PhD Thesis

Birgaitze energetikoak gizarte etxebizitzan
Portaera termikoaren analisia

Energy retrofits in social housing
Analysis of its thermal behaviour

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Zuzendariak
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The University of the Basque Country
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Laburpena

Doktorego – Tesi hau eraikinen birgaikuntza energetikoaren ebaluazioan datza, prozedura honek barne hartzen dituen atal ezberdinak, datu – eskuratzea eta monitorizazioa, datuen tratamendua (eraikinen ereduak erabiliz) eta lortutako emaitzen analisiak esaterako.

Tesi honen interesa gaur egungo egoera energetikotik sortu zen. Gaur egun, eraikinetan erabiltzen den energia kontsumoa Europar Batasuneko energia kontsumo osoko %40 baino gehiago da. Gainera, kontsumo hau azken urteetan zergati ezberdinen ondorioz goratu da, biztanleriaren etengabeko ugalketa edo barne erosotasunari lotutako estandar altuagoen eskaria esaterako. Beraz, energia iturrien beharra murriztea funtsezko faktore bat da. Horregatik, eraikinen eraginkortasun energetikoa Europar Batasunaren lehentasunezko helburu bat bihurtu da, eta ingurune eta energia egoera honek eraikinen portaera energetikoaren hobekuntzaren beharra ekarri du. Europar Batasuneko eraikin parkearen adina kontuan hartuz, eta batik bat, Espainiakoarena, eta garai batean eskatutako betebehar termiko baxuak, energia kontsumoa murrizteko, existitzen den eraikin parkean arreta jarri behar dela adierazi daiteke.

Egoera energetiko hau karbono dioxidoaren isuriei oso lotuta dago. Munduko ekonomiaren deskarbonizazio ugari bat beharrezkoa da, bizi estandarrak hobetzen diren bitartean. Hala eta guztiz, eraikinen portaera energetikoa aztertzean beste alderdi batzuk kontuan hartu behar dira. Premia ekonomikoek ingurumen kontzientziazioa deuseztatzen duteneko lekuetan edo biztanleriaren sektoreetan, eta klima aldaketari buruzko ardurak nahikoa ez diren lekuetan, eraikinen birgaikuntza energetikoa, pobrezia energetikoa leuntzeko estrategia oso erabilgarria izan liteke. Birgaikuntza energetikoaren onurak, karbono dioxidoaren isurien murrizketan eta energia aurrezteaz gain, alderdi ekonomikoan eta sozialean ere ikus genitzake, pobrezia energetikoaren izan dezakeen eragina kasu.

Hortaz, birgaitze energetiko ezberdinen eragina zehaztasunez neurtzeko metodologiak gero eta beharrezkoagoak dira, eraikinen birgaikuntza energetikoan barne izandako eragileek erabiltzeko.

Beraz, birgaitzeko estrategien eraginak aztertzeko metodologiak gero eta arrakasta handiagoa dute eraikinen birgaitzean lan egiten duten eragileen artean (legegileak, ingeniariak, arkitektoak). Legegileek, legeak eskatzen duten betebehar minimoak betetzen diren egiaztatzeko batetik, eta bestetik birgaitze bati emandako laguntzak egoki inbertitu diren aztertzeko erabiltzen dituzte estrategia hauek. Ingeniariek eta arkitektoek, birgaitzeko jokaerarik egokienak identifikatzeko erabiltzen dituzte berriz, eraikin bakoitzarentzat eta zona klimatiko bakoitzean.

Hortaz, doktorego tesi honen garapenak eraikinen birgaitze energetikoen analisia egiteko urratsak aurre ematen ditu. Euskadiko eraikinen parkearen analisi batekin hasten da. Geroago, datuak lortzeko bi metodologia posible aurkezten dira: batetik, etxe huts batean monitorizazioa, eraikin edo etxebizitzaren eraikuntza elementuen portaera termikoa definitzeko erabiliko den datuak lortzeko; bestetik, hamar etxebizitzak ezberdinen urte bateko monitorizazioa, etxebizitza sozialaren biztanleen energiari lotutako erabilera profilen informazioa lortzeko erabiliko dira. Bi landa azterketetan lortutako datuak bi eredu mota garatzeko erabiliko dira geroago. Azkenik, aipatutako ereduekin lortutako emaitzen azterketa zehazki erakusten da.

Aipatutako lanaren garapena erakusteko, tesi hau lau zatitan banatu da. Lehenak, **sarrerak**, lehen eta bigarren kapituluak barne hartzen ditu. Kapitulu hauetan, tesi honetan zehar aipatutako aspektuei buruzko literatura azterketa bat aurkezten da, eta helburuak eta jarraitutako metodologia deskribatzen dira.

Tesi honen bigarren atalean, egindako **atal esperimentala** erakusten da. Lehenik eta behin, hamar etxebizitza sozialaren landa azterketa bat aurkezten da hirugarren kapituluan. Etxebizitza hauen hautaketa egiteko, XX. mendeko etxebizitza parkearen adierazgarritasunaren irizpideak jarraitzen dira. Landa azterketa honek etxebizitza sozialen parkearen portaera termikoa ezagutzeko erabilgarri diren datu ugari ematen ditu. Etxebizitza bakoitzean barne tenperaturak eta hezetasun erlatiboa hamar minuturo neurtu dira urte batean zehar. Horrela, barne erosotasun termikoari buruzko informazioa lortu ez ezik, etxebizitza bakoitzean dauden erabilera profilei eta biztanleen portaerari buruzko informazioa ere lortu egin da. Energia fakturen bidez, energia kontsumoari buruzko informazioa biltzen da. Gainera, biztanleek galdeketak bete dituzte, beste iturrietatik lortutako informazioa osatzearren. Landa azterketa honek etxebizitza sozialaren portaera energetikoari buruzko ikuspegi orokorra ematen du. Bestalde, etxebizitza sozialaren erabilera profilak definitzeko erreferentzia garrantzitsua izango da geroago.

Era berean, laugarren kapituluak etxebizitza adierazgarri baten monitorizazioaren deskripzioan arreta jartzen du. Etxebizitza hau lehen kapituluan aurkeztutako sailkapena jarraituz hautatzen da. Bi egoera monitorizatzen dira: Lehena, 2012. urteko neguan garatuta, eta bigarrena urte bat geroago, 2013. urteko neguan eginda, leiho aldaketa bat egin ondoren. Etxebizitzan, hirurogei sentsore inguru jartzen dira, estazio klimatiko txiki bat bezalaxe. Monitorizazio honen bidez, etxebizitzaren eraikuntza elementuen portaera termikoak definitzeko behar diren datuak lortzen dira.

Geroago, atal esperimentalean lortutako **datuen tratamendua** garatzen da bi simulazio ereduren bidez. Aipatutako ereduen garapenak hirugarren atal honetan erakusten dira. Bi kapitulu barne hartzen ditu: bosgarren kapitulua (kutxa zuriaren eredua, TRNSYS) eta seigarren kapitulua (kutxa grisaren eredua). Laugarren kapituluan erakutsitako monitorizazioan lortutako datuak erabiltzen dira RC eredua (kutxa grisarena) definitzeko batetik, eta eredu biak baliozkotzeko eta egokitzeko bestetik. Bitartean, hirugarren kapituluan erakutsitako monitorizazioan lortutako datuak (hamar etxebizitzaren monitorizazioan) etxebizitza sozialaren erabilera profil adierazgarriak definitzeko erabiltzen dira.

Azkenik, tesi honen azken atalak simulazioen diseinuan eta aipatutako simulazioen bidez lortutako **emaitzen ebaluazioan** arreta jartzen du. Bi kapitulu ezberdinetan erakusten da. Inguratzailearen hobekuntzarako neurrien bidez lortutako energia aurrezteak, zazpigarren kapituluan erakusten eta aztertzen dira, alderdi energetikoak, ekonomikoak eta ingurumenari eta barne erosotasunari lotutakoak kontuan hartuz. Eraikinaren inguratzaile termikoa hobetzeko, hirurogeita lau energia aurrezteko neurriren emaitzak erakusten dira. Aztertutakoen artean, konbinazio bat hautatzen da, eta berokuntza kontrolerako estrategia ezberdinek energia kontsumoan eta barne erosotasunean duten eragina ebaluatzen da.

Bitartean, zortzigarren kapituluan, ikuspegi exergetikoak duen erabilgarritasuna aztertzen da. Kapitulu honek eraikinetan erabilitako ikuspegi exergetikoari buruzko literatura aztertze motz bat barne hartzen du. TU Delf-eko Arkitektura Fakultatean (Herbeheretan), 2012. urteko bigarren hiruhilekoan Sabine Jansen-ekin garatutako bi artikulu erakusten dira jarraian. Artikulu hauek, eraikinen birgaitze energetikoen analisian ikuspegi exergetikoaren aukerak aztertzen dituzte, tesi honetan garatutako etxebizitza erreferentea oinarrizko kasu hartuz.

Doktorego tesi honetan aurkeztutako ikerketa kontuan hartuz, alderdi ezberdinak azpimarratu litezke. Eraikinen birgaitze energetikoak potentzial handia dauka eraikuntza sektoreari lotutako karbono dioxidoaren isuriak murrizteko, baina honez gain, eskala ezberdinean onura sozial eta ekonomikoen sortzaile ere badela esan liteke. RC eta TRNSYS ereduak eraikinen energia kontsumoa aztertzeko erabilgarriak eta tresna egokiak izan daitezke. Azkenik, eraikin parkea aztertzean, ikuspegi holistiko bat erabiltzearen garrantzia frogatzen da tesi honetan, beste hainbat aspekturen rolak bezalaxe, hala nola, biztanleen portaerarena. Erabilera profilenak (tesi honetan erakutsitako simulazioek %50 inguruko diferentziak erakusten dute hartutako erabilera profilen arabera) eta berokuntza kontrolerako estrategiarena energia kontsumoan jokatzen duena.

Bi ildo identifikatzen dira etorkizunean garatzeko. RC ereduaren hobekuntza jorratzearen beharra, eta geroago, RC eredu honen eta TRNSYS ereduen arteko interakzioa. Bi ildo hauen Eraikuntzarako Sistema Termikoen Instalazio Esperimentalaren artekoa ere aztertu behar da.

Gainera, doktorego – tesi honetan egokitutako TRNSYS ereduaz gain, lehen lortutako emaitzak ere erabili behar dira eraikinen birgaitze energetikoari buruzko eskuliburu bat egiteko, eraikuntza sektorearen eragile ezberdinentzat erabilgarria izan dadin. Eskuliburu hau, Eusko Jaurlaritzako Eraikuntza Kalitatearen Kontrolerako Laborategiaren laguntzarekin garatua izango da, birgaitze energetikorako estrategia ezberdinen emaitza ekonomiko, energetiko eta ingurumenari loturikoak jorratzea helburu izanik, eraikin ezberdinetan, area klimatiko ezberdinetan, simulazio dinamikoan eta datu esperimentaletan oinarrituta.

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 ha obtenido 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.

Eskerrak - Agradecimientos - Aknowledgements

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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Nomenklatura eta laburtzapenak / Nomenclature and Abbreviations

Abbreviations / Laburtzapenak

ASHRAE	American Society of Heating, Refrigerating and Air - conditioning Engineers
BSH	Bilbao Social Housing / Bilboko Udal Etxebizitzak
CDF	Cumulative distribution functions / Banaketa - funtzioak
CTE	Spanish Technical Building Code / Eraikuntzaren Kode Teknikoa
DHW	Domestic Hot Water / Etxeko ur bero
DPP	Depreciated Payback Period / Berreskuratze – denbora (depreziatua)
ESIR	Energy Savings to Investment Ratio / Energia-aurreztearen eta inbertsioaren arteko ratio
ESM	Energy Savings Measures / Energia Aurrezteko Neurriak
EUSTAT	Statistics of the Basque Country / Euskal Estatistika Erakundea
EVE	Basque Energy Agency / Energiaren Euskal Erakundea
INE	Spanish Statistical Office / Espainiako Estatistika Erakundea
IRR	Internal Return Rate / Barne-errendimenduaren tasa
LCA	Life Cycle Assessment / Bizi – zikloaren Azterketa
LCCE	Laboratory for the Quality Control in Buildings / Eraikuntza Kalitatearen Kontrolerako Laborategia
NG	Natural Gas / Gas Naturala
NPV	Net Present Value / Balio eguneratu garbia
P.E.	Primary Energy / Energia primarioa
PLR	Partial load operation / Karga partziala erabilera
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PRBS	Pseudorandom Binary Sequence
PWF	Present Worth Factor
RH	Relative Humidity / Hezetasun erlatiboa
ROLBS	Randomly Ordered Logarithmic distributed Binary Sequence
SIR	Savings to Investment Ratio / Aurreztearen eta inbertsioaren arteko ratio
TH	Thermo Hygrometer / Termohigrometroa

Nomenclature / Nomenklatura

A	Area / Azalera
C	Heat Capacity / Bero – ahalmena
c	Cost / Kostua
cp	Isobaric heat capacity / Bero – ahalmen espezifikoa (isobarikoa)
D	Exergy Destruction / Exergia - suntsiketa
E	Electricity / Elektrizitatea
e	Thickness / Lodiera
ED	Energy Demand / Energia - eskaria
En	Energy Consumption / Energia – kontsumoa
f	Expenses related to operation / Erabilerari lotutako gastuak
F	Exergy Factor / Exergia – faktorea
G	Global Irradiation / Erradiazio globala
H	Heating consumption (In Chapter 6, Conductance is also referred as H) / Berokuntza kontsumoa (6. Kapituluan, H konduktantzia da ere)
I	Investment / Inbertsioa
L	Exergy losses / Exergia – galerak
LS	Lifespan / Bizitza – teknikoa
m	Mass / Masa
N	Lifetime / Bizitza – teknikoaren urte kopurua
n	Time period / Epearen urte kopuru
P	Power / Potentzia
PEF	Primary Energy Factor / Energia primario faktorea
Q	Heat and sensible heat / Beroa eta bero sentigarria
r	Market discount rate / Merkatuaren deskontu tasa
R	Resistance / Erresistentzia
S	Savings / Aurrezteak
T	Temperature / Tenperatura
t	Time / Denbora
U	Heat Transfer Coefficient / Bero transferentziako koefizientea
V	Volume / Bolumena
Vent	Ventilation / Aireztapena
x	Exergy / Exergia

Greek symbols / Letra grekoak

Δ	Increment / Gehikuntza
ε	Emissivity / Emisibitatea
η	Energy Efficiency / Eraginkortasun energetikoa
ρ	Density / Dentsitatea
Φ	Flow / Fluxua
Ψ	Exergy Efficiency / Eraginkortasun exergetikoa
τ	Time constant / denbora - konstantea

Superscripts / Goi-indizeak

BB	Black Body / Gorputz - beltz

Subscripts / Azpiindizeak

0	Reference / Erreferentzia
a	Related to air / Aireari lotuta
aft	After / Ondorengo egoera
B	Related to Base Case / kasu – baseari lotuta
bef	Before / Aurretiko egoera
c	Related to heaters / Berogailuei lotuta
CHP	Related to co - generation system / Baterako sorkuntza sistemei lotuta
conv	Related to convection / Konbentzioari lotuta
del	delivered / Gorputz - beltz
dem	demand / Hornitutakoa
e	Related to envelope / Inguratzaileari lotuta
E	Related to Electricity / Elektrizitateari lotuta
str	Related to structure / Egiturari lotuta
exp	exported / Esportatuta
ext	Related to external / Kanpoko egoerari lotuta
fi	Related to floor / Beheko forjatuari lotuta
fs	Related to ceiling / Goiko forjatuari lotuta
h	Related to horizontal / Horizontalari lotuta
H	Related to heating system / Berokuntza sistemari lotuta

HR	Related to heat recovery / bero – berreskuratzaileari lotuta
i	Stream / Korrontea
in	Indoor / Barne
inf	infiltrations / Infiltrazioak
inl	inlet / Sarrerako (korrontea)
Inp	Input / Sarrerako (datuak)
int	internal / Barneko
m	Related to indoor partitions / Barneko paretei lotuta
max	Maximum / Maximoa
min	Minimum / Minimoa
op	Operative (temperature) / (tenperatura) operatiboa
out	Outdoor / Kanpoko
outl	outlet / Irteerako (korrontea)
outp	output / Irteerako (datuak)
p	Related to pillars / Zutabeei lotuta
rad	Related to radiation / Erradiazioari lotuta
ret	return / Itzulera
s	Related to solar / Eguzkiari lotuta
sol	solar gains / Eguzki – irabaziei lotuta
sp	Setpoint
ST	Related to Solar thermal / Eguzki – energia termikoari lotuta
sum	Related to summer / Udari lotuta
sup	Supply / Hornidura
surf	Related to surface / Azalari lotuta
TES	Related to Thermal energy storage system / Energia termiko metatzeko sistemari lotuta
TESHT	Related to TES (High temperature) / TES-ari lotuta (tenperatura altuak)
TESLT	Related to TES (low temperature) / TES-ari lotuta (tenperatura baxuak)
trans	Transmission / Transmisioa
vent	ventilation / Aireztapena
v	Related to vertical / Bertikalari lotuta
w	Related to windows / Leihoei lotuta
wint	Related to winter / Neguari lotuta
X	related to exergy / Exergiari lotuta

1. ATALA
LITERATURA AZTERTZEA
PART 1. STATE OF ART

> *"If Nature had been comfortable, man never would have invented architecture"*
>
> *Oscar Wilde (1854 - 1900)*

1. KAPITULUA

SARRERA

LABURPENA

Kapitulu hauetan, tesi honen sarrera aurkezten da. Eraikinen birgaikuntza energetikoaren efektuak eta motibazioak (ez soilik energiari lotutako alderdiak, baizik eta alderdi sozialak eta ekonomikoak ere). Geroago, Eraikinen birgaikuntza energetikoaren elementu giltzagarrienen literatura aztertze bat aurkezten da: teknologia eskuragarriak eta ohiko estrategiak (Isolamendu termikoan eta inertzia termikoan oinarritutakoak, batik bat); eraginkortasun energetikoaren ebaluazioa eta biztanleen portaeraren eraginak eraikinen energia – kontsumoan; eraginkortasunari buruzko lege – eremua; amaitzeko, Euskal eraikin parkearen ezaugarriei buruzko ikuspegi orokorrean, eta parke honen sailkapen bat garatzen dira.

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 Sarrera

Gaur egun, fosil energia iturrien agorpena dela eta, baita berotze globaletik ere, energia sistema jasangarriak garatzea gero eta garrantzitsuagoa bihurtzen ari da [1]. Energia kontsumoa murrizteko hiru aukera daude: energia eskaria txikiagotu, sistemen eraginkortasun energetikoa maximizatu, eta energia baliabide berriztagarriak erabili.

Hauen guztien ondorioz, herrialde askotan, karbono dioxidoaren isuriak murrizteko helburua duten lege anitz garatu dira. Aldi berean, gobernu askok energia berriztagarrien erabilera proportzioa handitzeko neurriak ezarri dituzte.

Eraikinek eragin handia daukate baliabide naturalen kontsumoan, baita karbono dioxidoaren isurietan ere. Horrez gain, eraikinetako kontsumoak gora egin du azken urteetan, biztanleriaren hazkundea, barne ingurune osasuntsuagoa, erosoagoa eta produktiboagoaren eskaria, klima aldaketa globala, etabarren ondorioz. Gaur egun, eraikinetan erabiltzen den energia kontsumoa Europar Batasuneko energia kontsumo osoko %40 baino gehiago da [2].

Horregatik, berrikuntza giltzagarria bihurtu da eraikinetako eraginkortasun energetikoa hobetzeko. Espainiako Herri Lan Ministerioaren datuen arabera, 26 milioi etxebizitza baino gehiago zeuden 2011. urtean [3], 2002. urtetik 2008. urtera bitarteko aldian, %2.5eko urteko batez besteko hazkundea izan zelarik. Hala ere, 2008. urtetik hona, etxebizitzen eraikuntza erritmoa jaitsi da: adibidez, 2010. urtean, etxebizitza parkea %1.08 handitu zen soilik.

Bestalde, Espainiako Estatistika Erakundeak (INE) garatu zuen biztanleriaren eta etxebizitzen zentsuak Espainiako etxebizitza parkearen %56 1979. urtea baino lehen eraiki zela erakusten du, hau da, Espainiako aurreneko eraikinetako erregulazio termikoa (NBE - CT 79) onartu aurretik. Euskal Autonomia Erkidegoko egoera oso antzekoa da. Euskal etxebizitza parkearen %70 1980. urtea baino lehen eraiki zen [4]. Beraz, energia kontsumoa murrizteko esfortzurik handienak existitzen den etxebizitza parkera bideratuta izan behar dira. Alabaina, existitzen den etxebizitza bakoitzean egindako inbertsioari so eginez, Europar Batasuneko kopururik txikiena Espainia dagoela ondorioztatzen da (%30 inguru); Suedian edo Erresuma Batuan, ordea, ratio hauek %67.9 eta %62.1 dira hurrenez hurren [5].

Bien bitartean, gobernu askok esfortzu garrantzitsuak egin dituzte beraien etxebizitza parkearen energia - eraginkortasuna sustatzeko eta hobetzeko. Aldi berean, eraginkortasun hori hobetzera bideratuta diren aukerak aztertzeko eta garatzeko hainbat ikerketa egin dira, hala nola [6,7].

Ikerketa ugarik frogatu dutenez, eraikinen birgaitze energetikoak onura asko dauzka, baina erronkak ere badituztela aipatu beharra dago. Alde batetik, eraikinen birgaitze energetikoaren bidez, energia eraginkortasuna hobetzea, mantentze lanetako gastua urritzea edo etxebizitzaren barneko erosotasun termikoa gehitzea lor daiteke. Eskala handiagoan, eraikinen birgaitze energetiko estrategia batek energia ziurtasun nazionala handitzea eta enplegua sortzea lor dezake.

Bestetik, erronka handienetako bat estrategiaren hautaketan eragiten duten ziurgabetasunak dira (okupazio profila, gobernuen politikak, etab). Eraikinetako azpisistema ezberdinetako elkarrekintzek ere eragina dute, hautaketa hau konplexuagoa bihurtuz. Gobernuen diru laguntzak baldin ez badaude, etxebizitza alokairua hedatuta dagoen herrialdetan *"Split incentives"* (zatitutako sustapenak) beste oztopo bat dira, normalean birgaitzearen kostua etxebizitzen jabeei egokitzen baitzaie, nahiz eta birgaitzen onurei, berriz, errentariek onura ateratzen dizkieten. Hala eta guztiz ere, kontu hau ez luke arazo bat izan behar Espainian, herrialdeko biztanle gehienak bere etxebizitzaren jabe baitira. Alderdi honi oso lotuta dagoen beste oztopo mota bat biztanleen egoera ekonomikoa da [8]. Laburbilduz, aurretik aipatutako abantailak eta desabantailak kontuan hartzea, eta oreka egokiena aurkitzea beharrezkoak dira edozein eraikinen birgaitze proiektu iraunkorrean.

2 Eraikinen birgaitzeko ondorioak gizartean

Eraikinen birgaitzeak karbono dioxidoaren isuriak murrizteaz eta energia aurrezteaz gain alderdi ekonomiko eta sozialean ere onurak sortzen ditu. Haietako bat energia pobrezia deritzonaren murriztapena da. Energia pobreziak, bata eta besteari eragiten die. Energia pobreziaren inguruko literatura eta bibliografia nagusiena 1.1. eranskinean biltzen eta aurkezten da.

Beraz, pobrezia energetikoa kontuan hartuz, existitzen diren etxebizitza - eraikinen eraginkortasun energetikoa hobetzea estrategia nagusienetako bat da, karbono dioxidoaren isuriak murrizteko ez ezik, bero eskuragarria etxebizitzetara banatzeko ere. Bi alderdi hauek, hau da, energia - aurrezteak zein barne erosotasunaren hobekuntzak, birgaitze energetikorako proiektuetan kontuan hartu behar dira.

Izan ere, Baek eta Park-ek [5] etxebizitzen birgaitzearen politiketan lau helburu identifikatzen dituzte: portaera fisikoa hobetu, hirugarren adineko beharrekin bat etorri, energia - eraginkortasuna eta gizarte kohesioa hobetu eta ingurua biziberritu. Horietaz, energia primarioa murriztea eraikinen birgaitzea bultzatzeko beste arrazoi bat baino ez da, eta administraritzentzat eta gobernuentzat alderdi sozialak motibaziorik handienetako batzuk dira sarritan.

3 Giltzarri elementuak eraikinen birgaitze energetikoetan

M. Za et al.-ek aurkezten duten hautaketaren arabera [8], zeinahi eraikinen birgaitze energetikoan dauden giltzarri elementu batzuk deskribatzen dira atal honetan.

- **Eraikinari buruzko informazioa**

Kokapen geografikoa, eraikuntza - mota, neurria, antzinatasuna, erabilera, energia - iturriak eta eraikuntza ezaugarriak esaterako. Eraikin bat ahalik eta ondoen ezagutzen lehen urratsa izango da geroago birgaitzeko estrategikorik onena zehazteko.

- **Bezeroen baliabideak**

Bezeroen xedeek eta, batez ere, beraien baliabideek, proiektu baten helburuetan eragin handia daukate. Doktorego - tesi honek gizarte etxebizitzetan jarriko du arreta. Egoera hau errenta - maila txikia duen biztanleriari dago lotuta sarritan, baita haien baliabideei ere.

- **Birgaitze teknologiak**

Birgaitze energetiko baten irismena birgaitzerako eskuragarri dagoen teknologiaren arabera izango da. Birgaitze energetikorik onenak energia - eraginkortasunaren hobekuntza eta karbono dioxido isurien murrizketa bateratuko ditu. Hori dela eta, kostu - onuraren ikuspegitik, bi neurri hauen arteko oreka aurkitzea garrantzizkoa da. Kontu honetako laburpen bat kapitulu honen 4. atalean aurkezten da.

- **Giza faktorea**

Giza - faktoreak eraikinen energia - portaeran ondorioak izaten dituzte era berean. Erosotasun baldintzak, mantentze - lanak, erabilera eta eraikinen kudeaketa arlo honetan sartuta daude. Energia analisia egitean, birgaitze baten aurretik zein ondoren eragin hau kontuan hartzeko beharra dago. Kapitulu honen 5. atalean alderdi hauen inguruko literatura eta bibliografia nagusiena biltzen eta aurkezten da.

- **Politikak eta arauak**

Politiketan eta arauetan eraginkortasun energetikoaren estandarrak aurkezten dira. Haietan, eraginkortasun energetikoari dagokionez, eraikinen birgaitzerako gutxieneko baldintzak ezartzen dira. Batzuetan, Gobernuek eta administraritzek birgaitze energetikorako neurriak bultzatzeko diru - laguntzak eta erraztasun ekonomikoak eman ditzakete. Europar Batasuneko energia - arauei buruzko alderdi azpimarragarri batzuk kapitulu honen 6. atalean aurkezten dira.

- **Birgaitze energetikoari dagokion beste elementu garrantzitsu batzuk**

Z. Ma et al.-ek beste alderdi batzuk aurkezten dituzte [8]. Doktorego - tesi honen edukiak kontuan hartuz, jarraian aipatutakoak hartu dira interesagarrientzat:

- *Eraikin bakoitza bakarra da, ezaugarri ezberdinekin. Eraikin baten berriztatzerako onenak diren neurriak eraikin batean, agian ez dira egokiak beste eraikin batean.*

Horregatik, birgaitze arrakastatsu bat lortzeko edozein lan egin aurretik, eraikinaren analisi zuzena giltzarria da.

- *Eraikineko azpisistemen izaera elkarreragilearen ondorioz, Energia Aurrezteko Neurri anitz erabiltzearen onurak (ESM ingelesez: Energy Savings Measures) ez dira banakako ESM onuren batura, [9].*

Gai honi dagokionez, doktorego - tesi honetan ikuspegi sistemiko bat erabiltzen da, 3. kapituluan aurkezten den bezala.

- *Optimizazioa eredutan oinarritutako edo eredu gabeko hurbilketak erabiliz garatu daiteke.*

Horrela, tesi honetan, eredutan oinarritutako hurbilketa garatzen da; hau da, simulazio energetikoen bidez, hainbat Energia Aurrezteko Neurrien bidez lortutako energia - aurrezteak kalkulatzen dira. Ikerketa honen atal esperimentalaren ostean (3. eta 4. kapituluak), bi simulazio eredu erabiltzen dira, eta elkarren arteko konparaketa garatzen da (5. eta 6. kapituluak). Ondoren, hauetako eredu baten erabilera aurkezten da 7. eta 8. kapituluetan, etorkizunean egin ahal diren analisientzako hobetze iradokizun batzuk proposatuz.

4 Teknologia eskuragarriak eta ohiko estrategiak

T1.1 taulan aurkezten den bezala, birgaitze energetikorako neurrien sailkapena, lau azpi taldeetan zatitu daiteke. Alde batetik, birgaitze energetikoak eraikinetan daukaten portaeraren arabera banatu daitezke (pasiboa eta aktiboa). Bestalde, estrategia motaren arabera beste sailkapen bat egin daiteke, bi estrategia mota bereiziz: energia eskaera murrizteko estrategiak batetik (bero - galerak sahiestuz), eta inguruko energia - fluxuei probetxu ateratzeko estrategiak bestetik (eraikinaren energia sarrerak erabiliz; esaterako fatxadetako inertzia termikoa areagotzea, metatze termikoaren probetxu ateratzeko).

Eraikinen birgaitze energetikoaren beste sailkapen bat birgaitzean jorratutako elementuan oinarritzen da. Ikuspuntu honi dagokionez, hiru estrategia identifikatu daitezke: fatxadaren portaera termikoa hobetu, leihoen portaera termikoa hobetu eta instalazioen eraginkortasun energetikoak hobetu. Teknologia eta estrategia hauei buruzko alderdi azpimarragarri batzuk atal honetan aurkezten dira.

	Energia eskaera murrizteko	**Inguruko energia - fluxuen erabilera**
Portaera pasiboa	- Isolamendu termikoa fatxadetan - Leiho - aldaketak - Infiltrazioa murriztu	- Metatze termikoa - Aireztapen naturala - Beroaren berreskuratzea
Portaera aktiboa	- Instalazio eraginkorrak	- Eguzki - instalazio termikoak - Eguzki - instalazio fotovoltaikoa - Biomasa - energia - Energia geotermikoa

T1.1. Eraikinen birgaitzerako teknologien sailkapena

4.1 Erakinen fatxaden hobekuntza

Eraikinen fatxadei dagokionez, bi estrategia bereizi daitezke: fatxadaren erresistentzia termikoa hobetzera bideratzen diren estrategiak eta eraikinaren inertzia termikoa aldatzera bideratzen direnak.

4.1.1 Isolamendu termikoa

Isolamendu termikoa funtsezkoa da energia - aurrezteak lortzeko. Isolamendu termikoari esker, fatxadetan bero - transferentzia murriztu ez ezik beste arazo batzuk ere saihesten dira, kondentsazioak paretetan esaterako. Horrenbestez, ikerketa ugari egin dira eraikinen isolamendu termikoen erabilerari buruz. Adibidez, Papadopoulos-ek isolamendu termikoen ezaugarri nagusiei eta Europan ematen zaien erabilerei buruzko lana aurkezten du [10].

Isolamendu termikoei dagokionez, bi alderdi azpimarratu daitezke: materialen ezaugarriei lotuta daudenak, eta lodiera – optimizazioari lotuta daudenak.

4.1.1.1 Isolamendu termikoak. Materialak

Al – Homoud-ek isolamendu termikoak energia - eskaria murrizteko duen garrantzia nabarmentzen du [11]. Berak, isolamendu termikoaren printzipioei buruzko ikuspegi orokorra aurkezten du halaber, eta ohiko materialen ezaugarriak biltzen ditu, erresistentzia termikoa, su - erresistentzia, iraunkortasuna, osasun arriskua edo kostua esaterako. Era berean, Lollini et al.-ek isolamenduek inguruan eta energia kontsumoan dituzten eraginak aztertzen dituzte [12]. Lehenik eta behin, eraikinetan erabili ohi diren isolamendu termikoen kostu - analisia garatzen dute, arreta italiar merkatuan jarriz. Fabrikazio - prozesuek ingurumenaren gainean duten eraginaren ebaluazioari buruzko literatura ugaria da. Papadopoulus-ek eta Giama-k bi isolamendu termikoren fabrikazio - prozesua aztertzen dute, bizi zikloren analisiaren bidez.

Areago, ikerketa batzuk hezetasun eta eroankortasun termikoaren bitarteko erlazioan kontzentratzen dira [13], baita tenperatura eta eroankortasun termikoaren bitarteko erlazioan ere [14].

4.1.1.2 Optimizazioa

[15]erreferentzian aipatzen denez, isolamendu termiko gehiagoren erabilerak ez du zertan emaitza hobeetan bihurtu. Izan ere, isolamendu termiko mota erabakitzea eta bere lodiera ekonomikoa kalkulatzea gai nagusiak dira ikerketa askotan. Isolamendu termikoaren optimizazioa alderdi ezberdinen araberakoa da, hala nola klima, barne baldintzak, erabilitako erregaia, erregaiaren kostua, isolamendu termikoaren kostua eta ezaugarriak, interes - tasa, inflazio tasa eta materialaren iraunkortasuna.

Ikerketa askotan isolamenduren lodiera hobezina kalkulatzen da hozte edo berokuntza - kargak kontuan hartuz; beste batzuk, ostera, bata eta bestea kontuan hartzen dira.

Aurkitutako erreferentzia askotan, egun - gradu kontzeptua erabiltzen da energia - eskaria kalkulatzeko. Kontzeptu hau, metodorik errazenetako bat izanda, egoera geldikorrak kontsideratuz erabiltzen da [16].

Hasan-ek ikuspegi sistemiko bat aurkezten du, Palestinako baldintzetarako erabiliz [17]. Ucar-ek eta Balok isolamenduaren lodiera hobezina Turkiako lau zonaldetan baldintzarako kalkulatzen dute [18]. Batan zein bestean 10 urteko iraunkortasuna onartzen da. Isolamenduaren lodiera optimizatuz, A. Hasan-ek 1 – 1.7 urteetako berreskuratze - denbora lortzen du arroka - zuntz erabiliz gero, eta 1.3 - 2.3 urteetakoa poliestireno erabilita. Özkan-ek eta Onan-ek fatxadaren eta leihoen azaleraren bitarteko proportzioa kontuan hartzen dute isolamenduaren lodiera hobezina ateratzeko [19].

Artikulu kopuru txiki batean, metodologia dinamikoak erabiltzen dira fatxadetako bero transferentzia zenbatzeko. Adibide bat [20] artikuluan aurkitzen da, non Energy Plus deritzon programaren bidezko simulazio dinamikoa erabiltzen da.

Analisi ekonomikoei dagokienez, hiru metodo dira nagusiki isolamendu termikoaren lodiera optimizatzeko erabiltzen direnak.

Alde batetik, berreskuratze - denbora sinplea (*simple - payback*) metodoa dago. Metodo honen bitartez, inbestitze bat berreskuratzeko behar den denbora zenbatzen da. Metodo honen desabantailarik handiena balio - galtzearen tasa kontuan ez hartzean datza.

Bizi - zikloaren kostuaren analisia metodorik ohikoena da. Sistema baten kostua bere bizitza osoan zehar zenbatzen da. 10, 20, 25 edo 30 urteko bizitza onartu daiteke, ikertzaileen arabera. Kasu honetan, energia - aurrezteak *"Present worth Factor"* (PWF) erabiliz kalkulatzen dira. PWF inflazio eta deskontu - tasa kontuan hartuz ateratzen da. Adibide bat [21] erreferentzian aurkitu daiteke.

Azkenik, beste ikerketetan P_1 - P_2 deritzon metodoa erabiltzen da, [22] esaterako. P_1 konstantea aipatutako PWF da. Konstante hau ateratzeko, hiru aldagai hartu behar dira kontuan: iraunkorra *(n)*, operazioaren gastuen inflazio - tasa *(f)* eta deskontu - tasa *(r)*. Askotan, erregaiaren kostua inflazio - kostua kontuan hartzen da ere bai. P_2 bizi zikloen gastuen eta hasierako inbestitzearen arteko ratio bat da. Inbestitze gehiago egon ezik (hasierako inbestitze salbu), $P_2=1$ onartu daiteke [23].

Literaturan beste alderdi gehiago ikasten dira ere bai, hala nola isolamendu termikoaren kokapenaren eragina zein den [24]. Analisi ekonomikoei buruzko informazio gehiago doktorego - tesi honen 7. kapituluan ematen da. Kapitulu horretan, ESM batzuk ekonomiaren ikuspuntutik aztertzen dira.

4.1.2 Inertzia termikoa

Inertzia termikoa ere funtsezkoa da energia - aurrezteak lortzeko. Inertzia termikoak eta isolamendu termikoak portaera fisiko ezberdinak dauzkate eraikinetan. Isolamendu termikoak bero - fluxua murrizten du fatxadetan; inertzia termikoa, berriz, beroa metatzeko aukera ematen du bero gehiegi dagoenean, bero hori epe freskoagoetan eskatuz.

Nahiz eta eraikinen inertzia termikoaren azterketa tesi honen irismenaren kanpoan dagoen, inertzia termikoa kontuan hartu behar da edozein eraikinaren azterketa energetikoa egiterakoan. Al – Homoud-ek masa termikoaren eraginak biltzen ditu [11]. Besteak beste alderdien artean, Al – Homoud-ek masa termikoak eguneko gradiente – termiko handiak dituzten klima lehorretan duen garrantzia azpimarratzen du. Al – Homoud-ek dioenez, isolamendu termikoa, berriz, esanguratsuagoa da klima hezeetan, eguneroko tenperaturaren aldaketak.

4.2 Leihoen portaera termikoaren hobekuntza

Eraikinen kontsumo energetikoa murriztean arreta jartzen duten ikerketen artean, asko dira leiho energia eraginkorren erabilera hozte eta berokuntza kargak murrizten duen garrantzia azpimarratzen dutenak. Leihoetako bero - fluxu hiru osagaitan deskonposatu daiteke: beroaren eroapena, leihoaren erresistentzia termikoarekin erlazionatuta dagoena; eguzki - erradiazioaren bidezko bero irabaziak, *g - balio*ren arabera; eta infiltrazioa, aire isuriei lotutakoa. Ikerketa batzuek diotenez kalitate txarreko leihoek energia galera handia suposa dezakete. Haietako batzuk hurrengo paragrafoetan aipatzen dira.

Horrela, Bojic et al.-ek [25] simulazio energetiko baten bidez, leihoa batuek Txinako bi etxebizitzen energia kontsumoan dituzten efektuak aztertzen dituzte. Era berean, Stegou - Sagia et al.-ek [26], simulazio energetikoa erabiliz, leiho batzuen eraginei buruzko ikerketa geratu zuten, leiho eta fatxadaren arteko ratioa kontuan hartuz. Itzala egiten duten elementuk klima beroetan dituen ondorioak aztertzen dituzten ikerketak literaturan aurkitzen dira halaber. Esaterako, Ebrahimpour-ek eta Maerefat-ek [27] Energy Plus programa erabiliz kalkulatzen dute energia kontsumoa, arreta fatxaden irtengunetako itzalaren efektuetan jarriz.

Urbikainek eta Salak [28] etxebizitzen energia - aurrezteak zenbatzeko hiru metodo aztertzen dituzte. Ikerketa honen egileek leihoentzako puntuazio energetiko sistema bat (*Windows Energy Rating System*, WERS) proposatzen dute.

4.3 Instalazioen etekinaren hobekuntza

Instalazioen hobetzea eraikin baten eraginkortasun energetikoa hobetzeko beste aukera bat da. Gai honi buruz, ikuspuntu ezberdinetatik jorratutako ikerketa asko egin dira azken urteetan, bai instalazio baten elementu bakarrean arreta jarriz, bai instalazio baten konfigurazio osoa kontuan hartuz. Kontu honi buruzko erreferentzia batzuk 8. kapituluan aipatzen dira, arreta ebaluaketa exergetikoan jarriz.

5 Eraginkortasun energetikoaren azterketa

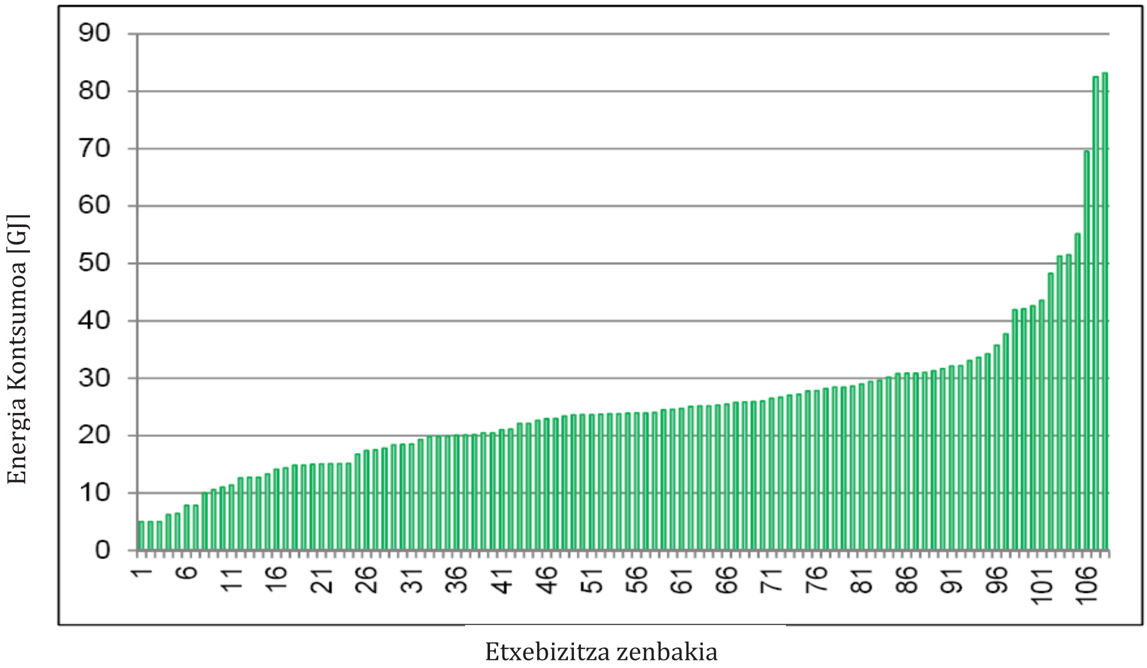
Atal honetan eraginkortasun energetikoa aztertzean kontuan hartu behar diren bost faktoreak deskribatzen dira. Alde batetik, biztanleen portaerak eragin handia izan dezake edozein eraikinaren portaera energetikoan. Halaber, *"rebound effect"* deritzona (*errebote efektua*) biztanleekin erlazionatuta dago ere bai. Gai hau 5.2. atalean deskribatzen da laburki. Bestetik, literaturaren arabera, badaude eraikinen eraginkortasun energetikoa aztertzean kontuan hartu beharreko ratio batzuk. Ratio hauek 5.3 atalean aurkezten dira.

5.1 Biztanleen portaeraren eragina

Biztanleen portaerak eraikinen energia kontsumoan duen eraginari dagokionez, Annex 53-ek efektu handia eduki dezakeela adierazten du. Efektu honen eragina eraikinaren ezaugarri fisikoek edo beste faktoreek dutena baino handiagoa izan daiteke [29]. Ikerketa batzuk antzeko eraikinen energia kontsumoan alde handia nabarmentzen dute, biztanleen portaera dela eta [30,31]. Esaterako, van der Aa-k energia erabilera, biztanle - profil eta portaera ereduen arteko harremanak aztertzen ditu [32] erreferentzian.

Gai hau argitzeko asmoz, [33] erreferentziatik hartutako grafiko adierazgarria I1.1 irudian erakusten da. Grafiko honetan, antzeko 110 etxebizitzaren energia - erabilerak irudikatzen dira, energia - erabilerarik handiena energia - erabilerarik txikiena baino 12 aldiz handiagoa izanik. Biztanleen portaera salbu, etxebizitza denek antzeko ezaugarriak zeuzkaten.

Horregatik, eraikinetako energia aurrezteak intereseko gai izan da gizarte psikologiako arloan ere. 1970eko hamarkadako testuingurua krisi energetikoa bazen; gaur egungoari, ingurumen arazoak (hala nola, berotze globala) ere gehitu zaizkio. Energia - erabilera, beraz, gizakien portaerari lotuta dago eta, ondorioz, portaera - aldaketen bidez murriztu daiteke [34].



I1.1. Energia - eskaria [GJ] 110 antzeko etxebizitzatan

Doktorego - tesi honen helburu diren gizarte etxebizitzetan efektu hau gehiago nabaritzen da. Brunner et al.-ek errenta txikien eta etxebizitzatako biztanleen portaeraren arteko harremanari buruzko gogoeta interesgarri batzuk nabarmentzen dituzte. Egileek "*eguneroko bizitzaren maila askotan normaltzat hartzen duten estandarrak pixkanaka - pixkanaka handitu diren bitartean (esaterako, eraikinen barruko erosotasun tenperatura, E. Shove-k dioenez), errenta txikiak dituzten ikertutako familiek beraien bizitza estandarrak beheratu zituzten beraien mugaketei aurre emateko,"normaltzat" hartzen diren egoerak baino baxuagoetara moldatuz* [35]*"* azpimarratzen dute.

5.2 *Rebound Effect* (errebote efektua)

Eraikin baten birgaitze energetiko bat aztertzean kontuan hartu behar den beste faktore bat errebote efektua da [36]. Errebote efektua (*Rebound effect*, edo *take - back effect*, ingelesez) definitu zuen lehen ikertzailea Daniel Khazzom izan zen. Errebote efektuak energia - erabileraren eraginkortasun energetikoaren hobekuntzaren ondorioz sistema energetiko baten energia – eskarian ematen den igoera adierazten du [37]. Errebote efektuak sistema energetikoen kostu baxuagoek (eraginkortasun energetikoaren hobekuntzaren ondorioz) biztanleen portaeran daukaten efektua azaltzen du. Birgaitzearen ondorioz aurrezten den energiaren kontsumitutako zatia da, bai sistema ordu gehiagotan zehar erabiltzen delako, bai sistemaren produktuen kalitatea handiagoa delako birgaitzearen ondoren [38]. *Backfire* deritzona eraginkortasun energetikoa hobetu eta gero emateten den energia eskariaren handiagotzea da. Kontzeptu hauetako definizio zehatzak [39] erreferentzian ematen dira.

Ikerketa askok errebote efektuak eraikinen birgaitze energetikoengan dituen ondorioak aztertu dituzte, esaterako [40]. I. Hamilton et al.-ek errebote efektua zenbatzeko metodologia bat aurkezten dute [41]. M. Shipworth-en ikerketa batean [42], eraikin batzuen energia erabilera birgaitze energetikoa egin eta gero ez zen izan espero bezain ona, nahiz eta eraikinen eraginkortasun energetikoa handiagotu zen. Efektu hau, biztanleek eskatzen ez zuten arren barneko tenperaturen igoeraren ondorio zen. Era berean, ikerketa batzuek eraginkortasun energetikoaren hobekuntzek espero ziren energia - eskarien murrizketak ez lortzea balitekeela adierazten dute, nahiz eta konforteko hobekuntzak kontuan hartu [43].

5.3 Eraikinen eraginkortasun energetikoa neurtzeko parametroak

Eraikinen birgaitzeekin lortutako emaitzak ebaluatzeko parametro eta irizpide ezberdinatik erabili daitezke. Eraginkortasun energetikoari lotutako batzuk *Energy Efficiency E - Houses* deritzon europar proiektuan [44] aurkezten dira. Ratio hauek lau taldetan bildu daitezke:

- *Parametro teknikoak:* Energia aurrezteak zenbatzeko erabilgarriak direnak, eta beraz, eraginkortasun energetikoa neurtzeko.
- *Ingurumen - parametroak:* Parametro teknikoei oso lotuta daudenak, hauen araberakoak dira eta. Hau da, adibidez, zenbat eta kontsumo energetikoa txikiagoa izan, hainbat eta isuri gutxiago izan.
- *Parametro ekonomikoak:* kontsumo energetiko eta energiaren kostuei lotuta daudenak.
- *Gizarte parametroak:* eraikinen barneko erosotasunarekin erlazionatuta daudenak. Eraikinaren baldintza orokorrek erosotasunari eragiten diote (eraikuntzan erabilitako teknikak, eraikinaren inguratzaile termikoa eta barne - banaketa), baita sistema energetikoek eta mantentze - lanek ere (biztanleen portaera eta sistema energetikoa azpisistemak).

Lehen hiru parametro - motak neurri daitezke. Gizarte parametroak, ordea, soilik zeharka puntuatu daitezke. T1.2 eta T1.3 tauletan aurkeztutako zerrendetan aipatutako parametroak biltzen dira. Haietako batzuek bi eszenario elkarrekin konparatzean jartzen dute arreta (birgaitze egin baino lehen eta birgaitzea egin ondoren, adibidez); Hala ere, gehienak ez dira soilik erabiltzen birgaitze energetikoak ebaluatzeko, baizik eta edozein eraikien eraginkortasun energetikoa ebaluatzeko.

Taldea	Azpitaldea	Kontzeptua	Unitateak
Parametro Teknikoak	Berokuntza	Berokuntzarako kontsumoa (pertsonako)	[kWh/pertsona]
		Berokuntzarako kontsumoa (m^2 bakoitzeko)	[kWh/m^2]
		Berokuntzarako kontsumoa (berokuntzako egun - gradu)	[kWh/HDD]
		Energia primarioaren kontsumoa (m^2 bakoitzeko)	[kWh_{PE}/m^2]
	Hoztea	hozterako kontsumoa (pertsonako)	[kWh/ pertsona]
		hozterako kontsumoa (m^2 bakoitzeko)	[kWh/m^2]
		hozterako kontsumoa (berokuntzako egun - gradu)	[kWh/CDD]
		Energia primarioaren kontsumoa (m^2 bakoitzeko)	[kWh_{PE}/m^2]
	Argiztatzea	Argiztatze - kontsumoa (pertsonako)	[kWh/ pertsona]
		Argiztatze - kontsumoa (m^2 bakoitzeko)	[kWh/m^2]
		Energia primarioaren kontsumoa	[kWh_{PE}/m^2]
	Etxetresna elektrikoak	Etxetresna elektrikoen kontsumoa (pertsonako)	[kWh/ pertsona]
		Energia primarioaren kontsumoa (pertsonako)	[kWh_{PE}/ pertsona]
	Ur kontsumoa	Ur kontsumoa (pertsona bakoitzeko)	[litre/ pertsona]
	Etxeko Ur beroa (Eguzki energia termikoa)	Etxeko ur bero kontsumoa (pertsonako)	[kWh/ pertsona]
		Energia primarioaren kontsumoa (pertsonako)	[kWh_{PE}/ pertsona]
	Besteak	Beste kontsumoak (pertsonako)	[kWh/ pertsona]
		Beste kontsumoak (m^2 bakoitzeko)	[kWh/m^2]
		Energia berriztagarrien ehunekoa	[%]

T1.2. Eraginkortasun energetikoa eraikinetan aztertzeko parametro teknikoak

Taldea	Azpitaldea	Kontzeptua	Unitateak
Ingurumen - parametroak	Berokuntza, Hoztea, Argiztea	CO_2 isuriak (m^2 bakoitzeko)	[CO_2/m^2]
		Saihestutako CO_2 isuriak (m^2 bakoitzeko)	[CO_2/m^2]
	Etxetresna elektronikoa Etxeko ur beroa,	CO_2 isuriak (pertsona bakoitzeko)	[CO_2/pertsona]
		Saihestutako CO_2 isuriak (pertsona bakoitzeko)	[CO_2/pertsona]
Parametro ekonomikoak	Sistema guztiak	Energiaren kostua (pertsona bakoitzeko)	[€/pertsona]
		Energiaren kostua (m^2 bakoitzeko)	[€/m^2]
		Energiaren kostua (diru - sarrera per capita kontuan hartuz)	[€/pertsona/ diru - sarrera per capita]
		Energia aurrezteen kostua	[€/kWh]
		Errentagarritasuna (*additional cost approach*)	[€]
		Errentagarritasuna (*full cost approach*)	[€]
		Finantziazio publikoa	[%]
Gizarte parametroak	Erosotasuna	Tenperatura	[ºC]
		Hezetasun erlatiboa	[%]
		Haizearen abiadura	[m/s]
		Predicted Mean Vote indizea (PMV)	[-]
		Percentage People Dissatisfied (PPD)	[%]

T1.3. Eraginkortasun energetikoa eraikinetan aztertzeko parametroak. Ingurumen parametroak, parametro ekonomikoak eta gizarte parametroak

6 Lege-eremua. Eraginkortasunari dagozkion sustapen - neurriak eta betebeharrak

Legeetan aipatutako betebeharrek eta sustapen – neurriek rol garrantzitsua jokatzen dute edozein herrialdeko eraikin parkearen eraginkortasun energetikoaren hobekuntzan. Gutxieneko betebeharrek alde batetik, eta eraikinen birgaitze energetikoa bultzatzeko sustapen - neurriek bestaldetik, birgaitzerako estrategietan eragin handia daukate.

Baek-ek eta Park-ek birgaitzerako politiken berrikuspen bat aurkeztu zuten 2012. urtean [5]. Artikulu honetan, lau europar herrialdetako birgaitzerako politikak (Frantzia, Alemania, Danimarka eta Suedia) zehazki aztertzen dira. Gaur egungo politikek, soilik ezaugarri fisikoen hobekuntza helburu zuten iraganeko politikak ez bezala, ikuspegi globalagoa dutela baieztatzen dute, arreta adineko biztanleriaren igoeran jartzen baitute, eraginkortasun energetikoa hobetuz eta segregazio soziala saihestuz.

Bi alderdi gehiago azpimarratu behar dira. Lehena sustapen ekonomikoei lotuta dago. Etxebizitzen birgaitze energetikorako diru laguntza asko aldatzen dira ikerketako lau herrialdeen arabera. Horrela, edadetuen erosotasuna beste kontsiderazioen gainetik baloratzen da Danimarkan. Sustapenerako diru laguntza lortutako eraginkortasun energetikoaren araberakoa da Alemanian (baita Herbeheretan ere), eta eraginkortasuna hobetzea politika horren helburu nagusia da. Frantzian, gizarteratzea da gehien baloratutako alderdia. Bigarren puntua eraikinetako nahitaezko egiaztapenei lotuta dago. Berotegi - efektuko gasen isuriak murrizteko egiaztapen hauek erabilgarriak badira ere, egileek egiaztapen hauek ezartzean oztopo batzuk aurkitzen direla baieztatzen dute. Kontrolak egiteko egokienak diren elementuak identifikatzea, baita kontrol subjektuak erabakitzen dituen zundaketa antolatzea ere, giltzagarriak dira arlo honetan.

2012. urteko lehen hiruhilekoan, eraikinen birgaitzeei lotutako arauen berrikustea egin zen. Analisi honetan, lau europar herrialdetako arauak (Alemania, Frantzia, Erresuma Batua eta Espainia) bata bestearekin konparatu ziren, arreta eraginkortasun energetikoarekin lotutako betebeharretan jarriz. Espainiako gutxieneko betebeharrak beste herrialdekoak baino baxuagoak direla azaltzen da txosten honetan. Alderdi honek Espainiako hobekuntza potentziala nahiko handia dela erakusten du. Gainera, txosten honen arabera, Espainian, orain arte, ez da egon interes handirik birgaitze energetikoetan, alderdi hau soilik azken urteetan kontuan hartzen hasi delarik, batez ere europar zuzentarauen ondorioz. Joera hau aldatzen hasi dela ematen du azken bolada honetan, eta gizartearen kontzientziazioa gai honengan nabarmenki handiagotu da. Izan ere, 2009 - 2012ko Espainiako Birgaitzerako Plana 2 milioi etxebizitza eta 150,000 eraikin baino gehiago birgaitzeko asmoa zeukan, 25,200 milioi euroko inbestitze batekin.

Europako Batasunaren beste estatu kideetan bezala, Europar zuzentarauek eragin handia daukate Espainiako legeetan. Eraikinen eraginkortasun energetikoari lotutako europar zuzentarauak laburki zerrendatzen dira T1.4 taulako ezkerreko zutabean.

Eskuinekoan, zuzentarau horren transposizioa ezartzen duten Espainiako legeak aurkezten dira.

EUROPAKO LEGE - EREMUA		**ESPAINIAKO LEGE - EREMUA**	
Urtea	**Izena**	**Urtea**	**Izena**
1993	*KONTSEILUAREN 93/76 ZUZENTARAUA*, energia - eraginkortasuna hobetuz karbono dioxido isurtzeen mugak jartzeari buruzkoa(SAVE)	1998	RITE 98 (Eraikinetako Instalazio Termikoen Araudia, EITA)
2002	*2002/91/EC ZUZENTARAUA*, eraikinen energia errendimenduari buruzkoa. (EPBD)	2006	CTE (Espainiako Eraikuntzaren Kode Teknikoa, EKT)
		2007	RITE 07(Eraikinetako Instalazio Termikoen Araudia, EITA)
		2007	47/2007 Errege Dekretua, eraikuntza berriko eraikinen energia - eraginkortasuna ziurtatzeko oinarrizko prozedura onartzen duena
2004	*2004/8/EC ZUZENTARAUA*, energiaren barne merkatuan bero erabilgarriaren eskarian oinarrituta, baterako sorkuntzaren sustapenaz dihardueną		
2006	*2006/32/EC ZUZENTARAUA*, energiaren amaierako erabileraren eraginkortasunari eta energia - zerbitzuei buruzkoa		
2009	*2009/28/EC ZUZENTARAUA*, energia iturri berriztagarrietatik datorren energia erabiltzea sustatzen duena		Ezarri barik
2009	*2009/72/EC ZUZENTARAUA,* elektrizitatearen barne - merkatuaren inguruko arau komunak ezartzen dituena	2012	13/2012 Errege Dekretua
2009	*2009/73/EC ZUZENTARAUA,* gas naturalaren barne - merkatuaren inguruko arau komunak ezartzen dituena		
2010	*2010/31/EB ZUZENTARAUA,* eraikinen energia - errendimenduari buruzkoa (bat egitea)	2013	240/2011 Errege Dekretua, eraikin berrien eraginkortasun energetikoaren ziurtagiria arautzen duena 235/2013 Errege Dekretua, eraikuntzen eraginkortasun energetikoa ziurtatzeko oinarrizko prozedura onartzen duena
2012	*2012/27/EB ZUZENTARAUA,* energia eraginkortasunari buruzkoa		

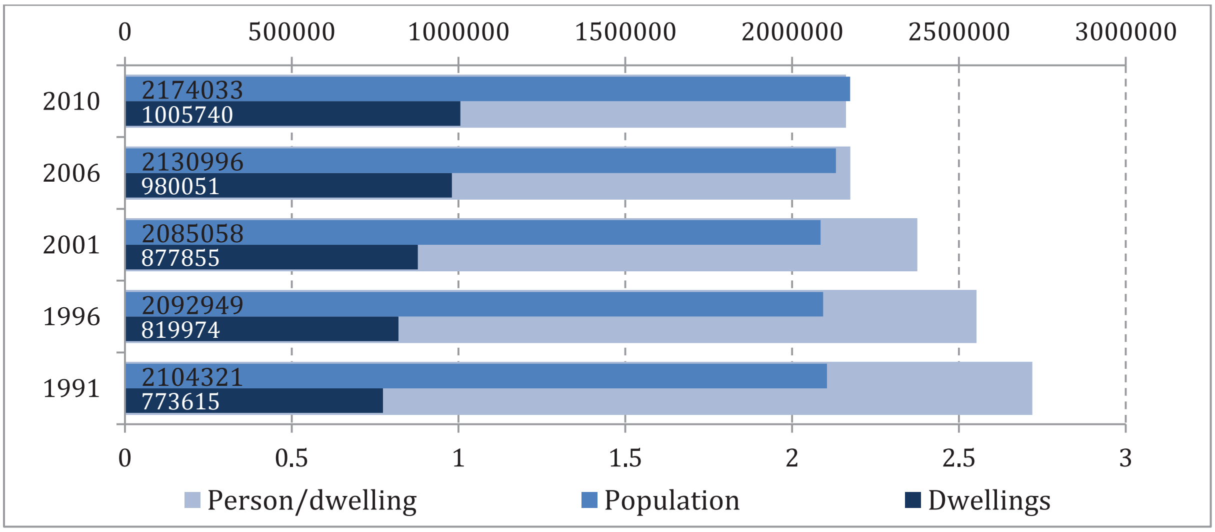
T1.4. Europar Zuzentarauak eta haien transposizioak Espainiako arauetan

Azkenik, 2010/31/EU zuzentarauari dagokionez, Espainian 235/2013 Errege Dekretuaren bidez ezartzen da. Dekretu hau eraikinen energia - eraginkortasuna ziurtatzeko oinarrizko prozedura onartzen du (2013ko apirilaren 13ko BOEa, eta

47/2007 Errege Dekretua indargabetzen eta bat egiten ditu). Euskal Autonomia Erkidegoan, 235/2013 Errege Dekretua Eraginkortasun Energetikoaren Ziurtagiriaren kanpoko kontrola arautzeko 2012ko Abenduaren 12ko aginduen bidez moldatzen da (EHAA 2013 - 1 - 22), eta 2013ko Apirilaren 2ko aginduaren bidez (EHAA 2013 - 5 - 20), eraikinen eraginkortasun energetikoaren ziurtagirien erregistroari buruzkoa.

7 Euskadiko etxebizitza parkearen ezaugarriak

Euskal Autonomia Erkidegoko etxebizitza parkea milioi bat etxebizitza inguruk osatzen dute. Euskadiko etxebizitzen batez besteko azalera 87 m^2 da. Familia - etxebizitza nagusiena da, guztikoaren %84 biltzen baitu. Etxebizitza horien %73 hiri - inguruneetan kokatzen da. Etxebizitzen kopurua biztanleena baino gehiago handiagotu da azken 20 urteetan. Horren ondorioz, etxebizitza bakoitzeko pertsona kopurua beheragotu da, 2.72tik 1991. urtean, 2.16ra 2010. urtean (I1.2 irudia).

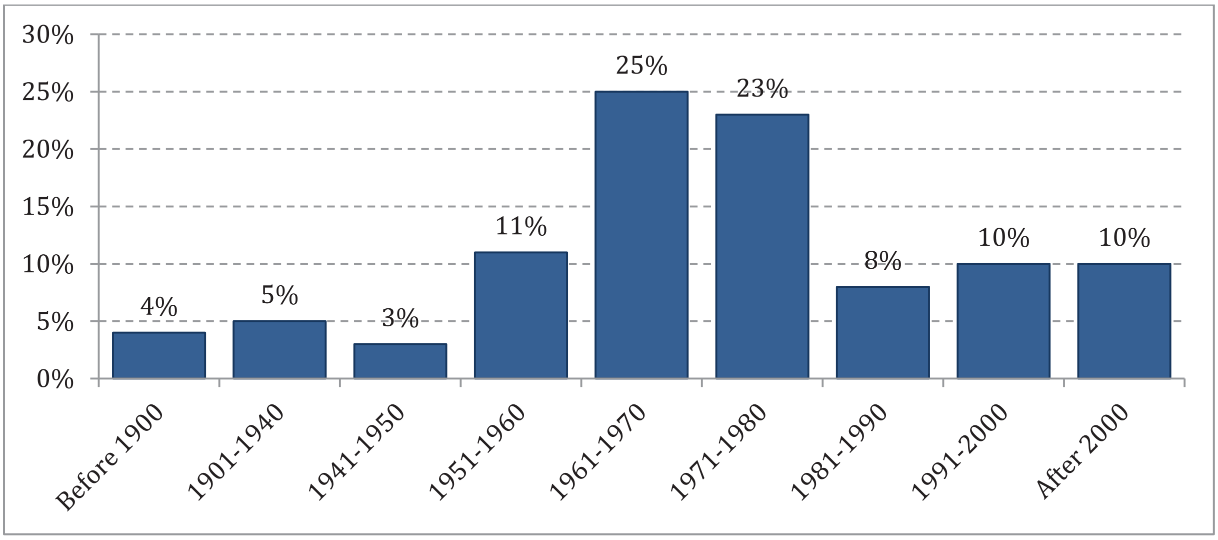


I1.2. Eraikin kopurua Vs populazioa (EVE, EUSTAT)

Euskadiko etxebizitza parkearen bi alderdi azpimarratu behar dira. Lehena, haien antzinakotasunari lotuta dago. EUSTAT-en datuen arabera, ia etxebizitzen %50 1961. urtetik 1980. urtera arteko aldian eraiki zen, eta EAEko etxebizitzen batez besteko antzinatasuna 39 urtekoa da. Etxebizitzen banaketa, eraiki zuten urtearen araberakoa, I1.3 irudian irudikatzen da.

Gainera, bukatutako etxebizitza kopuruak gutxiagotze handia izan du azken urteetan. Sektore honek hazkunde handia izan zuen 90eko hamarkadaren amaieratik aurrera.

Goreneko garaia 2002. urtean izan zuen, 18,200 eraikitako etxebizitzakin. Hala ere, 2005 urtetik aurrera beheranzko joera izan du (esaterako, 2011. urtean 11,300 etxebizitza eraikitzen bukatu ziren). Kopuru horrek behera egiten jarraitu du: izan ere, 2009. urtetik 2011. urtera bitarteko aldian soilik 7500 etxebizitza hasi dira urtean, batez beste.



I1.3. Eraikin kopurua, haien antzinakotasunaren arabera (EVE, EUSTAT)

Bi alderdi hauek kontuan hartuz, eraikinen birgaitzeak rol garrantzitsua jokatuko du hurrengo urteetan eta, beraz, Euskal etxebizitza parkearen errendimendu termikoa hobetzeko aukera. Gai hau argitzeko, Euskal parkearen energia eta berotegi efektuko gasen emisioei buruzko berrikusketa aurkezten da 1.2. eranskinean.

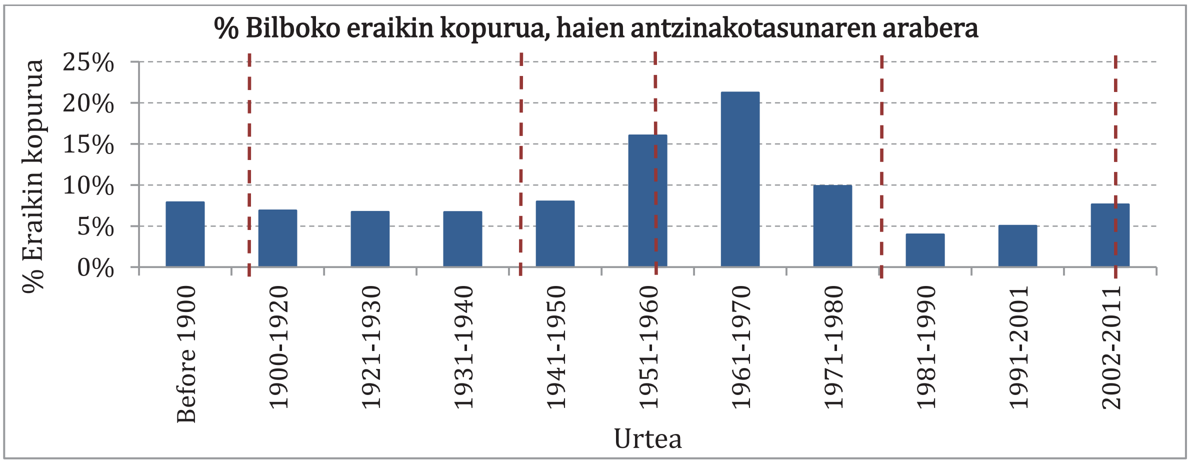
7.1 Eraikin sailkapenaren irizpideak

Eraikin parkearen ezaugarriak ezagutzea hobekuntza potentziala aztertzeko funtsezko alderdi bat da, eta, horrenbestez, birgaitzerako lanei modu egokian aurre egiteko. Beste herrialde batzuetan bezala, Espainiako etxebizitza parkea bere antzinatasunaren arabera sailkatu daiteke. Aipatu bezala eraikin baten ezaugarriengan eragiten duten beste faktore batzuek egoera soziala eta ekonomikoa, edo aipatutako lege eremua dira, esaterako. Espainiako kasuan, XX. Mendeko lehen hamarkadetan, Espainiako hiri batzuen lehen industrializazioak landa - nukleoetatik hirietarako biztanleriaren lekualdatzea ekarri zuen. Honen ondorioz, industrializatutako eskualdetako eraikin kopurua handiagotu zen, Bilbon gertatu bezala.

Espainiako Gerra Zibilaren ondoren, gerraosteko aldia egon zen, 50eko hamarkada arte. Desarrollismoa hamarkada horretan hasi zen. Desarrollismoan zehar bigarren industrializazioa izan zen, eta horren ondorioz, 50eko hamarkadatik 60eko hamarkadako azken urteetara bitarteko aldian Bilboko etxebizitza parkearen %20 baino gehiago eraiki zen.

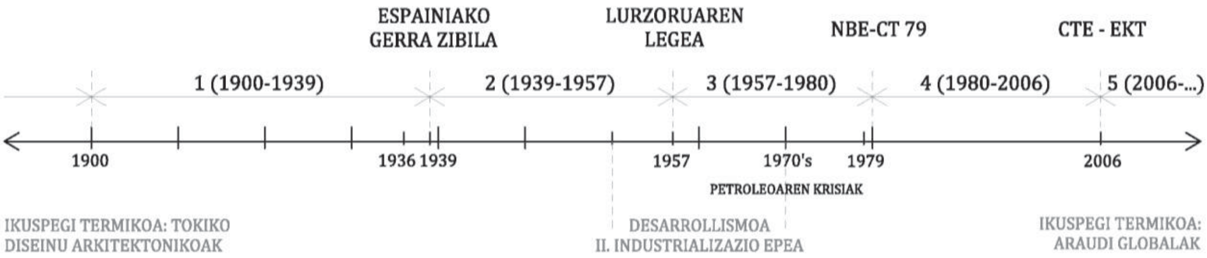
Hala eta guztiz ere, eredu ekonomiko hori, industria astunaren menpekoa (metalurgia eta ontzigintzaren sektorea, adibidez), 1973. urteko krisiaren ondorioz kolapsatu zen. Bilboren kasuan, krisi industriala oso gogorra izan zen, eta eraikuntzen murriztapen adierazgarria gertatu zen urte horretan.

Bestalde, 1973. urteko krisi energetikoa eta gero, beste europar herrialdetan bezala, Espainian ere isolamendu termikoaren gutxieneko betebeharrak indartu egin ziren. Helburu honekin, Espainiako lehen araudi termikoa 1979. urtean garatu zen. Hala ere, beste europar herrialdetan ez bezala, Espainian ez zen egon beste araudi termikorik 2006. urtera arte. Urte horretan, Espainiako Eraikuntzaren Kode Teknikoa (EKT) [45] indarrean sartu zen.



