can be explained with the fact that both studies have been carried out under different conditions (in this case, every monitored dwelling has been occupied during monitoring periods, whereas in [22] two dwellings out of the three were vacant). The way of using the heating system in winter, and ventilation management of the user in summer (both strategies regarding to occupants' behaviour) can increase significantly the indoor temperature range of the dwellings. As a matter of fact, this is proved with the result of diurnal range of temperatures in D4 in winter, (one of the lowest of the sample), which has no heating system, as well as in D6, (it presents the lowest temperature range) where the use of the heating system is very occasional, according to D6 questionnaire. This hypothesis is proved in summer as well. Dwelling D6, which is also the dwelling with the lowest temperature in summer, is vacant during this period. Other factors, such as the ratio of area of exposed envelope and dwelling area can complement the explanation of these results. Thus, the high values of D2 are also explained due to its location within the building, directly under the roof, whereas in D1 the effect of high C in the opaque walls could be counteracted by the low quality of the windows.

Indoor relative humidity (RH) has also been studied. The accepted range of RH for thermal comfort is from 30% to 70% [33]. Therefore, as shown Fig. 9, more than 99% of registered RH data were higher than 30% in all dwellings. However, the situation changes when the highest limit is observed. In four dwellings, more than 5% of registered data were out of comfort zone, and two of them gave especially high values: D6 (32.4% of the registered data out of comfort zone) and D7 (46.9% of the registered data out of comfort zone). Seasonal detailed information is presented in Table 7. The majority of collected data higher than RH 70% correspond to wintertime, except in D7 which has high RH values in every evaluated season.

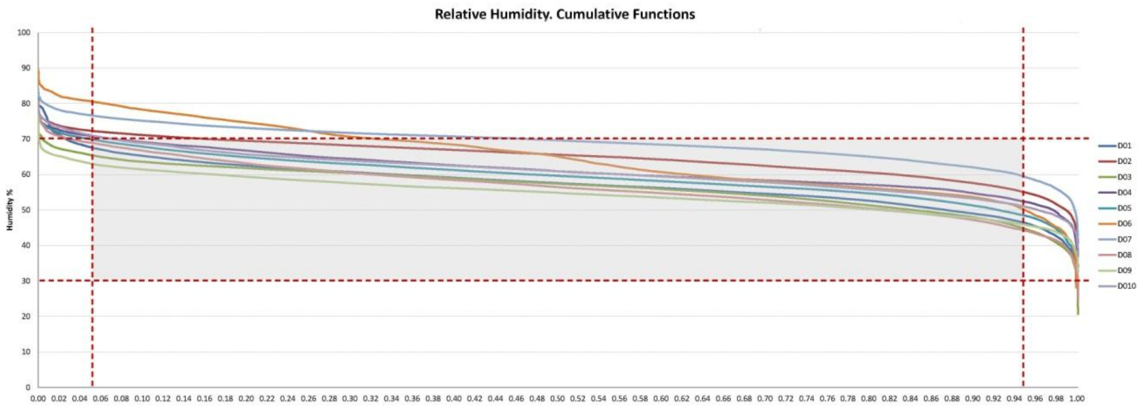


Fig. 9.Relative Humidity in the Dwellings. Cumulative Distribution Function.

R.H.	Dec 2011 – Sept 2012		Winter	Tempered season	Summer
	Measures up to 30% (%)	**Measures higher than 70% (%)**	Measures higher than 70% (%)	Measures higher than 70% (%)	Measures higher than 70% (%)
D1	**0.02%**	**3.7%**	8.1%	0.14%	0.36%
D2	**0.00%**	**16.2%**	27.5%	12.1%	3.9%
D3	**0.06%**	**0.3%**	0.82%	0.00%	0.1%
D4	**0.00%**	**7.2%**	16.2%	0.19%	0.02%
D5	**0.02%**	**4.9%**	9.2%	3.5%	0.02%
D6	**0.2%**	**32.4%**	63.2%	18.6%	0.81%
D7	**0.00%**	**46.9%**	40.6%	58.8%	47.5%
D8	**0.00%**	**3.0%**	0.85%	1.76%	6.9%
D9	**0.00%**	**0.08%**	0.03%	0.00%	0. 2%
D10	**0.00%**	**7.0%**	10.1%	2.3%	6.0%

Table 7. Summary of logged RH (%) during the whole period and by seasons: Winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and Summer (Jun-Jul-Aug 2012)

In occupied dwellings RH is directly affected by natural ventilation (there is no mechanical ventilation in the studied dwellings). Thus, this parameter can also give information about the ventilation rate, whether it has been enough or not. Indoor RH is related to outdoors RH, and with indoor humidity sources like cooking or human activity. Too high RH values could mean low ventilation rate, as well as low indoor temperatures.

6.2 Winter period

6.2.1 Overall analyisis

Winter period data (Dec 2011-Mar 2012) are presented in this section. Some temperature limits are defined to evaluate indoor temperatures in dwellings. For winter, thermal comfort limits have been set up around 18 ºC ±2 ºC based on the research presented in [22]. Moreover, the lowest limit (16 ºC) has been used as a reference in other studies for identifying "cold homes" when standardized temperatures are used [4].

Average indoor temperature in two dwellings in winter is lower than 16 ºC (D4 and D10). For dwellings D1, D2, D6 and D8 average indoor temperatures are also low (Table 8). The reasons of these low temperatures can be different in each case: recurring inoccupation of dwelling, inadequate heating equipment control, building and heating system characteristics, ventilation patterns…

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	25.80	-0.30	10.17	26.10	3.87
D1	24.46	9.73	16.94	14.73	1.85
D2	22.71	10.79	17.56	11.92	1.32
D3	26.13	14.36	19.35	11.77	1.86
D4	21.27	9.21	14.38	12.06	2.26
D5	23.86	12.94	18.79	10.91	1.59
D6	23.69	13.81	17.67	9.88	1.61
D7	22.39	14.27	18.71	8.13	1.25
D8	22.66	11.13	17.70	11.53	1.20
D9	24.22	13.64	20.48	10.58	1.04
D10	23.28	10.52	15.43	12.76	1.68

Table 8. Summary of logged temperatures (ºC) in Winter (Dic-Jan-Feb-Mar)

6.2.2 15-day and 48-hour periods

48-hour period and 15-day period analysis (Fig. 10 and Fig. 11 respectively) allows complementing the information gathered by questionnaires with real data obtained by the thermo-hygrometers. Ventilation (opening windows) and heating consumption patterns are easily identified in these analyses. Opening windows in winter are identified in the graphs because RH and temperature drops suddenly. In a similar way, when heating system is activated, temperature increases and RH drops at the same time. Two examples of this behaviour for dwellings D3 (Heating system activation) and D5 (opening windows) are depicted in Fig. 10.

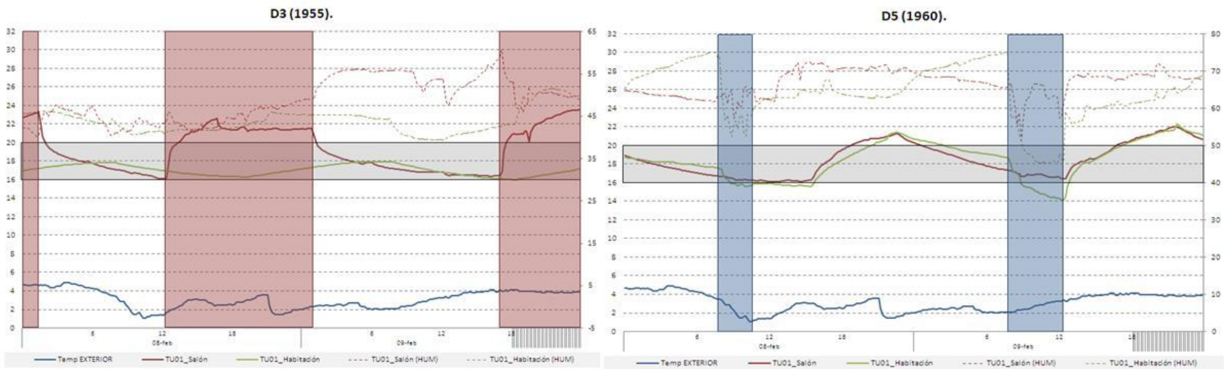


Fig. 10. 48-h analysis. Identification of heating system activation (left graph) or opening windows (right graph)

These analyses allow also comparing different heating systems, and the way of using them. For example, D1 and D3 use heaters only in some rooms of the whole dwelling. However, the results are quite different in each case (Fig. 11). Although both dwellings are occupied during the whole day, D1 only have some peaks with over 16 ºC in the heated area and in the 48-hour analysis there is a minimum of 12 ºC (in that moment, windows are open), whilst D3, a dwelling heated by a 2kW electric heater located in the living room, has a significant amount of logged data over 20 ºC in the heated area.

Several differences can also be found in the evolution of non-heated area temperatures in these dwellings. D4 (with no heating system) has a very low temperature during the coldest period. Temperature in the whole dwelling is stable and the same in the two studied points, and small peaks appear in the main room, due to the use of a small heater, whose consumption has been neglected in energy consumption estimations. Dwellings with natural gas and one radiator in each room have smaller temperature differences in the whole dwelling during the day (e.g. in D5 natural gas heating system with one heat radiator in each room is used. The system is commanded with a thermostat located in the living room). Energy consumption for heating is usually higher in these dwellings, but the whole dwelling works closer to comfort levels. Temperatures are similar in every room, and small variations are due to different ventilation patterns in each room.

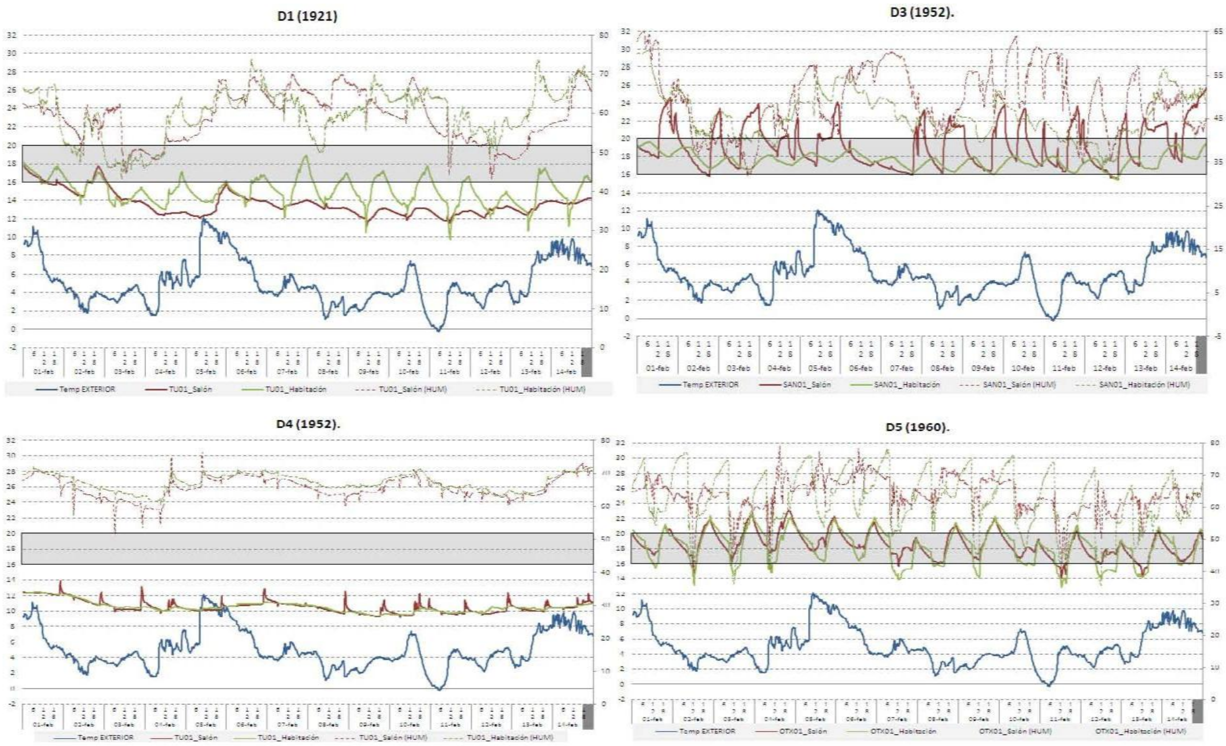


Fig. 11. Indoor RH and Temperature and outdoor temperature for D1, D3, D4 and D5 dwellings during 15-day period in winter.

In this analysed 15-day period, the 4 dwellings (D1, D4, D6 and D10) have an average temperature below 16 ºC and only one dwelling (D9) have an average temperature higher than 19 ºC (Table 9)

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	12.10	-0.30	5.08	12.40	2.54
D1	19.01	9.73	14.38	9.28	1.55
D2	21.10	12.99	16.95	8.11	1.43
D3	25.72	15.51	18.46	10.21	1.99
D4	13.91	9.21	10.57	4.69	0.76
D5	23.16	12.94	18.38	10.22	1.97
D6	17.68	13.81	15.04	3.87	0.84
D7	22.39	14.27	18.86	8.13	1.52
D8	18.60	12.85	16.75	5.76	0.92
D9	24.22	14.96	20.24	9.26	1.01
D10	22.32	10.52	14.81	11.81	1.97

Table 9. Summary of logged temperatures (ºC) in the 15 coldest days (1-14 Feb 2012)

6.3 Summer period

In order to assess the thermal behaviour of each building without any heating or cooling system, monitoring measures have also been carried out in summer, from June to August 2012. As it was expected in this climatic area, indoor thermal comfort is satisfactory without any cooling systems,. As shown in Table 10, the range of indoor average temperatures is between 6.82 (D7) and 12.34 (D2), with a standard deviation between 1.31 (D7) and 1.86 (D4). These data show the capacity of these dwellings to attenuate the impact of the diurnal summer thermal variations.

	Maximum Temp. (ºC)	Minimum Temp. (ºC)	Average Temp. (ºC)	Range (ºC)	Standard Deviation
Outdoors	36.90	12.40	20.35	24.50	3.53
D1	28.64	17.80	23.81	10.85	1.60
D2	29.12	16.77	23.87	12.34	1.70
D3	28.15	20.75	24.06	7.40	1.43
D4	29.99	20.25	24.32	9.75	1.86
D5	30.14	19.75	24.54	10.40	1.43
D6	28.72	20.32	24.62	8.40	1.78
D7	26.97	20.15	23.25	6.82	1.31
D8	29.57	18.89	22.99	10.68	1.38
D9	27.85	20.60	24.72	7.25	1.43
D10	26.72	18.46	23.27	8.26	1.42

Table 10. Summary of logged temperatures (ºC) in summer (June-August)

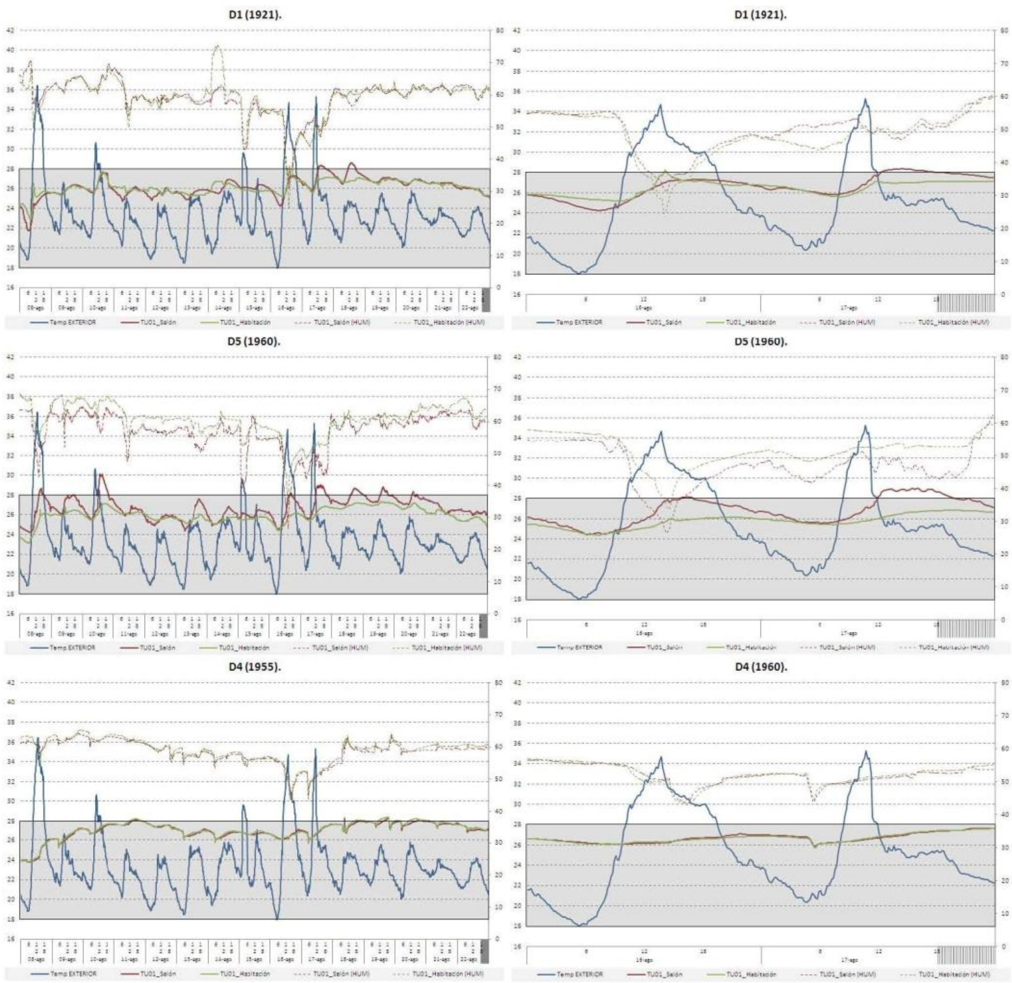


Fig. 12. 15-day and 48-hour period (the hottest period) analyses for D1, D4 and D5 in summer.

For this period, indoor temperatures are evaluated in detail as well (Fig. 12). Thermal comfort limits have been set up with a maximum value of 28 ºC. Even during the hottest period of the year, an optimised management of occupants (reduction of solar gains during day time and natural cooling at night) ensures a proper thermal regulation. This regulation is achieved thanks to the specific architectural designs of these dwellings, especially because its indoor distribution allows a cross ventilation and thermal draught created by existing temperature gradients between opposite façades, which allows adequate natural ventilation.

6.4 Spring period (tempered season)

Tempered season data (April-May 2012) have been assessed as well. Similar methodology has been followed to analyse these data. In this period, only in one dwelling (D10) the average indoor temperature is lower than 18 ºC. The other dwellings have average temperatures between 18.15 ºC (D4) and 21.19 ºC (D9). Standard deviations in this period are in general quite higher than those obtained in wintertime.

Regarding to 15-day and 48-hour period analyisis, although indoor thermal conditions between the dwellings are similar in this period, still several significant differences can be found. Some dwellings used the heating system during some days of this period.

6.5 Thermal imaging inspection

To analyse the heat consumption of a dwelling, another issue to take into account is the impact of thermal bridges. According to diverse consulted bibliography, the impact of thermal bridges on heat consumption can vary from 5% [35] (insulating the exterior of the building envelope) to 39% [36] (in many insulated single family houses with bad thermal bridge treatment).

Despite the complexity to carry out an accurate quantitatively IR inspection, the temperature profile in the thermal bridge created in the slab face of each building has been analysed, as shown in Fig. 13. The minimum temperature in the external surface of the façade (T_{min}) corresponds to a point far away from the thermal bridge, where the heat flux is supposed to be one-dimensional. The difference between the minimum and the maximum temperature (ΔT) indicates the level of the impact of the slab face thermal bridge. The higher ΔT, the higher the thermal bridge impact is.

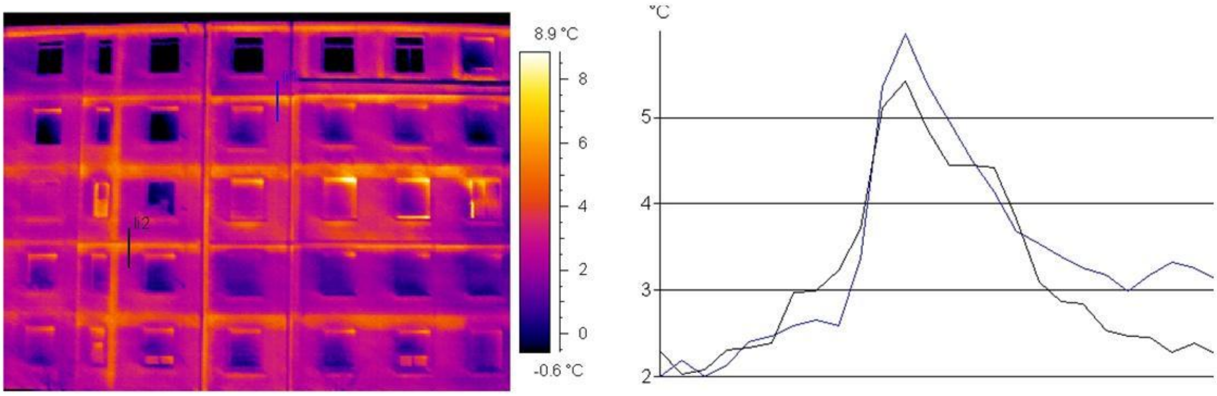


Fig. 13. Temperature profile in the slab face thermal bridge of dwelling D2.

The lowest difference of surface temperature (ΔT) has been found in the buildings corresponding to dwellings D3 and D7 (0,7 ºC), whilst the highest ΔT was registered in the façade of D2 (3,3 ºC). The possible effect of thermal bridges over the global thermal performance of the dwellings is not very well defined when these results and indoor temperatures or consumption in each dwelling are assessed together, due to the fact that the effect of other variables such as opening windows patterns, (see Fig. 10) make negligible the impact of thermal bridges. In this case, the fact that dwellings have been occupied during the monitoring period is a handicap to evaluate this effect. Studying quantitatively the thermal bridges effect on a dwelling requires to limit the effect of human behaviour, either by means of simulations, or by carrying out the study in vacant dwellings, since factors manipulated by the user (such as heating temperature set point, ventilation rates or internal gains) have a strong influence on the thermal gradient between indoors and outdoors. This fact can vary the ΔT value of a thermal bridge.

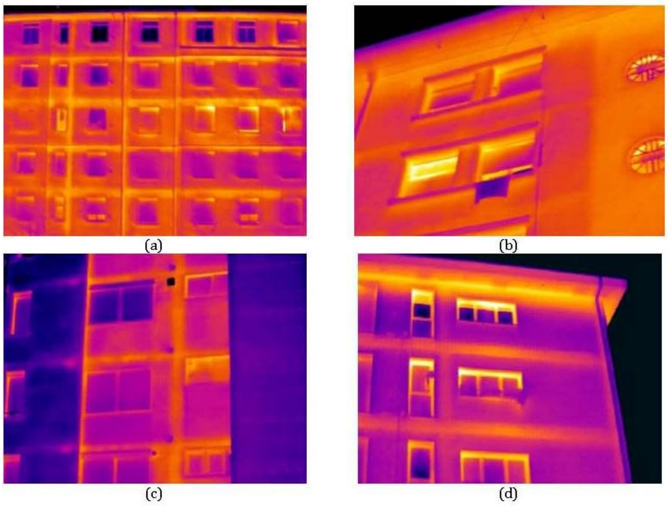


Fig. 14. Thermographs of some buildings studied (a) D2; (b) D3; (c) D5; (d) D8.

6.6 Indoor thermal comfort and risk of cold homes

Due to the fact that some of the logged temperature data in winter are much lower than expected, a study has been developed in order to evaluate indoor thermal comfort in winter, and the risk of cold homes. Thermal comfort is defined by ISO 7730 ([32]) as the mental condition expressing satisfaction with thermal environment. As it has been mentioned in section 4.4.4, recording all these parameters has not been possible. For this reason, an approximation based on the statistical analysis has been made, following the procedure presented in [22].

Cumulative distribution functions (CDF) were obtained with the series of registered temperatures in the studied dwellings during winter period, from 1st of December 2012 to 1st of April 2012 (Fig. 15). Significant differences can be found when CDF are compared. About 80% of the registered data in D4 in winter is lower than 16ºC. On the other hand, in D9 the share of the registered data below 16ºC is negligible, almost 70% of the time the temperature is over 20ºC, which could suggest that reducing the set point temperature would reduce energy consumption without reducing indoor environment comfort levels. CDF of D10, D1, D2 and D5 are also presented in Fig. 15. CDF of D2 shows a balanced indoor temperature management, where less than 5% of the registered data is below 16ºC and less than 5% of the registered data is over 20ºC.

A summary of logged temperatures according to these criteria is presented in Table 11. In this table the thermal performance of D4 must be highlighted. It is not only the coldest dwelling in winter, but also one of the dwellings with higher temperatures in summer (see Table 10) if it is compared to other dwellings. D6 logged high temperatures in summer, but this is due to the fact that the dwelling was empty during this summer period and thus, there was no ventilation during this period. D5 presents higher temperatures over the whole year. Thermal performance of D4 could be explained because the high U-value of its façade and especially because it is located in the upper floor of the building and the U-Value of its roof is too high.

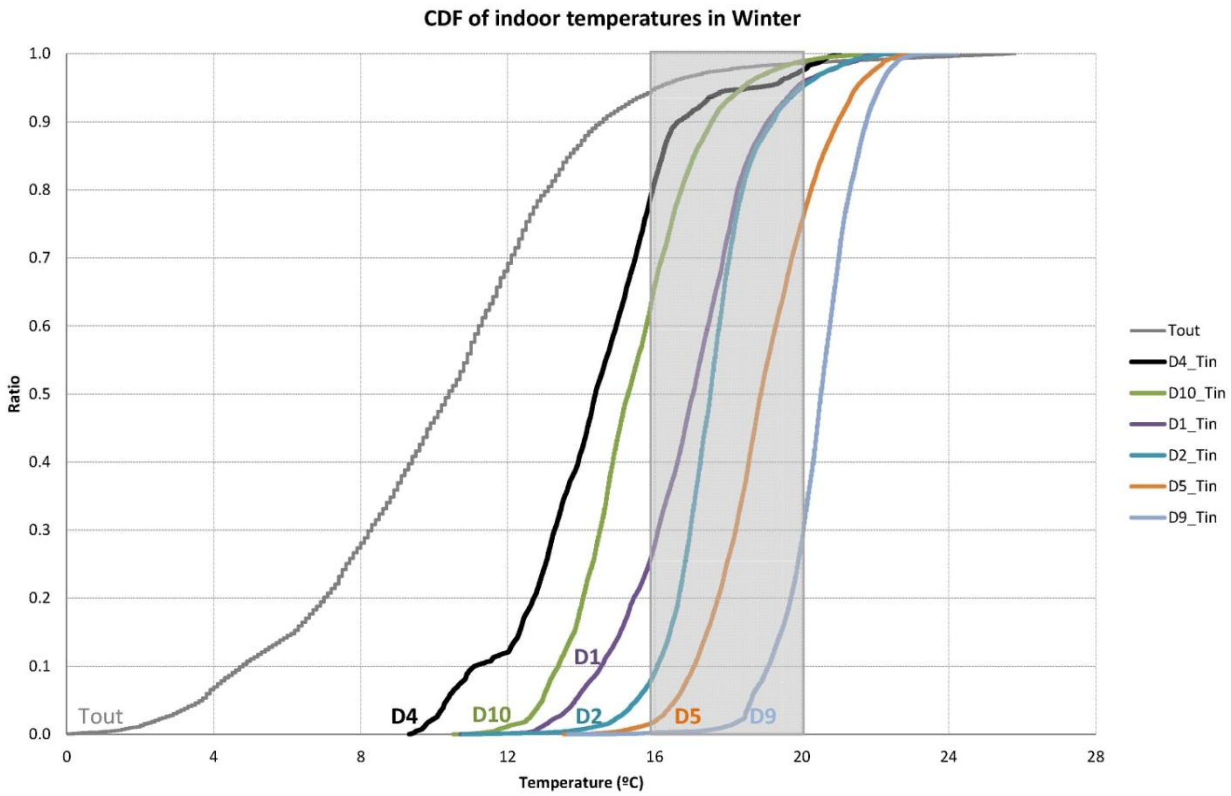


Fig. 15. Cumulative Distribution Function of 6 studied dwellings in winter (D4, D10, D1, D2, D5 and D9).

	Winter		Tempered season		Summer	
	Measures below 16 ºC	Measures over 20ºC	Measures below 16 ºC	Measures over 20ºC	Measures below 20 ºC	Measures over 28ºC
OUT	94.67%	1.41%	69.96%	10.43%	52.00%	3.43%
D1	24.6%	5.68 %	11.69%	41.69%	0.20%	0.02%
D2	9.06%	4.94 %	3.13%	39.77%	2.42%	0.17%
D3	0.83%	30.25%	1.15%	49.24%	0.00%	0.00%
D4	81.86%	2.27%	33.15%	29.33%	0.00%	1.36%
D5	0.94%	29.20%	0.00%	52.53%	0.00%	2.33%
D6	12.92%	5.96%	0.14%	46.69%	0.00%	5.07%
D7	1.09%	16.99%	0.31%	26.94%	0.00%	0.00%
D8	5.20%	4.75%	0.92%	30.26%	0.28%	0.03%
D9	0.26%	71.85%	0.00%	76.58%	0.00%	0.00%
D10	65.90%	1.13%	25.41%	18.27%	0.08%	0.00%

Table 11 Summary of logged temperatures in the main room (%) in winter (Dec 2011 - Mar 2012), tempered season (Apr-May 2012) and summer (Jun-Jul-Aug 2012)

These CDF analyses give quantitative information, but they don't describe the temperature evolution inside the dwellings. As described in [22] the difference between indoor and outdoor temperatures against outdoor temperature is analyzed (Fig. 16). The thermal comfort zone is marked in these graphs, so as to identify which measures are in the thermal comfort zone and which measures are not. The graphs also show the share of measures which are below 16 ºC. Previously mentioned thermal comfort limits are selected (18 ºC ±2 ºC) according to [22].

The CDF temperature in winter gives an idea of the heating system usage. Differences between D4, (where more than 80% of the measured temperatures are below 16 ºC), and D9, (where more than 99% of measured temperatures are higher than 16 ºC), are clear. In this case, one of the most influential factors is not the building envelop, the energy system or the building techniques but the building operation (i.e. the way that occupants use and manage the building) and specially, the way the heating system is used.

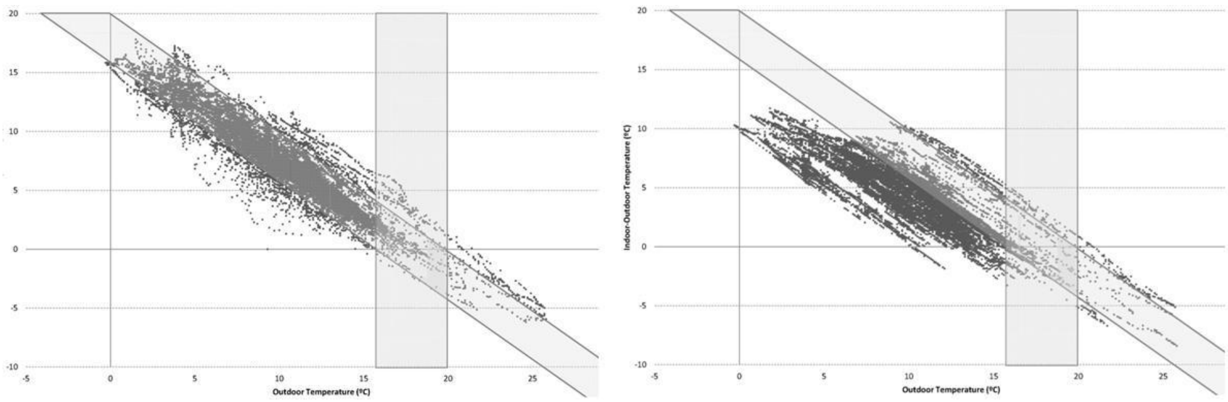


Fig. 16. Indoor-Outdoor temperature against outdoor temperatures in wintertime. (D2 and D4).

7 Discussion

7.1 Overall discussion of the results

Thermal behaviour of dwellings can be explained only when the building is studied under a global approach. In the case of the analyzed dwellings, occupants' behaviour (as affirmed in [37]) plays an important role in indoor thermal characteristics, moreover in summertime. In most of the studied cases, it can ensure a thermal regulation thanks to specific architectural design of the dwellings: crossing distribution of the indoor environment, distribution of rooms according to its uses and orientations or indoor distributions which allow natural ventilation. Thus, following the approach presented in Fig. 1, the results obtained may be summarized in the following points:

Outdoor environment and site. The studied dwellings are located in an area with a tempered climate, although sporadically peaks of temperature (both high and low) could be registered.

Heating systems. In the majority of the analysed dwellings the heating system efficiency could be improved, especially in rented ones, where the occupants usually decide not to invest on an efficient heating system.

Building envelope. In many dwellings windows have been replaced at least once, and *"Bilbao Social Housing"* have promoted and developed plans in this way, usually acting not on a building scale, but on a dwelling scale. However, there is still a great number of buildings and dwellings with envelopes displaying a poor thermal performance.

Building Techniques. The effects of the thermal bridges have not been appreciated due to their low impact compared to other effects, such as ventilation patterns, as it has been described in section 6.5.

Indoor design. In general, studied dwellings present a good indoor design, with crossing indoor distribution, adapted to uses and orientation.

Occupants. Occupation patterns, ventilation patterns or ways of using the heating system have a high repercussion in the comfort and in the energy consumption. This can be observed in Fig. 11, where the measured temperature profiles in three dwellings during two weeks in February are presented. The differences are not only in the heating system fuel, but also in ventilation patterns. In this way, strategies for increasing the occupants' awareness are recommended to be developed.

7.2 Remarks on indoor comfort

7.2.1 Winter period

As summarized in Table 8, four of the studied dwellings have an indoor average temperature lower than 16 ºC during the coldest period in winter, and two of them present an average temperature lower than 16 ºC when the whole winter is analyzed. On the contrary four dwellings have an average temperature over 18 ºC. In three of these four dwellings (D5, D7 and D9), the occupants are the owners. In the fourth one, although the average indoor temperature is higher than 18 ºC, it is quite unstable. These three dwellings are the only ones which have natural gas based heating system, and the household incomes of these dwellings are also the highest of the ten studied cases. Other studies have also demonstrated that amongst other factors, household incomes and energy consumption and therefore, indoor comfort at home, are closely linked [38].