I1.4.Bilboko eraikin kopurua, haien antzinakotasunaren arabera. (2013. Urteko eraikin kopurua: 10,406, INE)

Euskal etxebizitza parkea sailkatzeko, Bilbokoa erreferentzia moduan hartzen da. Bilboko etxebizitza parkearen antzinakotasunaren araberako sailkapena I1.4 irudian irudikatzen da. Antzinakotasunari dagokionez, bost epe identifikatzen dira 1900 urtetik aurrera, aipatutako gertaera gogoangarriak kontuan hartuz (I1.5 irudian). Aldi bakoitzaren fatxaden zeharkako sekzio adierazgarriak T1.5 taulan aurkezten dira. C (bero - ahalmena) eta U – balioak Eq. 1 eta Eq. 2 ekuazioen arabera kalkulatzen dira.



I1.5. XX. Mendeko eraikuntzaren epeak Bilbon

$$U_i = \frac{1}{R_{in} + R_i + R_{out}} \tag*{Eq. 1}$$

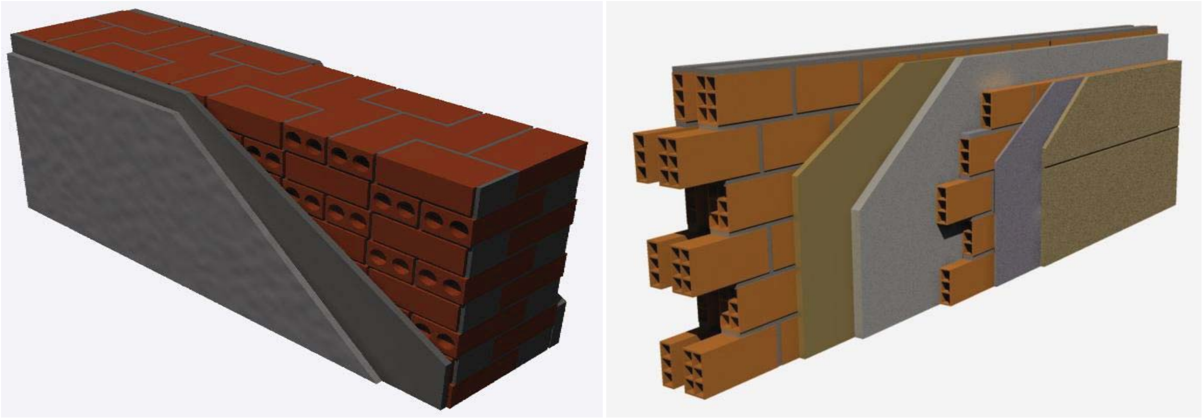
$$C = \sum \rho_i \times c_{p,i} \times e_i \tag*{Eq. 2}$$

non:

- R_{in} barneko azalaren erresistentzia termikoa da (0.13 m^2K/W) [46]
- R_i eraikuntza elementuaren erresistentzia termikoa da
- R_{out} kanpoko azalaren erresistentzia termikoa da (0.04 m^2K/W) [46]
- ρ_i i materialaren dentsitatea da
- Cp_i i materialaren bero - ahalmen espezifikoa da
- E_i i geruzaren lodiera da

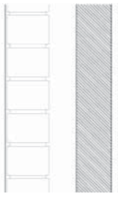
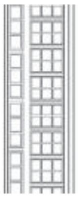
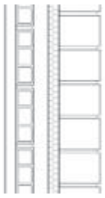
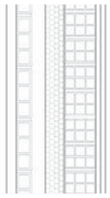
Aipatutako sekzioak, ondoren zerrendatuko den bezala, hiru talde nagusitan sailkatu daitezke, haien estrategia termikoaren arabera. Izan ere, hiru fatxadaren eraikuntza - mota erabili izan dira tradizionalki klima epeletako eraikinetan [47]:

- **Bero - ahalmena:** Eraikin tradizionaletan aurkitzen den estrategia, inertzia termiko altuarekin bere fatxadetan, bero metatze moduan jokatzen dutena. F.a. 1. talde honetan dago. Egile batzuek, esaterako Dili et al.-ek [48] edo S. Martín et al.-ek [49] sistema honen abantailak erakusten dituzte (I1.6. irudian ezkerrean).
- **Geruzapena:** geruza askoko inguratzaileetan aire barrunbeekin aurkitzen den estrategia. Gerizpek erresistentzia termiko eskasa eskaintzen dute, esaterako F.b eta F.c. Ikertzaile askok arreta estrategia honetan jarri dute, hala nola K. J. Kontoleon-ek eta Bikas-ek [50] (I1.6. irudian eskuinean).
- **Erresistentzia termikoa:** Isolamendu termiko materialak bero - galeraren aurka oztopo termiko baten moduan erabiltzen dira estrategia honetan. F.d eta F.e talde honetan daude. Egile askok estrategia honen efikazia frogatzen dute, esaterako Stazi et al.-ek [51].



I1.6. Fatxaden bi adibideak. Ezkerrean, bero – ahalmenenean oinarritutako fatxada. Eskuman, geruzapenean oinarritutakoa

Fatxadaren eraikuntza - sekzioa

						
F.a	**F.b**	**F.c**	**F.c.1**	**F.c.2**	**F.d**	**F.e**

Barneko azaletik (ezkerra) kanpoko azala (eskuina)

U [w/m²·K] C[kJ/ m²·K]	Fatxadaren geruzak (barneko azaletik - kanpokora)	Aldia	U [W/m²·K] C[kJ/ m²·K]	Fatxadaren geruzak (barneko azaletik - kanpokora)	Aldia
F.a. **U: 1.11** **C:463.8**	Igeltsua Adreilu zulatua (37 cm) Zementuzko morteroa	1	F.b **U: 1.16** **C: 359.8**	Igeltsua Adreilu huts (12.5 cm) Aire - ganbera Hormigoizko horma (10 cm) Zementuzko morteroa (2cm)	1 - 2
F.c **U: 1.44** **C: 160.0**	Igeltsua Adreilu huts (4.5 cm) Aire - ganbera Adreilu huts (12.5 cm) Zementuzko morteroa (2cm)	3	F.c.1 **U: 1.27** **C: 180.0**	Igeltsua Adreilu huts (4.5 cm) Aire - ganbera Adreilu huts (12.5 cm) Zementuzko morteroa (2cm) Arindutako Zementuzko morteroa (2cm)	3
F.c.2 **U: 0.43** **C: 238.4**	Igeltsua Adreilu huts (4.5 cm) Aire - ganbera Adreilu huts (12.5 cm) Zementuzko morteroa (2 cm) Isolamendu termikoa (4 cm) Adreilu huts (9 cm) Arindutako Zementuzko morteroa (2 cm)	3	F.d. **U: 0.48** **C: 189.0**	Igeltsua Adreilu huts (4.5 cm) Isolamendu termikoa (3 cm) Aire - ganbera Adreilu zulatua (12.5 cm)	4
F.e. **U: 0.41** **C: 162.6**	Igeltsua Adreilu huts (4.5 cm) Isolamendu termikoa (6 cm) Aire - ganbera Adreilu huts (12.5 cm) Zementuzko morteroa (2cm)	4 - 5			

T1.5. Fatxadaren eraikuntza - sekzioak (Bilboko Udal Etxebizitzen arabera)

8 Gizarte etxebizitzaren sektorearen hobetze potentziala

Aipatutako arrazoien ondorioz, eraginkortasun hobekuntzak eraikinetan, gizarte etxebizitzaren sektorean hain zuzen ere, lehentasunezko helburu bihurtu dira Europar Batasunean. Sektore honen ezaugarriak direla eta, (errenta txikiak edo eraikinen ezaugarri termikoak, adibidez) energia - pobrezian jausteko sektore bat zaurgarrienetako da. Horregatik, gizarte etxebizitzaren energia - aurrezte potentziala zenbatzea lehentasun bat bihurtu da. Etxebizitza parkearen portaera termikoa aztertu baino lehen, eraikuntza sozialen ezaugarriak jakitea ezinbestekoa da.

Bukatzeko, eraikin parkearen hobekuntza potentziala aztertzea gai konplexua dela baieztatu daiteke. Eraikinen portaera termikoaren ebaluaketak Ikuspuntu holistikoa eskatzen du. Ikuspuntu honetan, eraikin bakoitza azpisistema batzuez osatutako sistema baten moduan ulertzen da. Horrela, doktorego - tesi honen helburuak eta metodologia 2. kapituluan aurkeztu eta gero, okupatutako hamar etxebizitzen landa - azterketa aurkezten da 3. kapituluan. Landa - azterketa honetan ikuspuntu holistikoa erabili zen.

9 Aipatutako eranskinak

1.1. Eranskina: Energia - pobrezia. Literatura aztertzea. (Ingelesez).

1.2. Eranskina: Eraikinen euskal parkearen berotegi - efektuko gasen isuriak eta energia - kontsumoa. Gakoak (Ingelesez).

2. KAPITULUA

HELBURUAK, EGITURA ETA METODOLOGIA

LABURPENA

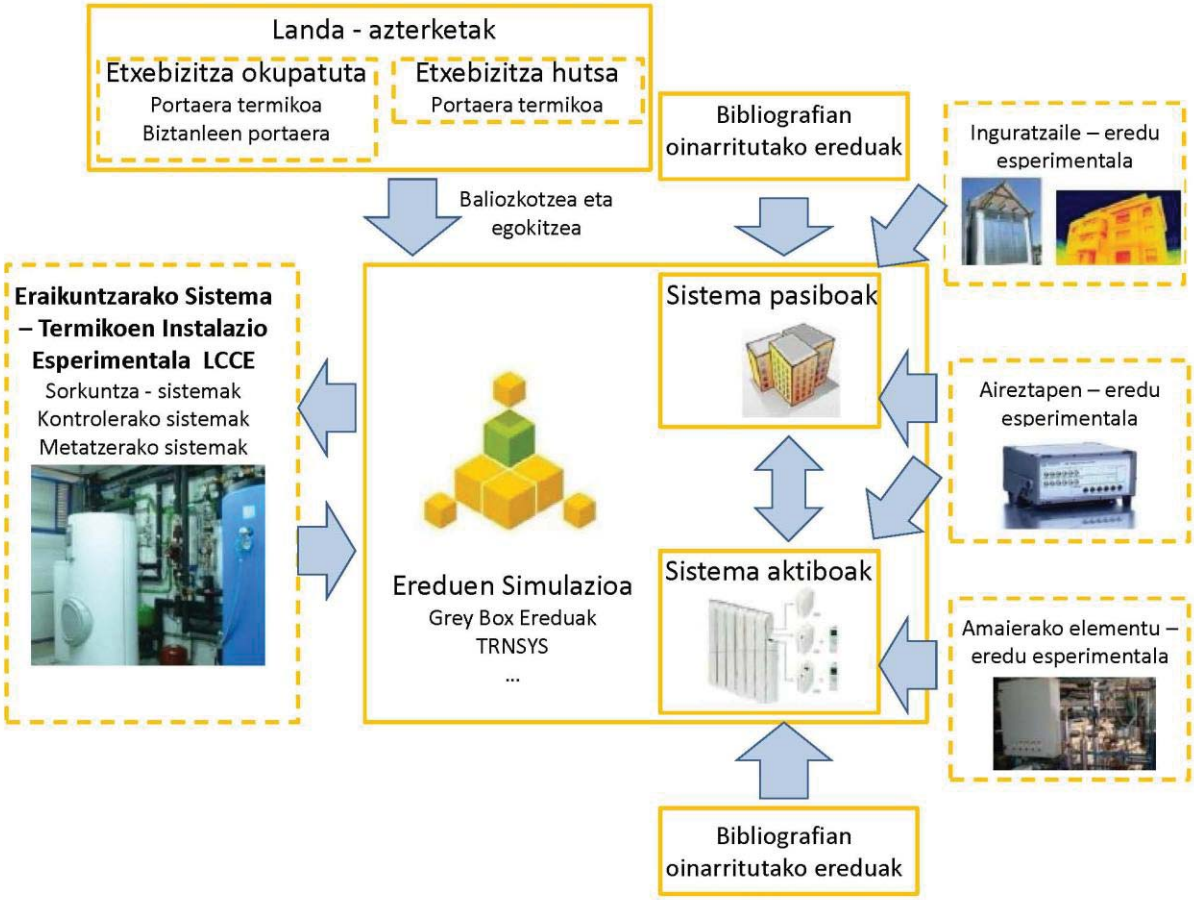
Doktorego – Tesi honen helburu nagusiak aurkezten dira kapitulu honetan, baita aipatutako helburuak erdiesteko jarraitutako metodologiari eta egiturari buruzko sarrera labur bat ere.

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 Tesiaren irismena

Tesi honetan garatutako ikerketa ENEDI taldeko ikerkuntzaren ildoetan kokatuta dago. Ikerkuntza ildo hauen eskema I2.1 irudian irudikatzen da.



I2.1. ENEDI taldeak jarraitutako ikerketa – lerroen eskema

Laburbilduz, bi ildo garatzen dira tesi honetan; bata esperimentala, eta beste bat simulazio - ereduei dagokiona. Atal esperimentalak azpisistemen zein eraikin osoaren saiakuntza esperimentalak barne hartzen ditu. Ikerkuntza esperimental honen bidez, bibliografia oinarri duten ereduekin batera, ereduak kalibratzeko eta erabiltzeko beharrezkoa diren datuak hartu daitezke. Bestalde, kalibratutako eredu hauek eraikuntzarako Sistema – Termikoen Instalazio Esperimentalean egiten diren saiakuntza erdi – birtualetan erabili daitezke. Testa hauetan, denbora errealeko ordenagailu bidezko – simulazioen emaitzak instalazio esperimentalean erabiltzen dira. Simulazio hauen emaitzak instalazio esperimentalean erabiltzen dira, eta aldi berean, instalazio esperimentalean lortutako neurriak simulazioan erabiltzen dira. Modu honetan, simulazioa eta saiakuntza esperimentala elkarri lotuta daude.

Horrela, ikerketa hau I2.1. irudian erakutsitako eskemaren barruan kokatzen da. Doktorego - tesi honetan eskemako bi zatitan jartzen da arreta: "landa azterketak" deritzon zatia, baita "simulaziorako ereduak" deritzona ere. Hori dela eta, doktorego - tesi honen atal esperimentalean eraikinen monitorizazioak aritzen dira, bai eraikin okupatuak, baita hutsak ere. Lortutako emaitzak geroago eraikinetako portaera termikoaren eredu bi garatzeko erabiltzen dira: *"Grey box"* eredu bat, eta *"White Box"* eredu bat.

Aipatutako eskema modularra da halaber. Eskemaren zati bakoitza bi modu ezberdinetan erabili daiteke: eskemako beste zati batekin elkarri eragiteko edo zati horretako informazio espezifikoa lortzeko. Hau da, batzuetan, irudikatutako prozesu osoa jarraitu daiteke; beste batzuetan, aldiz, simulazio zatia edo ikerketa esperimentala nahikoak dira bilatutako helburuak lortzeko.

Alderdi hau kontuan hartuz, eraikinen portaera termikoaren ereduei eta landa - azterketei dagokionez, garatutako posibilitateen abantailak eta desabantailak aztertzen dira tesi honetan, haien helburuak zein diren kontuan hartuz kasu bakoitzean.

2 Helburuak

Doktorego - tesi honen helburu orokorra eraikinen birgaitze energetikoaren ebaluaketari aurre egitea da, hau da, eraikinen birgaitzearen analisi eta optimizazio - prozesua aztertzea ondorengo atalak barne hartuz:

- Datu - eskuratzea eta monitorizazioa
- Datuen tratamendua: Eraikinen ereduak
- Tresnen analisia, ikuspuntu exergetikoarena esaterako, lortutako emaitzak ebaluatzeko eta hobekuntza potentzialak identifikatzeko.

Helburu hau bi eredu garatuz lortzen da, eta ikuspuntu exergetikoa hobekuntzarako estrategiak aztertzeko erabiliz.

Aipatutako xedea lortzeko, hurrengo helburuak betetzea espero da tesi honekin:

- Euskal etxebizitza parkeari gainbegiratu ikuspegi orokorra eman, arreta gizarte etxebizitzen sektorean jarriz. Bilboko gizarte etxebizitzak zehazki aztertzen dira, alderdi anitz kontuan hartuz: eraikuntza ezaugarriak, barne - giroaren baldintzak eta energia - kontsumoak. Bilboko etxebizitza parke soziala (Udal Etxebizitzak)[1] aurkezten da, eta urte bat baino gehiagotan zehar okupatutako etxebizitzen datuak lortzeko balio duen landa – azterketa bat egiteko hamar etxebizitza esanguratsu hautatzen direlarik.
- Eraikin baten portaera termikoari buruzko informazio zehatza eskuratu, hautatutako etxebizitza huts baten monitorizazioaren bidez. Ikerketa honetan hiru hilabetetan zehar eskuratutako datu ugari etxebizitzaren portaera termikoa karakterizatzeko erabiltzen dira.
- *Grey box* eredu bat garatu, aipatutako monitorizazioan lortzen diren datuak direla medio. Eredu hau birgaitze energetikorako aukera ezberdinak ekartzen dituzten energia - aurrezteak ebaluatzeko erabilgarria izango da.

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[1] Bere webgunean aurkezten duten bezala (https://www.bilbao.net/viviendas/), Udal Etxebizitzak erakundea baliabide eraginkorra da Bilboko Udalak etxebizitza babestuak sustatzeko politika aurrera eraman dezan. Helburua da beharrizana duten bilbotar guztiei etxebizitza baldintza duinetan eskaintzea eta, ahal dela, alokairuan. Bilboko Udal Etxebizitzak erakundeak kudeatu eta zaintzen duen higiezinen parkea 3.994 etxebizitzak osatzen dute.

- Eraikin adierazgarri baten portaera termikoaren modelo bat definitu, TRNSYS tresnaren bidez. Modelo hau landa - azterketan lortutako datuak erabiliz kalibratzen da. Modelo hau, berokuntza eskariaren kurbak zein energia - kontsumo ohiturak lortzeko erabiltzen da, besteak beste. Eskari - kurba hauek beste motatako eraikinen birgaitze energetikoak ikertzean erabilgarriak izango dira (sistema pasiboetan nahiz aktiboetan).
- Bi modeloak elkarrekin konparatu: *grey box* eta *white box* (TRNSYS tresnaren bidez garatutakoa) ereduak, beraien erabilera potentzialak identifikatuz eta bakoitzaren abantailak eta desabantailak aztertuz.
- Berokuntza kontrolerako estrategia ezberdinetan eraginak ebaluatu.
- Sistema energetikoen berriztatzeak eta eraikinen birgaitze energetikoak ebaluatzeko eta garatzeko ikuspegi exergetikoak duen erabilgarritasuna erakutsi.

3 Doktorego - tesi honen metodologia eta egitura

Zhenjun Ma et al.-ek diotenez [52], edozein eraikinen birgaitzerako proiektuan bost fase bereizi daitezke: (1) eraikinaren azterketa, (2) ebaluazio energetikoa, (3) birgaitze - aukeren identifikazioa, (4) inplementazioa kokalekuan eta (5) inplementazioaren ebaluazioa. Hauetako lau fase esplizituki edo inplizituki kontuan hartzen dira tesi honetan (1.a, 2.a, 3.a eta 5.a). Fase hauek tesi honen egitura ikusiz identifikatu daitezke, lau ataletan zatituta baitago.

Lehen atalak tesiaren sarrera, literatura aztertzea eta ikuspegi orokorra aurkezten ditu, lehen eta bigarren kapituluak barne hartzen dituelarik. Tesi honen bigarren atalak lan esperimentala garatzen eta aurkezten du, eta 3. eta 4. kapitulua barne hartzen ditu.

Etxebizitza parke sozialaren portaera termikoaren ikuspegi orokorra hirugarren kapituluan aurkezten da, Bilboko hamar etxebizitzaren landa azterketa bat dela medio. Aurrez, Bilboko gizarte etxebizitzaren analisi bat garatzen da, 20. Mendeko eraikuntzarako teknika ezberdinei berrikustea emanez. Hamar kasu - azterketen selekzioa ikerketa hau kontuan hartuz egiten da. Kasu - azterketen berokuntza eskarien eta barne - inguruko egoeren emaitzak aurkezten dira kapitulu horretan halaber.

Laugarren kapituluan 60. hamarkadan eraikitako etxebizitza bat zehatz - mehatz deskribatzen da. Bi datu - eskuratze aldi deskribatzen dira kapituluan: lehena, 2012ko Urtarriletik Apirilera egiten da, eta bigarrena 2012ko abendutik 2013ko otsailera egiten da, leihoak aldatu ondoren. Bi monitorizazio epeen emaitzak kapitulu honetan eskuratzen dira, baita metodologiari eta jarraitutako prozedurari buruzko ondorioak ere.

Hirugarren atalak eredu matematikoen deskribapena barne hartzen du. Bi kapitulu daude atal honetan: 5. eta 6. kapituluak. Kapitulu hauetan TRNSYS ereduaren ebaluazioa eta *grey box* ereduaren garapena aurkezten dira.

Bosgarren kapituluak monitorizatutako etxebizitzaren TRNSYS tresnaren bidezko eredu garapenean arreta jartzen du. Kasu honetan, landa - azterketan lortutako datuak erabiltzen dira TRNSYS eredua baliozkotzeko. Eredu hau eraikin adierazgarri batek Euskal Autonomia Erkidegoko klima ezberdinetan dituen eskari kurbak definitzera dago bideratuta. Bestalde, beste eraikin baten eraikuntza ezaugarriak erabiliz beste eskari kurbak lortu daitezke.

Seigarren kapituluan, laugarren kapituluan deskribatutako landa – azterketan lortutako datuak erabiliz, etxebizitza baten *grey box* ereduaren garapena jorratzen da. Eredu honen bidez, eraikinaren berokuntza - kontsumoa, eta bere portaera termikoa, lortu daitezke, baldintza ezberdinak kontsideratuz. Gainera, portaera termikoaren hobekuntzarako estrategia posibleen lorpenak aztertu daitezke. Esaterako, eredu honek etxebizitzaren portaera termikoa erakusten du, leihoak aldatu baino lehen. Parametro karakteristikoak aldatuz, eredu honek eraikinaren portaera termikoa leihoak aldatu ondoren zein den erakutsi dezake. Horrela, baldintza beretan konparaketa baten bidez, hobekuntza baten eraginkortasuna neurtu daiteke. Kapitulu honetan metodo honen erabilgarritasuna frogatzen da, batez ere eraikuntza birgaitzeari lotutako kasu batzuetan:

- Eraikin baten egoera edozein birgaitzerako lana baino lehen aztertzeko.
- Hobekuntza termikorako posibilitate ezberdinak aztertzeko, energia - aurrezteak kalkulatuz.

- Edozein birgaitze energetikoaren ondorio errealak ebaluatzeko, birgaitze baten aurretiko eta ondorengo egoerak irudikatzen dituzten ereduak baldintza berbetan elkarrekin konparatuz.

Laugarren atalak ereduaren bidez lortutako datuen tratamenduari aurre egiten dio. Beraz, zazpigarren kapituluan, aurretik garatutako TRNSYS eredua energia - aurrezterako neurri batzuk (neurri pasiboak) aztertzeko eta sailkatzeko erabiltzen da. Sailkapen hori neurri bakoitzaren energia aurreztearen arabera egiten da. Geroago, energia aurrezterako estrategia bat erabakitzen da, eta berokuntza sistemari lotutako parametro ezberdinak ebaluatzen dira, sistemaren tenperaturak eta kontrolak esaterako. Ebaluazio honek parametro bakoitzaren eraginak bai eraginkortasun energetikoan bai barneko erosotasunean aztertzen ditu. Kapitulu honetan aurkezten den kasuistika aurrerago plataforma erdi - birtualan egingo dituen saiakuntzak definitzeko erabili daiteke.

Geroago, 8. kapituluan eraikin baten analisi exergetikoa deskribatzen da. Kapitulu honek S. C. Jansenekin lankidetzaren fruitua den lana aurkezten du. Lan hau, 2012ko martxotik ekainera luzatu zena, TU Delft-eko Arkitektura Goi Eskola Teknikoan garatu zen eta *Energy & Buildings* Aldizkariko bi artikulutan aurkezten da [53,54].

Honela, 8. kapituluak ikuspegi exergetikoak eraikin sistema energetikoak garatzeko duen erabilgarritasuna ikertzen du. Horretarako, bost sistema ezberdin hartzen dira. Eraikinaren energia erabilera ikuspuntu globaletik ulertzen da, eta energiaren bidea, eraikinen inguratzaile termikotik energia ekoizpeneraino ikasten da, hobekuntzak bai inguratzaile termikoan baita sistema energetiketan ere kontuan hartuz.

Azkenik, 9. kapituluan, doktorego - tesi honen konklusio azpimarragarrien laburpen bat aurkezten da, baita ekarpenak eta proposatutako etorkizuneko lanak ere.

2. ATALA

AZTERKETA ESPERIMENTALA

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)

3. KAPITULUA

GIZARTE ETXEBIZITZAREN PORTAERA TERMIKOA. LANDA - AZTERKETA

LABURPENA

Eraikinen portaera termikoa aztertzeko metodologia bat deskribatzea du xede kapitulu honek. Horretarako, ikuspegi holistiko bat erabiliko da. Bilboko gizarte etxebizitza parkeari buruzko ikuspegi bat aurkezten da. Hamar etxebizitza adierazgarri hautatu ziren, lehen kapituluan aurkeztutako sailkapenean oinarrituz. Landa - azterketa 10 hilabetetan zehar garatu zen. Berokuntza sistemen kontsumoak, baita barne egoerak ere, aurkezten dira. Beste alderdi batzuen artean, biztanleen portaerak etxebizitzen portaera termikoan rol garrantzitsu bat jokatzen du. Bestalde, kapitulu honen emaitza nagusiak "Field assessment of thermal behaviour of social housing apartments in Bilbao, northern Spain" artikuluan aurkezten dira. Artikulu hau Energy & Buildings aldizkarian argitaratu zen 2013. urtean [55].

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 Sarrera

Barne tenperatura eta hezetasun erlatiboa eraikinetan biztanleen erosotasun termikoaren adierazle giltzagarriak dira.

Birgaitze energetikoak dakarren energia aurrezteak kalkulatzeko simulazio eredu ugari garatu dira azken urteetan. Kavgic et al.–en arabera [56], operazio – baldintzenetarako erabilitako hipotesiak profil estandarretan oinarritzen dira landa – azterketetan oinarritu beharrean.

Etxebizitzen egoera estandarren eta egoera errealen arteko ezberdintasunek emaitza okerrak eman ditzake energia-kontsumoan, kontsumo honek setpoint - tenperatura aldaketaren menpekotasun handia baitu. Adibidez, duela gutxi berokuntza sistema zentrala zuen Erresuma Batuko etxebizitza baten inguruan egin zen ikerketa batean, berokuntza sistemako setpoint - tenperaturaren 2ºC igoerak kontsumo energetikoaren %15eko hazkuntza ekartzen duela frogatu zen. Kontutan izan behar da kontsumo hau eraikinaren beste ezaugarri batzuen menpekoa dela, esaterako infiltrazio tasa, inguratzaile ezaugarri termikoak edo erabilitako berokuntza-sistema.

Horregatik, gizarte etxebizitzan birgaitze energetikoaren potentzialaren analisi zehatzagoa lortzeko barne-egoeren landa-azterketak garatzea beharrezkoa da. Izan ere, barne ingurunea eta berari lotutako energia-kontsumoari dagokionez, datu enpirikoen gabezia dago, gizarte etxebizitzaren sektorean batik bat.

Kapitulu honetan, hamar etxebizitzen landa-azterketa bat aurkezten da. Azterketa hau ikuspuntu holistikotik egin zen, etxebizitza bakoitzaren portaera termikoaren ikuspegi bat lortzeko. Eraikin mota ezberdinetan barne-erosotasuna eta energia-kontsumoa aztertzeko asmoz antzeko landa - azterketa anitz aurkitu daitezke: energia - baxuko eraikinetan [30], bulegoetako eraikinetan [57] edo eraikin historikotan [48,49,58]. Hala ere, ikerketa mota hauek gizarte etxebizitzaren sektorean aurkitzea ez da hain ohikoa. Salbuespen bat aipatutako *Warm Front Project* taldeak egin dituen eskala handiko lanketetan aurkitu daiteke [59].

2 Kapitulu honen helburuak

Lehen kapituluan eraikinen birgaitze energetikoaren lege-eremuari eta eraikuntza ezaugarri orokorrei buruzko laburpen bat eman da. Hala eta guztiz ere, soilik alderdi hauek kontuan hartzea ez da nahikoa, eta eraikinen birgaitzea lantzerakoan eraikinen portaera termikoa ikuspuntu globaletik ezagutu behar da. Eraikuntzaren portaera termikoa sistema konplexu batean eragina duten faktore ezberdinen arteko elkarrekintzen ondorio bezala ulertu behar da.

Horregatik kapitulu honetan, Gizarte etxebizitza parkearen portaera termikoaren landa - azterketa bat aurkezten da. Horrenbestez, kapitulu honen helburu nagusiak hurrengoak dira:

- Eraikinen portaera termikoaren azterketa egiteko erabiliko den ikuspegi holistikoa aurkeztu eta zehaztu.
- Bilboko Gizarte Etxebizitza parkearen portaera termikoa ulertu, eta bere energia - kontsumo erreala identifikatu.
- Bilboko Gizarte Etxebizitza parkearen hobekuntza termikoaren potentziala kalkulatu, Bilbo klima epeleko hiri bat dela kontutan hartuz, bai neguan, zein udan ere.
- Hamar etxebizitza hauetako energia kontsumoa eta barne ingurunearen neurriak lortu. Datu hauek biztanleen profilak xedetzeko beste ikerketan erabili daitezke, eta horrela, estandar egoeretan oinarritako profilak ez lirateke erabili behar, landa azterketan oinarritakoak baizik.

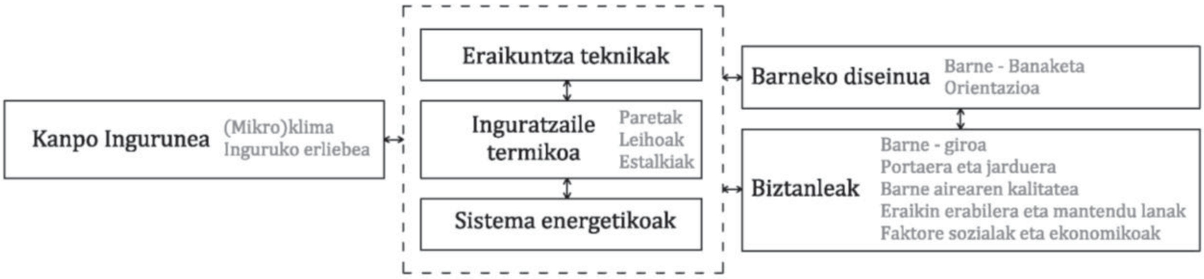
- Metodo holistikoaren bidez hautatutako hamar etxebizitzen bidez, Gizarte Etxebizitza parkearen portaera termikoaren analisi konparatibo eta kualitatiboa garatu.

Kapitulu honen arreta ez da soilik energia kontsumoan oinarritzen, baizik eta etxebizitzen konfort termikoan ere. Alabaina, lehen kapituluan aipatzen diren osasunari lotutako alderdiak kapitulu honen irismenaren kanpo daude, nahiz eta edozein birgaitze energetikoen hobekuntzak ebaluatzean kontuan hartu behar diren.

Helburu hauek betetzeko asmoarekin, lehen kapituluan aurkeztutako diren irizpideen arabera Bilboko Gizarte Etxebizitza parkea sailkatu da. Sailkapen hau erreferentzia gisa erabiliz, XX. mendeko sasoi bakoitzaren adierazgarriak diren hamar Gizarte Etxebizitza, ikuspuntu holistikotik arakatzen dira. Lortutako emaitzek datu - base garrantzitsu bat emango dute euskal etxebizitza parkearen birgaitzearen potentziala zenbatzeko.

3 Planteamendua

Kanpo esposizio egoerek (mikroklimak) eta transmisio termikoa erregulatzeko inguratzaile termikoaren gaitasunak eraikinaren portaera termikoa ezartzen dute. Etxe barneko erosotasun termikorako baldintzak pasiboki termo - erregulatzeko gaitasun hau, inguratzailea osatzen duen materialen eta itxura geometrikoaren araberakoa da. Aldi berean, etxebizitzaren barne - banaketak, zein instalazio energetikoei pertsonek emandako erabilera, zein instalazio termiko hauen ezaugarriek eraikin baten portaera termikoa definitzen dute.



I3.1. Hartutako azpisistemak

Aipatutako alderdi guztiak kontuan hartzeko, azterketa honetan ikuspegi holistikoa erabiltzen da. Ikuspegi sistemiko honetan, eraikinek sistema ireki bezala jokatzen dute, beraien eta bere inguruaren arteko elkarrekintzak aintzat hartuz. Eraikin historikoak aztertzeko antzeko planteamenduak erabiltzen eta azaltzen dira [58] erreferentzian, baita Annex 53an ere. Annex honen arabera, sei faktorek parte hartzen dute eraikinen energia kontsumoan: Klima, inguratzaile termikoa, sistema energetikoak eta instalazioak, eraikinaren erabilera eta mantentze - lanak, biztanleen jarduerak eta portaera eta emandako barne - ingurumenaren kalitatea [29]. Z. Yu et al.-ek antzeko zerrenda bat aurkezten dute beste ikerketa batean [60]. Kapitulu honetan erabiltzen den planteamendua erreferentzia hauek kontuan hartuz garatu zen. Hartutako azpi - sistema ezberdinak erakusten dira I3.1 irudian.

Eraikuntza teknikak, inguratzaile termikoa eta sistema energetikoak "muga - azpisistema" batentzat har daitezke. Azpisistema honek barne eta kanpo ingurumenen arteko banaketa markatzen du [61]. Faktore hauen arteko elkarrekintzak etxebizitzaren portaera termikoa dakar.

Orokorrean birgaitze energetikoaren arreta hiru azpisistemen hobekuntzan jartzen da: Eraikuntza tekniketan (esaterako, zubi termikoen efektuaren murrizpenean), inguratzaile termikoan eta sistema energetikoetan. Hala eta guztiz ere, edozein birgaitzearen oinarria sarritan azpisistema hauen hobekuntzan dagoen arren, azpisistema guztien elkarrekintzak eta elkarrekintza hauen ondorioak etxebizitzaren energia kontsumo globalean aintzakotzat hartzea garrantzitsua da. Kapitulu honetan aurkezten den azterlana ikuspegi sistemiko hau kontuan hartuz garatu zen.

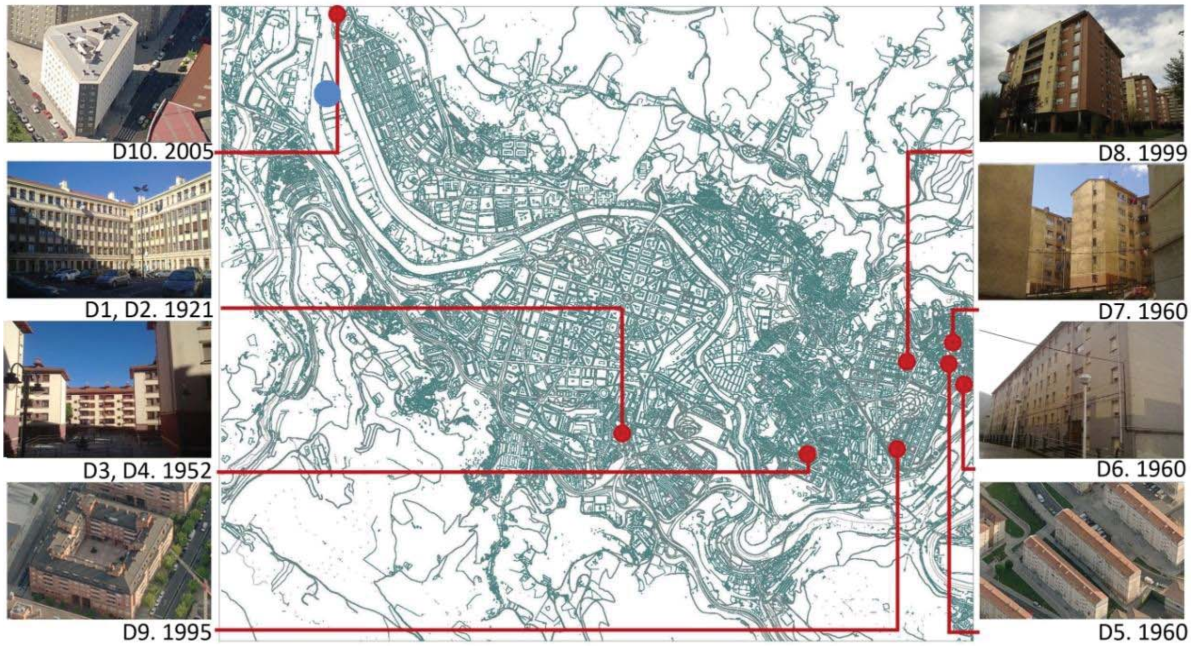
4 Metodologia

Landa - azterketa hau Bilbon garatu zen 10 hilabeteko iraupenarekin, 2011.eko Azarotik 2012.eko Irailera arte. Datu - eskuratzea egiten zen bitartean, etxebizitza guztiak okupatuta zeuden. Hauetako hiruren biztanleak jabeak ziren; beste kasu guztiak, berriz, errentako etxebizitzak ziren. Faktore hau alderdi ekonomikoei oso lotuta dago, eta familia - errentaren adierazletzat hartu daiteke, behintzat lan - azterketa honetan (jabeak ziren biztanleek ez zirenek baino errenta handiagoa zeukaten). Lehen kapituluan aipatu bezala, maila ekonomikoak biztanleen portaera energetikoan eragina du, eta horregatik, kontuan hartu behar da. Berokuntza sistemari dagokionez, hamar etxebizitzetan zehar ezberdintasunak aurkitu daitezke. Etxebizitzetako lauk gas naturala erabiltzen dute berokuntza eta ur berotarako, hiruk berogailu elektrikoak erabili zuten, batek keroseno - berogailua, beste batek butano - berogailua eta etxebizitza batean ez zegoen berokuntza sistemarik. Ikertutako etxebizitza bat bera ere ez zuen aireztapen mekanikorik.

Klimari dagokionez, Bilbo 43º N latitudean dago, eta itsasaldeko klima dauka. Itsasoaren hurbiltasunaren ondorioz, udako eta neguko tenperaturak epelak dira. Udako batez besteko tenperatura altuena 25 - 26 gradu inguru izan ohi da, eta neguko batez besteko tenperatura baxuena 6 - 7 gradu inguru izan daiteke.

4.1 Kasu - azterketen aukeraketa

Landa azterketa hau garatzeko hamar gizarte etxebizitza hautatu ziren (I3.2 irudia). Etxebizitza hauen hautaketa lehen kapituluan aurkeztu diren ezaugarrietan oinarritu zen ("Eraikuntza sailkatzeko irizpideak" atalean). Horrela, atal horretan aipaturiko sasoi guztietarako gutxienez bi etxebizitza zeuden laginean. Ikerketa honetan, 2005. urtean eraikitako etxebizitza berri bat ere gaineratu zen (Eraikuntzaren Kode Teknikoa onartu baino urte bat lehenago). I3.2 irudian agertzen den puntu urdinak ikerketan erabili diren estazio meteorologikoaren kokapena adierazten du. Estazio hau etxebizitzekiko hurbiltasunagatik aukeratu da.



I3.2. Hamar kasu azterketen kokapena

Eraikuntzaren ezaugarriei dagokionez, hautatutako etxebizitzak ez dira soilik Bilboko gizarte etxebizitza parkearen adierazgarri, baizik eta eskualdearen hiri - herrialde askoko parkearenak ere.

Etxebizitza bakoitza egitura konplexutzat hartzen da, kasu batzuetan biztanleen beharra ezberdinetara egokitzeko eraldatu dena. Alderdi eta ezaugarri ezberdinak kontuan hartu ziren etxebizitza bakoitzean, kapitulu honen 3. atalean azaltzen den ikuspegiaren arabera. Alderdi hauetako batzuk zerrendatzen dira T3.1 taulan (I3.1 irudian aurkezten diren mailaren arabera)

Taula honetan etxebizitza bakoitzaren antzinatasuna, azalera (metro karratuetan), fatxadeko ezaugarriak (Lehen kapituluan aurkeztutako sailkapenari lotuta), fatxadaren U - balioa, leihoen ezaugarri termikoak (beira eta marko mota, leihoen U - balioa eta infiltrazioen maila) erabilitako berokuntza - sistema eta azkenik, etxebizitzaren jabetasun mota aurkezten dira. Okupazio faktore batzuk, hala nola biztanleen adina, biztanle kopurua edo okupazio aldia, aintzakotzat hartu ziren ere.

		B.I.	**Inguratzaile**			**Leihoak**			**S.E.**	**Okup.**
Izena	**Urtea**	**Azalera (m^2)**	**Sek.**	**U_{wall} [W/m^2.k] (kalk)**	**C_{wall} [kJ/m^2.K] (kalk)**	**Leihoak**	**U_{win} (kalk)**	**Inf.**	**Berokuntza**	**Jabetasuna**
D1	1921	53.33	F.a	1.11	463.8	Egurra (f); Beira 6	5.35	Altua	Butano	Alok
D2	1921	45.68	F.a	1.11	463.8	PVC (m); Beira 4/6/4)	2.38	Baxua	Berogailu elektr.	Alok
D3	1952	51.5	F.b	1.16	359.8	Al (f); Beira 6 – Egurra (f); Beira 6	5.35 - 5.70	Altua - Erdi.	Berogailu elektr	Alok
D4	1952	51.5	F.b	1.16	359.8	Al (m); Beira 4/6/4)	3.37	Altua	Ezer ez	Alok
D5	1960	47.68	F.c.1	1.27	180	PVC (m); Beira 4/6/4)	2.38	Baxua	Gas Naturala	Jabet
D6	1960	39.7	F.c.2	0.43	238.4	PVC (m); Beira 4/6/4)	2.38	Baxua	Berogailu elektr	Alok
D7	1960	47.65	F.c.1	1.27	180	PVC (m); Beira 4/6/4)	2.38	Baxua	Gas Naturala	Jabet
D8	1995	68.3	F.d	0.48	189	PVC (m); Beira 4/6/4)	2.38	Baxua	Gas Naturala	Alok
D9	1995	87	F.d	0.48	189	PVC (m); Beira 4/6/4)	2.38	Baxua	Gas Naturala	Jabet
D10	2005	58.5	F.e	0.41	162.6	PVC (m); Beira 4/6/4)	2.38	Baxua	Kerosen o	Alok

T3.1. Aztertutako etxebizitzen ezaugarriei buruzko laburpena, I3.1 irudian aurkestutako azpisistemen arabera

4.2 Landa – azterketa

Aipatutako ikuspegi sistemikoa aintzakotzat hartuz, etxebizitza bakoitzean landa - azterketa egin zen. Lortutako datuak sei taldetan antolatu ziren, I3.1 irudian aurkeztutako sei azpisistemen arabera. Landa - neurketaren eta datu bibliografikoen bidez, kanpoko egoeraren datuak hartu ziren. Termografien bidez, eraikuntza teknikei buruzko datuak eskuratu ziren. Sistema energetikoei dagokionez, faktura energetikoen eta inkesten bidez informazio ugari lortzen da. Barne – egoerari buruzko datuak lortzeko, planoak eta landa - neurketak erabiltzen dira. Azkenik, biztanleen azpisistemako datuak inkesten bitartez jaso ziren. Inkesten bidez lortutako datuak landa - neurketen bidez lortutakoekin balioztatzen dira (T3.2 taula).

Azpisistema	Datuak	Informazio - iturria
Kanpoaldeko ingurumena	Parametro Geografikoak (Lat, Long)	landa - neurketak, Datu bibliografikoak
	Zona klimatikoa, eguzki - erradiazio	landa - neurketak, Datu bibliografikoak
	Mikroklima, Kanpoaldeko tenperatura eta hezetasun erlatiboa.	WEB datuak, Neurketak.
Eraikuntza teknikak	Zubi termikoak	Termografia
Inguratzailea	Fatxadaren ezaugarri termikoak	Datu bibliografikoak
Sistema Energetikoak	Sistema energetikoak	Inkestak, Energia - fakturak
Barne - banaketa	Etxebizitzaren barne - banaketa	Planoa, landa - neurketak.
Biztanleak	Barne ingurumena: planoak, sekzioak, fatxadak	landa - neurketak
	Jarduerak, portaera, ingurumen kalitatea	Inkestak, landa - neurketak

T3.2. Bildutako datuak

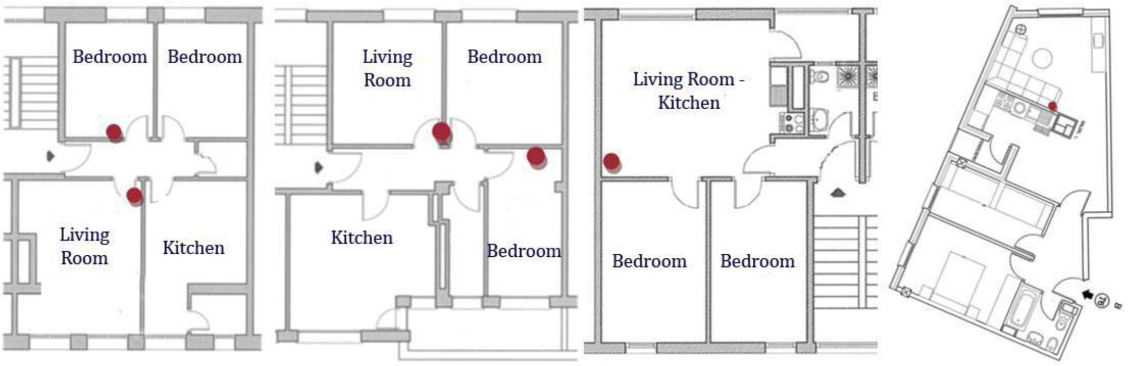
4.3 Datu - bilketa

4.3.1 Tenperatura eta hezetasun erlatiboa

Tenperatura eta hezetasunarekin erlazionatutako datuak lortzeko landa - azterketa asko aurki daitezke bibliografian. E. J. Hutchinson et al.-ek [62] erreferentzian aurkezten dituzten irizpideak erabiltzen dira kapitulu honetan. Irizpide hau kontuan hartuz, barne - tenperatura eta hezetasun erlatiboaren datuak '*Temp - RH Hobo Data loggers'* termo - higrometroen bidez (HOBO U12 - 011) jaso ziren. Termohigrometro honen bereizmena 0.03 gradukoa (25 ºC) da tenperaturarentzat eta %0.03koa hezetasun erlatiboarentzat; bere zehaztasuna, ±0.35 ºC eta ±%2.5koa da hurrenez hurren. Leihoetatik eta bero -

iturrietatik urrun kokatzen dira, eta metro bat inguruko altueran. Altuera hau hautatu zen, estratifikazio termikoa egonez gero, altuera hori biztanleen sentikortasun termikoarenaren antzekoa kontsidera daitekeelako. Bestalde, 1 m-ko altuaren aukeraketa beste ikerketa batzuetan erabili da ere.

Datu - erregistratzaileak hamar minuturo datuak hartzeko programatzen dira. Bibliografian aurki daitezkeen beste maiztasunak, 20 minutuetatik [63] 2 ordutara [58] doaz. Hala ere kapitulu honetan, 10 minutuko maiztasuna hautatzen da, maiztasun honi esker, biztanleen portaerari buruzko informazioa lortu baitaiteke, esaterako berokuntza sistemaren erabilera edo aireztapen profilak. Erabili ziren datu erregistratzaileak aldez aurretik Eusko Jaurlaritzako Eraikuntza Kalitatearen Kontrolerako Laborategian balioztatu eta kalibratu ziren. Termohigrometroa etxebizitza bakoitzeko gela nagusian (kasu gehienetan, egongelan) kokatzen da. Etxebizitza batzuetan, beste termohigrometro bat kokatzen da ere, logela nagusian alegia. (I3.3 irudian lau etxebizitzetako termohigrometroen kokapena irudikatzen da; Beste kasu guztiak 3.2. eranskinean aurkezten dira). Beste ikerketa askotan antzeko irizpideak jarraitu dira, esaterako [58] edo [43].



I3.3. Kasu – azterketa batzuen planoak (D1, D3 - D4, D6 eta D10)

Kanpo tenperaturari eta hezetasun erlatiboari buruzko datuak Deustun dagoen Eusko Jaurlaritzaren estazio meteorologiko batetik eskuratu ziren. Estazio honek aldagai anitz neurtzen ditu, besteak beste, aireko tenperatura, hezetasun erlatiboa, eguzki - erradiazio horizontala eta haizearen abiadura, Gainera, estazio honetan neurritzeko erabiltzen den maiztasuna 10 minutukoa da, eta termohigrometroarekin bat dator Bere kokalekua I3.2 irudian markatzen da puntu urdin baten bidez.

4.3.2 Energia - kontsumoa

Neguko berokuntzaren energia - kontsumoa kalkulatzeko, hipotesi batzuk burutu behar dira. Erabilitako informazio - iturriak etxebizitzaren arabera ezberdinak ziren: hamar etxebizitzetik seitan faktura energetikoak lortu ziren. Beste bi etxebizitzetan, berokuntza - kontsumoak galdeketa baten bidez lortu ziren. D4 etxebizitzan ez dago berokuntza sistemarik. Berez, berogailu elektriko bat erabiltzen da noizbehinka, baina bere kontsumoa baztergarritzat jo daiteke. D5eko kasuan berriz, faktura energetikoetatik lortutako datuak, kontagailuaren irakurketa batzuekin osatzen dira.

Etxebizitza bakoitzean bildutako datuak T3.3 taulan aurkezten dira. Bertan, etxebizitza bakoitzaren energia - kontsumoari buruzko informazio - iturriak aurkezten direlarik. Hala ere, data - multzo hauek beraien aldagarritasunaren ondorioz estandarizatzea beharrezkoa izan zen, (etxebizitza batzuetan soilik elektrizitatea erabiltzen zen, eta beste etxebizitza batzuetan, aldiz gas naturala etxeko ur bero eta berokuntza instalazioetarako). Kasu guztietan, berokuntza kontsumoa estrapolatu zen epe berdinerako (Abenduaren 1etik Apirilaren 1era), kasu guztietan berokuntza sistemak Abenduaren bigarren edo hirugarren astetik Martxoaren azken asterarte erabili baitzen.

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

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

Neguko berokuntza kontsumoa kalkulatzearren, Eq. 3 eta Eq. 4 erabili zen. En_B batez besteko eguneko oinarri energia kontsumoa da; En_{sum} udan kontsumitzen den energia da; En_{win} neguan kontsumitzen den energia da; H_{wint} kalkulatutako neguko berokuntza kontsumoa da; n_{sum} udan ebaluatutako egun - kopurua da eta n_{wint} neguan ebaluatutako egun - kopurua da. En_B (kWh/egun) udako eguneko energia kontsumoa kontuan hartuz kalkulatu zen. Metodo hau berokuntza kontsumoa zenbatzeko hurbilketa on bat da, ur bero eta berokuntza horniketa gas naturala galdara baten bidez egiten denean batez ere. Etxeko ur bero kontsumoa urtean zehar aldaketa handirik ez daukala onar daiteke. Beraz, berokuntza kontsumoa (soilik neguan), neguko gas natural kontsumoaren (etxeko ur bero + berokuntza) eta udakoaren (etxeko ur beroa soilik) arteko kenduraren bidez kalkulatzen da.

		Datu - bilketa		Kalkulatutako kontsumoa (1 Abe-1 Api)
	Informazio iturria	**Aldia**	**Kontsumoa**	**Hipotesiak**
[D1]	Galdeketak	Negua	4 butano - bonbona	1)
[D2]	Faktura elektrikoak	24 Aza - 20 Mar	1840 kWh	3) (Oinarri kontsumoa: 4.16 kWh/day)
[D3]	Faktura elektrikoak	12 Abe - 11 Api	863 kWh	3) (Oinarri kontsumoa: 4.16 kWh/day)
[D4]	Ez - Aplikagarri	Ez – Aplik.		MESPRETXAGARRI
[D5]	Gas Naturalaren Fakturak	18 Abe - 17Api	3600 kWh	2) (Oinarri kontsumoa: 6 kWh/day)
[D6]	Faktura elektrikoak		datu erabilgarririk ez dago	
[D7]	Gas Naturalaren Fakturak	15 Abe - 14Mar	3936 kWh	2) (Oinarri kontsumoa: 6 kWh/day)
[D8]	Gas Naturalaren Fakturak	15 Aza - 14Mar	2145 kWh	2) (Oinarri kontsumoa: 6.7 kWh/day)
[D9]	Gas Naturalaren Fakturak	15 Aza - 14Mar	3990 kWh	2) (Oinarri kontsumoa: 5 kWh/day)
[D10]	Galdeketak	Negua	20 l keroseno	4)

T3.3. Berokuntza kontsumoen datuak

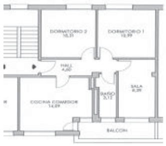
	Kalkulatutako Kontsumoa [kWh]	**Berotutako gelak**	**m^2 (Berot. azalera)**	**Kontsumoa [kWh/m^2.urte]**	**Zuzendutako kontsumoa [kWh/m^2.urtea]**
[D1]	636	Logelak (x2), Sukaldea	33.87	11.93	18.78
[D2]	1354	Etxebizitza osoa	45.68	29.64	29.64
[D3]	356	Egongela	10.31	6.91	34.52
[D4]		Ez - Aplik.			
[D5]	2880	Etxebizitza osoa	47.65	60.44	60.44
[D6]		datu erabilgarririk ez dago			
[D7]	3331	Etxebizitza osoa	47.65	67.37	67.37
[D8]	1335	Etxebizitza osoa	68.3	19.55	19.55
[D9]	3385	Etxebizitza osoa	87	38.91	38.91
[D10]	188	Egongela	12.6	3.21	14.92

T3.4. Bildutako berokuntza sistemaren kontsumoa eta kalkulatutako datuak

Horrenbestez, hurrengo hipotesiak hartu ziren oinarritzat, berokuntza kontsumoak kalkulatzeko:

1) 159 kWh / Butano - bonbona.
2) Eguneko oinarri - kontsumoa (berokuntza kontuan hartu barik) kalkulatzen da udako kontsumoaren datuak erabiliz (Eq. 3 ekuazioa). Neguko berokuntza kontsumo zenbatekoa Eq. 4 ekuazioaren bidez lortzen da.

3) Kasu honetan, IDAE-k dion oinarri - kontsumo elektrikoa erabiltzen da (etxebizitzaren udako kontsumoa oso aldakorra izan baitzen). Kalkulatutako neguko berokuntza kontsumoa Eq. 4 ekuazioaren bidez lortzen da.
4) Erabilitako kerosenoren berotze - ahalmena: 43,400 kJ/kg (9.4 kWh/l)

Berotutako azaleraren ezaugarri geometrikoak				
				
D1	D2	D3	D4	D5
				
D6	D7	D8	D9	D10

	Fatxadaren azalera (m², berotutako espazioarena)	IF		Fatxadaren azalera (m², berotutako espazioarena)	IF
[D1]	*Etxebizitzaren fatxada:* 32.5 (Fatxada) 6.5 (Leihoak; 20%) *Berotutako espazioarena:* 22.5 (Fatxada) 4.5 (Leihoak; 20%)	1.67	[D6]	*Etxebizitzaren fatxada:* 27.9 (Fatxada) 7 (Leihoak; 25%)	1.43
[D2]	*Etxebizitzaren fatxada:* 29.75 (Fatxada) 5.55 (Leihoak; 20%) *Berotutako espazioarena:* 29.75 (Fatxada) 5.55 (Leihoak; 20%)	1.51	[D7]	*Etxebizitzaren fatxada:* 41.25 (Fatxada) 10.23 (Leihoak; 25%) *Berotutako espazioarena:* 41.25 (Fatxada) 10.23 (Leihoak; 25%)	1.16
[D3]	*Etxebizitzaren fatxada:* 35 (Fatxada) 8.75 (Leihoak; 25%) *Berotutako espazioarena:* 7.5 (Fatxada) 1.95 (Leihoak; 26%)	1.37	[D8]	*Etxebizitzaren fatxada:* 46.8 (Fatxada) 11.5 (Leihoak; 25%) *Berotutako espazioarena:* 46.8 (Fatxada) 11.5 (Leihoak; 25%)	1.71
[D4]	*Etxebizitzaren fatxada:* 35 (Fatxada) 8.75 (Leihoak; 25%)	N/A	[D9]	*Etxebizitzaren fatxada:* 42.9 (Fatxada) 10.7 (Leihoak; 25%) *Berotutako espazioarena:* 42.9 (Fatxada) 10.7 (Leihoak; 25%)	1.59
[D5]	*Etxebizitzaren fatxada:* 41.25 (Fatxada) 10.23 (Leihoak; 25%) *Berotutako espazioarena:* 41.25 (Fatxada) 10.23 (Leihoak; 25%)	1.16	[D10]	*Etxebizitzaren fatxada:* 35.9 (Fatxada) 7.7 (Leihoak; 21%) *Berotutako espazioarena:* 14.95 (Fatxada) 2.72 (Leihoak; 18%)	0.86

T3.5. Berotutako azaleraren ezaugarri geometrikoak (IF: Inguratzaile Faktorea= Berotutako azalera (m^2)/Berotutako espazioaren fatxadaren azalera (m^2)

Bestalde, etxebizitza batzuek soilik gela batzuetan berokuntza sistema zeukaten (eta ez etxebizitza osoan). Kontu hau beste oztopo bat izan zen berokuntza kontsumoaren zenbatespena egiteko. Galdeketek eta neurketek erakutsitakoaren arabera, etxebizitza batzuetan (D1, D3 eta D10) soilik gela bat edo pare bat berotu ziren (ikusi T3.5 taula). Energia - kontsumoa egokitzeko eta metro bakoitzeko energia - kontsumoaren balio adierazgarriago bat lortzeko helburuarekin (kWh/m^2), berokuntza kontsumoaren (kWh) eta berotutako azalera errealaren (m^2) arteko harremana kalkulatu zen kasu bakoitzeko. Lortutako balio hauek, berez etxebizitzak elkarrekin konparatzeko erabili zirenak, T3.4 taulan biltzen dira.

Aipatutako etxebizitza bakoitzaren berotutako azalerari buruzko informazioa, baita inguratzaile termikoaren ezaugarri geometriko batzuk ere, T3.5 taulan zerrendatzen dira. Lehen lerroetan, etxebizitza bakoitzaren planoak irudikatzen dira, berotutako azalera gorriz nabarmentzen delarik. Beherago, etxebizitza bakoitzaren balio geometrikoak aurkezten dira, baita "inguratzaile - faktorea" (IF) ere. Faktore hau berotutako azaleraren eta berotutako espazioari dagokion fatxadaren azaleraren arteko ratioa da.

4.3.3 Termografiak

Landa azterketa egitean, termografietan oinarritutako azterketa bat burutu zen, bi azpisistema aztertzeko intentzioarekin: inguratzaile termikoa eta eraikuntza teknikak. Termografia erradiazio infragorrian oinarritutako teknika da. Zero absolutua baino tenperatura altuagoa edukitzeagatik, objektu guztiek erradiazio infragorria igortzen dute. Kamara infragorri batek erradiazio hau neurtzeko ahalmena du, eta gorputz beltzaren erradiazioaren legearen arabera azaleko tenperatura ematen du. Tenperatura hau, gorputz griserako emisibitatearekin zuzendu behar da.

Termografien bidez, inguratzailearen heterogeneotasun termikoak aurkitu daitezke (zubi termikoak, esaterako), edo U - balioaren aldaketak fatxadaren azal ezberdinetan. Jarraian ebaluazio infragorrian eragin handia daukaten alderdi batzuk definitzen dira [64]:

- **Emisibitatea (ε).** Azal batek igortzen duen energiaren eta tenperatura berberako gorputz beltz batek igortzen duenaren arteko ratioa da.

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

Eraikuntzako material gehienek 0.85 eta 0.95 tarteko emisibitatea dute, horregatik kamara infragorrian 0.9ko balioa erabili ohi da. Baina emisibitate baxuko materialen bat aztertu nahi bada, parametro honen aldaketa kontutan izan beharko da, tenperaturaren neurketan errore handirik ez jasotzeko.

- **Hezetasun erlatiboa (RH).** Lizunaren agerpena ez da beti detektatzen erradiazio infragorriaren bidez. Hala eta guztiz ere, lizuna agertu daitekeeneko leku kritikoak identifikatzea posiblea da. Kasu zehatz batzuetan, %50ko hezetasun erlatiboa baino balio altuagoa baldintza nahikoa izan daiteke bere garapenerako.

- **ΔT.** Barne tenperaturaren eta kanpokoaren arteko diferentzia gutxienez 10 - 15 ºC izatea komenigarria da termografiak egiten direnean.

- **Eguzki - erradiazioa.** Eguzki-erradiazioak fatxadetan duen eragina saihesteko eguzki-argia dagoenean termografiarik ez egtea gomendatzen da. Hau horrela izanda, eraikinen inertzia termikoa aintzakotzat hartu behar da ere. Eguzkia ezkutatu ondoren, eraikineak egunean zehar hartutako eguzki beroa askatzen du, eta efektu hau bero - galerak bezala gaizki ulertu daiteke.

Beste faktore batzuk (objekturekiko distantzia, airearen tenperatura, aireko hezetasun erlatiboa, haizea edo islatutako tenperatura, adibidez) kontuan hartu behar dira ere bai, batik bat analisi kuantitatiboa egiterakoan.

Parametro hauen arabera, argazki termikoak FLIR kamara infragorri batekin (PS60 eredua) egin ziren. Bere zehaztasuna tenperaturaren neurketan %2koa da. Kalkuluetan erabilitako emisibitatea 0.9 da, eraikuntza material gehienak emisibitate altuak baitauzkate. Argazki termikoak bi gau ezberdinetan egin ziren: 2012ko otsailaren 28an (1 am – 4 am) eta 2012ko martxoaren 2an (0 am – 1 am). Lehen gauean, tenperatura 6.5 gradukoa izan zen, eta hezetasun erlatiboa %88koa. Bigarrenean aldiz, tenperatura 9 gradukoa izan zen, eta hezetasun erlatiboa %88koa. Aurretiko egunean ez zuen euririk egin.

4.3.4 Erosotasun termikoa

Erosotasun termikoari buruzko ikerketan arreta berezia jarri zen. Erosotasun termikoa eta barne ingurumen osasuntsua edozein eraikinaren helburu garrantzitsuenetako bi dira. Kapitulu honetan erabilitako ikuspegian, alderdi hauek "Biztanleak" azpisisteman barneratu ziren. Faktore ezberdinek rol garrantzitsua jokatzen dute ingurune erosoaren definizioan, esaterako aireko tenperatura, hezetasun erlatiboa, haizearen abiadura, biztanleen jarduera edo arropa mota. Erosotasun termikoa aztertzeko PMV (*Predicted mean vote*, ingelesez) edo PPD (*Predicted Percentage Dissatisfied*, ingelesez) indizeak erabiltzen dira. PPD-ren definizioa PMV-ren terminoetan oinarritzen da. PMV jarduera, arropa, aireko tenperatura, tenperatura erradiatzaile, haizearen abiadura eta hezetasunaren araberakoa da [65]. Kapitulu honetan deskribatutako ikerketa okupatuta zeuden etxebizitzetan egin zenez, zenbait muga aurkitu ziren instrumentazioarekin, eta horren ondorioz, ezin izan ziren aipatutako parametro guztiak neurtu. Horregatik, metodo erraztu bat planteatu zen etxebizitzen erosotasun termikoaren ebaluazioa egiteko. Erabilitako metodoa 6.6 atalean aurkezten da.

4.3.5 Galdeketak

Ikerketa hau osatzeko, landa azterketa hasterakoan etxebizitza bakoitzaren biztanleek galdeketa - orri bat osatu zuten. Galdeketa honen bidez biztanleen inguruko informazio ugari lortu zen, hala nola, portaera, kontzientzia, energia - kontsumoa, sistema energetikoak, barneko airearen kalitatea eta okupazioaren profilei buruzko informazioa. Galdeketa - orriaren eredua 3.1. eranskinean gehitzen da.

4.4 Datu - analisia

Bildutako datuekin hainbat analisi egin ziren, landa - azterketaren epe ezberdinen arabera:

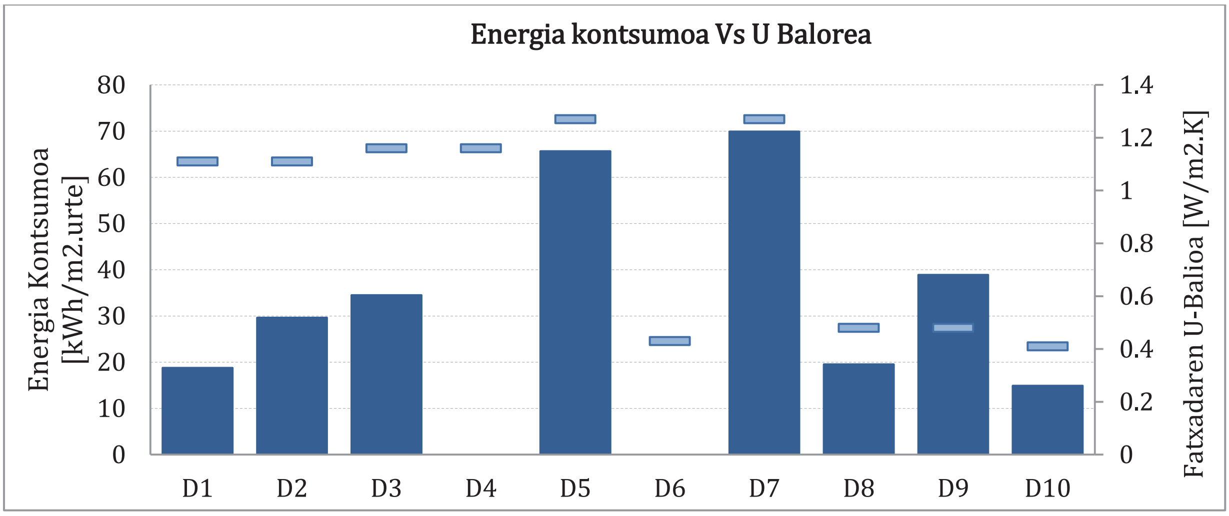
- Neguko (Abe - Urt - Ots - Mar), udaberriko (Api - Mai) eta udako (Eka - Uzt - Abu) urtaroko balioak aztertu ziren.
- 15 eguneko eperik hotzena (Otsailaren 1etik 14ra).
- Udaberriko 15 eguneko epea.
- 15 eguneko eperik beroena (Abuztuaren 8tik 22ra).

- 48 orduko epeak. Beroena (Abuztuaren 18tik 19ra), hotzena (Otsailaren 8tik 9ra) eta udaberrikoa (Apirilaren 24tik 25era).

Etxebizitza bakoitzarentzat hurrengo balioak eman ziren: balio minimo eta maximoak, batez besteko balioak, desbiderapen tipikoak eta barneko eta kanpoko tenperaturaren arteko korrelazioak.

5 Emaitzak

Etxebizitzen U - Balioak (I3.4 irudia) balio - tarte biren barnean daude. Alde batetik, etxebizitza berrienak (1980. urtea ondoren eraikitakoak) edo birgaitu direnak, 0.40 - 0.50 W/m^2.K-eko U - balioak daukate. Bestetik, Espainiako lehen erregelamendu termikoa onartu baino lehen eraikitako etxebizitzak (1979. urtea baino lehen) 1.10 - 1.30 W/m^2.K-eko U - balioak daukate.

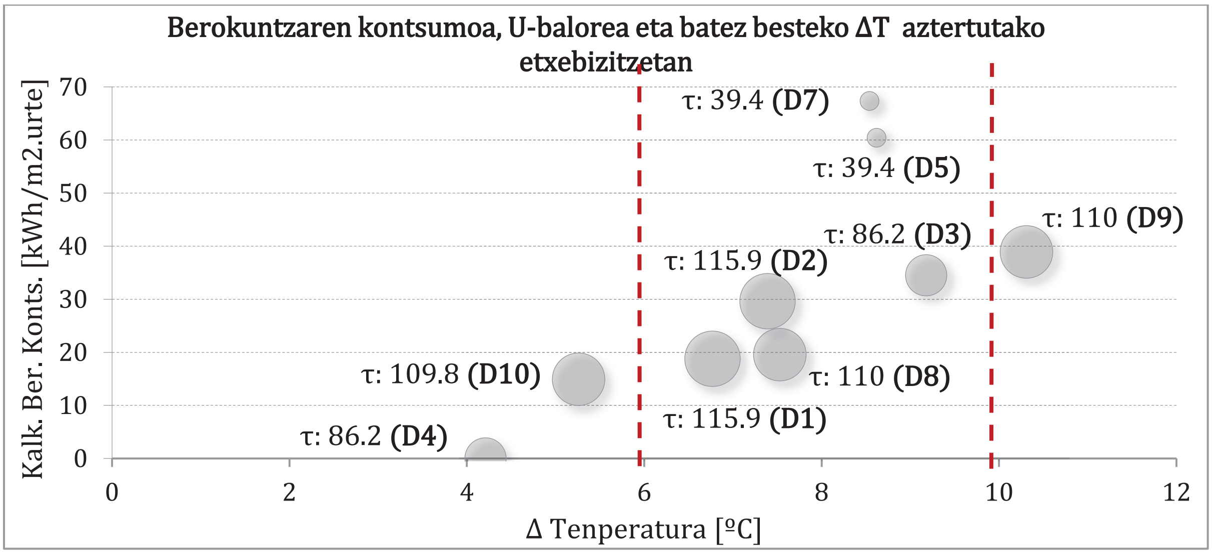


I3.4. U - balioaren eta energia - kontsumoaren arteko erlazioa

Bi korrelazio nabarmendu ziren. Lehenik eta behin, batez besteko barne eta kanpo tenperaturen arteko diferentziak kalkulatu ziren (ΔT). Zenbat eta ΔT handiagoa izan, orduan eta energia - kontsumoa altuagoa izango da. Horren ondorioz, espero bezala, bi etxebizitza elkarrekin konparatzean, energia - kontsumoa antzekoa zuten, U - baliorik baxuena zeukanak ΔT handiena zeukan.

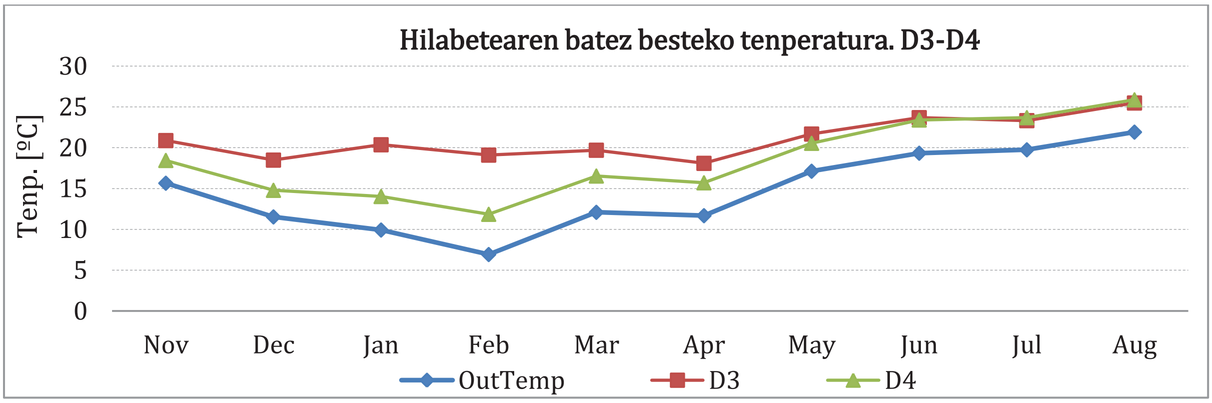
Joera hau I3.5 irudian irudikatutako grafikoan erakusten da. ASHRAE-k neguko konfort - zona 20 ºC eta 24 ºC artean definitzen duen arren [66], erosotasun termikoaren mugak 18 ºC ±2 ºC aukeratu ziren, Martin et al.-ek diotenez [49]. Grafiko honetan, ΔT neguko batez besteko barne eta kanpo tenperaturaren arteko diferentzia da. Hortaz, grafikoan irudikatutako puntu - lerro gorriak negurako erosotasun termikorako muga adierazten dute (barneko tenperatura limiteak 20 ºC eta 16 ºC izanik, ΔT 5.83 ºC eta 9.83 ºC dagokio). ISO 13790 [67] arauen arabera, denbora - konstantea (τ) lortu zen C [J/m^2.K] zati U [W/m^2.K] eginez, emaitza orduetan aurkezten delarik. Grafiko honetan, kontzeptu hau oso erabilgarria da, C eta U adagaiak termino bakarrean barneratzen baititu.

Grafiko hau ikustean bi etxebizitzatan espero ez zen portaera nabarmentzen da: kontsumorik altuenak (D5 eta D7koa) ez datoz ΔT baliorik handienekin bat. Puntu honek beste faktore batzuek, hala nola fatxadaren bero - ahalmenak, biztanleen portaerak, aireztapenak, leihoen kalitateak, zubi termikoak edo fatxadaren eta leihoen azaleraren arteko ratioak, etxebizitza hauen portaera termikoan rol garrantzitsu bat jokatzen dutela erakusten du. Bi etxebizitza hauek (D5 eta D7) U - balio altua (1.27 W/m^2.K) izateazk gain, fatxadaren bero - ahalmen baxua ere badute (180 kJ/m^2.K). Fatxadaren U - balio baxua daukaten beste etxebizitzek, ordea, bero - ahalmen altuagoa daukate (360 kJ/ m^{2}K - 423 kJ/ m^{2}K); D5 eta D7ren arteko diferentziaren argibidea aireztapen profilak eta biztanleen portaerak aintzakotzat hartzen direnean, aurkitu daiteke.

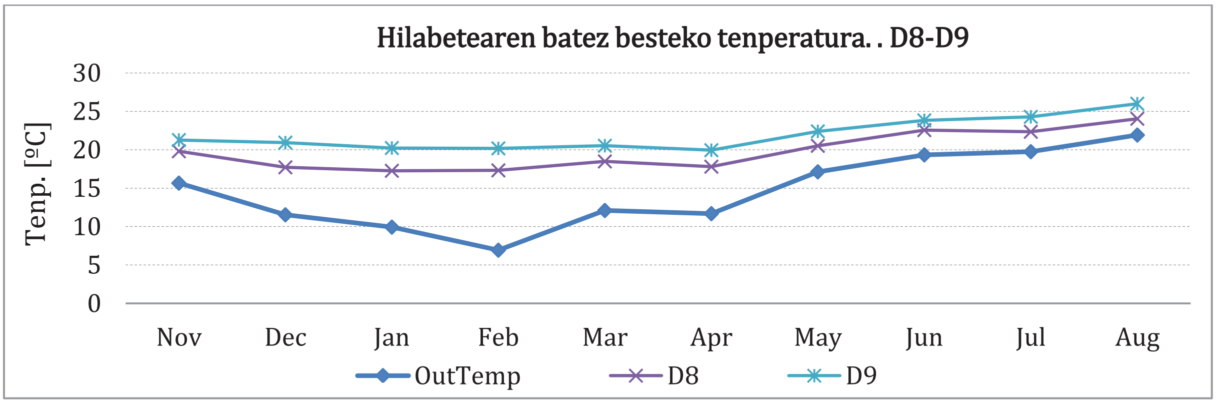


I3.5. Energia kontsumoa, denbora - konstantea eta batez besteko ΔT –ren arteko erlazioak. Batez besteko kanpo tenperatura: 10.17

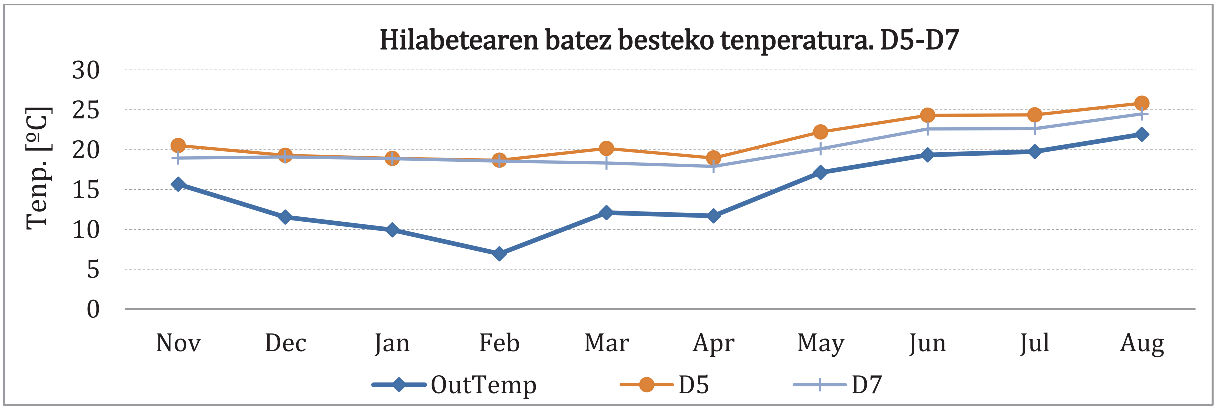
Beraz, etxebizitza bakoitzaren urteko energia – kontsumoaren arteko diferentzia hauek behar den moduan ebaluatu ahal izateko parametro gehiago aztertu beharko dira. D3 eta D4 oso antzekoak dira eraikuntzari dagokionez. Haien arteko ezberdintasunak berokuntza eta hilabeteko barne tenperaturak elkarrekin konparatu zirenean (I3.6 irudia), argitu ziren.



I3.6. Hilabetearen batez besteko tenperaturaren bilakaera D3 eta D4 etxebizitzetan (gela nagusian)



I3.7. Hilabetearen batez besteko tenperaturaren bilakaera D8 eta D9 etxebizitzetan (gela nagusian)



I3.8. Hilabetearen batez besteko tenperaturaren bilakaera D5 eta D7 etxebizitzetan (gela nagusian)

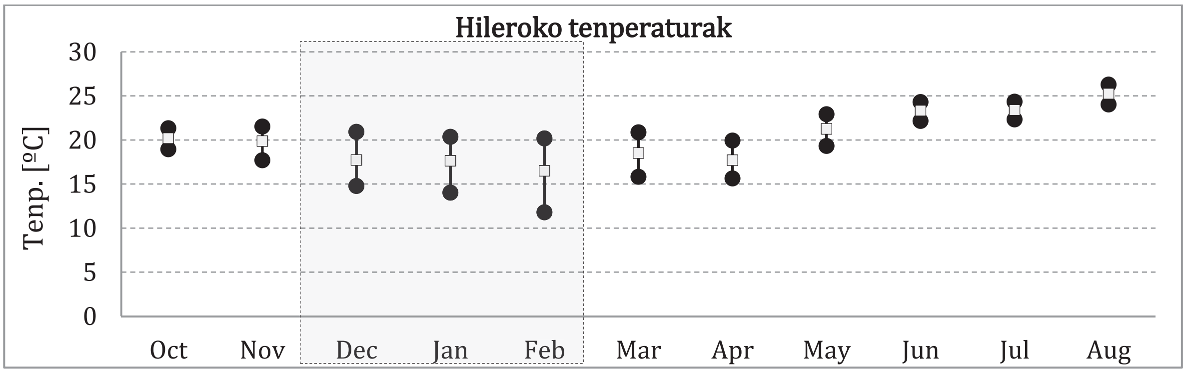
Berokuntza sistema berbera erabilita ere, hau da, gas natural goi - tenperatura erradiadoreekin eta hilabetearen batez besteko tenperatura baxuekin, berokuntza kontsumoan ezberdintasun adierazgarriak aurkitu ziren (%50 inguru), I3.7 irudiak D8 eta D9 kasuetan irudikatzen denez. D5 eta D7 elkarrekin konparatzean (I3.8 irudia, neguaren batez besteko barne tenperatura antzekoak izan zituzten biak) berokuntza kontsumoaren ezberdintasun txikiak (I3.5 irudia) biztanleen portaeraren ondorioak direla ondoriozta daiteke.

Berokuntza motak eta biztanleek erabilpen profil desberdinek, etxebizitzaren portaera termikoan eragin handia daukate, baita barne konfort termiko eta berokuntza kontsumoaren arteko erlazioan ere, 6.2.2. atalean zehatz - mehatz deskribatzen den bezala.

6 Emaitzen analisia

6.1 Urteko barne ingurunearen analisia

Egoera termikoari dagokionez, gizarte etxebizitzaren sektorea eraikin heterogeneoen multzo bat da. Aztertutako etxebizitzen artean, hilabetearen batez besteko tenperaturetan ezberdintasun garrantzitsuak aurkitu ziren, negukoetan batez ere, berokuntza sistema piztuta zegoenean eta, horren ondorioz, berokuntza kontsumoa altuena denean (I3.9 irudia). Epe hau zehatz - mehatz aztertuko da geroago.



I3.9. Hilabeteko barne tenperaturak: maximoak, minimoak eta batez bestekoak

Lehen aipatu denez, barne tenperaturen aldaketak faktore batzuen ondorioak ziren, eraikinaren egituraren bero ahalmena, berokuntza kontrola edo aireztapen profilak esaterako. Eguneko eta gaueko aldaketek barne tenperaturaren egonkortasunari buruzko ideia bat ematen dute. Barne eta kanpo tenperaturaren fluktuazioaren ratioak ($\Delta t_i/\Delta t_o$) barne eta kanpo tenperaturaren arteko korrelazioak erakusten ditu, eta faktore batzuen araberakoa da, esaterako etxebizitzaren ezaugarriak (eraikuntza teknikak, inguratzaile termikoa eta sistema energetikoak) eta beste batzuk, etxebizitzaren erabilera adibidez, biztanleen portaeraren arabera.

Urtaroko eguneko eta gaueko aldaketak T3.6 taulan zerrendatzen dira. Eguneko epe bakoitzerako (gauerako eta egunerako), tenperatura maximoaren eta minimoaren arteko diferentziaren bidez kalkulatzen dira. Geroago, haien urtaroaren batez besteko balioak kalkulatzen dira. Eguneko (8 am - 8 pm) eta gaueko (8 pm - 8 am) aldaketen baliorik handienak neguan zeuden, berokuntza sistema erabiltzen zenean. Epe honetako batez besteko eguneko aldaketak 3.18 graduren eta 1.16 graduren artean (D2 eta D6, hurrenez hurren) izan ziren; gaueko aldaketak, ostera, 3.63 graduren eta 0.82 graduren artean (D10 eta D6, hurrenez hurren). Hala ere, udan, aldaketak hauek txikiagoak ziren oro har, 3.36etik (D2) 0.8ra (D4 eta D6).

		Neguko epea (Abe - Mar)		Udaberriko Epea (Api - Mai)		Udako Epea (Eka - Abu)	
	C (kJ/m^2.K)	Eguneko Aldaketa	Gaueko Aldaketa	Eguneko Aldaketa	Gaueko Aldaketa	Eguneko Aldaketa	Gaueko Aldaketa
(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
Etxebizitza guztiaren batez bestekoa		2.24	2.29	1.52	1.50	1.40	1.41

T3.6. Aztertutako etxebizitzen gaueko eta eguneko aldaketaren barne eta kanpo tenperaturaren arteko ratioa (Gela nagusian neurtutako datuak)

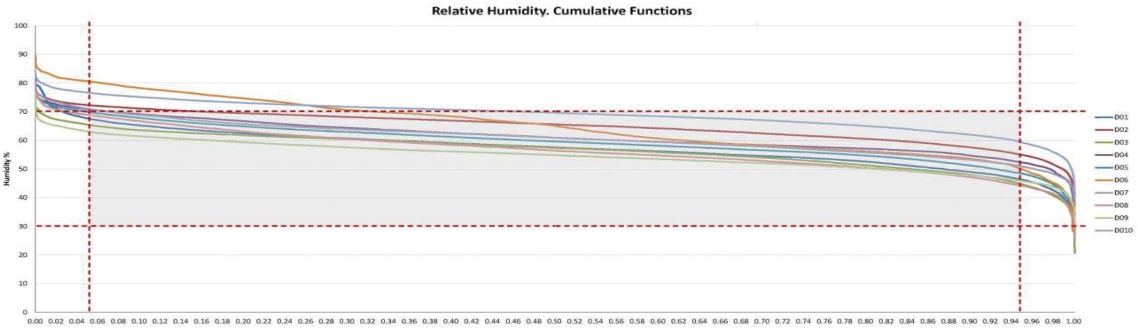
Etxebizitza bakarraren bi neurtutako gelak elkarrekin konparatzean ezberdintasunak aurkitu ziren ere, neguan batez ere. Etxebizitzaren gela guztietan berokuntza sistema zegoenean, gaueko eta eguneko aldaketak antzekoak izan ziren bi geletan (D5 esaterako, batez besteko eguneko aldaketa 2.84 izan zen gela nagusian, eta 2.70 izan zen logelan). Soilik etxebizitzaren gela batzuetan berokuntza sistema zegoenean, ezberdintasun handiagoak aurkitu ziren: D3 etxebizitzaren batez besteko eguneko aldaketa 3.11koa izan zen gela nagusian, eta 1.36koa logelan; aldi berean, gela nagusian egin ziren neurketaren batez besteko gaueko aldaketa 2.99koa izan zen, eta 1.27koa logelan.

Emaitza hauek eta S. Martín et al.-ek ematen dutenak [49] kontraesankorrak direla dirudi. S. Martín et al.-ek tenperaturaren gorabeherak estrukturaren bero - ahalmenari oso lotuta daudela aipatzen dute. Hala ere, gertakari hau ikerketak baldintza ezberdinetan garatzeagatik gertatzen da. Kapitulu honen ikerketako kasuan, aztertutako etxebizitza guztiak okupatuta zeuden neurketa egin bitartean; Martín et al.-ek egin zuten azterketan [49], berriz, hiruetako bi etxebizitza hutsik zeuden.

Berokuntza sistema nola erabiltzen den moduak neguan, eta biztanleen aireztapenaren kudeaketak udan (bata eta besteak biztanleen portaerari lotuta daude) etxebizitzaren barne tenperaturaren heina handiagotu dezakete. Izan ere, puntu hau D4 etxebizitzan lortutako neguko eguneko tenperaturaren heinekin frogatu zen, lagineko heinik baxuenetako bat. Aldi berean, D6 etxebizitzak tenperaturaren heinik baxuena erakutsi zuen, eta bere berokuntza sistema erabilera oso aldizkakoa zen, bere galdeketak dioenez. Hipotesi hau udarako frogatu zen ere. D6 etxebizitza, udan neurtutako tenperaturaren heinik baxuena erakutsi zena, hutsik egon zen epe horretan.

Beste faktore batzuek, aipatutako inguratzaile faktoreak esaterako, emaitza hauen argibidea osatzen dute. Beraz, D2 etxebizitzaren balio altuak inguratzaile faktorearen ondorio bat dira, hau da, estalki behean dago eta horren ondorioz, bere inguratzaile termikoaren azaleraren eta barneko azaleraren arteko ratioa altuagoa da. D1 etxebizitzan, berriz, fatxadaren bero - ahalmen altuaren efektuak leihoaren kalitate baxua indargabetzen du.

Barne hezetasun erlatiboa aztertu zen ere. Hezetasun erlatiboaren hein onargarria erosotasun termikorako %30 eta %70 bitartekoa da [66]. Ia neurtutako hezetasun erlatibozko datu guztiak (%99 baino gehiago) %30 baino altuagoak dira (I3.10 taula). Hala ere, goiko muga aztertzean egoera aldatzen da. Lau etxebizitzatan, neurtutako datuen %5 baino gehiago konfort zonaz kanpo egon ziren, eta haietako bik balio bereziki altuak erakutsi zituzten: D6 etxebizitzak (neurtutako datuen %32.4 konfort zonaz kanpo egon ziren) eta D7 etxebizitzak (neurtutako datuen %46.9 konfort zonaz kanpo egon ziren).



I3.10. Etxebizitzen hezetasun erlatiboa. Banaketa funtzioa

Urtaroen zehaztutako informazioa T3.7 taulan aurkezten da. %70en gainetik neurtu ziren hezetasun erlatiboaren datu gehienak neguan neurtu ziren, D7 etxebizitzan salbu, hezetasun erlatiboaren balio altuak urtaro guztietan erakutsi zirenekoa.

Okupatuta zeuden etxebizitzatan, aireztapen naturalak hezetasun erlatiboan eragin handia zeukan, ikerketako etxebizitzetan aireztapen mekanikoa ez baitzegoen. Beraz, parametro honek (hezetasun erlatiboak) aireztapen - tasari buruzko informazioa eman dezake, hau da, ea nahikoa den ala ez. Barne hezetasun erlatiboa kanpoko hezetasun erlatiboari lotuta dago, baita barneko hezetasun iturriari ere, sukaldaritza edo giza ekintzak esaterako. Hezetasun erlatibozko balio altuegiek aireztapen - tasa edo barne tenperaturak baxuegiak direla adierazi dezakete.

HE	Abe 2011 – Ira 2012		Negua	Udaberria	Uda
	%30 baino baxuago neurriak(%)	%70 baino altuago neurriak(%)	%70 baino altuago neurriak(%)	%70 baino altuago neurriak(%)	%70 baino altuago neurriak(%)
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%

T3.7. Neurtutako hezetasun erlatibozko datuen laburpena (%)urtaro bakoitzean: Negua (Abe 2011 - Mar 2012), udaberria (Api - Mai 2012) eta Uda (Eka - Abu 2012)

6.2 Negu aldia

6.2.1 Analisi orokorra

Negu aldian neurtutako datuak (2011ko Abendutik 2012ko Martxora) atal honetan aurkezten dira. Etxebizitzen barne tenperaturak aztertzeko, tenperatura hein bat definitu zen. S. Martín et al.-ek egin zuten ikerketan oinarritutakoa [49], konfort - zona 18 ºC ±2 graduko barnean definitu zen. Bestalde, definitutako muga baxuena (16 ºC) beste ikerketan *"cold homes"* (etxe hotz) deritzonak identifikatzeko erabiltzen da, estandarizatutako tenperaturak kontuan hartzean. Adibide bat [62] erreferentzian aurkitu daiteke.

Bi etxebizitzatan, negu aldiko batez besteko tenperatura 16 ºC baino baxuago izan zen (D4 and D10). D1, D2, D6 eta D8 etxebizitzetan, batez besteko tenperaturak oso baxuak ziren ere (T3.8 taula). Portaera hauen arrazoiak ezberdinak dira kasuaren arabera; adibidez egun batzuetan etxebizitza hutsik egotea, instalazio energetikoen kontrol desegokia, eraikinaren eta berokuntza sistemaren ezaugarriak, aireztapen profil ezberdinak, etab.

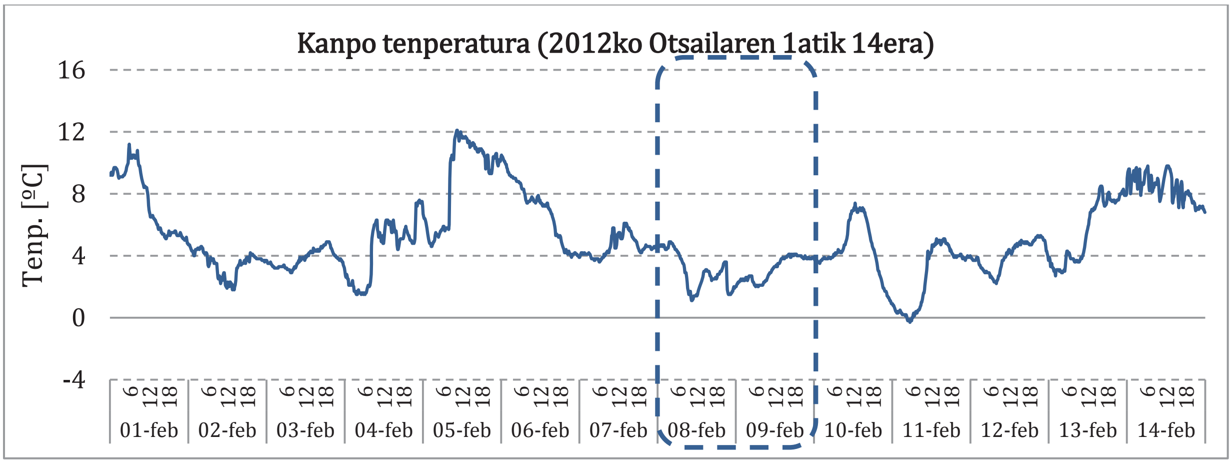
	Tenp. Maximoa (ºC)	Tenp. Minimoa (ºC)	Batez besteko Tenp. (ºC)	Heina (ºC)	Desbiderapen tipikoa
Kanpoan	25.80	- 0.30	10.17	26.10	3.87
D1	24.46	9.73	16.94	14.73	1.85
D2	22.71	10.79	17.56	11.92	1.32
D3	26.13	14.36	19.35	11.77	1.86
D4	21.27	9.21	14.38	12.06	2.26
D5	23.86	12.94	18.79	10.91	1.59
D6	23.69	13.81	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

T3.8. Neguan neurtutako tenperaturaren datuen laburpena (Abe - Mar)

Batez besteko barne tenperaturaren eta berokuntza kontsumoaren arteko erlazioak jadanik irudikatu dira I3.5 irudian. Lerro gorriak aipatutako neguko konfort zona mugatzen dira. Aipatu bezala, joera bat dagoela espero da, hau da, zenbat eta ΔT altuago, orduan eta energia kontsumoa gehiago. Energia kontsumoa antzekoa izatekotan (esaterako D1 eta D8 etxebizitzak), zenbat eta ΔT handiago, orduan eta U - balio baxuagoa zela ikusi zuen. Hala eta guztiz ere, bi etxebizitza (D5 eta D7 etxebizitzak, hain zuzen ere) ez dira joera honi jarraitzen. Kontu honen arrazoia biztanleen portaeran aurkitu zen, adibidez, bere aireztapen profilei lotuta, aztertutako 15 eguneko eta 48 orduko epean ikusten den bezala. Puntu hau egiaztatzeko, D5 etxebizitzan neurtutako 48 orduko eperik hotzena I3.12 irudian irudikatzen da. Irudi honetan, leihoak irekita zeuden momentuak urdinez nabarmentzen dira. Nahiz eta neurtutako eperik hotzena izan, bi egunetan leihoak irekita zeuden epe luzeak aurkitu ziren, batez ere logelan. Logelan, bi orduko epe bat identifikatzen dira Otsailaren 8an, baita lau ordu inguruko epeak Otsailaren 9an ere.

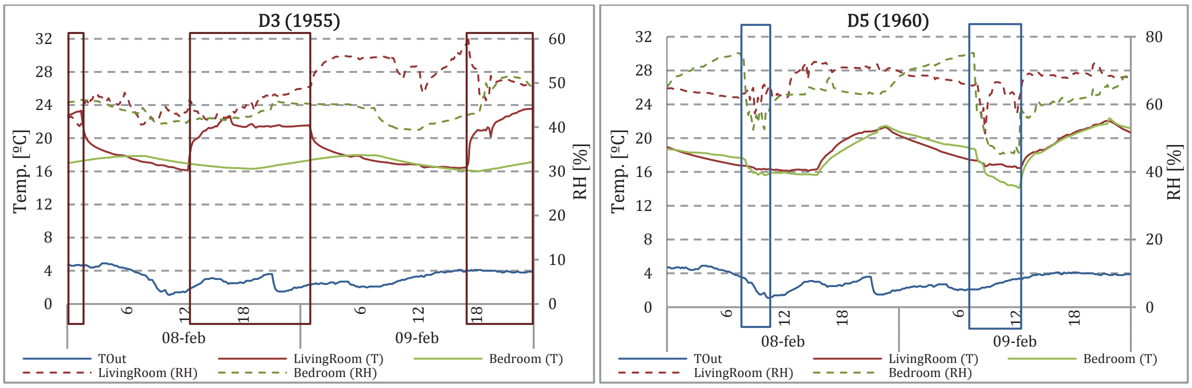
6.2.2 15 eguneko eta 48 orduko epeak

15 egun eta 48 orduko epeen analisiaren bidez, galdeketen bidez lortutako informazioa termo - higrometroarekin lortutako datuekin osatzen dira. 15 eguneko eperik hotzenaren neurtutako kanpo tenperatura I3.11 irudian irudikatzen da. Grafiko honetan, hautatutako 48 orduko epea nabarmentzen dira ere, puntu - lerro urdin baten bidez.

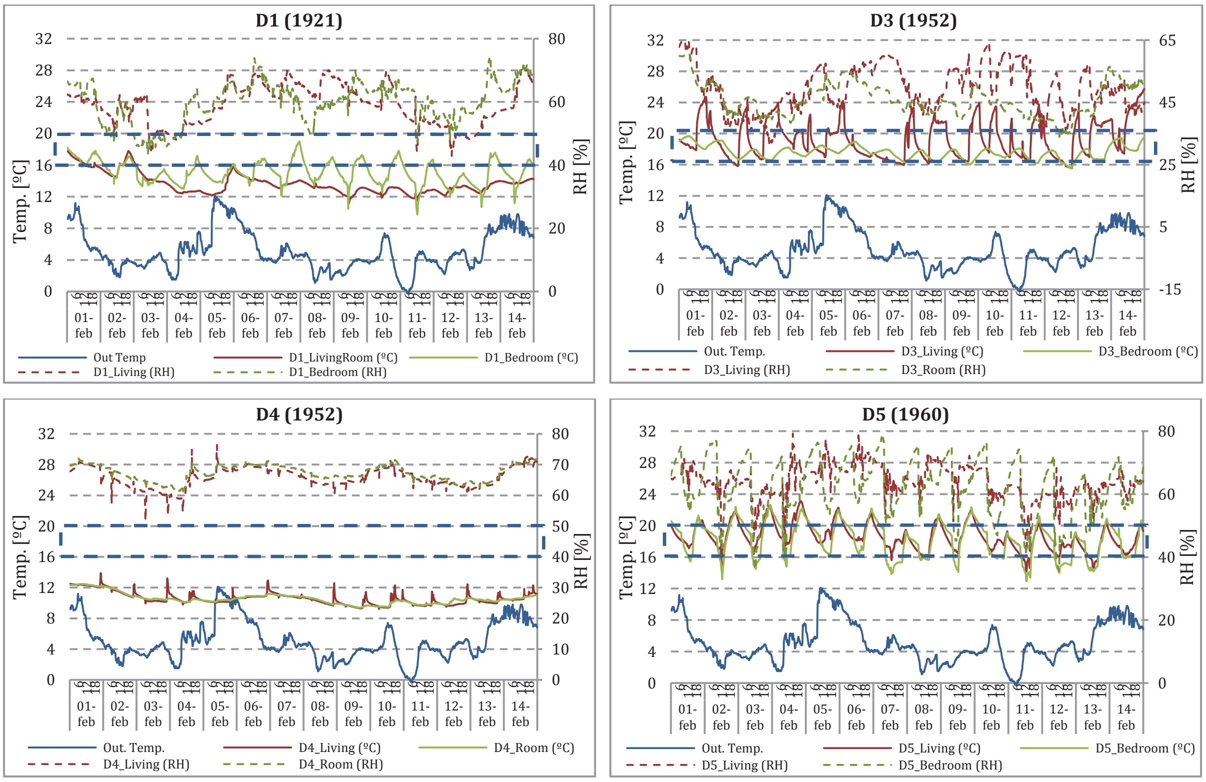


I3.11. 15 eguneko eperik hotzenaren kanpoko tenperatura

Analisi honetan, aireztapenaren eta berokuntzen profilak erraz identifikatzen dira. Leihoak irekita zeuden momentuak grafikoan identifikatzen dira, neurtutako hezetasun erlatiboa eta tenperatura bat - batean jausten baitira. Antzeko modu batean, berokuntza sistema aktibatzean, tenperatura igotzen da, eta aldi berean, hezetasun erlatiboa jausten da. Portaera honen bi adibide I3.12 irudian irudikatzen dira, D3 (berokuntza sistemaren aktibazioa) eta D5 (leihoak irekiak) etxebizitzenak direnak.



I3.12. (Ezkerrean) Berokuntza sistemaren aktibazioaren identifikazioa (D3) eta (Eskuinean) leiho - irekien identifikazioa (D5)



I3.13. Neurtutako barne tenperatura [ºC] eta hezetasun erlatiboa [%] D1, D3, D4 eta D5 etxebizitzak

Analisi hauen bidez, berokuntza sistema ezberdinak (baita haien erabilera ere) bata bestearekin konparatu daitezke. Adibidez, D1 eta D3 etxebizitzetan berogailua soilik gela batzuetan erabili zen. Hala ere, kasu bakoitzean emaitzak oso ezberdinak zen. Nahiz eta bi etxebizitzak egun osoan okupatuta zeuden, D1 etxebizitzan ordu gehienak 16 gradu azpitik egon ziren, eta 48 orduko epean neurtutako tenperatura minimoa 12 gradukoa zen, leihoak irekita zeuden momentu batean. Aldi berean, D3 etxebizitzan, egongelan 2kW-ko berogailu elektrikoa zeukana, berotutako zonan neurtutako datu ugari 20 gradu gainetik egon ziren. Hauetako grafiko batzuk I3.13 irudian aurkezten dira, eta kasu guztiak 3.2. eranskinean irudikatzen dira.

Diferentzia anitz etxebizitza hauen berotuta ez dauden gelen tenperaturetan aurkitu ziren. D4 etxebizitzan (Berokuntza sistemarik ez zeukana), eperik hotzenean tenperatura oso baxuak neurtu ziren. Etxebizitza osoaren tenperatura egonkorra izan zen bi neurtutako geletan. Gailur txiki bat gela nagusian neurtutako tenperaturan agertzen da, berogailu elektriko txiki baten erabileraren ondorioz. Energia kontsumoa kalkulatzean, berogailuaren kontsumoa mespretxatu zen, oso txikia baitzen.

	Tenp. Maximoa (ºC)	Tenp. Minimoa (ºC)	Batez besteko Tenp. (ºC)	Heina (ºC)	Desbiderapen tipikoa
Kanpoan	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

T3.9. Eguneko eperik hotzenean neurtutako tenperaturaren datuen laburpena (2012ko Otsailaren 1etik 14ra)

Gas naturala erabiltzen ziren etxebizitzak, edo berogailu bat gela bakoitzean zeukatenak, tenperaturaren diferentzia txikiagoak neurtu ziren. Adibidez, D5 etxebizitzan gas natural berokuntza sistema erabiltzen zen, eta gela guztiak berotuta zeuden. Sistema egongelan kokatutako termostato baten bidez agintzen da. Etxebizitza hauetan, berokuntza kontsumoa altuagoa izan zen sarritan, baina etxebizitza osoa konfort - zona barnean zegoen maiz. Tenperaturak gela guztietan antzekoak izan ziren, eta soilik aldaketa txikiak neurtu ziren, aireztapen profil ezberdinen ondorioz.

15 eguneko epearen analisi honetan, 4 etxebizitzen (D1, D4, D6 eta D10) batez besteko tenperaturak 16 gradu baino baxuagoak izan ziren, eta bakarrik etxebizitza baten (D9) batez besteko tenperatura 19 gradu baino altuagoa izan zen (T3.9 taula).

6.3 Udaberri aldia

Udaberri aldian neurtutako datuak (Api - Mai 2012) atal honetan aurkezten dira. Datu hauek aztertzeko, metodologia antzekoa jarraitu zen. Aldi honetan, soilik etxebizitza baten (D10) batez besteko tenperatura 18 gradu baino baxuagoa izan zen. Etxebizitza besteen batez besteko tenperaturak 18.15 graduren (D4) eta 21.19 graduren (D9) artean egon ziren. Lortutako desbiderapen tipikoak negukoak baino handitxoagoak izan ziren orokorrean. Aldi honetan neurtutako datuen laburpen bat T3.10 taulan aurkezten da.

15 eguneko eta 48 orduko epeen analisiari dagokionez, nahiz eta barneko egoera termikoak antzekoak ziren, oraindik diferentzia esanguratsu batzuk aurkitu ziren. Salbuespen pare batekin, etxebizitza gehienek epe honetan ez zuten berokuntza piztu.

	Tenp. Maximoa (ºC)	Tenp. Minimoa (ºC)	Batez besteko Tenp. (ºC)	Heina (ºC)	Desbiderapen tipikoa
Kanpoan	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

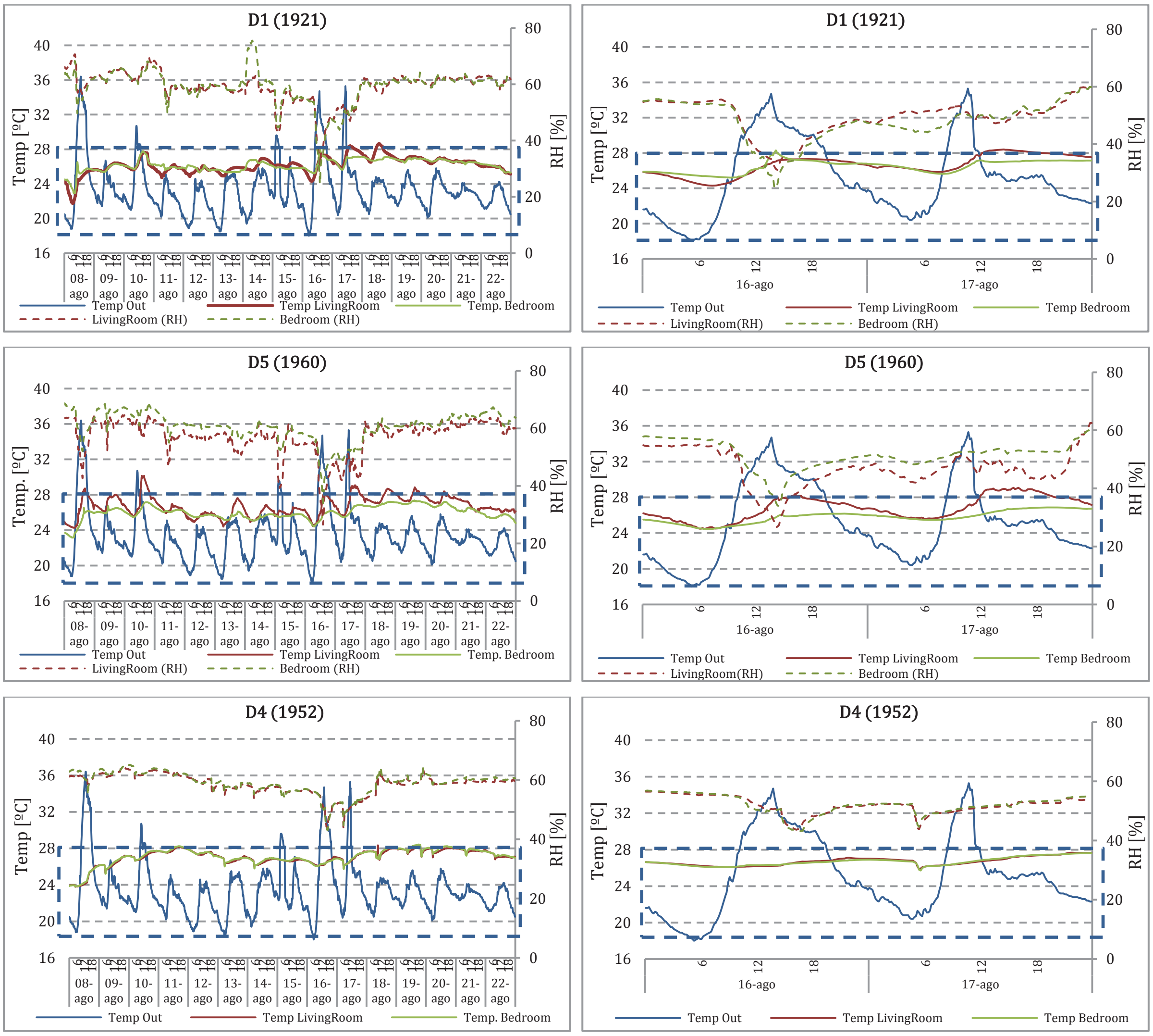
T3.10. Udaberrian neurtutako tenperaturaren datuen laburpena (Api - Mai)

6.4 Uda epea

Etxebizitza bakoitzaren portaera termikoa berokuntza sistema barik aztertzeko, haien barne egoerak neurtu ziren udan ere, 2012ko Ekainetik Abuztura. Zona klimatiko honetan espero bezala, barne erosotasun termikoa egokia izan zen hozte - sistemarik erabili barik. T3.11 taulan aurkezten den bezala, batez besteko barne tenperaturaren eta batez besteko kanpo tenperaturaren arteko diferentzia 6.82 (D7) eta 12.34 (D2) graduen artean egon ziren. Datu hauek etxebizitza hauen ahalmenak udako eguneko aldaketa termikoen inpaktua gutxitzen duela frogatzen du.

	Tenp. Maximoa (ºC)	Tenp. Minimoa (ºC)	Batez besteko Tenp. (ºC)	Heina (ºC)	Desbiderapen tipikoa
Kanpoan	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

T3.11. Udan neurtutako tenperaturaren datuen laburpena (Eka - Abu)



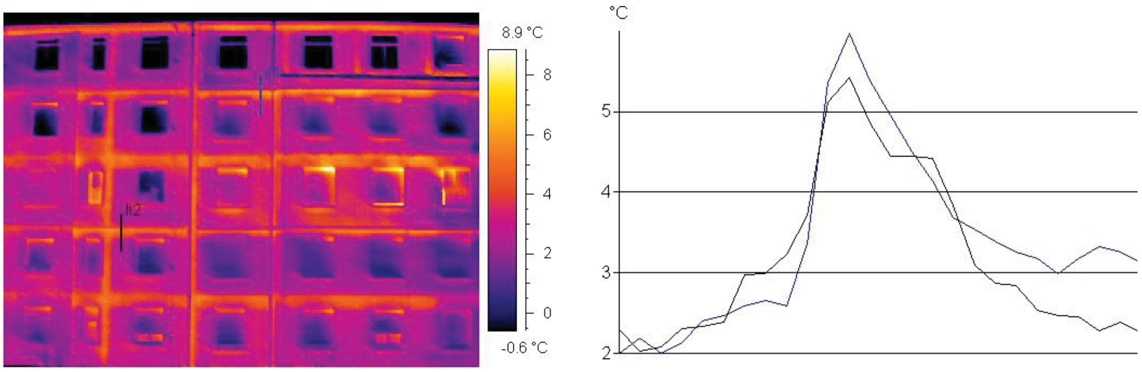
I3.14. Udan D1, D4 eta D5 etxebizitzen 15 eguneko eta 48 orduko epeen analisia

Portaera hau hobeto ulertzen da barne tenperaturak zehatz - mehatz aztertzen badira (I3.14 irudia). Udan neurtutako datuak aztertzeko, konfort - zonaren goiko muga 28 graduetan definitu zen. Urteko eperik beroena izanda ere, erregulazio termikoa egokia ziurtatu zen, etxebizitzaren kudeaketa egokiaren bidez, hau da, eguzki - irabaziak eguneko orduetan murrizteko eta aireztapen eta hozte naturalaren bidez gaueko orduetan. Erregulazio hau etxebizitzen arkitektura - diseinuari esker lortu zen, bereziki etxebizitzen barne - banaketari esker, aireztapen natural eraginkor bat erraztatzen duena.

6.5 Termografiak

Etxebizitzaren energia - kontsumoa aztertzean, zubi - termikoen eraginak aintzakotzat hartzea beste alderdi garrantzitsua da. Erreferentzia batzuek diotenez, zubi - termikoen eraginak etxebizitza baten energia - kontsumoan %5tik [68] (isolamendu termikoa inguratzaile termikoaren kanpokoan daudenean) %39ra (familia bakarreko etxe askotan zubi - termikorako tratamendu txarrarekin) aldatu daiteke [69].

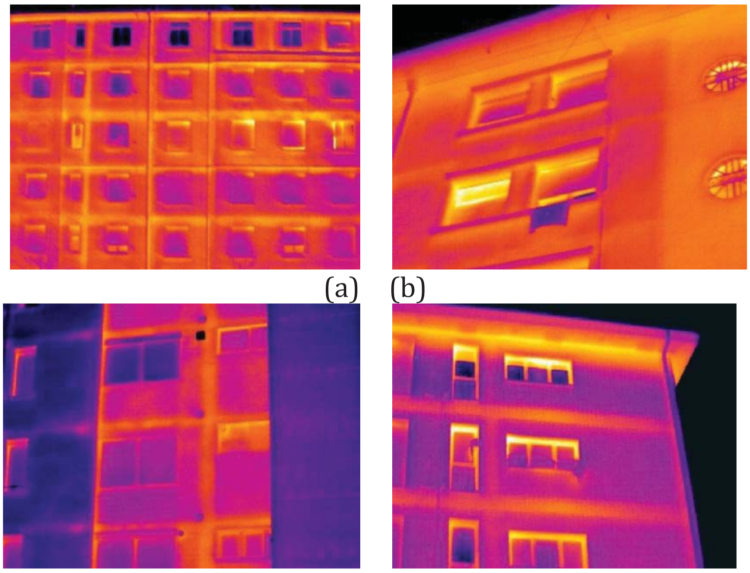
Termografietan oinarritako azterketa kuantitatibo eta zehazki bat egitea konplexua bada ere, eraikin bakoitzeko fatxadaren zubi - termikoen tenperaturen profila aztertu zen, I3.15 irudian irudikatzen den bezala. Fatxadaren kanpoko azalean neurtutako tenperatura minimoaren (T_{min}) eta tenperatura maximoaren arteko diferentziak (ΔT) zubi - termikoaren inpaktuaren maila adierazten du. Zenbat eta ΔT altuago, orduan eta zubi - termikoaren inpaktua handiago izango da.



I3.15. Zubi termiko baten tenperaturaren profila

Azaleko tenperaturaren diferentziarik txikiena (ΔT) D3 eta D7 etxebizitzetan aurkitu ziren (0.7 ºC); bestalde, diferentziarik altuena D2 etxebizitzaren fatxadan neurtu zen

(3.3 ºC). Zubi termikoen eragin posibleak etxebizitzen portaera termikoan ezin zen definitu emaitza hauek eta etxebizitzen barne tenperaturak edo energia - kontsumoak aztertu ziren elkarrekin. Puntu hau azaltzeko, arrazoi bat aurkitu zen: beste aldagai batzuek, aireztapen profilak esaterako, zubi termikoen eraginak murrizten zuten. Kasu honetan, landa - azterketan zehar etxebizitzak okupatuta egotea oztopo bat zen zubi - termikoen efektuak aztertzeko.


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

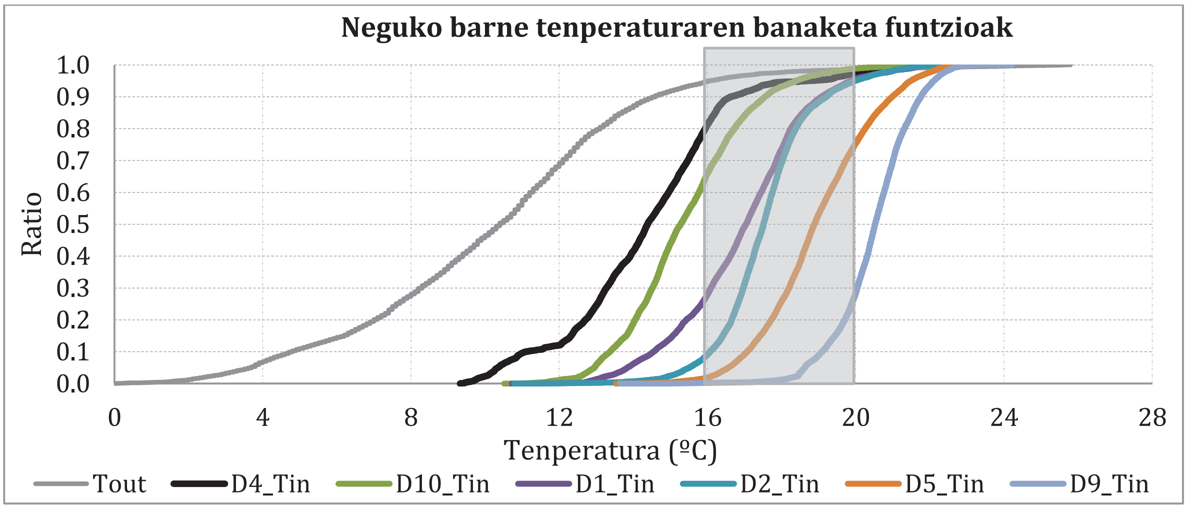
I3.16. Eraikin batzuen termografiak: (a) D2; (b) D3; (c) D5; (d) D8

Zubi termikoek etxebizitza batean daukaten efektua kuantifikatzeko biztanleen portaeraren efektua murriztu behar da, biztanleak kudeatzen diren faktore batzuk (berokuntza sistemaren setpoint tenperatura, aireztapen tasak edo barne irabazi termikoak esaterako) barneko eta kanpoko tenperaturaren arteko diferentzian rol garrantzitsua jokatzen direlako. Puntu honek zubi termiko baten ΔT nabariki aldatu dezake. Helburu hori lortzeko, bi aukera daude: simulazioaren bidez, edo termografiak egitea etxebizitzak hutsik egotean.

6.6 Barneko erosotasun termikoa eta etxe hotzaren arriskua

Neguan neurtutako tenperaturaren datu batzuk espero zirenak baino askoz ere baxuagoak baitziren, analisi sakonago bat egin zen, neguko barneko erosotasun termikoa eta bere ondoriozko etxe hotzaren arriskua aztertzeko. ISO 7730 arauak dioenez [65], erosotasun termikoa giro termikoarekin asebetetzea adierazten den egoera mentala da. Lehen aipatu bezala, ikerketa honen ezaugarrien ondorioz, erosotasun termikoa aztertzeko beharrezkoa den parametro guztiak ezin ziren neurtu. Horregatik, S. Martín et al.-ek garatzen duten prozedura jarraituz [49], analisi estatistikoan oinarritutako hurbilketa bat egin zen.

Erosotasun termikoa ebaluatzeko, neguko epean (2011ko abenduaren 1etik 2012ko apirilaren 1era) etxebizitza bakoitzaren neurtutako tenperaturaren datu multzoen banaketa - funtzioak (CDF, *Cumulative Distribution Functions* ingelesez) aztertu ziren. CDF bata besteekin konparatzean, ezberdintasun garrantzitsuak aurkitu ziren. D4 etxebizitzaren negu aldian neurtutako datuen %80 ingurukoa 16 gradu azpitik egon ziren. Bestalde, D9 etxebizitzan, 16 gradu azpitik neurtutako datu kopurua mespretxagarria izan zen. Ez hori soilik, baizik eta etxebizitza honetan neurtutako datuen %70 20 ºC baino altuagoak izan ziren. Puntu honek, tenperaturaren setpoint beheratuz baina barne giro erosotasunaren maila murriztu barik, D9 etxebizitzaren energia kontsumoa murriztu daitekela iradokitzen du. D10, D1, D2 eta D5 etxebizitzen CDF I3.17 irudian irudikatzen dira. D2 etxebizitzaren CDF-k barne tenperaturaren oreka ona erakusten du, neurtutako datuen %90 baino gehiago 16 eta 20 graduen artean daude. Etxebizitza guztien CDF grafikoak 3.2. eranskinean irudikatzen dira.



I3.17. Aztertutako etxebizitza batzuen neguko barne tenperaturaren banaketa - funtzioak (gela nagusian)

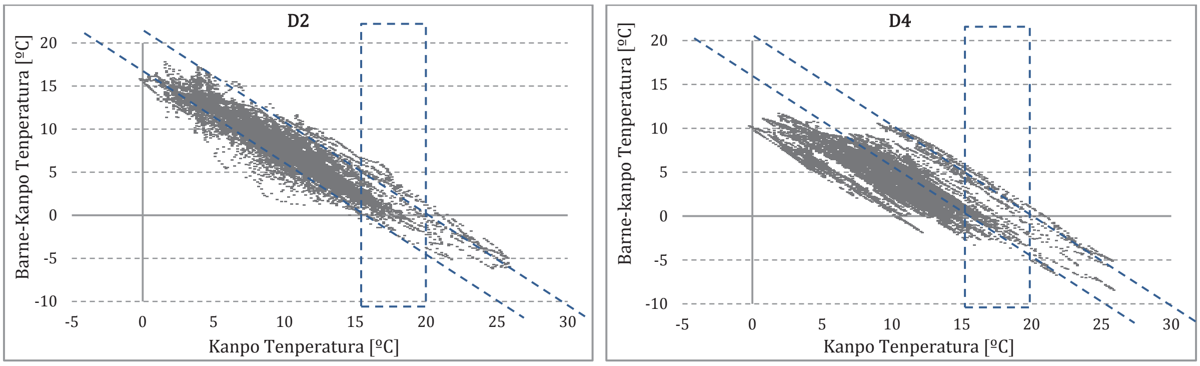
Neurtutako tenperaturen laburpena, irizpide hauen arabera, T3.12 taulan aurkezten da. Taula honetan agertzen diren datuak aztertzean, D4 etxebizitzaren portaera termikoa azpimarragarria da. D4 etxebizitza ez zen neguko etxebizitzarik hotzena soilik, baizik eta udako beroenetako bat ere (ikusi T3.11 taula). D6 etxebizitzan uda aldian, tenperatura altuak neurtu ziren ere, baina hilabete horietan zehar, etxebizitza hau hutsik egon zen, eta horren ondorioz, ez zen aireztapenik egon, eta D5 etxebizitzan tenperatura altuak urte osoan zehar neurtu ziren. D4 etxebizitzaren portaera termikoa bi arrazoiren ondorioa izan daiteke: alde batetik bere fatxadaren U balioa altua zen; gainera, estalki azpian zegoen eta estalkiaren U balioa oso altua zen ere.

	Negua		Udaberria		Uda	
	16 gradu azpitik neurketak (%)	20 ºC baino altuago neurketak (%)	16 gradu azpitik neurketak (%)	20 ºC baino altuago neurketak (%)	20 gradu azpitik neurketak (%)	28 ºC baino altuago neurketak (%)
Kanpoan	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%

T3.12. Gela nagusian neurtutako tenperaturen laburpena: Neguan (Abe 2011 - Mar 2012), Udaberrian (Api - Mai 2012) eta Udan (Eka - Abu 2012)

CDF analisi hauek informazio kuantitatiboa ematen dute, baina ez dute barne tenperaturen bilakaera deskribatzen. S. Martín et al.-ek diotenez [49], barne eta kanpo tenperaturen arteko diferentzia kanpo tenperaturaren aurka aztertu zen (I3.18 irudia, eta 3.2 eranskina). Konfort - zona termikoa grafikoetan markatzen da (lerro urdinen artean), zenbat neurketak konfort - zona barruan zeuden eta zenbat kanpoan identifikatzeko. Gainera, irudiak 16 gradu azpitik egon ziren neurketen proportzioa erakusten du ere. Lehen aipatutako mugak (18 ºC ±2 ºC) konfort - zona mugatzeko erabaki ziren.

Neguko datuen banaketa - funtzioak berokuntza sistemaren erabilerari buruzko informazioa ematen du ere. D4 etxebizitzaren (Neurtutako tenperaturen %80 baino gehiago 16 gradu azpitik daude) eta D9 etxebizitzaren (Neurtutako tenperaturen %99 baino gehiago 16 gradu baino altuagoak dira) arteko diferentziak azpimarragarriak izan ziren. Kasu honetan, eragin handikoenetako faktore bat eraikuntzaren inguratzaile termikoa, berokuntza sistemaren ezaugarriak edo eraikuntza teknikak ez ziren, eraikinaren erabilera eta batik bat, berokuntza sistemaren erabilera baizik.



I3.18. Negu aldiko barne minus kanpo tenperatura kanpo tenperaturaren aurka (D2 eta D4)

7 Eztabaida

7.1 Emaitzei buruzko eztabaida orokorra

I3.1 irudian aipatutako azpisistemak aintzakotzat hartuz, eraikinaren portaera termikoa ulertzeko ikuspegi orokorra erabili behar da. Kapitulu honetan aztertutako etxebizitzen kasuetan, biztanleen portaera adaptatiboak barne egoeraren ezaugarri termikoan rol garrantzitsua jokatu zuen, uda aldian batez ere ([70] erreferentzian aipatu bezala). Kasu gehienetan, portaera adaptatibo honek erregulazio termiko egokia ziurtatu zuen, etxebizitzen arkitektura - diseinuari esker. Etxebizitzaren barne - banaketa onak, etxebizitzaren erabilera eta orientazioa kontuan hartuz, aireztapen natural egokia erraztatzen du, aire - korronteak eraikinaren bi fatxadatan tenperaturen arteko diferentziaren ondorioz.

Kapitulu honetan aurkeztutako ikuspegi holistikoa jarraituz, lortutako emaitzak hurrengo puntuetan laburbildu daitezke:

- **Kokapena eta kanpoko ingurumena.** Etxebizitzak kokatzen direneko hiriak (Bilbao) klima epela dauka.
- **Berokuntza.** Aztertutako etxebizitza gehienen berokuntza sistemaren eraginkortasun energetikoa hobetu daiteke, batez ere etxe alokatuak direnaren berokuntza sistemena, etxe hauen biztanleek sarritan ez dute berokuntza sistema iraunkor batean inbertitzen.

- **Inguratzaile termikoa.** 1980. urtea baino lehen eraikitako eraikinetan, fatxaden eta jatorrizko leihoen U - balio altuak (1.11 - 1.27 W/m2.K) dauzkate. Infiltrazio - tasa ere altuegia da. Etxebizitza askotan, leihoak aldatu izan dira behin gutxienez, eta "Udal Etxebizitzak" bide honetan planak bultzatu eta garatu ditu, etxebizitzaren eta eraikinaren eskalan. Hala eta guztiz ere, oraindik portaera termikoa txarra erakusten duen inguratzaile bat daukaten eraikin kopuru handia dago.
- **Eraikuntza teknikak.** Zubi termikoaren eraginak ezin ziren argi bereizi, eragin termiko txikiak baitzeuzkan beste efektuekin konparatuz, aireztapen profilak esaterako.
- **Etxebizitzaren barne - banaketa.** Orokorrean, aztertutako etxebizitzen barne - banaketa ona ziren, erabilera eta orientaziora egokituta.
- **Biztanleak.** Okupazioaren profilak, aireztapenarenak, edo berokuntza sistema erabilera barne erosotasunean eta energia - kontsumoan eragin handia daukate. Beraz, biztanleen kontzientziazioa handitzeko estrategiak garatzea komenigarria da.

7.2 Barne giroko konfort termikoa

7.2.1 Negu aldiko epea

Lau etxebizitzatan, neguko eperik hotzenean neurtutako batez besteko barne tenperatura 16 gradu azpitik egon ziren, eta haietako bitan, negu aldi osoaren batez bestekoa 16 gradu baino gutxiago zen. Beste aldetik, lau etxebizitzaren tenperatura 18 ºC baino altuagoa zen. Lauetako hiruren (D5, D7 eta D9 etxebizitzak) biztanleak etxebizitzaren jabeak dira. Bestean, nahiz eta batez besteko barne tenperatura 18 gainetik egon zen, tenperaturaren bilakaera aldakorra izan zen. Aipatutako hiru etxebizitzak gas natural berokuntza sistema zeukaten bakarrak dira, eta etxebizitza hauetan, aztertutako etxebizitza guztien familia - errentarik altuenak ziren. Beste ikerketa batzuek energia kontsumoa (eta, zeharbidez, etxebizitzaren barneko erosotasun termikoa) familia - errentari oso lotuta dagoela frogatu dute [34].

Aztertutako etxebizitza gehienetan energia kontsumoa espero baino baxuagoa zen. Puntu honen arrazoi nagusia ez da etxebizitzen portaera termikoa berez ondo delakoa, barne tenperatura baxuaren ondorioa baizik.

Gizarte etxebizitza parkearen portaera termikoa hobetzearen helburua ez da soilik energia - kontsumoa murriztea, baizik eta (batez ere) barneko erosotasun termikoa hobetzea. Horregatik, gizarte etxebizitza bateko birgaitze energetikoaren eraginkortasuna aztertzen ari denean, barneko erosotasunaren parametroak, esaterako barne tenperatura eta hezetasun termikoa, aintzakotzat hartu behar dira. Barneko erosotasunaren hobekuntzak energia - aurrezteak bezain garrantzitsuak dira. Ikerketa honen irismenaren kanpoan geratu diren beste faktoreak, osasun faktoreek edo faktore sozialek esaterako, gizarte etxebizitzaren birgaitze egokitik onurak aterako dituzte.

7.2.2 Uda aldiko epea

Ikerketa honetan uda egon ziren barne egoerak ere kontuan hartu ziren. Udan barneko erosotasun termikoa aztertzeko, negu aldian egon ziren epearen barneko erosotasuna aztertzeko (6.6 atalean) erabili zenaren antzeko metodologiari jarraitu daiteke. Analisi hau ez da tesi honetan aurkezten, barne giroaren ezaugarriengatik, hau da, epe honetan neurtutako barne tenperaturak nahiko erosoak direlako, eta 28 gradutik gora nekez pasatu ziren, ezta urteko egunik beroenean, espero zen zona klimatiko honetan.

8 Ondorioak

Eraikin parkearen birgaitze energetikorako estrategia on bat definitzeko, eraikin parkearen portaera termikoari buruzko informazio zehatz edukitzea beharrezkoa da. Kapitulu honetan, gizarte etxebizitzaren portaera termikoa aztertzeko asmoz garatzen den metodologia bat aurkeztu da. Neurtutako datuak gizarte etxebizitzaren portaera termikoaren eta energia - kontsumoaren joera orokorrak definitzeko, baita gizarte etxebizitzaren erabilera eta profil errealak ere, erabili dira. etxebizitzaren erabilera estandarren eta errealaren (neurtutako datuetan oinarrizkoak direnen) arteko konparaketan, ezberdintasun azpimarragarriak aurkitu dira. Ikerketa honek Bilboko gizarte etxebizitza parkearen erakusgarriak diren hamar etxebizitzaren karakterizazio kuantitatibo eta kualitatibo bat eman du.

Landa - azterketa honetan gizarte etxebizitza hauen energia - kontsumoa espero zena baino baxuagoa zela erakutsi zen. Puntu honen arrazoi nagusia ez da etxebizitzen portaera termikoa berez ondo delakoa, barne erosotasunaren maila murrizteagatik baizik. Beraz, etorkizuneko birgaitze energetikorako estrategiek arreta alderdi honetan jarri beharko dute haien eraginkortasuna aztertzean. Hau da, eraikinetan birgaitze energetikoak ebaluatzeko, ez dira soilik energia - aurrezteak kontuan hartu behar, baizik eta irizpide ekonomiko eta sozialak ere. Etxe hotz kopurua murrizteko helburua energia - aurrezteak berez bezain garrantzitsua da, gizarte etxebizitzaren sektorean batik bat.

Aztertutako etxebizitzaren berokuntza kontsumoaren arteko ezberdintasunak aurkitu ziren. Ezberdintasun hauen kausak ez ziren azaldu eraikinaren eraikuntza ezaugarrien bidez kasu guztietan (esaterako, zenbat eta U balioa altuago izan, orduan eta berokuntza kontsumoa baxuago izan). Biztanleek neguan eskatzen duten batez besteko barne tenperaturak garrantzi handia dauka. Eskari hau, lehen aipatu bezala, familia - errentari oso lotuta dago sarritan. Etxebizitzaren berokuntza sistemak eta bere erabilerak ere barneko egoeretan ezberdintasun hauei eragiten diete. Berokuntza sistemak barneko erosotasun termikoari eragiten diola frogatu zen; bai berokuntza sistema motak berez, baita erabiltzen den moduak ere.

Ikerketa honek etxebizitza gehienen barne - banaketa ona zela erakutsi du ere, erregulazio termikoa errazten duena biztanleen portaera adaptatiboa medio. Hortaz, gizarte etxebizitzaren birgaitze energetikoak sistema energetikoak eta inguratzaile termikoa hobetzera bideratu behar dira.

Edozein birgaitze energetikoa egin aurretik, lehen aipatutako sailkapenaren arabera, gizarte etxebizitzaren mota ezberdinak zehatz - mehatz aztertzea beharrezkoa da. 1920. urtean eraikitako etxebizitza baten portaera termikoa (bero ahalmen handiko fatxadarekin) hobetzeko birgaitze - estrategiarik onena 1960. urtean eraikitakoarena (fatxada arinarekin) hobetzeko estrategiarik onena denaren bezalakoa ez dela posiblea da.

Laburbilduz, gizarte etxebizitza pobrezia energetikora jausteko arrisku gehien daukaten sektoretako bat da. Beraz, gizarte etxebizitza, 1980. urtea baino lehen eraikitakoa batik bat, lehentasuna birgaitze energetikorako estrategietan izan behar da, bai bere hobekuntza potentzialagatik, baita etxe hotza eta pobreza energetikoa eragozteko ere. Birgaitze energetiko hauen eraginkorra aztertzeko ez dira soilik energia - aurrezteak kontuan hartu behar, baizik eta hobekuntza soziala eta ekonomikoak ere.

Azkenik, parametroak estandarizatzeko eta okupatuta dauden etxebizitza ezberdinen portaera termikoa egoki aztertzeko (urtaro eta klima egoera ezberdinetan), estrategia eta metodologia berriak inplementatu behar dira. Bestela, ez litzateke posiblea izango datu - basea garatzea ezta birgaitzerako etxebizitzen lehentasun bat ezartzea ere. Gainera, metodologia hau eraikinen birgaitze energetikoa egin aurretik eta ondoren aztertzeko erabilgarria izan behar da. Birgaitzearen eraginkortasunari buruzko datu errealak lortu eta, aipatutako metodologiaren bidez, bi egoeraren arteko konparaketak egin behar dira (birgaitze egin baino lehen eta birgaitze egin eta gero) baldintza berberetan (hau da, biztanleen portaera eta baldintza klimatikoen efektuak baztertuz). Horregatik, hurrengo kapituluetan, eraikinen portaera termikoaren eredu ezberdinak garatzean eta aztertzean, baita bere emaitzak elkarrekin konparatzean ere, arreta jartzen da.

Hurrengo kapituluan, tesi honen atal esperimental nagusia deskribatzen da. Atal esperimental horretan, Bilboko eraikin parkeko etxebizitza adierazgarri bat hautatu zen, eta landa - azterketa sakon baten bidez, etxebizitzaren portaera energetikoaren aztertzeko datu anitz lortu ziren. Datu hauekin, etxebizitzaren portaera termikoaren eredu ezberdinak 5. eta 6. kapituluetan garatuko eta analizatuko dira. Horrela, eredu hauen bidez, birgaitzerako estrategia ezberdinen efektuak arlo ezberdinetan (barneko erosotasun termikoan edo energia - kontsumoa, adibidez) aurresan daitezke.

9 Aipatutako eranskinak

3.1. Eranskina: Galdeketa - orri txantiloia.

3.2. Eranskina: Landa - azterketaren neurketak.

3.3. Eranskina: Eranskin honetan landa - azterketa honen ondoriozko artikulua aurkezten da (Ingelesez):

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

4. KAPITULUA

GIZARTE ETXEBIZITZA ADIERAZGARRIAREN XEHATUTAKO AZTERKETA

LABURPENA

Kapitulu honetan, tesi honen atal esperimentala nagusia zehatzen da. Bilbon dagoen gizarte etxebizitza adierazgarri baten monitorizazio termiko bat da. Bilboko Udal Etxebizitzak birgaitze bat egin zuen 2012. urteko udan. Beraz, landa – azterketa honek bi egoera barne hartzen ditu: lehena, 2012. urteko neguan, birgaikuntzaren aurretik; bigarrena, birgaikuntza lanak egin ondoren, 2013. urteko neguan. Etxebizitzan hirurogei inguru sentsore jarri ziren, baita estazio klimatiko txiki bat ere. Datu eskuratzeko sistemak datuen bilketa minuturo egiten zuen. Monitorizazio hau Eusko Jaurlaritzako Eraikuntza Kalitatearen Kontrolerako Laborategiaren laguntzarekin garatu zen. Landa – azterketa honen bidez lortutako emaitzak hurrengo kapituluetan erabiliko dira, eraikinen portaera termiko – ereduak baliozkotzeko. Gainera, datuen lehen analisi bat aurkezten da kapitulu honetan.

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 Sarrera

Kapitulu honetan doktorego - tesi honen atal esperimental nagusia deskribatzen da. Alde batetik, eraikin baten portaera termikoa birgaitze egin baino lehen neurketen bidez, datu lortzen dira eraikinaren portaera termiko erreala aztertzeko, eta horrela, hobekuntza potentziala identifikatzea eta estrategiarik egokiena erabakitzea. Bestetik, birgaitze egin ondorengo egoeraren neurketak edukiz gero, ea erabakitako birgaitzerako estrategiak espero zen moduan jokatzen den ala ez, eta ea espero ziren helburuak lortu dituen egiaztatu daiteke.

Aurretiko kapituluan aipatu bezala, eraikin baten birgaitzearen emaitzak azpisistema ezberdinen arteko interakzioen ondorioak dira. Horregatik, ez da gauza erraza alderdi honi ekitea. Izan ere, bero - galerak, diseinu fasean kalkulatutakoak baino askoz altuagoak dira sarritan [71].

Arreta eraikinen energia - kontsumoetan jarri dituzten ikerketa asko aurkitzen dira bibliografian. bai xede industrialekin, baita ikerkuntzarakoekin ere. Atal honetan bi ikerketa aipatzen dira adibide gisa.

Ikerketei dagokionez, P. Bacher eta H. Madsen-ek garatu zuten lana azpimarragarria da. 2010. urtean eraikinen portaera termikoaren ereduak identifikatzeko prozedura aurkeztu zuten. Bulegoetako eraikin batean, “Flex House” deritzona, monitorizazio bat egin zen eta lortutako emaitzekin, eredu bat garatu zen [72].

Merkataritzako erabilerara bideratutakoa (ESCO-ak eta antzekoak) IPMVP da. IPMVP Energia Berriztagarria eta Eraginkortasun Energetikoaren Bulegoaren protokolo bat da, Estatu Batuetako Energia - Sailak garatutakoa [73]. Gaur egungo egoerari buruzko informazioa biltzen eta terminologia komun bat definitzen du, neurketa eta egiaztatzearen praktika onak zabaltzeko asmoz.

Kapitulu honetan, hautatutako gizarte etxebizitza baten landa - azterketa deskribatzen da. Etxebizitza bi epe ezberdinetan monitorizatu zen: lehen monitorizazioa 2012. urteko lehen hilabeteetan garatu zen; bigarrena, hurrengo neguan, 2012ko Azarotik 2013ko Otsailera, Bilboko Udal Etxebizitzak birgaitze bat egin ondoren.

Landa - azterketa honetan, datu erabilgarriak lortu ziren hurrengo kapituluetan deskribatutako ereduak definitzeko eta baliozkotzeko. Monitorizazio honen helburu nagusia hurrengo kapituluetan erabiltzeko datu nahikoak lortzea izan arren, lortutako informazioak alderdi nabarmengarri batzuk dauka kapitulu bat garatzeko. Beraz, kapitulu honetan, landa - azterketaren ikuspegi eta diseinua aurkezten dira, baita lortutako emaitzak ere. Izan ere, ondorio interesgarriak aurkitu ziren lortutako emaitzak aztertu ondoren.

Kapitulu honetan aurkeztutako monitorizazioaren analisiak etxebizitzaren portaera termikoan (bere eraikuntza - ezaugarriei lotuta) arreta jartzen duela aipatzea garrantzitsua da. Hau da, aurretiko kapituluetan, deskribatutako ikuspegi sistemikoa jarraituz, hiru etxebizitza - azpisistemaren (eraikuntza teknikak, inguratzaile termikoa eta barne - banaketa) erantzuna kanpoko egoera berariazkoetan aztertzen eta definitzen saiatzen da orain. Biztanle eta sistema energetikoen eraginak hurrengo kapituluetan kontuan hartuko dira.

1.1 Kapituluaren egitura

Kapitulu honetan zehar bi monitorizazio - epeak aurkezten dira, birgaitze egin aurretik eta ondoren. Bigarren atalean helburuak aurkezten dira eta gero, etxebizitzaren deskripzioa (bi egoeretan) hirugarren atalean aurkezten da. Erabilitako instrumentazioa, baita jarraitutako metodologia eta ikuspegia ere, aurkezten dira laugarren atalean. Emaitzak aurkezten eta aztertzen dira bosgarren eta seigarren ataletan. Aurretiko ataletan aurkeztutako egitura jarraituz, lehen emaitzak egoera bakoitzean aurkezten dira, eta gero, bi egoeren datuen arteko konparaketa garatzen da. Azkenik, kapituluaren ondorioak zerrendatzen dira zazpigarren atalean.