The majority of the analyzed dwellings have lower energy consumption than expected. This is not due so much to the building thermal performance itself, but to the indoor temperatures which take in some cases very low values.

Improving the thermal performance of the stock of social dwelling not only must aim at reducing energy consumption, but also at improving indoor comfort. For that reason, when the effectiveness of a renovation in a social dwelling is evaluated, indoor environment parameters, such as indoor temperature and RH, must be taken into account. The improvements on the indoor comfort should be considered as positively as energy savings itself. Factors which are out of the scope of our study, such as health and social factors will also be benefitted through a proper renovation of social dwellings.

7.2.2 Summer Period

Indoor conditions in summer have also been considered in this study. Similar methodology to the one used in section 6.6 to evaluate indoor comfort in winter could be followed to study the indoor thermal comfort in summer. In this case, it has not been accomplished because the registered indoor temperatures in summer are in general quite comfortable, rarely higher than 28 ºC even during the hottest days of the year, as expected in this climatic area.

8 Conclusions

In order to establish a good energy renovation strategy of the building stock, and to consider different priority criteria, it is necessary to have accurate data on the thermal performance of the building stock. This paper has shown a methodology for studying thermal performance of social dwellings based on a long term monitoring of 10 dwellings. Collected data have been used to define general trends on energy consumption and thermal performance of social housing sector, as well as enough data to define the operation conditions in social dwellings, based on this field study, and not in standards. Significant differences have been found comparing standard operation conditions and operation conditions based on gathered measurements. This study also provides qualitative and quantitative characterization of ten reference dwellings, representative of the Social Housing Sector in Bilbao.

The field investigation shows that energy consumption of these social dwellings is lower than expected. In section 6.2 has been shown that this situation is not due that much to a good thermal performance of the studied dwellings, but to a lowering of the indoor comfort levels, and low indoor temperatures in winter. This way, future energy retrofitting strategies will have to bear in mind this aspect when their effectiveness will be assessed. That is, sustainability on building renovations does not have to be evaluated only in terms of energy savings, but also under economic and social criteria. The aim of reducing cold homes (and this way the risks which they involve) must be considered as important as energy savings themselves, especially in social housing sector.

Differences on energy consumption for heating have been found amongst the studied dwellings. Those differences can only be explained properly when all subsystems and their interactions are considered in the study. Especially important is the indoor average temperature required by the occupants in winter, which is closely linked to household incomes. The highest indoor temperatures have been found in the dwellings with higher household incomes. These differences on indoor conditions also depend on the heating system and its use, as described in section 0. It proves the heating system influence on the indoor thermal comfort, both the kind of heating system itself and the use of it given by the occupant.

It could be interesting to carry out further researches about the influence of the occupants on energy consumption and indoor comfort. Many aspects which are strongly dependent on the occupants, such as the mentioned heating system usage, ventilation patterns, set point temperatures or closing the window shutters at night, involve great variations on the final energy consumption of a building.

The study also shows that the majority of dwellings have a good design, which can allow thermal regulation by means of the occupants' adaptive behaviour. Energy renovations in social dwellings in this city has to be leaded mainly to improve energy systems and building envelope, both walls and windows if necessary.

It is necessary to investigate accurately the different types of social dwellings before any retrofitting intervention, according to the classification previously mentioned. The best retrofitting strategy for improving thermal performance of a building constructed in 1920, with high thermal mass in façade will be different than the best one for a building constructed in 1960 with a light façade.

In this research, a sample of ten different dwellings has been studied. Some of them present a low U value in façade, some of them present a high C in façade, and two of them present high U value and low C in façade at the same time. However, none of them have a façade with both low U-Value and high C. It could be interesting to study the thermal behaviour of a dwelling with these features in further researches.

Finally, in another research line, the risk of cold homes in Spain is a factor to be taken into account. Although this problem could seem to be only linked to northern countries, this research has shown that, at least in social housing sector, cold home is a real problem. This problem will be aggravated in the near future due to the economic crisis and the steady increment of the energy prices. More studies focusing on cold home concept should be carried out.

In short, social dwelling stock is one of the sectors with more risk of energy poverty. Hence, social housing stock, especially those built before 1980, should be a priority in energy renovation strategies, both due to its potential of improvement and the need to fight against the risk of fuel poverty and cold homes.

9 Acknowledgements

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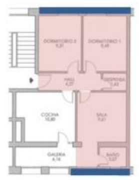
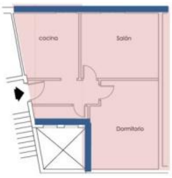
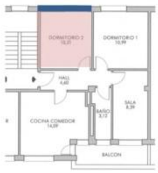
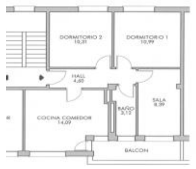
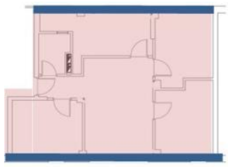
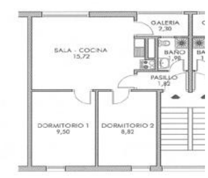
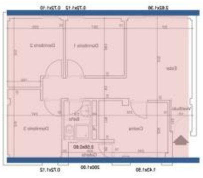
10 Appendix

A summary of geometrical and other features of the heating area in each studied dwelling are presented in Table A1.

Geometrical features of the heated areas				
				
D1	**D2**	**D3**	**D4**	**D5**
				
D6	**D7**	**D8**	**D9**	**D10**

	m² façade (of heated area)	EF		m² façade (of heated area)	EF
[D1]	*Apartment Façade:* 32.5 (Façade) 6.5 (Windows; 20%) *Heated Area Façade:* 22.5 (Façade) 4.5 (Windows; 20%)	1.67	[D6]	*Apartment Façade:* 27.9 (Façade) 7 (Windows; 25%)	1.43
[D2]	*Apartment Façade:* 29.75 (Façade) 5.55 (Windows; 20%) *Heated Area Façade:* 29.75 (Façade) 5.55 (Windows; 20%)	1.51	[D7]	*Apartment Façade:* 41.25 (Façade) 10.23 (Windows; 25%) *Heated Area Façade:* 41.25 (Façade) 10.23 (Windows; 25%)	1.16
[D3]	*Apartment Façade:* 35 (Façade) 8.75 (Windows; 25%) *Heated Area Façade:* 7.5 (Façade) 1.95 (Windows; 26%)	1.37	[D8]	*Apartment Façade:* 46.8 (Façade) 11.5 (Windows; 25%) *Heated Area Façade:* 46.8 (Façade) 11.5 (Windows; 25%)	1,71
[D4]	*Apartment Façade:* 35 (Façade) 8.75 (Windows; 25%)	N/A	[D9]	*Apartment Façade:* 42.9 (Façade) 10.7 (Windows; 25%) *Heated Area Façade:* 42.9 (Façade) 10.7 (Windows; 25%)	1.59
[D5]	*Apartment Façade:* 41.25 (Façade) 10.23 (Windows; 25%) *Heated Area Façade:* 41.25 (Façade) 10.23 (Windows; 25%)	1.16	[D10]	*Apartment Façade:* 35.9 (Façade) 7.7 (Windows;21%) *Heated Area Façade:* 14.95 (Façade) 2.72 (Windows; 18%)	0.86

Table A1. Geometrical features of the heating area in each dwelling. (EF: Envelope Factor= m² heated area /m² façade of heated area)

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Appendix 5.1. Combinations of TRNSYS model parameters

	Capacity [kJ/K]				Infiltrations [ren/h]		Coupling Air Flow [kg/h]	Adj. Dwellings' teperatures [ºC]		
	R1	R2	R3	LR	Dwelling	Staircase		B1P3A	B1P5A	B1PAB
MV1	82	100	164	450	0.05	30	**LR.** R3:75; R2:28; R1:40 **R1.** R2:40	17	16	No heating
MV2	140	180	240	550	0.05	30	**LR.** R3:75; R2:28; R1:40 **R1.** R2:40	17	16	No heating
MV3	82	120	164	900	0.15	30	**LR.** R3:225; R2:30; R1:0 **R1.** R2:60	17	16	No heating
MV4	100	120	164	750	0.15	30	**LR.** R3:225; R2:30; R1:0 **R1.** R2:60	17	16	No heating
MV5	100	120	164	750	0.2	30	**LR.** R3:225; R2:30; R1:0; SC: 10 **R1.** R2:60	17	16	No heating
MV6	100	120	164	750	0.2	30	**LR.** R3:225; R2:30; R1:0; SC: 10 **R1.** R2:60	M-F: 18 S-S: OFF	16	No heating
MV7	100	120	164	1500	0.2	30	**LR.** R3:225; R2:30; R1:0; SC: 2 **R1.** R2:60	M-F: 18 S-S: 16.2	16	No heating
MV8	100	120	164	750	0.2	30	**LR.** R3:225; R2:30; R1:0; SC: 2 **R1.** R2:60	M-F: 18 S-S: 16.2	16	No heating
MV9	100	120	164	750	0.1	30	**LR.** R3:225; R2:30; R1:0; SC: 2 **R1.** R2:60	M-F: 18 S-S: 16.2	16	No heating
MV10	100	120	164	650	0.1	30	**LR.** R3:400; R2:30; R1:0; SC: 10 **R1.** R2:60	M-F: 18 S-S: 16.2	16	No heating
MV11	100	120	164	650	0.1	10	**LR.** R3:400; R2:30; R1:0; SC: 15 **R1.** R2:80	M-F: 18 S-S: 16.2	16	No heating
MV12	100	120	164	650	0.1	10	**LR.** R3:400; R2:30; R1:0; SC: 15 **R1.** R2:80	M-F: 17 S-S: 15.3	16	No heating
MV13	100	120	164	650	0.2	20	**LR.** R3:400; R2:30; R1:0; SC: 22 **R1.** R2:100	M-F: 16.5 M-F: 14.9	M-F: 16 M-F: 14.4	No heating
MV14	100	120	164	650	0.1	10	**LR.** R3:400; R2:30; R1:0; SC: 22 **R1.** R2:100	M-F: 16.5 M-F: 14.9	M-F: 16 M-F: 14.4	No heating
MV15	100	120	164	650	0.1	10	**LR.** R3:400; R2:30; R1:0; SC: 22 **R1.** R2:100	No heating	No heating	No heating

Selected model: MV14

R1: Room 1; R2: Room 2; R3: Room 3; LR: Living Room; SC: Staircase

Fig. A.5.1. 1. Configuration of the parameters of the last fifteen evaluated models

Appendix 5.2. Residual analysis of validation model results

The residuals from a fitted model are the differences between the responses observed and the measured data. In addition to qualitative analysis of the residuals carried out analyzing the graphs, a single quantitative analysis was also developed. Thus, average of absolute value of residuals, average of real value of residuals, standard deviation and normal distribution of data corresponding to each air node and average dwelling were analysed for each model.

		Analysis of Residuals			
		Average (Abs. Values)	Average (Real Values)	Standard Desv.	Normal Distribution
V1	***Dwelling***	***0.45***	**0.11**	***0.53***	***0.41***
	R1	0.44	-0.08	0.52	0.56
	R2	0.38	0.04	0.49	0.46
	R3	0.76	-0.70	0.55	0.90
	Living	0.57	0.03	0.68	0.48
V2	***Dwelling***	***0.44***	**0.11**	***0.52***	***0.42***
	R1	0.42	-0.09	0.50	0.57
	R2	0.38	0.04	0.48	0.47
	R3	0.75	-0.71	0.54	0.91
	Living	0.54	0.02	0.65	0.49
V3	***Dwelling***	***0.54***	**0.41**	***0.53***	***0.22***
	R1	0.46	0.29	0.50	0.28
	R2	0.49	0.37	0.49	0.22
	R3	0.51	-0.29	0.54	0.71
	Living	0.58	0.24	0.66	0.36
V4	***Dwelling***	***0.51***	**0.34**	***0.52***	***0.25***
	R1	0.43	0.06	0.53	0.46
	R2	0.43	0.25	0.49	0.31
	R3	0.49	-0.29	0.52	0.71
	Living	0.55	0.23	0.64	0.36
V5	***Dwelling***	***0.62***	**0.54**	***0.53***	***0.15***
	R1	0.46	0.18	0.54	0.37
	R2	0.50	0.39	0.50	0.22
	R3	0.45	-0.10	0.53	0.58
	Living	0.65	0.46	0.64	0.24
V6	***Dwelling***	***0.59***	**0.51**	***0.51***	***0.16***
	R1	0.43	0.17	0.52	0.37
	R2	0.47	0.37	0.47	0.21
	R3	0.44	-0.13	0.50	0.60
	Living	0.61	0.42	0.63	0.25
V7	***Dwelling***	***0.50***	**0.36**	***0.49***	***0.23***
	R1	0.42	0.11	0.51	0.41
	R2	0.43	0.30	0.46	0.26
	R3	0.43	-0.26	0.46	0.71
	Living	0.50	0.22	0.58	0.35

Table A.5.2. 1. Some statistical values of obtained residuals (V1-V7)

		Analysis of Residuals			
		Average (Abs. Values)	Average (Real Values)	Standard Desv.	Normal Distribution
V8	***Dwelling***	***0.52***	**0.37**	***0.51***	***0.23***
	R1	0.43	0.11	0.53	0.41
	R2	0.45	0.30	0.48	0.26
	R3	0.47	-0.25	0.51	0.69
	Living	0.55	0.24	0.63	0.35
V9	***Dwelling***	***0.44***	**0.18**	***0.50***	***0.36***
	R1	0.43	-0.08	0.52	0.56
	R2	0.37	0.10	0.47	0.41
	R3	0.56	-0.45	0.50	0.81
	Living	0.52	0.04	0.62	0.48
V10	***Dwelling***	***0.45***	**0.22**	***0.51***	***0.33***
	R1	0.43	-0.06	0.52	0.55
	R2	0.38	0.13	0.47	0.40
	R3	0.53	-0.39	0.51	0.78
	Living	0.54	0.09	0.64	0.44
V11	***Dwelling***	***0.43***	**0.16**	***0.50***	***0.37***
	R1	0.43	-0.09	0.51	0.57
	R2	0.37	0.08	0.47	0.43
	R3	0.56	-0.46	0.50	0.82
	Living	0.53	0.03	0.62	0.48
V12	***Dwelling***	***0.44***	**0.21**	***0.50***	***0.34***
	R1	0.43	-0.07	0.51	0.55
	R2	0.37	0.10	0.47	0.41
	R3	0.54	-0.42	0.50	0.80
	Living	0.53	0.09	0.62	0.44
V13	***Dwelling***	***0.56***	**0.48**	***0.49***	***0.17***
	R1	0.42	0.12	0.51	0.41
	R2	0.42	0.29	0.46	0.26
	R3	0.44	-0.16	0.50	0.63
	Living	0.59	0.41	0.62	0.25
V14	***Dwelling***	***0.39***	**0.16**	***0.46***	***0.36***
	R1	0.45	-0.27	0.46	0.72
	R2	0.34	-0.02	0.43	0.51
	R3	0.55	-0.47	0.46	0.84
	Living	0.50	0.11	0.59	0.43
V15	***Dwelling***	***0.85***	**0.83**	***0.60***	***0.08***
	R1	0.48	0.27	0.55	0.31
	R2	0.59	0.55	0.52	0.15
	R3	0.50	0.19	0.60	0.38
	Living	0.93	0.86	0.74	0.12

Table A.5.2. 2. Some statistical values of obtained residuals (V8-V15)

Appendix 7.1. Energy, economic and environmental criteria description

1 Energy Analysis

Energy efficiency is usually measured by energy savings, i.e. the different of yearly energy consumption before and after ESM implementation (for a typical year and under the same operating conditions). Three different values are presented for each ESM: annual energy demand, annual energy demand savings and annual primary energy (PE) savings.

1.1 Energy demand

Values of annual energy demand of the building were calculated for each of the 64 ESM scenarios presented in this chapter. These values were directly obtained from TRNSYS simulations and presented in kWh.

1.2 Savings of energy demand

Once obtained by TRNSYS the energy demand values before and after the renovation, also the savings of energy demand are presented for each scenario, calculating the energy difference in kWh, between both situations.

2 Economic Analysis

Several evaluation methods exist to evaluate the economic performance of an ESM, such as Payback Period, Net Present Value, Internal Rate of Return and ratio of savings and investment, to name a few.

Some parameters must be taken into account for the analysis of mentioned attributes. The most basic ones are the investment (I), which is paid a single time in the beginning of the lifespan of the ESM [€], and savings or avoided costs (S) which are obtained in a yearly basis [€/year].

The assumed capital investment for each ESM has been already presented in section 4. Yearly savings are closely linked to the energy savings obtained by simulations. In order to calculate energy consumption savings (only energy demand values were calculated in the first simulations) a standard heating system with natural gas boiler, with a harmonized energy efficiency of 0.9 [118] was assumed. Thus, savings are calculated according to Eq. 44.

$$S_{7.f.r.w.} = \eta_{HS} \cdot \left(ED_{7.0.0.0.} - ED_{7.f.r.w.}\right) \cdot C_{N.G.} \qquad \text{Eq. 44}$$

Where $S_{7.f.r.w.}$ are savings per year [€/year] or the specific ESM combination, η_{HS} is the harmonized energy efficiency of the assumed heating system, $ED_{7.0.0.0.}$ is the yearly energy demand calculated by TRNSYS for the base case, $ED_{7.f.r.w.}$ is the yearly energy demand calculated by TRNSYS for the specific ESM combination, and $c_{N.G.}$ is the natural gas cost.

2.1 Payback Period

The payback period is defined as the period of time required for the return on an investment to repay the sum of the original investment. It can be calculated a simple payback period or a depreciated payback period. Simple payback period does not take into account the time value of money, as it is calculated as described in Eq. 45.

$$PP_{Simple} = \frac{I[€]}{S[€/year]} \qquad \text{Eq. 45}$$

The Depreciated Payback Period (DPP) constitutes a variant of the PP. As the PP, this method determines the number of years that are required until the investor recovers the initial investment, through net cash flows that are expected as a result of the investment (in this case, yearly savings S_n). However, DPP takes also into account the cost of capital r and it is calculated as presented by Eq. 46.

$$DPP = \frac{-ln\left(1 - \frac{r \cdot I}{S_n}\right)}{ln(1+r)} \qquad \text{Eq. 46}$$

Where LS is the assumed lifespan of the ESM, and r is the mentioned cost of capital [%].

Similarly, net cash flows (in the case study, yearly savings) can be assumed as constant or variable. On the first case, it can be assumed they remain constant for every *t*. On the second case, however variations connected to expected increase of the natural gas cost can be assumed.

2.2 Net Present Value (NPV)

The NPV sums the initial capital investment and the present net cash flows over the lifespan of the ESM. Bearing in mind that no maintenance costs are assumed in this study, the only cash flow is the yearly savings. Therefore, NPV is calculates as follows:

$$NPV = -I + \sum_{n=0}^{LS} \frac{S_n}{(1+r)^n} \qquad \text{Eq. 47}$$

Where n is the time period and S_n are the savings for year n. If only economic criteria is taken into account, an investment should be realised only if NPV>0, whilst in case different ESM are compared, the best of them would be the one with the highest NPV.

2.3 Internal Return Rate (IRR)

IRR calculation is based on Eq. 48. This method aims at the determination of the discount rate r that renders the present value of future discounted cash flows of an investment (yearly savings) equal to the initial investment, i.e. IRR determines the r that involves that NPV equals 0.

$$NPV = -I + \sum_{n=0}^{LS} \frac{S_n}{(1+r^*)^n} = 0 \qquad \text{Eq. 48}$$

Hence, IRR constitutes the highest interest that can be paid for finding the capital that is required for an investment. Thus, an investment is attractive when IRR is greater than the minimum acceptable interest rate, or than r. The higher IRR is, the more attractive investment is.

2.4 Savings to investment ratio (SIR)

This parameter is calculated by dividing the present value of the future inflows (yearly savings) for the years of the evaluation (lifespan), by the present value of the future outflows (investment and costs) for the same period, as described in Eq. 49.

$$SIR = \frac{\sum_{n=o}^{LS} \frac{S_n}{(1+r)^n}}{\sum_{n=o}^{LS} \frac{c_n}{(1+r)^n}} \qquad \text{Eq. 49}$$

Where S_n are the savings for the year n, and c_n are de cost for the year n. Since not maintenance costs were assumed in this work, and then, the cost of each ESM is just the initial investment I, Eq. 49. can be simplified as follows:

$$SIR = \frac{\sum_{n=o}^{LS} \frac{S_n}{(1+r)^n}}{I} \qquad \text{Eq. 50}$$

When the present value of inflows (the sum of yearly savings) is equal to the initial investment, i.e. NPV =0, then SIR=1, while if it is greater (smaller) then SIR >1 (SIR<1). Thus, under the SIR point of view, the higher SIR is obtained for a specific ESM, the more attractive the ESM is.

2.5 Energy savings to investment ratio (ESIR)

Similarly to previous SIR, other reference value can be evaluated for assessing and comparing different ESM, which is the yearly energy savings to investment ratio [kWh/€], which refers the amount of yearly energy savings per invested euro. It is calculated as follows:

$$ESIR = \frac{S_{En}}{I} \qquad \text{Eq. 51}$$

In this case, the higher ESIR is, the most attractive the investment is.

3 Environmental Impact

Environmental impact of an ESM can be measured by means of different parameters, such as depletion of ozone layer, acidification or CO_2 emission equivalent. The analysis also can be focusing on different stages (impact reduction by reduction of energy use, environmental impact of the renovation process regarding to material manufacturing and transport…).

In this case, CO_2 emission equivalent of the building energy use for each ESM combination is presented, and so, the environmental impact is evaluated by means of avoided CO_2 emission equivalent for each case.

Avoided CO_2 emission equivalent is calculated by subtracting the CO_2 emission equivalent obtained for each combination to CO_2 emission equivalent of the base case. CO_2 emission equivalent is calculated using the conversion factor corresponding to each energy source (in this case, natural gas), as presented in Eq. 52.

$$CO_{2.}ee = E_{dem,7.f.r.w.} - F_{em,NG} \qquad \text{Eq. 52}$$

Appendix 7.2. Energy, economic and environmental values of the evaluated ESM combinations

1 Energy and Environmental values

			Window type 0															
			Roof 0				Roof 1				Roof 2				Roof 3			
		Model	7.0.0.0.	7.1.0.0.	7.2.0.0.	7.3.0.0.	7.0.1.0.	7.1.1.0.	7.2.1.0.	7.3.1.0.	7.0.2.0.	7.1.2.0.	7.2.2.0.	7.3.2.0.	7.0.3.0.	7.1.3.0.	7.2.3.0.	7.3.3.0.
Energy	[MWh]	Energy Demand	94.67	81.27	78.11	73.01	87.44	73.54	70.26	64.95	85.64	71.57	68.25	62.88	85.11	70.99	67.65	62.26
		Savings	-	13.40	16.55	21.66	7.23	21.13	24.41	29.71	9.02	23.09	26.41	31.79	9.56	23.68	27.02	32.41
		%	-	14.15%	17.49%	22.88%	7.64%	22.32%	25.78%	31.39%	9.53%	24.39%	27.90%	33.58%	10.10%	25.02%	28.54%	34.23%
		PE Savings	-	15931.14	19680.00	25747.67	8593.39	25118.46	29015.15	35325.29	10726.96	27454.31	31402.06	37790.08	11363.96	28155.55	32119.15	38531.13
EI	[tCO_2]	CO2 eq. Savings	-	2.80	3.46	4.53	1.51	4.42	5.10	6.21	1.89	4.83	5.52	6.64	2.00	4.95	5.65	6.77

			Window type 1															
			Roof 0				Roof 1				Roof 2				Roof 3			
		Model	7.0.0.1.	7.1.0.1.	7.2.0.1.	7.3.0.1.	7.0.1.1.	7.1.1.1.	7.2.1.1.	7.3.1.1.	7.0.2.1.	7.1.2.1.	7.2.2.1.	7.3.2.1.	7.0.3.1.	7.1.3.1.	7.2.3.1.	7.3.3.1.
Energy	[MWh]	Energy Demand	85.68	72.22	69.07	63.97	78.41	64.46	61.19	55.91	76.60	62.49	59.18	53.84	76.06	61.90	58.58	53.23
		Savings	8.99	22.44	25.60	30.70	16.26	30.20	33.48	38.76	18.06	32.18	35.49	40.82	18.60	32.77	36.09	41.44
		%	9.49%	23.71%	27.04%	32.43%	17.17%	31.90%	35.36%	40.94%	19.08%	33.99%	37.49%	43.12%	19.65%	34.61%	38.12%	43.77%
		PE Savings	10684.03	26684.50	30438.07	36494.60	19325.50	35907.31	39802.36	46082.68	21476.43	38253.46	42191.80	48533.99	22118.55	38956.31	42907.81	49267.12
EI	[tCO_2]	CO2 eq. Savings	1.88	4.69	5.35	6.42	3.40	6.31	7.00	8.10	3.78	6.72	7.42	8.53	3.89	6.85	7.54	8.66

			Window type 2															
			Roof 0				Roof 1				Roof 2				Roof 3			
		Model	7.0.0.2.	7.1.0.2.	7.2.0.2.	7.3.0.2.	7.0.1.2.	7.1.1.2.	7.2.1.2.	7.3.1.2.	7.0.2.2.	7.1.2.2.	7.2.2.2.	7.3.2.2.	7.0.3.2.	7.1.3.2.	7.2.3.2.	7.3.3.2.
Energy	[MWh]	Energy Demand	74.44	60.69	57.48	52.31	67.03	52.80	49.47	44.13	65.17	50.79	47.44	42.04	64.62	50.19	46.83	41.42
		Savings	20.23	33.97	37.19	42.36	27.64	41.87	45.20	50.54	29.50	43.88	47.23	52.62	30.05	44.48	47.84	53.25
		%	21.37%	35.89%	39.28%	44.75%	29.20%	44.23%	47.74%	53.39%	31.16%	46.35%	49.89%	55.59%	31.74%	46.98%	50.54%	56.25%
		PE Savings	24047.66	40391.01	44209.39	50360.47	32862.10	49779.99	53732.02	60085.39	35066.99	52167.06	56152.24	62564.40	35725.84	52878.96	56876.78	63305.74
EI	[tCO_2]	CO2 eq. Savings	4.23	7.10	7.77	8.85	5.78	8.75	9.45	10.56	6.16	9.17	9.87	11.00	6.28	9.30	10.00	11.13

			Window type 3															
			Roof 0				Roof 1				Roof 2				Roof 3			
		Model	7.0.0.3.	7.1.0.3.	7.2.0.3.	7.3.0.3.	7.0.1.3.	7.1.1.3.	7.2.1.3.	7.3.1.3.	7.0.2.3.	7.1.2.3.	7.2.2.3.	7.3.2.3.	7.0.3.3.	7.1.3.3.	7.2.3.3.	7.3.3.3.
Energy	[MWh]	Energy Demand	66.55	52.66	49.43	44.23	59.06	44.70	41.36	36.02	57.18	42.68	39.32	33.94	56.61	42.08	38.70	33.32
		Savings	28.11	42.00	45.24	50.44	35.61	49.97	53.31	58.65	37.49	51.99	55.35	60.73	38.05	52.59	55.96	61.34
		%	29.70%	44.37%	47.79%	53.28%	37.61%	52.78%	56.31%	61.96%	39.60%	54.92%	58.47%	64.15%	40.20%	55.55%	59.12%	64.80%
		PE Savings	33422.54	49936.84	53784.80	59968.19	42334.87	59406.54	63374.12	69730.83	44573.20	61808.09	65807.52	72199.92	45242.76	62525.99	66533.45	72931.89
EI	[tCO_2]	CO2 eq. Savings	5.88	8.78	9.46	10.54	7.44	10.44	11.14	12.26	7.84	10.87	11.57	12.69	7.95	10.99	11.70	12.82

2 Economic values

ESIR value for each combination is presented in Fig. A.7.1. 2. In Fig. A.7.1. 3, IRR set values is depicted, by its maximum, minimum and average value for each combination.

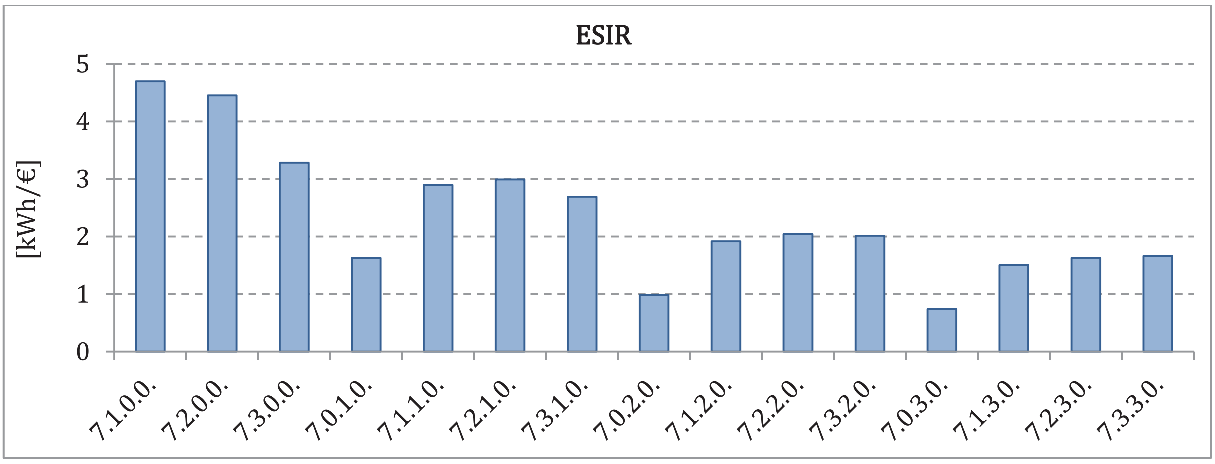


Fig. A.7.1. 2. ESIR

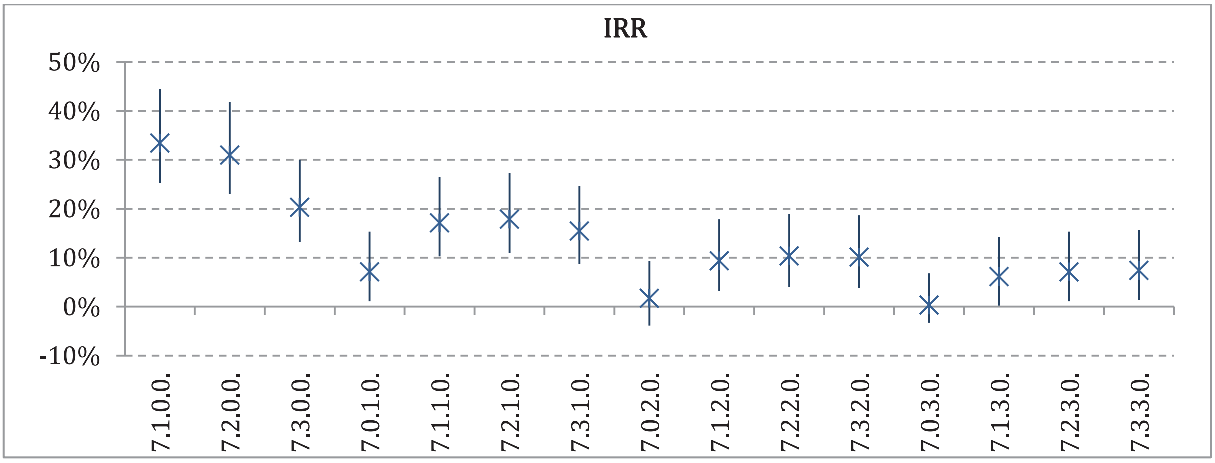


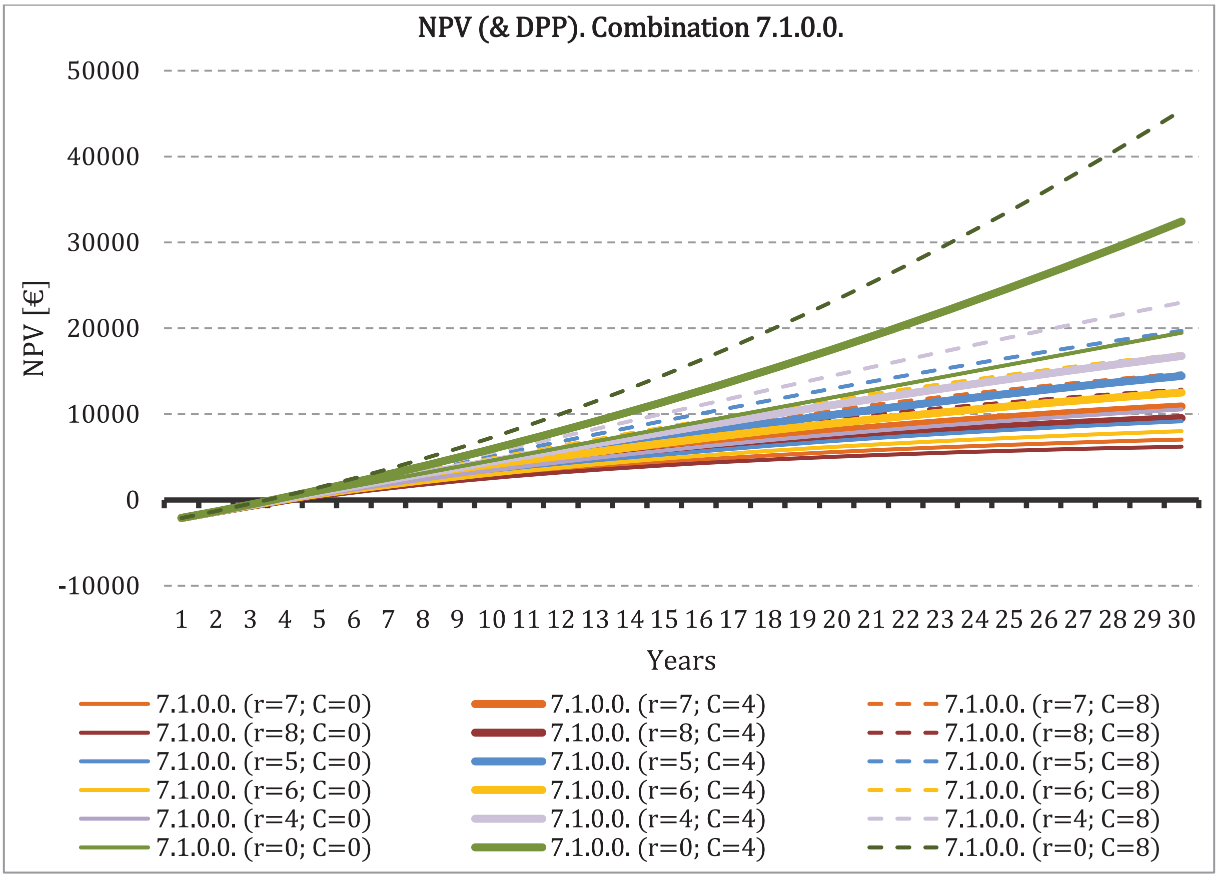
Fig. A.7.1. 3 Maximum, minimum and average IRR values

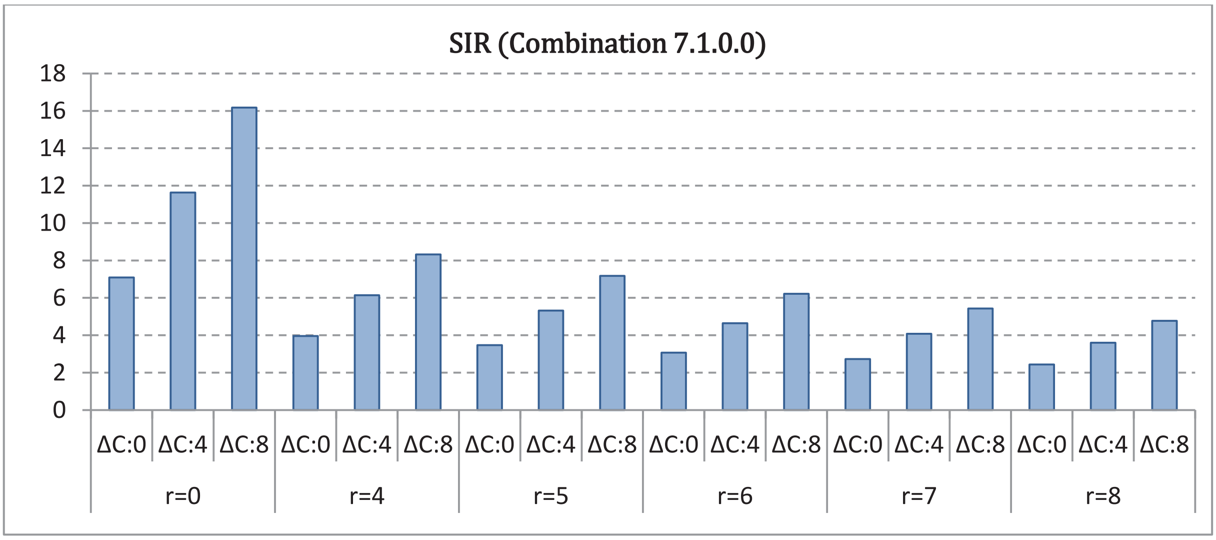
Economic values for each assessed scenario are presented in the following charts. Mentioned values are presented in two graphs and one table for each model. The first graph depicts the NPV during the considered lifespan (30 years). Moreover, this graph also depicts the depreciated payback period (DPP) of each scenario, which is the point when NPV becomes 0.