2 Kapituluaren helburuak

Kapitulu honetan aurkezten den landa - azterketaren helburuak zerrendatzen dira jarraian:

- Etxebizitza adierazgarri baten portaera termikoari buruzko datuak biltzea, eta datu hauek hurrengo kapituluetan aurkeztutako eraikinen portaera termikoaren ereduak definitzeko eta baliozkotzeko erabiltzea.
- Etxebizitza adierazgarri baten energia - kontsumoak lortzea, birgaitzearen aurretik eta ondoren, okupazioaren eraginak kontuan hartu barik.
- Etxebizitzaren elementu ezberdinetan zehar dauden bero - galerak kuantifikatzea: fatxadatik, barneko pareetatik, zubi termikoetatik, leihoetatik …
- Etxebizitza baten birgaitze energetiko baten efektuak (kasu honetan, leihoen aldaketarenak) bere portaera termikoan elkarrekin konparatzea eta aztertzea.

3 Kasu - azterketa

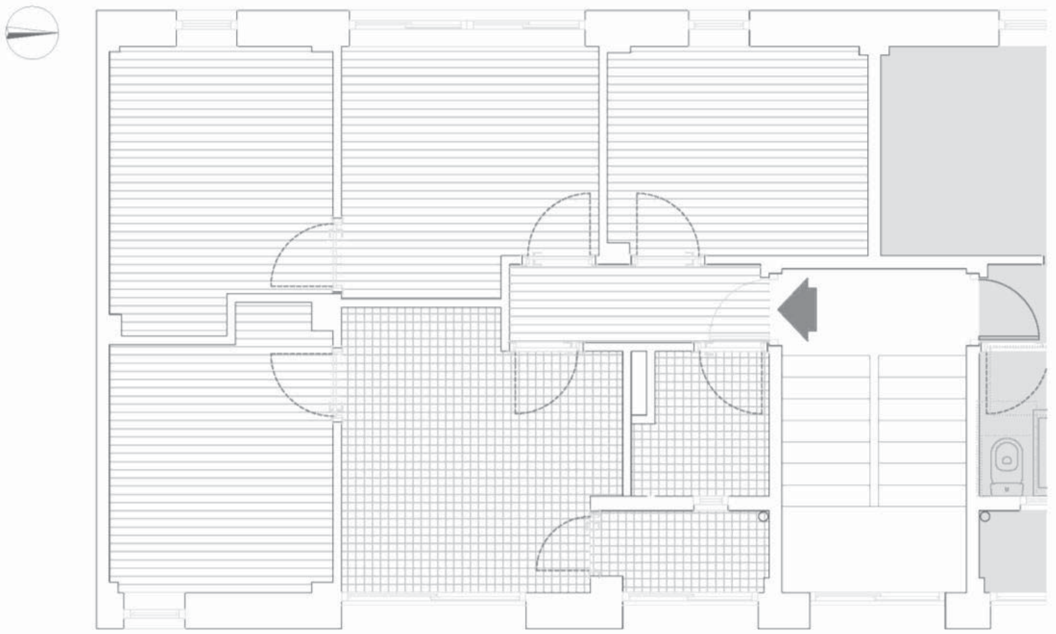
Bilbon kokatuta dagoen gizarte etxebizitza bat aukeratu zen. Hautaketa hau tesi honen 1. eta 3. kapituluetan aipatutako eraikin parkearen sailkapenaren irizpideetan oinarrituta egon zen. Nahiz eta “eraikin estandar bat” definitzea zaila izan (eraikin parkearen heterogeneotasun eta konplexutasunaren ondorioz), hautatutako eraikina 20. mendeko epe baten (60. hamarkadaren) eraikin adierazgarria dela esan daiteke. Hamarkada honetan, gaur egungo eraikin kopuru garrantzitsu bat eraiki ziren, hiri industrialetan batez ere. Bilboko kasuetan, gaur egungo eraikin parkearen %20 inguru hamarkada horretan eraiki ziren.

Gainera, Otxarkoaga auzoa (I4.1 irudian) bi urte eskasetan eraiki ziren. Eraikina 1959. urtean eraikitzen hasi zen, eta proiektutako 3672 etxebizitzaren eraikuntza 1961. urtean bukatu zen.

I4.1. Otxarkoaga auzoaren ikuste orokor bat

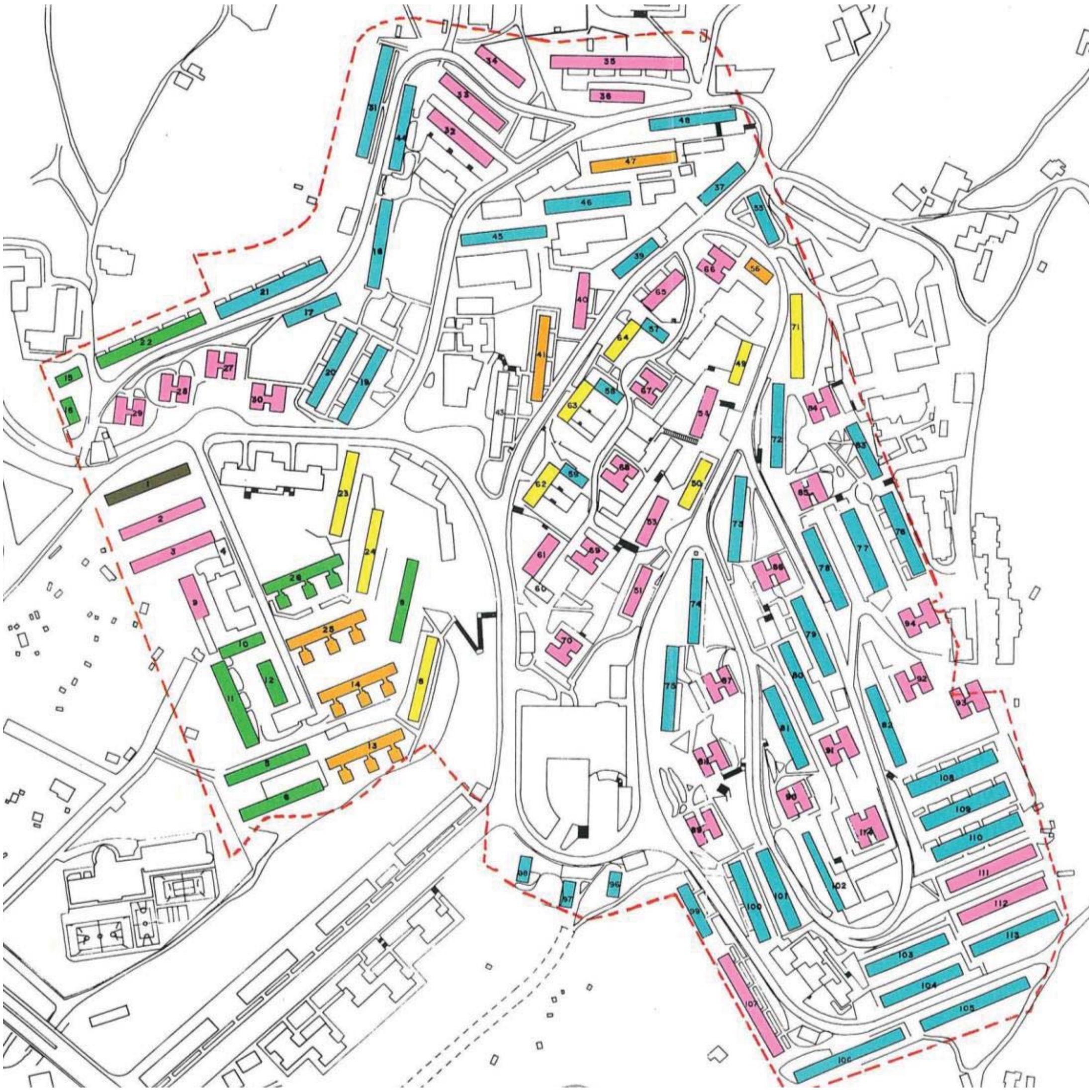
3.1 Birgaitze energetikoaren aurretiko etxebizitzaren deskribapena

Aztertutako etxebizitza, etxebizitza - bloke batean kokatuta dago. Etxebizitzaren planoa I4.2 irudian irudikatzen da, eta argazki batzuk aurkezten dira I4.3 irudian. 52.52 metro karratuko azalera garbia eta 2.47 metroko garaiera du. Etxebizitzak hiru kanporako fatxadak dauzka, mendebalderantz, hegoalderantz eta ekialderantz orientatuta. Haietako bik leihoak dauzkate.



I4.2. Birgaitzearen aurretiko etxebizitzaren planoa

I4.3. Etxebizitzaren kanpoko argazkiak



Eraikuntza sistemak

🟪	Zement. morteroa + pintura geruza	🟧	Zementuzko mortero koloreduna
🟨	Zementuzko mortero arina	🟩	Fatxadan eta leihoetan geruza berri bat gehikuntza
🟦	Fatxadan geruza berri bat gehikuntza		

I4.4. Otxarkoaga auzoko planoa. Eraikinak koloreztatuta daude 1980. urtean egindako birgaitzearen arabera (Iturria: Bilboko Udal Etxebizitza)

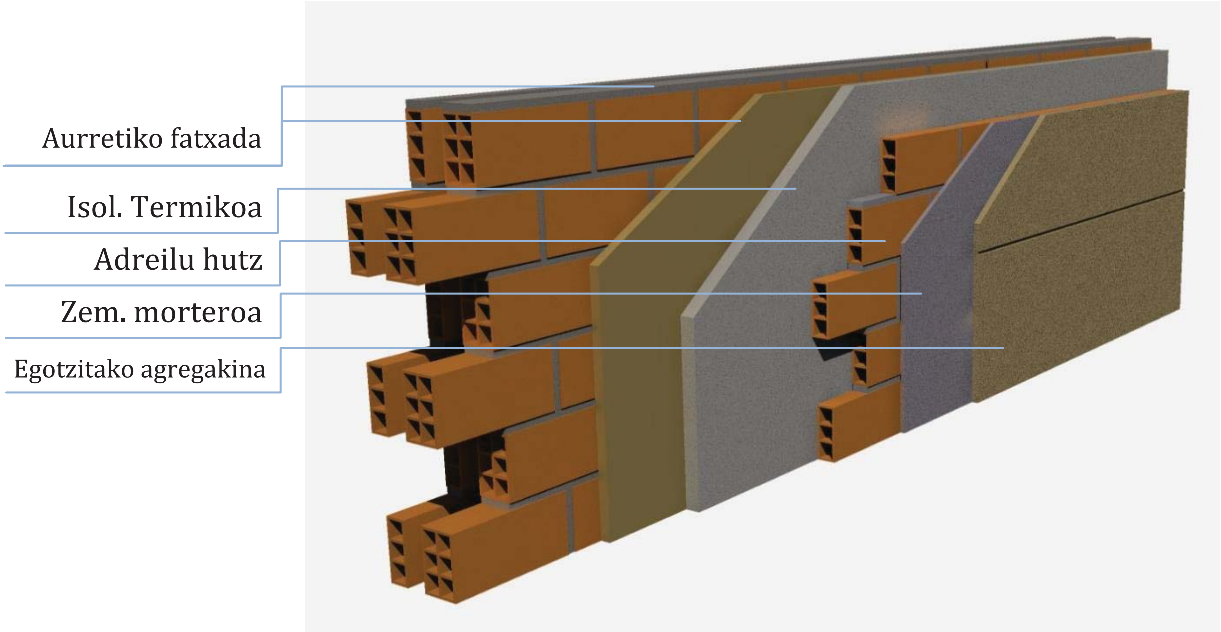
3.1.1 Eraikinaren eraikuntza ezaugarriak

1980. urtetik 1989 urtera arteko aldian Bilboko Udalak birgaitzerako lanak bultzatu zituen auzoan, birgaitzerako estrategia desberdinen bidez. Haietako batzuk portaera termikoa hobetzen ziren ere, esaterako fatxadetan zementuzko mortero arinaren gehikuntza, edo isolamendu termikoaren gehikuntza kasu gutxitan. Auzoko eraikin guztiak irudikatzen dira I4.4 irudian, egindako birgaitzearen arabera koloreztatuta.

Bistan denez, egoera hau (aipatutako birgaitzearen ondorengoa) kapitulu honetan hartu zen erreferentzia kasua bezala. Beraz, hurrengo eraikuntza ezaugarrien deskribapena etxebizitzaren egoera lehen monitorizazioaren epea egin zenean deskribatzen da (2012. urteko lehen hilabeteetan).

3.1.1.1 Fatxada

Bilboko Udal Etxebizitzak emandako informazioaren arabera, etxebizitzaren fatxadak adreilu hutsaren bi geruza dauzka, aire - ganbera batek bananduta. Fatxaden barneko azalak igeltsu geruza bat daukate. Kanpoko azala 1987. urtean egin zen birgaitzearen ondorioa da. Lehen aipatutako informazioaren arabera, beste leihoaren eta fatxadaren orriak eraiki ziren birgaitze horretan.



I4.5. Fatxadaren sekzioa (Bilboko Udal Etxebizitzaren arabera)

Hala eta guztiz ere, aldaketarik ez zen aurkitu leihoetan etxebizitzako begiz bilatzean. Birgaitze balkoiei eragin zioten, itxi zirenak, eta esekileku batean bihurtu zen etxe

]

bakoitzean. Fatxadei dagokionez, geruza berriaren gehikuntza I4.5 irudian irudikatzen da, Bilboko Udal Etxebizitzak emandako informazioaren arabera. Isolamendu termikoaren lodiera oso txikia zen, eta kasu batzuetan, mespretxagarria.

Fatxadaren sekzio zehaztuta, baita barneko pareten ere T4.1 taulan zerrendatzen dira.

Pareta Mota	Sekzioa	U – Balioa (Kalkulatuta) [W/m²K]
Fatxada	Igeltsua Adreilu huts (4.5 cm) Aire - ganbera Adreilu huts (12.5 cm) Isolamendu term. (2 cm) Adreilu huts (4.5 cm) Zementozko morteroa (2cm) Agregakin egotzita (1.5 cm)	0.74
Barneko paretak	Igeltsua Adreilu huts (4.5 cm) Igeltsua	3.59
Etxebizitza Eskailera - kaxarekin/Beste Etxebizitzarekin	Igeltsua Adreilu huts (12.5 cm) Igeltsua	2.26

T4.1. Etxebizitzaren elementu nagusien eraikuntza sekzioa

3.1.1.2 Leihoak

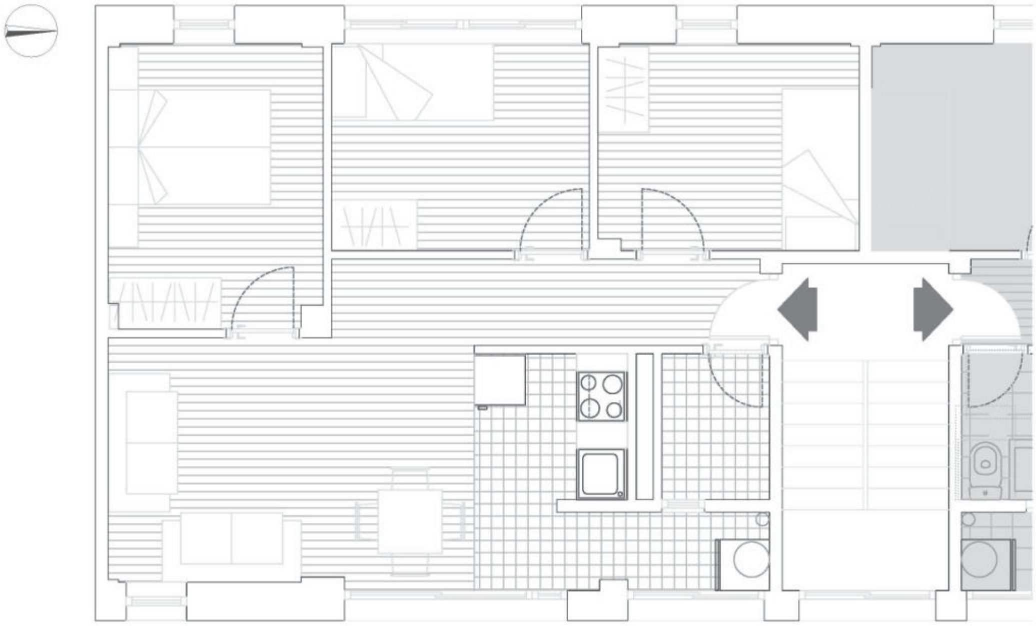
Bi leiho mota ezberdinak aurkitu daitezke birgaitzearen aurretiko etxebizitza, biak aluminiozko markoarekin, zubi termikoaren haustura barik. Leiho hauek ez dira jatorrizkoa, seguruenik. Gela 5eko leihoa (ikusi I4.11 irudia) beira soil zeukan; beste leihoak, berriz, beira - bikoitza zeukaten.

3.1.1.3 Egitura

Epe horretako beste eraikinak bezala, eraikinaren egitura hormigoi armatuzkoa da. Forjatuak, hebexka - forjatuak dira.

3.2 Birgaitze energetikoaren ondorengo etxebizitzaren deskribapena

Birgaitze lana batzuk egin ziren etxebizitzan 2012. urteko udaberri eta udan zehar. Haien artean, leiho guztiak aldatu ziren. Aldaketa honek bigarren monitorizazioaren epearen emaitzetan eragin handia daukala espero da, portaera termikoaren hobekuntza aztertzean. Gainera, etxebizitzaren barne - banaketa aldaketa txikiak izan zituen (I4.6 irudian). Beraz, ikuspegi termiko batetik, leiho aldaketa birgaitze ondorengo etxebizitzaren aldaketa nagusia da. PVC-zko leiho berriak, beira - bikoitzarekin, jarri ziren birgaitzean.



I4.6. Birgaitzearen aurretiko etxebizitzaren planoa

4 Metodologia

4.1 Neurketa ekipamendua

53 PT100 (100 Ω - zko platino - erresistentziazko termometroak) erabili ziren barne eta kanpo tenperaturak neurtzeko. Lau fluxumetro (*Ahlborn Instruments*) erabili ziren ere fatxadetan eta forjatuetan zehar zeuden bero - fluxuak neurtzeko. Fluxumetroak lortutako balioak beste bildutako datuak egiaztatzeko erabili ziren.

Estazio meteorologiko bat eguzki - erradiazioa, haizearen abiadura eta presio atmosferikoa neurtzeko jarri zen. Bost berogailu elektriko erabili ziren etxebizitza berotzeko. Haien bero - sarrera neurtu ziren SINEAX M561 (energia neurgailua monofasiko bat) erabiliz. Bere zehaztasuna %0.2koa da.

Funtzioa	Heina	Bereizmena	Errore
Tentsioa	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
Intentsitatea	10 mA	0.01 μA	2 μA
	100 mA	0.1 μA	5 μA
	1:00 AM	1 μA	100 μA
Erresistentzia	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

T4.2. Datuak eskuratzeko sistemaren ezaugarriak

Agilent 34980A datuak eskuratzeko sistema bat erabili zen neurtutako datuak biltzeko, 34921A txartelarekin eta 34921T konexio - blokearekin. Sistema honi buruzko informazio gehiago T4.2 taulan aurkezten da.

Sentsore guztiak Eusko Jaurlaritzako Eraikuntza Kalitatearen Kontrolerako Laborategian kalibratu eta baliozkotu ziren. Ekipamenduaren ezaugarriari buruzko zehaztutako informazioa T4.3 taulan aurkezten da.

Parametroa	Unitateak	Sentsorea	Ziurgabetasuna
Tenperatura	[°C]	PT100. A class (4 wire)	± 0.2 °C
Bero fluxua	[W/m²]	Ahlborn FQA - 0801 - H	± 5 %
Anemometroa	[m/s]	Meteo Multi FMA510	± 0.5 / ± 0.3 m/s
Presio barometrikoa	[bar]	Meteo Multi FMA510	± 0.5 mbar
Hezetasun erlatiboa	[%]	Meteo Multi FMA510	± 3 %
Eguzki - erradiazioa	[W/m²]	Kipp and Zonen CMP11	± 3 %

T4.3. Erabilitako sentsoreen ezaugarriak

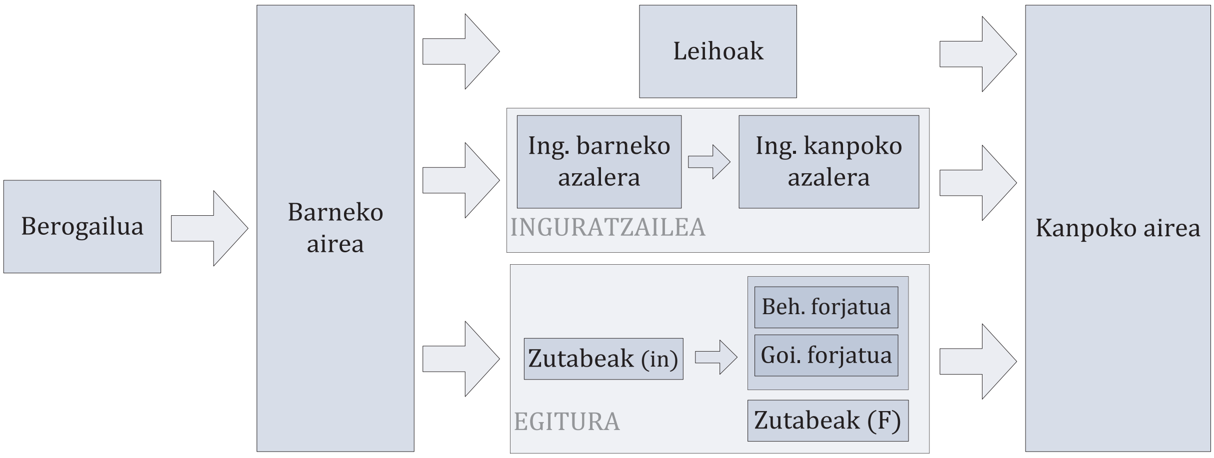
4.2 Metodologia

Lehen aipatu den bezala, kasu - azterketa 50 metro karratutako etxebizitza bat da. Gelak batetik zortzira zenbatu ziren (I4.11 irudian). Bi monitorizazio egin ziren. Lehenean, etxebizitza lau hilabetetan zehar (2012ko Otsailetik Maiatzera) monitorizatu zen. Leiho aldaketaren ondoren, monitorizazio berri bat egin zen hiru hilabetetan zehar (2012ko azarotik 2013ko otsailera). Etxebizitza hutsik egon zen bi epeetan zehar.

Etxebizitzaren bero - hornidura elektrikoa zen. Berogailu elektriko bana 1 - 5 gela nagusi bakoitzean (1 - 5) kokatu ziren, eta berogailu bakoitza 400 W-koa zen (nahiz eta neurketak 1800Wkoa potentzia totala eman ziren, 2000 W-koaren ordez).

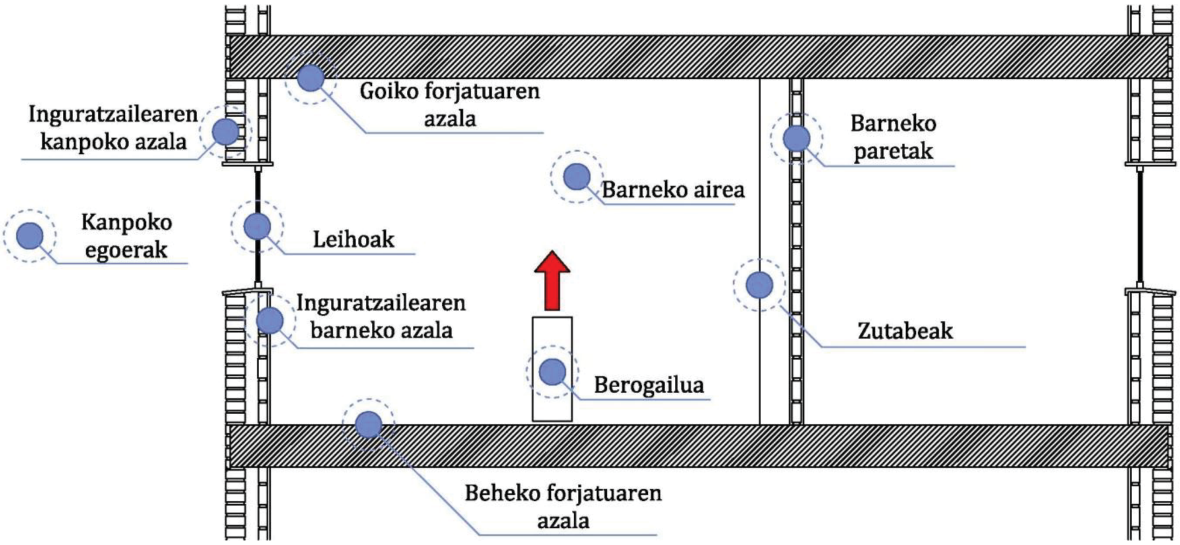
4.2.1 Monitorizazioaren ikuspegia

Landa - azterketa hau diseinatzeko, bero katea berogailutik kanpo airera, kontuan hartu zen, Annex 49 [74] egiten den antzekoa. Kasu honetan, haatik, monitorizazioaren eskalaren ondorioz, sistemaren mugak mugitu zen, eta azterketa ez da energia primario bihurketan hasi, berogailuetan baizik. Ikuspegi honetan, bero - katea azpisistema batzuetan banandu zen. Bero kate honen eskema bat I4.7 irudian irudikatzen da.



I4.7. Bero katea, berogailutik kanpo airera

Ikuspegi honen oinarritutakoa, monitorizazioa diseinatu zen azpisistema bakoitzari buruzko informazioa lortzeko. Beraz, tenperatura azpisistema bakoitzean neurtu zen. Gainera, beste datu batzuk azpisistema batzuetan bildu ziren ere, esaterako berogailuetan, (haien energia kontsumoa neurtu zen) edo kanpoko ingurumenean, (haizearen abiadura eta eguzki - erradiazioa neurtu ziren). Sentsore hauen banaketa irudi eskematiko batean aurkezten da I4.8 irudian.



I4.8. Neurtutako azpisistemak

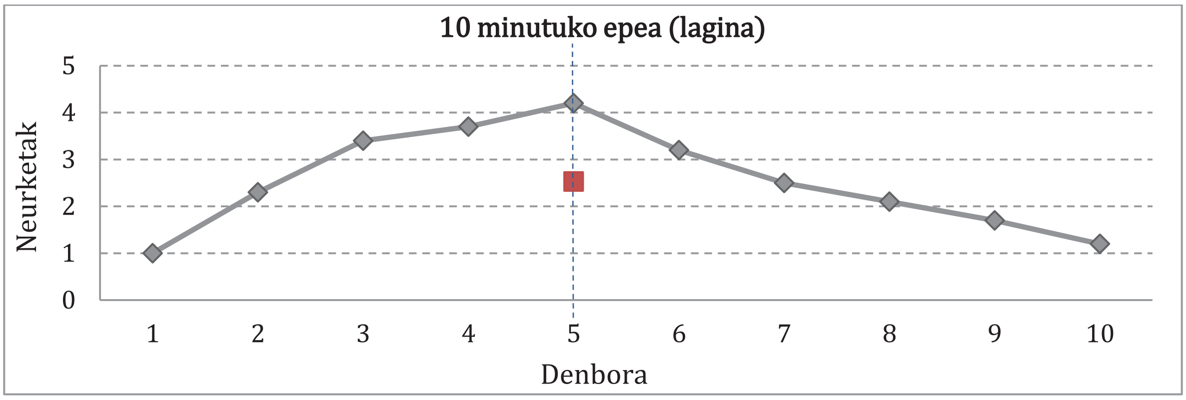
4.2.2 Datu - eskuratzearen prozedura eta datuen tratamendua

Neurketak minuturo hartu ziren. Datu eskuratzeko sistemak iragazki integratu bat zeukan. Horrela, neurtutako datuak iragazki honetan zehar pasatu ziren seinalearen kalitatea hobetzeko.

4.2.2.1 Neurketen maiztasuna

Neurketen maiztasuna hautatu behar da aztertutako objektuaren denbora erantzunaren arabera. Eraikinen kasuan, denbora erantzun hau 30 minuturen 60 minuturen artean dago. Hala ere, aipatu bezala, hautatutako neurketen maiztasuna landa - azterketa honetarako minutu batekoa zen.

Neurketen maiztasun honen bidez, aldaketa termikoak zehatz - mehatz aztertu daitezke. Lehen azterketa honen ondoren, datuak 10 minutuko epetan integratu ziren, epe bakoitzeko batez besteko balioa kalkuluen bidez. Horrela, batez besteko balio hau balio banaka bat hartzea baino adierazgarriagoa da, baita epe honetako informazio zehatzagoa dauka ere. Datu - multzo sinple bat I4.9 irudian irudikatzen da, kontu hau azaltzeko. Datu - multzo baten hamar neurketak aintzakotzat hartuz, hamar balio hauen batez bestekoa (puntu gorri bat irudikatuta) balio puntukari bat erabilera baino adierazgarriagoa da. Hau da, metodo hau jarraituz, zehaztasun handiagoa lortzen da.



I4.9. Adibide bat balio bakar baten eta batez bestekoaren adierazgarritasunak elkarrekin konparatzeko

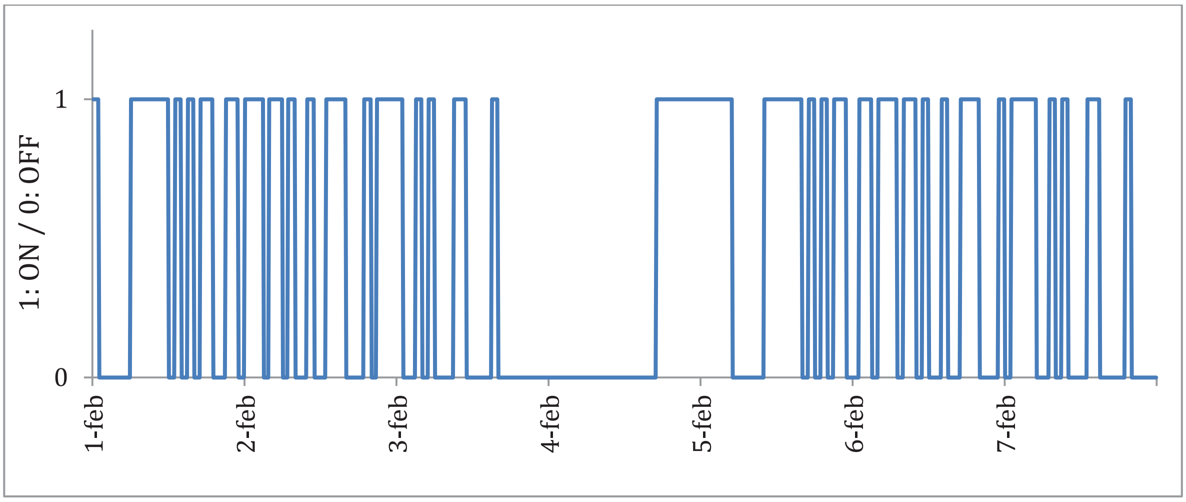
4.2.2.2 emaitzen ebaluazioa

Datu eskuratzeko sistemak datu - fitxategi bat sortzen du egunero. Fitxategi bakoitza ("*raw data*") tratatu zen lehenik eta behin, eta sentsore bakoitzetik lortutako neurketak kalibrazioaren faktoretan zehar pasatu ziren. Kalibrazioren faktore hauek lortu ziren aipatutako kalibrazioaren prozedura medio.

Kalibratutako emaitzak aztertu ziren jarraian azalduko den moduan. Lehenik eta behin, egun bakotzako emaitzak aztertu ziren. Prozedura honen bidez, edozein sentsoreen ustekabeko portaera identifikatu daiteke (sentsore guztiak zuzen konektatuta dauden egiaztatzea, adibidez). Lehen azterketa hau egin eta gero, datu hauek 10 - minutuko epetan integratu ziren, lehen aipatu bezala, eta elementu bakoitzaren batez besteko balioak (barne airearen tenperaturaren, fatxadaren kanpoko azaleko tenperaturakoa, etab) lortzen ziren.

4.2.3 Test - errutina

Bero sarreraren errutina diseinatzeko, bi errutina ezagunaren konbinazio bat jarraitu zen: goi - maiztasuneko errutina bat, ROLBS deritzona (*Randomly Ordered Logarithmic distributed Binary Sequence*, ingelesez) eta behe - maiztasuneko errutina bat, PRBS deritzona (*Pseudorandom Binary Sequence*). Ondoriozko errutinak ez dauka korrelaziorik beste sarrerekin, eta diseinatu zen maiztasun ezberdinetan sistema sutzeko, eraikinaren denbora - konstanteak espero denekoa [72]. Denbora - konstante hauek 60 minutuko urratsetik 12 orduko urratsetara aldatzen dira. Aste bateko bero sarreraren errutinaren adibide bat I4.10 irudian irudikatzen da.



I4.10. Etxebizitzaren bero - sarreraren kontrol - seinalea, Otsailaren 1etik 7ra

4.2.4 *Co-heating* metodoa

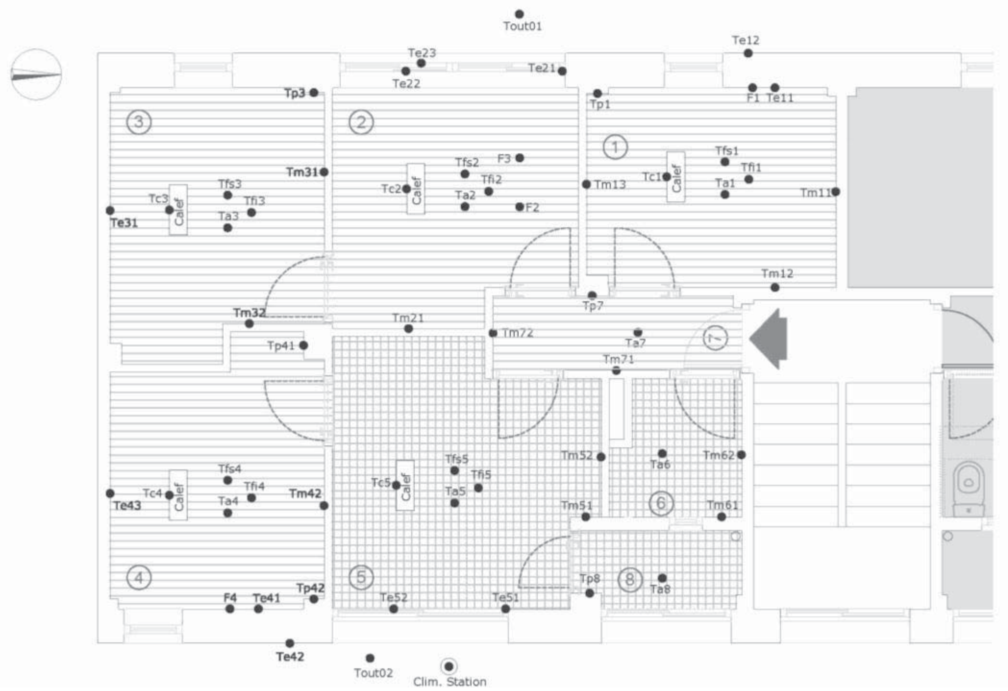
Lortutako datuak erabiliko dira inguratzailearen transmisio - faktore globala kalkulatzeko, *co-heating* metodoaren bidez. *Co-heating* test neurketa - metodo bat da. Etxebizitzaren bero - galera globalak zenbatzen ditu (W/K), hurbilketa baten bidez.

Co-heating metodoa ez da kontzeptu berri bat. Estatu Batuetan garatu zen 1970. hamarkadako azken urteotan, eta Erresuma Batuan sarritan erabiltzen zen 1980. hamarkadan. Metodo hau egiteko, etxebizitza berogailu elektrikoen bidez berotu behar da bere batez besteko barne tenperatura igotzeko, eta tenperatura hori epe batean zehar mantentzeko, 1 - 3 asteko epean, normalean. Egun bakoitzeko bero - sarrera etxebizitzan kalkulatu daiteke energia elektriko kopuruaren neurketaren bidez. Aipatutako bero - galeraren koefizientea kalkulatu daiteke bero sarreraren eta barne eta kanpo tenperaturaren arteko diferentziaren erlazioa medio. Erlazio hau irudikatuz gero, lortutako maldak bero - galera koefizientea (W/K) ematen du [75]. Hau da, bero - galera koefizientea Eq. 5 ekuazioa medio kalkulatu daiteke.

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

Bestalde, komenigarria da nahikoa ΔT (barne eta kanpo tenperaturaren arteko diferentzia) lortzeko, bero - transferentzian parte hartzen duten bero fluxu ezberdinak maximizatzeko. Horrela, lortutako balioa zehatzagoa da. Horregatik, askoz gomendagarria da *co-heating* test negu aldian egitea, Azaroaren eta Martxoaren arteko epean, leku bakoitzeko klima egoeren arabera. Epe honetan, test hau egitearen beste abantaila bat eguzki - erradiazioaren eraginak murrizten direla. Modu honetan, aldaketa txiki batzuekin, [75] erreferentzian deskribatutako metodologia kontuan hartu zen landa - azterketa hau diseinatu zenean.

4.2.5 Scenario 1. Egoera 1. Birgaitzearen aurretiko monitorizazioa



I4.11. Birgaitzearen aurretiko etxebizitzaren planoa. Sentsoreen kokapena

Datu - multzoa		Sentsore kopurua
Barne tenperatura	[Ta]	6
Fatxadaren azaleko tenperatura	[Te]	6
- *Barneko azala*		*4*
- *Kanpoko azala*		*2*
Leihoen azaleko tenperatura	[Te]	5
Egituraren azaleko tenperatura	[Tstr]	16
- *Goiko forjatuak*	*[Tfs]*	*5*
- *Beheko forjatuak*	*[Tfi]*	*5*
- *Zutabeak (in)*	*[Tp]*	*2*
- *Zutabeak (out)*	*[Tp]*	*4*
Berogailuaren Tenperatura	[Tc]	5
Barneko pareten azaleko tenperatura	[Tm]	13
Kanpoko egoerak (Airearen tenperatura Tout (x2), haizearen abiadura, eguzki - erradiazioa)	-	4
Fluxumetroak	[F]	4

T4.4. Lehen egoeraren etxebizitzaren puntu azpimarragarriak

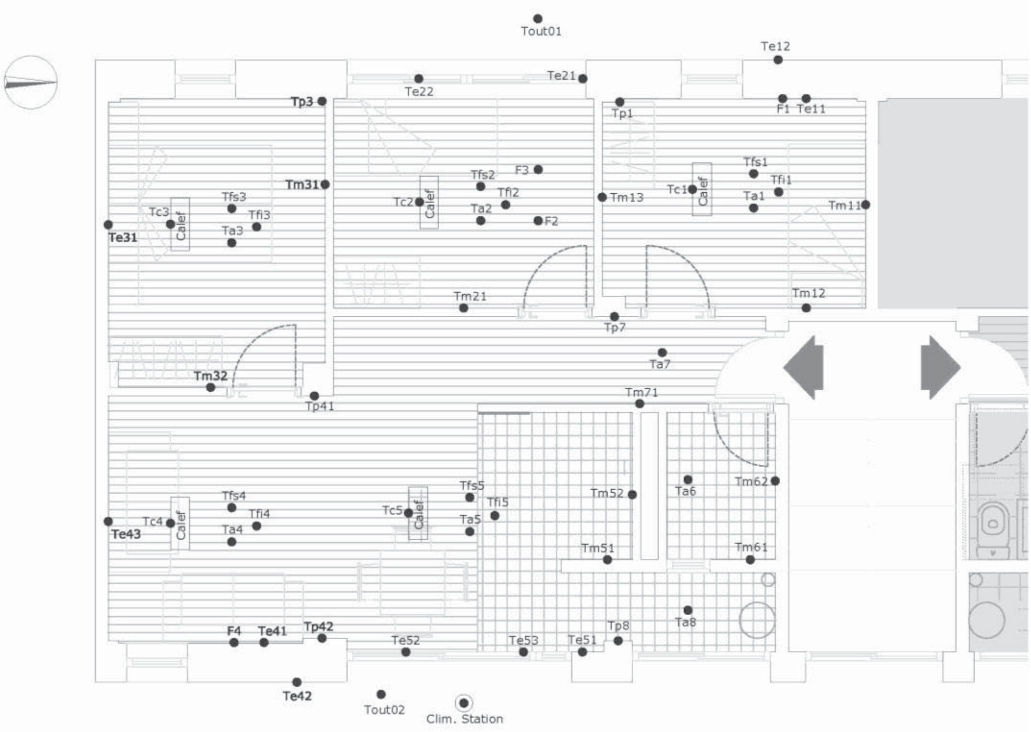
Etxebizitzaren plano bat irudikatzen da I4.11 irudian. Plano honetan gelak zenbatuta daude eta sentsoreen kokapena aurkezten da, 4.2.1 atalean deskribatutako ikuspegian oinarritutakoa.

I4.12. Lehen monitorizazioaren lau argazki

Lehen monitorizazioan erabilitako sentsoreak zerrendatzen dira T4.4 taulan, lehen aipatutako taldeen arabera: barne tenperatura zortzi puntutan neurtu zen, egituraren tenperatura 16 puntutan neurtu zen, inguratzailearen tenperatura 9 puntutan (haietako lau, fatxadan, eta besteak, leihoetan) eta kanpo tenperatura bi puntutan neurtu zen. Gainera, barneko pareten azaleko tenperatura 15 puntutan neurtu zen, eta 4 fluxumetro ekialdeko eta mendebaldeko fatxadetan eta forjatuan (goikoa eta behekoa) kokatu ziren. Berogailu bakoitzaren alboko airearen tenperatura neurtu zen ere, modu egokian ibiltzen zirela egiaztatzeko. Orobat, balio hauek berogailuaren erresistentziaren inguruko tenperatura edukitzeko erabili daitezke. Monitorizazio honen argazki batzuk aurkezten dira I4.12 irudian. Paretan kokatutako PT100 bat eta fluxumetro bat lehen argazkian erakusten dira; estazio meteorologikoa bigarrenean; erabilitako berogailu bat hirugarrenean; eta airearen tenperatura neurtu ziren sentsore baten kokapena laugarrenean.

4.2.6 Egoera 2. Birgaitzearen ondorengo monitorizazioa

Etxebizitzaren barne - banaketan aldaketa batzuk egon ziren. Hobekuntza termiko nagusia leihoen aldaketa zen. Sentsoreen kokapena lehen monitorizazioaren oso antzekoa zen, bi sentsore salbu (T_m42 and T_m72) mugitu behar zirenak, lehen monitorizazioen kokatzen zireneko paretak ez zeuden bigarren monitorizazioa, I4.13 irudian erakusten denez. Bigarren egoeraren sentsoreen zerrenda T4.5 taulan zerrendatzen da.



I4.13. Birgaitzearen ondorengo etxebizitzaren planoa. Sentsoreen kokapena

Bestalde, bi epe ezberdinak bereizten dira bigarren monitorizazio honetan. Instalatutako leiho berriek aireztapeneko saretak zeuzkaten. Monitorizazio honen lehen asteetan zehar, 2012ko abenduaren 12ra arte, irekita zeuden. Egun horretan, aireztapen saretak zigilatu ziren (I4.14 irudian erakusten den bezala) eta bigarren fasea hasi zen. Bigarren fase hau 2013ko otsailaren 20a arte iraun zen, monitorizazioa bukatu zenean.

I4.14. Aireztapeneko sareta zigiluak

Datu - multzoa		Sentsore kopurua
Barne Tenperatura	[Ta]	6
Fatxadaren azaleko tenperatura	[Te]	6
- *Barneko azala*		*4*
- *Kanpoko azala*		*2*
Leihoen azaleko tenperatura	[Te]	5
Egituraren azaleko tenperatura	[Tstr]	16
- *Goiko forjatuak*	*[Tfs]*	*5*
- *Beheko forjatuak*	*[Tfi]*	*5*
- *Zutabeak (in)*	*[Tp]*	*2*
- *Zutabeak (out)*	*[Tp]*	*4*
Berogailuaren Tenperatura	[Tc]	5
Barne pareten azaleko tenperatura	[Tm]	11
Kanpoko egoerak (Airearen tenperatura Tout (x2), haizearen abiadura, eguzki - erradiazioa)	-	4
Fluxumetroak	[F]	4

T4.5. Bigarren egoeraren etxebizitzaren puntu azpimarragarriak

I4.15. Bigarren monitorizazioaren hiru argazki (2012ko Azarotik 2013ko otsailera)

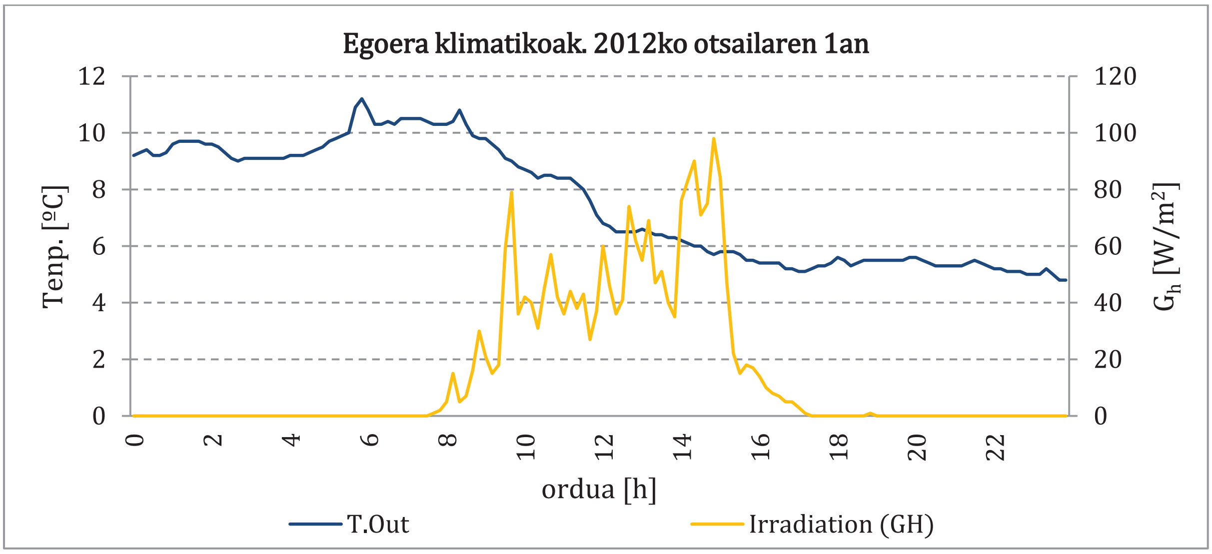
Horrela, bi faseen emaitzen arteko konparaketa bat eginez, aireztapenari lotutako energia kontsumoaren diferentzia lortzen da, birgaitzearen ondoren ezin baitzen gas trazatzaile bidezko entsegua egin. Epe honetako argazki batzuk aurkezten dira I4.15 irudian.

5 Emaitzak

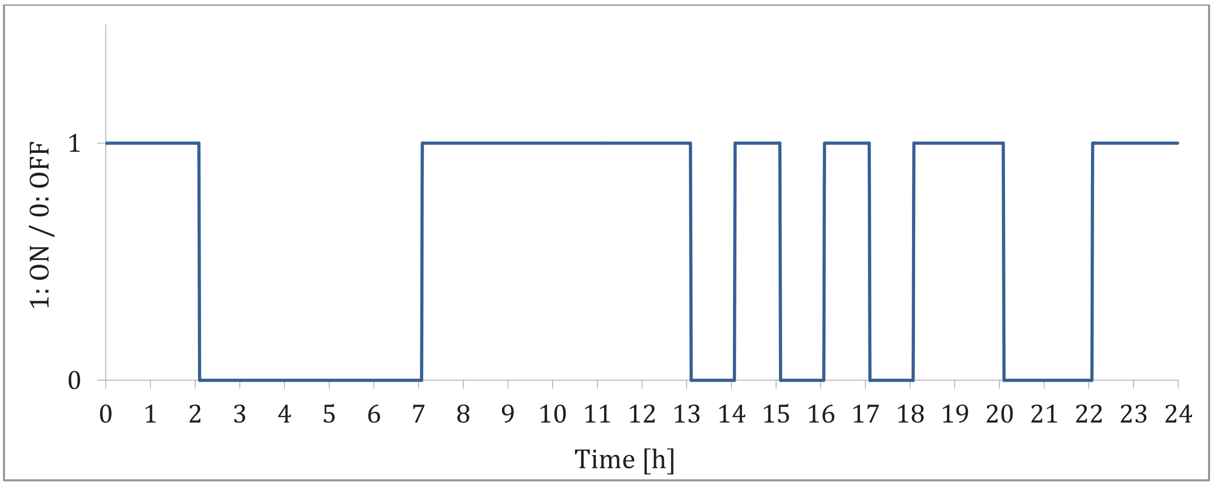
Lortutako emaitzak erabili ziren hurrengo kapituluetan garatutako eraikinen ereduak definitzeko eta garatzeko. Hala ere, nahiz eta emaitzak hauek soilik urrats erdiko bat izan eredu horiek garatzeko eta helburuzko emaitzak lortzeko simulazioen bidez, informazio interesgarria aurkitu zen emaitza hauek aztertu zirenean.

5.1 Datu esperimentala. Birgaitzearen aurretiko emaitzak

4.2.2.2 Atalean deskribatzen den bezala, lortutako datuak aztertu ziren urrats ezberdinak jarraituz. Lehenik eta behin, egun bakoitzeko datu multzoak aztertu ziren. Modu honetan, lortutako neurketen koherentzia ebaluatzen da eta sentsoreei lotuta diren erroreak, esaterako kontaktu txarrak edo konexioen erroreak aurkitzen dira. Gainera, analisi zehatzak egiten dira emaitza hauek erabiliz. Adibidez, 2012ko Otsailaren 1ean neurtutako datu multzoaren analisia aurkezten da jarraian. Egun horretako egoera klimatikoak (kanpo airearen tenperatura, haizearen abiadura eta eguzki - erradiazioa) eta bero - sarreraren kontrol - seinalea I4.16 eta I4.17 irudietan aurkezten dira, hurrenez hurren.



I4.16. 2012ko otsailaren 1an neurtutako egoera klimatikoak (Euskalmet)



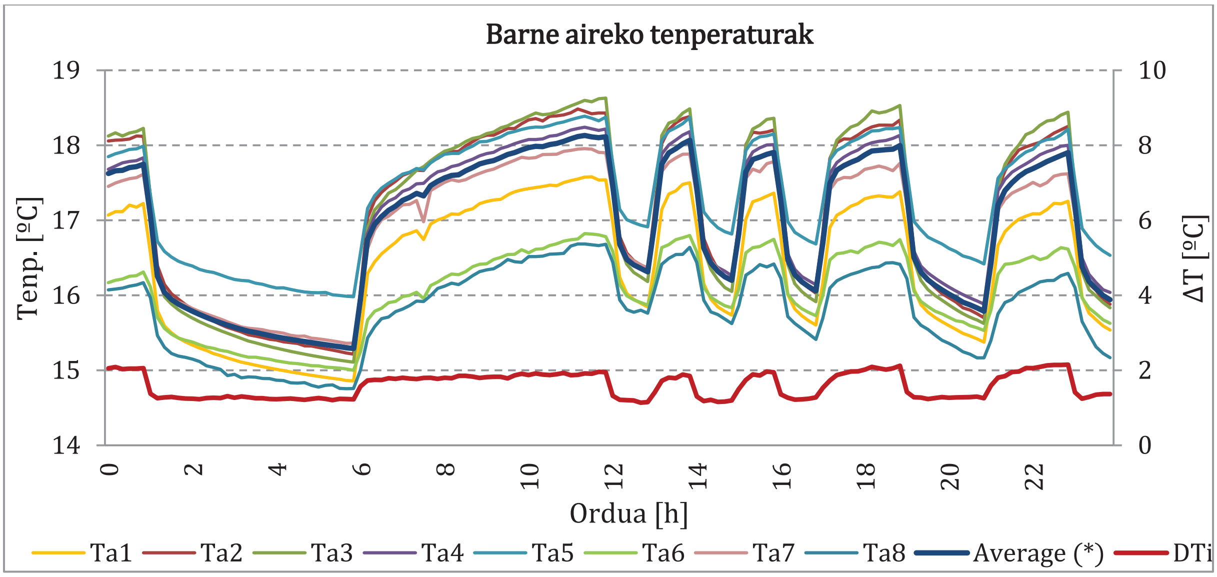
I4.17. 2012ko otsailaren 1an bero sarreraren errutina

5.1.1 Sistema eta azpisistema bakoitzaren emaitzak

Sistema eta azpisistema (I4.8 irudian irudikatutako eskemaren arabera) bakoitzaren eguneroko emaitzak monitorizazioaren epean zehar aztertu ziren.

5.1.1.1 barne airearen tenperatura

Gela bakoitzean neurtutako tenperatura, baita batez besteko barne tenperatura eta ΔT (tenperatura minimoaren eta maximoaren arteko diferentzia) ere I4.18 irudian aurkezten dira. Barne tenperaturaren kasuan, bi neurketa - multzoen balioak (T_a6 eta T_a8) bestearenak baino baxuagoak ziren. Gela hauen diferentzia (komuna eta esekilekua) gela hauetan berogailurik ez egotearen ondorioa da. Beraz, gela hauetan tenperatura baxuak espero ziren, eta berotuta geletan neurtutako tenperaturek (gelak 2 - 5), baita gela 7 ere, 0.5 graduko diferentziak erakusten dituzte. Bitartean, gela 1ean neurtutako tenperatura (T_a1) beste geletako tenperaturaren 0.5 bat gradu azpitik dago. Fenomeno hau hauteman zen ere eguneroko batez besteko balioak aztertzean. Kontu hau monitorizazio - epearen egun gehienetan ohartu zen, eta egun hotzenetan nabarmengarriagoa da.

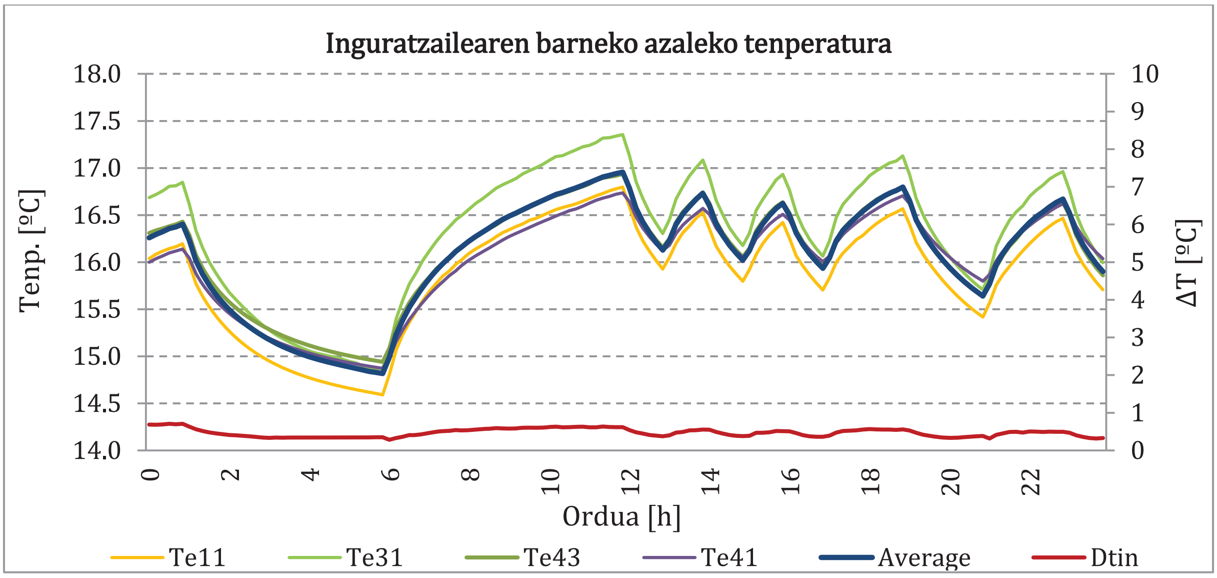


I4.18. 2012ko otsailaren 1an neurtutako barne airearen tenperaturak

Ez da batere erraza arrazoi bat aurkitzea efektu hau azaltzeko, soilik orain arte aurkezten diren datuak kontuan hartuz gero. Gelaren azalera besteen antzekoa da eta bero sarrera berdina da (gelaren erdian kokatutako berogailu elektriko bat). Gela honen kokapena etxebizitzan intuitiboki are eta onuragarriagoa da, batez ere gela 3 edo 4ekin konparatuz, fatxadaren ratio handiagoa daukatenak. Fenomeno honen azalpena geroago aurkeztuko da, parametro gehiago aztertu ondoren.

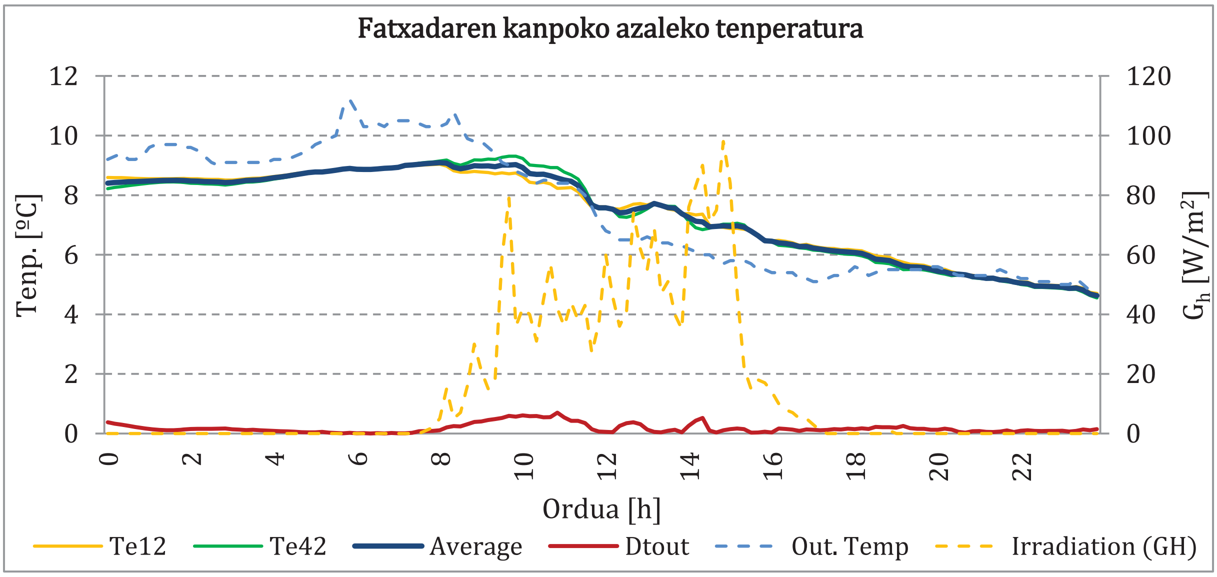
5.1.1.2 Inguratzailearen barneko azaleko tenperatura

Inguratzailearen barneko azaleko tenperaturari dagozkion eguneroko datu - multzoak I4.19 irudian irudikatzen dira. Neurtutako barneko azal guztien portaera antzekoa da. Kasu honetan, tenperaturen arteko diferentziak 0.5 bat gradu ziren. Kasu honetan ere, tenperaturarik baxuena gela 1ean neurtu zen.



I4.19. 2012ko otsailaren 1an neurtutako inguratzailearen barneko azaleko tenperatura

5.1.1.3 Inguratzailearen kanpoko azaleko tenperatura



I4.20. 2012ko otsailaren 1an neurtutako inguratzailearen kanpoko azaleko tenperatura

Fatxadaren kanpoko azalean kokatutako sentsoreak neurtu ziren datuak I4.20 irudian irudikatzen da. Fatxadaren kanpoko azaleko tenperatura bi puntu ezberdinak neurtu zen: sentsore bat mendebaldeko fatxadan kokatu zen (T_e12) eta beste sentsore bat ekialdekoan (T_e42). Kanpo tenperatura eta eguzki - erradiazioa ere I4.20 irudian sartzen dira, interesgarritzat hartzen direlako, egoera klimatikoek fatxadaren kanpoko azalari asko eragin baitiote.

Bi alderdi azpimarratu daitezke fatxadaren kanpoko azaleko tenperaturak aztertzen direnean. Alde batetik, fatxadaren kanpoko azalaren eta zeruaren arteko erradiaziozko bero trukearen garrantzia; bestalde, eguzki - erradiazioaren eraginak fatxadan.

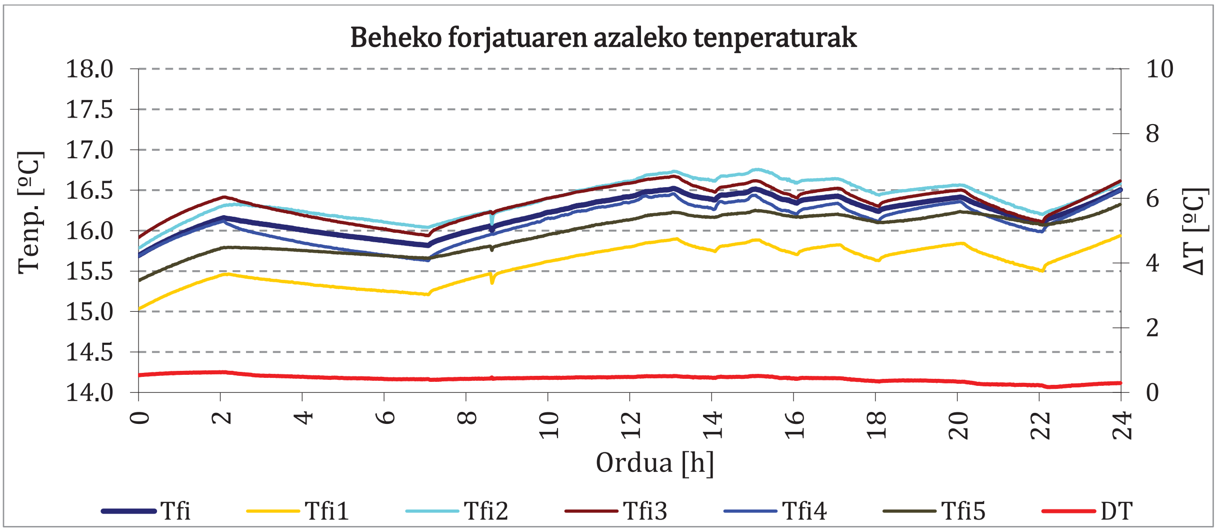
Lehen puntuari dagokionez, fatxadaren kanpoko azalaren eta zeruaren arteko erradiaziozko bero trukearen ondoriozko bero - galerak, fatxadaren kanpoko azaleko tenperatura kanpo airearen tenperatura baino baxuagoa izatearen eragileak dira, eta beraz, bero fluxua barne girotik kanpora handiagotzen da. Hau da, negu aldian, erradiaziozko bero trukearen ondoriozko bero - galerak fatxadaren kanpoko azalaren eta kanpo airearen arteko konbekzioaren ondoriozkoak bezain garrantzitsuak dira gutxienez. Izan ere, kanpoko azalako tenperatura kanpo tenperatura baino baxuagoa izan daiteke, eta honen ondorioz, bero fluxuaren noranzkoa aldatzen da, bero irabaziak konbekzioaren bidez edukiz (nahiz eta erradiaziozko bero trukearen ondoriozko bero - galerak askoz handiagoak izango dira).

Eguzki - erradiazioari dagokionez, nahiz eta otsailaren 1a egun hodeitsu bat izan (eguzki - erradiazioa ez zuen 100 W/m^2 goititu egun honetan), 0.80 gradu inguruko diferentziak aurkitu ziren goizean (ekialdeko fatxadan baino tenperatura altuagoak neurtu ziren). Logikoki, egoera kontrakoa da arratsaldean: mendebaldeko fatxadan 0.5 gradu inguruko tenperatura altuagoak neurtu ziren. Gauean zehar, eguzki - erradiaziorik ez dagoenean, fatxaden azaleko tenperaturaren arteko diferentziak mespretxagarriak ziren.

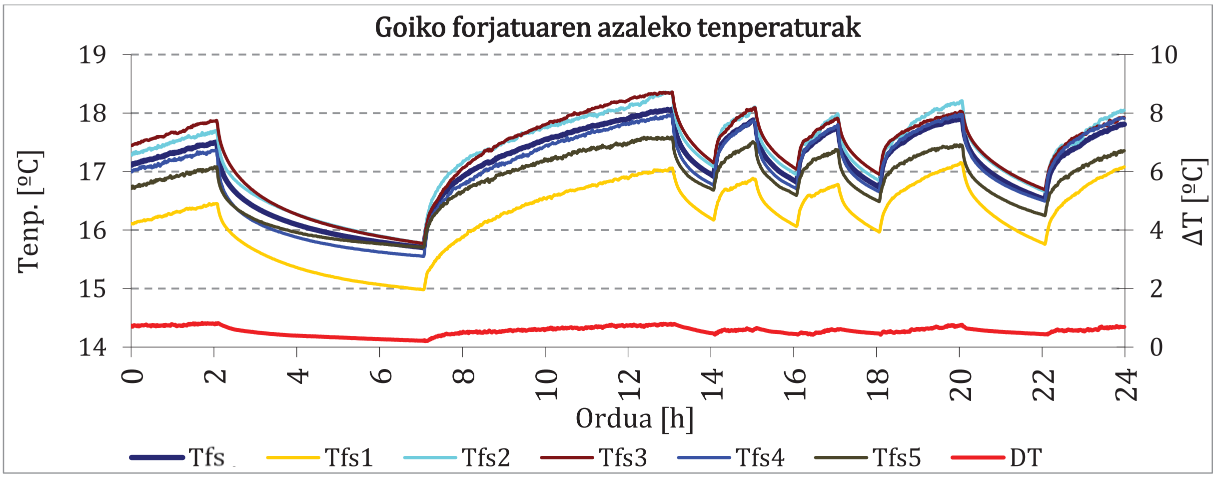
Egun eguzkitsuetan efektu hau nabarmengarriagoa da, 5.1.3. atalean deskribatuko den bezala.

5.1.1.4 Forjatuen azaleko tenperatura

Forjatuen azaleko tenperaturak I4.21 eta I4.22 irudietan irudikatzen dira. Gela 1ean neurtutako tenperaturaren balioak beste geletan neurtutakoak baino baxuagoak ziren ere. Beste geletako batez besteko ΔTko balioak (irudietan irudikatutako lerro gorriak, Gela 1eko tenperatura ez zen kontuan ΔT kalkulatzeko) 0.4 gradukoa izan zen beheko forjatuaren tenperaturak, eta 0.6 gradukoa izan zen goiko forjatuaren tenperaturak. Gainera, datu - multzo hauei buruzko azalpen batzuk egin daitezke.

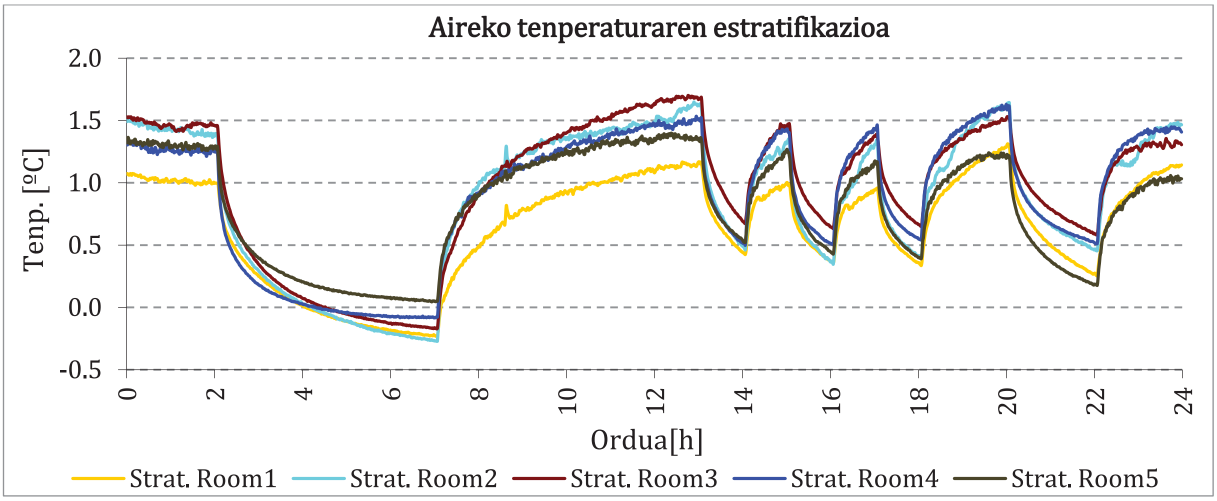


I4.21. Otsailaren 1an neurtutako beheko forjatuaren azaleko tenperaturak



I4.22. Otsailaren 1an neurtutako beheko forjatuaren azaleko tenperaturak

Beheko eta goiko forjatuen arteko konparaketa egitekotan, aire - estratifikazio termikoa kontuan hartu behar da. Hau da, beheko eta goiko forjatuen azaleko tenperaturen arteko diferentziak ez dira soilik forjatuetan zehar dauden bero - galeraren ondorioz. Aipatutako estratifikazioa oso nabarmengarria da berogailuak konektatuta dudenean, nahiz eta nabarmengarria izan bero - sarrerak ez daudenean ere. Berogailuak konektatuta daudeneko epeetan, I4.23 irudian irudikatu bezala, 2 gradu baino handiagoko diferentziak aurkitzen dira.



I4.23. Airearen tenperaturaren estratifikazioa. 2012ko Otsailaren 1ean ΔT (Tfs - Tfi)

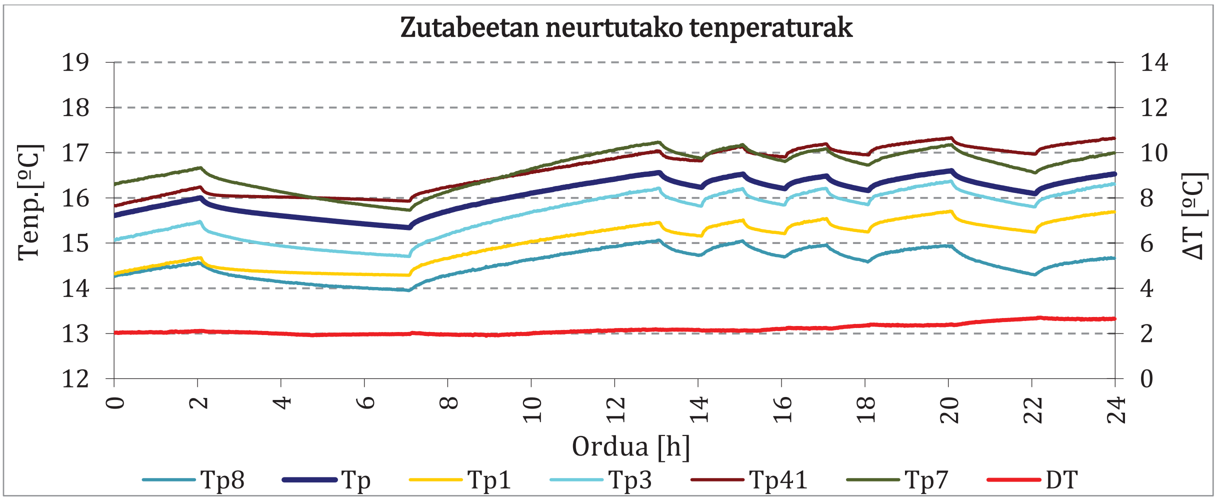
Espero bezala, goiko forjatuaren azala behekoarena baino sentikorragoa da bero - sarreraren aldaketekiko, I4.21 eta I4.22 irudietan erakutsi bezala. Efektu hau aire - estratifikazioaren ondorio bat da. Berogailuak konektatuta daudenean, aire beroa igotzen da, eta beheko aire geruzaren tenperatura astiroago gehitzen da. Estratifikazio honen ondorioz, bero - galerak goiko forjatutan zehar, behekotan zehar baino handiagoak ohi dira.

Efektu hau argi eta garbi erakusten da ere F2 eta F3 fluxumetroen neurketak aztertzekotan. Berogailuak konektatuta ez zeudenean, bero fluxuak bi forjatuetan zehar ia zero izan zen. Hau adierazi daiteke forjatuaren bi azalak tenperatura antzekoa izan zuten. Hala ere, berogailuak konektatuta zeudenean, eta orduan, barne tenperatura igotzen zinen, goiko forjatuan zehar dauden bero - galerak behekoan zehar daudenak baino askoz handiagoak ziren.

5.1.1.5 Zutabeen tenperatura

Bi portaera ezberdinak zutabeetan neurtutako tenperaturan aurkitzen dira, I4.24 irudian aurkezten den bezala. Alde batetik, fatxadetan ez dauden zutabeek (T_p41 eta T_p7) azaleko tenperaturak altuenak izan zituzten. Bestetik, fatxadan dauden zutabeek (T_p1, T_p3 eta T_p8) aurkeztu zuten tenperaturak batez besteko balioak baino baxuagoa ziren.

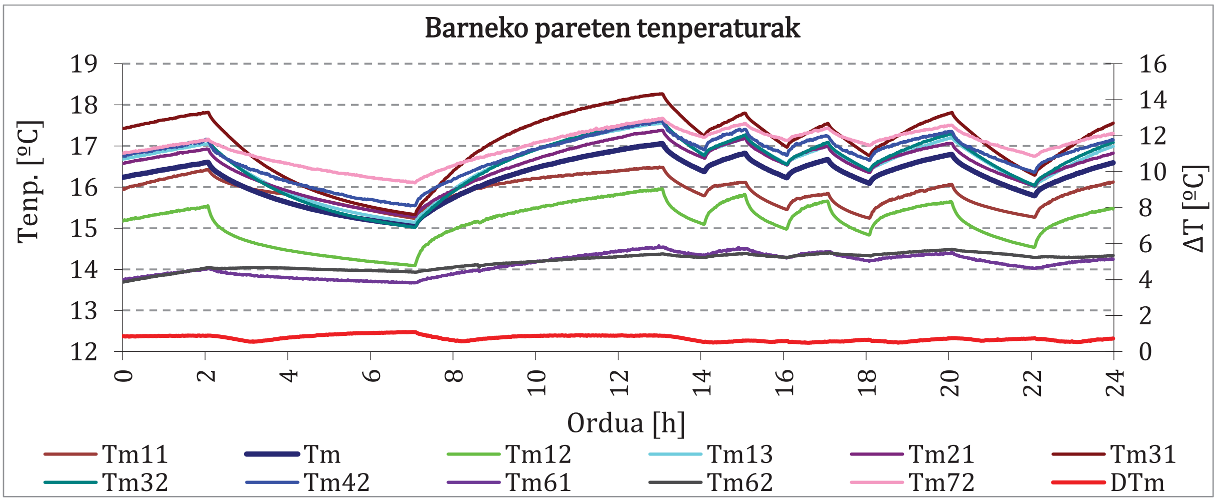
Hala ere, T_p41 eta T_p7 tenperaturek ez zituzten diferentzia handiak aurkeztu eta bi pilaretan neurtutako tenperaturak oso antzekoak zirenen bitartean, T_p1, T_p3 eta T_p8 balioetan diferentzia nabarmengarriak aurkitu ziren. T_p8aren kasuan, diferentzia hauek neurtutako zutabearen azala berotuta ez zegoen gela batean egotearen ondorioak dira. Teorian, T_p1 eta T_p3 antzekoak beharko luke, kokapena direneko gelak ezaugarri berak zeuzkaten (Orientazio berbera, bero - sarrera berbera...). Hala ere, gela 1an neurtutako beste neurketak bezala, gela honetan neurtu ziren zutabearen azaleko tenperaturak gela 3an neurtutakoak baino baxuagoak dira (0.5 gradu inguruko diferentziak).



I4.24. 2012ko Otsailaren 1an zutabeetan neurtutako tenperaturak

5.1.1.6 barneko pareten azaleko tenperaturak

Barneko pareten azaleko tenperaturak aztertzean, gela 1an neurtutako tenperaturen balio baxuen zergatia aurkitu daiteke.



I4.25. 2012ko Otsailaren 1an barneko paretetan neurtutako tenperaturak

Otsailaren 1an neurtutako barneko pareten tenperaturak I4.25 irudian irudikatzen dira. Gela 1 eta gela 6an kokatu ziren sentsoreak (T_m11 eta T_m12; T_m61 eta T_m62, hurrenez hurren) kontuan hartu ezean, ΔT (I4.25 irudian lerro gorrian irudikatzen dena) egun horren batez besteko balioa 0.7 gradukoa zen.

Baina portaera ezberdinak izan zituzten datu multzotan arreta jarri dezagun, hau da, T_m11, T_m12, T_m61 eta T_m62. Gela 6an neurtutako datuei dagokionez, tenperatura baxu horiek gela bero - sarrerarik ez edukiaren (ez zegoen berogailurik gela honetan) ondorioa dira.

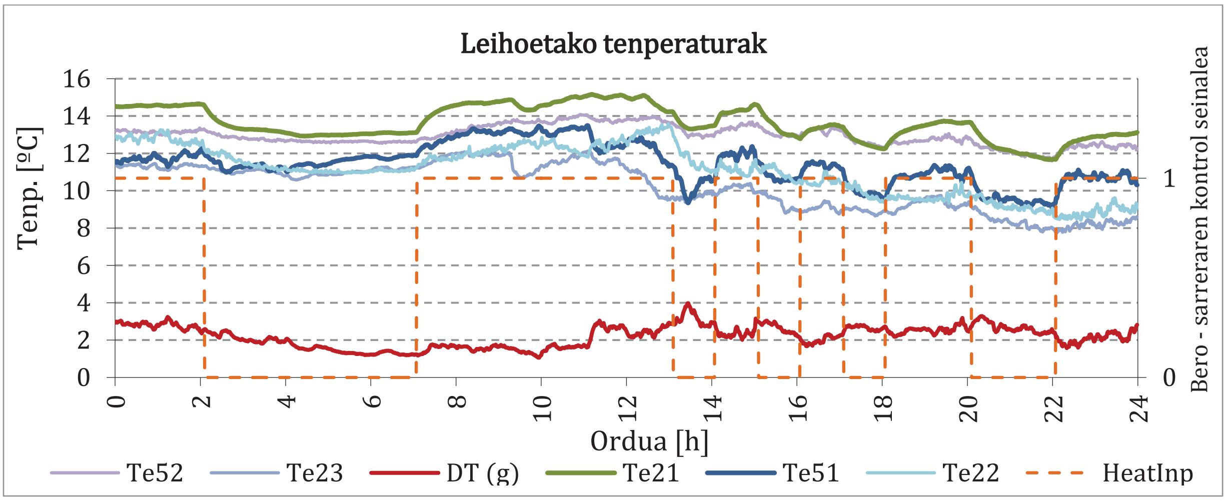
Gela 1an neurtutako datuei dagokionez, tenperatura hauek beste berotutako geletan neurtutako tenperaturak baino baxuagoak ziren. Hala ere, balio hauek zehatz - mehatz aztertuz, tenperatura hauek ez direla gelako tenperatura baxuaren ondorio bat, zergatia baizik ondorioztatu daiteke. Paretetan neurtutako tenperaturarik baxuena $T_m11$koa zen (sentsore hau aztertutako etxebizitzaren eta albokoaren arteko zegoen paretan kokatuta zegoen) eta $T_m12$koa (sentsore hau etxebizitzaren eta eskailera - kaxaren arteko zegoen paretan kokatuta zegoen) bereziki baxuak izan ziren ere.

Neurketa hauek pareta hauetan zehar alboko etxebizitzarantz eta, batez ere, eskailera - kaxara bero - galera handiak zeudela pentsarazten dute. Lehen kasuan, berokuntza sistemaren erabilera eskasa alboko etxebizitzan azaldu daiteke galera hauek T_m11 kokatuta zegoeneko paretan zehar. T_m12 kokatuta zegoeneko paretan zehar galerak nabarmengarrienak dira, ondorioztatu bezala I4.25 irudia ikusiz.

Hipotesi hau indartzen da ere tenperaturaren bilakaerari arreta jarriz. Zenbat eta berotutako gelen arteko diferentziak handiagoak izan (hau da, gela 1en eta alboko etxebizitzaren edo eskailera - kaxaren arteko ΔT altuagoa izan), orduan eta neurtutako bero fluxua altuago izango da, eta horren ondorioz, bero - galerak handiagoak izango dira. Hau da, bi antzeko gelek antzeko bero sarrerak edukiz gero, haien arteko diferentziak haien bero irteeren diferentziei oso lotuta izango dira, hau da, bero galerei.

5.1.1.7 Leihoetako tenperaturak

Bost sentsore kokatu ziren leihoetako tenperaturak lortzeko (I4.26 irudia). Lehen aipatu bezala, leiho guztiak beira bikoitza zeukaten, gela 5koa salbu. Horrela, bi leiho mota aztertu ziren: beira sinplea zeukan leiho bat, eta beira bikoitza zeukan leiho bat (gela 2koa). Beira eta markoen azaleko tenperaturak neurtu ziren. Beira bikoitza zuen leihoaren kasuan, kanpoko eta barneko azaleretako tenperaturak neurtu ziren; beira sinple zuenaren kasuan, aldiz, soilik barne azaleko tenperatura neurtu zen. Sentsoreen nomenklatura T4.6 taulan aurkezten da.



I4.26. Otsailaren 1an leihoetan neurtutako tenperaturak

Elementua	Azala	Gela 2 (Beira bikoitza)	Gela 5 (Beira sinplea)
Beira	Barneko azala	Te21	Te51
	Kanpoko azala	Te22	-
Markoa	Barneko azala	Te23	Te52

T4.6. Leihoetan kokatutako tenperatura sentsoreen nomenklatura

Desberdintasun adierazgarriak aurkitu ziren beira sinple eta bikoitzaren arteko konparaketan (diferentziak 2 gradu baino altuagoak aurkitu ziren haien barneko azaleko tenperaturak elkarrekin konparatzean). T_e22 eta T_e51 antzekoak ziren ere. Beira sinple bateko barneko eta kanpoko azaleko tenperaturak ia berdinak direla onartu daiteke. T_e52 tenperaturaren balioak espero zirenak baino altuagoak ziren, aluminiozko markoaren kalitate baxua kontuan hartuz.

Elementu bakoitza bere aldetik aztertu eta gero, batez besteko balioak kalkulatu ziren T4.7 taulan agertzen diren datu - multzoen arabera, elementu bakoitzaren balio adierazgarri bat lortzeko. Lehenik eta behin, ΔT (momentu bakoitzean neurtutako balio minimoaren eta maximoaren arteko diferentzia) analizatu zen sentsore guztien adierazgarritasuna ziurtatuko.

Berogailuetan kokatutako sentsoreen arteko ezberdintasun nabarmengarriak aurkitu ziren, sentsorearen eta erresistentziaren arteko distantzia ez baitziren zehazki berdina sentsore guztietan, eta ezberdintasun txiki horiek neurtutako tenperaturaren arteko diferentzia nabarmengarriak ekarri ditzakete. Horrela, neurtutako T_c1 balioak erreferentzia - balioa hartu ziren (T4.7 taula).

5.1.2 Batez besteko tenperaturak

	Inizialak	Nomenklatura	Kontuan hartutako balioak
BEROG.	**Tc**	Erreferentziako berogailuaren tenperatura	Tc1
	P	Bero - sarrera	5 berogailutan neurtutako potentzia
	Ta	Batez besteko barne tenperatura (haztatu)	Ta1 - Ta8
FATXADA	**Tfin**	Batez besteko fatxadaren barneko azaleko tenperatura	Te11, Te31, Te41, Te43
	Tfout	Batez besteko fatxadaren kanpoko azaleko tenperatura	Te12, Te42
	Tw	Batez besteko leihoen azaleko tenperatura	Te21, Te51
EGITURA	**Tstr**	Batez besteko egituraren tenperatura	Tfs1 - Tfs5, Tfi1 - Tfi5, Tp1, Tp3
	Tfs	*Batez besteko goiko forjatuaren tenperatura*	*Tfs1 - Tfs5*
	Tfi	*Batez besteko beheko forjatuaren tenperatura*	*Tfi1 - Tfi5*
	Tp	*Batez besteko zutabearen tenperatura*	*Tp1, Tp3*
KANP.	**Tout**	Kanpo tenperatura	Web (Euskalmet)
	Gh	Eguzki - erradiazioa	Web (Euskalmet)

T4.7. Datu - multzoak

Batez besteko barne airearen tenperatura kalkulatu zen zortzi sentsoreekin (Ta1 - Ta8) lortutako neurriak erabiliz. Sentsore bakoitzaren datu - multzoa haztatu zen kokatuta zegoeneko gelaren azalera erabiliz, Eq. 6 ekuazioak aurkeztu bezala.

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

non:

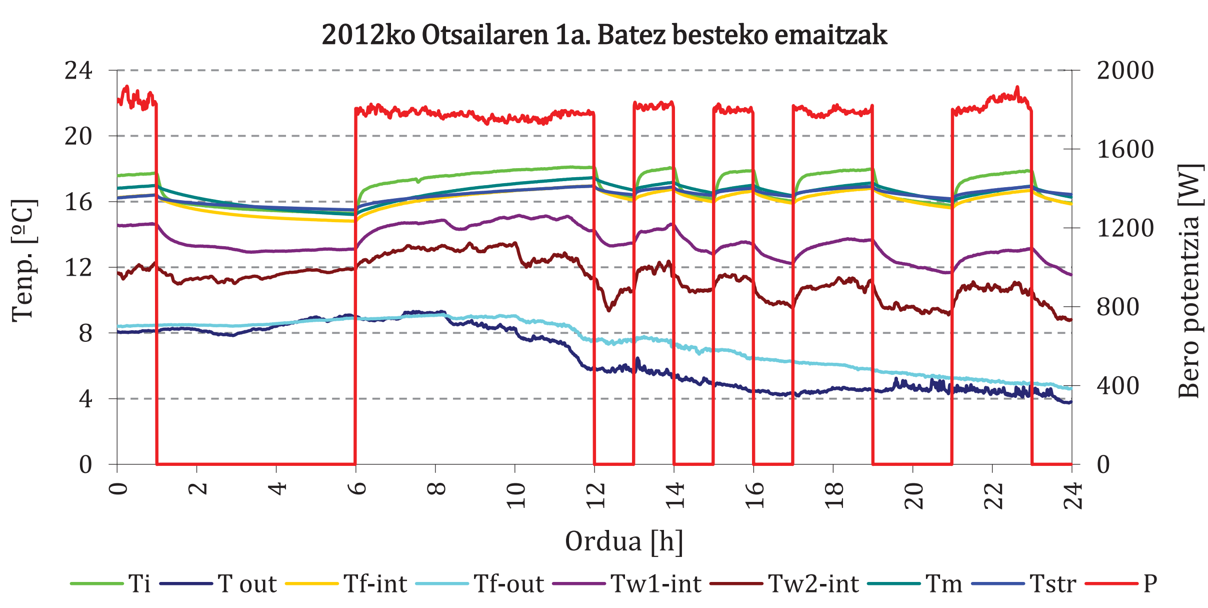
- T_a Batez besteko barne airearen tenperatura haztatua da.
- T_i sentsore bakoitzak neurtutako barne airearen tenperatura da.
- A_i gela bakoitzaren azalera da.

Horrela, lortutako balioak adierazgarriagoak dira, zeren eta gelaren azalera kontuan ez hartzean aurkitutako arazoa bi gela txikiak berogailurik ez zeukaten (esekilekua eta bainugela) batez besteko tenperatura jaitsi zutela da. Horren ondorioz, gelaren azalera kontuan hartu ezean, lortutako batez besteko balioak errealitatekoak baino baxuagoa ziren.

Gainerako batez besteko balioak ($T_{f,in}$, $T_{f.out}$, T_w, T_{str}, T_{fs}, T_{fi} and T_p) lortu ziren T4.7 taulan aipatutako sentsoreak lortutako neurrien bidez. Sentsore batzuk ez ziren kontuan hartu batez besteko balioak kalkulatzeko (T_p42 adibidez), zeren eta ez ziren egoki ibili monitorizazio epean.

Nahiz eta estazio meteorologiko txiki bat instalatu zen ekialdeko fatxadan, azkenik egoera klimatikoari buruzko informazioa Eusko Jaurlaritzaren estazio batik, Deustun kokatzen dena, eskuratu ziren (aurretiko kapituluan aipatu zen estazio klimatikoa), estazio honek neurtutako G_h fatxadaren estazioak neurtutako $G_{v,east}$ baino egokiagoa zen. Deustuko estazio klimatikoa Otxarkoagatik gertu dago, eta beraz, neurtutako balioak balio onargarritzat hartu ziren.

Hipotesi hauek aintzakotzat hartu, egun guztietako batez besteko balioak kalkulatu ziren. Esaterako, 2012ko otsailaren 1eko batez besteko balioak aurkezten dira I4.27 irudian.



I4.27. 2012ko Otsailaren 1an lortutako emaitzak

Puntu batzuk azpimarratu behar dira grafiko honetan. Lehenik eta behin, I4.7 irudian irudikatutako bero - katea argi eta garbi erakusten da. Beroa punturik beroenetik (berogailuaren erresistentzia) punturik hotzenera (kanpo airera) joaten da. Bide hau grafikoan aurkezten da, goitik behera, berogailua konektatuta dagoenean batez ere: beroa erresistentziatik ateratzen da, barne airera joaten da, barne airetik barneko paretetara, fatxadaren barneko azala, egiturara eta leihoetara: fatxadaren barneko azaletik fatxadaren kanpoko azalera; eta azkenik, beroa kanpo airera askatzen da.

Elementu bakoitzaren bero - ahalmena grafikoan aurkezten da ere. Berogailuak konektatzen direnean, barne airearen tenperatura arin - arin erantzuten da; fatxadaren barneko azala, ordea, (edo egituraren tenperatura T_{est} batez ere), askoz egonkorragoa da.

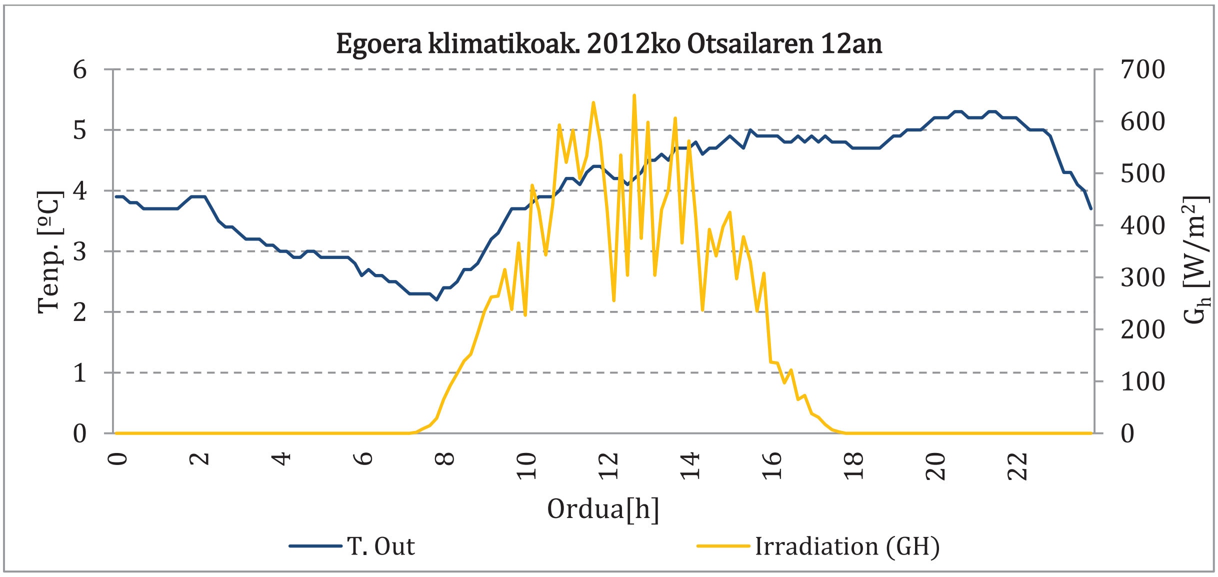
Kanpoko ingurunearen edo berogailuen eraginak etxebizitzan adierazi daitezke ere grafiko honen bidez. Berogailuek barne airearen tenperaturari eta barneko azalerei gehiago eragiten diete, batez ere egun eguzkitsua ez denean. Bestalde, barneko aldaketek fatxadaren kanpoko azalari nekez eragiten diote. Bi portaera ezberdinak aurkitzen dira leihoetan, bere beiraren arabera. Barne ingurunearen egoerek beira bikoitzak dauzkaten leihoei gehiago eragiten diete; kanpoko egoerek, ordea, beira sinplea daukan leihoari gehiago eragiten diote.

Azkenik, leihoen tenperaturen arteko ezberdintasunak azpimarratu behar dira. Beira sinplea daukan leihoaren beirako tenperaturak (T_v2) beira bikoitza daukatenaren beirako tenperaturak (T_v1) baino bi gradu baxuagoa izan ziren orokorrean.

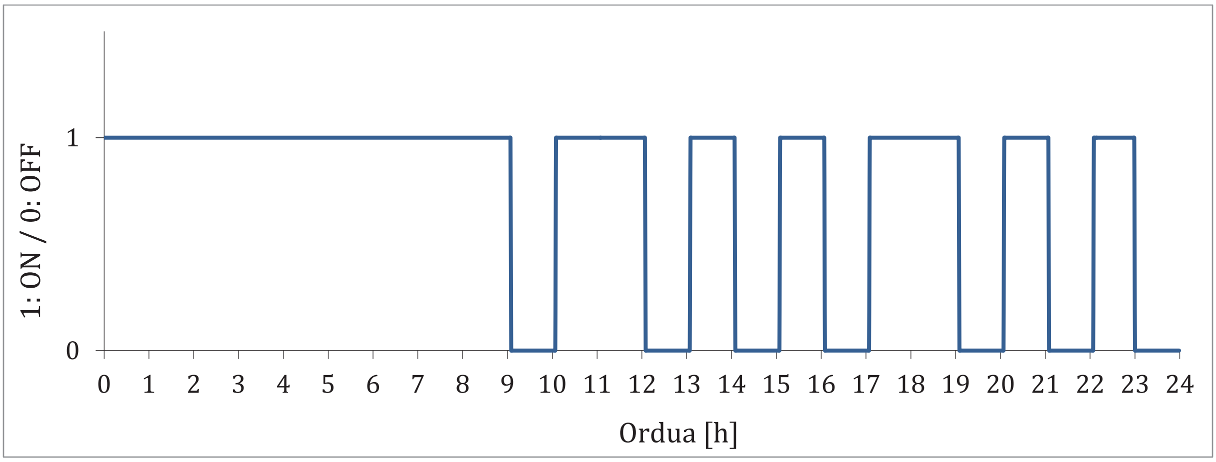
5.1.3 Beste gogoetak

2012ko otsailaren 1ean neurtutako datuak adibide honetan erabili dira bildutako datuen analisia argitzeko, eta etxebizitzaren portaera termikoaren ezaugarri garrantzitsuenak azpimarratzeko. Nahiz eta faktore giltzagarri gehienak aipatutako eguna erabiliz azaldu daitezken, datuen analisia osatugabea litzateke eguzki - erradiazioaren efektua kontuan hartuko ez balitz. Horregatik, egun eguzkitsu batean eguzki - erradiazioak gehiago eragindako elementuen analisi labur bat azpiatal honetan aurkezten dira.

Helburu honekin, 2012ko Otsailaren 12an neurtutako datuak erabili dira adibide gisa. Egun honetako egoera klimatikoari buruzko datuak I4.28 irudian irudikatzen dira. Grafiko honetan irudikatzen denez, egun eguzkitsua izan zen, tenperatura baxuekin, are eta aurretiko aztertutako egunarenak baino baxuagoak. Bero sarreraren errutina I4.29 irudian aurkezten da.



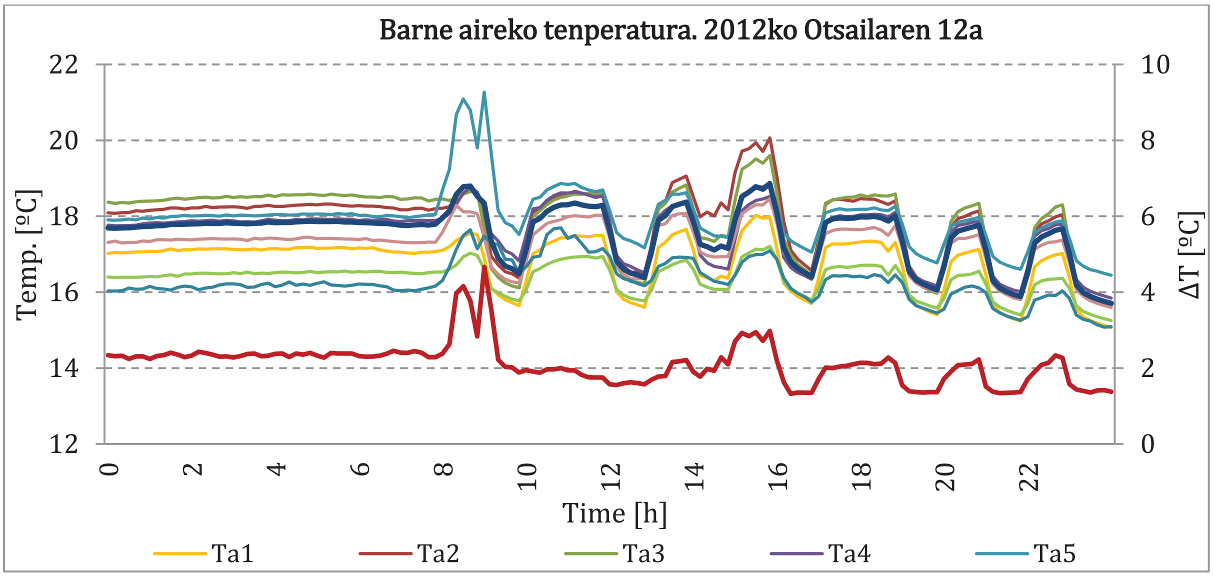
I4.28. 2012ko Otsailaren 12an neurtutako egoera klimatikoak (Euskalmet)



I4.29. 2012ko Otsailaren 12ko bero sarreraren kontrol - seinalea

5.1.3.1 Barne airearen tenperatura

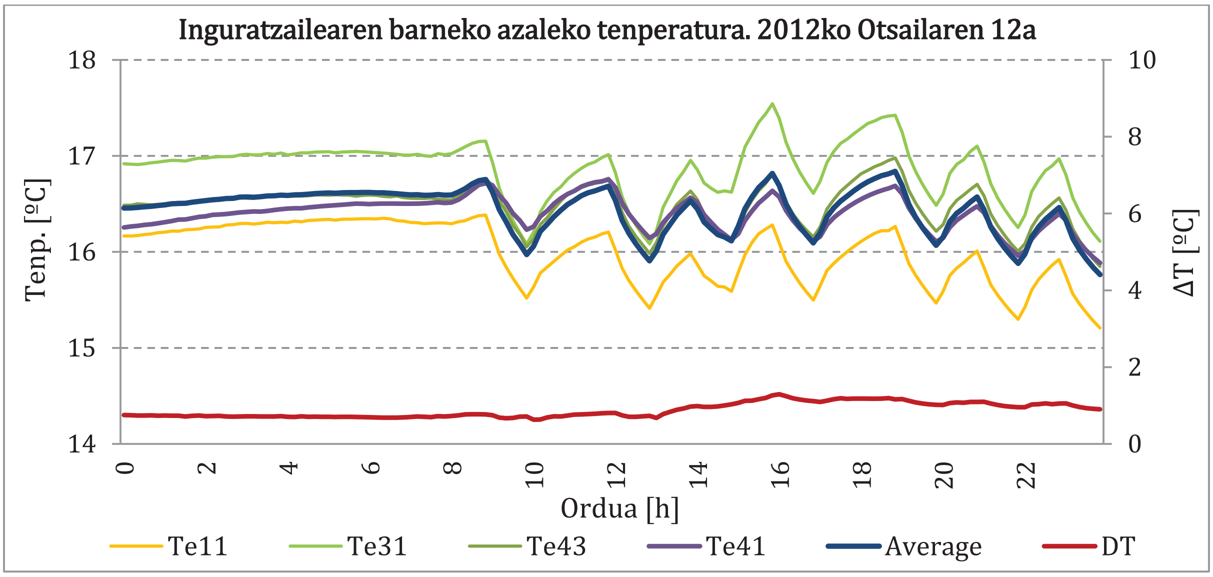
2012ko Otsailaren 12an neurtutako barne airearen tenperaturak I4.30 irudian irudikatzen dira. T_a4 eta, batik bat T_a5 tenperaturak, goizeko lehen orduetan igotzen dira (2 gradu baino gehiago, $T_a5$eko kasuan), eguzki - erradiazioa leihoetan zehar sartzen zenean. Antzeko zerbait gertatzen da arratsaldean mendebaldeko fatxadan: T_a1, T_a2 eta T_a3 igotzen dira arratsaldean, 1.5 gradu inguruko gehikuntzarekin.



I4.30. 2012ko Otsailaren 12an neurtutako barne airearen tenperatura

5.1.3.2 Inguratzailearen barneko azaleko tenperatura

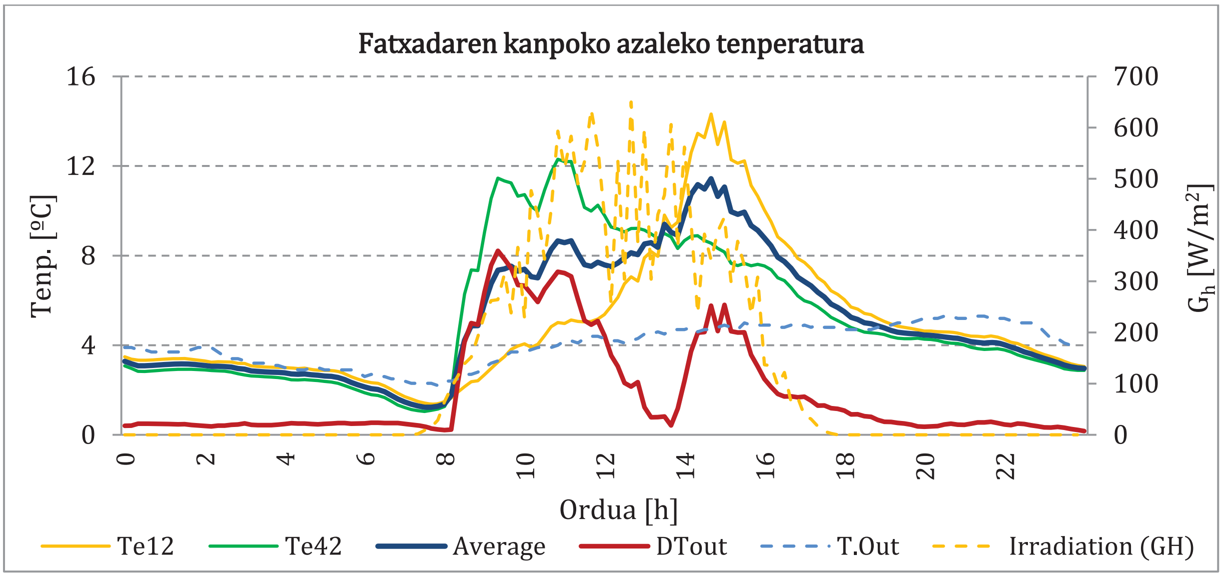
2012ko Otsailaren 12an neurtutako inguratzailearen barneko azaleko tenperaturak I4.31 irudian irudikatzen dira. Diferentzia handirik ez da aurkitzen aurretiko atalean aurkeztutako datuekin konparatuz.



I4.31. 2012ko Otsailaren 12an neurtutako inguratzailearen barneko azaleko tenperatura

5.1.3.3 Inguratzailearen barneko azaleko tenperatura

Egun eguzkitsu bateko datuak eta hodeitsu batekoak elkarrekin konparatzean, ezberdintasun handienak, jakina, inguratzailearen kanpoko azaleko tenperaturetan aurkitzen dira. Eragin hau I4.32 irudian irudikatzen da.



I4.32. 2012ko Otsailaren 12an neurtutako inguratzailearen kanpoko azaleko tenperatura

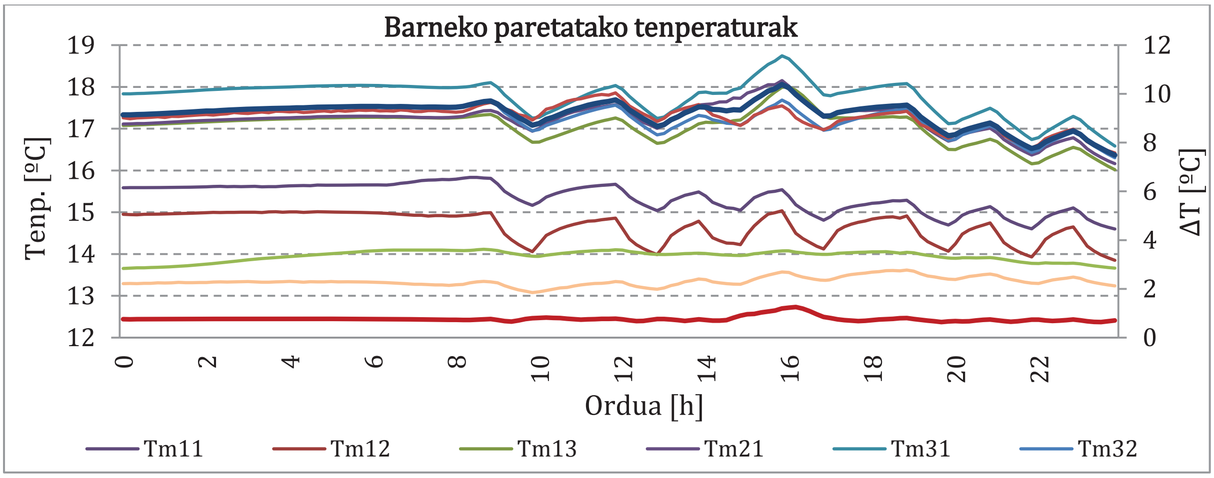
Beraz, T_e12 (mendebaldeko fatxadan kokatuta) tenperaturarik altuenera iritsi zen arratsaldean, zuzeneko eguzki - erradiazioa zeukanean; ekialdeko fatxadan, berriz, tenperaturarik altuenera goizean iritsi zen. Fatxaden arteko diferentziarik handienera goizean iritzi zen. ΔT balioak 8 gradu baino altuagoak bildu ziren. Eguzki - erradiazioaren eragina fatxadaren kanpoko azaleko tenperaturan grafikoan argi aurkezten dela nabarmengarria da ere. Gauean zehar, bi fatxadak ia tenperatura berdina izan zuten, eta kanpo airearen tenperaturaren oso antzekoa zen, are eta baxuago, aipatutako fatxadaren kanpoko azalaren eta zeruaren arteko erradiaziozko bero trukearen bidez bero galeren ondorioz.

Bestalde, egunean zehar, azaleko tenperatura kanpo airearen tenperatura baino altuagoa zen, zuzenezko eguzki - erradiazioa ez zenean azalera iristen. Goizeko lehen orduetako $T_e12$ko balioak aztertzean, fatxadaren kanpoko azalaren eta zeruaren arteko erradiaziozko bero trukearen ondoriozko bero - galerak drastikoki murriztu ziren, are eta mendebaldeko fatxadak ez du zuzenezko eguzki - erradiazioa ordu horietan jaso. Fatxadak zuzenezko eguzki - erradiazioa jaso zuenean, bere azaleko tenperatura igo zen, airearen tenperaturaren 8 gradu gainetik ekialdeko fatxadaren kasuan (lerro berdea, T_e42) eta ia 10 gradu gainetik mendebaldeko fatxadaren kasuan (T_e12). Honek erradiaziozko bero trukearen eraginak inguratzailearen portaera termikoan frogatzen ditu.

Azkenik, fatxadaren bero - metatzerako ahalmenaren ebaluazio kualitatibo bat egin daiteke grafiko honen bidez. Bi fatxadaren tenperaturak drastikoki murriztu ziren ilundu ondoren (6 pm inguru). Hirugarren kapituluan aurkeztutako informazioan oinarritakoa, fatxada honen eraikuntza - ezaugarriak F.c.1en antzekoak dira. F.c.1en C (bero - ahalmena) 180 kJ/m^{2}K-ekoa zen. Interesgarria izango zen balio hauek bero - ahalmen altuaren fatxada baten balioekin konparatzea (esaterako F.a, 460 kJ/m^{2}K-ekoa) eta haien arteko ezberdintasunak aztertzea.

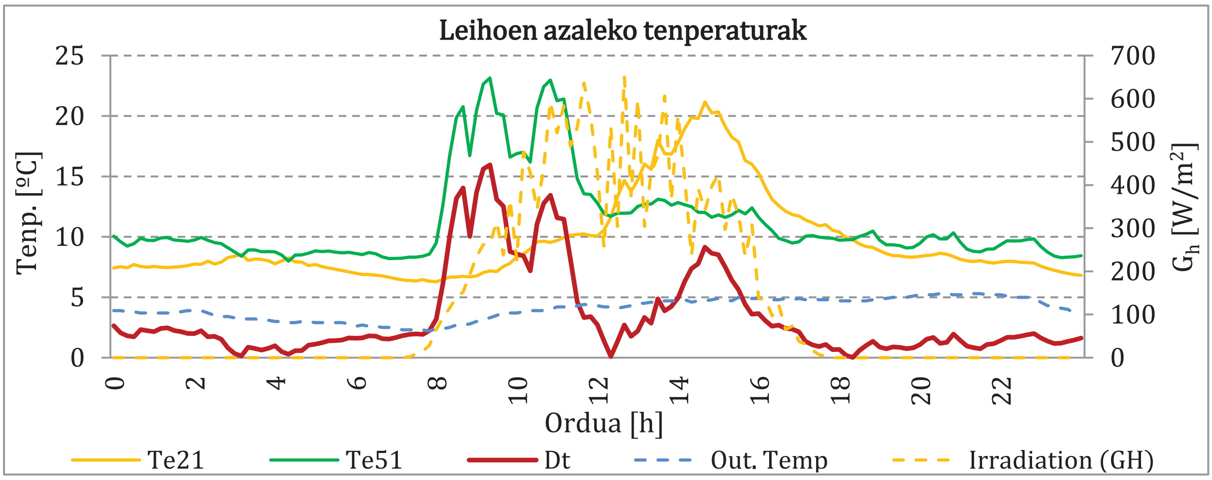
5.1.3.4 Barneko paretatako tenperaturak

Barneko paretatako tenperaturak aztertzean, ez zen informazio gehigarria aurkitu. 2012ko Otsailaren 12an neurtutako barneko paretatako tenperaturak I4.33 irudian irudikatzen dira.



I4.33. 2012ko Otsailaren 12an neurtutako barneko pareten azaleko tenperaturak

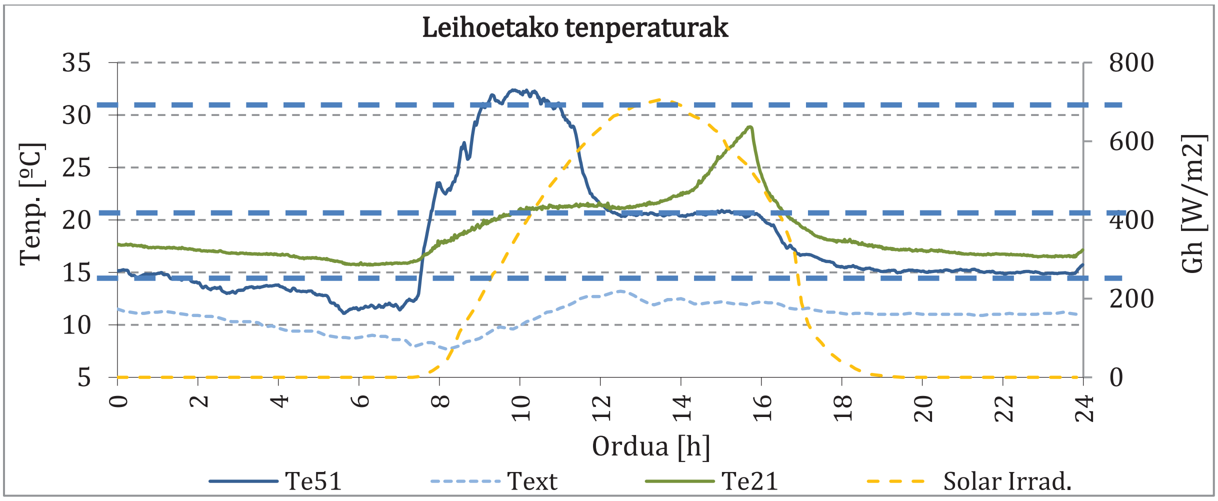
5.1.3.5 Leihoetako tenperaturak



I4.34. 2012ko Otsailaren 12an neurtutako leihoen azaleko tenperaturak

Azkenik, 2012ko Otsailaren 12an neurtutako leihoetako tenperaturak I4.34 irudian irudikatzen dira. Datu hauek ematen duten informazioa fatxadaren kanpoko azaleko tenperaturen bidez lortutakoaren oso antzekoa da. Agian, kasu honetan erradiaziozko bero trukearen efektua nabarmengarriagoa da, beirak bero ahalmenik ia ez dauka eta.

Baina efektu hau detektatzea ez zen batere erraza 2012ko Otsailaren 12an neurtutako datuak aztertzean (I4.34 irudia), argi eta garbi erakusten da I4.35 irudian, 2012ko Martxoaren 15ean neurtutako tenperaturak aurkezten direnekoa. Egun horretan, kanpo tenperatura 10 gradu ingurukoa zen egun osoan. Hala ere, egun eguzkitsua zen, eta G_h - ren balio maximoa 700 W/m^2 - koa izan zen. Hiru tenperaturazko maila ezberdinak identifikatzen dira egun horretan neurtutako datuak aztertzen direnean. Hiru maila hauek I4.35 irudian gutxi gorabehera irudikatzen dira lerro urdinez.



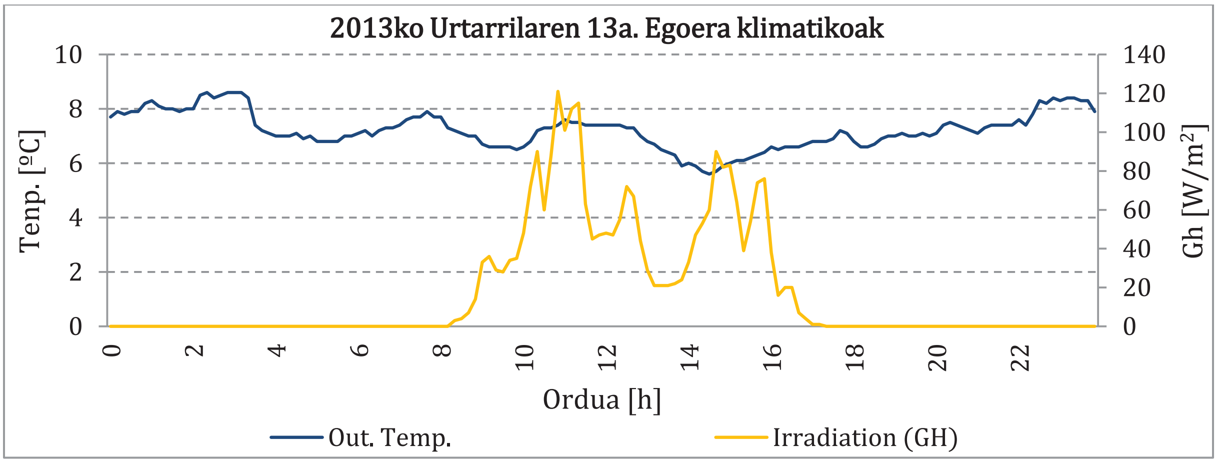
I4.35. 2012ko Martxoaren 12an neurtutako leihoetako tenperaturak

Lehen maila, 15 gradu inguruan, gaueko leihoen tenperaturakoa da, erradiaziozko bero trukearen ondoriozko bero - galerak handiagoak direnean. Bigarren maila, 20 gradu inguruan, beiran iristen den tenperatura egunean zehar, leihoek zuzenezko eguzki - erradiaziorik ez daukatenean. Azkenik, hirugarren maila 30 gradutan jarri daiteke. Hau da beiran iristen den tenperatura leihoek zuzenezko eguzki - erradiazioa jasotzen dutenean. Horrela, nola ekialdeko leihoko (T_e51) tenperatura eguna argitu ondoren drastikoki igo zela ikusi zen. Bi ordutan baino gutxiago, tenperatura 12.26 gradutik 31.44 gradura igo zen. Hamaiketan (GMT ordua) zuzenezko eguzki - erradiazioa jasotzeari utzi zion eta horren ondorioz, bere tenperatura minutu gutxitan 20 gradura jaitsi zen, gaua heldu arte, bere tenperatura 15 gradura jaitsi zenean ere.

Mendebaldeko leihoak antzeko portaera izan zuten. Bere tenperatura astiroago igo zen goizean, zuzenezko eguzki - erradiaziorik ez zenean jasotzen, baina azalaren eta zeruaren arteko erradiaziozko bero trukearen ondoriozko bero - galerak murriztu zirenean eguna argitu eta gero. Tenperaturaren igoera garrantzitsu bat ikusi zen zuzenezko eguzki - erradiazio jasotzen hasi zenean arratsaldean, eta azkenik, leihoaren tenperatura drastikoki jaitsi zen iluntzean, are eta ekialdeko leihoetan baino gehiago, mendebaldeko leihoetan aldi berean erradiaziozko bero trukearen ondoriozko galerak eta zuzenezko eguzki - erradiazioaren jasotzeari uztea jasaten baitira. Hau da ekialdeko leihoen portaeraren kontrako goizeko egoera, erradiaziozko bero trukearen ondoriozko galerak bat batean murrizten direnean eta zuzenezko eguzki - erradiazioaren ondoriozko irabaziak gehitzen direnean.

5.2 Datu esperimentala. Birgaitzearen ondorengo emaitzak

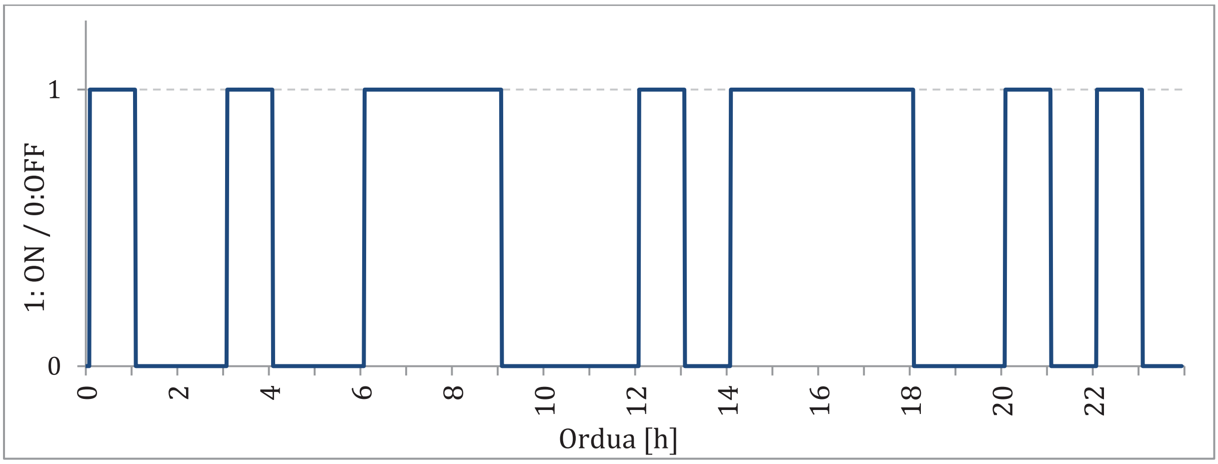
Atal honetan birgaitzearen ondoren neurtutako emaitza garrantzitsuenak aurkezten dira. Sistema guztien datuak berriro aurkeztea errepikakorra izan daiteke, eta kasu askotan, ez du informazio gehigarrizkoa ematen. Beraz, atal honetan aurkezten den informazioak barne airearen tenperaturaren eta leihoetako tenperaturaren datuetan arreta jartzen du. Hauek bi sistemarik eraginenak dira birgaitzea egin eta gero.



I4.36. 2013ko Urtarrilaren 13an neurtutako tenperatura eta eguzki - erradiazioa (Euskalmet)

Kasu honetan, 2013ko Urtarrilaren 13an neurtutako datuak adibide hautatu dira. Egun horretako egoera klimatikoak 2012ko Otsailaren 1eko egoeraren oso antzekoak izan ziren, aurretiko atalean erabili den erreferentzia - eguna dena, I4.36 irudian ageri den bezala. Grafiko honetan, 2013ko Urtarrilaren 13an neurtutako tenperatura eta eguzki -

erradiazioa irudikatzen dira. Berokuntza sistemak jarraitutako errutina I4.37 irudian aurkezten da.

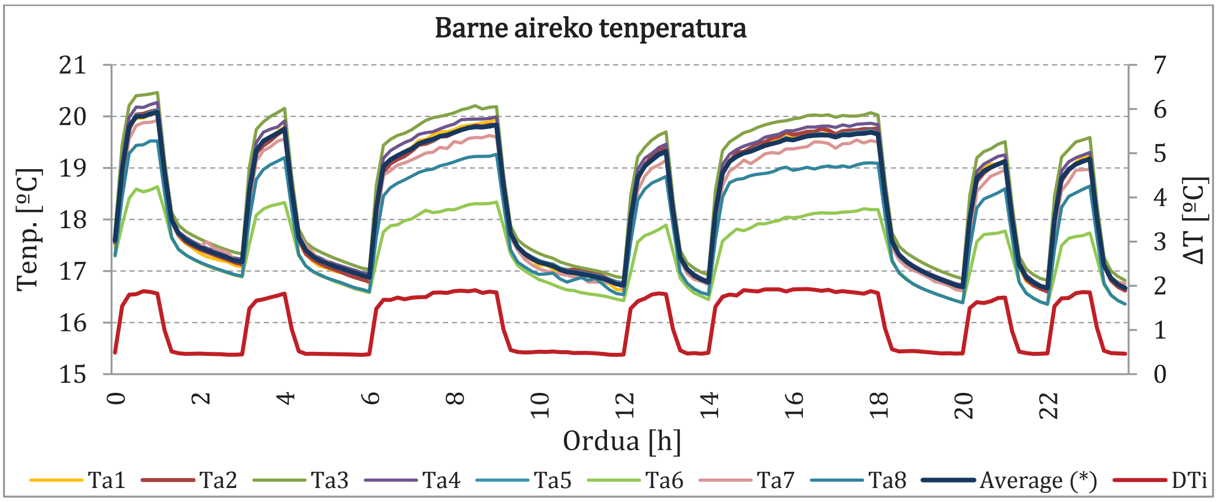


I4.37. 2013ko Urtarrilaren 13an erabilitako bero sarreraren kontrol - seinalea

5.2.1 Sistema eta azpisistemen emaitzak

5.2.1.1 Barne airearen tenperatura

Gela bakoitzean neurtutako barne airearen tenperatura I4.38 irudian irudikatzen dira. Orokorrean, tenperatura hauek barne tenperatura birgaitzearen aurretik neurtutakoak baino altuagoak ziren. Efektu hau birgaitzearen ekarpenik nabarmengarrientzat hartu daiteke, nahiz eta baieztapen hau arretaz egin behar, beste faktore batzuek barne tenperaturan eragin handiak eduki baititzakete, eta azterketa sakonak hurrengo kapituluetan egingo dira.

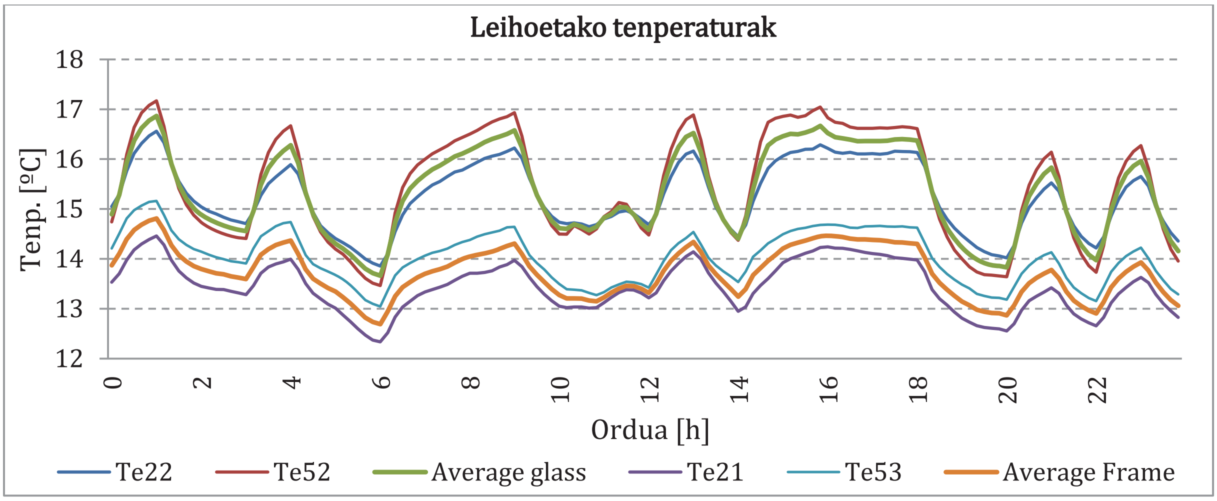


I4.38. 2013ko Urtarrilaren 13an neurtutako barne airearen tenperaturak

Batez ere, gela 1eko barne airearen tenperaturaren joeraren aldaketa azpimarragarria zen. Birgaitzearen aurretik neurtutako tenperaturak ez bezala, leihoen aldaketa egin ondoren gela 1ean neurtutako tenperaturak etxebizitzaren batez besteko tenperaturen oso antzekoak ziren. Hau azpimarragarria da zeren eta egindako birgaitzearekin ez ziren puntu horretan hobekuntzarik espero izaten (T_m12 eta T_m11 sentsoreak kokatzen zireneko paretak ez ziren hobetu birgaitzean). Alboko etxebizitzaren erabileraren edo eskailera - kaxan aireztapen profilaren aldaketek efektu hau adierazi dezakete.

5.2.1.2 Leihoak

Jakina, aldaketa nagusiak leihoetan neurtutako datuetan aurkitu ziren. Hautatutako egunean beiretako eta markoetako tenperaturak I4.39 irudian irudikatzen dira. 1.5 - 2 gradu inguruko gehikuntza bat leiho berrietako tenperaturaren datuetan aurkitu zen, lehen monitoriazioan lortutakoekin konparatuz. Gainera, leihoetako tenperaturaren aldaketak barne egoera termikoaren aldaketei oso lotuta daude, lehen monitorizazio epean ez bezala. Azkenik, datu hauek beiren portaera termikoa markoena baino hobeto zela aurkeztu zuten, zubi termikoaren haustura eduki arren.



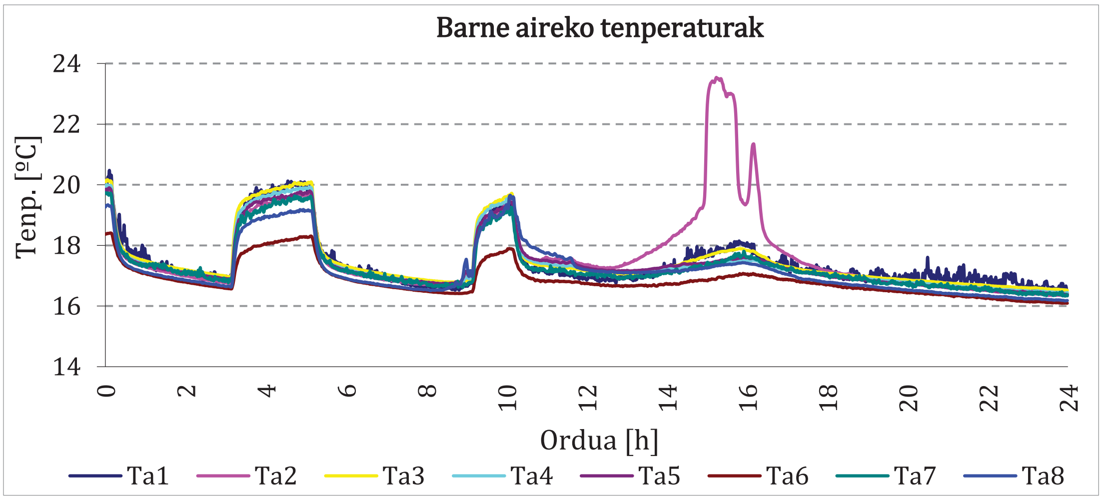
I4.39. 2013ko Urtarrilaren 13an neurtutako leihoen azaleko tenperaturak

5.2.2 Batez besteko tenperaturak

Birgaitzearen aurretik lortutako datuekin egin zen bezala, birgaitzea egin ondoren neurtutako balioak 10 - minutuko epetan integratu ziren. Geroago, elementu bakoitzaren batez besteko balioak kalkulatu ziren, T4.8 taulan aurkezten den bezala.

Batez besteko balio hauek lortzeko, lehen aipatutako irizpide antzekoak jarraitu ziren. Hala ere, landa - azterketa guztiak haien berezitasunak baitauzkate, egokitze batzuk egin behar ziren. Egindako egokitzeak hurrengo puntuetan laburtzen dira:

- Nahiz eta bigarren monitorizazioaren epea Azaroaren azken astean hasi, hasierako arazo guztiak (konexio erroreak, adibidez) ez ziren zuzendu Abenduaren hirugarren aste arte. Horregatik, 2012ko Abenduaren 4tik 2013ko Otsailaren 20ra arteko epean lortutako datuak aztertu ziren.
- Airearen tenperaturaren kasuan, haien balioak gela azalerarekin haztatu ziren bigarren monitorizazio epean ere.
- Gela 2an lortutako airearen tenperaturaren balioak baztertu ziren batez besteko tenperatura kalkulatzeko, zeren eta, sentsore bakoitzak emandako balioak aztertzean, gela 2an kokatzen zen sentsoreak emandako balioak beste logeletan kokatzen zirenak emandakoaren oso antzekoa ziren arren, salbuespen batzuk egun eguzkitsu epe batzuetan aurkitu zituen. Epe horietan, neurtutako tenperaturak 6 graduko diferentzietara iritsi ziren beste geletan neurtutakoarekin konparatuz, I4.40 irudian aurkezten den bezala.



I4.40. 2013ko Urtarrilaren 28an neurtutako barne airearen tenperaturak

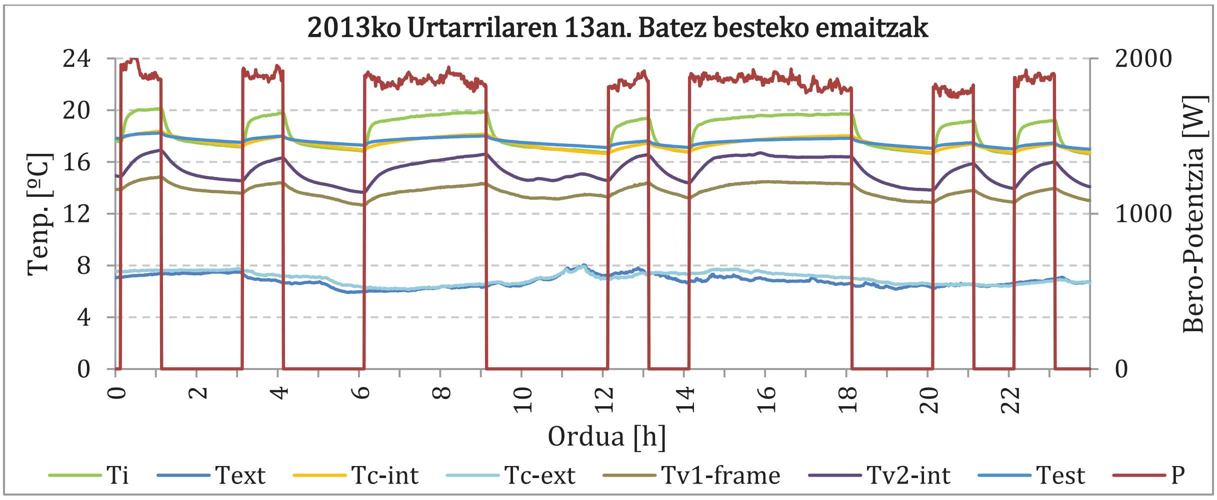
Irudi honetan 2013ko Urtarrilaren 28an neurtutako tenperaturak irudikatzen dira. Tenperatura maximoa iritsi zen gela 2ko fatxadak eta leihoak (mendebaldean) zuzenezko eguzki - erradiazioa jaso zuten. Tenperatura hau ez zela gelako tenperaturaren adierazgarria frogatu zuten Gela 1 eta 3 (orientazio berbera) ez zuten izan gailur hori ordu horretan, nahiz eta eguzki -

erradiazioaren efektu txiki bat ikusi daiteken I4.40 irudian. Sentsoreak zuzenezko eguzki - erradiazioa jasotzen zuela ondorioztatu zen. Beraz, nahiz eta batez besteko balioan eragin txikia eduki, ez zen kontuan hartu batez besteko tenperatura kalkulatzean. Bestalde, beste orduetan, neurketak antzekoak ziren gelak elkarrekin konparatuz, batik bat, Gela 1 eta 3an neurtutakoak, eta horregatik, lortutako batez besteko tenperaturak adierazgarri eta fidagarritzat hartu daitezke.

	Inizialak	Nomenklatura	Kontuan hartutako balioak
BEROG.	**Tc**	Erreferentziako berogailuaren tenperatura	Tc4
	P	Bero - sarrera	5 berogailutan neurtutako potentzia
	Ta	Batez besteko barne tenperatura (haztatu)	Ta1 - Ta8
FATXADA	**Tfin**	Batez besteko fatxadaren barneko azaleko tenperatura	Te11, Te33, Te41, Te43
	Tfout	Batez besteko fatxadaren kanpoko azaleko tenperatura	Te12
	Tw	Batez besteko leihoen azaleko tenperatura	Te22, Te52
EGITURA	**Tstr**	Batez besteko egituraren tenperatura	Tfs1 - Tfs5, Tfi1 - Tfi5, Tp1, Tp3, Tp42, Tp8
	Tfs	*Batez besteko goiko forjatuaren tenperatura*	*Tfs1 - Tfs5*
	Tfi	*Batez besteko beheko forjatuaren tenperatura*	*Tfi1 - Tfi5*
	Tp	*Batez besteko zutabearen tenperatura*	*Tp1, Tp3, Tp42, Tp8*
KANP.	**Tout**	Kanpo tenperatura	Web (Euskalmet)
	Gh	Eguzki - erradiazioa	Web (Euskalmet)

T4.8. Bigarren egoerako datu – multzoak

2013ko Urtarrilaren 13ko batez besteko emaitzak I4.41 irudian aurkezten dira. Egituraren eta fatxadaren barneko azalaren erantzunak birgaitzearen aurretik neurtutakoen oso antzekoak ziren. Hala eta guztiz ere, grafikoan leihoen hobekuntza argi eta garbi aurkezten da: beiraren barneko azaleko tenperatura egonkorragoa da, baita kanpoko egoeraren menpeko gutxiago ere.



I4.41. 2013ko Urtarrilaren 13ko batez besteko emaitzak

6 Eztabaida

Bi puntu nagusi azpimarratu behar dira lortutako datuen lehen analisi hau egin ondoren: etxebizitzaren aldamenean dauden lekuetara bero - galerak, eta inguratzailearen erradiaziozko bero trukea.

Lehenari dagokionez, eskailera - kaxara eta, batik bat, alboko etxebizitzara, bero - galera adierazgarriak aurkitu ziren, batez ere gela 1ean lehen monitorizazio epean zehar, kapitulu honetan aipatu den bezala. Bero - galera hauek, etxebizitzaren guztizko bero - galeraren parte garrantzitsu bat dena, kontuan hartu behar dira etxebizitzaren portaera termikoa aztertzean. Barneko paretetako kalitate baxua epe askotan ohikoa izan da orain dela gutxi arte, are eta portaera termikoaren kontzientzia egotekotan, sarritan soilik inguratzailean arreta jartzen zen. Horren ondorioz, etxebizitzaren barne tenperatura alboko etxebizitzaren egoera termikoaren menpekoa da. Puntu hau are eta serioagoa da gizarte etxebizitzaren kasuan, zeren eta etxebizitza askotan berokuntza sistemarik ez da erabili, eta beraz, berokuntza sistema bat erabiltzen diren etxebizitzen bero - galerak handiagotzen dira.

Antzeko arrazoiengatik, eskailera - kaxara bero - galerak adierazgarriak ziren ere. Bestalde, eskailera - kaxako leihoak irekita zegoen ia egun osoan, egoera okerragotu zena, zeren eta eskailera - kaxako barneko airearen tenperatura kanpoko airearen tenperaturaren oso antzekoa zen, eta gainera, pareta honek ez daukat, bere kokapenaren ondorioz, eguzki - erradiazioaren ondoriozko bero irabaziak. Laburbilduz, eskailera - kaxako paretek fatxadak baino kalitate termiko baxuagoak daukate, nahiz eta eskaileraren eta kanpoko egoera termikoak oso antzekoak ziren haien artean.

Erradiaziozko bero trukeari dagokionez, bi monitorizazioen bidez lortutako datuek bere efektua erakutsi dute inguratzailearen kanpoko azaleko tenperaturan, bere efektuak estalkian nabarmengarriagoak izan arren.

6.1 Leiho - aldaketaren onurak

Nahiz eta egindako birgaitzearen aldaketa nagusia soilik leihoen hobekuntza izan, egoera termikoaren hobekuntza nabarmengarria da emaitzak aztertzean. Aipatu bezala, beirako barneko azaleko tenperatura igo zen eta bere erantzuna barneko aldaketari hobea zen. Halaber, puntu honek barne airearen tenperaturan eragina dauka, T4.9 taulan aurkezten den bezala.

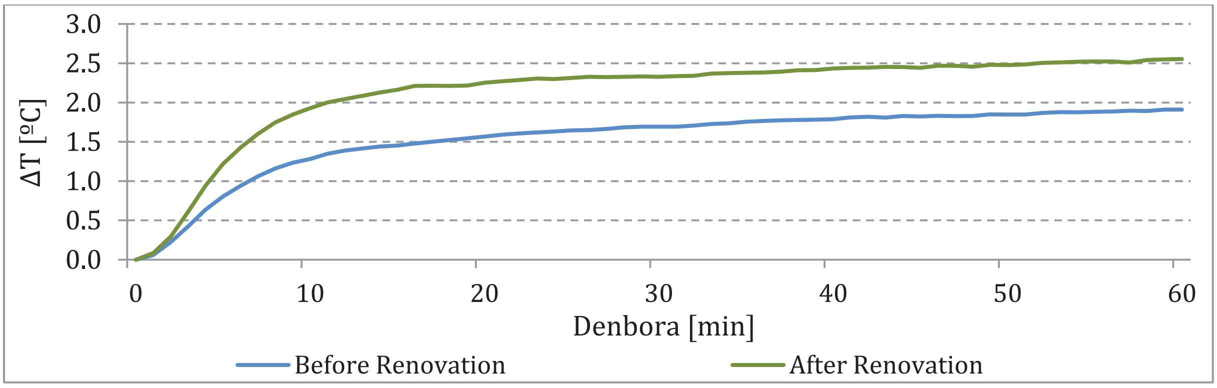
Birgaitzearen aurretik (2012ko Otsailaren 1a)				Birgaitzearen ondoren (2013ko Urtarrilaren 13a)			
	00 m	30m	60m		00 m	30m	60m
6 - 7 am	15.28 ºC	16.98 ºC	17.20 ºC	**6 - 7 am**	16.87 ºC	19.12 ºC	19.16 ºC
1 - 2 pm	16.29 ºC	17.90 ºC	18.05 ºC	**12 am - 1 pm**	16.73 ºC	18.95 ºC	19.32 ºC
3 - 4 pm	16.20 ºC	17.81 ºC	17.90 ºC	**2 - 3 pm**	16.80 ºC	19.04 ºC	19.29 ºC

T4.9. Tenperaturaren gehikuntza berogailua konektatu ondorengo lehen orduan

Bi antzeko egun hautatu ziren efektu hau erakusteko: bata birgaitzearen aurretik (2012ko Otsailaren 1a) eta bestea, birgaitzearen ondoren (2013ko Urtarrilaren 13a). Bi egunak hodeitsua zen. 2012ko Otsailaren 1ean neurtutako kanpo tenperatura 8 graduko izan zen goizean; 2013ko Urtarrilaren 13an, kanpo tenperatura 6 gradukoa izan zen. Egoera berberak hain zuzen ere ez izan arren (eta horren ondorioz, ez da posiblea konparaketa kuantitatiboa berehala egitea), antzeko egoerak ziren eta konparaketa kualitatiboa egin daiteke leihoen aldaketaren efektuari buruzko lehen ideia bat egiteko. Hurrengo kapituluetan analisi gehiago egingo dira, baina lortutako datuen azterketa orokor lehen batek aipatutako efektuari buruzko ideia bat eman dezake, jarraian azaldu bezala.