Second graph depicts the SIR for each scenario, depending on the r and yearly increasing of natural gas cost (%) assumed, whereas IRR values related with mentioned parameters are presented in the table.

- **Combination 7.1.0.0.**

ESIR: 4.70 kWh/€

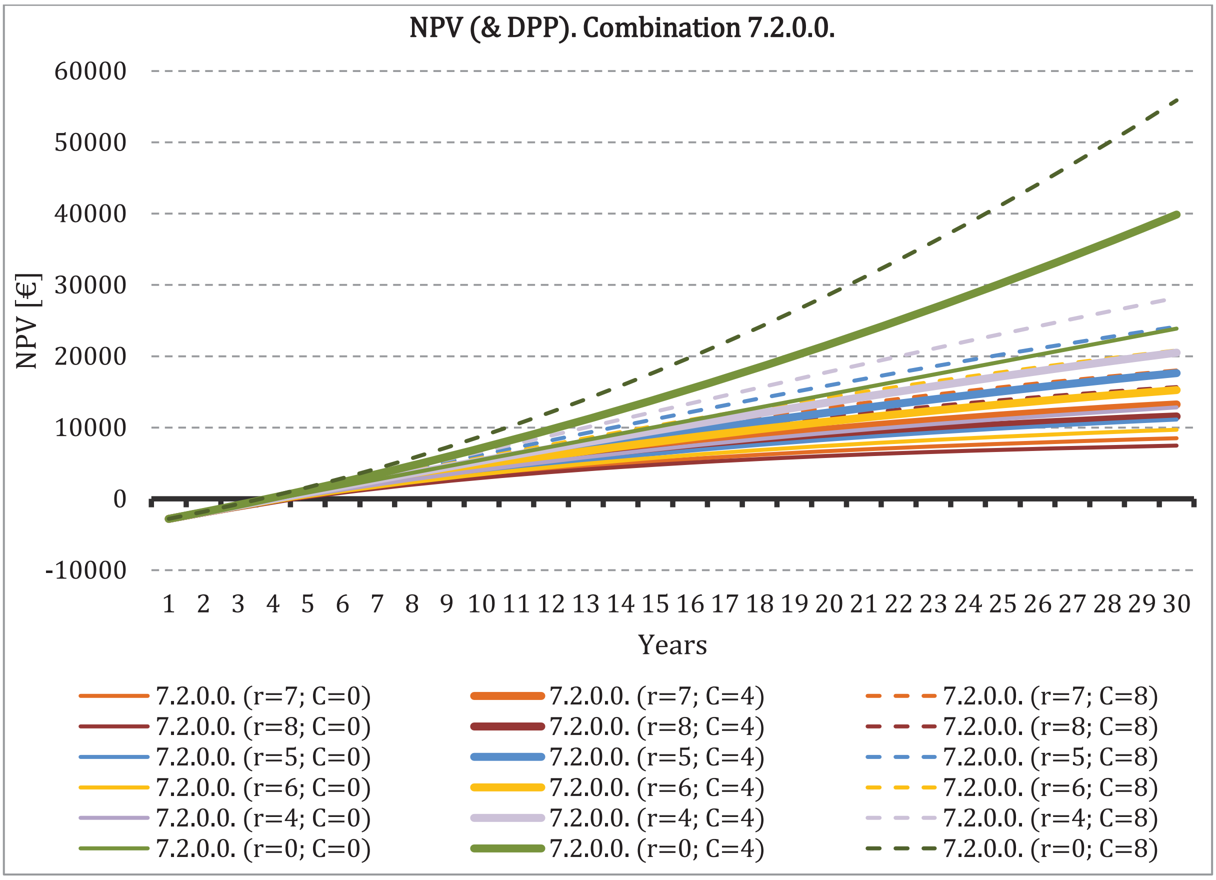


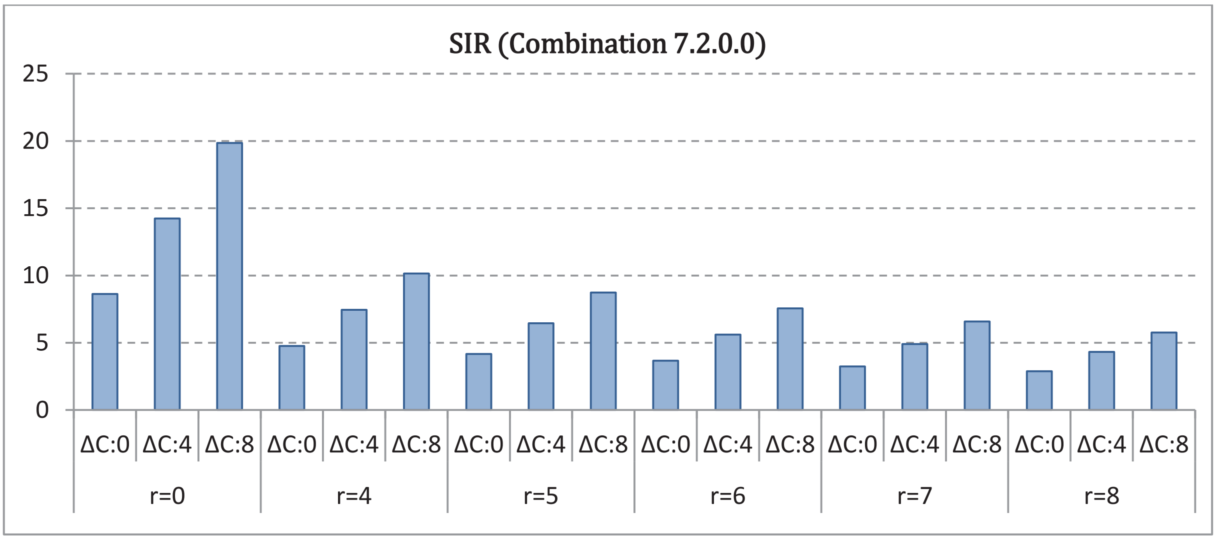


IRR 7.1.0.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	35.32%	30.11%	28.87%	27.66%	26.46%	25.29%
ΔC:4	40.24%	34.85%	33.56%	32.30%	31.07%	29.85%
ΔC:8	44.49%	38.94%	37.61%	36.32%	35.04%	33.79%

- **Combination 7.2.0.0.**

ESIR: 4.45 kWh/€

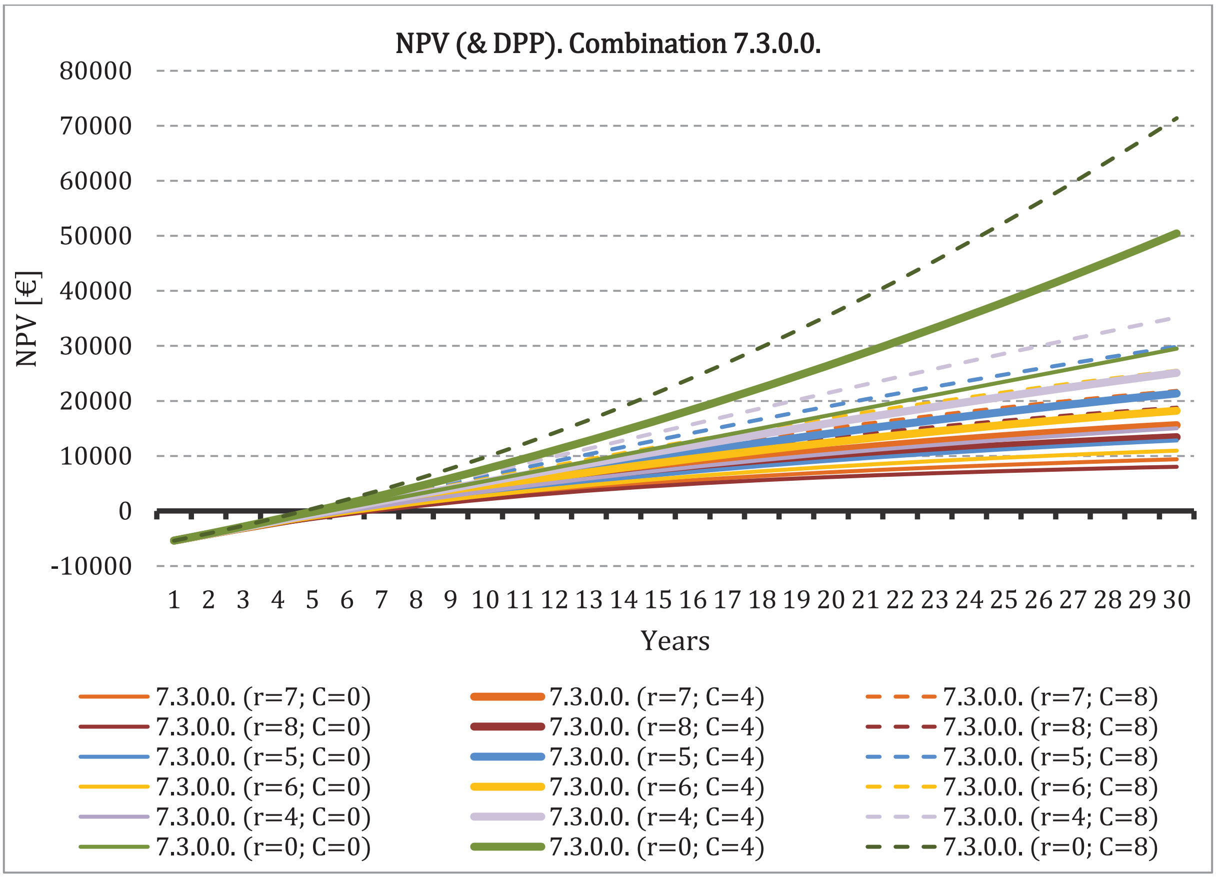


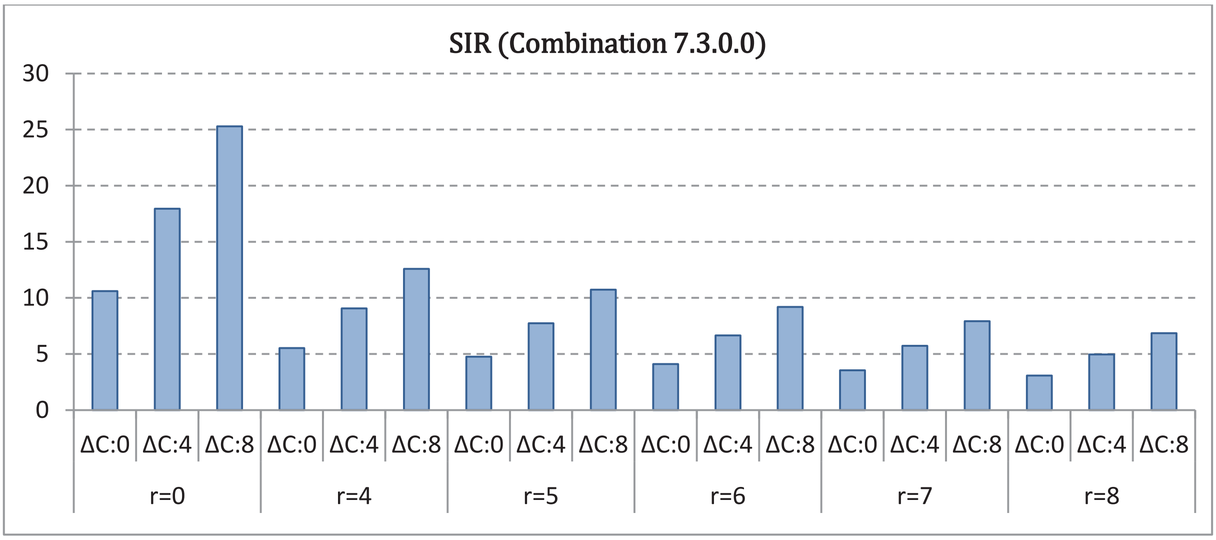


IRR 7.2.0.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	32.86%	27.75%	26.53%	25.34%	24.17%	23.02%
ΔC:4	37.67%	32.37%	31.11%	29.88%	28.66%	27.47%
ΔC:8	41.79%	36.33%	35.04%	33.76%	32.51%	31.28%

- ## Combination 7.3.0.0.

ESIR: 3.28 kWh/€

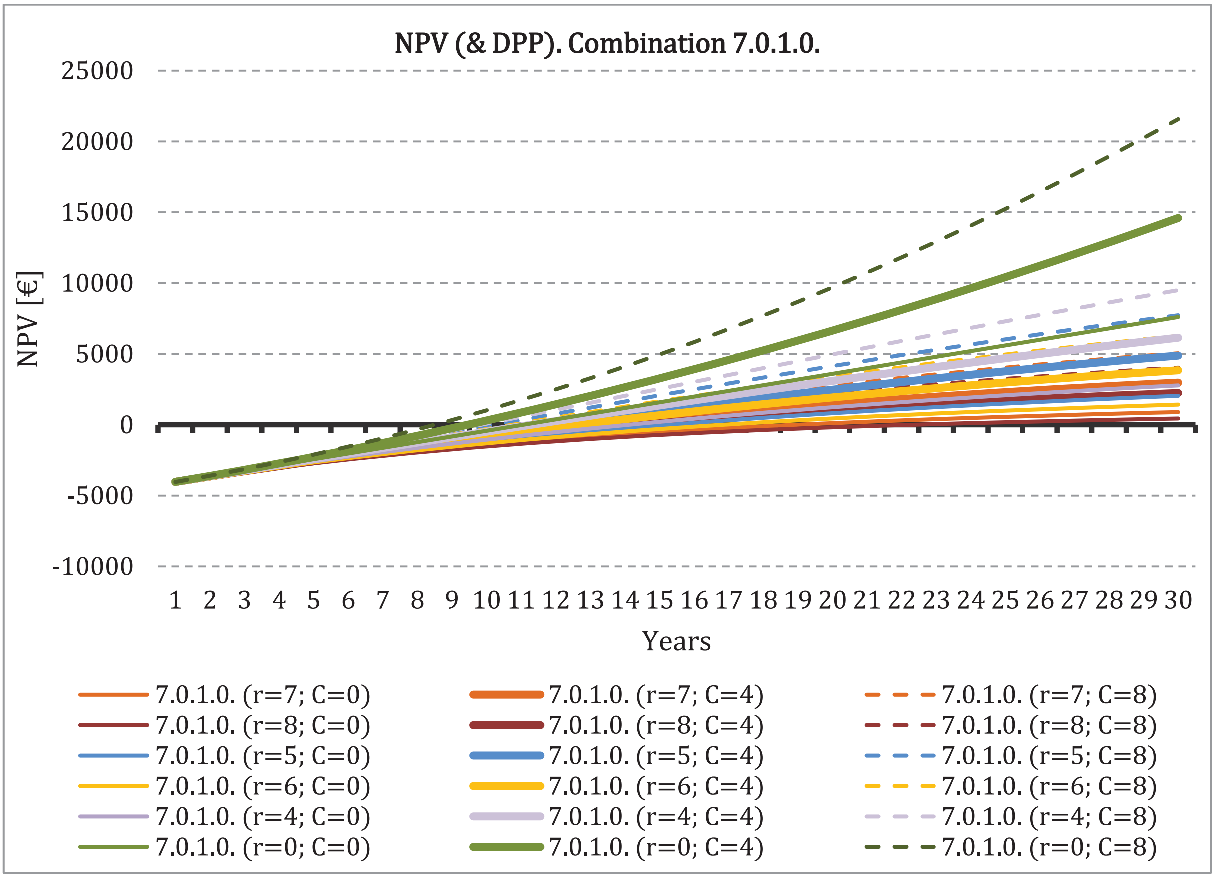


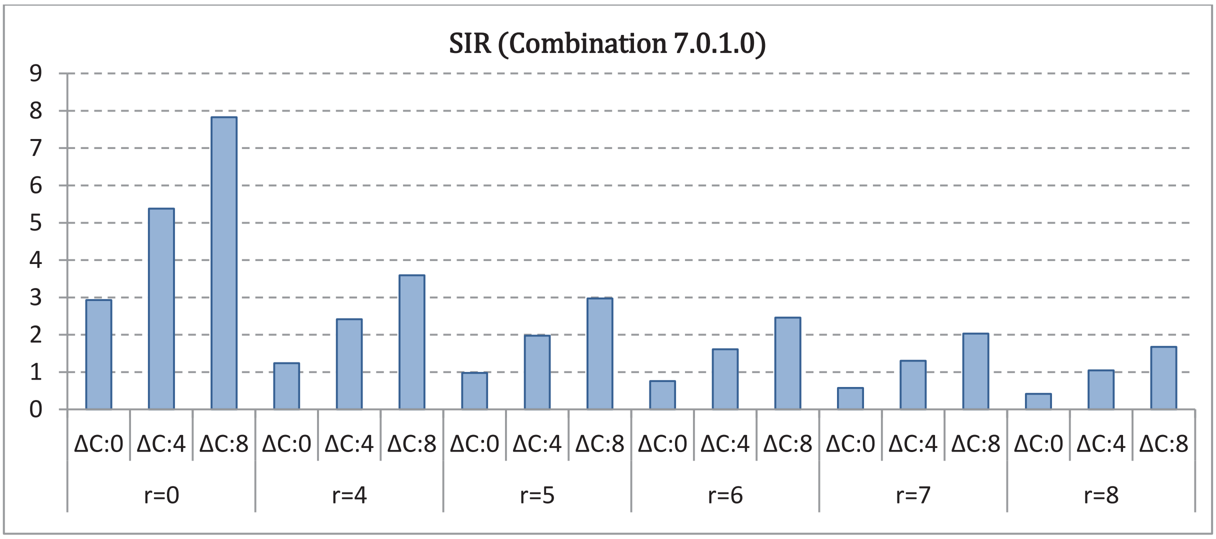


IRR 7.3.0.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	22.24%	17.54%	16.42%	15.32%	14.25%	13.19%
ΔC:4	26.51%	21.65%	20.49%	19.35%	18.24%	17.14%
ΔC:8	30.00%	25.00%	23.81%	22.64%	21.50%	20.37%

- **Combination 7.0.1.0.**

ESIR: 1.63 kWh/€

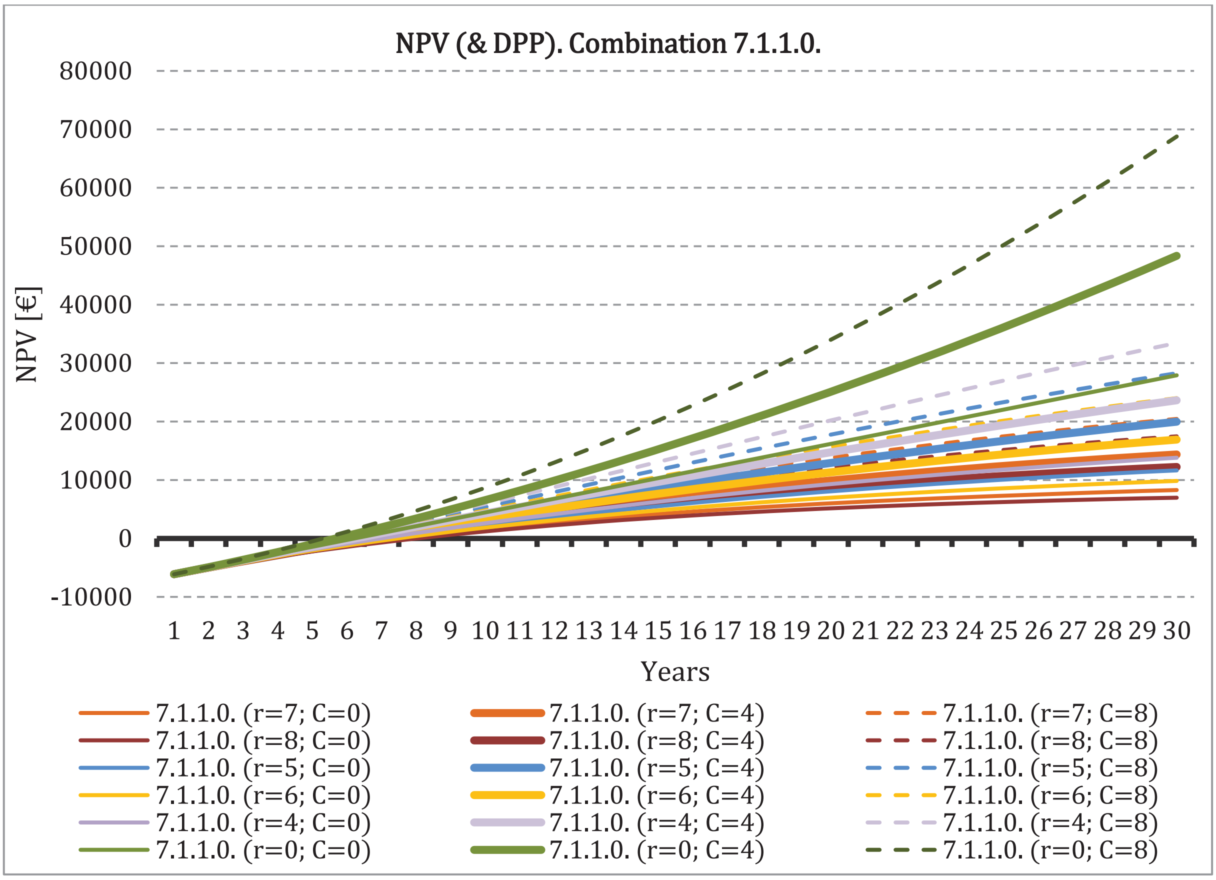


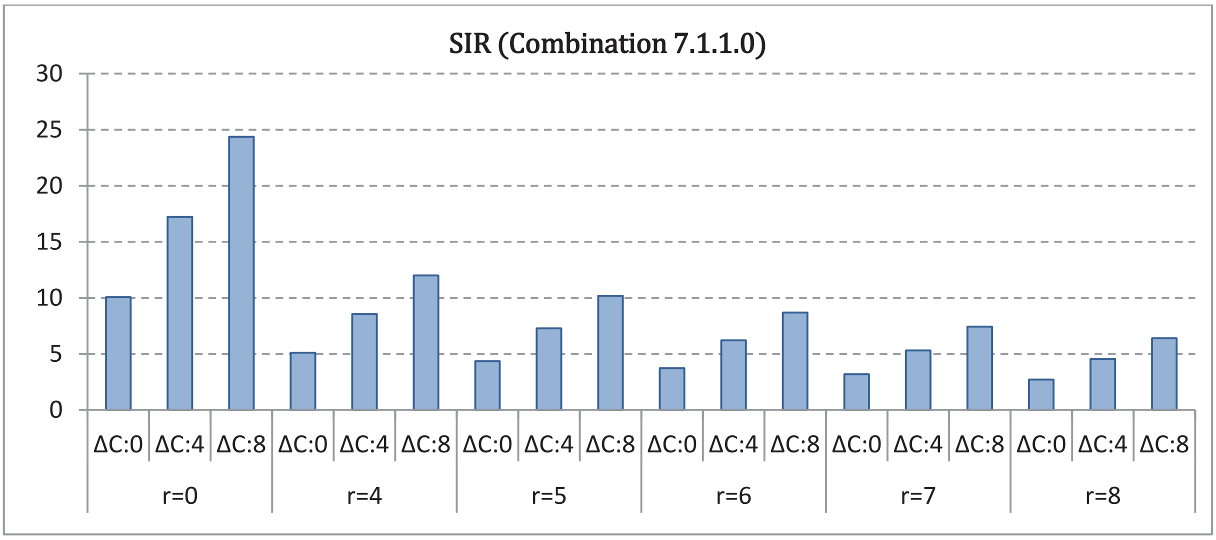


7.0.1.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	9.17%	4.97%	3.97%	2.99%	2.03%	1.08%
ΔC:4	12.70%	8.37%	7.34%	6.32%	5.33%	4.35%
ΔC:8	15.32%	10.88%	9.83%	8.79%	7.77%	6.78%

- **Combination 7.1.1.0.**

ESIR: 2.90 kWh/€

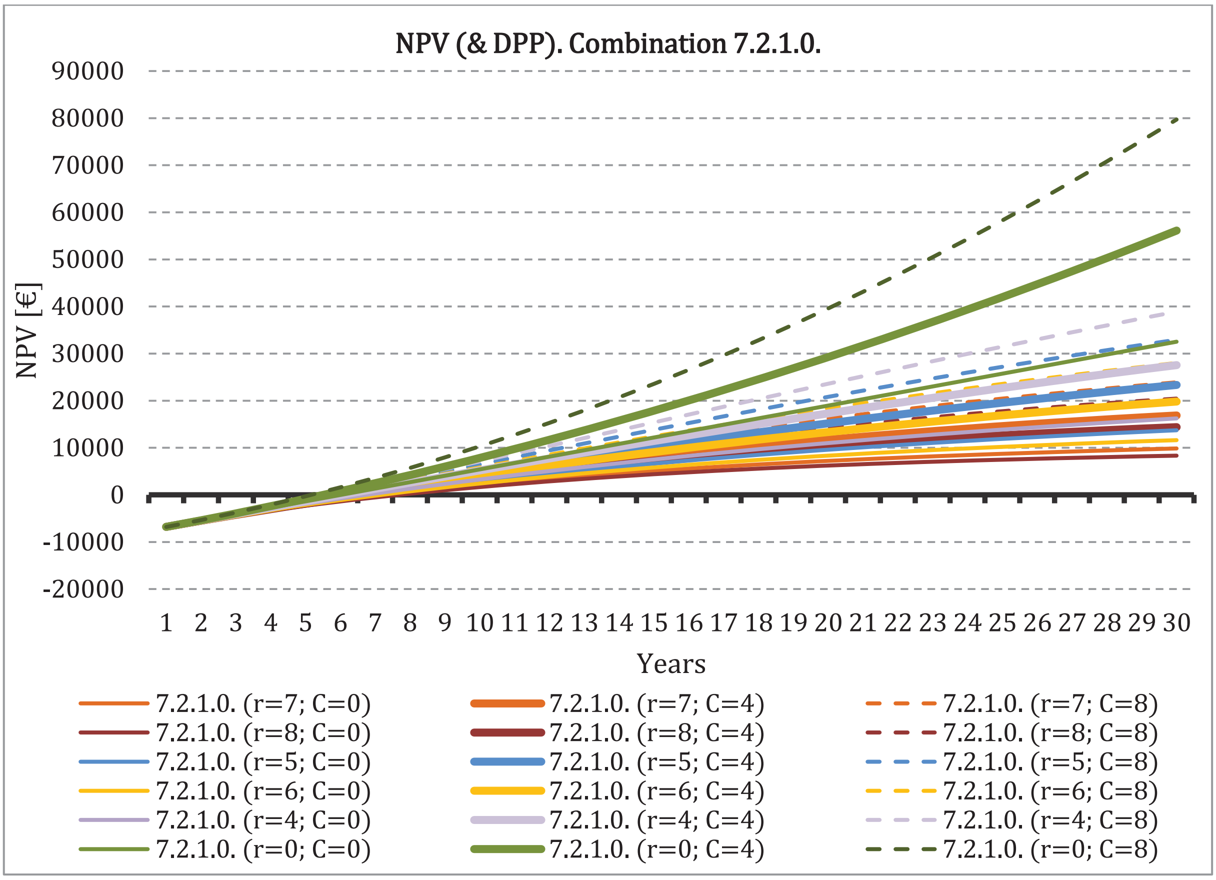


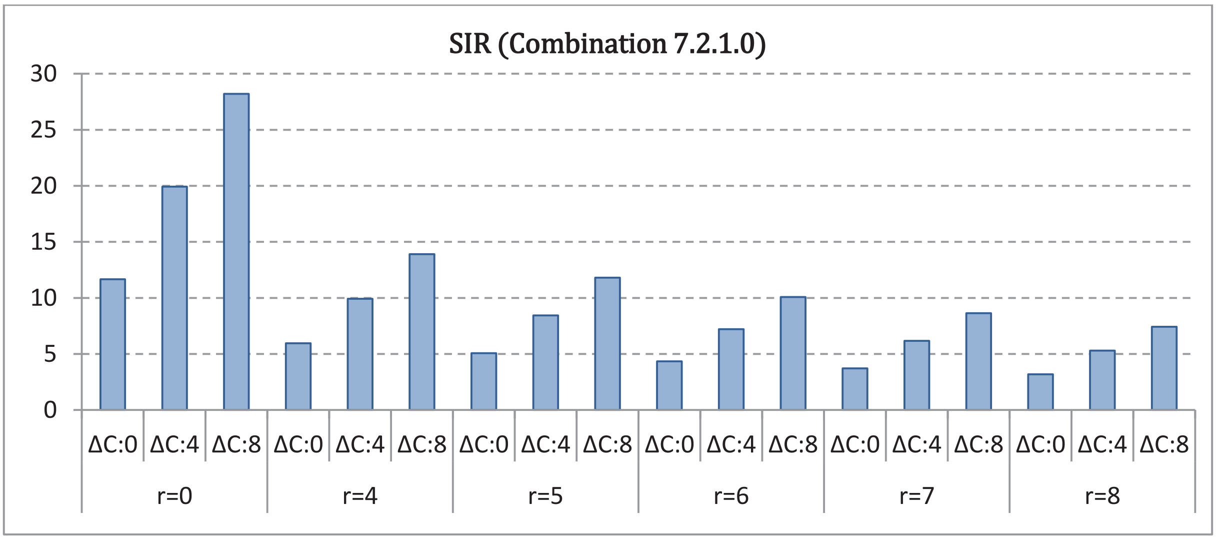


7.1.1.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	19.07%	14.49%	13.40%	12.33%	11.28%	10.25%
ΔC:4	23.17%	18.43%	17.30%	16.20%	15.11%	14.04%
ΔC:8	26.45%	21.59%	20.43%	19.30%	18.18%	17.09%

- ## Combination 7.2.1.0.