Berogailu konektatu ondorengo lehen orduko batez besteko barne airearen tenperaturak T4.9 taulan aurkezten dira. 2012ko Otsailaren 1ean berogailuak konektatuta egon ziren ordutegi honetan: *6 - 12 am*, *1 - 2 pm*, *3 - 4 pm*, 5 - 7 pm and 9 - 11 pm; 2013ko Urtarrilaren 13an berogailuak konektatuta egon ziren ordutegi honetan: 0 - 1 am, 3 - 4 am, *6 - 9 am*, *12 am - 1 pm*, *2 - 6 pm*, 8 - 9 pm and 10 - 11 pm. Letra etzanaz idazten diren epe bakoitzaren lehen ordua T4.9 taulan laburbildu dira. 1.70 eta 1.92 graduen arteko ΔT bat aurkitu daiteke 2012ko otsailean neurtutako datuetan. Bestalde, 2.29 eta 2.59 graduen arteko ΔT bat aurkitu zen 2013ko urtarrilean neurtutako datuak aztertzean.

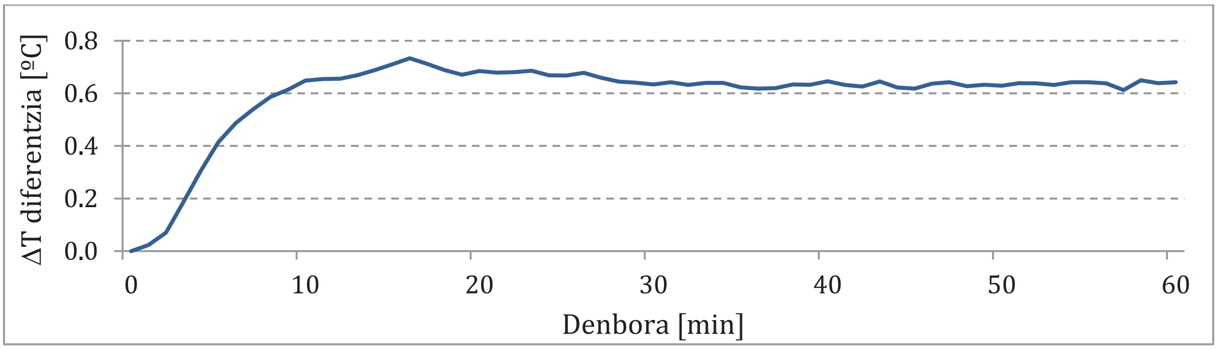
Eragin hau argi eta garbi erakusten da I4.42 irudian irudikatzen den grafikoan. Grafiko honetan, berogailuak konektatu ondorengo lehen orduko ΔT irudikatzen da.



I4.42. Berogailuak konektatu ondorengo lehen orduko barne airearen tenperaturako ΔT

Birgaitzearen aurretiko ΔT (lerro urdina) 2012ko Otsailaren 1eko (6 - 7 am) batez besteko tenperatura erakusten da; Birgaitzearen ondorengo ΔT (lerro berdea) 2013ko Urtarrilaren 13ko (6 - 7 am) batez besteko tenperatura erakusten da (T4.9 taulan markatuta dauden bi epeak). Hasieran, denbora "0" izatean (bi epeetan goizeko seietan) berogailuak aktibatzen da. Ezberdintasunik handiena lehen hamar minutuetan ikusten da. Hamar minutu pasa bezain agudo, tenperatura 1.28 gradu igo zen (15.28 gradutik 16.57 gradura) birgaitzearen aurretiko egoeran. Birgaitze egin ondorengoan, berriz, hamar minutu horietan tenperatura 1.93 gradu igo zen (16.83 gradutik 18.76 gradura). Honek frogatzen du inguratzailearen bero - transferentziaren koefizientea hobetu zen (antzeko mugalde - baldintzak, bero - sarrera berbera eta barne airearen tenperaturaren gehikuntza handiagoa, beraz, bero - galerak baxuagoak dira).

Birgaitzearen aurretiko eta ondorengo ΔTren arteko diferentzia I4.43 irudian irudikatzen da. Aipatu bezala, bi epeen arteko ezberdintasunik handiena lehen hamar minututan aurkitu zen. Hamar minutu pasa bezain laster, birgaitzearen aurretiko eta ondorengo ΔTren arteko diferentzia ia egonkortu zen, 0.65 gradu inguruan.



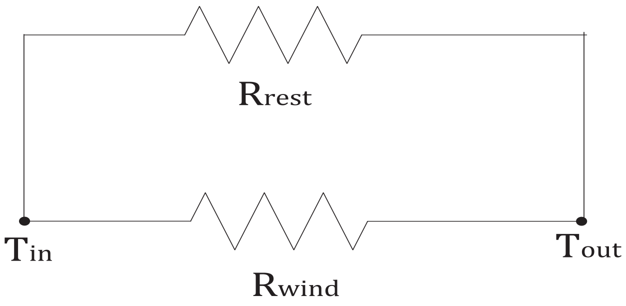
I4.43. Birgaitzearen aurretiko eta ondorengo ΔTren arteko diferentzia

6.2 UA - Balioaren kalkuluak

Atal honetan, lortutako datuen lehen analisi kuantitatibo bat egiten da. Helburu honekin, kapitulu honetako 4.2.4. atalean aipatutako *co-heating* metodoan oinarritutako metodologia bat ezarri zen, bi monitorizazio epeetan neurtutako datuak erabiliz

6.2.1 Espero izan zen balioa

Espero zen leihoen hobekuntzaren zenbatespen bat kalkulatu zen, leiho - aldaketaren ondoriozko UA - balioko murriztapena kalkulatuz. Beraz, eskema sinple bat UA kalkulatzeko I4.44 irudian irudikatzen da. Bi nodok barne eta kanpo tenperatura (T_{in} eta T_{out}, hurrenez hurren) erakusten dituzte. Paraleloko konexioan, bi erresistentzia termikok aipatutako nodoak konektatzen dute haien artean. Erresistentzia termiko hauek leihoak (R_{wind}) eta gainerako bero galeren bideak (R_{rest}) adierazten dituzte.



I4.44. Etxebizitzaren RC sare baten eskema sinple bat

UA_{rest} bi egoeretan berdina da, zeren eta leihoarenak kenduta, ez ziren beste aldaketak etxebizitzan egon. Horregatik, kalkuluak egin daitezke hurrengo ekuazioak jarraituz:

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

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

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

Zenbatetsitako hobekuntza kalkulatzeko, zahar eta berri leihoen hartutako U balioak jarraian aurkezten dira:

- Birgaitzearen aurretiko leihoen U - balioa: 4.55 W/m^{2}K
- Birgaitzearen ondorengo leihoen U - balioa: 3.09 W/ m^{2}K

Leihoetako azalera osoa (11.5 m^2) kontuan hartuz, etxebizitzaren UA balioaren hobekuntza, leiho - aldaketa egin eta gero, 15 W/K inguruan hobetu da.

6.2.2 Lortutako balioa

Argibide batzuk azaldu behar dira balio hauek aurkeztu baino lehen. Lehen aipatu bezala, *co-heating* metodoa etxebizitza bat berotzean datza, barne airearen tenperatura egonkorra mantentzeko (25 gradu inguru) denbora - epe espezifiko batean zehar (1 - 3 aste, normalean). Hala ere, tesi honen atal esperimentala diseinatu zen eraikinaren portaera dinamikoa karakterizatzeko, hain zuzen ere, 6. kapituluan deskribatutako eta garatutako RC ereduaren parametro karakteristikoak lortzeko. Jarraitutako metodologiaren eta *co-heating* metodologiaren arteko ezberdintasun nagusia erabilitako bero - sarreraren errutina da. hau da, *co-heating* metodoa egiteko, erabilitako bero sarreraren errutina etengabea eta berogailuaren potentzia modularra izan behar dira; kapitulu honetan aurkeztu den monitorizazioa, berriz, berogailuen potentzia ez da modularra, eta bero sarreraren errutina ez da etengabea. Beraz, barne tenperatura ez da egonkorra, UA balio zehatz bat lortutako iradokitzen den ez bezala.

Mugaketa hauek aintzakotzat hartuz, orduan, helburua ez dela *co-heating* metodoa garatzea, etxebizitzaren (birgaitzearen aurretiko eta ondorengo) erreferentziazko balio batzuk lortzea baizik adierazi daiteke.

Horregatik, soilik berogailuak konektatuta egon zen epeak kontuan hartu ziren UA balioa kalkulatzeko (Epe hauek iraupen ezberdinak dauzkate, 1 - 33 ordu). Egoera kuasi - geldikorra lortzeko, iraupen luzeagoak behar dira (*co-heating* metodoaren testen iraupena 1 - 3 astekoa ohi dira). Beraz, beste efektuak, eraikinaren inertzia termikoa adibidez, lortutako emaitzei eragin ahal baitiete, emaitzak arretaz aztertu behar dira. Metodo honen bidez lortutako emaitzak T4.10 eta T4.11 tauletan aurkezten dira, birgaitzearen aurretik eta ondoren, hurrenez hurren.

Kalkulu hauek koherentziarik ez daukate (balio hauen arabera, birgaitzearen ondorengo egoerak birgaitzearen aurretikoak baino balio txarragoa dauka). Lehen balio hauen inkoherentziaren ondorioz, lortutako datuen analisi sakon bat gehiago egin zen.

Berogailuak konektatuta egon zireneko ordu kopurua		**Bat. besteko potentzia**	**Batez besteko ΔT**	**UA**
OTS 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
API 2012	224h 20 min	1715.05	9.91	173.06 W/K
		BATEZ BESTEKO UA		**168.61 W/K**

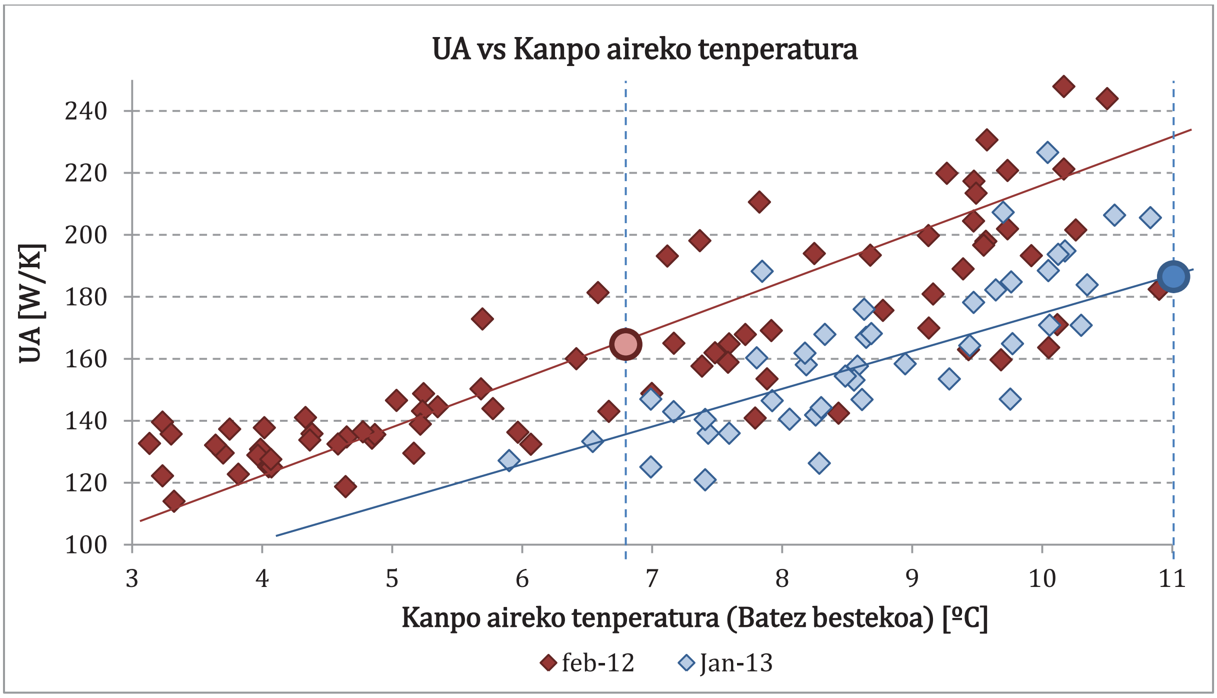
T4.10. Leiho - aldaketaren aurretiko hilabeteroko balioak

Berogailuak konektatuta egon zireneko ordu kopurua		**Bat. besteko potentzia**	**Batez besteko ΔT**	**UA**
ABE 2012	306 h	1740.32	8.22	211.73 W/K
URT 2013	342h 10 min	1760.6	9. 58	183.87 W/K
OTS 2013	204h 20 min	1747.28	8.78	198.96 W/K
		BATEZ BESTEKO UA (Epe osoa)		**197.49 W/K**
		BATEZ BESTEKO UA (Urt - Ots)		**189.51 W/K**

T4.11. Leiho - aldaketaren ondorengo hilabeteroko balioak

Lehenik eta behin, UAren kalkuluetan eragin daukaten gaiak (Eq. 5 ekuazioaren arabera) aztertu ziren. Monitorizazio epe bakoitzaren lehen hilabetean arreta jarriko da: 2012ko otsailean eta 2013ko Urtarrilean (2012ko Abenduan, aireztapen saretak ez ziren zigilatu). Bi egoeretan bero potentzia berdina zen (1800 W inguru). Batez besteko barne tenperaturak berogailuak konektatuta egon ziren epeetan 18.34 gradukoa izan zen lehen monitorizazioan; bigarrenean, ordea, 19.72 gradukoa izan zen. Batez besteko kanpo tenperaturak 6.91 ºC eta 10.98 ºC izan zen hurrenez hurren. Monitorizazioaren ezaugarriak eta ΔTaren garrantzitsua kalkuluan kontuan hartuz, epe bakoitzean lortutako UA balioaren eta kanpo tenperturaren arteko erlazioa aztertu ziren, ea kanpo tenperaturen arteko diferentziek UA balioei eragin ahal dieten identifikatzeko. Erlazio hauek I4.45 grafikoan irudikatzen da.

UA balioetan kanpo tenperaturaren eraginak azpimarratu behar dira. Monitorizazio bakoitzaren emaitzak elkarrekin konparatuz, analisi kualitatibo bat egin daiteke. UA balioen eta batez besteko kanpo tenperaturen arteko korrelazio bat ikusi daiteke: zenbat eta kanpo tenperatura altuago izan, hainbat eta UA balioak altuago lortuko dira. Beraz, lehen monitorizazioan neurtutako tenperatura baxuagoen ondorioz, lehen egoeran lortutako UA balioak bigarren egoeran lortutakoak baino baxuagoak ziren (batez besteko kanpo tenperaturak, baita bi epeetan lortutako UA balioak ere, grafikoan irudikatzen dira). Hala eta guztiz ere, bigarren monitorizazioan lortutako UA balioak lehen monitorizazioan lortutakoak baino baxuagoak direneko joera bat ikusten da.



I4.45. Bi monitorizazio epeetako UA vs. Kanpo airearen tenperatura

6.2.3 Kontuan hartu behar diren beste alderdi batzuk

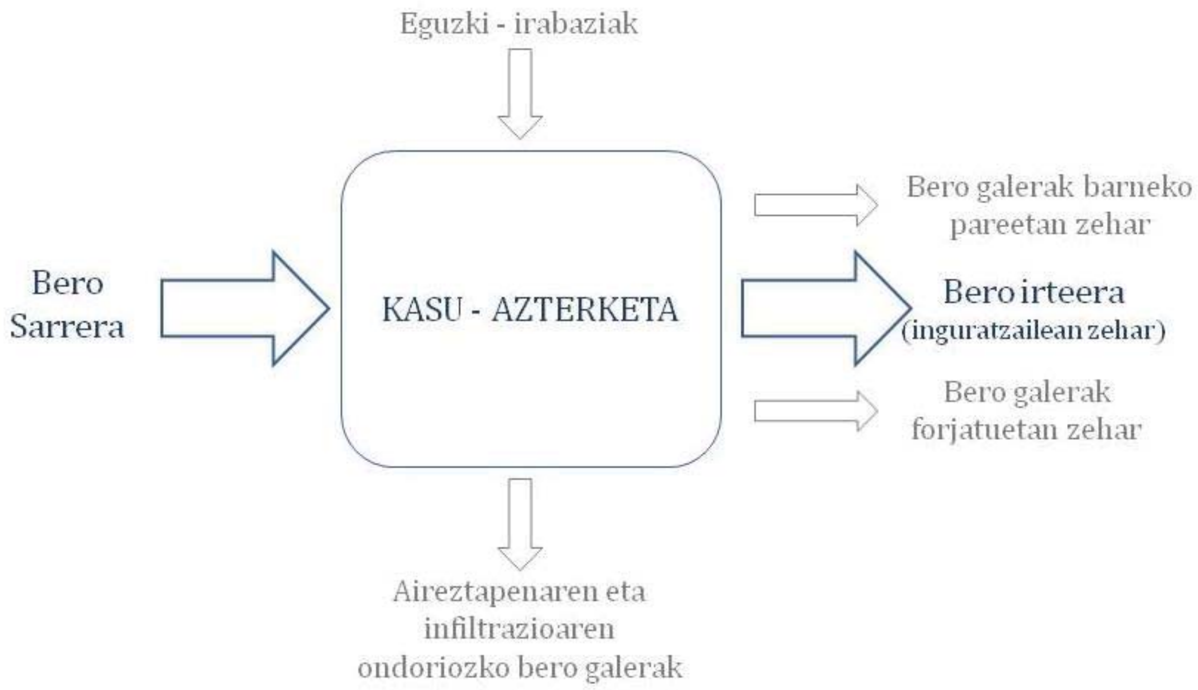
Aipatutako guztiaren ondorioz, azpimarratu behar da azpi - atal honetan aurkeztutako metodologia ez da *co-heating* metodoa hertsiki; aitzitik, *co-heating* metodoan erabiltzen den ekuazioa bi monitorizazio epeetako erreferentziazko balio batzuk kalkulatzeko erabili da. *Co-heating* metodoaren bidez balio zehatz lortzeko, aztertutako eraikinak egoera egonkor bati iritsi behar du. Horretarako, barne airearen tenperatura egonkorra epe luze batean zehar mantendu behar da. Kapitulu honetan aurkezten den monitorizazioan, ordea, bere ezaugarrien ondorioz, ez zen egoera hau iritsi, eta horregatik, lehen aipatutako korrelazioak aurkitzen dira lortutako emaitzak aztertzean. Dena dela, kalkulu hauei buruzko puntu batzuk azpimarratu daitezke, jarraian aurkezten direnak.

Co-heating metodoa egitean, eraikinak sistema sinple bat da, I4.46 irudian irudikatzen den bezala. Ikuspegi honetan, bero - sarrera neurtzen da, eta bero - galerak inguratzailean zehar, UA - balio orokorraren arabera dira, lehen azaldu bezala lortzen dena. Beraz, edozein eraikin inguratzailearen hobekuntzak (fatxadan, estalkian, leihoetan…) eraikunaren UA balioa murrizten laguntzen du, eta horren ondorioz, inguratzailean zehar daude bero - galerak murrizten.

I4.46. *Co-heating* metodoaren printzipioaren eskema

Hala ere, ikerketa honen kasu - azterketa eraikineko etxebizitza bat da (eta ez da eraikin osoa). Horregatik, bero sarrera eta irteera berriak eskeman agertzen dira (I4.47 irudian). Izan ere, eguzki irabaziak eraikinaren eskalan agertzen dira ere bai, eta kontuan hartu behar dira inguratzailearen UA - balio zehatzagoa lortzeko, baita infiltrazio eta aireztapenaren tasei lotutako bero - galerak ere. Baina kasu - azterketa eta alboko etxebizitzaren arteko trukatutako bero - fluxuak (goiko eta beheko forjatuen zehar, baita barneko paretetan zehar ere) garrantzitsuak daitezke etxebizitzaren energia orekan. Horren ondorioz, etxebizitza hauen erabilerak rola garrantzitsu bat jokatu dezakete *co-heating* metodoaren bidez lortutako emaitzan.

Eskema hauetan oinarrituta, puntu hauen eragina hurrengo paragrafoetan aztertzen dira, *co-heating* metodoaren bidez lortutako emaitzen arrazoiak identifikatzeko.



I4.47. Etxebizitza baten portaera errealaren printzipioaren eskema

6.2.3.1 aireztapenaren ondoriozko galerak

Aireztapen profilek eragin handia eduki dezakete *co-heating* metodoan. Hala eta guztiz ere, alderdi hau kontuan hartu zen bi monitorizaio epeetan, eta aireztapen saretak zigilatu ziren, batik bat bigarren epean (esaterako ikusi I4.14 irudia). Bestalde, infiltrazio tasen arteko ezberdintasunak baztertu ziren, zeren eta lehen monitorizazio epean egindako testek infiltrazio tasak oso baxuak erakutsi dute, eta leiho aldaketak, nolanahi ere, infiltrazio tasak murrizten du.

6.2.3.2 Alboko etxebizitzetarako bero - galerak

Lehen aipatu bezala, *co-heating* metodoa egitean, bero sarrera osoa inguratzailean zehar galtzen dela onartzen da. Orduan, lortutako UA, etxebizitza inguratzaile osoarena da, hau da, fatxada eta leihoak, baita alboko etxebizitzatik banatzen duten barneko paretak eta goiko eta beheko forjatuak ere. Elementu hauetan zehar dauden bero fluxuak, alboko etxebizitzetako erabileraren oso menpekoak dira, hau da, alboko etxebizitza baten barne egoeren aldaketa bat UA emaitzetan eragin handia eduki daiteke.

6.2.3.3 Eguzki irabazien aldaketak

Eguzki irabaziak kalkulu honetan eragin handia daukate ere. Kasu honetan, pertsianak irekita zeuden bi monitorizazio epeetan zehar (baldintza hau beharrezkoa zen hurrengo kapituluan aurkezten den eredua definitzeko). Beraz, eguzki - erradiazioa etxebizitzara irteten ziren leihoetan zehar.

6.2.4 UA kalkuluei buruzko faktore azpimarragarriak

UA balio ilogikoak lortu ziren zeren eta monitorizazioak ez ziren diseinatu *co-heating* metodoa aplikatzeko, eta jarraitutako metodologia ez da egokiena metodo hau egiteko. Hiru alderdi azpimarratu daitezke analisi mota hauek egitean, jarraian deskribatzen direnak:

- **Kanpo airearen tenperaturen neurketen akatsarekiko sentiberatasuna:** Lehen aipatu bezala, *co-heating* metodoan oinarritutako UA balioen kalkuluak egin ziren Eq. 5 jarraituz. Bi monitorizazio epeetan iritsitako ΔT (10 ºC inguru) kontuan hartuz, tenperaturaren akats txikiek aldaketa nabarmengarriak kalkulatutako U - balioan ekarri dezakete. Barne airearen tenperatura neurtzeko, zortzi tenperaturaren sentsore (PT 100) erabili ziren eta zehaztasun ona lortzen dela onartzen da. Kanpo airearen tenperatura lortzeko, berriz, etxebizitzaren gertu zegoen estazio klimatiko bat erabili zen. ΔT handitzea (barne airearen tenperatura igotzearen bidez), U balioa kalkulatzean kanpo airearen tenperaturaren neurketen akatsen eragina murriztuko zen.
- **Eguzki - erradiazioaren eragina:** Eguzki - erradiazioaren eragina etxebizitzan erakutsi da ere. Monitorizazioaren diseinua prestatu zen hurrengo kapituluan aurkezten den ereduaren definizioan beharrezkoa diren datuak lortzeko. Horregatik, eguzki irabaziak egotea beharrezkoa izan zen. Beraz, pertsianak ez ziren itxita monitorizazio epeetan zehar. Hala ere, *co-heating* metodoa egitekotan, pertsianak ixtea komenigarria da.
- **Alboko etxebizitzara joaten diren bero fluxuen neurketetan akatsak:** Nahiz eta fluxometroak kalibratu ziren bi monitorizazio epeen aurretik, fluxometro baten kokapen txarra balio txarrak eman ditzake, eta balio oker hauek, P_{env} balioan akatsak ekarri ditzakete P_{env} balioan.

7 Ondorioak

Kapitulu honetan Bilboko gizarte etxebizitza batean egindako monitorizazioa zehatz - mehatz deskribatu da. Datuak bi epe ezberdinetan bildu ziren, birgaitze baten aurretik eta ondoren. Landa - azterketa hau tesi honen atal esperimentalaren mamia da. Hau da, kapitulu honetan aurkezten diren emaitzak hurrengo kapituluan erabiliko dira eredu mota ezberdinak definitzeko eta baliozkotzeko.

Hala eta guztiz ere, nahiz eta kapitulu honen helburu nagusia tesi honen atal esperimental nagusia eta aipatutako emaitzak lortzeko egindako landa - azterketa deskribatzea izan da, puntu batzuk azpimarratu daitezke, bai metodologiari buruz, bai emaitzei buruz.

7.1 Metodologia

Atal esperimentalean, bi alderdi azpimarratu behar dira. Alde batetik, Monitorizazioa ondo diseinatzea, bilatutako helburuaren arabera, erakutsi da. Monitorizazioaren helburua argi izan ondoren, sentiberatasun handienak daukaten datuak zein diren identifikatzea komenigarria da landa - azterketa mota hautena. Aurkitutako arazoak *co-heating* metodoa erabiltzeko beste helburuarekin diseinatutako monitorizazio baten bidez neurtutako datuekin (hau da, hurrengo kapituluetan definitutako ereduak) puntu honen adibide bat dira.

Aldi berean, monitorizazioaren diseinuan malgutasuna komenigarria da, posiblea bada. Landa azterketetan, sentsore batzuk neurri okerrak ematen dituztela, edo kanpo egoerak onenak ez direla posiblea da. Horregatik, posibilitate hauek aurrez ikustea komenigarria da, eta malgutasun nahikoa edukitzea arazo hauei aurre egiteko (sentsore kopurua, monitorizaioaren iraupena...)

7.2 Emaitzak

Landa - azterketa honetan lortutako datuen analisiri esker, beste moduan oharkabean joan luketen portaera batzuk aurkitu daitezke, Gela 1ean aurkitutako bero galerek (lehen monitorizazio epean nabarmenagoak zirenak) garrantzi berezi bat daukate. Puntu honek ez eraikinaren inguratzailea soilik, baizik eta etxebizitzen arteko banaketako paretak ere kontuan hartzearen garrantzia azpimarratu du hobekuntza termiko bat diseinatzean. Bero - galera hauek garrantzitsuak izan daitezke, batik bat alboko etxebizitzetan erabileraren profil ezberdinak daukatenean.

7.3 Hurrengo urratsak

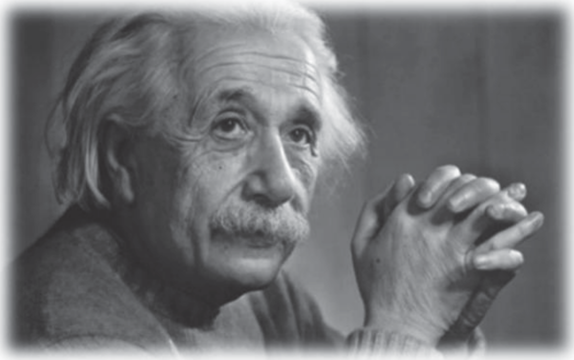
Hurrengo bi kapituluetan (eredu matematikoak) bi eraikinen eredu termiko mota garatuko dira, kapitulu honetan aurkezten den landa - azterketan lortutako datuak erabiliz. Eredu hauen bidez, etxebizitzaren portaera termikoa aztertu daiteke, bai kualitatiboki, bai kuantitatiboki, eta etxebizitzaren portaera termikoaren analisi sakonago bat lortu daiteke. Hori dela eta, 5. kapituluan TRNSYS eredu bat definitzen eta egokitzen da (hau da, kutxa zuriaren eredua) aztertutako etxebizitzaren portaera termikoa analizatzeko, eta 6. kapituluan, kutxa grisaren eredu bat garatzen da.

3. ATALA

EREDU MATEMATIKOAK

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)*



5. KAPITULUA

KUTXA ZURIAREN EREDUAK. TRNSYS EREDUAREN GARAPENA

LABURPENA

Laugarren kapituluan aurkeztutako etxebizitzaren eredu bat garatzen da kapitulu honetan. Lehen monitorizazio epean bildutako datuak erabili ziren ereduaren parametroak egokitzeko. Geroago, leiho – aldaketari esker lortutako energia – aurrezteak zenbatu ziren eredu honen bidez. Bi egoera ezberdin aukeratu ziren kalkuluak egiteko: lehen egoeretan, erabilera – profilak zehaztu ziren bibliografiaren arabera (IDAE-ren gidaliburuak, hain zuzen ere); bigarrenean, ordea, tesi honen hirugarren kapituluan aurkeztutako landa – azterketan lortutako ondorioetan oinarritutako erabilera – profilak erabili ziren. Azkenik, bi egoeren arteko ezberdintasunak aztertu ziren.

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 Sarrera

Aurretiko kapituluetan aipatzen den bezala, eraikin baten portaera erreala aurrez ikustea eta aztertzea faktore giltzagarria da, bai birgaitze optimoa erabakitzearren, bai birgaitzerako estrategia baten portaera ebaluatzearren.

Hala eta guztiz ere, hainbat zailtasunak aurkitzen dira, batik bat birgaitze energetikoen kasutan. Eraikin baten birgaitze baten eraginkortasuna aztertuz gero, birgaitzearen aurretiko eta ondorengo energia - kontsumoa elkarrekin konparatu behar dira. Haatik, energia kontsumoaren neurketak zuzenean birgaitzearen aurretiko eta ondorengo epeetan ez dira nahikoak, zeren eta parametro askok energia kontsumoari eragiten diote, esaterako egoera klimatikoak, etxebizitzaren erabilera edo errebote efektua, epe bakoitzean ezberdinak direnak.

Beraz, konparaketa - esparru ideala definitzeko, kontsumoen neurketak egoera berdinetan egin behar dira. Are eta etxe huts baten monitorizazio batean, egoera klimatikoak ez dira berdinak, eta orduan, bildutako datuak estandarizatzea beharrezkoa da emaitza zehatzak lortzeko.

Eraikinaren simulazio ereduei esker, eraikin ezberdinak elkarrekin konparatu daitezke, edo eraikin batean daukan birgaitzerako estrategia ezberdinen eraginak aztertu daitezke. Simulazioa erarik onenetako bat da birgaitze baten eraginkortasuna baieztatzeko.

Eredu mota asko aurkitu daitezke eraikinen portaera termikoa aztertzearren [76]. Haien artean, kutxa zuriaren ereduak deritzonak. Simulazio programa asko daude eredu mota hau garatzeko, esaterako TRNSYS [77,78] edo Energy Plus [78 - 80], ezagunetako bi baino ez aipatzeko. Eredu zurien abantaila nagusietako bat da datu esperimentalik ez direla beharrezkoak (nahiz eta komenigarriak izan eredua baliozkotzeko eta egokitzeko, kapitulu honetan erakutsi bezala).

Hala ere, eredu mota honetan sarrera - datu ugari sartu behar da eraikin bat definitzeko, eta sarritan, honek zehaztasunik ezak egitera eraman dezake, bai datuen akatsen ondorioz, bai datu eskuragarriaren gabeziaren ondorioz. Eraikin zaharren kasuetan, zailtasun hau are handiagoa da, zeren eta eraikuntzari buruzko informazio gutxiago eskuragarria dago askotan. Gainera, are eta eraikin berritan (proiektuaren bidez, ia eraikuntzari buruzko informazio guztia eskuragarria da) ezberdintasun garrantzitsuak aurkitzen dira proiektuan agertzen diren datuen eta eraikuntza errealaren datuen arteko konparaketa egitean, lehen kapituluan aipatu bezala. Horregatik, guztiz gomendatzen da, are eta eredu zuriak erabiliz, landa - azterketaren bidez lortutako neurketa batzuk edukitzea, eredua baliozkotzeko eta egokitzeko eraikin espezifiko bat aztertzean. Kapitulu honetan, ikuspegi hau jarraitzen da.

2 Kapitulu honen helburuak

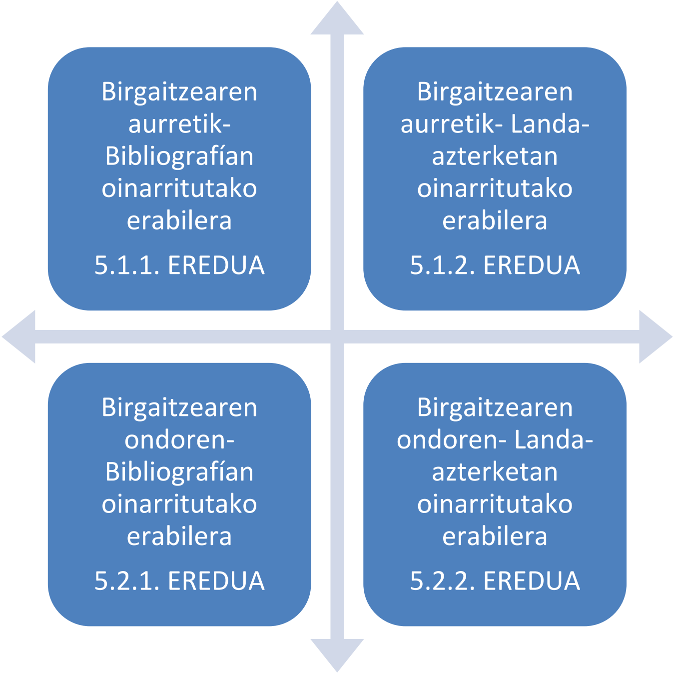
Hortaz, kapitulu honen helburu nagusia 60. hamarkadan eraikitako eraikin adierazgarri baten eredu bat TRNSYS tresnaren bidez definitzea da. Laugarren kapituluan aurkeztutako landa - azterketaren bidez lortutako datuak erabili ziren ereduaren parametroak baliozkotzeko eta egokitzeko.

Eredua geroago erabiliko da birgaitzerako estrategia ezberdinak aztertzeko. Honetaz aparte, baliozkotutako eredua beste ikerketetan erreferentzia - eraikintzat hartu daiteke, zeren eta bere eraikuntza - ezaugarriak oso arruntak ohi dira 60. hamarkadan lurralde honetan eraikitako eraikinetan (etxebizitza parkearen parte handi bat urte horretan eraikin ziren, tesi honen lehen kapituluan aipatu bezala) eta bere hobekuntzarako potentziala oso handia da.

3 Kapitulu honen egitura

Honela, kapitulu honetan TRNSYS bi eratan erabiltzen da kapitulu honetan. Alde batetik, leiho - aldaketaren bidez lortutako energia - aurrezteak zenbatzerako tresna baten bezala erabiltzen da. Gainera, eredu honen bidez lortutako emaitzak eta kutxa grisaren eredu baten bidez lortutakoak elkarrekin konparatu daitezke. Bestetik, TRNSYS tresnaren bidez garatutako eredua hurrengo kapituluetan erabiliko da hainbat birgaitze estrategia ezberdinak aztertzeko, ikuspegi ezberdinak eta alderdi batzuk kontuan hartuz, esaterako ikuspegi energetikoa, ekonomikoa, ingurugiro alderdiak, erosotasuna, edo ikuspegi exergetikoa. Printzipio hauek aintzakotzat hartuz, kapitulu honen egitura azaltzen da jarraian.

Lehenik eta behin, aintzakotzat hartutako eraikuntza - ezaugarriak TRNSYS ereduaren sarrera - datuak sartzean (eraikinetik lortutako informazioan oinarrituta) deskribatzen dira. Geroago, 2012ko Otsailaren 1etik 9ra arteko epearen egoera espezifikoei buruzko datuak erabiltzen dira garatutako eredua baliozkotzeko, eta baliozkotze hau aurkezten da.



I5.1. TRNSYS tresnaren bidez aztertutako lau egoerak

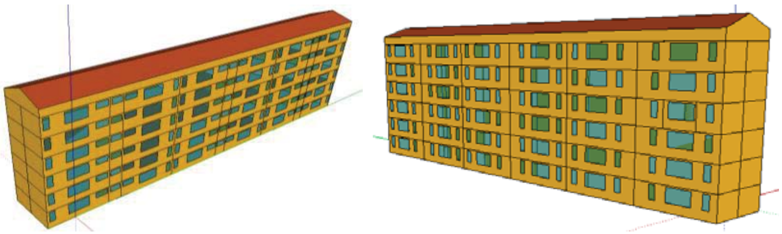
Gainera, bibliografian oinarritutako etxebizitzaren erabilera - profil estandarra urtean zehar energia eskaria zenbatzeko aurkezten dira. Aldi berean, beste erabilera - profil bat finkatzen da. Erabilera - profil hau 3. kapituluan xehatzen den landa - azterketaren bidez lortutako datuetan oinarrituta dago. Geroztik, eredua baliozkotzea eta egokitzea aurkezten da.

Lehenik, bibliografian oinarritutako ereduen bidez (birgaitzearen aurretik eta birgaitzearen ondoren) lortutako energia - eskariari buruzko emaitzak aurkezten dira. Landa - azterketan oinarritutako ereduen bidez lortutako energia eskariari buruzko emaitzak aurkezten dira geroago.

Amaitzeko, ikuspegi biak elkarrekin konparatzen dira, I5.1 eskeman irudikatzen denez, eta kapituluaren ondorioak zerrendatzen dira.

4 Hautatutako etxebizitzaren TRNSYS tresnaren bidez garatutako eredua

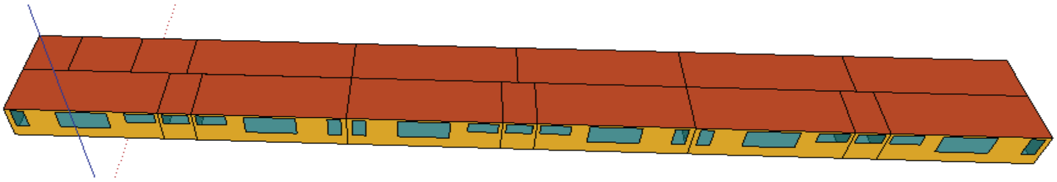
Eraikin osoa xehatu zen *Google Sketch Up* deritzona erabili dela medio, Bilboko Gizarte etxebizitzak emandako planoen eta egindako neurketen arabera. Bi programaren kapturak irudikatzen dira I5.2 irudian.



I5.2. *Sketch Up 3D* tresnaren bidez garatutako eraikinaren ereduaren bi kaptura

4.1 Eraikuntzaren datuak eta datu geometrikoak

Eraikinaren etxebizitzak leku termiko edo aire - nodo termiko ezberdinetan banandu ziren, I5.3 irudian irudikatu bezala. Etxebizitza bakoitza bi nodo termiko dauzka: haietako batek etxebizitzaren mendebaldeko partea barne hartzen du, hau da, logelak; besteak, etxebizitzaren ekialdekoa, (esekilekua, bainugela, sukaldea eta egongela) barne hartzen duena. Banaketa egoki bat aukeratzearen garrantzia azpimarratzen da bibliografian [81].



I5.3. Ereduan definitutako nodo termikoak

Era berean, monitorizatutako etxebizitza azaltzen den ereduaren zatia xehatuago banandu ziren, lau nodo termiko erabiliz: bana logela bakoitzean, eta beste nodo bat, egongela, bainugela, sukaldea eta esekilekua barne hartzen zituena. Amaitzeko, eskailera - kaxa area termiko independente bat bezala irudikatu zen. Beraz, banaketa hau I5.4 irudian irudikatzen da. Irudi honetan, monitorizatutako etxebizitza (ezkerrean) eta beste etxebizitzen banaketa (eskuinean) irudikatzen da, baita eskailera - kaxa ere.

I5.4. Eraikinaren ereduan xehatutako area termikoa

Ereduan hartutako eraikuntzari buruzko informazio zehatza T5.1 eta T5.2 tauletan aurkezten da. *Bilboko Gizarte etxebizitzak* emandako datuetan oinarrituta dago.

	Lodiera (cm)	Konduktantzia (kJ/hmK)	Bero - ahalmena (kJ/kgK)	Dentsitatea (kg/m³)	Erresistentzia Termikoa
FATXADA					
Igeltsua	1	1.8	1	900	-
Adreilu huts	4.5	1.76	0.9	1200	-
Aire - ganbera (bert)	4	-	-	-	0.047
Adreilu huts	12.5	1.76	0.9	1200	-
Beira - zuntza	2	0.144	0.84	12	-
Adreilu huts	4.5	1.76	0.9	1200	-
Zementuzko morteroa	3.5	5.04	1.1	2000	-
Fatxadaren U - balioa	*0.74*				

T5.1. Eraikuntzaren datuak (I. partea)

	Lodiera (cm)	Konduktantzia (kJ/hmK)	Bero - ahalmena (kJ/kgK)	Dentsitatea (kg/m^3)	Erresistentzia Termikoa
ESTALKIA					
Harea eta zementuzko morteroa	1	3.6	1	1800	-
Adreilu huts	4.5	1.76	0.9	1200	-
Harea eta zementuzko morteroa	1	3.6	1	1800	-
Aire - ganbera (horiz)	2	-	-	-	0.022
Teila	1	3.6	0.8	2000	-
Estalkiaren U - balioa	*2.7*				
BARNEKO PARETAK					
Harea eta zementuzko morteroa	1	3.6	1	1800	-
Adreilu huts	12.5	1.76	0.9	1200	-
Harea eta zementuzko morteroa	1	3.6	1	1800	-
Barne pareten U - balioa	*2.25*				
FORJATUAK					
Konifero - zuerezko zorua	1	0.504	2.8	600	-
Aire - ganbera (horiz)	1	-	-	-	0.042
Gangatila forjatua (20+4)	24	3.75	1	1500	-
Igeltsua	1	1.44	1	1000	-
Forjatuen U - balioa	*2.27*				

T5.2. Eraikuntzaren datuak (II. partea)

Era berean, egoera bakoitzean kontuan hartutako leihoen ezaugarri nagusiak T5.3 taulan aurkezten dira.

	Markoa (30%)	U_{marko} [W/m^2.K]/[kJ/h.m^2.K]	Beira	U_{beira} [W/m^2.K]
Leiho zaharrak	Metalezkoa (ZT hauste barik)	5.7 / 20.52	4/6/4	3.44
Leiho berriak	PVC (2 ganbera)	2.2 / 7.92	6/12/6	3.0

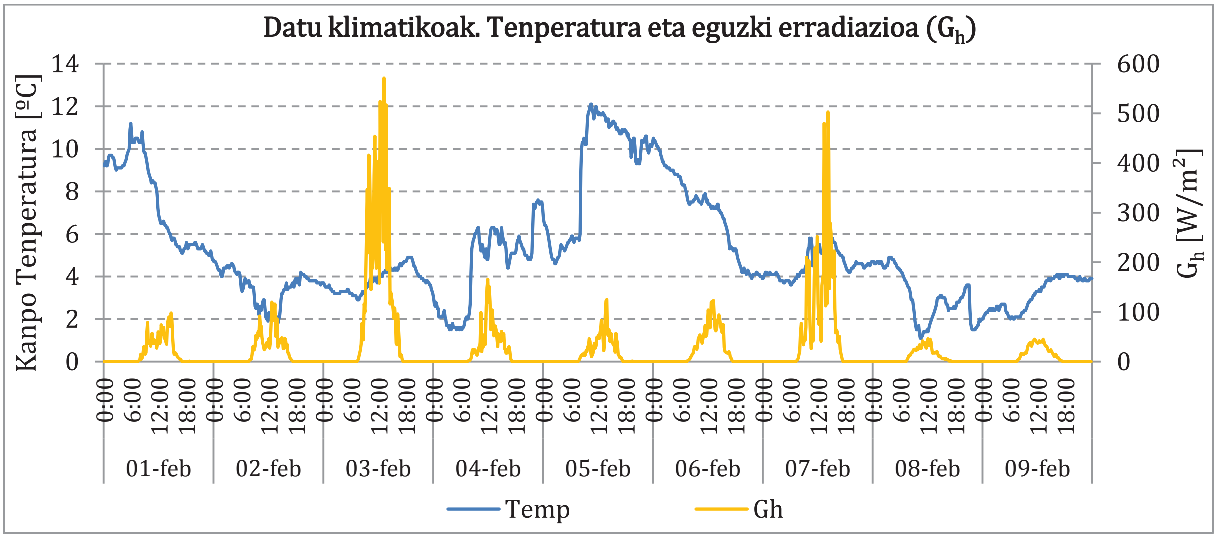
T5.3. TRNSYS ereduan definitutako leihoen ezaugarriak

4.2 Erabilera - profilak eta kalkulu oinarriak eredu baliozkotzerako

Laugarren kapituluan aurkeztetako monitorizazioaren bidez lortutako Otsailaren lehen egunetako datuak (2012ko otsailaren 1etik 9ra arteko epekoak) erabili ziren TRNSYS tresnaren bidez garatutako eredua baliozkotzeko eta egokitzeko.

4.2.1 Datu klimatikoak

Datu klimatiko - fitxategia (I5.5 irudia) aldatu zen monitorizazio epean egon ziren egoera klimatikoak sartzeko. Euskalmet-en estazio klimatikoan (Deustun kokatuta, aurretiko kapituluan aipatzen denez) bildutako datuak TRNSYS tresnaren datu klimatiko - fitxategian sartu ziren. Neurtutako datuen ezaugarrien ondorioz, hipotesi batzuk hartu behar ziren, jarraian xehatu bezala.

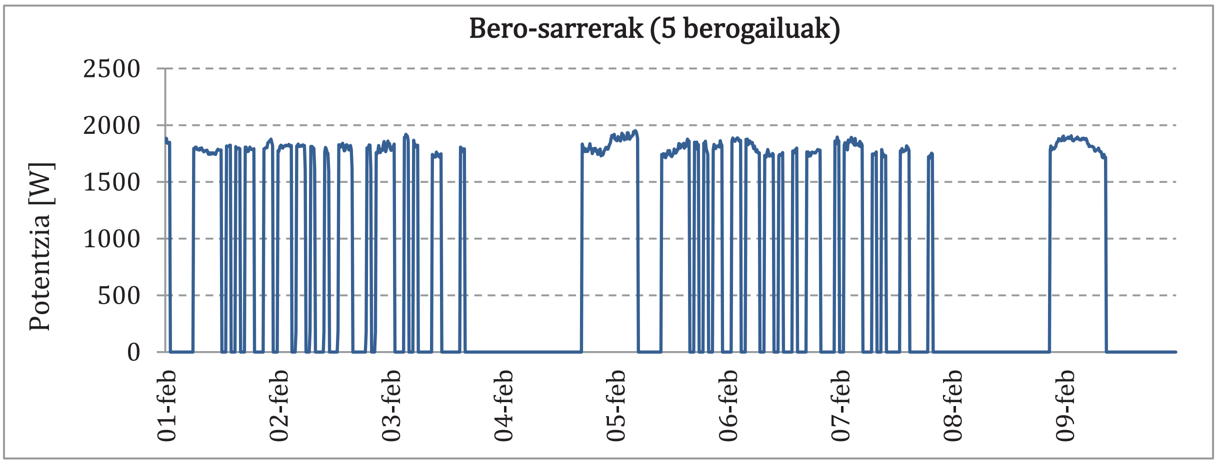


I5.5. Kanpo airearen tenperatura eta eguzki - erradiazioa (G_h)

Aurre egin behar zen arazo nagusia zuzenezko eguzki - erradiazioaren eta eguzki - erradiazio barreiatuaren artean bereiztea izan zen, eguzki - erradiazio totala baino ez delako estazio klimatiko honetan. Datu klimatiko - fitxategian zuzenezko eguzki - erradiazioa eta eguzki - erradiazio barreiatua bereiz barne sartzearen beharraren ondorioz, hipotesi batzuk hartu behar ziren.

Lehenik eta behin, zuzenezko eguzki - erradiazioaren eta eguzki - erradiazio barreiatuaren arteko banaketaren zailtasuna ahalik eta gehien murrizteko egun eguzkitsutan (egun hodeitsu baten, erradiazio totalaren ia %100 erradiazio barreiatua da) hodeitsu egun multzo bat hautatu zen, bi egun eguzkitsu baino ez zirenekoa. Bi egun hauetako zuzenezko eguzki - erradiazio normala ordu eguzkitsuetan, eguzki - erradiazio totalaren %50 hartu zen. Balio hau Meteonorm datu basetik lortutako Bilboko urte tipo batean oinarritu zen.

4.2.2 Berogailuen errutina



I5.6. Bero - sarrera totala etxebizitzan baliozkotzerako epean zehar

Monitorizazio epean zehar, bero - sarrera totala neurtu zen. Datu hauek baliozkotzerako epekoak dira (ikusi I5.6 irudia). Irudikatutako potentzia bost berogailuak emandakoa da, eta bero - irabazi hauek TRNSYS ereduan barne hartu ziren baliozkotzeko.

4.2.3 Aireztapen eta infiltrazioaren tasa

Aireztapen motarik ez zen egon bi monitorizazio epeetan. Izan ere, are eta leiho berrien aireztapen saretak zigilatu ziren bigarren monitorizazio epean. Beraz, aireztapen tasarik ez zuen TRNSYS ereduan hartu.

Laugarren kapituluan aipatu bezala, lehen monitorizazio epean neurtutako infiltrazio tasa oso baxua izan zen. Neurketa horiek oinarrituta, lau infiltrazio tasa konstante hartu ziren eredua baliozkotzeko. Infiltrazio tasaren balioak hurrengoak ziren: 0.05, 0.1, 0.15 and 0.2 ACH (*Air Changes per Hour*, ingelesez).

4.2.4 Simulazioari buruzko informazio gehiago

Simulazioan rola garrantzitsu bat jokatzen diren datu nabarmengarri gehiago, esaterako nodo termikoen arteko aire - aldaketa dagoen edo alboko etxebizitzetako tenperaturak egokitu ziren baliozkotzean, iterazio - prozesu baten bidez, 6. atalean xehatu bezala.

5 Erreferentzia - ereduaren erabilera - profilak

Eredua baliozkotzea eta doikuntza batzuk egin eta gero, simulazioa egin zen. Simulazio hauen erabilitako datuak eta profilak atal honetan aurkezten dira.

Beraz, erabilera - profilak (aireztapen eta infiltrazio tasak, barne bero - irabaziak, setpoint tenperatura, elektrizitate - eskaria, etxeko ur beroaren eskaria eta datu klimatikoak) hurrengo ataletan zehatz - mehatz aurkezten dira. Haietako batzuk (esaterako elektrizitate - eskaria eta etxeko ur beroaren eskaria) kapitulu honetan aurkeztutako kalkuluetan ez ziren erabili, 8. kapituluan aurkeztutakoetan baizik. Hala ere, atal honetan profil eta datu guztiak aurkeztea, eta hurrengo kapituluetan soilik erreferentzia labur bat egitea garbiagoa dela uste da.

Lehen aipatu bezala, bi erabilera - profil aurkezten dira. Alde batetik, bibliografian oinarritutako erabilera - profil multzo baten deskribapen bat xehatzen da, IDAE-k aurkezten dituen irizpideen arabera. Gainera, beste erabilera - profil multzo berri bat zehazten da, 3. kapituluan erakutsitako landa - azterketaren bidez lortutako emaitzetan oinarrituta.

5.1 Aireztapen eta infiltrazio - tasa

Espainiako Eraikuntzaren Kode Teknikoan (EKT), eraikin berriak bete behar dituzten aireztapen baldintza minimoak finkatzen dira. Aireztapen betebehar hauek T5.4 taulan zerrendatzen dira. T5.5 Taulan, balioak kalkulatu izan ziren betekizun hauek kontuan hartuz.

	Min. q_v [l/s]		
	Pertsonako	Metro karratutako	Beste parametro batzuen arabera
Logela	5		
Egongelak	3		
Bainugela			15 gelako
Sukaldea		2	50 gelako (*)

T5.4. EKT - an finkatutako aireztapen tasako betebehar minimoak

Hala eta guztiz ere, balio hauek egoerarik kontrakoenari lotuta daude, gela guztiek aireztapen tasa konstantea daukatenean. Hainbat estrategiak jarraitu daiteke aireztapeneko instalazioaren eraginkortasuna gehitzeko, barne airearen kalitate berbera lortzearren aireztapen tasa txikiagoak erabiltzera bultzatzen duena. Horregatik, IDAE-k 1 ACH-ko aireztapen tasa hartzea gomendatzen du. Izan ere, Espainian ziurtagiri energetikoa kalkulatzeko erabiltzen den simulazio tresnak (Calener deritzona) balio hau erabiltzen du [82]. Balio hau baxuago izan daiteke, aireztapen tasa murriztea (barne airearen kalitatea mantenduz) frogatuz gero.

IDAE-k emandako irizpideen arabera [83], 0.24 ACH-ko infiltrazio tasa balioa finkatu zen.

Aldeak	Azalera Garbia	Bol.	EKT - ren arabera		ZVH
	m^2	m^3	dm^3/s	m^3/h	Bol/ordua
Gela 1 (Logela)	7.73	19. 1	5	18	
Gela 2 (Egongela)	8.06	19.91	9	32.4	
Gela 3 (Logela)	8.25	20.38	5	18	
Gela 4 (Logela)	8.25	20.38	5	18	
Gela 5 (Sukaldea)	9.51	23.49	19.02	68.472	
Gela 6 (Bainugela)	2.41	5.95	15	54	
Gela 7 (atondoa)	2.82	6.97	-	-	
Gela 8 - - -	2.04	5.04	-	-	
TOTALA	49.07	121.2		208.9	1.72

T5.5. Erreferentzia etxebizitzaren balioak, EKT-k finkatutako betebeharren arabera

5.1.1 Bibliografian oinarritutako sarrerako datuak (1. Egoera. Birgaitzearen aurretik)

Aireztapen tasa: EKT gainditu baino lehen eraikina eraikin zen eta, aireztapeneko instalaziorik ez dago etxebizitzan. Beraz, ordu bat (goizeko zazpitik zortzira) eguneroko aireztapen naturala (leihoak irekitzea) hartu zen. Hartutako balioa 4 ACH-koa zen. Eskailera - kaxan, ordea, aireztapenik ez zen hartu.

Infiltrazio tasa: 0.6 ACH-ko infiltrazio tasa konstantea hartu zen etxebizitzetan, eta 0.9 ACH-koa eskailera - kaxan.

5.1.2 Bibliografian oinarritutako sarrerako datuak (2. Egoera. Birgaitzearen ondoren)

EKT eta IDAE-ren dokumentuetan xehatutako betebehar minimoak [83] jarraitu behar dira etxebizitzetako infiltrazio eta aireztapen tasak finkatzeko. Eskailera - kaxan aldaketarik ez zen egin.

Aireztapen tasa: IDAE-ren dokumentuetan xehatutako aireztapeneko betebehar minimoa 1 ACH-koa da.

Infiltrazio tasa: Balio konstante bat hartu zen kasu - azterketa hauetan. 0.24 ACH-ko infiltrazio tasa konstantea hartu zen etxebizitzetan. Infiltrazio tasaren murrizteak leihoen hobekuntzari esker dira.

Laburbilduz, bibliografian oinarritutako hartzen diren balioak T5.6 taulan zerrendatzen dira.

	Birgaitzearen aurretiko egoera	Birgaitzearen ondorengo egoerak
Aireztapena	4 (7 - 8 am)	1
Infiltrazioa	0.6	0.24

T5.6. Hartutako aireztapen eta infiltrazio tasa balioak

5.1.3 Landa - azterketan lortutako datuetan oinarritutako TRNSYS ereduan sarrerako datuak

Bai birgaitze aurretik lortutako infiltrazio neurketak, bai TRNSYS eredua kalibratu ondoren lortutako balioak, oso antzekoak ziren haien artean, 0.15 ACH inguru. Beraz, nahiz eta infiltrazio tasa hainbat baldintzen arabera da (kanpo aireko presioa edo haize - abiadura, adibidez) 0.15 ACH-ko balio konstantea hartu zen.

5.1.4 Bosgarren kapituluan aireztapen eta infiltrazio tasen tratamendu berezia

Goian aipatutako egiteak egonda ere, aireztapen eta infiltrazio tasen balio berberak hartu ziren bi egoeretan. Horrela, birgaitze estrategia ezberdinen eraginak erosotasun termikoan eta energia - kontsumoan aztertzen dira egoera berberetan.

Egiatan, birgaitze askotan infiltrazio tasa murrizten da birgaitzearen ondoren. Esaterako leiho - hobekuntza batean energia - kontsumoan murrizteak bultzatzen da, bai bero - transferentzia leihoetan zeharko galerak murrizten dira eta (eroankortasun termikoa murrizten da eta), bai infiltrazio tasa leihoetan zehar murrizten da eta, eta bi efektu hauek birgaitzeari erantsi behar dira. Hala ere, infiltrazio tasa murrizketa honek noizbehinka aireztapen tasa handiagotze bat ekarri dezake, barne airearen kalitatea mantentzearren. Bestalde, aireztapeneko instalazio eraginkorra ez da soilik aireztapen tasa optimizatuz lortzen, baizik eta bero – berreskuratzaile bat instalatuz ere. Kasu honetan, gainera, infiltrazio tasa birgaitzearen aurretik, lehen aipatu bezala, oso baxua zen jadanik. Dena dela, hartutako hipotesi honen ondorioz, energia - aurrezteak murriztu daitekeela aintzakotzat hartu behar da.

Hortaz, 0.1 ACH-ko infiltrazio tasa konstantea hartu zen azterketa - landan oinarritutako erabilera - profila erabiltzen den ereduko bi egoeretan, eta 0.6 ACH - koa bibliografian oinarritutakoa erabiltzen den eredukoetan. Era berean, aireztapenari dagokionez, 4 ACH-ko aireztapen tasa goizeko zapitik zortzira hartu zen kasu guztietan. Balio hauek laburbiltzen dira T5.7 taulan.

	Bibliografian oinarritutakoa	**Landa - azterketan oinarritutakoa**
Aireztapen	4 (7 - 8 am)	4 (7 - 8 am)
Infiltrazioa	0.6	0.1

T5.7. Hartutako infiltrazio eta aireztapen tasa balioak

5.2 Barne bero - irabaziak

IDAE-k emandako barne bero - irabazien profila atal honetan xehatzen dira [83].

- **Okupazioren ondoriozko bero - irabaziak**

Okupazio ondoriozko bero - irabaziak bero sentigarriaren eta bero sorraren arteko bereizten dira. Okupazio ondoriozko bero irabazien konbekzio - zatikia bero sentigarri zatiaren %40 da. Honela definitutako datuak T5.8 taulan erakusten dira.

	0 - 7 am		**7 am - 3 pm**		**3 - 11 pm**		**11 - 12 pm**	
[W/m^2]	**Sentig.**	**Sorra**	**Sentig.**	**Sorra**	**Sentig.**	**Sorra**	**Sentig.**	**Sorra**
Asteguna	2.15	1.36	0.54	0.34	1.08	0.68	2.15	1.36
Larunbata	2.15	1.36	2.15	1.36	2.15	1.36	2.15	1.36
Igandea	2.15	1.36	2.15	1.36	2.15	1.36	2.15	1.36

T5.8. Barne bero - irabaziak. Okupazioaren ondoriozkoak

- **Argiztapen artifizialaren ondoriozko bero - irabaziak**

Argiztapen artifizialaren ondoriozko bero irabazien konbekzio - zatikia totalaren %20 da. Bere bero - irabazien profilak T5.9 taulan erakusten dira.

[W/m^2]	**0-7 pm**	**7 am-6 pm**	**6-7 pm**	**7-11 pm**	**11-12 pm**
Egunero	0.44	1.32	2.20	4.40	2.20

T5.9. Barne bero - irabaziak. Argiztapen artifizialaren ondoriozkoak

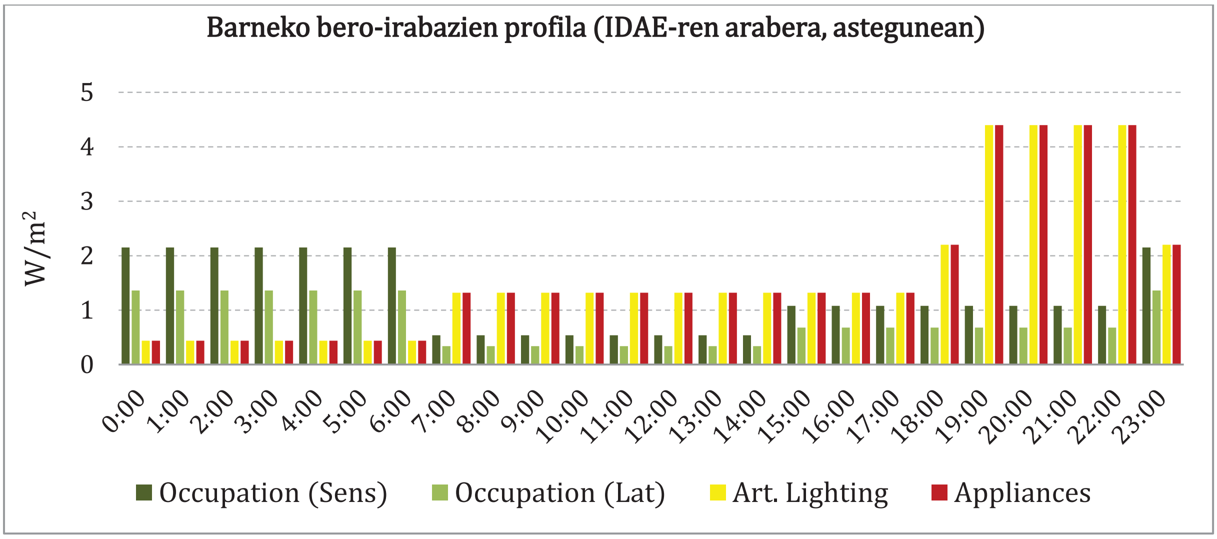
- **Etxe - tresnen ondoriozko bero - irabaziak**

Etxe - tresnen ondoriozko bero irabazien konbekzio - zatikia totalaren %30 da. Etxe - tresnen bero - irabazien profilak T5.10 taulan erakusten dira.

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

T5.10. Barne bero - irabaziak. Etxe - tresnen ondoriozkoak

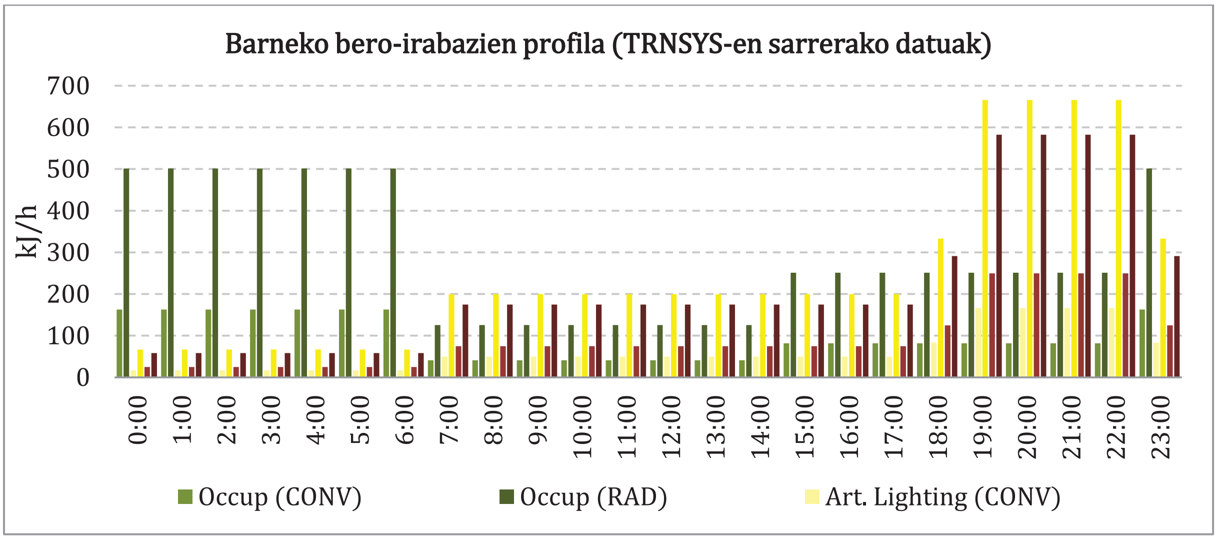
Laburbilduz, barne bero - irabazi guztiak I5.7 irudia irudikatzen dira.



I5.7. Barne bero - irabazien profila

5.2.1 Bibliografian oinarritutako sarrerako datuak

Aipatutako iturrietan kontuan hartuz, barne bero - irabaziak modelatzen dira T5.11 eta T5.12 tauletan agertzen diren bezala. Astegunen eta asteburuko egunen artean ez ziren bereizi; beraz, aldaketa batzuk egin ziren IDAE-k emandako balioekin konparatuz. Hartutako barne bero - irabaziak I5.8 irudian erakusten dira, kilojulio ordukoan (TRNSYS-ek eskatzen dituen unitateak).



I5.8. Hartutako barne bero - irabazien profila. TRNSYS - en sarrerako datuak [kJ/h.m²]

[kJ/h.m²]	Okupazioaren Ond.			Argiztapen Art. Ond.			Etxe - tresnen Ond.		
	Konv.	Errad.	TOT.	Konv.	Errad.	TOT.	Konv.	Errad.	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

T5.11. Barne bero - irabazi guztiak ereduan [kJ/h.m²]

[kJ/h]	Okupazioaren Ond.		Argiztapen Art. Ond.		Etxe - tresnen Ond.	
	Konv.	Errad.	Konv.	Errad.	Konv.	Errad.
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

T5.12. Barne bero - irabazi guztiak ereduan [kJ/h]

5.2.2 Landa - azterketan lortutako neurketetan oinarritutako sarrerako datuak

Barne bero - irabaziak aztertzean, mota honetako eraikin baten barne bero - irabazi errealekin konparatuz, oso altuak direla uste zen. Horregatik, ENEDI taldearen esperientzian oinarritutako barne bero - irabazien profil berri bat xehatu zen.

Okupazio profilak definitzeko, etxebizitza lau pertsona bizi zirenaren hipotesia hartu zen. Zeren eta etxebizitzaren eredua area termiko ezberdinetan banandu zen, okupazio profil ezberdinak hartu ziren area termiko bakoitzean (esaterako, egongela gauean okupaziorik ez zegoenaren hipotesia hartu zen).

Antzeko irizpideak jarraitu ziren argiztapen artifiziala definitzeko. Horrela, egunean zehar (eguneko argia zegoenean) argiztapen artifizialaren ondoriozko bero - irabazirik egon ez zirenaren hipotesia hartu zen. Horren bitartez, erreferentzia etxebizitzaren ereduan hartutako barne bero - irabaziak nodo termiko bakoitzean T5.13 taulan erakusten dira.

			Egongela - sukaldea	Gela 1	Gela 2	Gela 3
Okupazioa (Pertsona kopurua)	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
Argiztapen Artifiziala (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
Etxe - tresna (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

T5.13. Hartutako barne bero - irabaziak etxebizitzaren eredua

5.3 Setpoint tenperatura

IDAE-k [83] berokuntza erabiltzen deneko urtaroko setpoint tenperatura xehatzen du, hau da, egunero Urtarriletik Maiatzera eta Urritik Abendura. Urtaro honetako egun tipiko baten setpoint tenperaturaren profila jarraian erakusten da:

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

5.3.1 Bibliografian oinarritutako sarrerako datuak

IDAE-k gomendatutako profiletan aldaketa txiki bat egin zen. Zeren eta goizeko zazpitik zortzira leihoak irekita zeudela onartu zen, berokuntza sistema ez zela konektatu ordu horretan onartu zen:

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

5.3.2 Landa - azterketan lortutako neurketetan oinarritutako sarrerako datuak

Hirugarren kapituluan deskribatutako landa - azterketan aztertutako etxebizitzen barne tenperatura IDAE-k deskribatutakoak baino baxuagoak izan zirela erakutsi da. Nahiz eta setpoint tenperatura nabarmen aldatu daiteke biztanleen arabera (3. kapituluan ageri den bezala) hurrengo profil estandarra adierazgarria zela onartu zen:

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

Onartutako erradiadoreen zatiki radiatiboa simulazioan %0 izan zen.

5.4 Elektrizitate - eskaria

Lehen aipatu bezala, kapitulu honetan ez ziren datu hauek erabili, 8. kapituluan baizik. Zortzigarren kapituluan erabilitako elektrizitate - eskariaren profila hurrengo azpi ataletan xehatzen da.

5.4.1 Bibliografian oinarritutako sarrerako datuak

Elektrizitate - eskariaren profila aipatutako IDAE-k emandako barne bero - irabazietan oinarrituta dago. Azken finean, barne bero - irabaziak biztanleek sortutakoen eta elektrizitate - eskariak sortutakoen (etxe - tresnak eta argiztapen artifiziala) batura da, elektrizitate osoa barne bero - irabaziak bihurtzen dira eta. Hau da, elektrizitate - eskaria IDAE-k emandako argiztapen artifizialaren eta etxe - tresnen profiletan oinarrituta dago. Irizpide honen arabera, T5.14 taulan erakutsitako profilak hartu zen simulazioa egiteko.

[kJ/h]	W/m^2	Tot. W	Tot. kJ/h	Total kJ (Epean)
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/egun*

T5.14. Etxebizitza bakoitzaren elektrizitate - eskaria [kJ/h]

Hartutako elektrizitate - eskaria 14,977.45 kJ/egun da (4.16 kWh/egun edo 1518.55 kWh/urte).

5.4.2 Landa - azterketan lortutako neurketetan oinarritutako sarrerako datuak

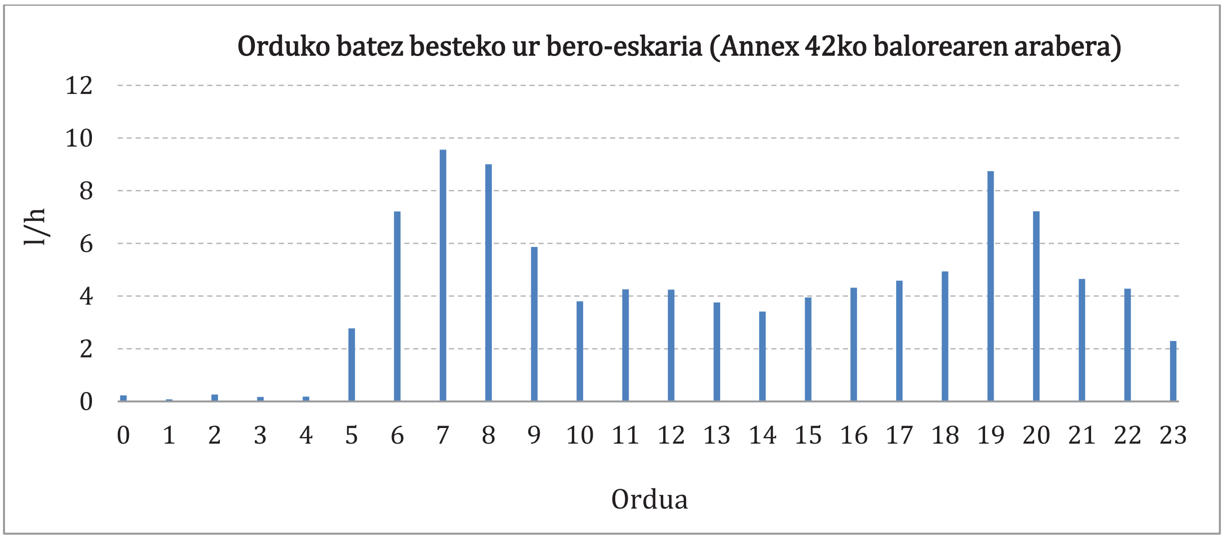
Zeren eta parametro hau ez zen zehazki neurtu landa - azterketan, ez zen aldaketarik egin elektrizitate - eskarian, eta aurretiko atalean xehatutakoa erabili zen.

5.5 Etxeko ur bero - eskaria

Bi aukera kontuan hartu daitezke etxeko ur bero – eskaria definitzeko.

- **Annex 42k emandako profiletan oinarritutako etxeko ur bero - eskariaren profila**

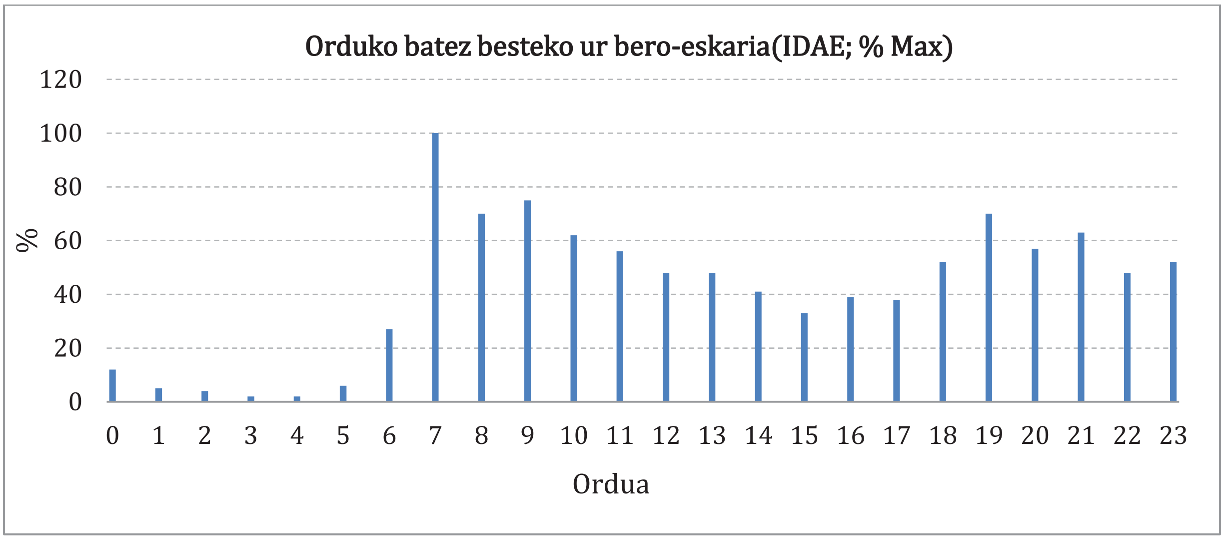
Etxeko ur beroaren eguneroko profil berbera egun guztietan erabili zen. Hala eta guztiz ere, ur berotzeko erabilitako energia - eskaria ezberdina da, hornidura tenperaturaren arabera da eta. Etxeko ur bero - eskaria litrotan xehatzeko, Annex 42-k emandako balioak erabili daitezke, 100 litro/eguneko onartuz. Egun tipiko bateko orduko batez besteko balioak hartu ziren. Balio hauek, etxeko ur bero kontsumoa erakusten direnak, I5.9 irudian irudikatzen dira.



I5.9. Orduko batez besteko ur bero - eskaria (Annex 42ko balioaren arabera)

- **IDAE-k emandako profiletan oinarritutako etxeko ur bero - eskariaren profila**

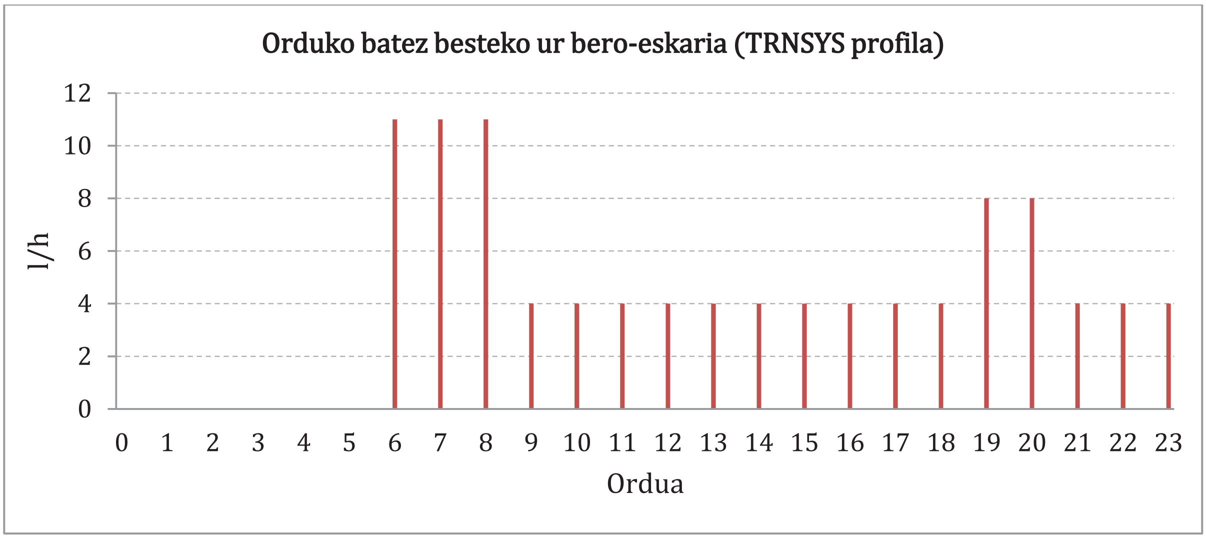
IDAE-k xehatutako etxeko ur bero - eskariaren profila [83], I5.10 grafikoan irudikatutako profila definitu zen.



I5.10. Orduko batez besteko eskaria (IDAE; % Max)

5.5.1 Bibliografian oinarritutako sarrerako datuak

Goian aipatutako bi profiletan oinarrituta, Ereduan setpoint sinple baina dinamiko bat erabili zen. 101 litro eguneroko eskaria onartu zen. Definitutako eguneko eskari hau I5.11 grafikoan irudikatzen da.



I5.11. Orduko batez besteko eskaria (TRNSYS profila)

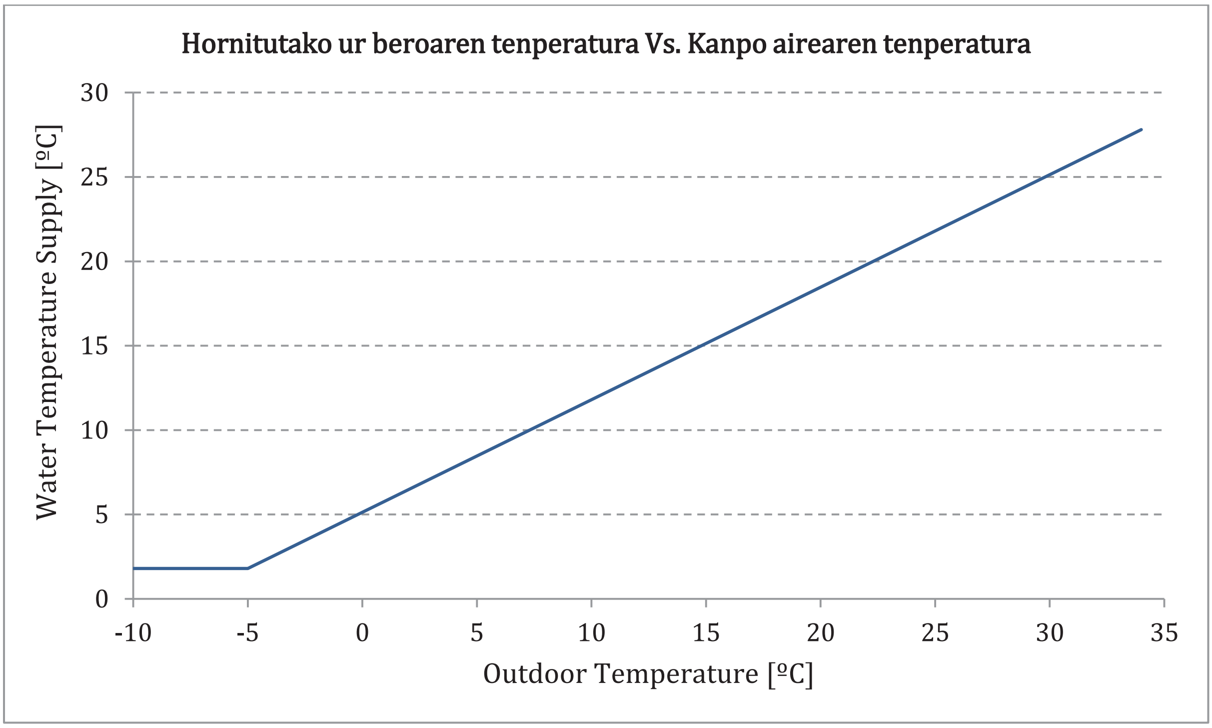
- 0 - 6 am: 0
- 6 - 9 am: 11 litro/orduko
- 9 am - 7 pm: 4 litro/orduko
- 7 - 9 pm: 8 litro/orduko
- 9 - 12 pm: 4 litro/orduko

Etxeko ur bero ekoizpen tenperatura 60 gradutan finkatu zen. Urteko batez besteko hornidura tenperatura 15.4 gradukoa da, Bilbao Ur Partzuergoak 2011. Urtean *Venta Altan* neurtutako datuen arabera. Balio hau aintzakotzat hartuz, hornitutako ur bero tenperatura Eq. 10 ekuazioaren bidez kalkulatzen da ([53] erreferentzian Jansen-ek erakusten duen formulan oinarrituta)

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

Eq. 10

Hortaz, hornitutako ur bero tenperatura kanpo airearen tenperaturari lotuta dago. Horrela, tenperatura minimoa 1.8 gradukoa da, eta maximoa, aldiz, 27 gradukoa da. Bilboko urte tipiko baten tenperaturarik altuena (Meteonormen arabera) 33.7 gradukoa da. Hornitutako ur bero eta kanpo airearen tenperaturaren arteko erlazioa I5.12 grafikoan irudikatzen da.



I5.12. Hornitutako ur beroaren tenperatura Vs Kanpo airearen tenperatura

5.5.2 Landa - azterketan lortutako neurketetan oinarritutako sarrerako datuak

Elektrizitate - eskariaren kasuan bezala, aurretiko atalean aipaturiko datuak erabiltzen dira, parametro hau ez baitzen zehazki neurtu landa - azterketan.

5.6 Datu klimatikoak

5.6.1 Sarrerako datuak

Bilboko datu klimatiko (Meteonorm) simulazioetan erabili ziren. Datu - fitxategi hauek urte tipiko baten dira.

5.7 Simulazioari buruzko informazio gehiago

Bero ahalmena, nodoen arteko dagoen aire trukea edo alboko etxebizitzen tenperaturak finkatu ziren ereduan baliozkotzean erabilitako balioak kontuan hartuz. Balio hauek 6. atalean aurkezten dira. Eredua baliozkotzea ordu bateko denbora tarteko simulazioen bidez egin zen.

6 Eredua baliozkotzea

Eredua baliozkotzea erabiltzen da ea eredu bat sistema erreal baten irudipen zehatz den baliozkotzeko. Baliozkotzea ereduaren kalibrazioaren bidez egiten da. Kalibrazioa iterazio - prozesu bat da. Prozesu honetan, ereduaren eta sistema errealaren portaeren arteko konparazio bat egiten da, eta haien arteko desadostasunak erabiltzen dira eredua hobetzeko. Prozesu hau errepikatzen da ereduaren bilatutako zehaztasuna lortu arte.

Gainera, baliozkotzearen bidez, eraikinen portaera termikoan parametro garrantzitsuenak zein diren identifikatzen dira.

Aurretik aipatu bezala, eredua baliozkotzeak behar ditu:

- Datu klimatiko - fitxategia baliozkotzerako hautatutako epearen kanpo egoera klimatikoarekin egitea.
- Bero - sarreraren profilak xehatzea.

6.1 Hartutako parametro - konbinazioa

Kalibrazioa eta baliozkotzea egiteko, hainbat parametro doitu ziren ereduan. Doikuntza hau parametro hauek aldatuz iterazio - prozesu batean egin zen. Aipatutako parametroak hurrengoak dira:

- Nodo bakoitzaren kapazitantzia

- Etxebizitzaren infiltrazio tasa
- Nodo termiko ezberdinen arteko dagoen aire aldaketa (esaterako, logelen eta egongelaren arteko dagoena)

Aldameneko etxebizitzen tenperaturek rola garrantzitsu bat jokatzen dute etxebizitzaren barne airearen tenperaturan. Aldameneko etxebizitzen berokuntza sistemaren errutinak ezagutzea ia ezinezkoa da eta (alboko etxebizitzak ez ziren neurtu), setpoint-eko balio konstantea hartu ziren simulazioak egiteko.

Berrogei parametro konbinazio edo simulatu ziren ereduan. Haietako azkenei buruzko xehetasun batzuk zerrendatzen dira 5.1. eranskinean.

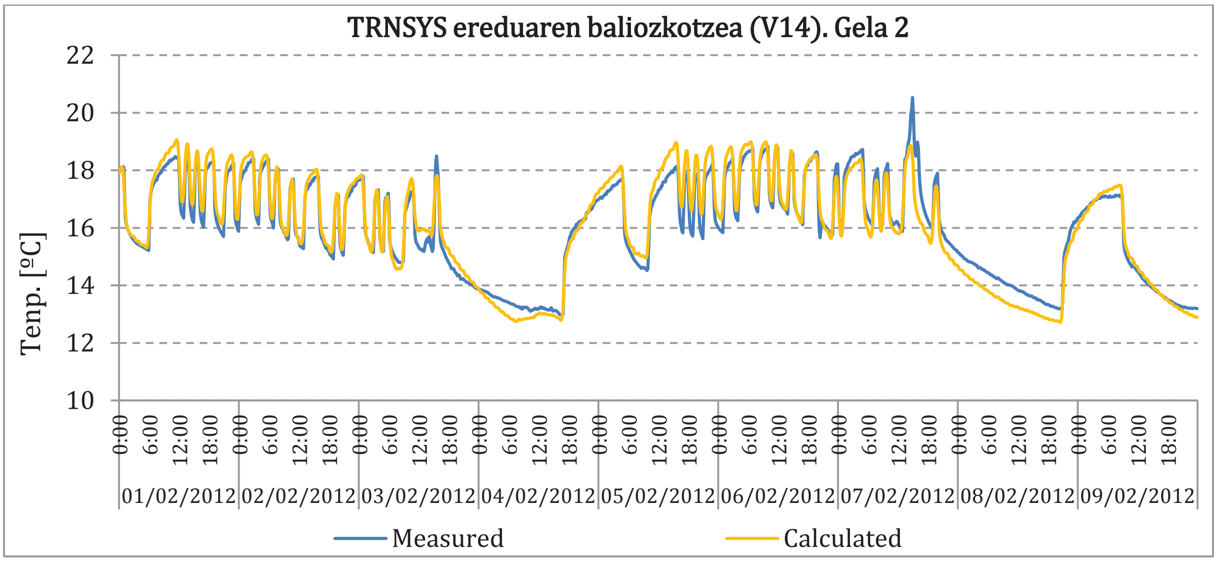
6.2 Emaitzen analisia

Barne airearen tenperatura adierazletzat hartu zen ereduak kalkulatutako balioak eta lehen monitorizazio epean neurtutako datuak elkarrekin konparatzeko. 5.2. eranskinean deskribatutako ereduaren egiaztapena etxebizitzaren nodo bakoitzaren tenperaturatan egin zen, baita etxebizitzaren batez besteko tenperaturan. Parametro - konbinazio bakoitzaren emaitzak 5.2. eranskinean aurkezten dira.

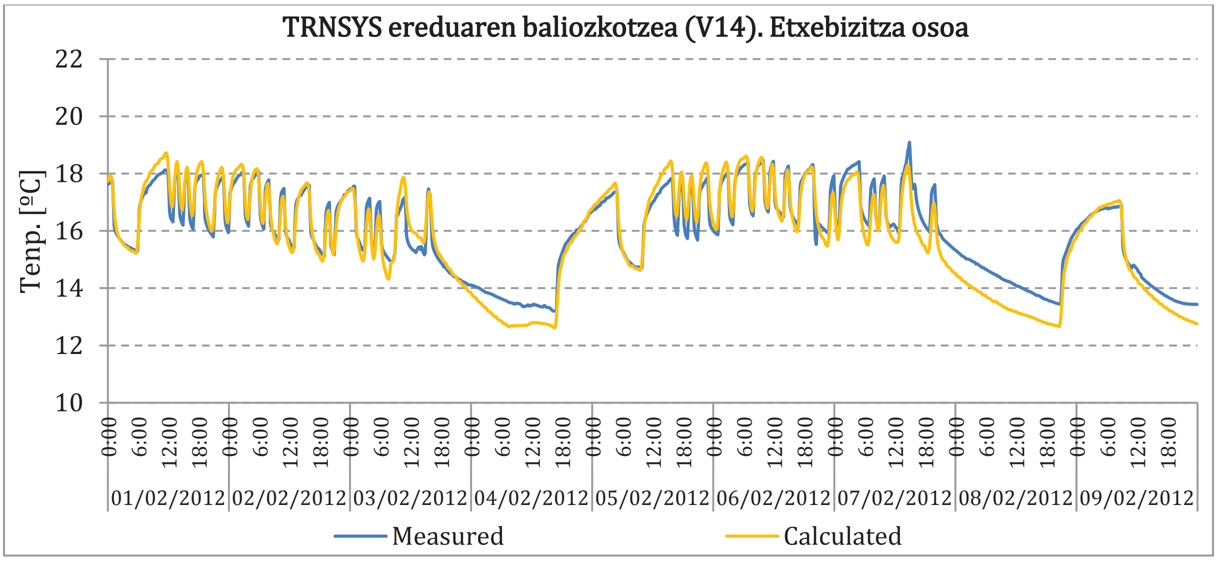
6.3 Hautatutako eredua

Aipatutako analisiari jarraituz, eredurik egokiena MV14 izan zen. Gela bateko neurtutako eta kalkulatutako tenperatura (kasu honetan, gela bikoa), eta etxebizitza osoko batez besteko tenperatura irudikatzen dira I5.13 eta I5.14 irudietan urrenez hurren.

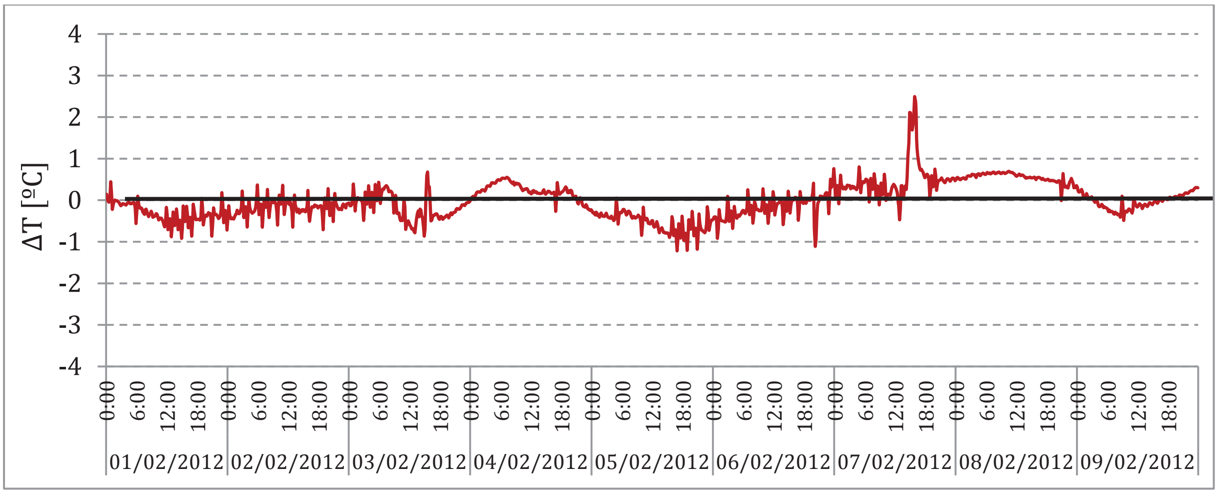
Parametro konbinazio ezberdinen hondarren analisiak egin ziren. Adibidez, hautatutako ereduaren gela 2an kalkulatutako balioen hondarra I5.15 grafikoan irudikatzen da. Nahiz eta hondarrek balio altuegiak erakutsi ez zituzten (Gela 2ren tenperaturen batez besteko hondarra 0.34 gradukoa da, eta etxebizitza osoarena, 0.39 gradukoa), alderdi batzuk argitu behar dira.



I5.13. Neurtutako eta kalkulatutako datuen arteko konparaketa gela 2an (MV14)

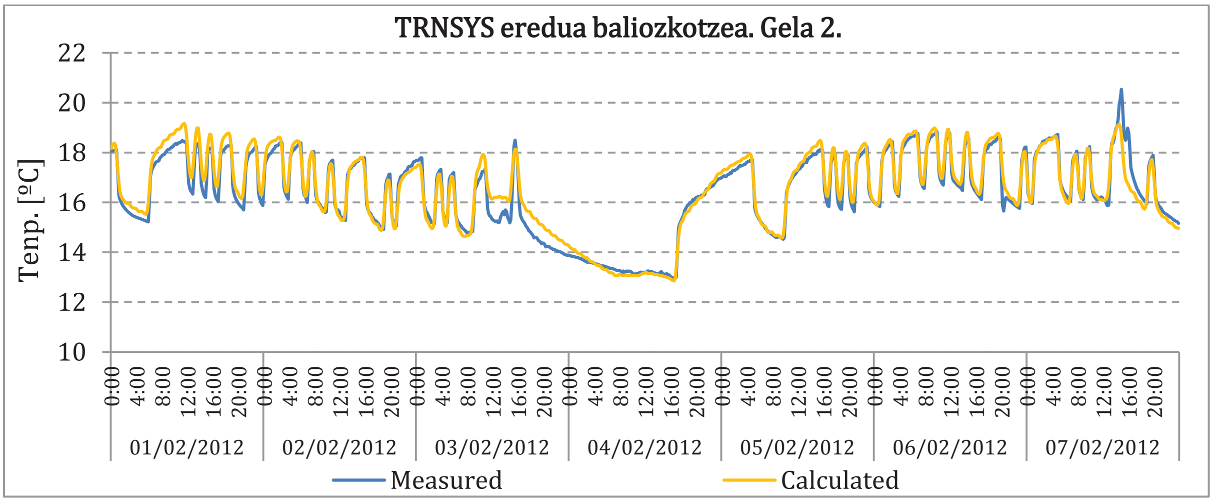


I5.14. Neurtutako eta kalkulatutako datuen arteko konparaketa etxebizitza osoan (MV14)

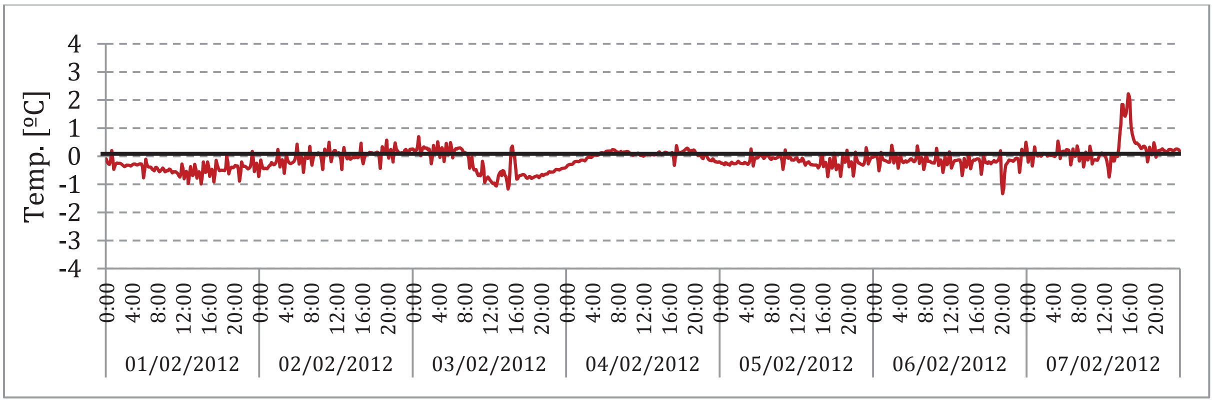


I5.15. MV14 ereduaren hondarra (Gela 2ren batez besteko tenperatura)

Alde batetik, Otsailaren 7an arratsaldean dagoen adostasunik eza zuzenezko eguzki - erradiazioaren une batekin aldi batera gertatzen da. Hau zuzenezko eguzki - erradiazioaren hartutako hipotesiak zehatz nahikoa ez zirenari lotuta egon daiteke. Puntu honetaz aparte, hondarrek 0 inguruko joera jarraitzen dute, nahiz eta egun batzuetan joera zero baino altuagoa zen (esaterako Otsailaren 4an) eta beste egun batzuetan, joera zero baino baxuagoa zen (esaterako Otsailaren 5ean eta 6an). Lehen aipatu bezala, alboko etxebizitzen erabilera - profilek rola garrantzitsu bat jokatzen dute aztertutako etxebizitzaren portaera termikoa, batik bat negualdian, eta hortaz, barne airearen tenperaturetan. Izan ere, hondar hauek murriztu daitezke beste setpoint tenperaturak alboko etxebizitzetan hartuz gero. Kasu honetan, gela 2 zehatz - mehatz aztertzean, goiko eta beheko etxebizitzen setpoint tenperaturak aldatzearen ondorioz, I5.16 irudian aurkeztutako doikuntza lortu zen. Hondarrak I5.17 grafikoan irudikatzen dira ere.



I5.16. Neurtutako datuak VS kalkulatutakoak (gela 2), alboko etxebizitzen setpoint tenperaturak aldatu eta gero



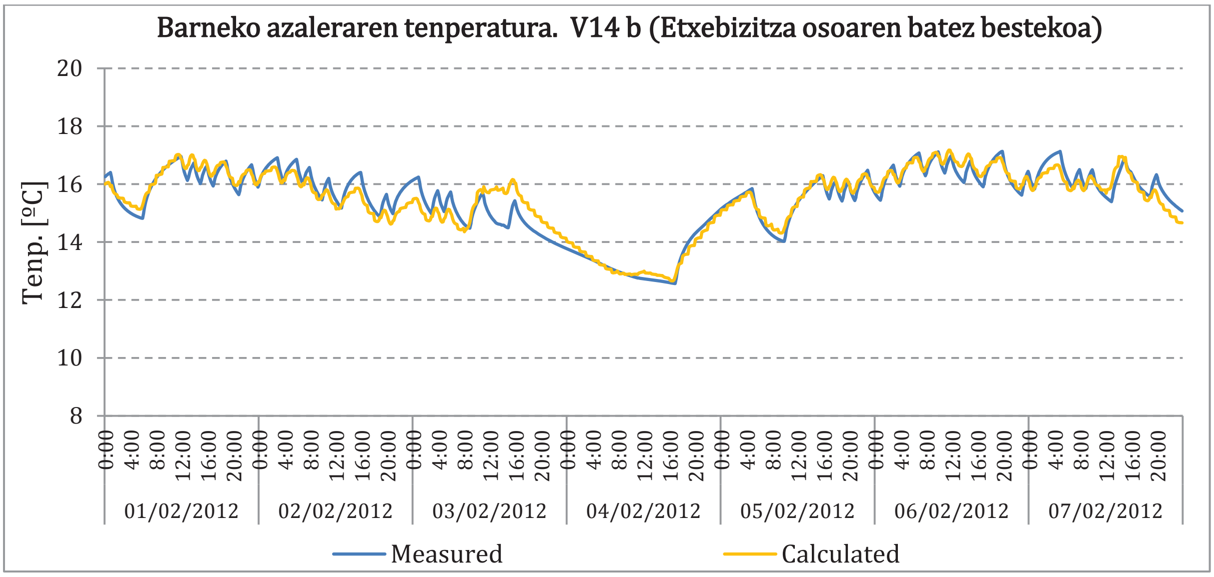
I5.17. I5.16 irudian irudikatutako datu - multzoaren hondarrak

Alboko etxebizitzen hartutako erabilera - profilak T5.15 irudian erakusten dira.

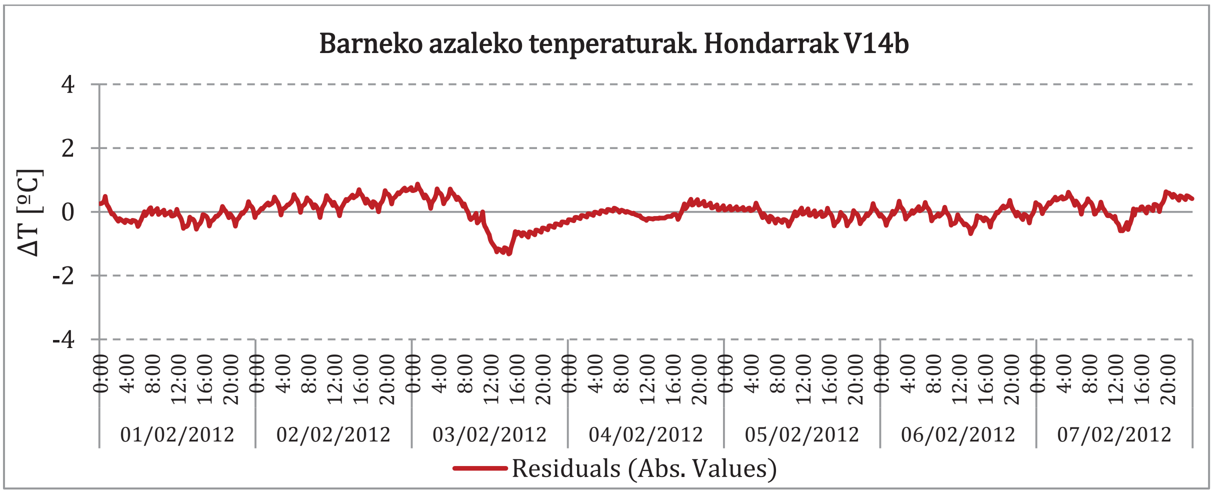
ºC	Al.	Aar.	Aaz.	Oste.	Osti. [0 - 8h]	Osti. [8 - 24h]	Lar.	Iga.
B1P5A	13.6	17.2	16	15.2	15.2	- (12)	16.8	- (12)
B1P3A	14	17.75	16.5	15.7	15.7	- (12.4)	17.3	- (12.4)
B1P4B	Berokuntza sistemarik gabe							

T5.15. Alboko etxebizitzen hartutako setpoint tenperaturak

Barne azaleko tenperaturak ere kalkulatu ziren, eta neurtutako datuekin konparatu ziren. Nahiz eta doikuntza hau ez zen barne airearen tenperaturetan lortutakoa bezain ona, hurbilketa on bat zela onartu daiteke, I5.18 irudian ageri denez. Haien hondarrak, bere aldetik, I5.19 grafikoan irudikatzen dira.



I5.18. Barneko azaleko tenperatura. Neurtutakoa Vs. Kalkulatutakoa



I5.19. Barneko azaleko tenperatura. Hondarrak

Beraz, aipaturiko ziurgabetasunak eta haien eraginak aztertutako etxebizitzaren portaera termikoan kontuan hartuz, neurtutako datuen eta simulazioen bidez lortutako datuen arteko hurbilketa bat on zela onartu daiteke. Ondorioz, ereduaren ezaugarri nagusia eta lortutako emaitzen zehaztasuna onargarritzat hartu ziren. Eraikin ereduan behin betiko hartutako balioak T5.16 taulan zerrendatzen dira.

	Gela 1	Gela 2	Gela 3	Egongela	Esk - kaxa
Infiltrazioa (Kanpotik) [ACH]	0.1	0.1	0.1	0.1	10
Ahalmena [kJ/K]	100	120	164	650	-
Infiltrazioa (Esk. kaxatik) [ACH]	-	-	-	0.26	-
Fatxadaren bero transferentziaren konbekzio - koefizientea [kJ/h.m^2.K]	24				

T5.16. Ereduan hartutako behin betiko parametroak

Ereduaren beste parametroak aurkeztu dira jadanik. Horrela, eraikuntzari buruzko datuak 4.1 atalean erakutsi da, aireztapeneko irizpideak 5.1 atalean aurkeztu dira, bareko bero - irabaziak 5.2. atalean xehatu dira, hartutako setpoint tenperaturak 5.3. atalean deskribatu dira, eta elektrizitatearen eta etxeko ur beroaren eskariak 5.4 eta 5.5 ataletan deskribatu dira, hurrenez hurren

7 Emaitzak

Eraikin osorako simulazioak egin ziren. Etxebizitzak izendatu ziren haien eraikinean kokapenaren arabera. Hortaz, I5.3 irudian ageri den bezala, aztertutako eraikinak 3 eskailera - kaxa dauzka, bina etxebizitza solairuko eskailera - kaxa bakoitzari lotuta. Lehen eskailera - kaxaren (eraikiaren hegoaldean) etxebizitzak "B1" identifikatzen dira, erdiko eskailera - kaxaren etxebizitzak, "B2", eta etxebizitzak iparraldeko eskailera - kaxari lotuta "B3" dira. Solairua kodearen hurrengo zatian erakusten da (esaterako, P1 lehenengo solairuan dagoela adierazten da). Azkenik, azken letra ea etxebizitza ezkerrean (A) edo eskuinean (B) dagoen adierazten da. Adibidez, B1P4A etxebizitza lehen eskailera - kaxan, laugarren solairuan eta ezkerrean kokatzen da.

Goian aipaturiko nomenklatura erabiliz, aztertutako eraikinaren 36 etxebizitzak T5.17 taulan aurkezten diren moduan izendatu ziren. Taula hau I5.2 irudikatutako aurretiko bistan gainezjarri daiteke. Hurrengo atalean (7.1 eta 7.2), A egoeraren emaitzak (bibliografian oinarritutako erabilera - profilak) eta B egoeraren emaitzak (landa - azterketan neurtutako datuetan oinarritutakoak) aurkezten dira.

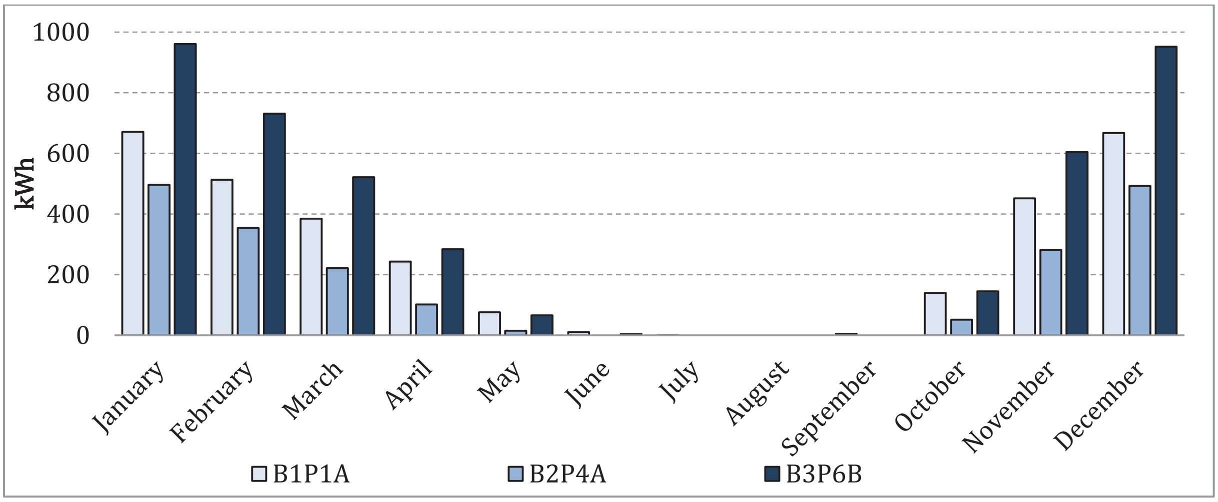
	Eskailera - kaxa 1 (B1)		Eskailera - kaxa 2 (B2)		Eskailera - kaxa 3 (B3)	
Solairua	**A**	**B**	**A**	**B**	**A**	**B**
6	B1P6A	B1P6B	B2P6A	B2P6B	B3P6A	B3P6B
5	B1P5A	B1P5B	B2P5A	B2P5B	B3P5A	B3P5B
4	B1P4A	B1P4B	B2P4A	B2P4B	B3P4A	B3P4B
3	B1P3A	B1P3B	B2P3A	B2P3B	B3P3A	B3P3B
2	B1P2A	B1P2B	B2P2A	B2P2B	B3P2A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

T5.17. 36 etxebizitzen nomenklatura

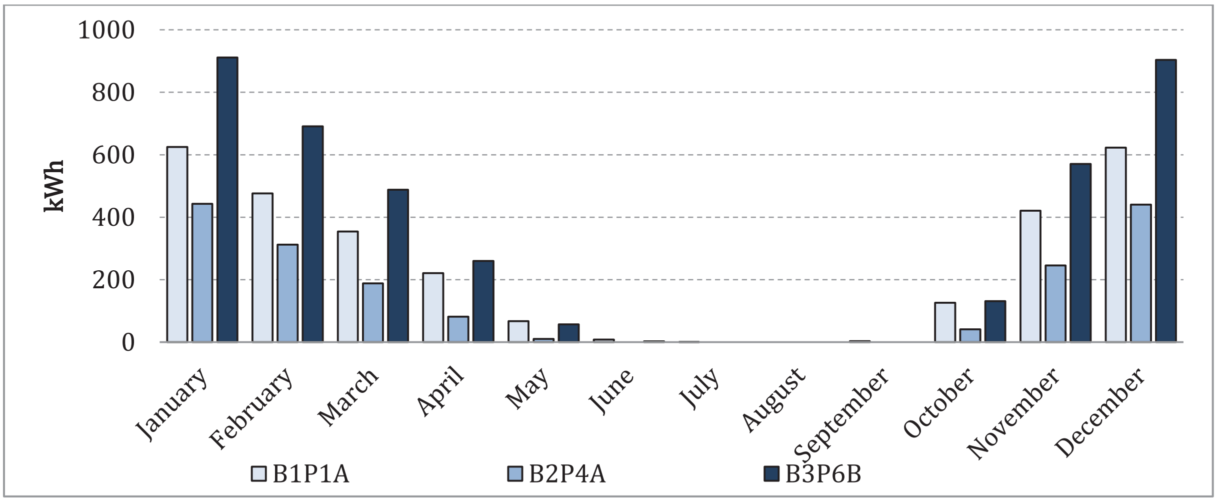
7.1 A Egoera. 6.1.1. eta 6.2.1. ereduak

Lehenik eta behin, eraikin osoaren bero - eskariak lortu ziren. Hiru etxebizitzaren hilabeteroko bero eskariak, leiho - aldaketaren aurretik eta ondoren, I5.20 eta I5.21 grafikoetan irudikatzen dira. Hiru etxebizitza hauek hautatu ziren haien kokapena eraikinaren barruan dela eta. Izan ere, etxebizitza bat lehen solairuan hegoaldeko partean dago (B1P1A), beste etxebizitza bat iparreko partean, azken solairuan dago (B3P6B), eta beste etxebizitza eraikinaren erdian dago (B2P4A). Espero den bezala, diferentzia nabarmengarriak haien arteko konparaketa egitean aurkitu ziren. Esaterako %50 inguruko diferentziak aurkitu ziren B2P4A (eraikinaren erdian kokatutako etxebizitza) eta B3P6B (azken solairuan kokatutakoa) elkarrekin konparatu ziren.

Leiho - aldaketari esker lortutako urteroko bero - eskariaren energia - aurrezteak T5.18 taulan erakusten dira. Energia - aurrezteko portzentajerik handiena lortu ziren erdiko solairuetan, bero galerak forjatuetan zehar oso txikiak direlako, eta horren ondorioz, etxebizitza horietan bero - galera gehienak leihoetan eta fatxadan zehar dira (Beraz, elementu hauen hobekuntzak energia - aurrezteetan askoz nabarmengarriak dira etxebizitza hauetan). Kalkulatutako bero - galerak, hala ere, oso antzekoak dira etxebizitza guztietan balio absolutuak elkarrekin konparatzen direnean.



I5.20. Hilabeteroko bero - eskariak leiho - aldaketaren aurretik. Bibliografian oinarritutako erabilera - profilak (6.1.1. eredua)



I5.21. Hilabeteroko bero - eskariak leiho - aldaketaren ondoren. Bibliografian oinarritutako erabilera - profilak (6.2.1. eredua)

[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
Aurrezteak	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%

T5.18. Urteroko bero - eskaria [kWh] eta aurrezteak (eskarian) etxebizitzako (bibliografian oinarritutako erabilera - profilak)

Azkenik, hilabeteroko energia - aurrezteak etxebizitza bakoitzean aztertu ziren erabilera - profil hauek erabiliz. Haietako bi kasu T5.19 taulan aurkezten dira. Orokorrean, murrizterik handienak Martxoan, Apirilean eta Urrian lortzen dira. Leiho - aldaketak epe hauetan berokuntza sistemaren pizketak murrizten dituzte ere. Honek, zeharka, gehigarrizko energia - kontsumoaren murriztea lortzen da (energia - kontsumoa hurrengo kapituluan aztertuko da), zeren eta berokuntza sistemaren pizketek sarritan energia - kontsumoaren punta bat ekartzen dute.

	B2P4A				**B3P6B**			
	Energia - eskaria [kWh]		**Aurrezteak**		**Energia - eskaria [kWh]**		**Aurrezteak**	
	6.1.1.	**6.2.1.**	**[kWh]**	**%**	**6.1.1.**	**6.2.1.**	**Savings**	**%**
URTARRILA	496.18	442.90	53.28	10.74%	960.87	911.40	49.48	5.15%
OTSAILA	354.31	312.25	42.05	11.87%	731.08	691.14	39.94	5.46%
MARTXOA	221.84	188.49	33.35	15.03%	521.56	488.16	33.40	6.40%
APIRILA	101.91	81.70	20.21	19.83%	284.00	259.85	24.15	8.51%
MAIATZA	15.50	10.29	5.20	33.57%	65.95	57.29	8.66	13.13%
EKAINA	0.00	0.00	NA	NA	4.36	2.86	1.50	34.37%
UZT – IRA	0.00	0.00	NA	NA	0.00	0.00	NA	NA
URRIA	51.72	41.13	10.59	20.47%	145.30	131.61	13.69	9.42%
AZAROA	282.08	245.66	36.42	12.91%	604.35	570.53	33.82	5.60%
ABENDUA	492.44	440.67	51.77	10.51%	951.66	903.57	48.08	5.05%

T5.19. Hilabeteroko bero - eskariaren murriztεak handiena eta txikiena daukaten etxebizitzetan

7.2 B Egoera. 6.1.2. eta 6.2.2. ereduak

Simulazioak egin ziren ere landa - azterketan neurtutako datuetan oinarritutako erabilera - profilak erabiliz. Hala ere, argiagoa izateko, kasu honetan, kasu - azterketa ez zen eraikin osoa, erreferentzia etxebizitza baizik. Nahiz eta bero - eskariak baxuagoa lortu, energia - aurrezteen balio erlatiboan oso antzekoak ziren, are handiagoak ziren landa - azterketan neurtutako datuetan oinarritutako erabilera - profilak erabili zeneko egoeran. Informazio hau T5.20 taulan laburbiltzen da.

Gizarte etxebizitzen erabilera - profilen antzekoak erabili zenean, energia - aurrezteen balio absolutuak baxuagoak zirela ikusten da, T5.20 taulan ageri den bezala. Kalkulatutako urteroko energia - aurrezteak bibliografian oinarritutako egoeraren profilak erabiliz 258.38 kWh ziren. Landa - azterketan neurtutako datuetan oinarritutako egoeraren profilak erabiliz, berriz, 150.1 kWh, %40 inguruko ezberdintasuna bi ereduen artean. Puntu honek erabileraren profilen garrantzitsua etxebizitzaren energia - kontsumoa kalkulatzean berriro erakusten du. Beraz, simulazioak egitean, egoeraren profil egokiak xehatzearen garrantzia azpimarratu behar da.

	EGOERA A				EGOERA B			
	Energia Kontsumoa [kWh]		Aurrezteak		Energia Kontsumoa [kWh]		Aurrezteak	
	6.1.1.	6.2.1.	[kWh]	%	6.1.2.	6.2.2.	[kWh]	%
URTARRILA	571.55	517.81	53.74	9.40%	320.56	283.36	37.20	11.60%
OTSAILA	413.43	370.61	42.82	10.36%	206.23	179.13	27.10	13.14%
MARTXOA	266.27	232.38	33.89	12.73%	97.89	81.36	16.53	16.89%
APIRILA	131.74	110.06	21.69	16.46%	32.60	25.89	6.71	20.59%
MAIATZA	22.85	17.17	5.68	24.84%	0.23	0.00	0.23	100.00%
EKAINA	0.04	0.00	0.04	100.00%	0.00	0.00	NA	NA
UZT – IRA	0.00	0.00	NA	NA	0.00	0.00	NA	NA
URRIA	63.17	51.99	11.18	17.70%	17.67	14.09	3.58	20.27%
AZAROA	329.59	292.70	36.89	11.19%	158.27	136.14	22.13	13.98%
ABENDUA	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%

T5.20. Hilabeteroko bero - eskariaren kalkulatutako murrizteak erreferentzia etxebizitzan (B1P4A), hartutako erabilera - profilen arabera

Hala eta guztiz ere, aurretiko kapituluetan aipatu den bezala, soilik energia - aurrezteak ez dira kontuan hartzen birgaitze energetikoak, baizik eta barne erosotasun termikoan ere, batik bat gizarte etxebizitzetan. Tesi honen hirugarren kapituluan aipatu den bezala, gizarte etxebizitzetan energia - kontsumoa estandarrak baino baxuagoa da, eta horregatik, birgaitze energetikoen eraginak etxebizitza hauetan ez dira erabilera - profil estandarrak daukaten etxebizitzan daudenak bezain nabarmengarriak, zeren eta erosotasun termikoa gizarte etxebizitzetan sarritan baxuagoa da. Beraz, kasu hauetan batez ere, erosotasun termikoan hobekuntzetan arreta jartzen behar da. Bestela, soilik alderdi ekonomikoak edo energetikoak kontuan hartuz gero, birgaitze energetikoak gizarte etxebizitzetan oportunitatetzat hartzea identifikatzea zaila izango da.

Bestalde, barne erosotasun termikoaren egoerak ia bermatzen dira bibliografian oinarritutako erabilera - profilak hartuz, landa - azterketan neurtutako datuetan oinarritutako erabilera - profilak hartzean ez bezala. Beraz, barne erosotasun termikoa kontuan hartu behar da edozein birgaitze energetikoan, eta batez ere gizarte etxebizitzen kasuetan.

Erosotasun termikoa ebaluatu zen ere landa - azterketan neurtutako datuetan oinarritutako erabilera - profilak erabili zeneko simulazioan lortutako emaitzak aztertu zirenean, erreferentzia etxebizitzan arreta jarriz (B1P4A). Hautatutako erosotasun termikoaren heinak hirugarren kapituluan (baita [55] erreferentzian ere, hirugarren kapituluan aipatuta) erakutsi direnak dira. Beraz, muga 16 graduan finkatu zen. Balio hau aintzakotzat hartuz, bi egoeretan (birgaitzearen aurretikoa eta ondorengoa) erreferentzia etxebizitzan lortutako emaitzen arteko konparazio bat egin zen, hilabeteroko balioak eta etxebizitzan 16 gradu baino gutxiago daudeneko ordu kopuruak T5.21 eta T5.22 tauletan aurkezten dira hurrenez hurren.

[Ordu kopurua]	Egongela	Gela1	Gela2	Gela3	Batez Bestekoa
URTARRILA	99	34	64	32	68
OTSAILA	70	31	42	20	44
MARTXOA	43	17	32	12	30
APIRILA	12	2	12	2	8
MAIATZA	1	0	1	0	0
EKA –IRA	0	0	0	0	0
URRIA	2	0	1	0	2
AZAROA	44	14	33	9	28
ABENDUA	98	33	57	30	64
NEGUKO TOTALA (AZA - API)	366	131	240	105	242

T5.21. Etxebizitzan 16 Gradu baino gutxiago daudeneko ordu kopurua (1. Egoera. 6.1.2. Eredua)

[Ordu kopurua]	Egongela	Gela1	Gela2	Gela3	Batez Bestekoa
URTARRILA	86	31	49	23	55
OTSAILA	56	29	36	13	39
MARTXOA	33	15	30	10	25
APIRILA	10	2	7	1	5
MAIATZA	0	0	0	0	0
EKA –IRA	0	0	0	0	0
URRIA	2	0	0	0	0
AZAROA	36	9	22	5	19
ABENDUA	80	30	46	20	50
NEGUKO TOTALA (AZA - API)	301	116	190	72	193

T5.22. Etxebizitzan 16 Gradu baino gutxiago daudeneko ordu kopurua (2. Egoera. 6.2.2. Eredua)

Beste balio batzuk aztertu ziren ere, esaterako hilabeteroko batez besteko tenperatura eta tenperatura minimoa. Balio estatistikoak T5.23 eta T5.24 tauletan aurkezten dira. Hilaberoko batez besteko tenperatura aztertzean, hobekuntza txikiak aurkitu ziren.

	Batez Bestekoa	Tenp. Min.	Desbiderapen estandarra	16 gradutik azpitik ordu (%)
URTARRILA	17.84	12.16	1.48	%9.1
OTSAILA	18.09	12.86	1.49	%6.5
MARTXOA	18.96	13.48	1.72	%4.0
APIRILA	20.28	15.00	2.01	%1.1
MAIATZA	23.81	16.22	3.34	%0.0
URRIA	22.03	15.80	2.64	%0.3
AZAROA	18.45	14.05	1.32	%3.9
ABENDUA	17.84	12.43	1.44	%8.6
NEGUKO TOTALA (AZA - API)				%5.6

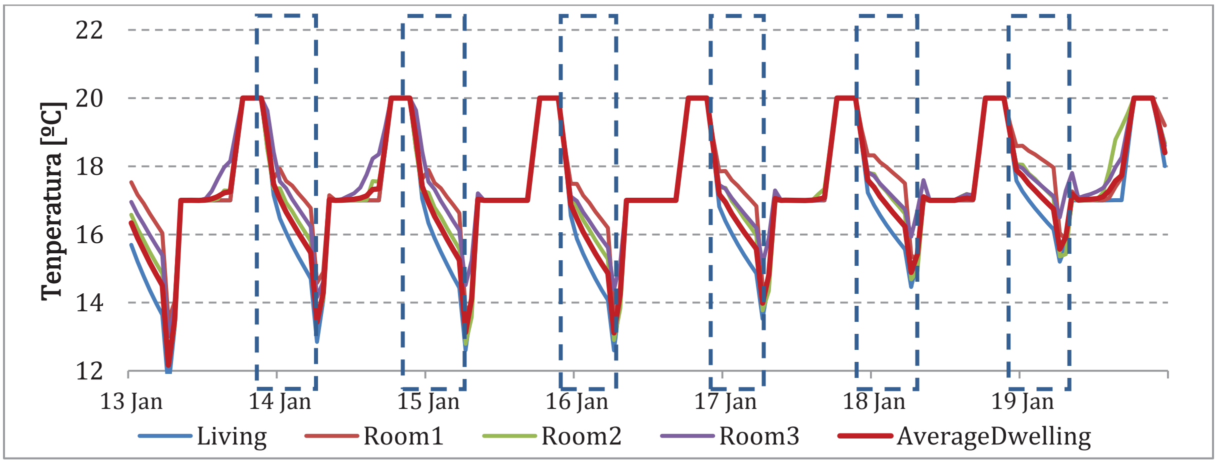
T5.23. Etxebizitzan birgaitzearen aurretik lortutako tenperaturen balio estatistikoak (6.1.2. Eredua)

	Batez Bestekoa	Tenp. Min.	Desbiderapen estandarra	16 gradutik azpitik ordu (%)
URTARRILA	17.96	12.55	1.43	%7.4
OTSAILA	18.23	13.27	1.44	%5.8
MARTXOA	19.16	13.81	1.68	%3.4
APIRILA	20.57	15.37	1.98	%0.7
MAIATZA	24.10	16.51	3.31	%0.0
URRIA	22.29	16.10	2.60	%0.0
AZAROA	18.59	14.36	1.27	%2.6
ABENDUA	17.95	12.79	1.39	%6.7
NEGUKO TOTALA (AZA - API)				%4.4

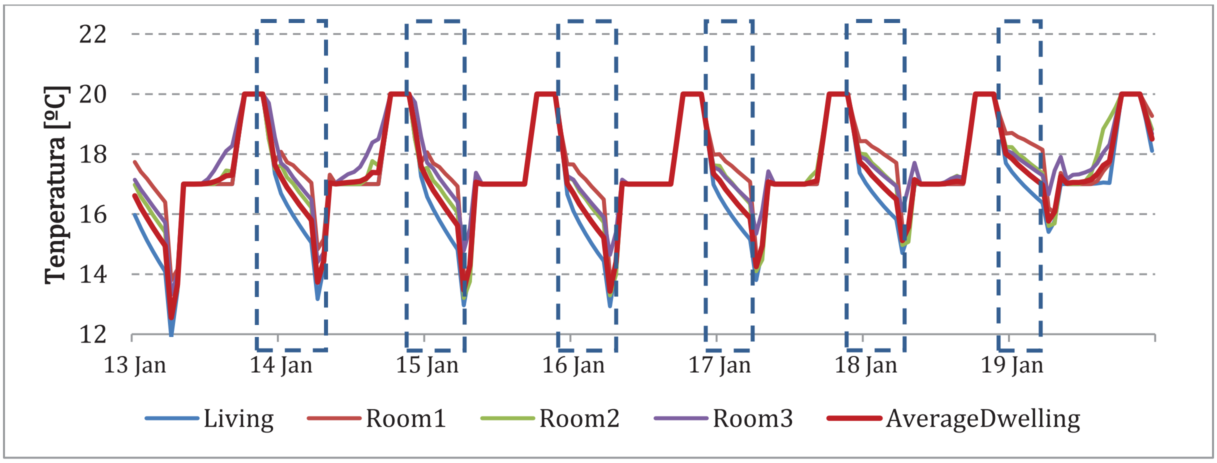
T5.24. Etxebizitzan birgaitzearen ondoren lortutako tenperaturen balio estatistikoak (6.2.2. Eredua)

Azkenik, landa - azterketan neurtutako datuetan oinarritutako emaitzen eta bibliografian oinarritutakoen arteko konparaketa kualitatibo batzuk egin ziren. Bero - eskariak (eta ez berorako energia - kontsumoa) aztertu zen, hau da, une bakoitzean, setpointean finkatutako tenperatura lortzeko energia kopuru zehatz hornitzen duen berokuntza sistema ideal bat hartzen da. Horregatik, neguan neurtutako balioak aztertzean, analisi hau setpoint finkatzen tenperaturarik ez zen epeetan (gauaz) baino ez zen arreta jarri, eta eraikinak eraikin astable bat bezala egiten du.

Tenperatura astableak eraikinaren barne tenperatura kanpoko giroarekin oreka termikoan ez berokuntza ezta hozte sistemarik ere erabiltzen ez denean erakusten du. Negualdian zeuden tenperatura astablearen (hau da, 0 - 8 am) analisi bat egin zen. Helburu honekin, aste hotz bat aukeratu zen azterketa hau egiteko, hain zuzen ere urtarrilaren 13tik 19ra (I5.22eta I5.23 irudietan irudikatuta).



I5.22. 6.1.2 ereduak kalkulatutako barne airearen tenperatura [ºC]



I5.23. 6.2.2 ereduak kalkulatutako barne airearen tenperatura [ºC]

Bi azpi - epe ezberdinak bereizten dira aipatutako epean: lehena, gaueko hamabitik goizeko zazpitara; bigarrena, goizeko zazpitatik goizeko zortzitara, aireztapen tasa bat hartzen deneko ordua dena. Zazpietan zegoen barne airearen tenperaturan arreta berezia jarri zen, aireztapen tasa hastean eta berokuntza erabilerarik ez zazpi ordu ondoren. Orokorrean, ordu horretan lortutako tenperaturak leiho - aldaketaren ondoren ordu horretan lortutakoak leiho - aldaketaren aurretik baino 0.5 gradu inguru altuagoak ziren.

7.3 Bi egoeren arteko konparaketa

Lehen aipatu bezala, bi egoeren arteko diferentziarik handiena bero - eskariaren balio absolutuak aztertzean aurkitu zen. T5.20 taulan ageri den bezala, landa - azterketan oinarritutako erabilera - profilak erabiltzearen bidez kalkulatutako bero - eskaria bibliografian oinarritutakoaren bidez kalkulatutakoak baino %40 baxuagoak ziren. Leiho - aldaketaren aurretiko egoeraren bero - eskaria landa - azterketan oinarritutako erabilera - profilak hartuz, leiho - aldaketaren aurretikoarena bibliografian oinarritutakoak hartzearen %57.3 izan zen; birgaitzearen ondoren, %56 izan zen. Egoera antzekoa aurkitu zen energia - aurrezteen balio absolutuen arteko konparaketak egitean.

Alderantziz, energia - aurrezteen balio erlatiboak elkarrekin konparatzean, bi kasu antzekoak ziren, hartutako erabilera - profilak edonolakoa zirela ere (9.22% eta 11.23%, T5.20 taulan ageri den bezala)

8 Ondorioak

Baliozkotzerako prozesuak kasu - azterketa etxebizitza bat denean kontrolatu ezin diren aldagaien (esaterako alboko etxebizitzen erabilera - profilak) eragin handia erakutsi zuen. Arazo hau sarritan murrizten (are eta mespretxagarria bihurtzen) da kasu - azterketa eraikin bat izatekotan (eta horren ondorioz, mugalde - baldintzen informazioa lortzea askoz errazagoak da, egoera klimatikoaren informazioa, adibidez).

Aukeratutako erabilera - profilen eragina energia - aurreztearen emaitzetan nabarmengarria da ere, 7.3. atalean aipatu bezala. Alderdi hau ez da adierazgarria helburu nagusia birgaitze energetikorako estrategia ezberdinen eraginak elkarrekin konparatzea denean, zeren eta energia - aurrezteen lortutako balio erlatiboak oso antzekoak ziren bi hipotesitan. Ordea, ezberdintasun hauek kontuan hartu behar dira balio absolutuak elkarrekin konparatuz gero, esaterako berreskuratze - denborak kalkulatzean, edo produktuaren bizi - zikloaren azterketak (BZA) egitean. Kasu hauetan, erabilera - profilak ahalik eta errealaren antzekoagoak hartzea emaitza zehatzagoak lortzearren faktore giltzagarria da.

Beraz, nahiz eta etxebizitza bakoitzaren erabilera - profilak biztanleen arabera izan, eta horren ondorioz, biztanleen portaera zein izango den ezagutzea ez da posiblea askotan, erabilera - profil estandar batzuk xehatzea posiblea da, biztanleen profil ezberdintasunen talde - sailkapen baten arabera, batik bat biztanle sektore espezifiko bat aztertuz gero (tesi honen kasuan, gizarte etxebizitza). Lagin txikia izanda ere (hamar etxebizitza soilik), hirugarren kapituluan sektore honen biztanle arruntaren erabilera - profilen eta IDAE-k proposatutako profil estandarren arteko diferentziak erakutsi ziren.

Azkenik, tesi honetan erakutsi bezala, landa - azterketan neurtutako datuetan oinarritutako erabilera - profilak erabiltzearen bidez lortutako energia - aurrezteak espero denak baino balio txikiagoak izan daitekeela azpimarratu behar da. Hala ere, hau ez da oztopo bat izan behar gizarte etxebizitzetan birgaitze energetikoak egiteko. Ostera, tesi honen lehen kapituluetan jadanik aipatu bezala, birgaitze energetikoak irizpide anitzeko ikuspegi batetik aztertu behar dira, hau da, alderdi ekonomiko edo energetikoak ez kontuan hartu soilik, baizik eta alderdi sozialak eta osasunari lotutakoak (barne erosotasunari lotutakoak, nolabait) ere.

9 Aipatutako eranskinak

5.1. Eranskina: Ereduen parametroen konbinazioa.

5.2. Eranskina: Baliozkotutako ereduaren emaitzen analisia.

CHAPTER 6

GREY BOX MODEL BASED IN RC – NETWORK. MODEL DEFINITION.

LABURPENA

Kapitulu honetan RC ereduaren garapena erakusten da. Eredu honek laugarren kapituluan xehatutako erreferentzia – etxebizitzaren portaera termikoa irudikatzea du helburu. Eredua aipatutako kapituluan zehaztutako lehen monitorizazioaren bidez lortutako datuak (hau da, birgaitze egin aurretik bildutako datuak) erabiliz garatzen da.

Beraz, RC ereduen erabilerari buruzko sarrera labur bat aurkezten da lehenik. Bigarrenez, jarraitutako ikuspegia eta ereduaren diseinua deskribatzen dira, baita bere oinarri matematikoak ere. Gero, ereduaren lortutako parametro karakteristikoak erakusten dira, eta parametro hauek barne hartu ondoren ereduaren erabilera zehazten da. Geroago, baliozkotze – prozedura erakusten da, eta eredua erabiltzen da aurretiko kapituluan erabilitako base kasua simulatzeko. Gero, bi ereduen bidez lortutako emaitzak (TRNSYS eta RC ereduak) elkarrekin konparatzen dira. Ondorioak, bai kapitulu honen ondorioak, baita tesi honen hirugarren atal osoarenak ere, zerrendatzen dira.

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.

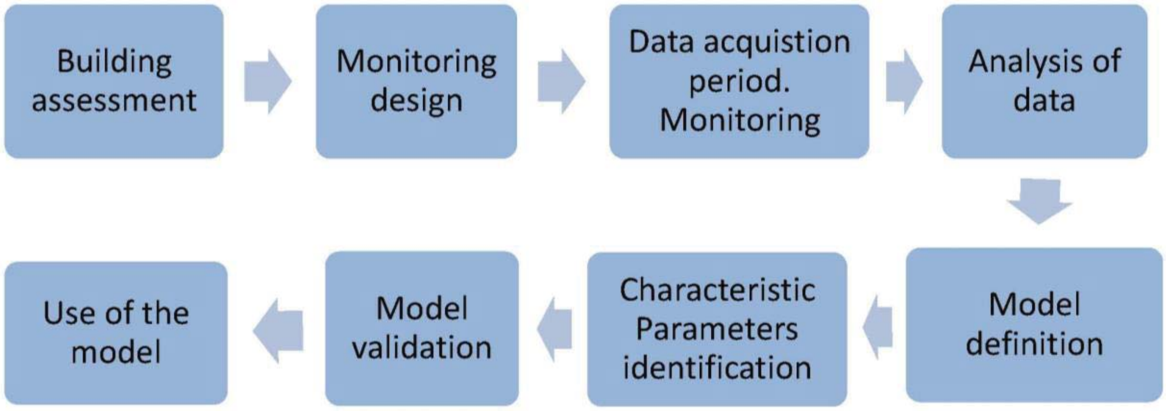


Fig. 6. 1. Steps followed to develop the RC Model of the reference dwelling

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 ($A, B\ldots$), 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.

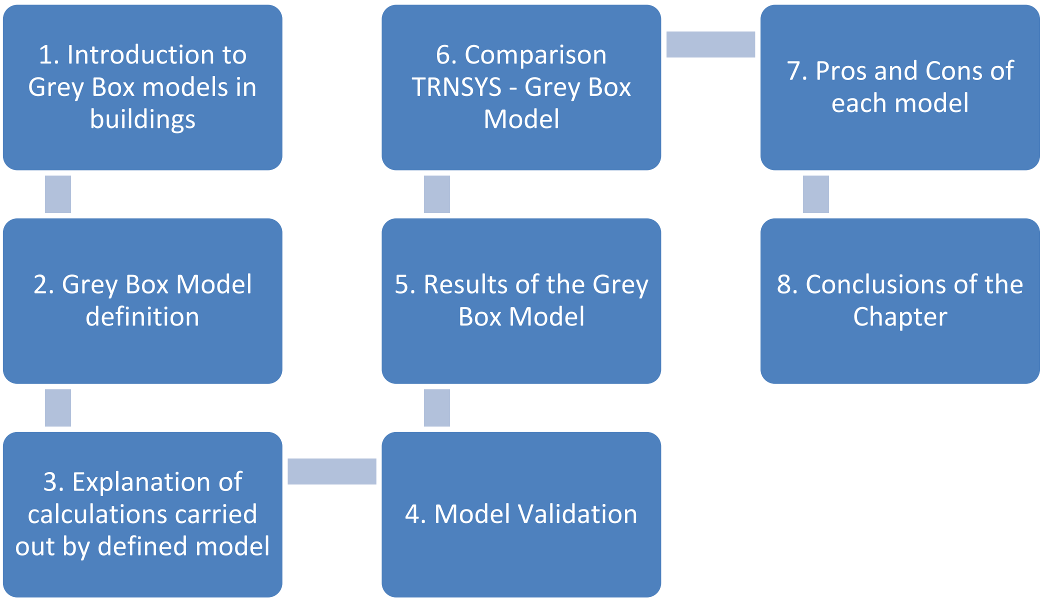


Fig. 6. 3. Structure of the chapter

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).

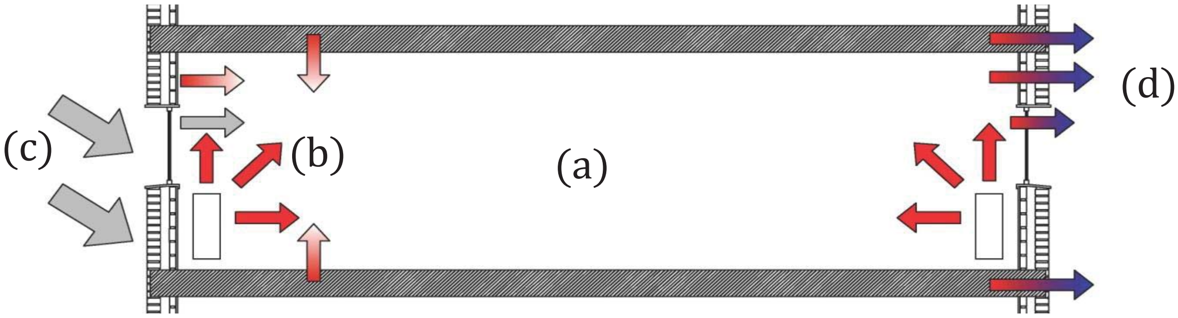


Fig. 6. 4. Single sketch of heat flux in dwellings

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.

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.

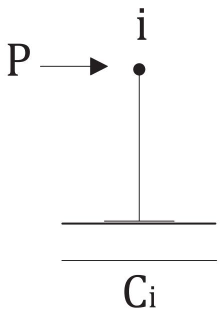


Fig. 6. 5. Single model encompassed by a node I with an excitement P and a capacity C

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.

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

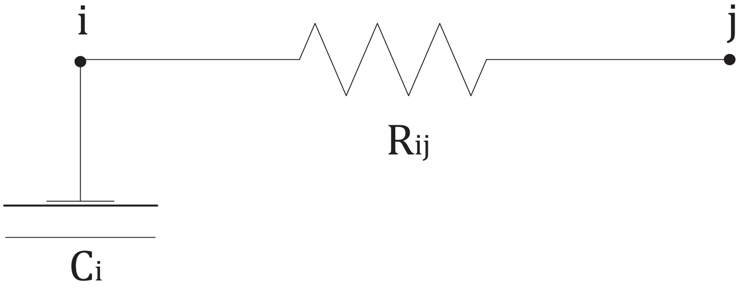


Fig. 6. 6. RC model formed by one resistor and one capacity

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-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-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-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.

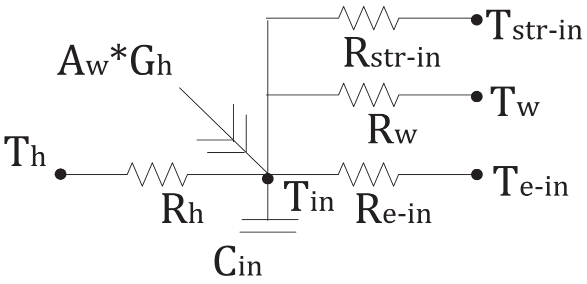


Fig. 6. 7. RC model formed by one resistor and one capacity

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.

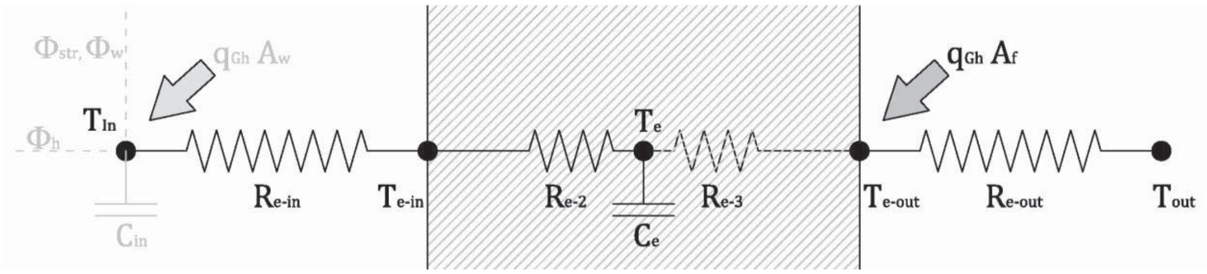


Fig. 6. 8. Façade branch of the developed model

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 $q_{gh}A$) branch can be handled in an analogous way. A scheme of the window branch is depicted in Fig. 6. 9.

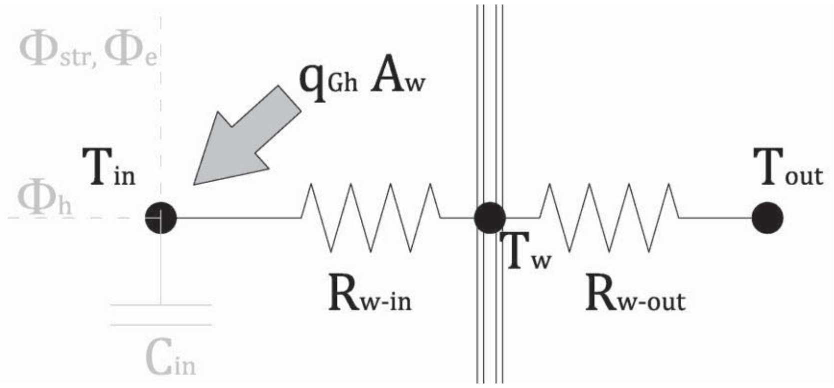


Fig. 6. 9. Windows branch of the developed model

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.