ESIR: 2.99 kWh/€

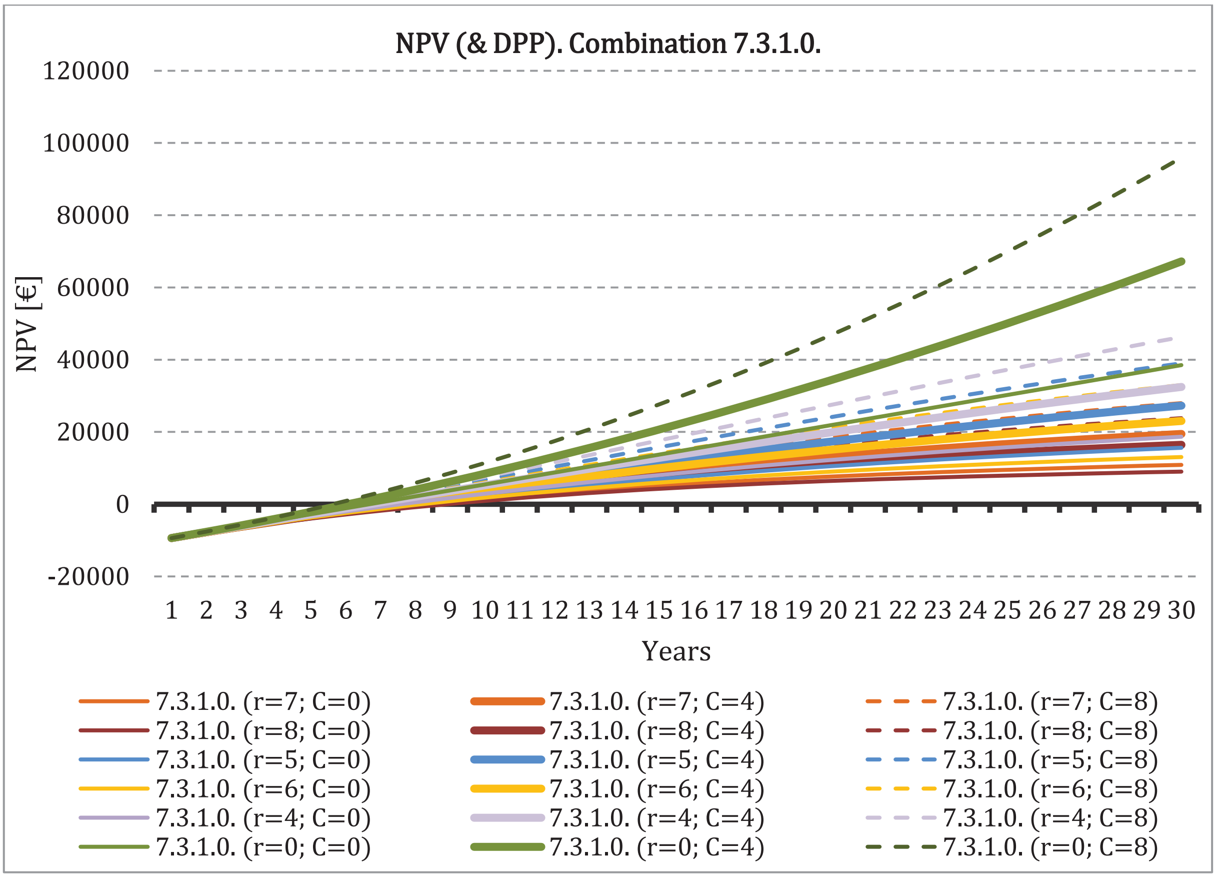


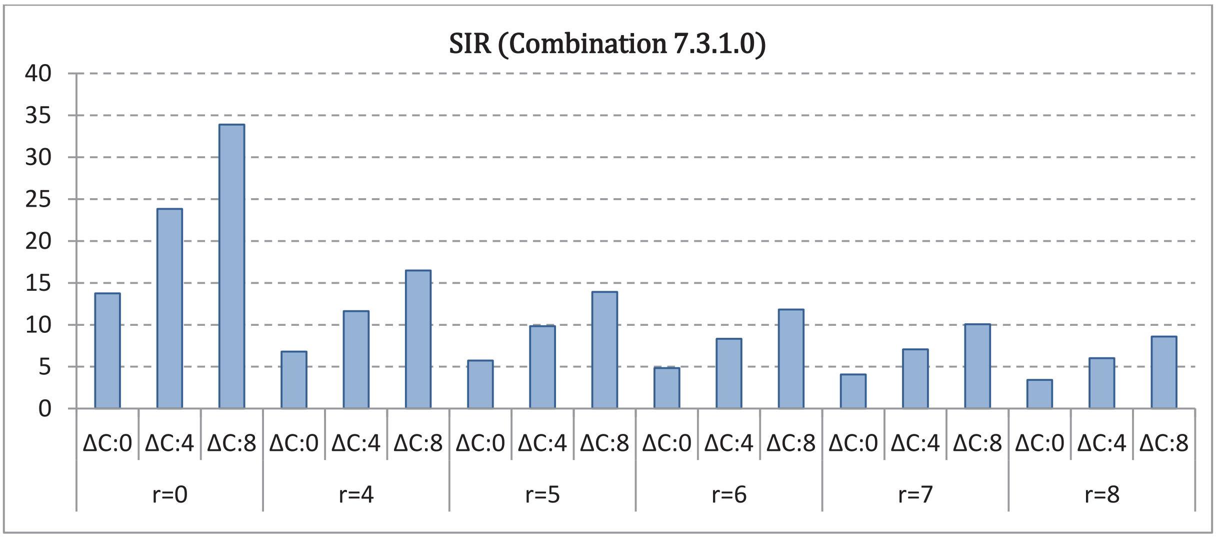


7.2.1.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	19.84%	15.23%	14.13%	13.05%	12.00%	10.96%
ΔC:4	23.98%	19.21%	18.07%	16.96%	15.86%	14.79%
ΔC:8	27.31%	22.42%	21.25%	20.11%	18.98%	17.88%

- ## Combination 7.3.1.0.

ESIR: 2.69 kWh/€

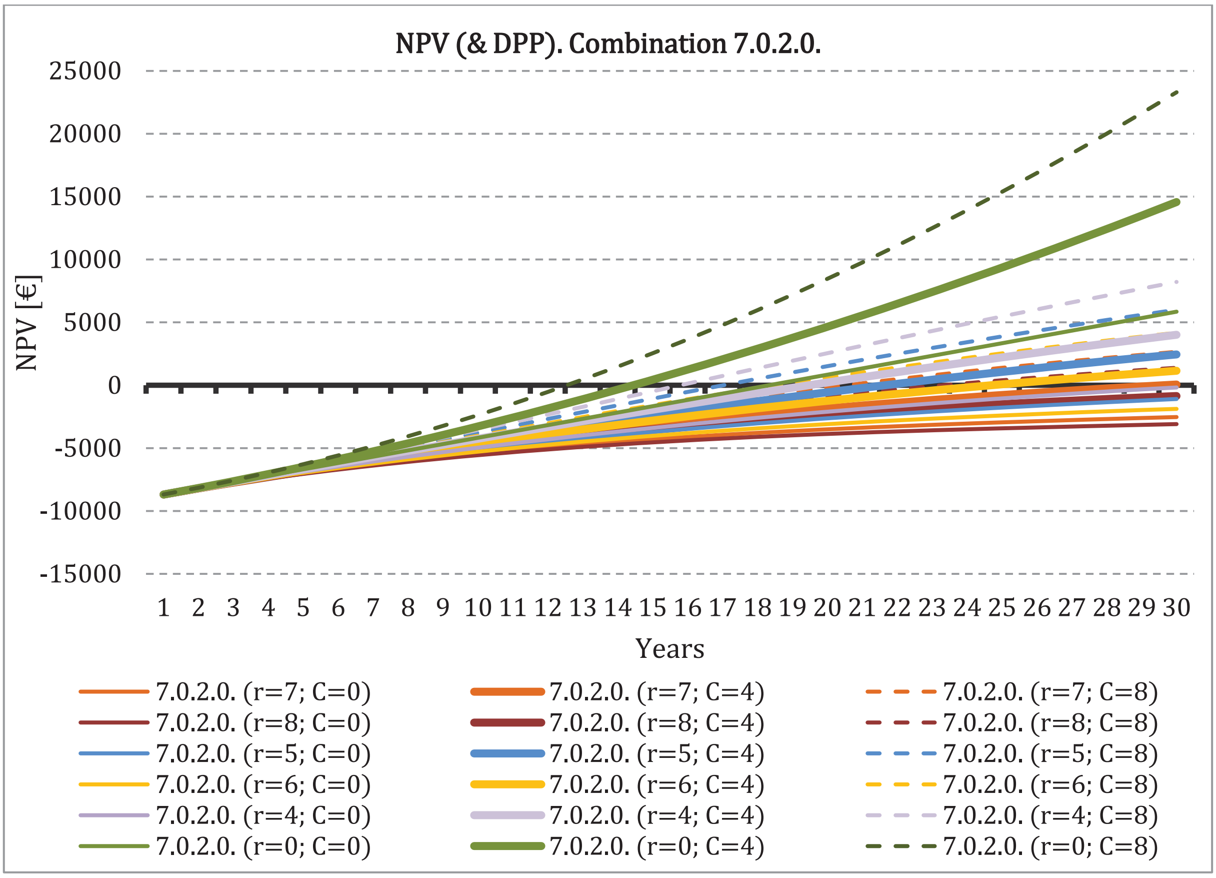


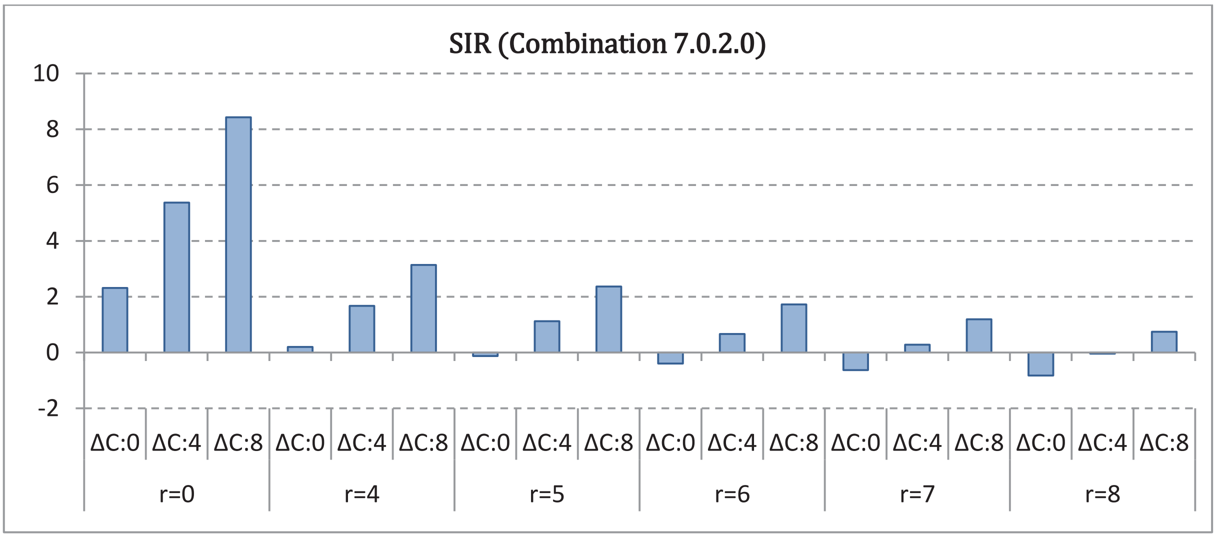


7.3.1.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	17.43%	12.91%	11.84%	10.78%	9.74%	8.73%
ΔC:4	21.43%	16.76%	15.65%	14.56%	13.49%	12.44%
ΔC:8	24.61%	19.82%	18.68%	17.56%	16.46%	15.38%

▪ Combination 7.0.2.0.

ESIR: 0.98 kWh/€

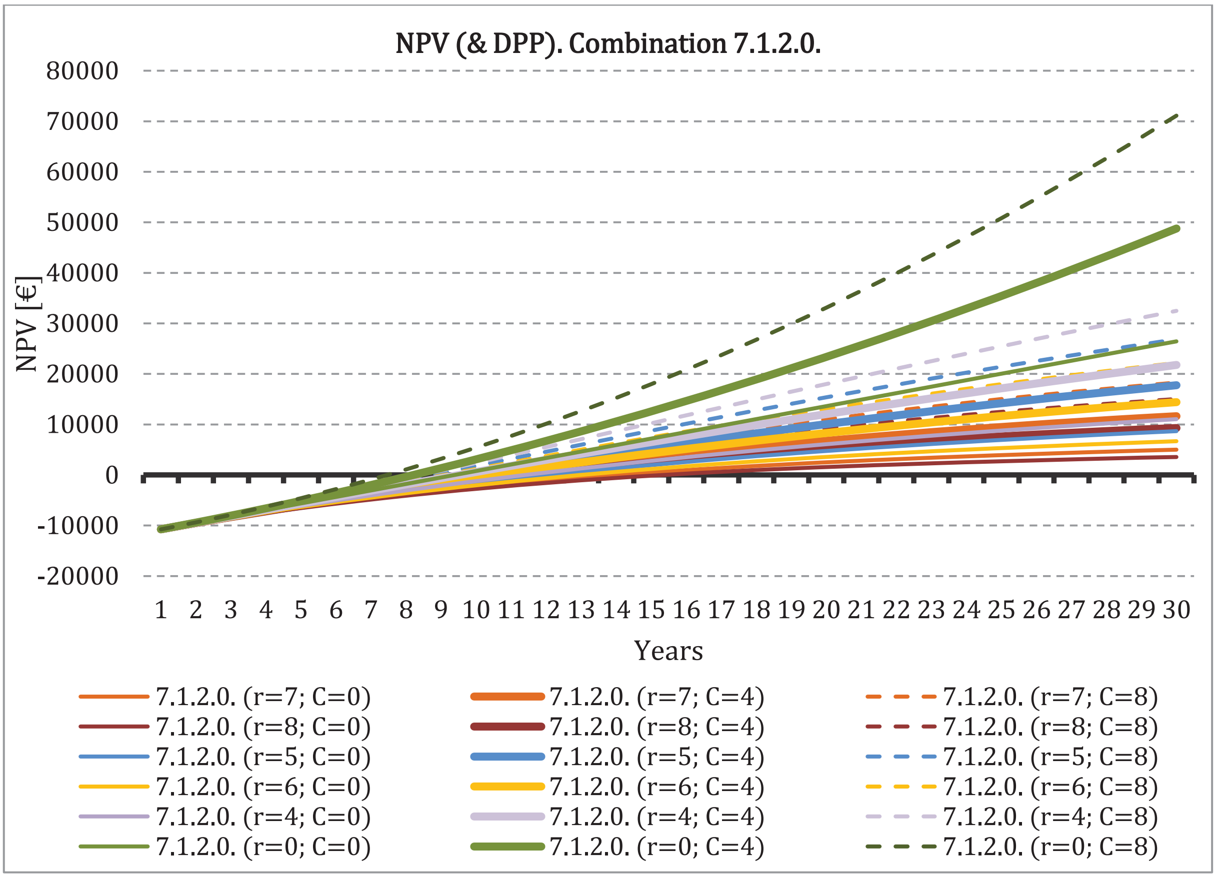


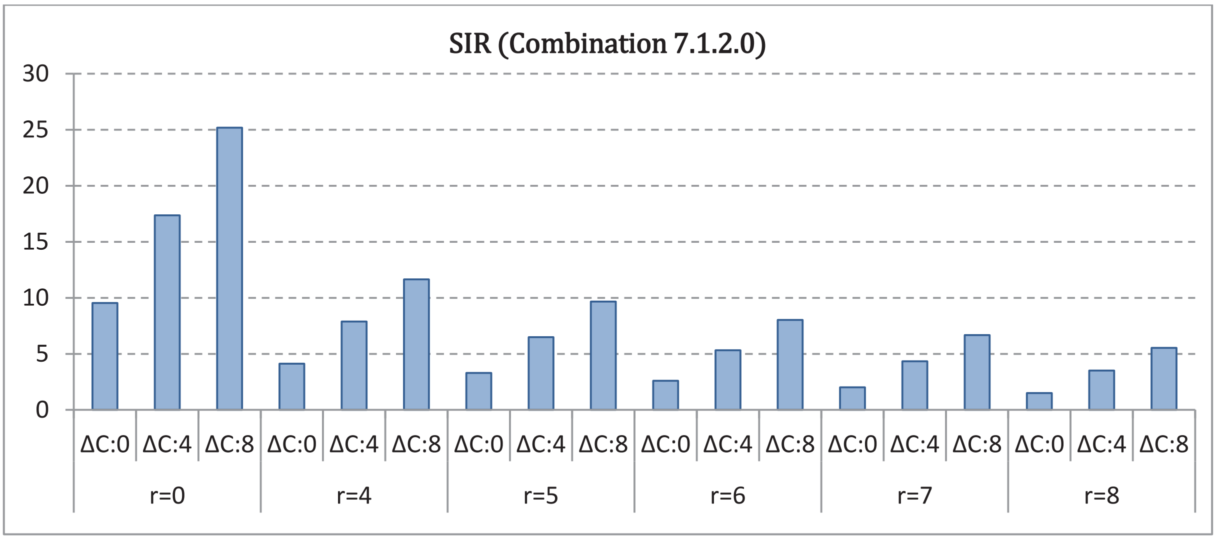


7.0.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	3.83%	-0.16%	-1.11%	-2.05%	-2.96%	-3.86%
ΔC:4	7.06%	2.95%	1.97%	1.00%	0.06%	-0.87%
ΔC:8	9.33%	5.13%	4.13%	3.14%	2.18%	1.23%

- ## Combination 7.1.2.0.

ESIR: 1.92 kWh/€

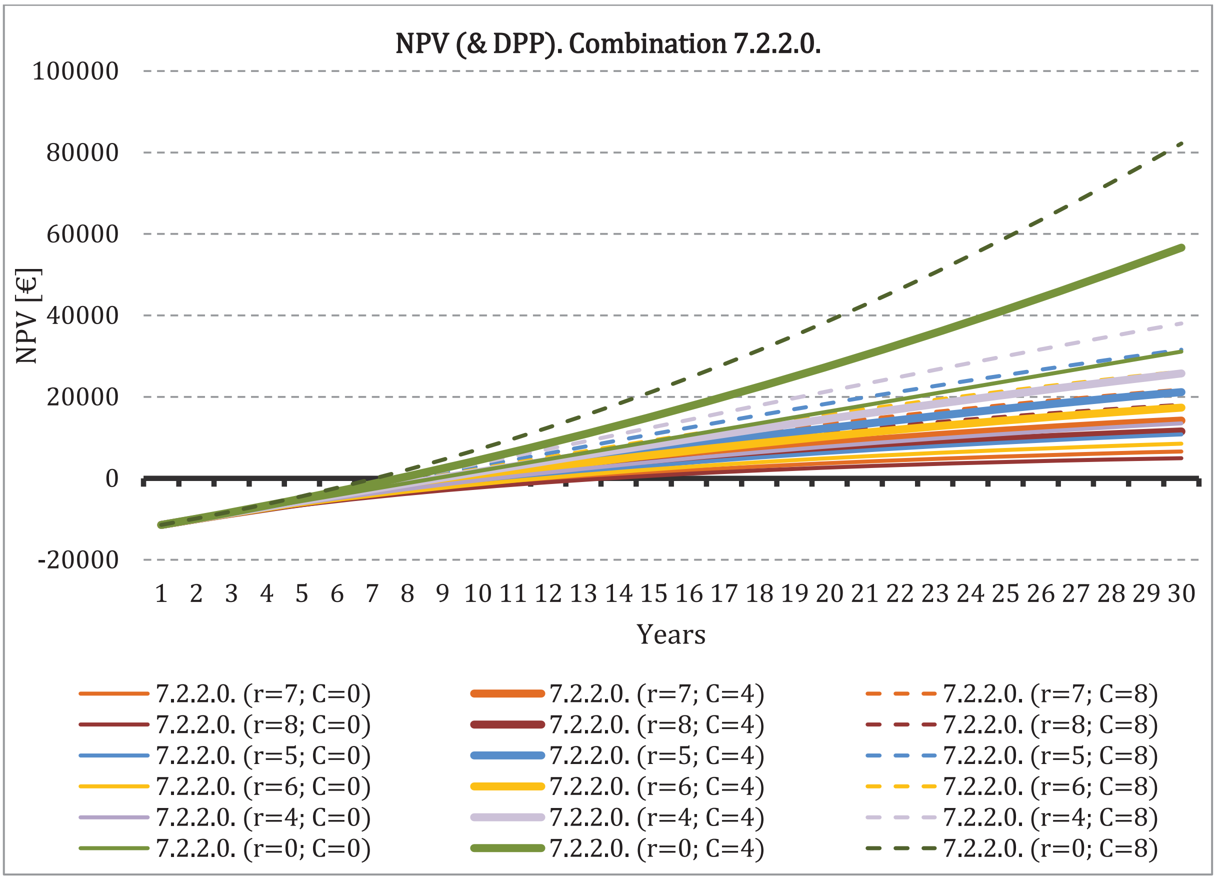


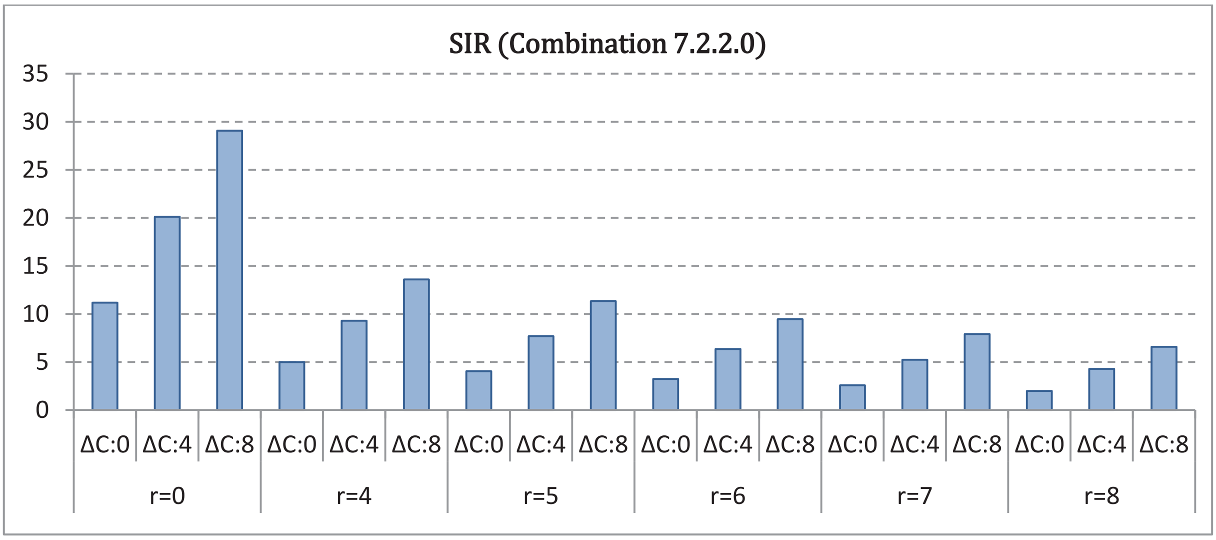


7.1.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	11.41%	7.12%	6.10%	5.10%	4.12%	3.15%
ΔC:4	15.07%	10.64%	9.59%	8.55%	7.54%	6.54%
ΔC:8	17.84%	13.30%	12.23%	11.17%	10.13%	9.11%

- **Combination 7.2.2.0.**

ESIR: 2.05 kWh/€

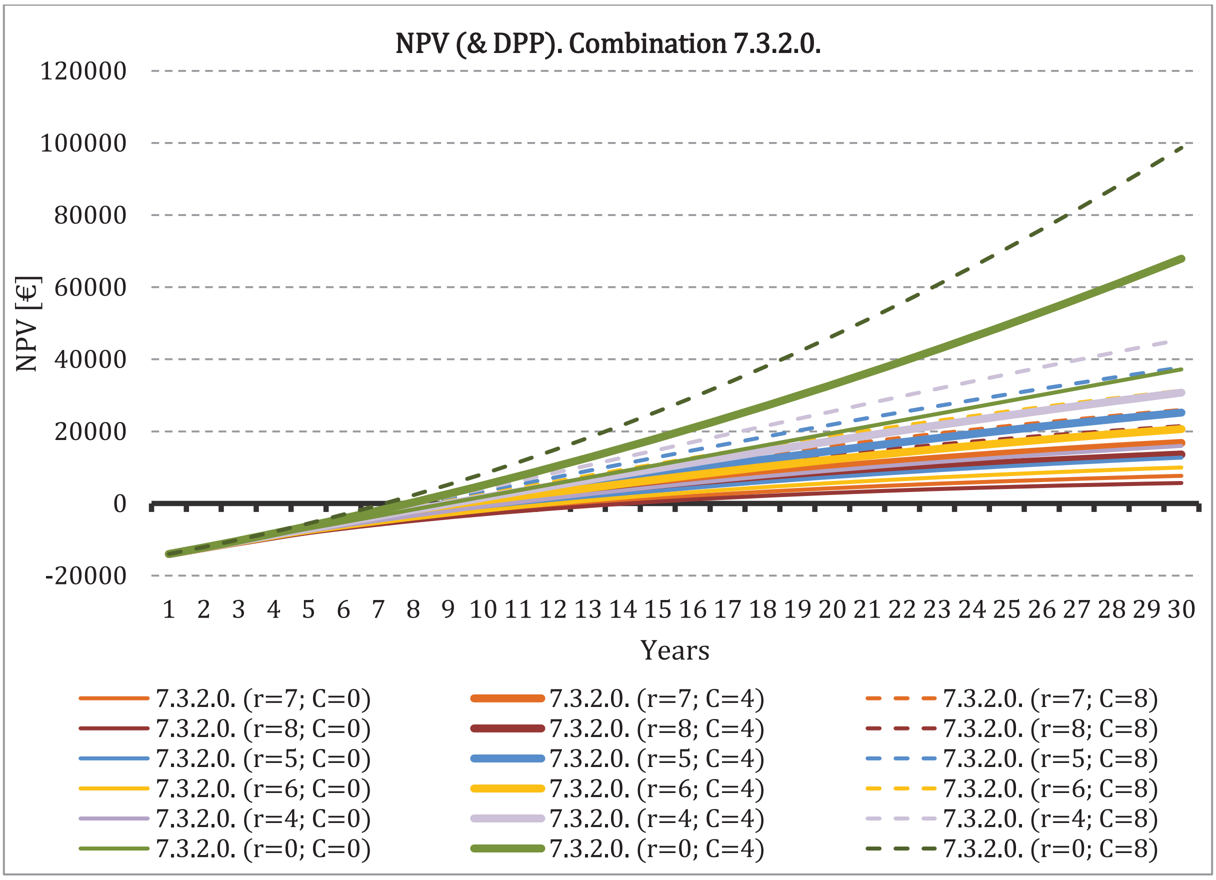


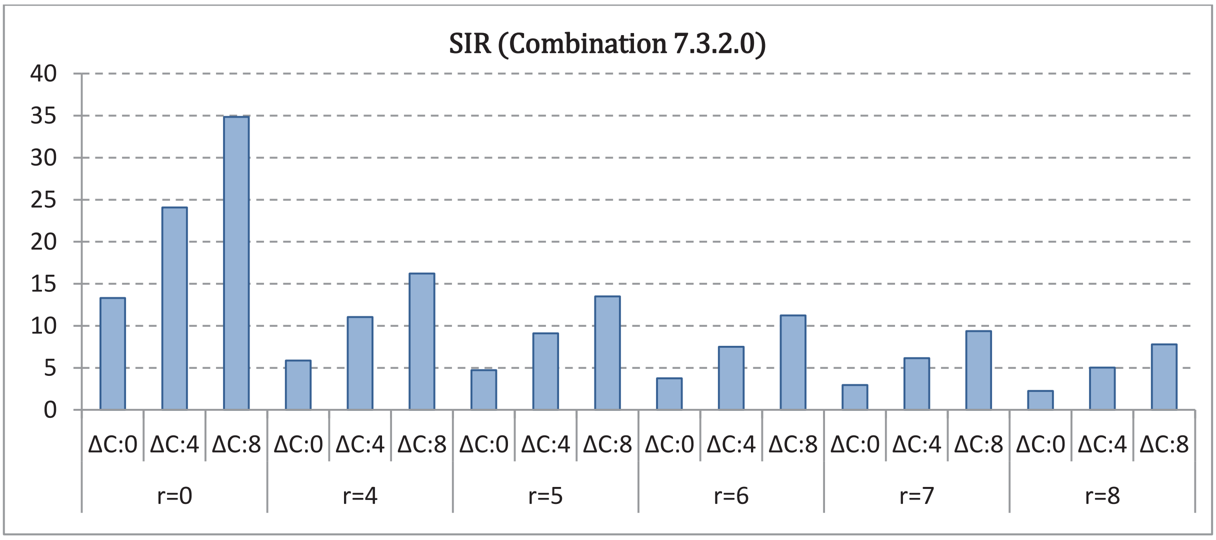


7.2.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	12.40%	8.07%	7.04%	6.03%	5.04%	4.07%
ΔC:4	16.11%	11.65%	10.59%	9.54%	8.52%	7.51%
ΔC:8	18.95%	14.38%	13.29%	12.22%	11.17%	10.14%

- ## Combination 7.3.2.0.

ESIR: 2.01 kWh/€

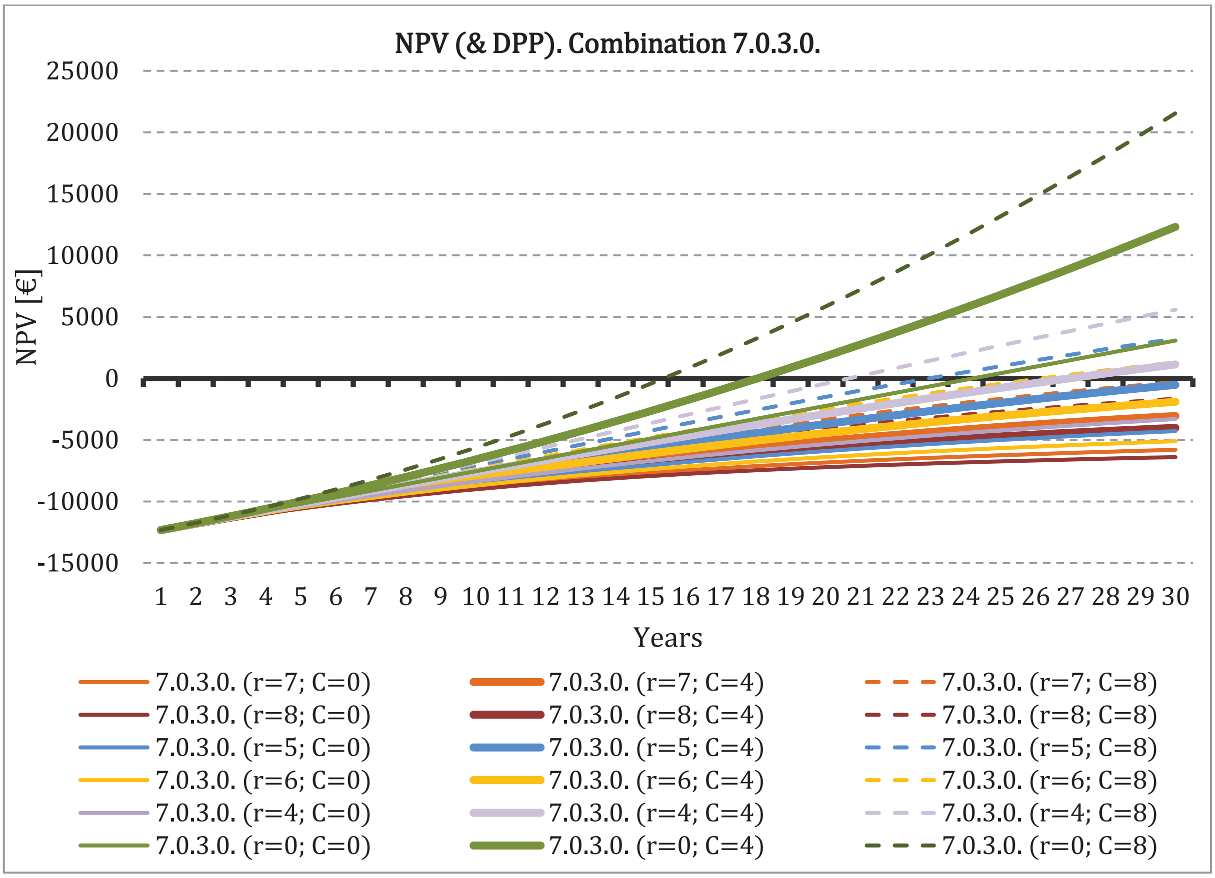


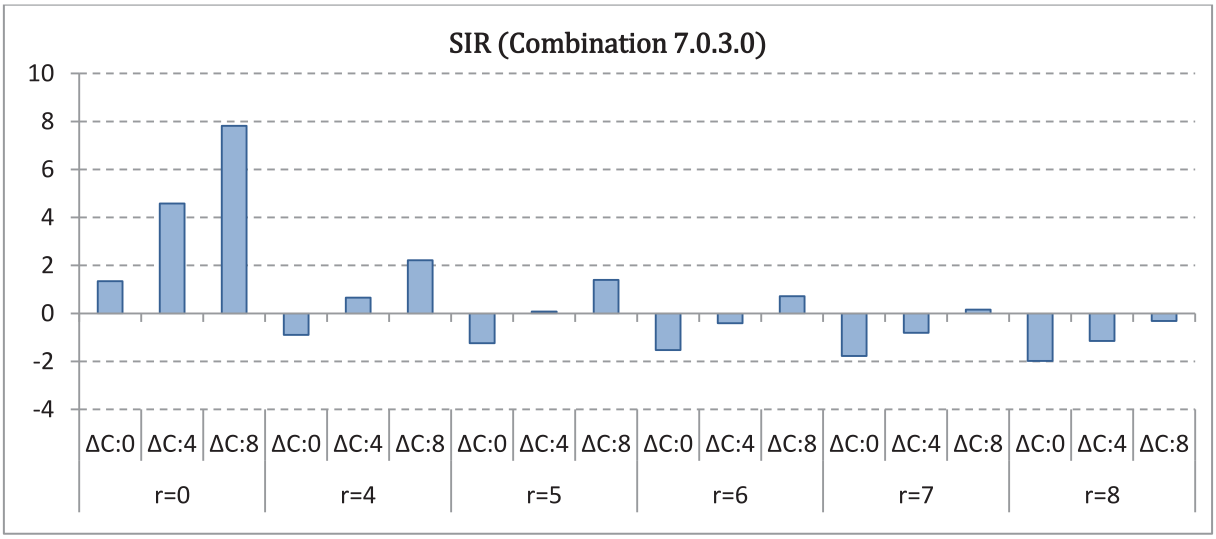


7.3.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	12.14%	7.83%	6.80%	5.80%	4.81%	3.84%
ΔC:4	15.85%	11.39%	10.33%	9.29%	8.27%	7.27%
ΔC:8	18.67%	14.10%	13.02%	11.95%	10.90%	9.88%

- ## Combination 7.0.3.0.

ESIR: 0.74 kWh/€

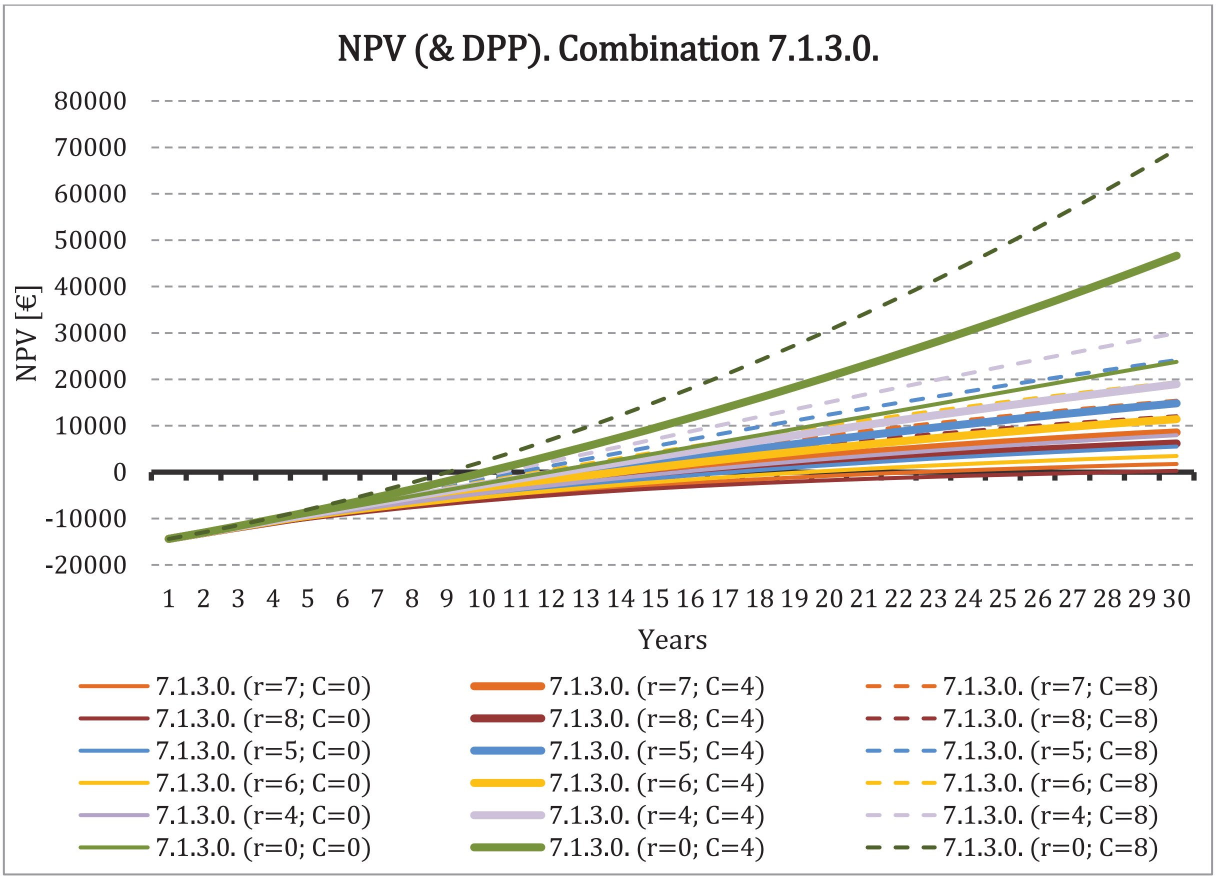


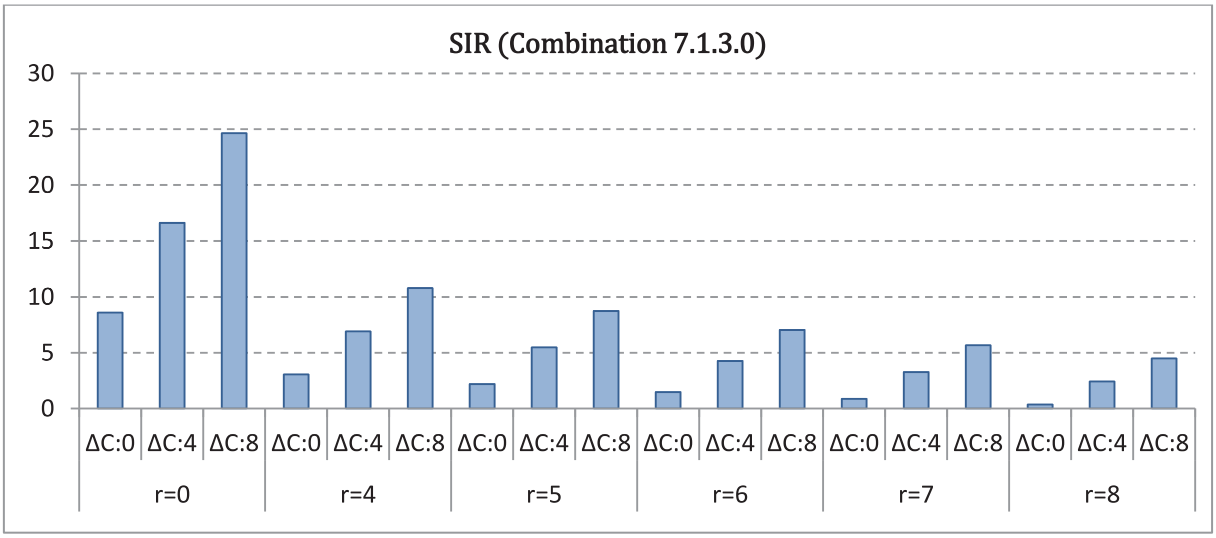


7.0.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	1.55%	-2.35%	-3.28%	-	-	-
ΔC:4	4.67%	0.64%	-0.32%	-1.26%	-2.18%	-3.09%
ΔC:8	6.80%	2.69%	1.71%	0.75%	-0.19%	-1.11%

- ## Combination 7.1.3.0.

ESIR: 1.51 kWh/€

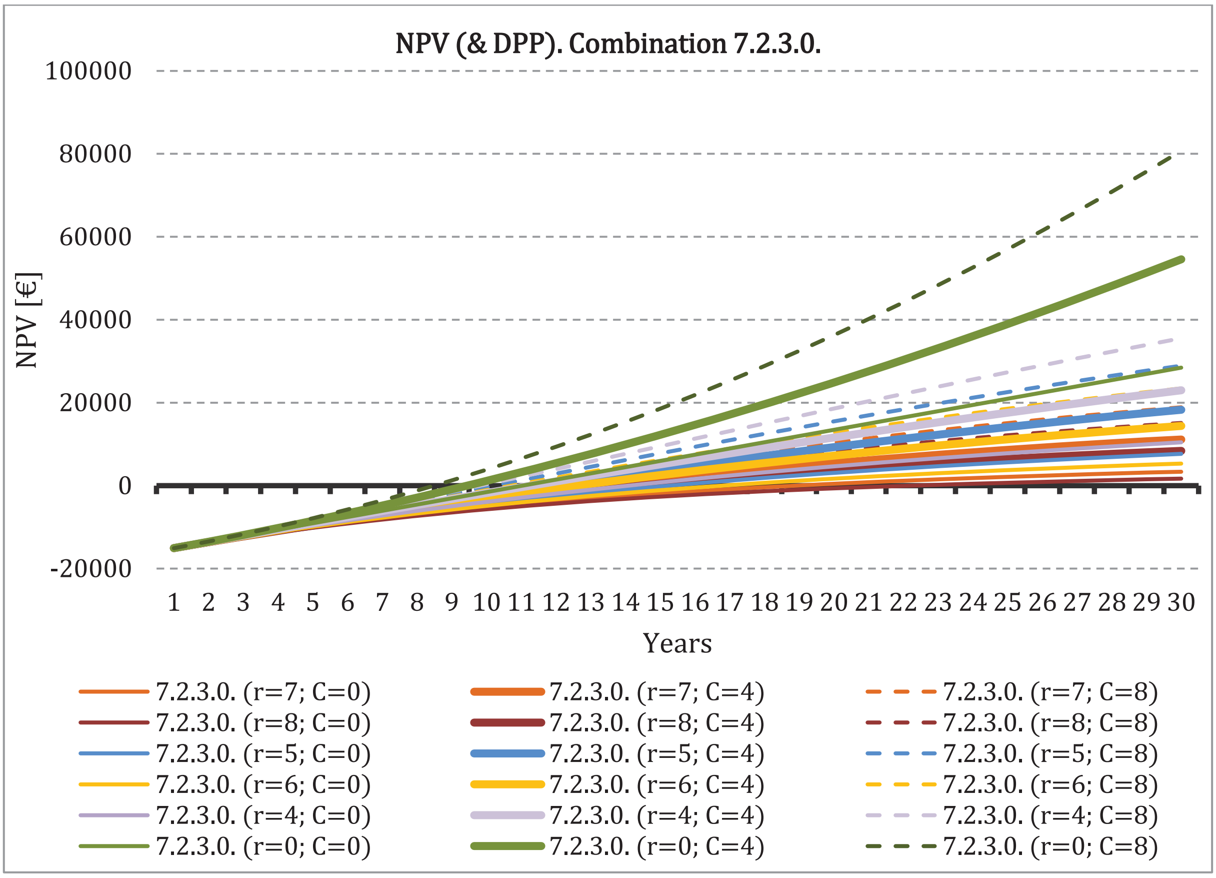


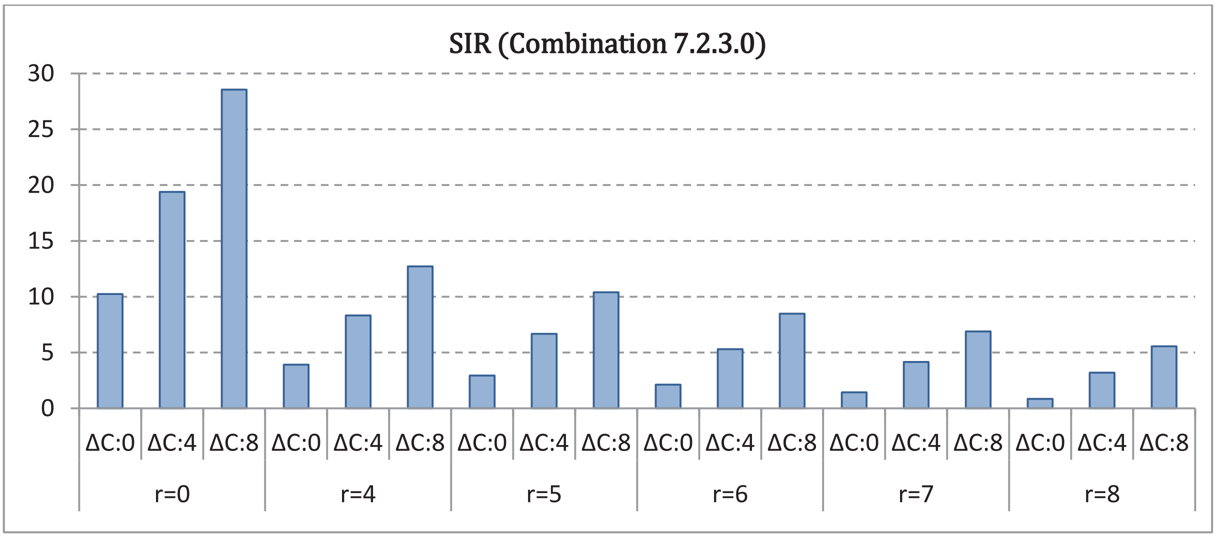


7.1.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	8.22%	4.06%	3.07%	2.09%	1.14%	0.20%
ΔC:4	11.70%	7.40%	6.38%	5.37%	4.39%	3.42%
ΔC:8	14.25%	9.85%	8.81%	7.78%	6.77%	5.79%

- ## Combination 7.2.3.0.

ESIR: 1.63 kWh/€

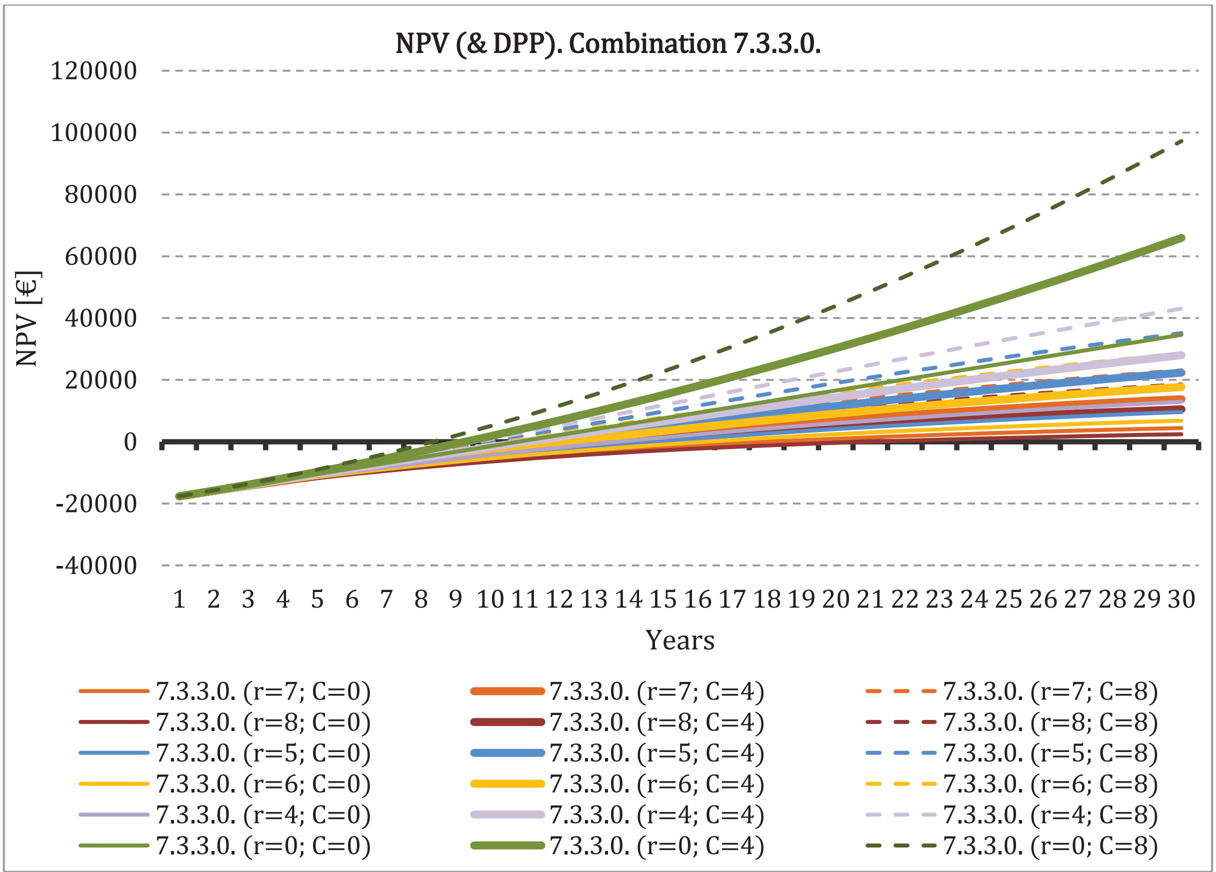


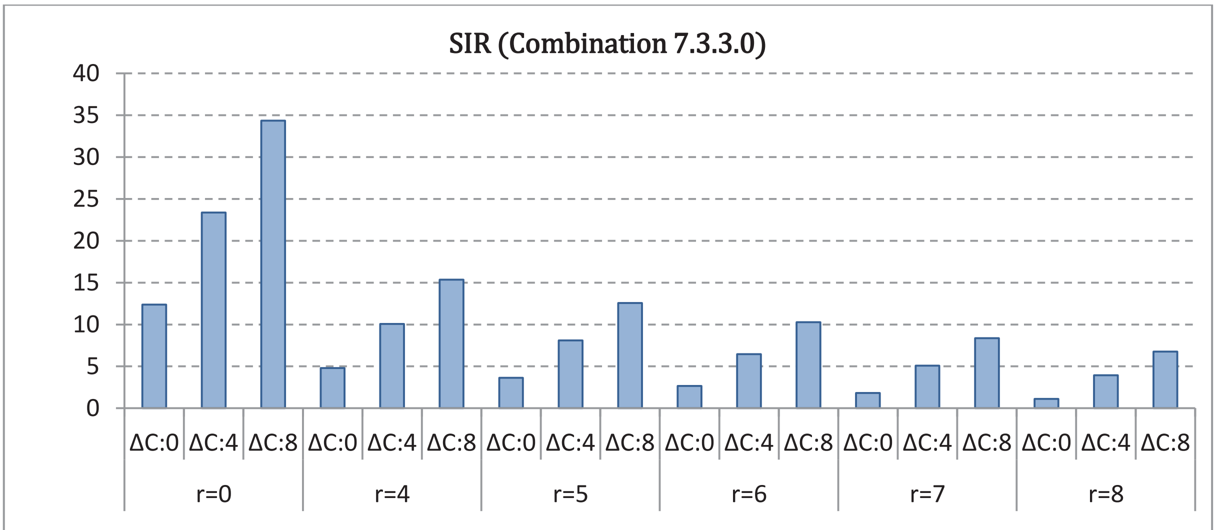


7.2.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	9.18%	4.98%	3.98%	3.00%	2.04%	1.09%
ΔC:4	12.71%	8.38%	7.35%	6.33%	5.34%	4.36%
ΔC:8	15.33%	10.89%	9.84%	8.80%	7.79%	6.79%

- **Combination 7.3.3.0.**

ESIR: 1.67 kWh/€





7.3.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	9.46%	5.25%	4.25%	3.27%	2.30%	1.35%
ΔC:4	13.01%	8.66%	7.63%	6.61%	5.62%	4.64%
ΔC:8	15.65%	11.20%	10.14%	9.10%	8.08%	7.08%

Appendix 8.1. The exergy approach for evaluating and developing an energy system for social dwelling

- *"The exergy approach for evaluating and developing an energy system for a social dwelling"*, published in Energy and Buildings in December 2012 (Vol 55, pag 693-703) [53]

Appendix 8.2. Dynamic exergy analysis of energy systems for a social dwelling

- *"Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement"*, published in Energy and Buildings in September 2013 (Vol. 64, pag 359-371) [54]

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The exergy approach for evaluating and developing an energy system for a social dwelling

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Abstract

In this paper the energy and exergy performance of a social dwelling of a multi-family building from the 1960's in Bilbao (Spain) is presented and various improved energy concepts based on exergy principles are proposed and investigated. The aim of this paper is to explore and demonstrate the usefulness of the exergy approach in the assessment and development of an energy system for the dwelling under consideration. The total energy supply system is analysed, including the demand (space heating, domestic hot water and electricity), the system components (for conversion, storage and distribution) and the energy input from energy resources (primary energy and renewable resources). The study includes a comparison of the primary energy input of all cases considered and an analysis of the energy and exergy losses of each system component. The study has shown that the exergy analysis reveals thermodynamic losses that are not revealed using energy analysis and secondly, that taking into account the exergy principles in the development of an improved energy system has resulted in a significantly reduced primary energy input compared to the reference situation.

Keywords:* *exergy analysis, building simulation, exergy design principles, building retrofitting

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1 Introduction

The energy demand for heating and cooling in the built environment is mainly a demand for 'low quality' energy, due to the associated temperatures required. Exergy is a thermodynamic concept which indicates the 'quality' of the energy, by expressing the thermodynamic ideal work potential of a certain form of energy. The first law of thermodynamics states that energy cannot be destroyed, but according to the second law exergy *can* be destroyed. Explanations of the exergy theory can be found in many textbooks on thermodynamics, such as [1-3].

Thermodynamic ideal processes are reversible, which means no exergy is destroyed and the original situation can be re-obtained. In real processes, however, exergy is always destroyed, often even in large amounts. The exergy destruction of a process indicates the ideal thermodynamic improvement potential of this process. This improvement potential is not shown in energy analysis; exergy analysis therefore has an added value for the evaluation of the performance and improvement potential of a system [4].

The 'low exergy' heating and cooling demands in the built environment are generally met with 'high exergy' energy sources, such as gas or electricity and usually a lot of exergy is being destroyed in these systems. This means there is much room for improvement. Exergy analysis of heating and cooling systems in the built environment is an emerging field of science in recent decades, as it is shown by a large number of publications and international research activities such as ([5-7].

In this paper the exergy performance of a social dwelling of a multi-family building from the 1960's in Bilbao (Spain) is presented and improved energy concepts based on smart exergy use are proposed and investigated. The aim of this paper is to explore and demonstrate the usefulness of the exergy approach in the assessment and development of an energy system for the dwelling under consideration.

The following cases are studied and presented:

- Case I) Original situation (no insulation, single glazing);
- Case II) Case study assuming the usual retrofitting works;
- Case III) Improved cases based on exergy principles.

For the improved cases (Case III) six options have been developed based on exergy principles. These options are evaluated using steady state analysis, but based on a dynamic energy and exergy demand calculation. In part 2 of this paper [8] three of the improved energy system options are evaluated using dynamic simulations, in order to assess the performance and improvement potential in more detail.

2 Methodology

This study aims at demonstrating the usefulness of applying the exergy approach for the development of an efficient energy system for a dwelling of a social multi-family building located in Bilbao (Spain). In this first part the reference cases are presented, the development of improved cases applying exergy principles is described and the energy and exergy performance - based on steady state analysis - of all cases is discussed. A detailed dynamic analysis of three improved options can be found in [8].

The following relevant methodology aspects for this study are described in this chapter: (1) the analysis framework according to the input-output approach; (2) the energy calculation method used; (3) the exergy calculation approach and (4) the exergy principles used for the development of exergetically improved options.

2.1 Analysis framework

In this study the total energy chain is analysed, which is composed of the energy demand, the energy system components (conversion, distribution and storage) and the energy resources. These are analysed according to the input-output approach described in [9] and [10]: The demand is the start of the analysis and for all subsequent energy system components the required input of the component equals the output of the next component. This way all energy and exergy losses are assigned to a component. In this study the demand for space heating and cooling as well as domestic hot water (DHW) and electricity for lighting and appliances is also considered. A scheme of the framework is shown in Fig. 1:

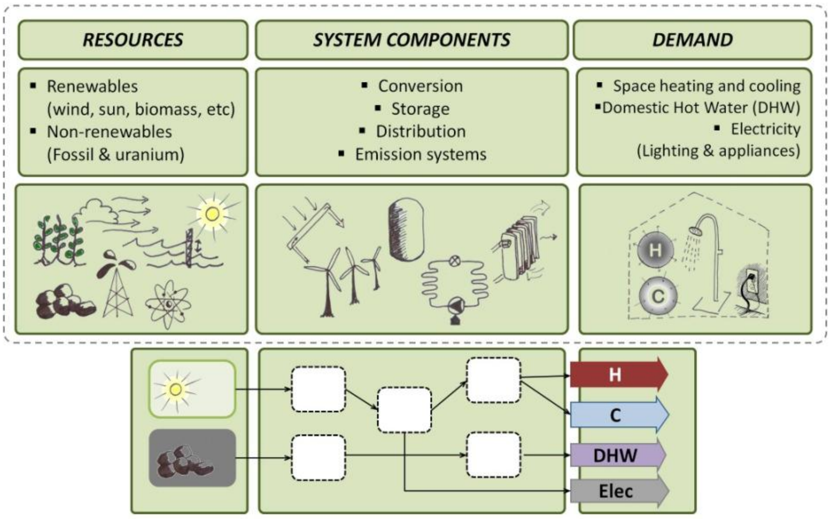


Fig. 1. Analysis framework consisting of demand, energy system components and energy resources

2.2 Calculation method

The analysis of the cases has been performed using dynamic simulations for the calculation of the energy and exergy demand of the building and using a simplified steady state approach for the energy performance of system components, as described below.

2.2.1 Dynamic energy and exergy demand calculation

The energy and exergy demands calculations are performed using the internationally well-known transient energy simulation software TRNSYS (V 17). An annual simulation has been carried out using a 1-h time-step. The energy demand for space heating for the different scenarios studied here are modelled using TRNSYS type 56. Only sensible heat is taken into account, in accordance with [11]. Cooling is not treated in this study as it does not usually exist in residential buildings in this area. The exergy demand is not a standard output of the TRNSYS software and is calculated for each time step according to the method explained in section 2.3.1. The demands for domestic hot water (DHW) and electricity for lighting and appliances are included as a schedule based on literature, as is further explained in the next chapter. The detailed building properties and operation schedules can be found in the appendix.

2.2.2 Steady state energy system analysis

The energy inputs and outputs of the subsequent energy system components for conversion and storage are calculated in a simplified way using a steady state approach. The analysis has been performed for the heating season (October until March) and the summer season (April until September). For this steady-state analysis the total demands resulting from dynamic simulation have been used. The exergy calculations are based on the energy values and the seasonal average temperatures, where the outdoor temperature is considered as the reference temperature as recommended by [10]. For this aim the average outdoor temperature is weighted by the heat demand per one hour time step; in this way the exergy calculations are more correct then when using the straight average outdoor temperature [12].

2.3 Exergy analysis approach

The exergy of an amount of energy can be calculated by multiplying this amount of energy with its exergy factor (F), which is defined as the exergy to energy ratio. This approach is used for calculating the exergy of the inputs and outputs of all energy system components as well as of the resources. The exergy factor of the fuels used is given in the Appendix. The exergy factor of heat at constant temperature can be calculated using eq. 1, while the exergy factor of sensible heat of an amount of matter ($m \cdot cp \cdot (T_2 - T_1)$) can be calculated using eq. 2. [9, 10, 13, 14]. Eq 1 is thus used to calculate the exergy of heat transfers across a system boundary, while eq. 2 is used to calculate the exergy of the sensible heat transferred by a flow of matter such as ventilation air or water.

$F(Q) = 1 - \frac{T_0}{T}$	**eq. 1**
$F(Q_{sens}, T_2 - T_1) = \left(1 - \frac{T_0}{T_2 - T_1} \cdot \ln\frac{T_2}{T_1}\right)$	**eq. 2**

2.3.1 The exergy demand for heating

The exergy demand for heating is calculated using the simplified approach as described in [9, 10, 12, 14]. In this approach the heat required is supposed to be delivered at the indoor temperature T_i. The exergy demand is therefore calculated using eq. 3.

$Ex_{dem,H} = Q_{dem,H} \cdot F_{dem} = Q_{dem,H} \cdot \left(1 - \frac{T_0}{T_i}\right)$	**eq. 3**

2.3.2 Room air

Between the demand for heating (required at T_i) and the emission system (e.g. a radiator) the fictive component 'room air' , as introduced by [9], is used to account for the exergy losses between emission system and demand which are a result of the temperature drop. No energy is lost in this step, but the exergy losses in the ‘room air’ component are a direct result of the mismatch between demand temperature and supply temperature.

2.4 Guidelines for exergy efficient energy systems for the built environment

The different options for improved energy and exergy performance have been developed using guidelines that are based on the exergy principle. Guidelines from the fields of mechanical engineering can be found in thermodynamic textbooks such as [3, 15]. Guidelines that are applicable to the built environment can be found in for example [10, 16, 17]. Based on literature as well as on previous studies [12, 18] the following guidelines are developed for and used in the study presented in this paper:

Principle 1: Use renewables and other flows of free or waste energy

This principle is in fact not an exergy based principle, but one of the most important strategies towards sustainability and is therefore also explicitly mentioned. It is important to make an inventory of all the free and renewable energy potential in order to make - exergetic- optimal use of it.

Principle 2: Match the quality levels of demand and supply (or in other words: use the lowest quality energy input as possible). This principle can be further elaborated into the following guidelines:

a) **Use low temperature heating (LTH) and high temperature cooling (HTC)**;

   This way exergy of the demand for heating and cooling, which represents a very low exergy demand, is still low at the emission system (i.e. radiator or floor heating) and a minimum exergy destruction between emission system and the thermal zones of the building takes place**;**

b) **Minimize temperature differences when exchanging heat;**

c) **Use low temperature energy flows existing in or around the building;**

   These energy flows include for example the heat from exhaust ventilation air or domestic hot water return, possible nearby surface water or waste water from industry.

d) **Use cascading principle (at building or district level);**

   When demands at multiple temperature levels are to be met, the principle of cascading can be applied, meaning high temperature heat flows are used for high temperature demands, and the return flow of this first demand is used to meet demands at lower temperatures. At building level cascading can theoretically be applied between the demand for domestic hot water (DHW) at 60 °C and space heating at ca. 30 °C. [10, 16]

Principle 3: Optimize storage strategies

Especially renewables and free energy sources are not always available at the time they are required, so when using renewable energy or waste flows storage becomes more important in the design of a system. Storage should also be optimised using the exergy principle by organizing storage at different temperature levels if present [17];

Principle 4: Use high quality energy sources as smart as possible

Also some components that make use of high quality energy input can be exergy efficient for heating purposes. In general the exergy efficiency of the system components should be considered rather than the energy efficiency. For the built environment the following conversion devices make smart use of the high quality input:

- **A heat pump (which generates more heat or cold than the electricity input)**

  For optimal use the temperature lift should be minimized [19];

- **A cogeneration system (combining the production of heat and power)**

  This option is only profitable if both outputs can be used. The electricity production should be large in order to have high exergy efficiency.

Principle 5: Avoid processes known to cause exergy losses

Exergy destructive processes include: Combustion, resistance heating, mixing, throttling, large driving forces (i.e. large temperature differences).

3 Description of the reference cases

The dwelling studied is a social sector dwelling located in a multi-family building built in 1960. This dwelling is selected since it is a representative apartment of the social sector housing stock in Bilbao. A plan of the dwelling is shown in Fig. 2. The net floor area is 52.52 m^2 and the floor to ceiling height is 2,47 m. The specific dwelling considered has 3 external façades, orientated East, West and South, but only two of them (E and W) have windows.

Fig. 2. Plan of the dwelling.

The total building consists of six storeys with six dwellings per floor, which means there is a total of 36 dwellings in the whole building. For the analysis only one dwelling is used and the results are also presented on a dwelling level (and not for the 36 dwellings). However, for the development of improved energy the whole building is taken into account with regards to the characteristics of certain technologies (such as combined heat and power (CHP) devices) or the use of renewables (i.e. $1/36^{th}$ of the roof surface can be used by each dwelling).

The two reference situations (Case I, without any renovation works and Case II, with the usual renovation works) are described in 3.1 and 3.2 respectively; the development and description of the improved options can be found in section 4. In the appendix the characteristics of the dwelling are described in detail.

3.1 Case I. Base Case

Case I corresponds to the original situation of the dwelling, which represents the dwellings without any renovations since it was built in 1960: the façades have no insulation and for all windows single glazing is assumed. The space heating system is based on 3 electric heaters and domestic hot water (DHW) is provided with a natural gas boiler. Electricity (for lighting and appliances) is provided by the national grid. In the original situation there is no controlled ventilation system but ventilation through open windows is assumed.

3.2 Case II. After Usual Renovation Works

Bilbao Social Housing renovates about 100 dwellings per year. The majority of these renovations are "dwelling scale" renovations. The measures adopted in these renovations are usually similar in every case. Case II represents this situation with the usual renovation works, which include placement of insulation (4cm of rock wool installation), replacement of the windows (clear double glazing), central heating using high temperature radiators and a natural gas combi-boiler (for both space heating and DHW). Air tightness is improved to decrease the infiltration rate, and fixed ventilation rates are assumed according to the Spanish Technical Building Code [20].

4 Case III. New proposals based on exergy guidelines.

To develop new exergy efficient proposals, several options have been considered, based on the guidelines mentioned in section 2.4. Three options requiring rather radical interventions have been considered as well as three options needing less radical renovation works. All options considered are assessed using steady state energy and exergy analyses, and a selection is made for further analysis in [8]. In this chapter the important features of the developed cases are described. All detailed characteristics can be found in the Appendix.

4.1 Considerations

The development of improved cases considers the total system as shown in figure 1 according to the exergy principles, aiming at an optimal solution combining a reduction of the demand, more efficient system components and increased use of renewable resources.

Firstly, for all cases the energy demand is further reduced by increasing the insulation value of the external façades (increased insulation thickness to 8 cm). Secondly, for options 1 until 3 a ventilation heat recovery system has been assumed, in order to further reduction of the heat to be delivered by the emission system.

Regarding the emission system the first three options are considered to have a floor heating system, which can operate at very low temperatures (35-30 ^{0}C). The required heating capacity for these options is 75 W/m² which means floor heating is feasible [21], even though attention still has to be paid to comfort issues [22]. The options 4 until 6, which should have less radical improvements, are considered to have low temperature radiators (40-35 ^{0}C).

The use of available energy flows is also taken into account in the development of the options. The heat from exhaust ventilation air is used for heat recovery in the first three cases. Option 4 considers the use of ventilation exhaust air as a source for a heat pump, which means only mechanical exhaust is required and no mechanical air supply has to be designed. In options 5 and 6 exhaust ventilation air is not used, which means the ventilation system can be natural. Return flows of domestic hot water are not considered.

Furthermore an inventory of the potential of available renewable resources has been made. The solar irradiation on 80% of the total roof surface of the building (360 m², covering a total of 36 dwellings) is determined and the potential supply of heat using solar thermal collectors (ST, assuming 44% energy efficiency) or electricity using photovoltaic panels (PV, assuming 15% energy efficiency) is investigated.

Solar thermal collectors are considered more suitable for meeting the Domestic Hot Water demand and less for meeting the space heating demand, since the seasons of space heating demand and solar supply do not match. For this aim a surface area of 110 m^2 has been considered most favourable. According to calculations carried out with TRNSYS, this area can supply the total DHW demand from May until August, and significant parts (>80%) can be met in April and September. When opting for larger surface area's the overproduction of energy in summer becomes very high, while only increasing the supply in winter to a smaller extent. This is illustrated in the Fig. 3.

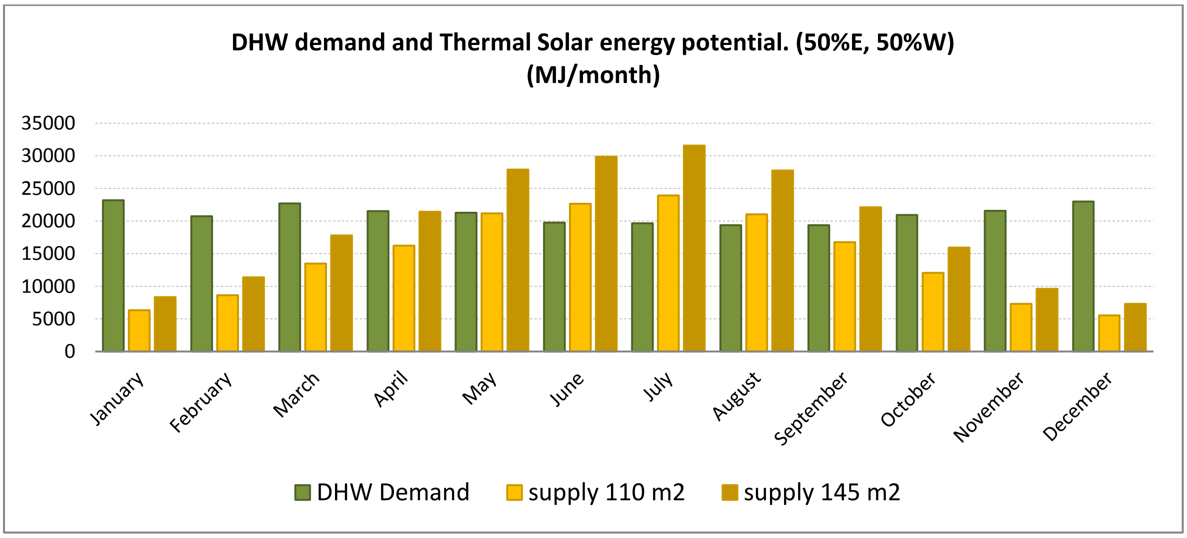


Fig. 3. DHW demand and Thermal Solar energy potential (It represents the DHW demand for the whole building of 36 dwellings)

Photovoltaic energy is considered in all options, the available surface area depending on the use of solar thermal energy, which depends on the total system configuration considered. When considering PV to be placed on the total roof surface, the total annual electricity demand (for lighting and appliances) can be met, though be it with a shortage in winter season and an overproduction in summer.

Wind energy (small urban turbines on the roof) has been investigated assuming small urban wind turbines (1 meter diameter wind turbines). The resulting annual electricity production is estimated about 40 kWh/year (1.5 kWh/year per dwelling), which is rather insignificant compared to the solar energy potential. Wind energy is therefore not further considered in this study.

For meeting the remainder of the demand several configurations of a heat pump based system and a CHP based options have been considered, as well as one option including both. A heat pump is considered optimal for meeting the low quality space heating demand, while the heat output from the CHP can also be used for domestic hot water. An air source heat pump is considered, using the outside air as a heat source (only option 4 also uses ventilation exhaust air as a heat source, as far as available).

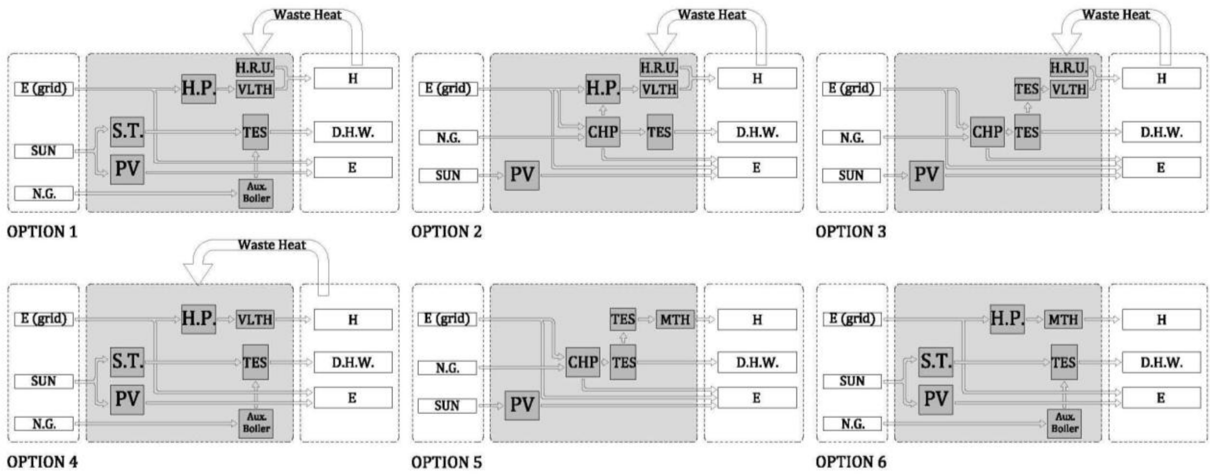
4.2 Options considered.

All considerations have led to six options described in Table 1, of which schemes are shown in Fig. 4:

Option 1: Drastic / HP	Using heat recovery, low temperature floor heating, a heat pump to meet the space heating demand, solar thermal (110 m2) and PV (250 m²).
Option 2: Drastic / HP+CHP	Using heat recovery, low temperature floor heating, a heat pump to meet the space heating demand and CHP for domestic hot water and electricity, and PV (360 m²).
Option 3: Drastic / CHP	Using heat recovery, medium temperature radiators, a CHP for space heating, domestic hot water and electricity, and PV (360 m²).
Option 4: Moderate / HP(+)	Medium temperature radiators, space heating supplied by a heat pump (also using ventilation exhaust air as heat source), solar thermal (110 m2) and PV (250 m²).
Option 5: Moderate / CHP	Medium temperature radiators, a CHP for space heating, domestic hot water and electricity, and PV (360 m²). (similar to option 3 but without heat recovery)
Option 6: Moderate / HP	Medium temperature radiators, space heating supplied by a heat pump, solar thermal (110 m2) and PV (250 m²).

Drastic = options with very low temperature heating (floor heating) (35-30 °C) and ventilation heat recovery;
Moderate = options with low temperature radiator (40-35 °C)
HP = heat pump; HP(+)= heat pump making use of ventilation exhaust air; CHP = combined heat and power

Table 1: overview of the improved options developed



	OPTION 1	OPTION 2	OPTION 3	OPTION 4	OPTION 5	OPTION 6
Heat Pump	✓	✓	✗	✓	✗	✓
Heat Recovery	✓	✓	✓	✗	✗	✗
CHP	✗	✓	✓	✗	✓	✗
Very Low Temp. Radiator	✓	✓	✓	✗	✗	✗
PV	250	360	360	250	360	250
Solar Thermal Energy	110	✗	✗	110	✗	110

Fig. 4. Schemes of the improved options developed.

5 Results and discussion

5.1 Resulting energy and exergy demands

The annual energy and exergy demands for all cases are listed in the Table 2. As explained in the methodology section the demands for space heating are calculated using the dynamic simulation software TRNSYS. The demands for DHW and electricity are considered equal for all cases.

demand	Case I		Case II		Case III, option 1,2,3		Case III, option 4,5,6	
	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy
Space heating	26,166	1,035	16,044	613	7,800	305	14,688	555
DHW	7,031	524	7,031	524	7,031	524	7,031	524
Electricity	5,466	5,466	5,466	5,466	5,466	5,466	5,466	5,466

Table 2: Annual energy and exergy demands for all cases studied [MJ/year]

It can be seen that the measures taken in Case II reduce the energy demand for space heating by ca. 40%. All options of Case III have further reduced demand for space heating as a result of higher insulation values; options 1 until 3 realize an even larger reduction of the heat demand due to the use of ventilation heat recovery. As could be expected the exergy demand for space heating and domestic hot water is much lower than the energy demand for these outputs due to the low exergy factor of these demands: In energy terms the demand for space heating is the largest demand; in exergy terms however the electricity demand is the largest.

5.2 Energy system results and discussion

5.2.1 Case I and Case II

In Fig. 5 the (steady state) annual results of the energy systems of Case I and Case II is presented. It shows the energy and exergy demand, the energy and exergy losses in the system components and the total primary energy input. For primary energy the exergy content equals the energy content, since an exergy factor of 1 is assumed for the primary energy, as explained in the appendix.

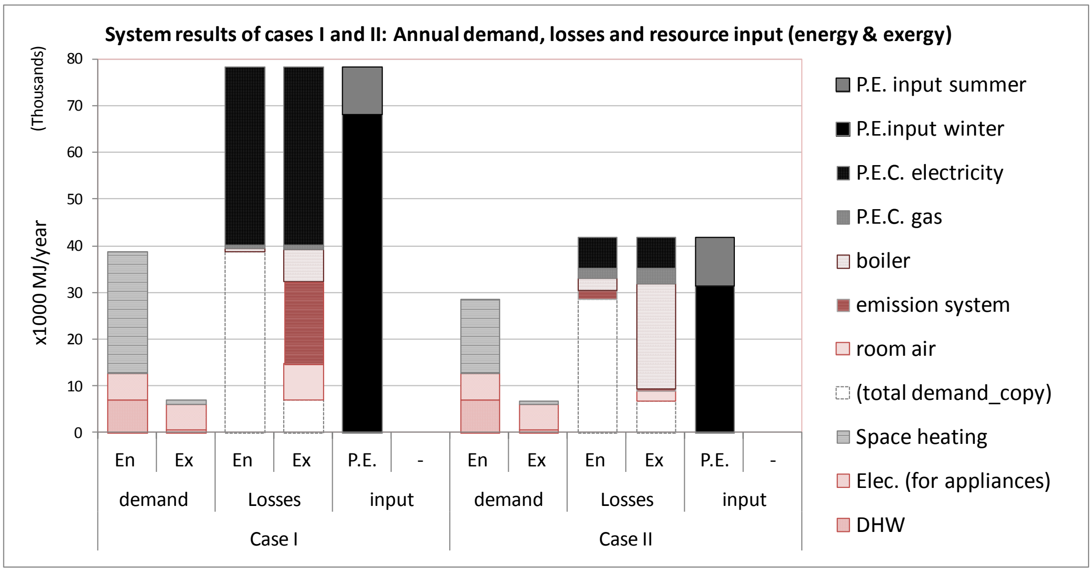


Fig. 5. Annual results of Case I and Case II: energy and energy demand, energy and exergy losses of the various system components and primary energy input (energy equals exergy in this case)

The results of the two reference cases show that in case I a total system energy efficiency of ca 50% is obtained, while for Case II a total system energy efficiency is ca 70%. The total system exergy efficiency is around 10% and 16% respectively. According to an energy analysis the losses in the system are almost solely caused by the primary energy conversion for grid electricity (P.E.C. electricity, see Appendix) in case I, and some by the boiler and the primary energy conversion for gas supply from the grid for Case II. The exergy losses however reveal significant additional losses that are not shown with the energy approach:

- Exergy losses of the 'room air' component, due to the difference in required indoor temperature Ti and the temperature supplied by the emission system (electrical heater and radiator respectively);
- Exergy losses of the emission system of Case I (electrical boiler) due to conversion of electricity into heat;
- Exergy losses in the boiler due to the conversion of gas into heat.

In line with the guidelines mentioned previously it has been tried to avoid these losses in the development of the improved options, which are discussed in the next paragraph.

5.2.2 Case III options 1 until 6.

The results of the improved options (Case III) are slightly more complex to clearly illustrate, since they include the input of renewable energy and 'free' outdoor energy. For correctly understanding the results of the improved options the following aspects have to be taken into account:

- The steady state approach involves the inability to take into account daily and hourly profiles. This means the demand and input of solar gains are not evaluated hourly and thus the total energy need from the grid and total energy returned to the grid is not obtained; only the net monthly electricity demand from the grid is calculated.
- However, a possible monthly surplus of thermal heat from the solar collectors is considered as 'unused' heat and thus not included in the results;
- In case of the use of a CHP and the total roof covered with PV (cases 2, 3 and 5) the results for the summer season show a large surplus of electricity production. In reality this means the output of the energy system in these cases (2,3, and 5) is different from the output of the other cases (1, 4 and 6). For comparison between the cases, however, it is desired to compare the input required for the same output. Since a CHP by definition provides two useful outputs for the same input, it is not possible to subtract a part of the input responsible for the electricity overproduction. In order to make the cases comparable it has therefore been chosen to reduce the primary energy input with the amount of primary energy that - due to the electricity overproduction - does not need to be spent by the national grid. This method of making the cases comparable to each other increases the sensitivity of the results to the primary energy factor (PEF), as will be further shown in the next paragraph.

The resulting energy and exergy demands according to the assumptions described above can be seen shown in Fig. 6 and Fig. 7. For all cases the primary energy or exergy input for the summer season is very small relative to the annual input. This is mainly caused by the fact that in summer there is no demand for space heating and there is a lot of electricity overproduction (especially in cases with a CHP, being 2,3 and 5).

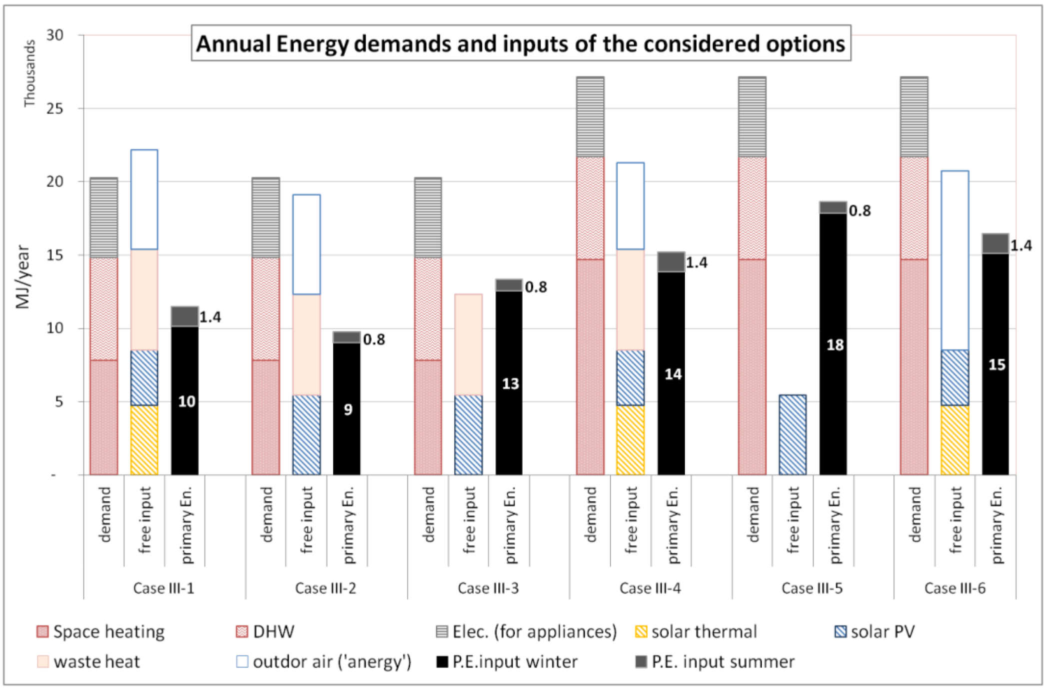


Fig. 6: Results Case III options 1-6: Annual energy demands (=system output) and energy inputs.

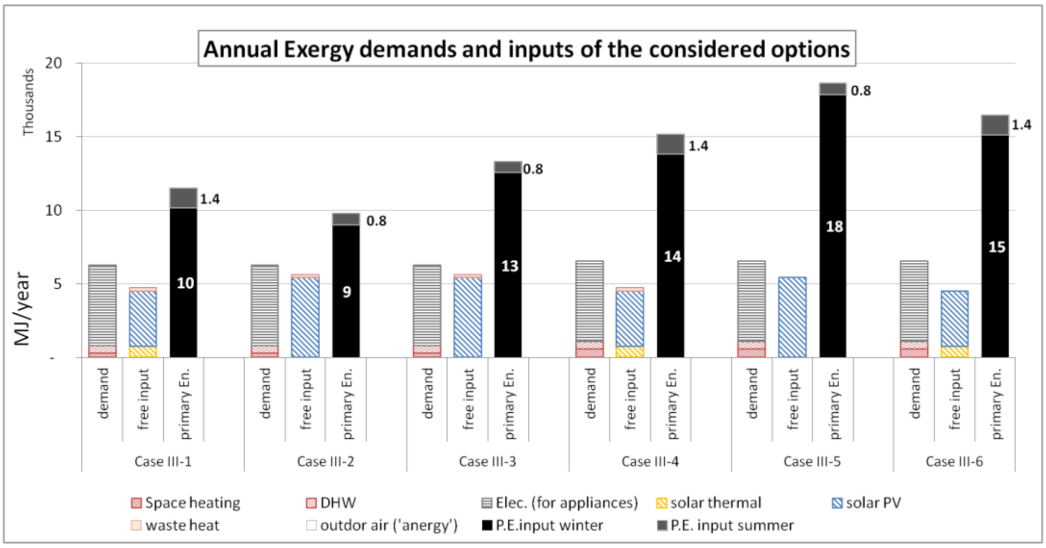


Fig. 7: Results Case III options 1-6: Annual exergy demands (= output) and exergy inputs.

The results show that the improved options perform significantly better than both reference cases with respect to primary energy input. This is caused by a further reduction of the demand for space heating, the use of renewable energy sources and the more exergy efficient system components and configuration.

Of the ‘drastic’ first 3 cases, the results show that Option 2 (with both a heat pump and a CHP) results in the lowest primary energy input, since it combines the advantages of the HP and the CHP; The second best case is Option 1 using mainly a heat pump. The performance however depends greatly on the actual component characteristics assumed as well as on the primary energy factors, as will be shown in the next paragraph.

Of cases 4 until 6 the heat pump cases also show the best performance. Option 4 performs a little better than option 6, since it makes use of the ventilation waste heat.

An analysis of the losses of case III 1 until III-6 during the heating season is shown in Fig. 8. For each option the energy losses and exergy losses per component are shown.

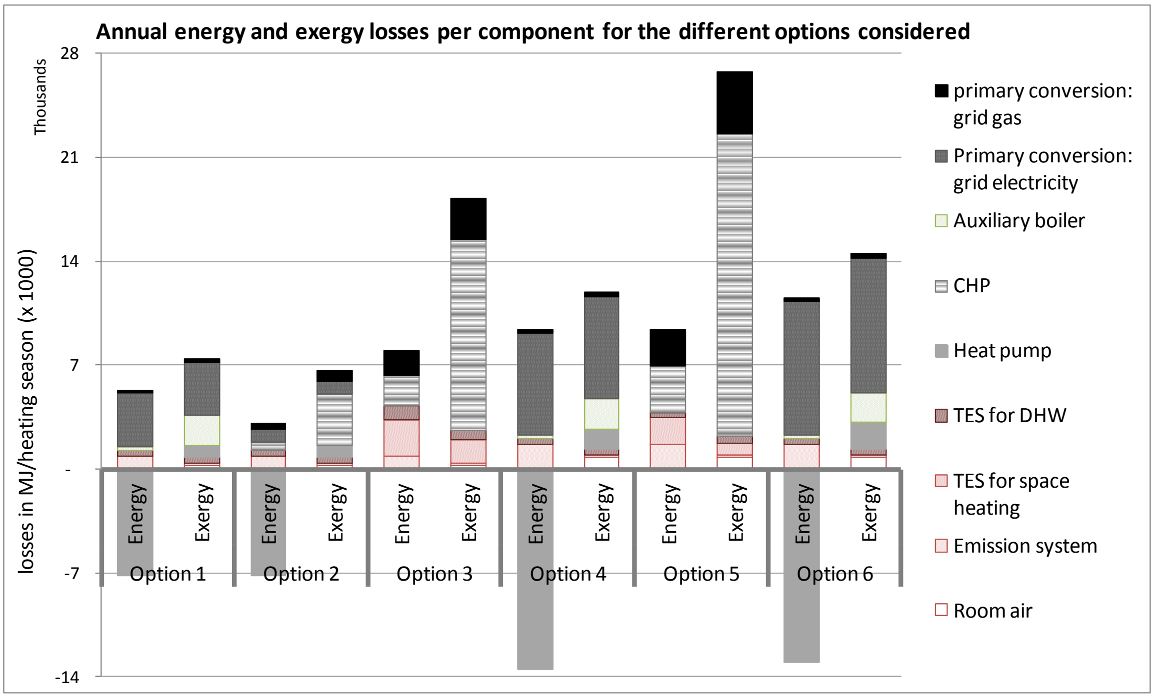


Fig. 8 Energy and exergy losses per energy system component, for each of the improved options considered (according to steady state evaluation of the heating season).

In the analysis of the losses again large differences between the energy and exergy analysis are present. These are especially important in the evaluation of the heat pump and the CHP. The energy performance of the heat pump is very positive since the heat output is larger than the electricity input (free energy input is disregarded, so negative losses are presented); the exergy of the heat output however is smaller than the exergy of the electricity input, which means there are exergy losses. The energy performance of the CHP is also more positive than its exergy performance, since the low value (i.e. low exergy content) of the heat produced by the CHP is not considered in the energy evaluation.

5.3 Sensitivity analysis

All results are naturally dependent on the input parameters as described in the appendix. Figure 8 shows that for all improved options the biggest losses occur in the primary energy conversion and in the CHP component, therefore a sensitivity check of the input parameters used for these components has been performed.

The sensitivity to the electrical efficiency of the CHP is shown in Fig. 9 a. For this sensitivity check the total energy efficiency (electrical efficiency plus thermal efficiency) is kept constant at 91 % (according to the CHP type chosen for the steady state analysis, from [23]) but the electrical efficiency is varied between 20% and 40%. The sensitivity of the resulting primary energy input for options 5 and 6 on the primary energy factor(PEF) for (national grid) electricity production is shown in Fig. 9 b. The PEF is varied between 2.00 and 2.80; the current PEF for Spain according to [24] is 2.21.

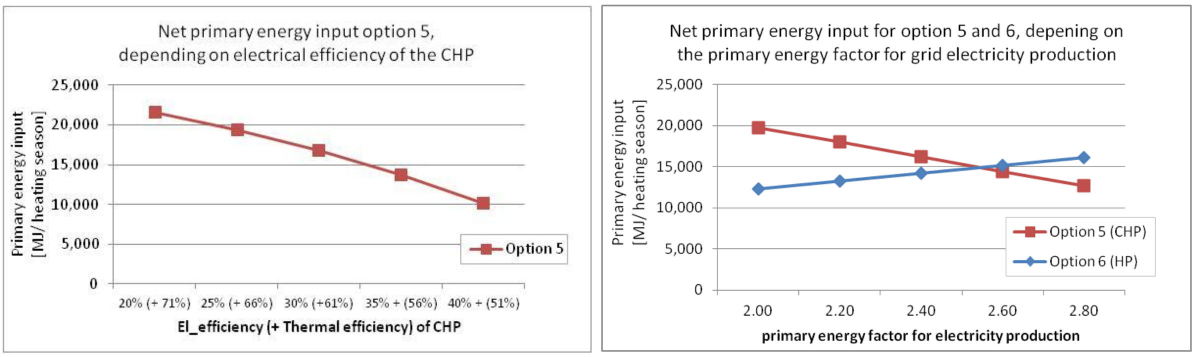


Fig. 9. (a): Sensitivity of the net primary energy input of option 5 to the electrical efficiency of the CHP (left graph), and (b): Sensitivity of the net primary energy input of options 5 and 6 to the primary energy factor for electricity from the national grid (right graph).

As could be expected from the analysis of the exergy losses, the results are very sensitive to the primary energy factor for electricity production as well as on the actual performance of the CHP. This means it is important to take these factors into account when selecting promising options. Also scenarios for future developments of these aspects could be considered.

5.4 Selected options

For further investigation in part II of this paper [8] Option 1, 5 and 6 have been chosen. Option 2 performs best but this is considered not a feasible option due to the high costs of using both a heat pump and a CHP. In a larger scale case study this configuration might be an option.

6 Conclusions and recommendations

This paper has demonstrated the added value of the exergy approach in the analysis and development of an energy system for the built environment, in this case a social dwelling in Bilbao, Spain. It has shown that an exergy analysis reveals thermodynamic losses that are not revealed using energy analysis. Additionally it has shown that taking into account the exergy approach and the exergy guidelines in the development of an energy system configuration for this dwelling resulted in significantly reduced primary energy input compared to both the original situation and the situation with usual retrofitting works. This reduction was caused by a further reduction of the demand, the use of renewable resources, the exergy efficiency of the energy system components and an exergy conscious design of the system as a whole.

It has been shown with the sensitivity analysis that the influence of specific component characteristics on the final results can be very large. The system is more sensitive to parameters of components causing the largest exergy losses. The results of this study have shown to be especially sensitive to the primary energy factor for electricity production and to the electrical efficiency of the CHP unit.

For further development of the energy system the exergy losses should be analysed into more detail and an optimization between exergy efficiency and other objectives, such as costs should be performed. A detailed analysis is performed in part 2 of this paper [8].

7 Acknowledgements

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Appendix

In this appendix the building characteristics of the dwelling shown in chapter 3 and the operational aspects relevant to its energy performance are presented. The data are based on reference values given by TRNSYS, CTE (Spanish Technical Building Code) and The Institute for Energy Diversification and Saving [25].

A.1 Geometrical and construction data

The dwelling has been modelled divided into two zones. Extensive research has been done in other simulations to investigate the influence on the results of the single zone model versus a model divided into more zones. Since the differences are relatively small and the final aim of the project is to investigate the added value of exergy analysis in the evaluation and development of the total systems, the choice to use a simplified model of 2 zones has been made.

A.2 Construction data

A dwelling on the 4th floor of a multifamily building of 6 floors has been chosen, so the ceiling and floor of the study case have been considered adiabatic in the TRNSYS simulation. The physical properties of the building envelope components are presented in Table A. 1.

No	Function (*1)	Or.	Area [m2]	CASE 1		CASE 2		CASE 3	
				U-Value [W/m^{2}K]	g-Value	U-Value [W/m^{2}K]	g-Value	U-Value [W/m^{2}K]	g-Value
1-3	Façade	W,S,E	56.9	1.49	-	0.59	-	0.375	-
4-5	Internal partition	N	17.68	2.39	-	0.70	-	0.70	-
6-7	Ceiling and floor	Hor.	3.97	2.23	-	2.23	-	2.23	-
W	Windows (*1)	E, W.	10.55	5.68	0.855	2.83	0.755	2.83	0.755

(* 1) Values for Solar Absorbance, Convective heat Transfer coefficient and F_{sky} are according to the standard values provided by TRNSYS.
(*2) For windows only the U value of the glass is presented. The frame covers 15% of the total window surface and has a U-value of 2,15 W/m²K in all cases.

Table A. 1. Physical properties of the building envelope components

A.3 Schedules and dwelling operation

A.3.1 Overview

Table A. 2 summarizes the different schedules for all relevant dwelling operation aspects. It is noted that in the original situation there is a large infiltration rate but no controlled ventilation system is present; for this case it is assumed that the windows are one hour a day for fresh air (see ventilation column).

	Infiltration		Ventilation		Internal Gains			Heating Operation	Demands	
	[(m^3/h)/m^3]		[(m^3/h)/m^3]		[kJ/h]			[ºC]	[w/m^2]	[l/h]
	CI	CII&III	CI	CII&III	Occup.	Lighting	Appl.	Set-Point Temp.	Elect Demand	DHW Demand
00.00-06.00h	1.3	0.24	0	1.72	12,64	1,58	1,58	17	0.88	0
06.00-07.00h	1.3	0.24	0	1.72	12,64	1,58	1,58	17	0.88	11
07.00-08.00h	1.3	0.24	4	1.72	3,17	4,75	4,75	20	2.64	11
08.00-09.00h	1.3	0.24	0	1.72	3,17	4,75	4,75	20	2.64	11
09.00-15.00h	1.3	0.24	0	1.72	3,17	4,75	4,75	20	2.64	4
15.00-18.00h	1.3	0.24	0	1.72	6,34	4,75	4,75	20	2.64	4
18.00-19.00h	1.3	0.24	0	1.72	6,34	7.92	7.92	20	4.4	4
19.00-21.00h	1.3	0.24	0	1.72	6,34	15,84	15,84	20	8.8	8
21.00-23.00h	1.3	0.24	0	1.72	6,34	15,84	15,84	20	8.8	4
23.00-00.00h	1.3	0.24	0	1.72	12,64	7.92	7.92	17	4.4	4

Table A. 2. Schedules and operation values assumed in TRNSYS model

A.3.2 Notes and references

Alls schedules in this study are based on CTE and [25]. However, since no difference between weekdays and weekends is assumed in this paper some adaptations to the scheduled from these sources have been made. Additional information for some items is provided below.

A.3.2.1 Air infiltration and ventilation

In the original situation as it was built in the 1960's there is no controlled ventilation. Therefore manual ventilation (opening windows) is assumed for an hour with an air change rate of 4 $(m^3/h)/m^3$, whilst Infiltration airflow rate is assumed constant at 1,3 $(m^3/h)/m^3$ in the dwelling.

For study cases II and III the minimal requirements according to [20] and [25] are followed. This leads to a constant ventilation rate of 1,72$(m^3/h)/m^3$ and a constant infiltration rate of 0,2 $(m^3/h)/m^3$.

The reduced infiltration airflow rate of case II and III is mainly due to the better air tightness of window frames. The retrofitted case also will consider an extra air change rate of 0,24 $(m^3/h)/m^3$ in ventilation.

A.3.2.2 Set point Temperatures

The setpoint and setback temperature shown in table A.2 are based on the criteria given by IDAE [25] Annex III. However, the TRNSYS software is programmed in such a way that the ideal heating demand calculation in principle reacts to the *air temperature* of a thermal zone, while for a more correct evaluation of comfort the *operative zone temperature* (T_{op}) should be controlled. This control is in TRNSYS obtained using eq. A. 1 and eq. A. 2, where T_{mean_surf} is the average surface temperature of all surrounding (wall and window) surfaces in the zone. T_{mean_surf} is result of the TRNSYS simulation. (The set-point temperature is for this reason modelled as an input from the TRNSYS studio instead of a direct value in the TRNBUILD program).

$T_{op} = \frac{T_{air} + T_{mean\_surf}}{2}$	**eq. A. 1**
$T_{air,sp} = (T_{op,sp} - 0.5 \cdot T_{mean\_surf}) \cdot 2$	**eq. A. 2**

A.3.2.3 Electricity Demand

The electricity demand schedule is based on the IDAE criteria for internal gains, assuming that all heat gains from lighting and appliances are a result of electricity consumption. The electricity Demand sums up to 14977,45 kJ/day, which equals 4,16 kWh/day and 1518,55 kWh/year

A.3.2.4 Domestic Heating Water Demand (DHW)

The schedule assumed for the DHW demand is based on profiles defined in [25], which is similar to the profiles as described in [26]. A daily demand of 101 litres of warm water is assumed, according to the schedule shown in Table A. 3, with a desired (output) temperature of 60 ºC. The water supply temperature is calculated using eq. A. 3, with an annual average supply temperature assumed at 15,4 ºC.

- $If\ T_{out} < -5ºC \xrightarrow{then} T_{Sup\_DHW} = 1{,}8$
- $If\ T_{out} \geq -5ºC \xrightarrow{then} T_{Sup\_DHW} = \frac{(2 \cdot T_{out} + 15.4)}{3}$

eq. A. 3

Thus, the DHW supply temperature follows the outdoor temperature in a tempered way. In addition the minimum temperature is 1,8 degrees and the maximum is 26 degrees (since the highest outdoor temperature in Bilbao in the EPW data files for a typical year is 30,6 ºC, 27th of July at 5.00 PM)

A.4 Energy system components

In table A.3 the assumed properties of the energy systems components are presented: Energy Efficiency η (if it is a fixed value), Inlet Exergy Factor, Outlet exergy Factor, and temperatures used for calculating the exergy factor when applicable. Equation 1 and 2 used for the calculation of the exergy factor are explained in section 2 of this paper.

Component	η	INPUT			OUTPUT		
		T_{inl}	T_{ret}	F	T_{inl}	T_{ret}	F
Demands							
Space heating	N/A	Ti		1	N/A		
DHW	N/A	60 ºC	eq. A. 3.	eq. 2			
Electricity	N/A	N/A		1			
Emission systems							
Elect. heater	1	N/A		1(Electricity)	150 ºC		eq. 1
H.T. Rad.	0.9	70 ºC	55º C	eq. 2	70 ºC	55º C	eq. 2
M.T. Rad.	0.9	40 ºC	35 ºC	eq. 2	40 ºC	35 ºC	eq. 2
L.T. Rad / floor	0.9	35 ºC	30 ºC	eq. 2	35 ºC	30 ºC	eq. 2
Conversion components							
Boiler	0.9	N/A		0.95 (NG)	DHW or emission system		eq. 2
Heat Pump	(*1)	N/A		1(Electricity)	35 ºC	30 ºC	eq. 2
CHP (elec/thermal)	0.28/ 0.63	N/A		0.95 (NG)	80 ºC	60 ºC	1(Electricity) / eq. 2
Solar Thermal	0.44	N/A		0.95 (Sol)	80 ºC	Type 4	eq. 2
PV	0.15	N/A		0.95 (Sol)	N/A		1(Electricity)
Storage							
H.T. TES	0.9	80 ºC	60 ºC	eq. 2	(DHW)		
M.T. TES	0.9	60 ºC	40º C	eq. 2	40 ºC	35 ºC	eq. 2
Primary energy conversion (P.E.C.) of grid electricity and grid gas.							
P.E.C. elec	0.45(*2)	Primary energy, F is assumed 1 (*3)			1(Electricity)		
P.E.C. gas	0.93 (*2)				0.95 (NG)		

(*1) The COP of the heat pump is calculated assuming a performance of 50% of the Carnot COP [19].
(*2) These values are the inverse of the following primary energy factors taken from [24]: PEF_{Elect}= 2.21 and PEF_{NG}=1.07, for electricity and gas respectively.
(*3) the exergy content of the primary energy is in fact dependent on the mix of resources used to obtain the energy output. But this calculation is out of the scope of this research.

Table A.3: Properties of the energy system component for each case

Nomenclature

A	[m^2]	Area
c_p	[$J\ kg^{-1}\ K^{-1}$]	Isobaric heat capacity
E	[J]	Electricity
En	[J]	Energy
Ex	[J]	Exergy
F	[-]	Exergy Factor (Exergy to energy ratio)
H	[J]	(space) heating
Q	[J]	Heat
Q_{sens}	[J]	Sensible heat
T	[K]	Temperature (^{0}C if explicitly mentioned)
U	[$W\ m^{-2}\ K^{-1}$]	Heat transfer coefficient
V	[m^3]	Volume

Greek symbols

Ψ	[-]	Exergy Efficiency
η	[-]	Energy Efficiency

Subscripts

0	Reference
dem	Demand
i	indoor
inl	Inlet
op	Operative (Temperature)
outp	output
ret	return
sp	Set-point (Temperature)
sup	Supply

Abbreviations (also used as subscript)

CHP	Combined Heat and Power (Cogeneration)
DHW	Domestic hot water
H.R.U.	Heat recovery unit
H.T.	High temperature
L.T.	Low temperature
M.T.	Medium temperature
NG	Natural gas
P.E.C.	Primary energy Conversion
P.E.F.	Primary energy factor
PV	Photo Voltaic (energy)
S.T.	Solar thermal (energy)
TES	Thermal energy storage
V.L.T.	Very low temperature

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Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement

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Abstract

This paper presents a study of the usefulness of the exergy approach in the development of energy systems for the built environment. The energy and exergy performance of five different energy systems for a social dwelling in a multifamily building from 1960's in Bilbao (Spain) are studied; two reference cases as well as three improved options. The total energy chain is considered from the energy demand to the energy resources and the analyses are performed using dynamic simulations. The exergy losses of energy system components are identified and quantified and efficiency values in terms of energy and exergy are evaluated. Based on an analysis of the exergy losses further improvements are investigated. This study has shown the exergy concept to be a useful addition to the energy concept, giving a more rational analysis than an analysis solely based on the energy concept. It has also shown that identification and quantification of exergy losses can support the further improvement of energy system configurations, leading to a further reduction of exergy losses and thus a further reduction of high quality energy use.

KEYWORDS: Exergy Analysis, Building Simulation, Exergy design principles, building retrofitting.

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1 Introduction

Developing sustainable energy systems is becoming more and more important in today's world due to the depletion of fossil energy resources and the global warming problems related to the use of these resources. Reducing the need for energy sources is a key factor in the development towards a sustainable energy future [1]. The built environment uses more than 40% of the total final energy consumption in the European Union [2]. A significant share of the energy use in buildings is related to heating and cooling and thus to near-environmental temperatures at around 20 °C. Due to this temperature level, the energy demand for heating and cooling in the built environment is mainly a demand for "low quality" energy. However, this demand is usually met by high quality energy carriers, such as fossil fuels or electricity. The building sector has a high potential for improving the quality match between energy supply and demand and thereby reducing the required input of high quality energy sources.

Exergy is a thermodynamic concept which can be regarded as the quality of a form of energy, by expressing the maximum theoretical work that can ideally be obtained from it in a given reference environment. In ideal energy conversion processes no exergy is lost, but in any real process exergy destruction takes place; exergy is therefore a more rational measure of the performance of an energy conversion process than energy [3]. Originally the concept was primarily applied to chemical processes and thermal plant analysis [4]. An extensive number of studies has been carried out in the last decades in this field, such as [5,6,7].

The exergy approach in the built environment is relatively new but may be considered an emerging field of science. The concept has been used in building efficiency studies with several international research projects, such as IEA ECBCS Annex 37 [8] and Annex 49 [9]. Also several studies on energy systems used in the built environment can be found in the last years, such as [10, 11, 12, 13, 14, 15, 16], to name but a few. Most exergy studies in the built environment are based on steady state calculations. Exergy analysis may also be fruitfully applied to renewable energy-based systems in order to identify the optimal use of the available renewable sources [17].

This paper applies the exergy approach to the assessment and development of (more efficient) energy systems for a social dwelling located in Bilbao, Spain. The exergy approach used in this study consists of two steps of which this paper describes the second one. In the first step promising energy scenarios were developed based on exergy principles and a steady state evaluation has been performed, as described in a previous research article [18]. In the present paper more detailed dynamic calculations have been performed for the two reference cases and the three most promising solutions presented in [18]. In addition the analysis of exergy losses occurring in each energy system component is used to assist the further improvement of the promising solutions, aiming at a further reduction of exergy losses.

2 Methodology

Like many exergy studies applied in buildings, this work also has been carried out using an input – output approach, described in [10] and [19]. The energy chain considered consists of the energy demand of the users of the building (heating, domestic hot water and electricity - cooling is not considered), the energy transformation components for conversion, storage and distribution of energy, and finally the resources. A scheme of the energy chain is shown in Fig. 1.

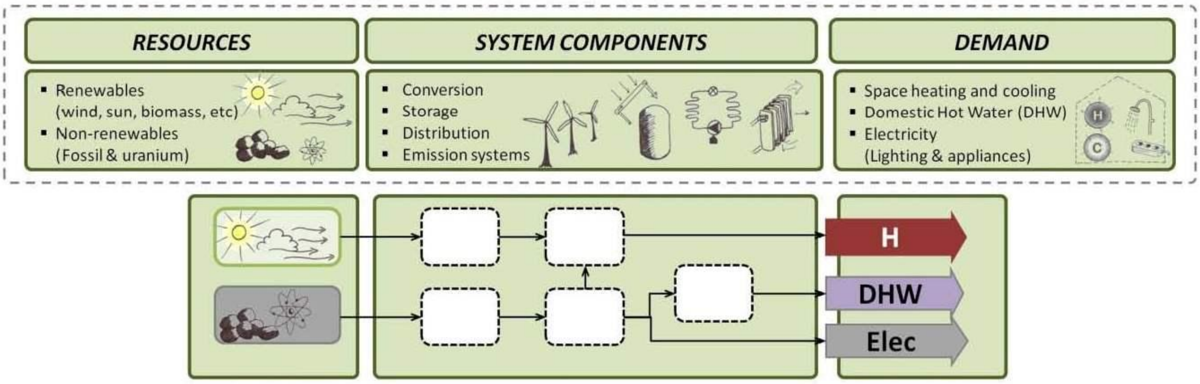

Fig. 1. Scheme of the energy chain

2.1 Dynamic energy simulation

The analysis has been performed using dynamic simulations by means of the well-known transient energy simulation software TRNSYS (V17). The energy demands for space heating are modelled using TRNSYS type 56. The study cases and related systems components, described in section 3, have been modelled and simulated according to the parameters presented in the Appendix. The weather data used for the city of Bilbao are obtained from the Meteonorm database available within TRNSYS.

2.2 Exergy calculation

The exergy values are calculated for each time-step (1-hour) of the simulation, based on the energy values and the relevant temperatures. This means the exergy calculations are in fact semi dynamic. Only sensible heat is taken into account in accordance with [20]. The reference environment is therefore simplified to the reference temperature T_0 only, for which the varying outdoor temperature at each simulation time-step is taken, as recommended in [19].

The exergy of an amount of energy is calculated by multiplying the energy with its related exergy factor (F). For heat at constant temperature T this can be calculated by means of eq. 1; for sensible heat of an amount of matter eq. 2 can be used (see also [10,18,21]).

$$F(Q) = 1 - \frac{T_0}{T}$$	**eq. 1**
$$F(Q_{sens}, T_2 - T_1) = \left(1 - \frac{T_0}{T_2 - T_1} \cdot \ln \frac{T_2}{T_1}\right)$$	**eq. 2**

The Exergy factors of inputs and outputs of the energy system components and of used fuels used are given in the Appendix. For Primary Energy the exergy content equals the energy content, since an exergy factor of 1 is assumed for the primary energy as is further explained in the appendix.

2.3 Electricity Production and calculation of the net primary energy input

In some energy system solutions presented electricity is produced at building level (e.g. by solar PV panels). No electricity storage is considered and therefore in each simulation time step there can be either a need for additional electricity supply from the grid or an overproduction at building level which has to be sent back to the grid. This means on an annual basis the sums of all electricity balances at each time-step results in:

- An annual amount of electricity input delivered by the grid, (E_{del});
- An amount of electricity exported to the grid (E_{exp}).

In order to evaluate the performance of the energy systems components these values are presented separately. However, in order to compare the different case studies the required primary energy input for the same output has to be compared and therefore the “Net Primary Energy Input” (NPE) is calculated using eq.3, according to [22].

$$NPE = \sum\left(E_{del,i} \cdot PEF_{E,del,i}\right) - \sum\left(E_{\exp,i} \cdot PEF_{E,\exp,i}\right)$$	**eq. 3**

where the primary energy factor for delivered electricity ($PEF_{E,del}$) equals the primary energy factor for electricity exported to the grid ($PEF_{E,exp}$).

3 Description of the Case Studies

The dwelling studied is a social sector dwelling located in a multi-family building built in 1960. The net floor area is 52.52 m^2 and the plan is depicted in Fig. 2. The floor to ceiling height is 2.47 m. The dwelling has 3 external façades, oriented East, West and South, two of them (E and W) having windows. More detailed information about the dwelling the operation schedules (e.g. temperature set-points and internal gains) and the assumed energy systems can be found in the Appendix.

Fig. 2. Plan of the dwelling.

For the analysis only one dwelling is considered and the results are also presented on a dwelling level. The total building however consists of 36 dwellings and for the developed energy concepts the possibility of using the roof of the total building for solar energy as well as the use of larger equipment to serve the whole building is taken into account. The five case studies of this dwelling - two reference cases and three improved cases are described in the following sections and illustrated in Fig. 3. Further optimization of the three improved scenarios is described in section 5.

3.1 Case I and II. Reference Cases

There are two reference situations: Case I corresponds to the original situation of the dwelling, which represents the dwelling without any renovations since it was built in 1960. Case II represents the dwelling after standard renovation carried out by *Bilbao Social Housing*, which includes placement of insulation (4 cm of rock wool installation) replacement of the windows (clear double glazing), central heating using high temperature radiators and a natural gas combi-boiler. Air tightness is improved, and fixed ventilation rates are assumed according to the Spanish Technical Building Code [23]

3.2 Case III. New proposals based on exergy guidelines.

In the previous study [18] six improved scenarios were developed and studied by means of steady state exergy analyses. Three of them have been selected for evaluation under dynamic conditions in the present paper. Option 1 has been selected for it has the second best performance, after option 2, while being financially more feasible. Options 5 and 6 have been selected since these do not require the rather drastic revisions of mechanical ventilation and floor heating. The selected options have been renamed and they will be called Case III Option A, Option B and Option C. For all options increased insulation values of external facades and windows are assumed. The characteristics are described in the Appendix.

3.2.1 Case III- Option A

Case III-Option A represents the case with the most drastic improvements: A ventilation Heat Recovery system and a very low temperature floor heating system (35-30°C) are assumed. The space heating demand is met by a heat pump. Solar thermal collectors and PV panels are included (110 m^2 and 250 m^2 respectively for the whole building of 36 dwellings). The remaining heat demand for domestic hot water is produced by a condensing boiler. Option A corresponds to Option 1 in [18].

3.2.2 Case III - Option B

A moderate improvement has been studied in option B assuming a low temperature heating system (40-35°C), which can be realised with radiators. Space heating and domestic hot water demands are met by a collective combined heat and power unit (CHP), which also produces electricity (see also §2.3). No heat recovery unit is assumed and 360 m^2 of PV panels (for the total of 36 dwellings) is considered. This option corresponds to Option 5 in [18].

3.2.3 Case III - Option C

Case III - Option C is similar to option A but with less drastic improvements at building level; no heat recovery system is assumed and instead of very low temperature floor heating a low temperature emission system (40-35 °C) is regarded. Space heating is generated by a heat pump. The system includes solar thermal collectors for domestic hot water and PV panels (110 m^2 and 250 m^2 respectively). The remaining domestic hot water demand is provided by a condensing boiler. This option corresponds to Option 6 in [18].

3.2.4 Overview of the options

The main features of each studied scenario are presented in Table 1; In the Appendix the details of the energy system components of each case are presented. The schemes of the scenarios are presented in Fig. 3.

		U-Value (Façade)	U-Value (Windows)	Use of Exhaust air	Heating system	Electricity
CASE I		1.49	5.68	No	Electric resistance	Grid
CASE II		0.59	2.63	No	Gas Boiler with High Temp	Grid
CASE III	Option A	0.375	2.63	Heat Recovery	HP	Grid
	Option B			No	CHP	Grid + CHP
	OptionC			No	HP	Grid

Table 1. Highlights of the dwelling for each studied scenario.

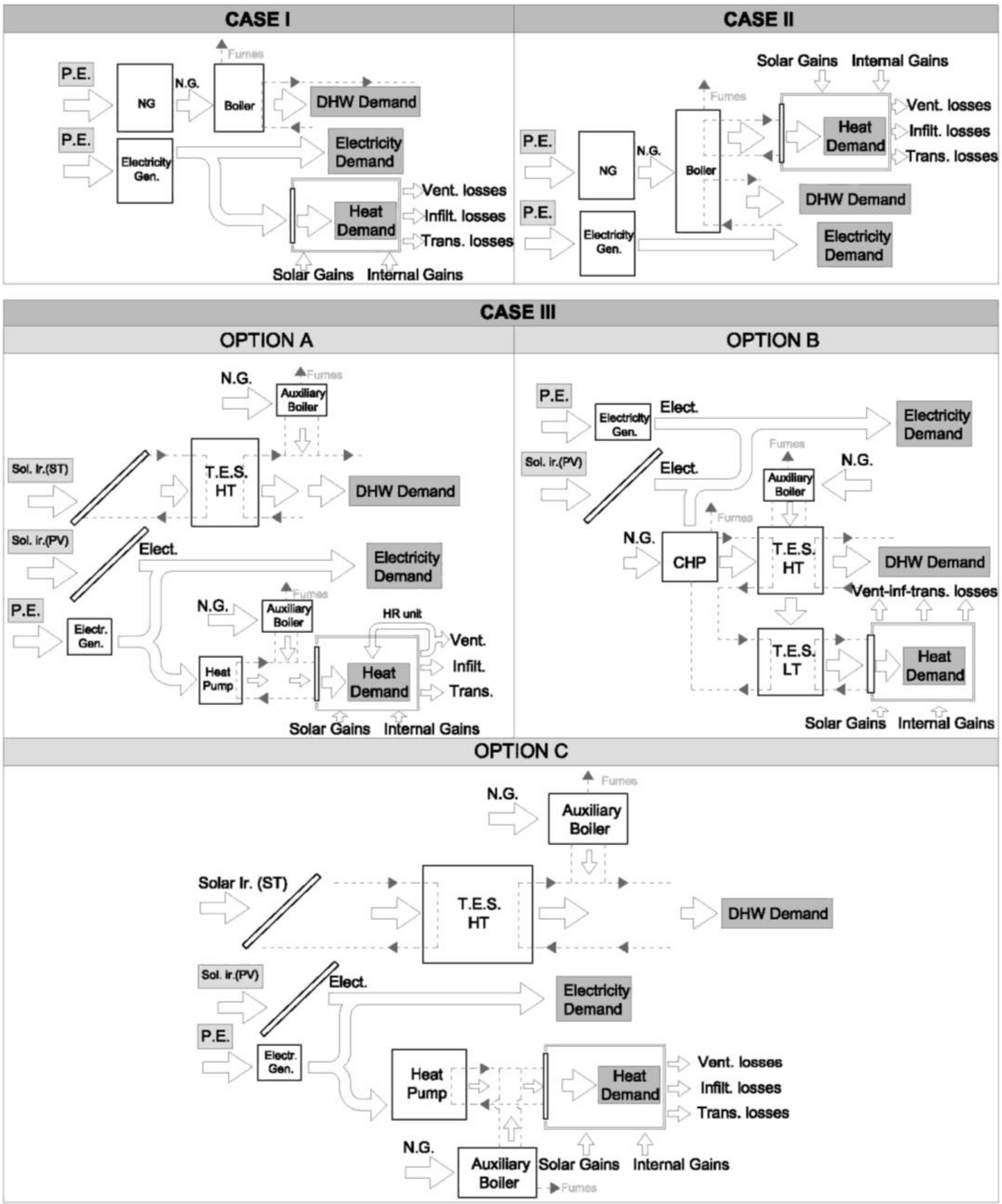

Fig. 3 Detailed schemes of the reference cases (Case I and II) and the improved options selected (Case III, options A, B and C).

4 Dynamic analysis: results and discussion

4.1 General results

In Table 2 the resulting energy demands as well as primary energy input for all cases is presented.

Anual results	CASE I		CASE II		CASE IIIa		CASE IIIb		CASE IIIc	
MJ/year	Energy	Exergy	Energy	Energy	Energy	Exergy	Energy	Exergy	Energy	Exergy
DEMANDS										
Heat Demand	*26166*	*1035*	*16044*	*613*	*7560*	*308*	*14375*	*555*	*14375*	*555*
DHW	*7031*	*524*	*7031*	*524*	*7031*	*524*	*7031*	*524*	*7031*	*524*
Elect. App & Light.	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*	*5466*
Electricity exported	-	-	-	-	*1946*	*1946*	*12269*	*12269*	*1843*	*1843*
P.E. Inputs										
Total P.E. Input)	*78164*		*41634*		*14772*		*48441*		*18826*	
Net P.E. Input (see §2.3)	*78164*		*41634*		*10478*		*21351*		*14760*	
Renewable Energy	-	-	-	-	*8606*	*4275*	*5427*	*5427*	*8606*	*4275*

Table 2. Annual energy and exergy demands and P.E inputs †.

The energy demand of Case I is 26.166 MJ/year and in case II it is reduced to 16.044 MJ/year. The exergy values are 1035 and 613 MJ/year respectively. Case III-Option A results in a demand for space heating of 7560 MJ/year due to the use of ventilation heat recovery, while cases III- Options B and C have a space heating demand of 14375 MJ/year, being a little lower than Case II. The exergy demand of all cases is considerably lower than the energy demand, as is previously explained in [18]. As can be seen all improved options (Cases III) include electricity exported to the grid. The net primary energy input is calculated as explained in 2.3.

The resulting net primary energy input as obtained from dynamic analysis confirm the results obtained in the previous steady state study. As could be expected, Case III-Option A is the best performing case, because it includes ventilation heat recovery and very low temperature (floor) heating emission system. As described in [18] the results are quite sensitive to the actual components characteristics as well as on the primary energy factor for national electricity production. The detailed analysis of the losses can be found in the next paragraph.

4.2 Detailed analysis of exergy losses of system components

The related values for energy and exergy for each component in every case can be found in Table 3 and Table 4. The different calculation assumptions are explained in the Appendix.

† Authors' note: The results presented in this paper are somewhat different than those presented in [18], showing slight differences in three energy demand values. This is caused by the fact that the results in [18]were obtained using a 0.25h-timestep, although it mistakenly stated that a 1 hour timestep was used. These minor differences do not influence any of the conclusions or relevance of either paper.

Of each case the performance of the energy system components is summarized (Table 3 and Table 4), by using the following parameters:

- η - (annual) energy efficiency, defined as: (used energy output) / (total energy input)
- L - (annual) energy losses, defined as: (total energy input) – (used energy output)
- ψ - (annual) exergy efficiency, defined as: (used exergy output) / (total exergy input)
- D - (annual) exergy destruction, defined as: (total exergy input) – (used exergy output)

4.2.1 Detailed results of Case I and Case II.

The results of Case I and Case II are presented in Table 3. In this table energy and exergy efficiency values (η and ψ respectively) as well as energy losses (L) and exergy destruction (D) in each component are presented.

	CASE I				CASE II			
	Output En (*Ex*) [MJ/y]	Input EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Output En (*Ex*) [MJ/y]	Input EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]
Component								
Room Air	*26166 (1035)*	*26166 (8712)*	*- (0.12)*	*- (7677)*	*16044 (613)*	*16044 (2563)*	*- (0.24)*	*- (1950)*
Electric Heater	*26166 (8712)*	*26166 (26.166)*	*1.00 (0.33)*	*0 (17454)*	*N/A*			
H. Temp. Radiator	*N/A*				*16.044 (2563)*	*17826 (2848)*	*0.90 (0.90)*	*1783 (285)*
Boiler	*7031 (524)*	*7813 (7422)*	*0.90 (0.07)*	*782 (6899)*	*24857 (3372)*	*27620 (26239)*	*0.90 (0.13)*	*2763 (22867)*
P.E. Transf. (NG)	*7813 (7422)*	*8360 (8360)*	*0.93 (0.89)*	*547 (938)*	*27620 (26239)*	*29553 (29553)*	*0.93 (0.89)*	*1933 (3314)*
P.E. Transf. (Elec)	*31632 (31632)*	*69804 (69804)*	*0.45 (0.45)*	*38172 (38172)*	*5466 (5466)*	*12081 (12081)*	*0.45 (0.45)*	*6615 (6615)*

Table 3. Annual performance of the energy system components used in cases I and II. (η = energy efficiency; L = energy losses; ψ = exergy efficiency; D = exergy destruction)

For both reference cases the largest energy losses occur in the primary energy conversion for electricity production. From the exergy values however it can be seen that apart from the electricity production large thermodynamic losses are present in the conversion of either electricity (Case I) or gas (Case II) into heat. These heating methods (resistance heating and combustion for heating) are therefore avoided in the improved options. Also, for both reference cases the losses in the component 'room air', showing the mismatch between the temperature of the heat supplied to the room and the temperature of the heat required, are significant: in Case I (where 150 °C on the heater surface is considered) the exergy output of the electrical heater is 8712 MJ/year to cover an exergy heat demand of 1035 MJ/year, which means that almost a 90% of the exergy is lost in the mismatch. Case II shows smaller losses (also due to a lower demand), but there is still a significant mismatch between demand and supply. This is also improved in Cases III by using low temperature heating systems.

4.2.2 Detailed results of Cases III (A, B, C)

As in the previous section, energy and exergy efficiency, energy losses and exergy destruction values are presented in Table 4. This table is based on all the flows depicted in Fig. 3 and calculated by TRNSYS V17.

The results of Case III (Options A,B and C) are also graphically shown in Fig 4, Fig 5 and Fig. 6, where the losses occurring in each system component are presented. Also the relative contribution of each component to the total exergy losses of non-renewable primary energy is shown in the red bars in the upper part of each figure.

	OPTION A				OPTION B				OPTION C			
	Outp En (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Outp EN (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Outp En (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η [–]	L (D) [MJ/y]
Comp.												
Room Air	7560 (308)	7560 (598)	- (0.52)	- (290)	14375 (555)	14375 (1334)	- (0.42)	- (779)	14375 (555)	14375 (1334)	- (0.42)	- (779)
V.L.T. Heating	7560 (598)	8400 (664)	0.90 (0.90)	840 (66)	*N/A*				*N/A*			
L. T. Heating	*N/A*				14375 (1334)	15973 (1482)	0.90 (0.90)	1597 (148)	14375 (1334)	15973 (1482)	0.90 (0.90)	1597 (148)
Heat Pump	8400 (664)	1557 (1557)	5.40 (0.43)	-6843 (893)	*N/A*				15674 (1450)	3335 (3335)	4.70 (0.43)	-12339 (1885)
TES (LT)	*N/A*				15973 (1482)	17747 (2265)	0.90 (0.65)	1775 (783)	*N/A*			
TES (HT)	4158 (225)	4569 (435)	0.91 (0.52)	411 (210)	24778 (2789)	27532 (4801)	0.90 (0.58)	2754 (2012)	4158 (225)	4569 (435)	0.91 (0.52)	411 (210)
CHP	*N/A*				34729 (14837)	38164 (36256)	0.91 (0.41)	3435 (21419)				
Aux.Boiler (DHW)	2873 (299)	3193 (3033)	0.90 (0.10)	319 (2734)	3489 (650)	3876 (3682)	0.90 (0.18)	388 (3032)	2873 (299)	3193 (3033)	0.90 (0.10)	319 (2734)
Aux. Boiler (Heat)	*N/A*				*N/A*				298 (32)	332 (314)	0.90 (0.10)	34 (282)
P.E. Transf. (NG)	3193 (3033)	3418 (3418)	0.93 (0.89)	225 (385)	42040 (39938)	44983 (44983)	0.93 (0.89)	2943 (5045)	3525 (3347)	3771 (3771)	0.93 (0.89)	246 (424)
P.E. Transf. (Elect from the Grid)	5137 (5137)	11354 (11354)	0.45 (0.45)	6217 (6217)	1565 (1565)	3458 (3458)	0.45 (0.45)	1893 (1893)	6812 (6812)	15055 (15055)	0.45 (0.45)	8243 (8243)

Table 4. Annual performance of the energy system components used in case III, options A, B and C. (η = energy efficiency; L = energy losses; ψ = exergy efficiency; D = exergy destruction)

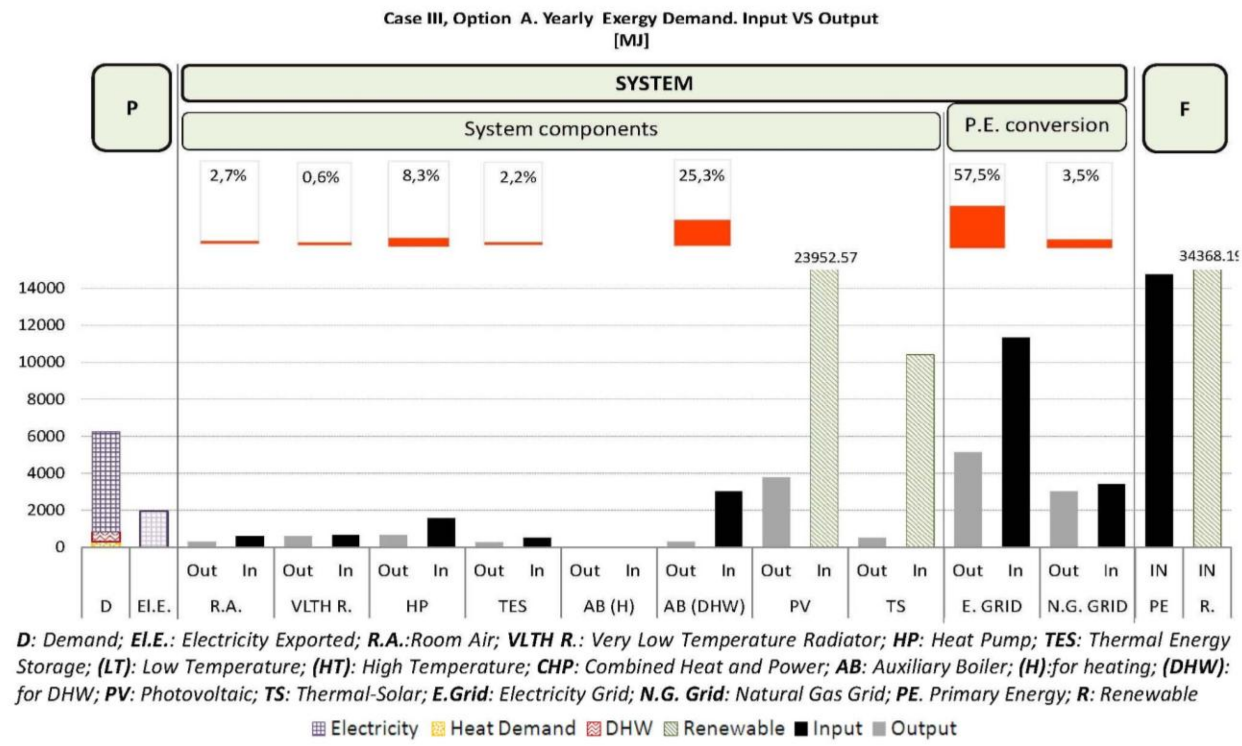

Fig. 4. Detailed analysis of the input and output in each component of the system. (Case III-Option A)

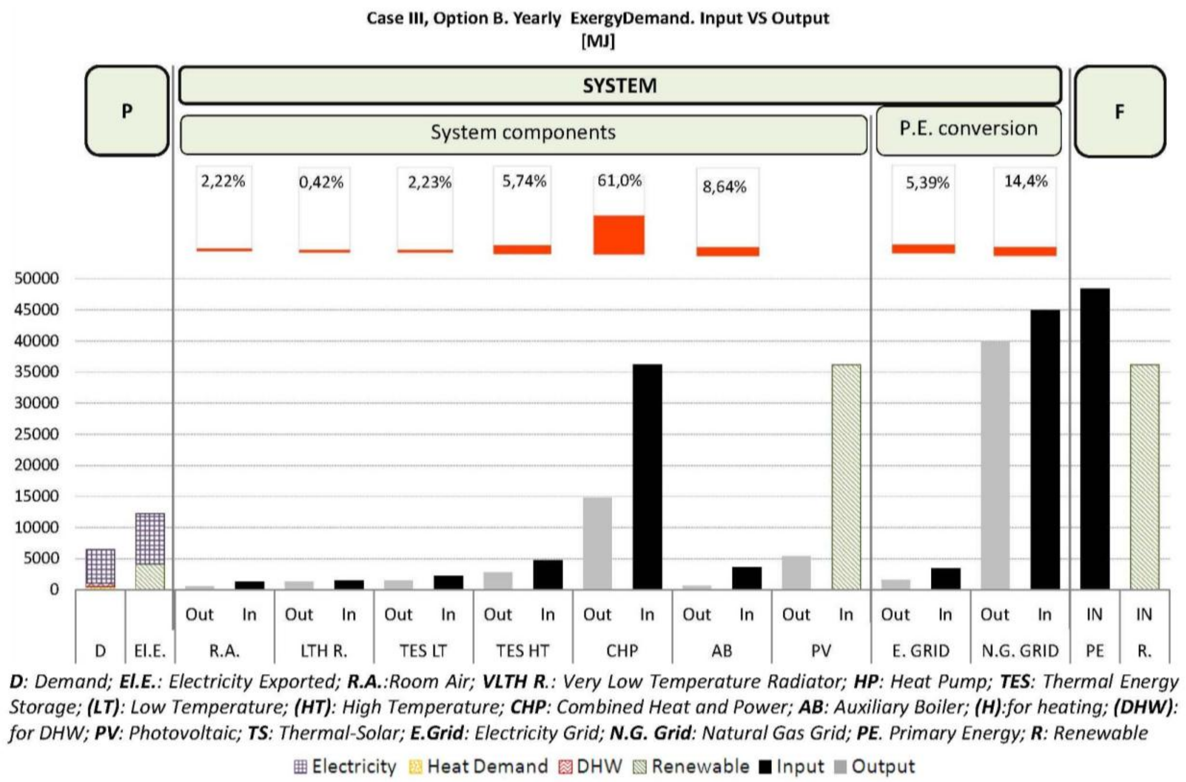

Fig. 5. Detailed analysis of the input and output in each component of the system. (Case III-Option B)

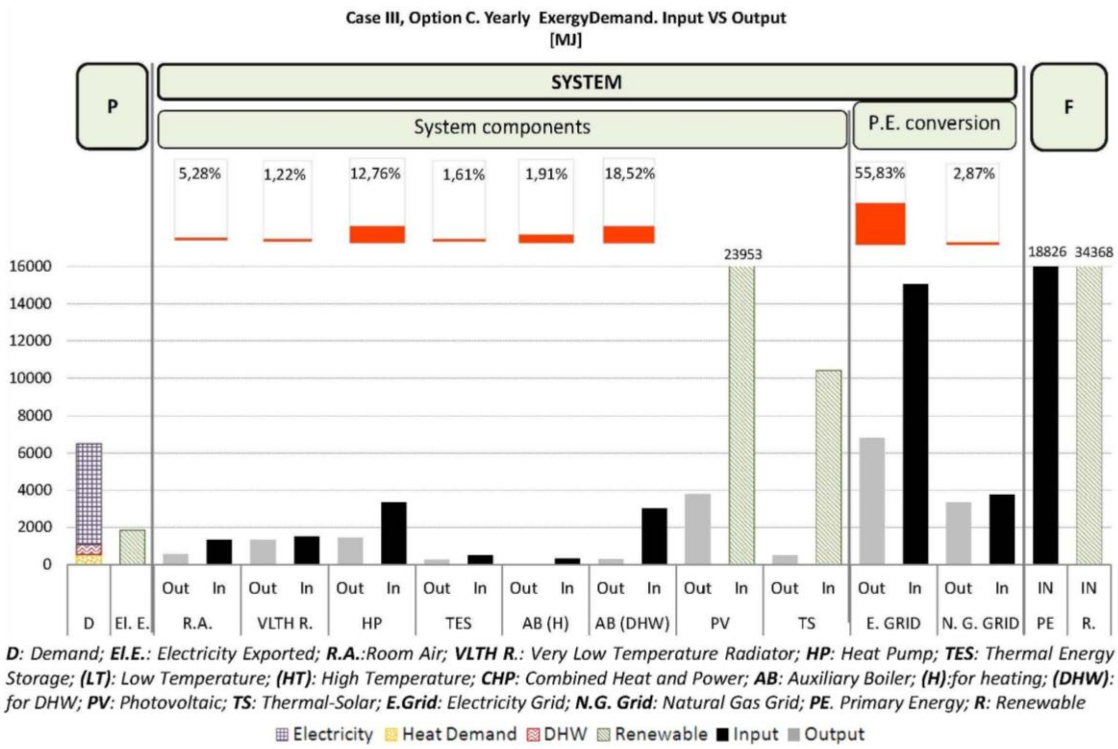

Fig. 6. Detailed analysis of the input and output in each component of the system. (Case III-Option C)

4.2.3 Discussion

The reduced demands of case III are discussed in the previous paragraph. Related to the exergy losses of system components also many improvements can be identified: Due to the low temperature heating system the losses in the 'room air' component are reduced compared to Cases I and II: the output of the low temperature floor heating is 598 MJ/year (Table 4) to cover the exergy demand for heating of 302 MJ/year, which means an exergy loss of about 50% in the mismatch, quite less than the case I and II.

The negative energy losses of the heat pump presented in Table 4 are the result of not considering the free energy taken from the environment. In exergy terms the energy of the environment is by definition 0 exergy, thus the exergy losses of the heat pump represent the true exergy losses. The heat pump appears on the energy analysis to be the best performing component; however, in the exergy analysis it can be seen that there are still thermodynamic losses and the related ideal improvement potential can be identified.

From Fig. 4-6 it becomes clear that for Case III options A and C, (using a heat pump) the largest energy losses take place in the primary energy conversion for electricity i.e. the national electricity grid. The other losses are in energy terms all rather insignificant. In exergy terms however the losses of the auxiliary boiler are also important, which is even more striking when considering the small contribution of the auxiliary boiler to meet the total demand (see Fig. 4-6 and Table 4). Also the heat pump has significant losses according to the exergy principle.

In Case III Option B the biggest losses take place in the CHP, which also supplies most of the demand. It has to be taken into account that these losses from table 5 relate to the losses related to the total output including the large amount of electricity exported (see 3.3.3). Other relevant losses include the primary energy transformation and the thermal energy storage components.

5 Further improvements

The losses discussed in the previous section represent the thermodynamic ideal improvement potential of the system under consideration and point out the directions for improvement. In section 5.1 recommendations to further improve case III Options A, B and C are given. In section 5.2 some recommendations for Case III Option A have been tested using dynamic analyses. Case III Option A has been chosen since it represents the most ambitious energy concept and further improving it will show the highest potential of the exergy approach.

In practice the optimization of energy concepts usually has multiple criteria, such as costs or environmental impact. Some optimization strategies based on the exergy approach can be found in literature [24, 25, 26] but this is not further treated in this paper. The improvements sought in this research article relate to thermodynamic improvements, i.e. the reduction of exergy losses leading to a reduction of the input of (non-renewable) resources.

5.1 Recommendations based on analysis of exergy losses

From the identified exergy losses the directions for further improvements can be found. For the heat pump cases (Case III, options A and C) a main objective could be to minimize the use of the auxiliary boiler, for example by preheating the DHW using the heat pump. Furthermore the primary energy conversion losses are very large. It can be investigated whether increasing the ratio of PV on the roof will improve the total performance, although a negative consequence due to increased use of the auxiliary boiler should be avoided.

For option B a CHP with a higher electrical efficiency will increase the exergy efficiency of the CHP and thereby of the total system. The overproduction of electricity will however only make sense when a nearby electricity demand can be met.

For both options increasing the input of renewables (for example electricity from a nearby wind mill or biomass for the CHP) will decrease the primary energy input.

The exergy losses of renewable resources are also quite substantial. This is due to the fact that solar radiation is also high exergy and in case of the solar thermal collectors the output is low exergy heat. However, its exploitation with low exergy efficiencies has not the same relevance as in the case of fossil fuels. Solar energy is abundant and its destruction takes place anyway, regardless of human caption. The main problem with renewable sources is their availability. For this reason, more exergy studies in detail about storage systems and their repercussion on the global performance of the system could be interesting in further investigations.

Greater improvements can be achieved when the system boundaries of the improvements are shifted from the building level to the community level, since this increases the potential of for example using waste heat or applying the principle of cascading [19, 27].

5.2 Further improving Case A

According to the aforementioned recommendations, further improvements of Case A have been simulated. Three improved configurations have been evaluated.

5.2.1 Improvement 1. Increasing the PV area

As previously stated, the highest losses in option A take place in the production of Electricity from the Grid. For that reason, reducing the electricity need from the grid will be a good strategy to reduce P.E. input. For this aim, increasing the ratio of PV area on the roof in order to improve the total performance has been considered as potential improvement. However, this strategy can have a negative impact due to the reduction of supply from solar thermal panels (ST), which implies the increased use of the auxiliary boiler for DHW. Therefore a sensitivity check of the influence of the ratio PV-ST on the global performance has been performed.

Simulations with different PV to Solar thermal area (ST) ratios area have been carried out in this sensitivity check. ST collectors are assumed in the east side of the roof, as explained in [18]. The results are depicted in Fig. 7.

In this figure, X-axis shows % of available roof area with Solar thermal / PV. Assumed available roof area is 360 m^2, which equals 80% of the total roof surface of the building. The P.E (black line) depicts total Primary Energy input into the system, both regarding to NG and Electricity. The Net P.E. Input (green line) is calculated as described in section 2.3. The purple line is the electricity produced (Elect. Prod.) by the system (by PV), both used onsite and exported. The grey dashed line represents the annual electricity exported to the grid (electricity which is not demanded by the system at the moment that it is produced).

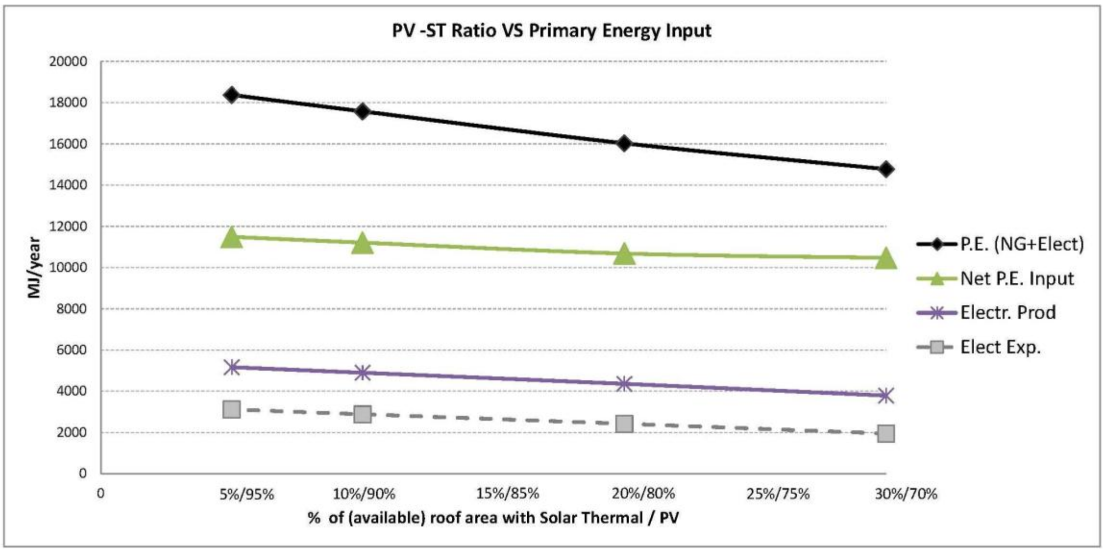

Fig. 7. ST-PV Ratio Vs Primary Energy input

As shown in Fig. 7, the smaller the area covered with solar thermal (or what is the same, the greater the area with PV), the higher the electricity produced as well as exported (grey line), as could be expected. However, a smaller area with solar thermal collectors also implies a higher total Primary Energy input from the grid (Black line) as well as a higher net primary energy input (green line), due to higher use of the Auxiliary Boiler.

According to this sensitivity evaluation, it can be confirmed that reducing ratio of solar thermal collectors in favour of more PV area in this option A does not involve improvements in the reduction of the net P. E. input.

5.2.2 Improvement 2. Using the Heat Pump to preheat DHW

Another possibility to improve the exergy performance of the option A is to minimize the use of the auxiliary boiler. For this aim, the use of the heat pump for preheating the DHW supply has been studied, assuming the heat pump to preheat the water before entering the thermal energy storage system (TES), as is shown in Fig. 8. This configuration is chosen in order for the heat pump to function as much as possible at the lowest temperatures (between the delivery temperature of the water and 30-35 degrees), where it performs best (i.e. reaches higher COP's). Occasionally in summer this has the effect that the water is preheated by the HP while the solar energy would have sufficed, but this rarely occurs, also since the temperature of supply of the water in summer is already quite high and the HP is used little as a consequence.

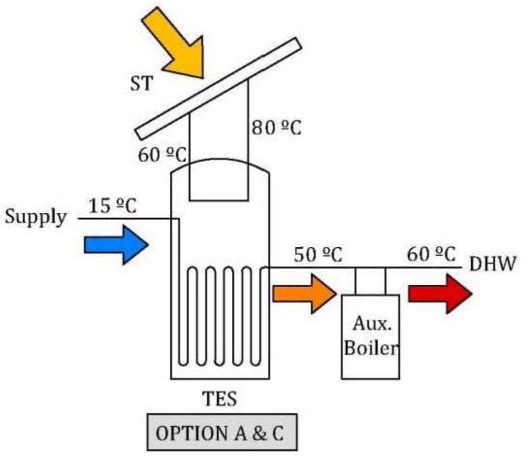

Fig. 8. Scheme of the 2nd improvement. The left picture depicts the system in option A and C, and right picture depicts the improvement.

Fig. 9 shows the HP input during a year. The grey line represents the HP input in the scenario of Case III-Option A, and the black one depicts the HP input in this scenario with improvement 2. The results show that in this way the heat pump can be used more often as it is used for preheating the DHW before entering the storage (TES). Consequently, the use of the auxiliary boiler is reduced, and the exergy input of natural gas from the grid decreases with about 65% in energy terms, from 3193 MJ/year to 1097 MJ/year. (in exergy terms, from 3033 MJ/year to 1042 MJ/year). The exergy output of the auxiliary boiler for DHW also decreases significantly, with about 59% (from 299 MJ/year to 124 MJ/year). The exergy efficiency of the Auxiliary Boiler is also improved (from 0.10 to 0.12) since the ΔT is reduced (inlet-outlet)

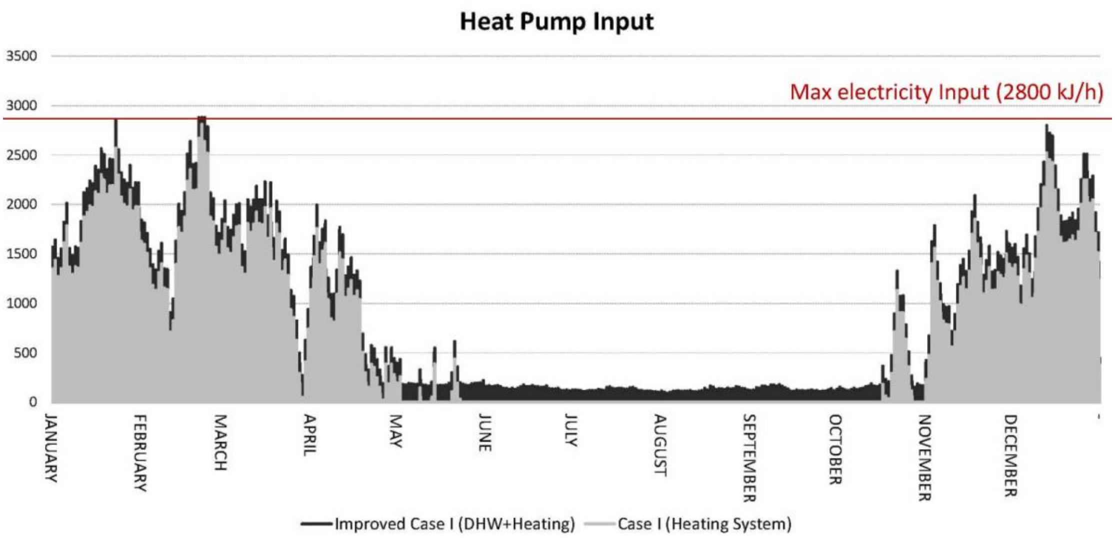

Fig. 9. Heat Pump input (Case I, in grey, Improved Case I, in Black)

This significantly reduced use of the auxiliary boiler results in a reduction of the net P.E. input of more than 10%, from 10470MJ/year to 9361 MJ/year, as shown in Table 5. A detailed scheme of the improved system demand, component exergy losses and primary energy input is shown in Fig. 10.

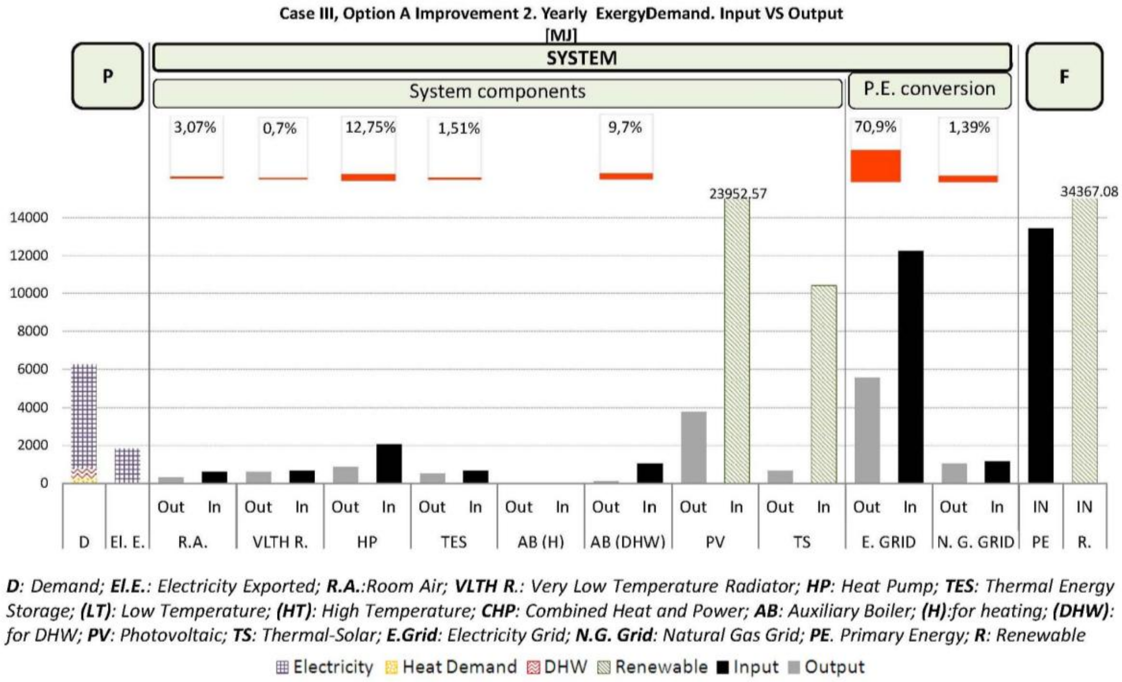

Fig. 10. Detailed analysis of the input and output in each component of the improved system.

5.2.3 Combination of improvement 1 and 2

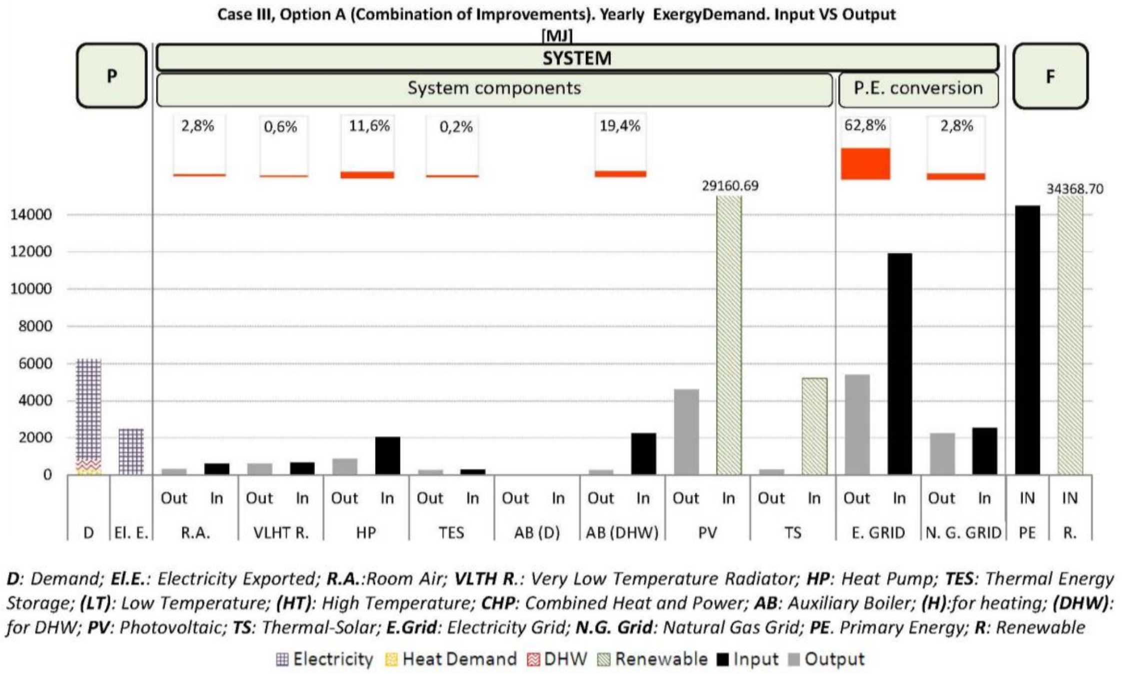

Fig. 11. Detailed analysis of the input and output in each component of the system with the combination of improvements.

As a third option a combination of two improvements is evaluated, including an increased PV area on the roof as well as preheating the DHW by means of a heat pump, in order to reduce the use of the auxiliary boiler. The results from dynamic analysis show that this option could be considered the best of the evaluated ones according to its net primary energy input (8927 MJ/year), representing a reduction of required primary energy input of almost 15 % compared to the original Case III-option A. Obviously, the results of this option are very sensitive to the applied primary energy factor (PEF) as was studied previously in [18].

5.2.4 Overview of the tested improvements

The results of all improved options are presented in Table 5. Concluding it can be stated that the insight from the exergy losses has in this case contributed to the further reduction of required net primary energy input. The influences of envisioned improvements however have to be tested using dynamic analysis in order to tackle possible negative side effects, as is the case with improvement 1.

CASE	P.E. Input [MJ/year]	Elec. Exported [MJ/year]	Net P.E. [MJ/year]
Case III-A	14771	1946	**10470**
Case III-A Improvement1 (PV 85%-TS 15%)	16744	2636	**10918**
Case III-A Improvement2 (preheating by HP)	13421	1837	**9361**
Case III-A. Improvement 3 (Combination)	14472	2509	**8927**

Table 5. Values of the Case A without improvements, with Improvement 2 (HP for DHW) and with the combination of 2 improvements (Net P.E. calculated according to procedure described in section 2.3)

6 Conclusions

Five different energy scenarios for a social dwelling in a multi-family building in Bilbao from the 1960's have been analysed, using the exergy approach under dynamic conditions. Two reference cases (the original situation and the situation after standard renovation works) and three improved cases based on previous studies have been analysed. Possible further reduction of the required primary energy input of the improved options has been investigated using a detailed analysis of the exergy losses.

Significant differences between energy and exergy performance of the systems and components are shown in this paper. As has been shown in other studies, the exergy approach complements and gives a more rational analysis than an analysis solely based on the energy approach. For all cases evaluated in this study several exergy losses have been revealed that cannot be identified using energy analyses. These losses represent the ideal thermodynamic improvement potential and indicate a direction for further improvement of the system.

The most important exergy losses revealed in this study which are not revealed using energy analysis are: exergy losses of heating systems using combustion or resistance heating (Annual energy losses in the electric heater system are negligible, but annual exergy losses are 17455 MJ/Year of the total losses of 71140 MJ/year, including losses in the P.E. transformation), exergy losses between the energy demand and the energy supplied by the emission system where the exergetic efficiency varies from 0.12 (using an electric heater) to 0.52 (using very low temperature floor heating); exergy losses of the combined heat and power (CHP) unit (21419 MJ/year of the total of 35111 MJ/year, including losses in the P.E. transformation), which are much bigger than its energy losses (3435 MJ/year), and the exergy losses in a heat pump (893 MJ/year and 1885 MJ/year, in Case III option A and C respectively), which are nonexistent in an energy approach. The quantification of the exergy losses as has been performed in this study directly shows which components are most responsible for the losses and thus are most responsible for the required input of resources.

The analysis of the exergy losses has been used to develop further improvement of one exemplary case (Case III-Option A). The study has shown that this analysis of exergy losses can support the development of improved systems with reduced exergy losses and thus reduced high quality energy input. For the exemplary case studied in this paper the improved configuration has further reduced net primary energy input by almost 15 %. It is however noted that these results are very sensitive to the primary energy factors of the electricity production and it is therefore recommended to further investigate the calculation of the exergy of primary energy and to the implication of using national primary energy factors (PEF's).

According to this study the exergy approach has shown to be useful to improve energy system configurations, by quantifying the exergy losses at each energy system component. It is recommended to further investigate how exergy analysis can contribute to the improvement of energy systems for the built environment, also taking other requirements into account.

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Appendix A. Building characteristics.

In this appendix the building characteristics of the case study and the operational aspects relevant to its energy performance are presented. The data are based on reference values given by TRNSYS, CTE (Spanish Technical Building Code) and The Institute for Energy Diversification and Saving [28]

A.1 Construction data

The heat demand of the social housing unit has been calculated by means of TRNSYS simulation, with TYPE 56. A dwelling on the 4th floor of a multifamily building of 6 floors has been chosen, so the ceiling and floor of the study case have been considered adiabatic in the TRNSYS simulation. The physical properties of the building envelope components are presented in Table A. 1.

No	Function (*1)	Or.	Area [m2]	CASE 1		CASE 2		CASE 3	
				U-Value [W/m^{2}K]	g-Value	U-Value [W/m^{2}K]	g-Value	U-Value [W/m^{2}K]	g-Value
1-3	Façade	W,S,E	56.9	1.49	-	0.59	-	0.375	-
4-5	Internal partition	N	17.68	2.39	-	0.70	-	0.70	-
6-7	Ceiling and floor	Hor.	3.97	2.23	-	2.23	-	2.23	-
W	Windows (*1)	E, W.	10.55	5.68	0.855	2.83	0.755	2.83	0.755

(* 1) Values for Solar Absorbance, Convective heat Transfer coefficient and F_{sky} are according to the standard values provided by TRNSYS.

(*2) For windows only the U value of the glass is presented. The frame covers 15% of the total window surface and has a U-value of 2,15 W/m²K in all cases.

Table A. 1. Physical properties of the building envelope components

A.2 Dwelling operation

A.3.1 Overview

	Infiltration [(m^3/h)/m^3]		Ventilation [(m^3/h)/m^3]		Internal Gains [kJ/h]			Heating Operation [ºC]	Demands [w/m^2]	Demands [l/h]
	CI	**CII&III**	**CI**	**CII&III**	**Occup.**	**Lighting**	**Appl.**	**Set-Point Temp.**	**Elect Demand**	**DHW Demand**
00.00-06.00h	1.3	0.24	0	1.72	12,64	1,58	1,58	17	0.88	0
06.00-07.00h	1.3	0.24	0	1.72	12,64	1,58	1,58	17	0.88	11
07.00-08.00h	1.3	0.24	4	1.72	3,17	4,75	4,75	20	2.64	11
08.00-09.00h	1.3	0.24	0	1.72	3,17	4,75	4,75	20	2.64	11
09.00-15.00h	1.3	0.24	0	1.72	3,17	4,75	4,75	20	2.64	4
15.00-18.00h	1.3	0.24	0	1.72	6,34	4,75	4,75	20	2.64	4
18.00-19.00h	1.3	0.24	0	1.72	6,34	7.92	7.92	20	4.4	4
19.00-21.00h	1.3	0.24	0	1.72	6,34	15,84	15,84	20	8.8	8
21.00-23.00h	1.3	0.24	0	1.72	6,34	15,84	15,84	20	8.8	4
23.00-00.00h	1.3	0.24	0	1.72	12,64	7.92	7.92	17	4.4	4

Table A. 2. Schedules and operation values assumed in TRNSYS model

Table A.2 summarizes the different schedules for all relevant dwelling operation aspects. It is noted that in the original situation there is a large infiltration rate but no controlled ventilation system is present; for this case it is assumed that the windows are one hour per day for fresh air (see ventilation column).

A.3.2.2 Set point Temperatures. Operative Temperature.

The TRNSYS software is programmed in such a way that the ideal heating demand calculation in principle reacts to the *air temperature* of a thermal zone, while for a more correct evaluation of comfort the *operative zone temperature* (T_{op}) should be controlled. This control is in TRNSYS obtained using eq. A. 1 and eq. A. 2, where T_{mean_surf} is the average surface temperature of all surrounding (wall and window) surfaces in the zone. T_{mean_surf} is result of the TRNSYS simulation. (The set-point temperature is for this reason modelled as an input from the TRNSYS studio instead of a direct value in the TRNBUILD program).

$$T_{op} = \frac{T_{air} + T_{mean\_surface}}{2}$$	**eq. A. 1**
$$T_{air,sp} = \left(T_{op,sp} - 0.5 \cdot T_{mean\_surf}\right) \cdot 2$$	**eq. A. 2**

A.3.2.4 Domestic Heating Water Demand (DHW)

A daily demand of 101 litres of warm water is assumed, according to the schedule shown in Table A. 3, with a desired (output) temperature of 60 ºC. The water supply temperature is calculated using eq. A. 3, with an annual average supply temperature assumed at 15,4 ºC. The heat losses through the piping system are neglected.

• If $T_{out} < -5^{o}C \rightarrow T_{sup\_DHW} = 1.8$ • If $T_{out} \geq -5^{o}C \rightarrow T_{sup\_DHW} = \left(2 \cdot T_{out} + 15.4\right)/3$	**eq. A. 3**

A.4 Energy system components

In table A.3 the assumed properties of the energy systems components are presented: Energy Efficiency η (if it is a fixed value), Inlet Exergy Factor, Outlet exergy Factor, and temperatures used for calculating the exergy factor when applicable. Equation 1 and 2 used for the calculation of the exergy factor are explained in section 2 of this paper.

Component	η	INPUT			OUTPUT		
		T_{inl}	T_{ret}	F	T_{inl}	T_{ret}	F
Demands							
Space heating	N/A	Ti		1	N/A		
DHW	N/A	60 ºC	eq. A. 3.	eq. 2			
Electricity	N/A	N/A		1			
Emission systems							
Elect. heater	1	N/A		1(Electricity)	150 ºC		eq. 1
H.T. Rad.	0.9	70 ºC	55º C	eq. 2	70 ºC	55º C	eq. 2
L.T. Rad.	0.9	40 ºC	35 ºC	eq. 2	40 ºC	35 ºC	eq. 2
V.L.T. floor	0.9	35 ºC	30 ºC	eq. 2	35 ºC	30 ºC	eq. 2
Conversion components							
Boiler	0.9	N/A		0.95 (NG)	DHW or emission system		eq. 2
Heat Pump	(*1)	N/A		1(Electricity)	35 ºC	30 ºC	eq. 2
CHP (elec/thermal)	0.28/ 0.63	N/A		0.95 (NG)	80 ºC	60 ºC	1(Electricity) / eq. 2
Solar Thermal	0.44	N/A		0.95 (Sol)	80 ºC	Type 4	eq. 2
PV	0.15	N/A		0.95 (Sol)	N/A		1(Electricity)
Storage							
H.T. TES	0.9	80 ºC	60 ºC	eq. 2	(DHW)		
M.T. TES	0.9	60 ºC	40º C	eq. 2	40 ºC	35 ºC	eq. 2
Primary energy conversion (P.E.C.) of grid electricity and grid gas.							
P.E.C. elec	0.45(*2)	Primary energy, F is assumed 1 (*3)			1(Electricity)		
P.E.C. gas	0.93 (*2)				0.95 (NG)		

(*1) The COP of the heat pump is calculated assuming a performance of 50% of the Carnot COP [8].
(*2) These values are the inverse of the following primary energy factors taken from [9]: PEF_{Elect}= 2.21 and PEF_{NG}=1.07, for electricity and gas respectively.
(*3) the exergy content of the primary energy is in fact dependent on the mix of resources used to obtain the energy output. But this calculation is out of the scope of this research.

Table A.3: Properties of the energy system component for each case

A.5 Assumptions and calculations

The calculations are based on the input-output approach. The simulation of several components has been developed in a simplified way, based in their energy efficiency in each time steep of the simulation. However, in some specific components dynamic assumptions have been considered, as it is described below.

7.1.1 Heat Recovery. (Type 91)

An Efficiency of 60% is assumed in the Heat Recovery Unit. According to ventilation criteria shown in [18] ventilation air temperature is ruled by eq. A 4:

- If $T_{in} < 23^{o}C \rightarrow T_{vent} = T_{HR}$
- If $T_{in} \geq 23^{o}C \rightarrow T_{vent} = T_{out}$

eq. A 4

7.1.2 Heat Pump

For simulating the Heat Pump performance, Type 42 of the standard TRNSYS component library has been used. The COP is calculated assuming a performance of 50% of the Carnot COP [29]. The thermodynamic equivalent temperatures of T_H (load side) and T_L (source side) are used for the calculation of COP_{Carnot}, assuming a load temperature according to the required input of the emission system (in case of floor heating 35-30 degrees and in case of low temperature radiators 40-35 degrees) and a source temperature of the outdoor temperature with 5 degrees temperature drop as a result of the heat intake by the heat pump. A maximum electricity input in the Heat Pump of 0.8 kW is assumed and an auxiliary boiler is assumed to cover the remaining demand if present.

7.1.3 Thermal Energy Storage (TES)

For simulating the TES tank in principle a simplified approach is taken. In this simplified approach in fact no storage effect is taken into account; the losses caused by the storage are simply included in a steady state manner. This simplified approach means the component delivering the thermal energy to the storage device is thus supposed to deliver the energy at the time step it is demanded by the system taking energy from the storage tank (i.e. the emission system for space heating or DWH demand profile). This simplification is considered acceptable since the aim is to the study the energy and exergy losses and not the optimization of the storage strategy.

For the analysis of option A and C however, where solar thermal energy is used to deliver the DHW demand the storage has to be taken into account more dynamically since the profiles of supply (the solar radiation) and demand (DHW profile) do not match. For these cases TRNSYS type 4a has been used, with the following assumptions:

- The tank volume is considered is 0.23 m^3 (230 litres)

  It is calculated according to $Q_{stored}=V \cdot \rho \cdot c_p \cdot \Delta T$, where Q_{stored}= the daily heat demand for DHW (Q_{DHW}= 7,031 MJ/year = 19263 kJ/day), ΔT is based on a supply inlet temperature from the solar collectors of 80 °C and a return temperature of 60 °C.

  N.B. In reality probably a larger tank will be used to provide DHW for the whole building. This means transmission losses will be less but some distribution losses will increase.
- The Tank Loss Coefficient is considered 0.35 W/m^2K, considering 10 cm insulation material (λ=0.035 W/mK)
- The demand side flowrate is resulting from the DHW demand profile described in Table A.2.
- The load (or supply side) flowrate is equal to the flowrate assumed for the solar collector (see also Fig 10 for this configuration). It is calculated using eq. A 5, where Q_{coll} = the thermal heat available from the collector,

$T_{out,coll}$ is the desired output temperature of the collector of 80 °C and $T_{return,TES}$, is the temperature of the load side return flow from the TES, resulting from type 4a. Practical limitations to maximum and minimum flowrate are neglected.

$$\dot{m} = \frac{Q_{coll}}{(T_{out,coll} - T_{return,TES}) \cdot c_p} \qquad \textbf{eq. A 5}$$

7.1.4 CHP

CHP supplies a maximum thermal power of 3 kW per dwelling (108kW unit) When the TES of High Temperature (TESHT input) demand is higher than that value, the rest of the demand is supply by an auxiliary Boiler. Moreover, it is assumed that the CHP is running in function to the demand (In a real case it could be running for a continued period and storage the energy in the TES)

According to these assumptions, the equations which rule the working of CHP in the model are defined in eq. A 6, eq. A 7 and eq. A 8.:

$Q_{CHP,output}$

$$\begin{aligned} &\text{If } \mathrm{Q}_{\mathrm{TESHT,inp}} < 10800kJ \rightarrow Q_{CHP,outp} = Q_{TESHT,inp} \\ &\text{If } \mathrm{Q}_{\mathrm{TESHT,inp}} \geq 10800kJ \rightarrow Q_{CHP,outp} = 10800kJ \end{aligned} \qquad \textbf{eq. A 6}$$

$$\mathrm{Q}_{\mathrm{CHP,inp}} = \mathrm{Q}_{\mathrm{CHP,outp}} / \eta_{CHP,Q} \qquad \textbf{eq. A 7}$$

$$\mathrm{E}_{\mathrm{CHP,outp}} = \mathrm{Q}_{\mathrm{CHP,inp}} / \eta_{CHP,E} \qquad \textbf{eq. A 8}$$

Where the electric η of the CHP is assumed as a constant value of 0.28 and the thermal η of the CHP is assumed as a constant value of 0.63.

7.1.5 Transformation to Primary Energy

The Total Primary energy is obtained from the sum of the different primary energy supplied to Auxiliary Boiler and CHP (By means of Natural Gas) and electricity supply. The conversion factors assumed has been taken from [30]. These factors are F_{NG}=1.07 and F_{Elect}= 2.21.

P. Ex. of electricity could be calculated more in detail based on the electricity mix, by calculating the exergy value of each source (Nuclear, wind, solar…) and weighting them according to the electricity mix of the country. In this paper, however, a simplification has been done, assuming that Primary energy equals Primary Exergy.

8 Nomenclature

A	[m^2]	Area	PE		Primary Energy
c_p	[J kg^{-1} K^{-1}]	Isobaric heat capacity	PEF	[-]	Primary Energy Factor
D	[MJ/y]	Annual exergy destruction	Q	[MJ/y]	Heat and sensible heat
E	[MJ/y]	Electricity	T	[ºC]	Air Temperature
F	[-]	Exergy Factor	U	[W m^{-2} K^{-1}]	Heat transfer coefficient
L	[MJ_{ex}/y]	Annual exergy losses	V	[m^3]	Volume
m	[kg]	Mass	x	[MJ_{ex}/y]	Exergy
$\dot{m}$	[kg/s]	Mass flow rate			

Greek symbols

Ψ	[-]	Exergy Efficiency
η	[-]	Energy Efficiency

Subscripts

CHP	Related to co-generation system	*out*	Outdoor
DHW	Related to Domestic hot water	*outl*	Outlet
del	Delivered	*outp*	Output
dem	Demand	*ret*	return
E	Related to electricity	*sp*	Set-point (Temperature)
exp	Exported	*sol*	Solar gains
H	Related to heating system	*ST*	Related to Solar Thermal.
HR	Related to Heat Recovery	*sup*	Supply
i	Stream	*TES*	Related to Thermal Energy Storage system
in	Indoor	*TESHT*	Related to Thermal Energy Storage system (High Temp.)
inl	Inlet	*TESLT*	Related to Thermal Energy Storage system (Low Temp.)
inf	Infiltrations	*trans*	Transmission
Inp	Input	*vent*	Ventilation
int	Internal gains	*X*	Related to exergy
op	Operative (Temperature)	*0*	Reference

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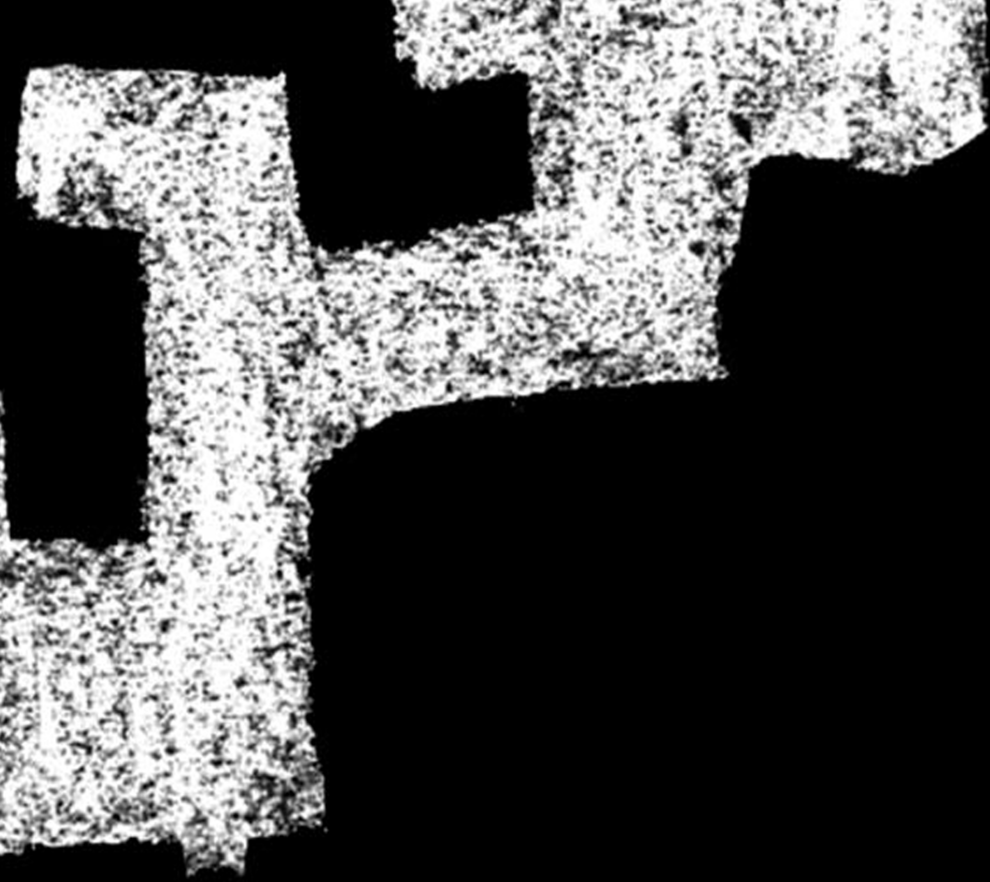

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Energy in Buildings

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