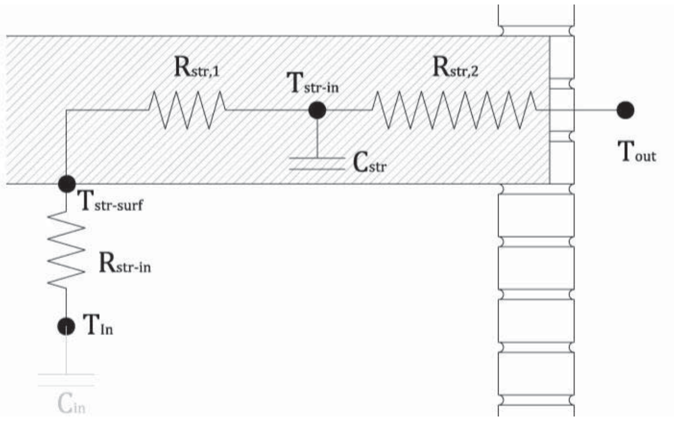


Fig. 6. 10. Structure branch of the developed model

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.

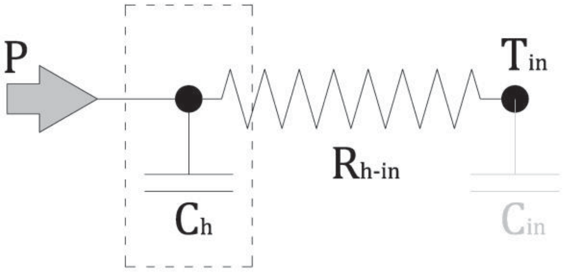


Fig. 6. 11. RC network representing the heat flux from the heating system to indoor air

The balance the heater node can be expressed as follows:

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

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].

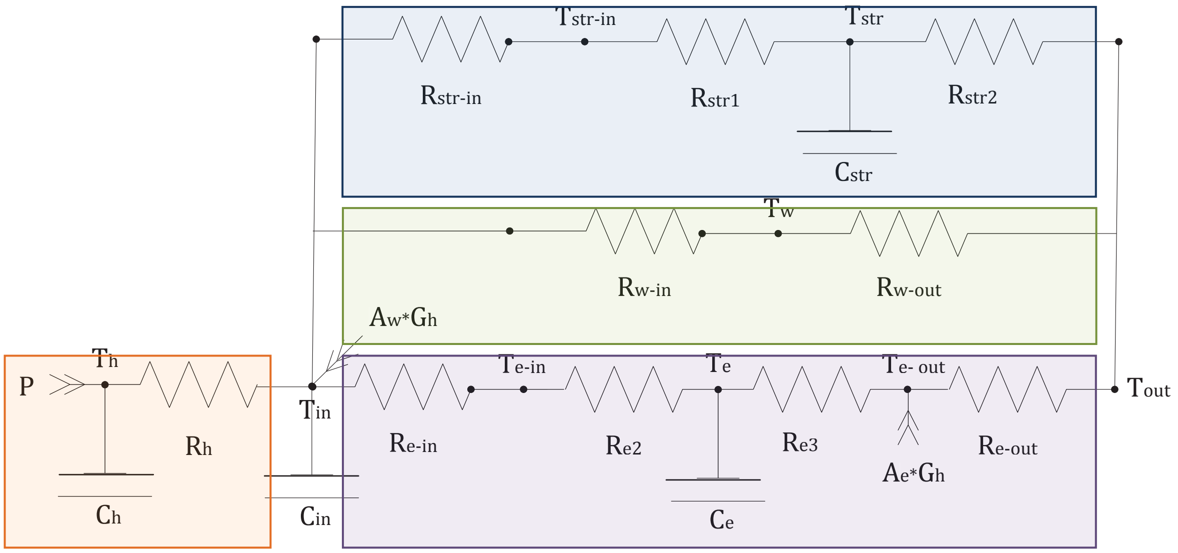


Fig. 6. 12. RC network of the selected model, with the different branches highlighted

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-in}, R_{str2}, R_{w1}, R_{w2}, R_{e-in} and R_{e-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].

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

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:

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

$$dT_e = \frac{1}{C_e(R_{e-in} + R_{e2})}(T_{in} - T_e)dt + \frac{1}{C_e(R_{e-out} + R_{e3})}(T_{out} + A_e G_h R_{e-out} - T_e)dt + \sigma_e d\omega_e \quad \text{Eq. 23}$$

$$dT_{str} = \frac{1}{C_{str}(R_{str-in} + R_{str1})}(T_{in} - T_{str})dt + \frac{1}{C_{str}R_{str2}}(T_{out} - T_{str})dt + \sigma_{str} d\omega_{str} \quad \text{Eq. 24}$$

$$dT_h = \frac{1}{C_h}Pdt + \frac{1}{C_h R_h}(T_{in} - T_h)dt + \sigma_h d\omega_h \quad \text{Eq. 25}$$

Together to these equations, steady state equations are used to calculate intermediate nodes which have no C assumed, based on Eq. 26.

$$\phi_{ij} = \left(T_i - T_j\right) \cdot H_{ij} \quad \text{Eq. 26}$$

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:

$$T_{i,k}^{m} = T_{i,k} + e_k \quad \text{Eq. 27}$$

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.

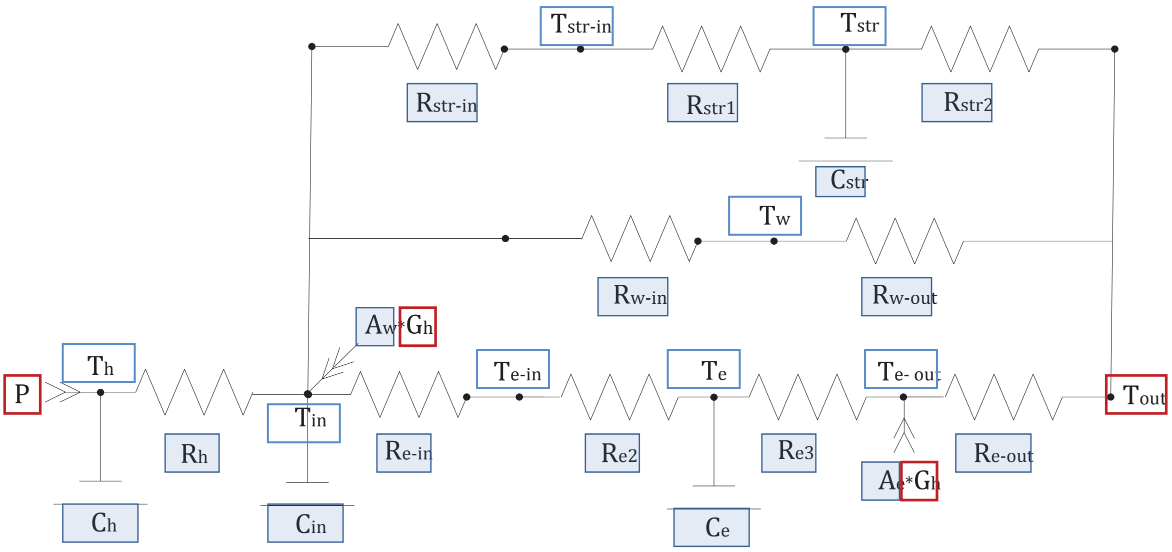


Fig. 6. 13. RC network of the developed model, with different highlights for its x, y and $f_{(x)}$

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.

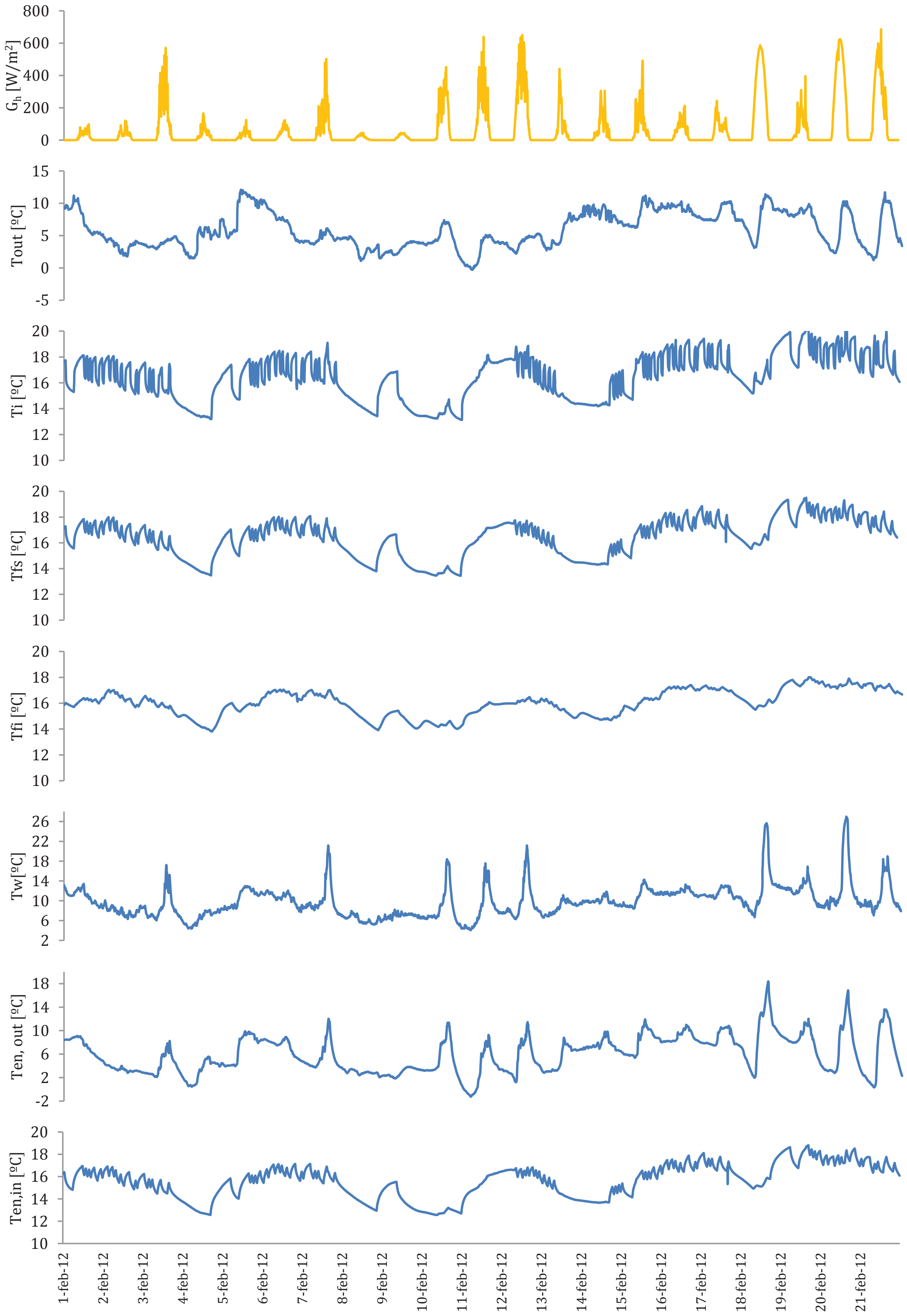


Fig. 6. 14. Some plots of the data used for defining the grey box model (1st - 21st Feb 2012)

- T_{str-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-in} and T_{e-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-in} and R_{w-out}). R_{w-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-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-out}, T_{str-in}, T_{e-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.

$$0 = C_h \cdot \frac{\left(T_h - T_{h,-1}\right)}{\Delta t} - P + (T_h - T_{in}) \cdot H_h \qquad \text{Eq. 31}$$

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.

$$0 = C_{str} \cdot \frac{\left(T_{str-in} - T_{str-in,-1}\right)}{\Delta t} - (T_{in} - T_{str-in}) \cdot H_{str(in,1)} + (T_{str-in} - T_{out}) \cdot H_{str,2} \qquad \text{Eq. 32}$$

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.

$$0 = C_e \cdot \frac{\left(T_e - T_{e,-1}\right)}{\Delta t} - (T_{in} - T_e) \cdot H_{e,(in,1)} + (T_e - T_{out}) \cdot H_{e,(2,out)} - A_2 \cdot G_h \qquad \text{Eq. 33}$$

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}.

$$T_{e,out} = \frac{(T_e \cdot H_{e3}) + (T_{out} \cdot H_{e-out}) + (A_2 \cdot G_h)}{(H_{e3} + H_{e-out})} \qquad \text{Eq. 34}$$

6.3.6 Structure temperature (T_{str})

The same procedure is used to calculate the temperature in this node, as presented in Eq. 35.

$$T_{str} = \frac{(T_{in} \cdot H_{str-in}) + (T_{str-in} \cdot H_{str1})}{(H_{str-in} + H_{str1})} \qquad \text{Eq. 35}$$

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)

$$T_w = \frac{\left(T_{in} \cdot H_{w,in}\right) + \left(T_{out} \cdot H_{w,out}\right)}{\left(H_{w,in} + H_{w,out}\right)} \quad \text{Eq. 37}$$

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.

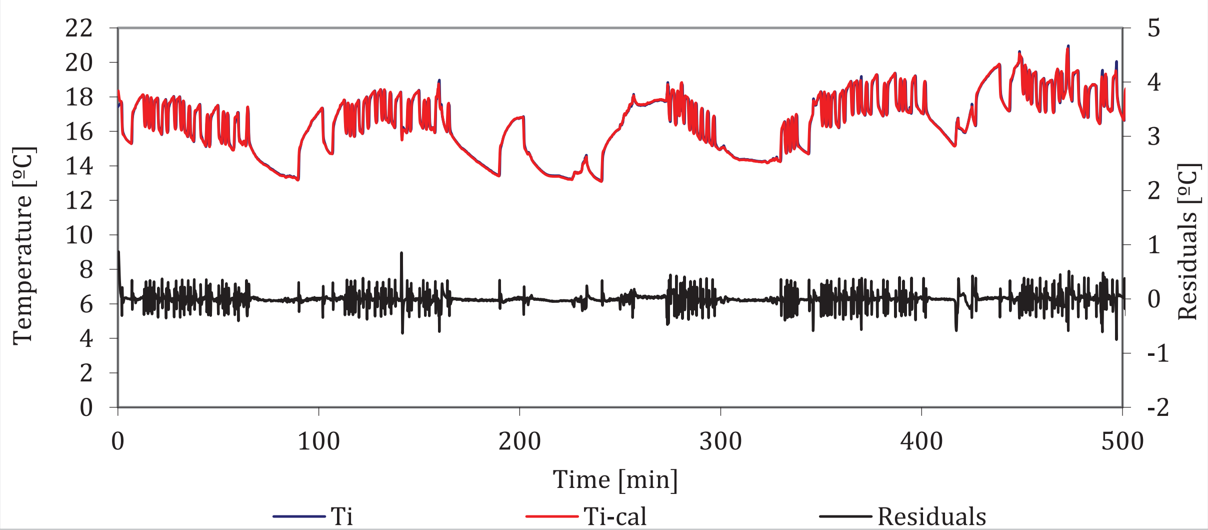


Fig. 6. 15. Indoor temperature calculated (red) Vs. observed (blue), and residuals (black)

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.

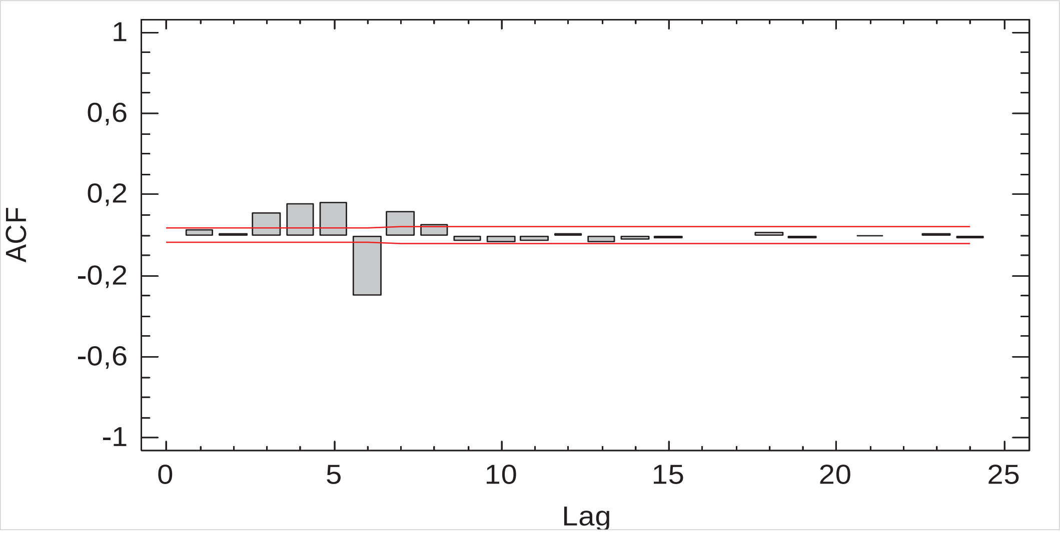


Fig. 6. 16. Autocorrelation Function (ACF) of residuals

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.

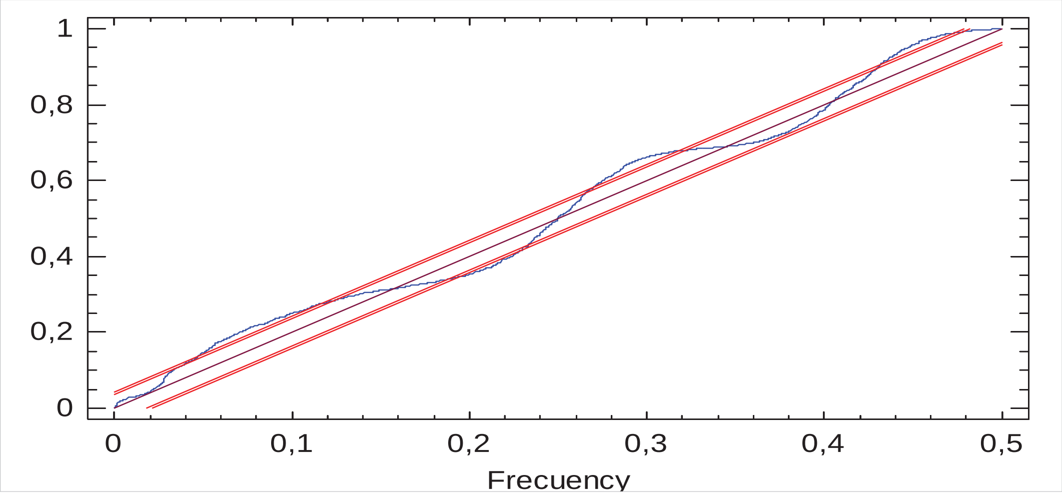


Fig. 6. 17. Cumulated periodogram of residuals

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^2K/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^2K/W, and the external surface thermal resistance of 0.04 m^2K/W, it can be deduced that the global thermal resistance of the windows equal to 0.19231 m^2K/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.

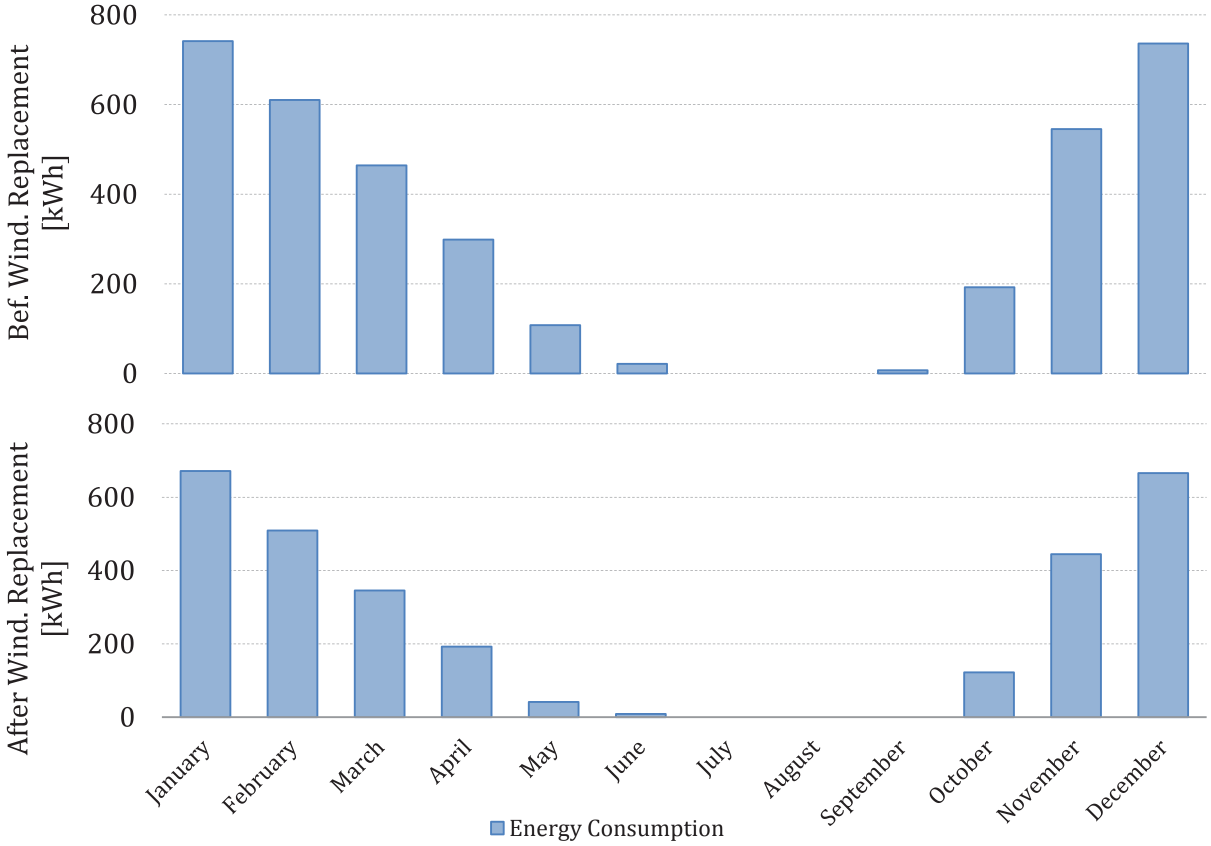


Fig. 6. 18. Energy consumptions obtained by the RC model for both scenarios

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.

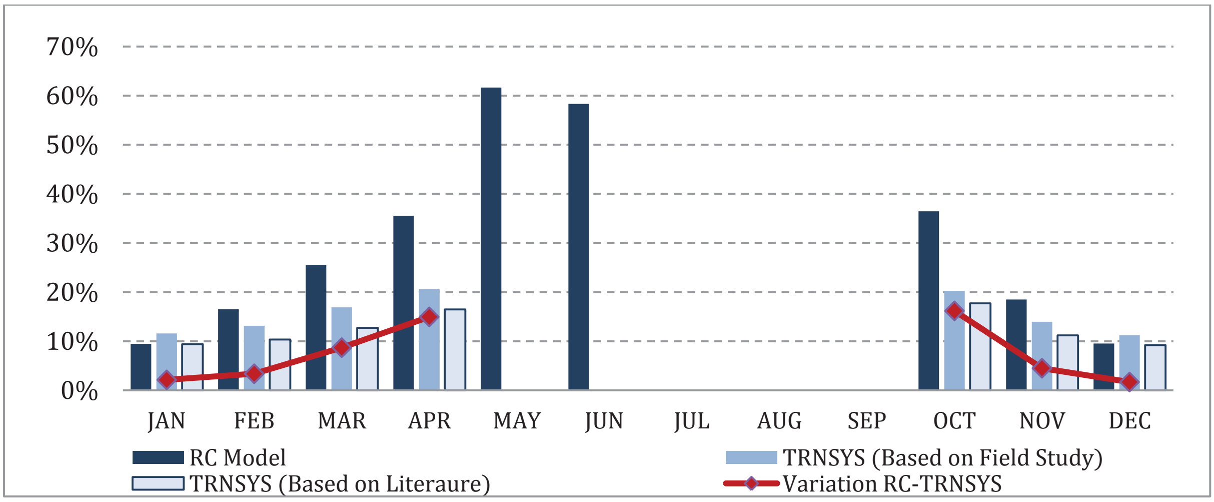


Fig. 6. 19. Percentage of energy saving obtained by the carried out different simulations

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.

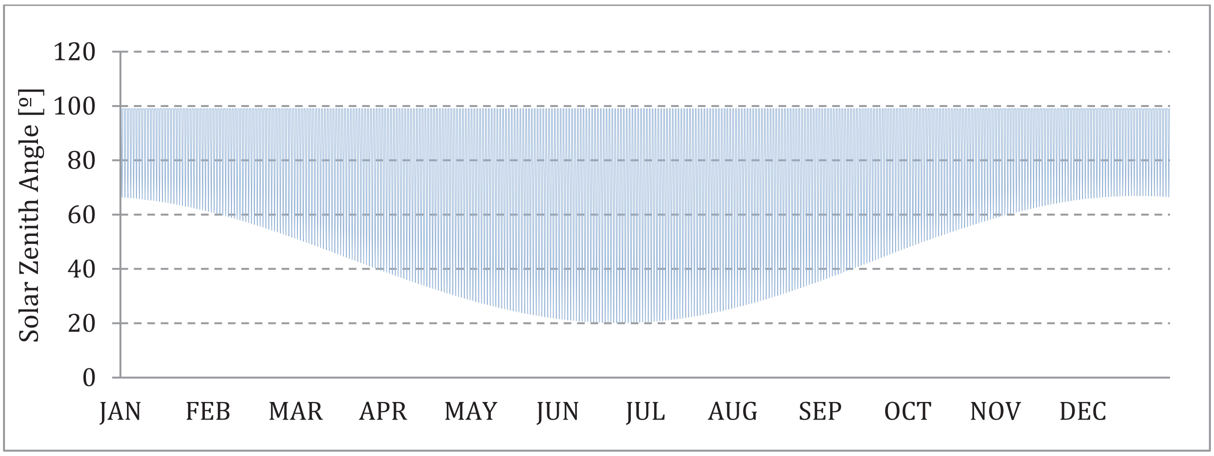


Fig. 6. 20. Solar zenith angle in Bilbao during the whole year

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.

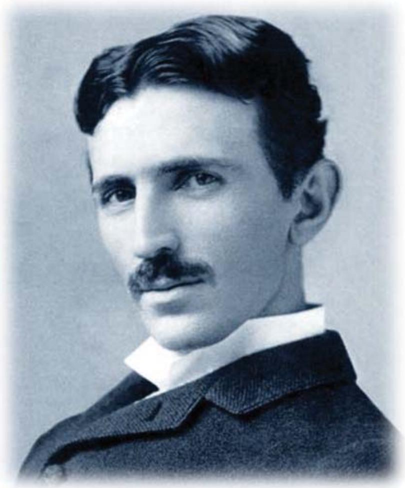
Besides, in this third part of the thesis, two different kinds of models have been presented and developed to represent the thermal performance of the chosen reference dwelling. Both methods were built and adjusted based on experimental data, and both of them allow the thermal characterization of the 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.

PART 4
SIMULATIONS
4. ATALA. SIMULAZIOAK

"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

LABURPENA

Kapitulu honetan, hobekuntza ezberdinen bidez lortutako energia – aurrezteak TRNSYS eredua erabiliz. Proposatutako neurri ezberdinak aztertzen dira, irizpide ekonomikoak, energetikoak, eta ingurugiro eta barne erosotasunari lotutakoak kontuan hartuz. Kapitulu honetan erakutsitako ikerketa etxebizitza – eskalan garatu zen, erreferentzia – etxebizitza erabiliz. Lehenik, 64 energia aurrezteko neurriak eraikinaren inguratzaile termikoa hobetzeko zehazten dira, eta haien emaitzak erakusten dira. Aztertutakoen artean, konbinazio bat hautatzen da, eta berokuntza – kontrolerako estrategia ezberdinen eraginak energia – kontsumoan eta barne erosotasunean ebaluatzen dira.

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 [€/m^2]			
	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/m²·K]	2.7	0.53	0.26	0.19
Investment [€/m²]	-	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/m²·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/m²·K]	3.44	3.0	1.76	0.7
U_{wind} [W/m²·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.

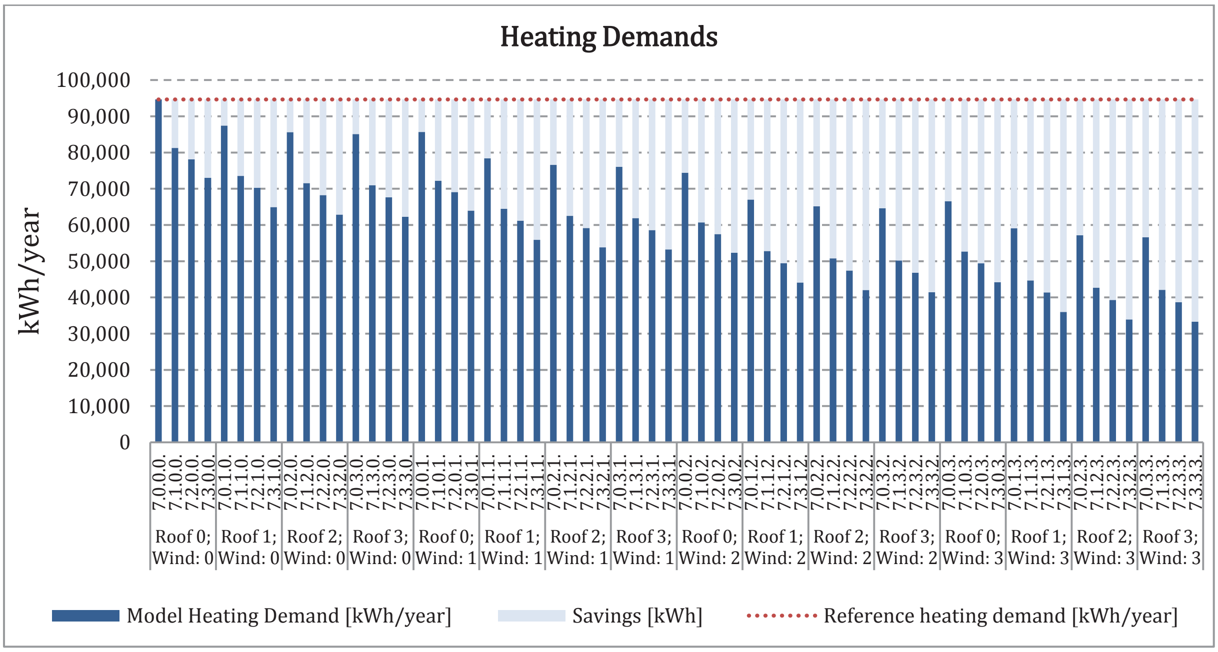


Fig. 7. 1. Yearly heating demands

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.).

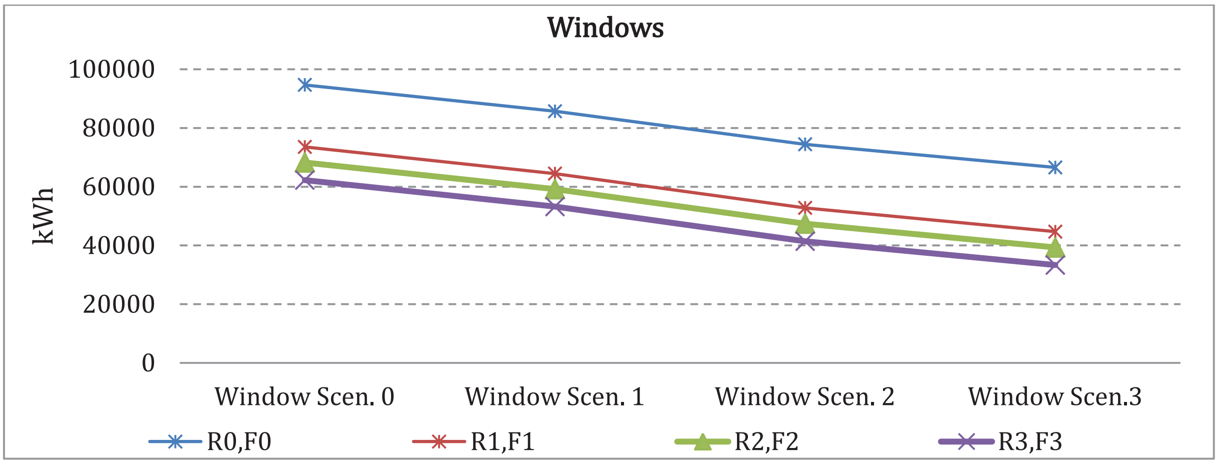


Fig. 7. 2. Energy consumption of scenarios improving windows

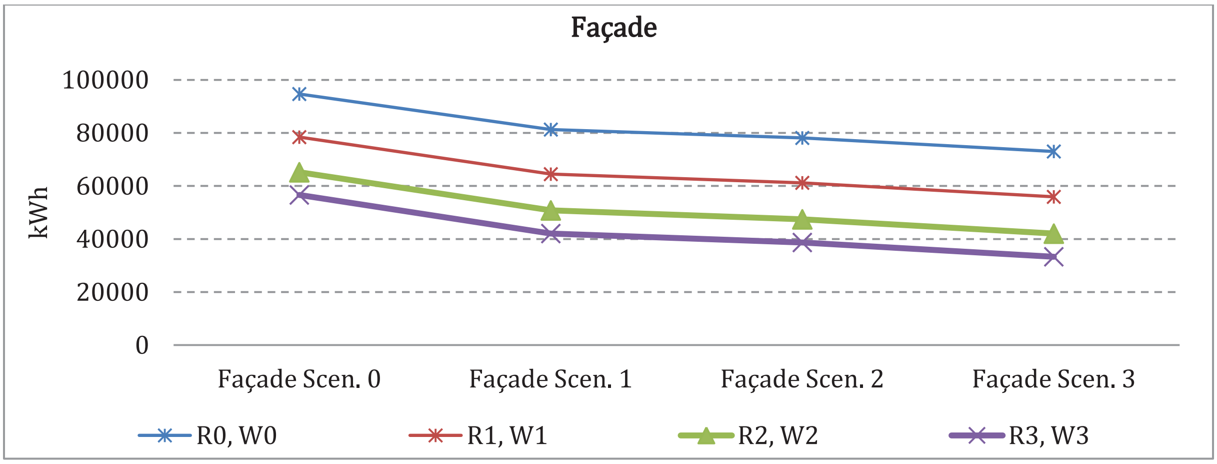


Fig. 7. 3. Energy consumption of scenarios improving façade

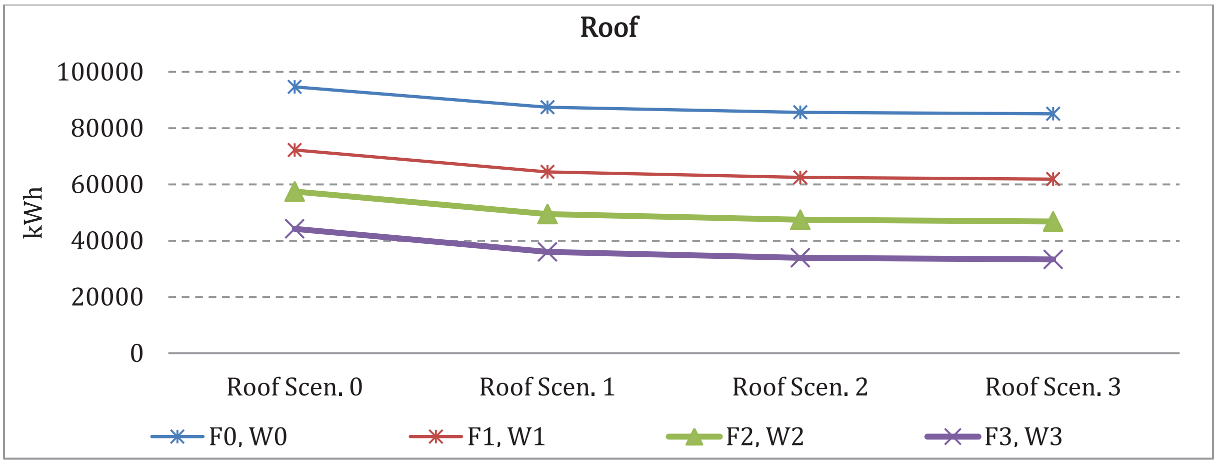


Fig. 7. 4. Energy consumption of scenarios improving roof

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.

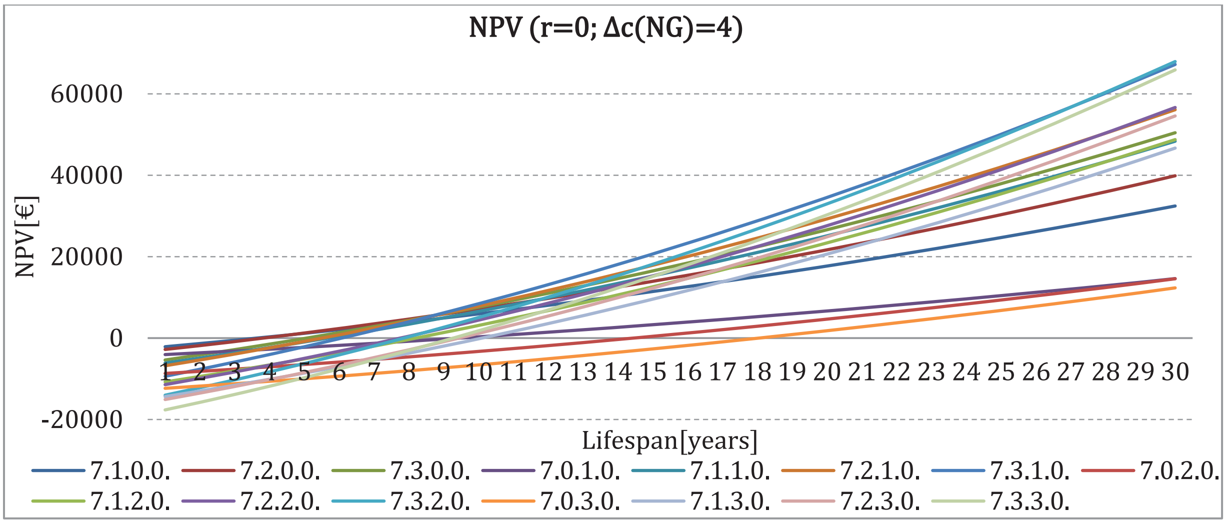


Fig. 7. 5. NPV (r=0, NG Cost increment: 4%)

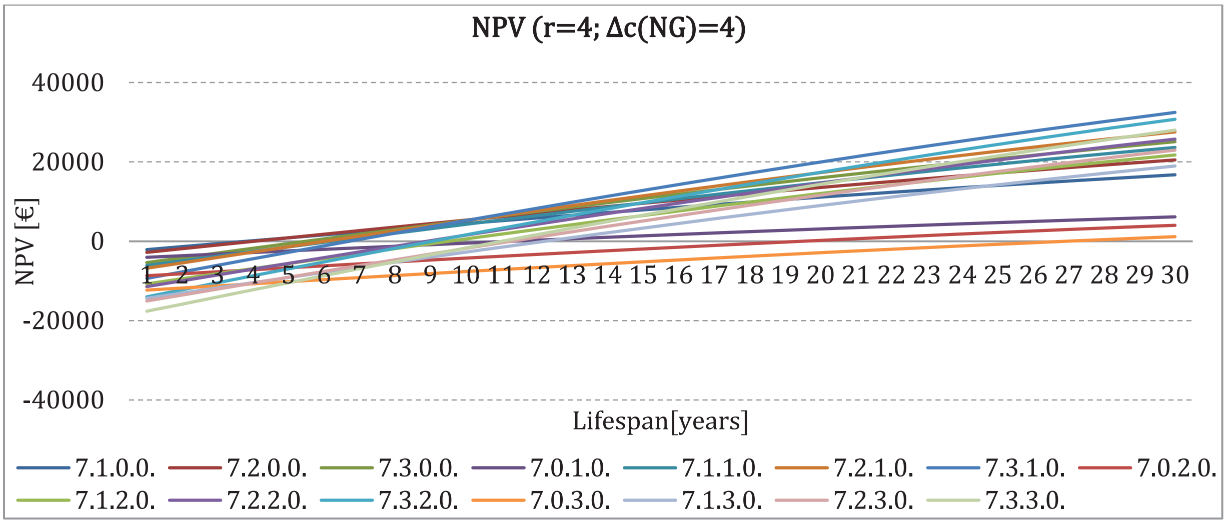


Fig. 7. 6. NPV (r=4%, NG Cost increment: 4%)

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.

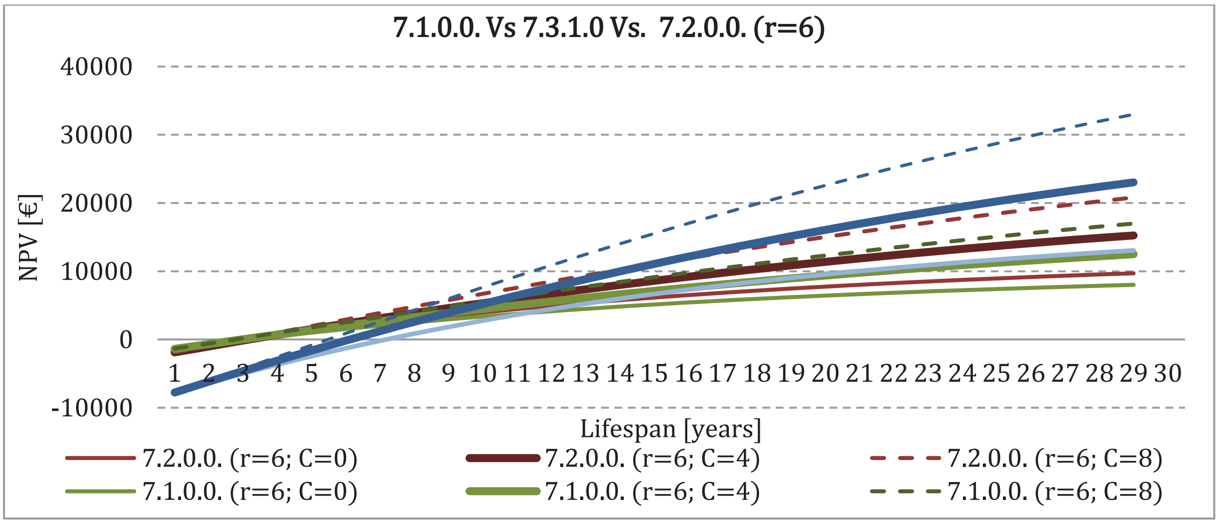


Fig. 7. 7. NPV of the three preselected models

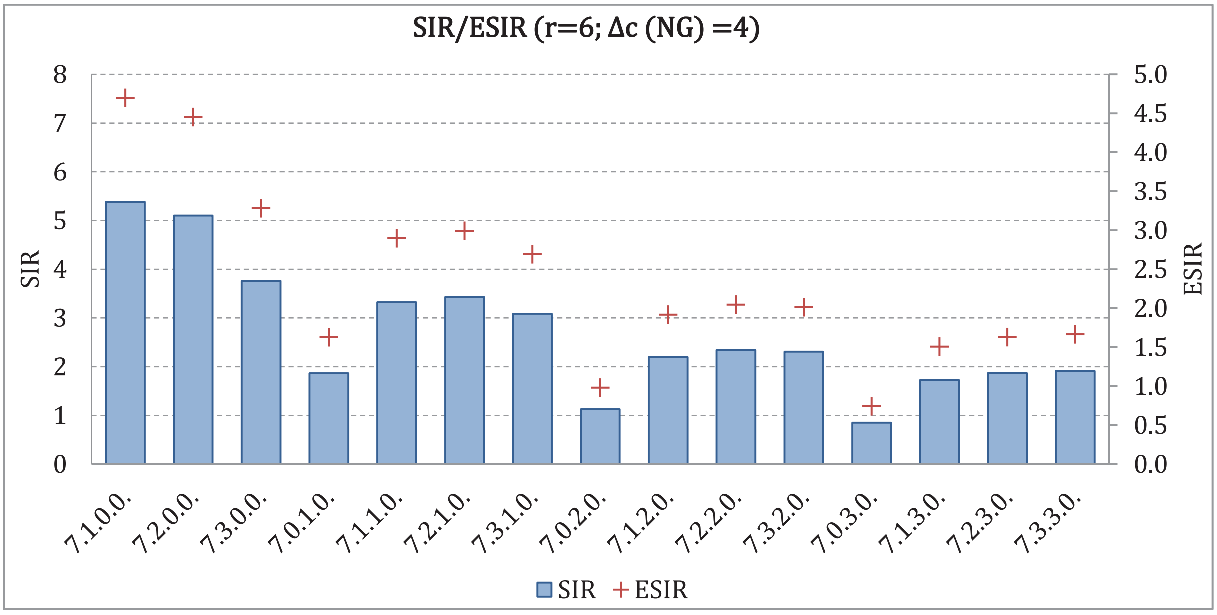


Fig. 7. 8. SIR and ESIR of the ESM of roof and façade combinations (r=6; C=4)

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.

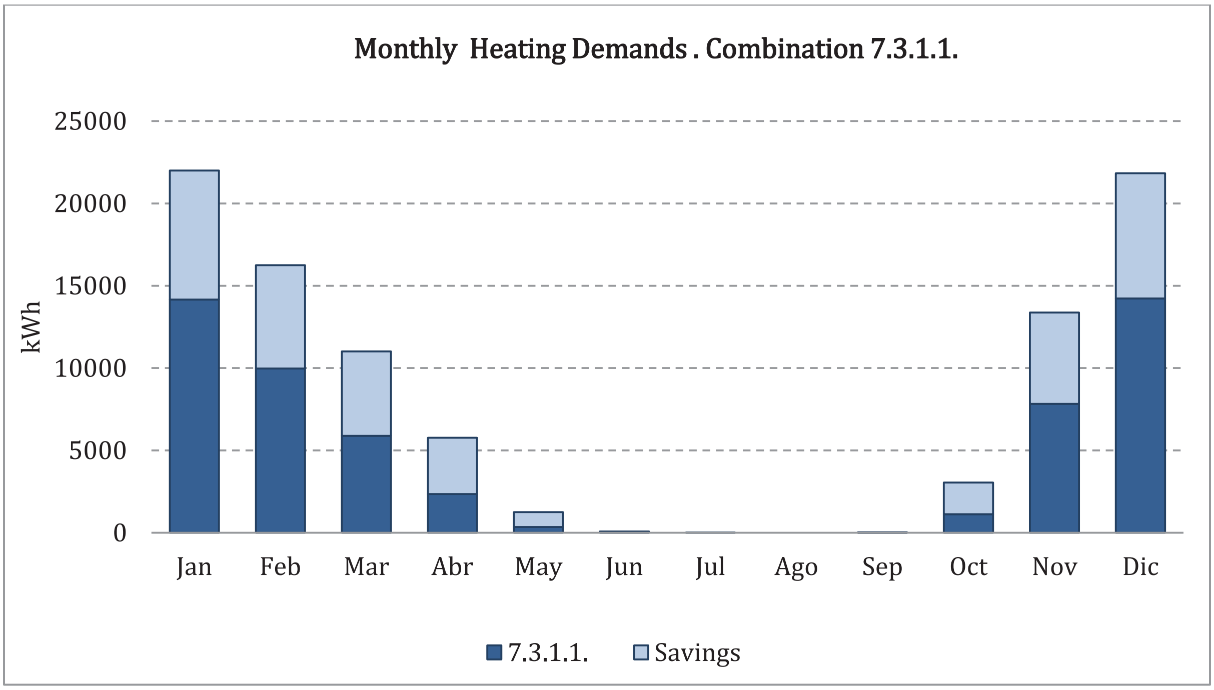


Fig. 7. 9. Monthly heating demands (7.3.1.1.)

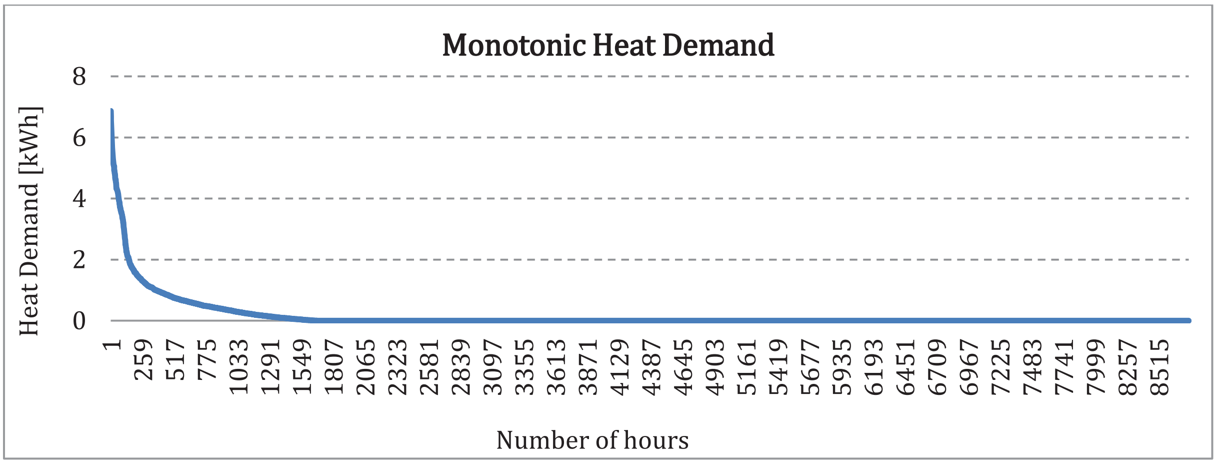


Fig. 7. 10. Monotonic heat demand for 7.3.1.1. (DHW is not considered)

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.

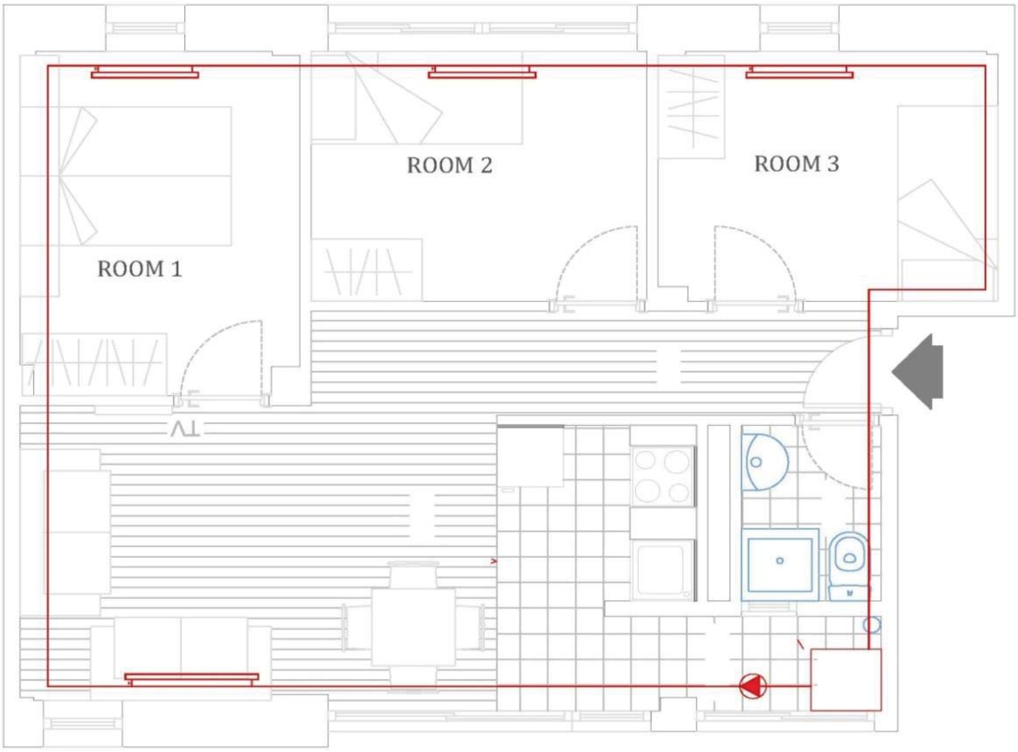


Fig. 7. 11. Sketch of the assumed heating system in the dwelling

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.

$$\eta_{Boiler} = (-160.40233 + 26.6297 \cdot T_{in} - 1.06398 \cdot {T_{in}}^2 + 0.02041 \cdot {T_{in}}^3 - 1.90629 \cdot 10^{-4} \cdot {T_{in}}^4 + 6.97436 \cdot 10^{-7} \cdot {T_{in}}^5) \cdot \left(1 + \frac{1 - PLR}{10}\right) \quad \text{Eq. 38}$$

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.

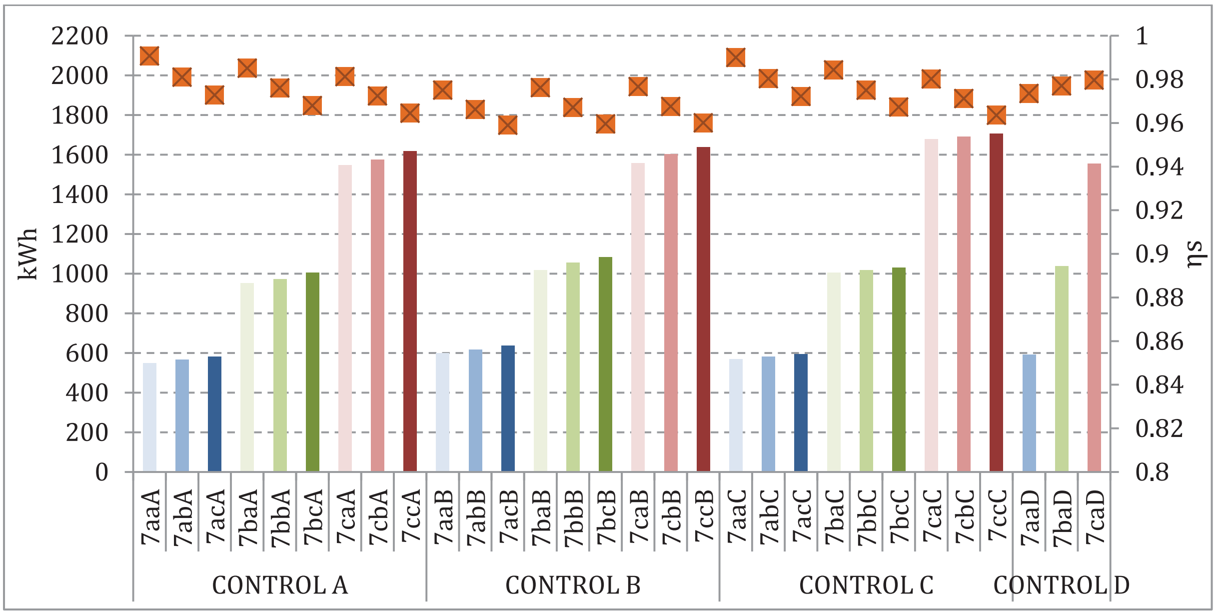


Fig. 7. 12. Yearly boiler energy consumption for each model

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.

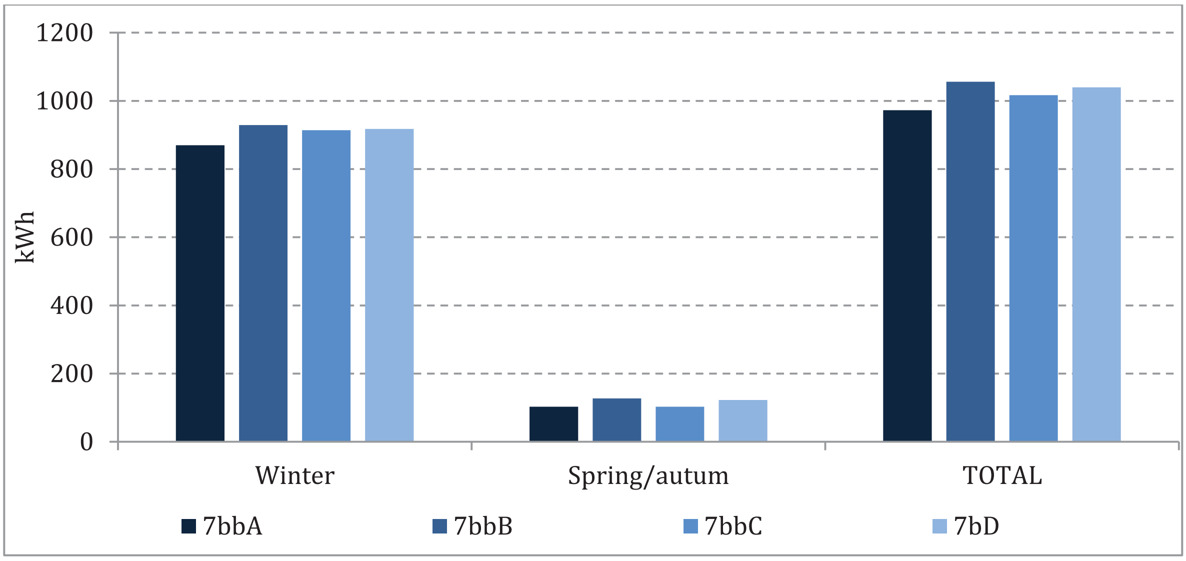


Fig. 7. 13. Seasonal boiler energy consumption for models "bb"

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.

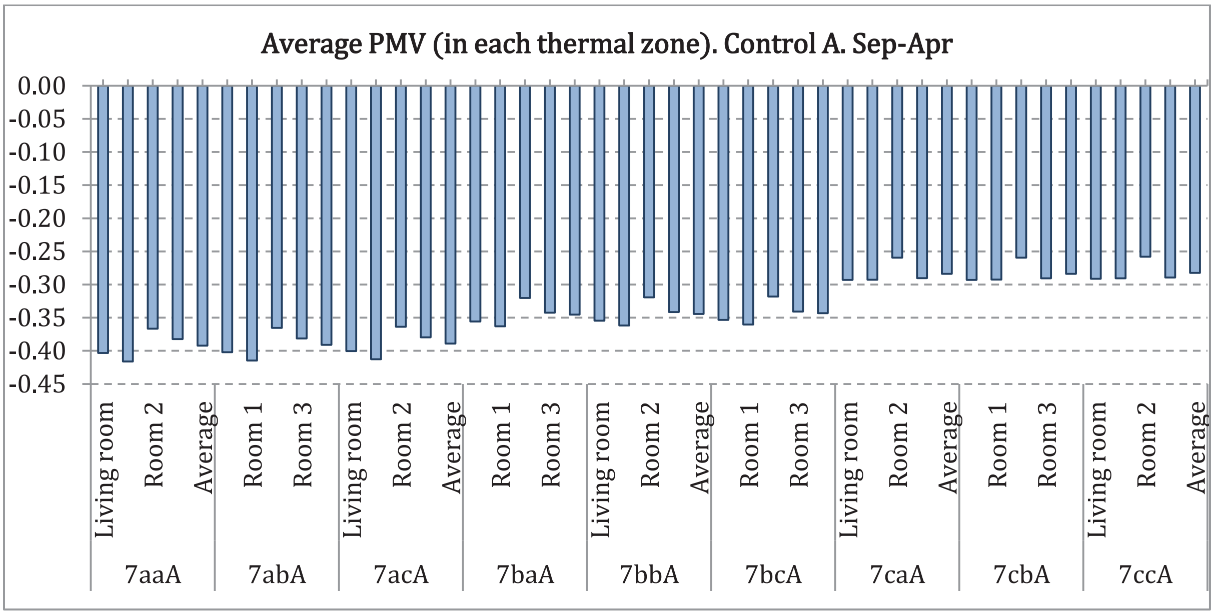


Fig. 7. 14. Average PMV in each thermal zone: living room, room 1, room 2, room 3 and dwelling average (Control A, Sep - Apr)

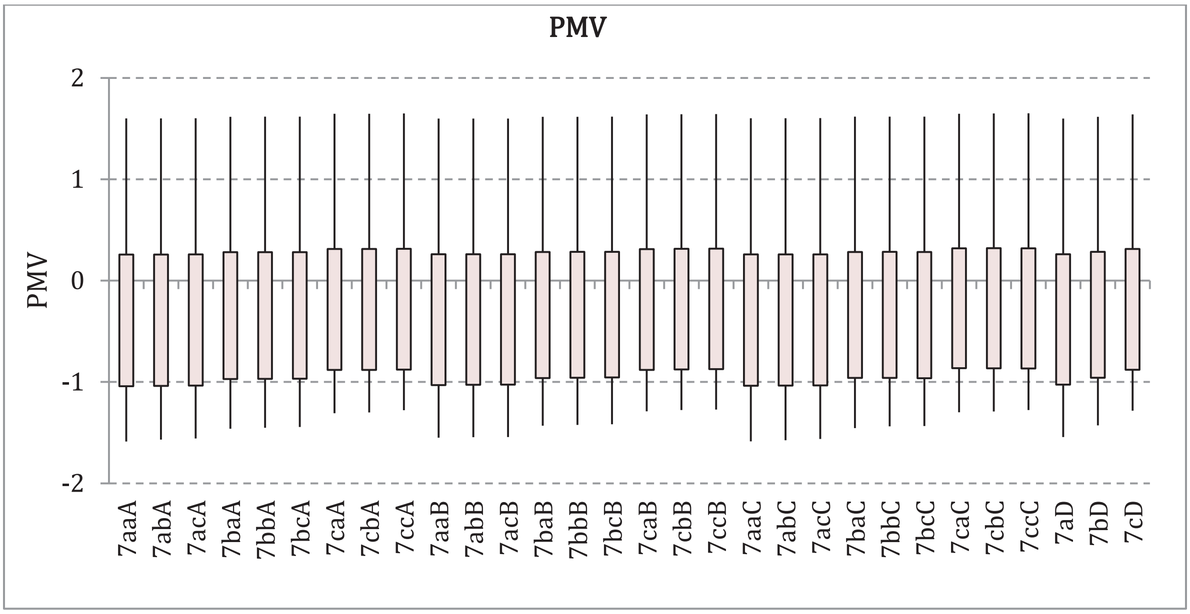


Fig. 7. 15. PMV in each combination (Average values from September to April)

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.

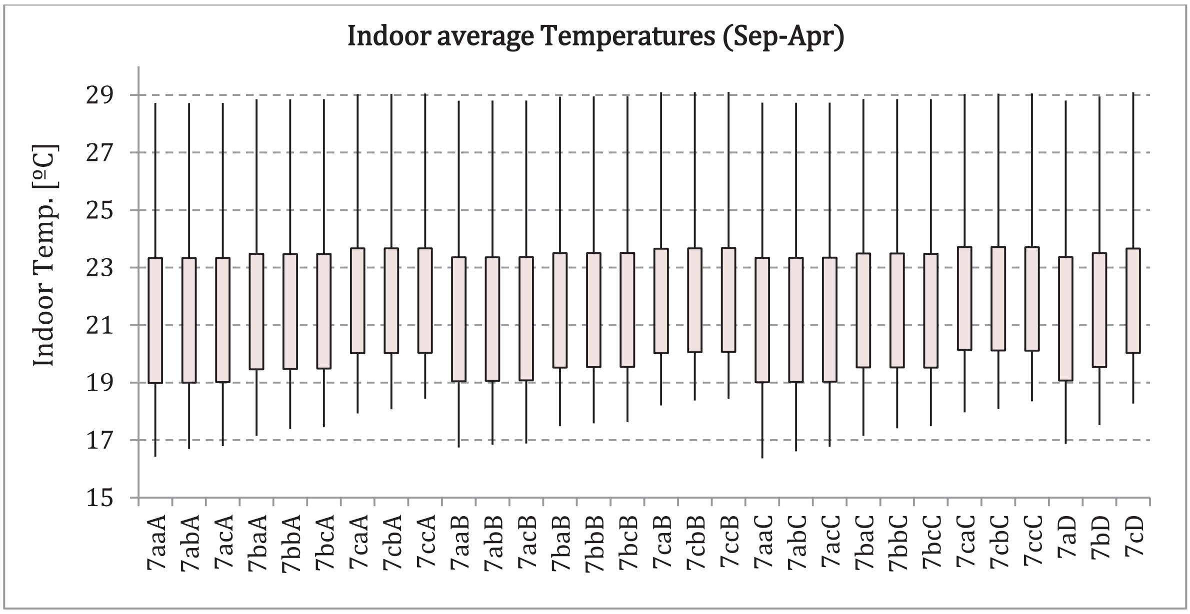


Fig. 7. 16. Indoor average temperatures for each model

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.

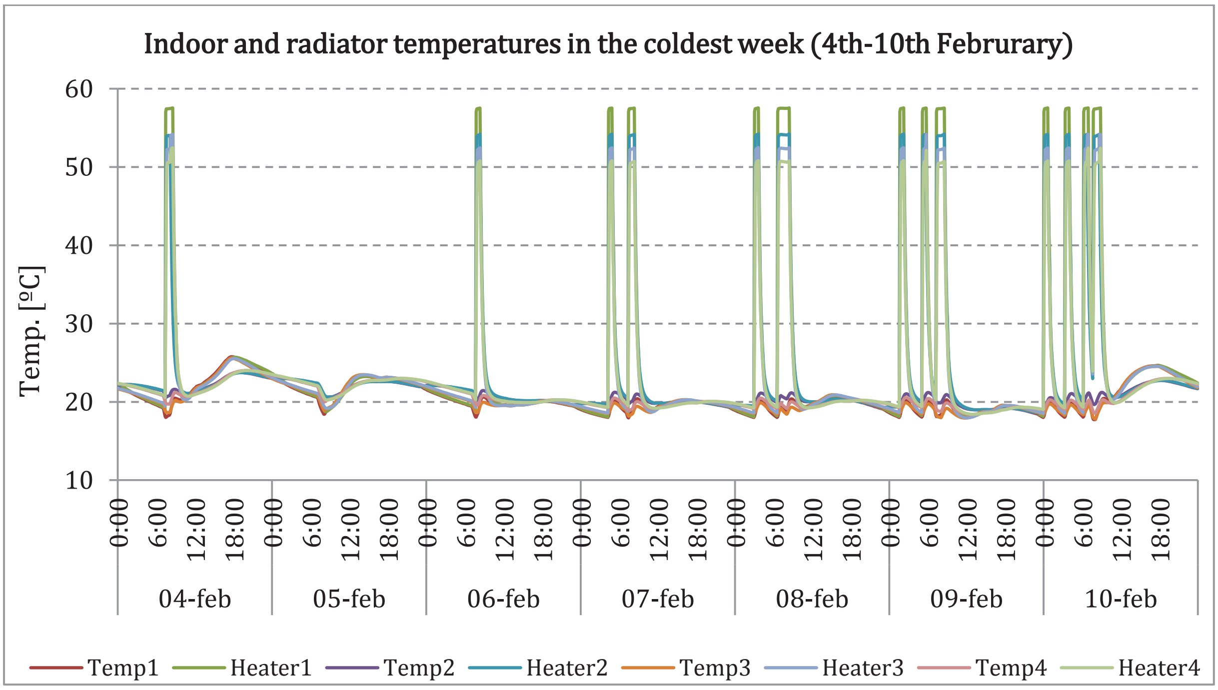


Fig. 7. 17. Indoor temperature and radiator temperature in the coldest week (7.b.b.B.)

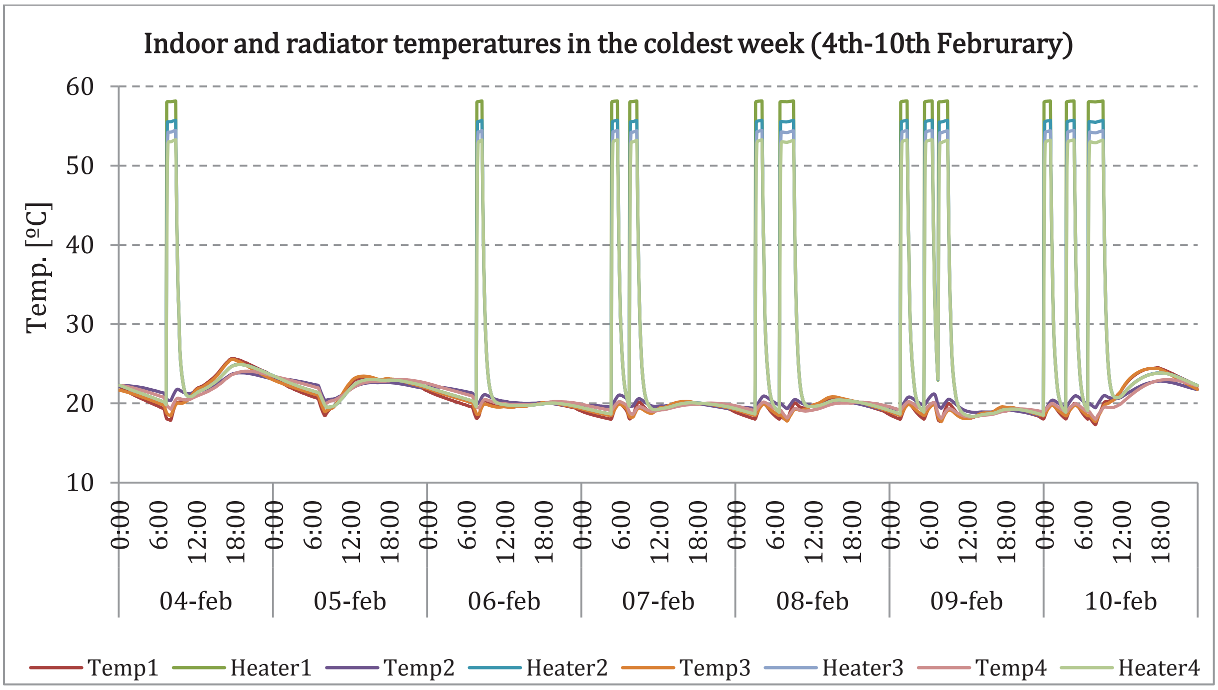


Fig. 7. 18. Indoor temperature and radiator temperature in the coldest week (7.b.b.A.)

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.

LABURPENA

Kapitulu honetan, exergiaren erabilgarritasuna birgaitze energetikorako estrategia ezberdinak aztertzeko ikertzen da. Kapitulu honek eraikinetan erabilitako ikuspegi exergetikoari buruzko literatura aztertze motz bat barne hartzen du. Bestalde, TU Delf-eko Arkitektura Fakultatean (Herbeheretan), 2012. urteko bigarren hiruhilekoan Sabine Jansen-ekin garatutako ikerketa erakusten da.

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. 1. 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.	$\boldsymbol{E = T_0\left(S_{eq}^{tot} - S^{tot}\right)}$ 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. 1. 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.

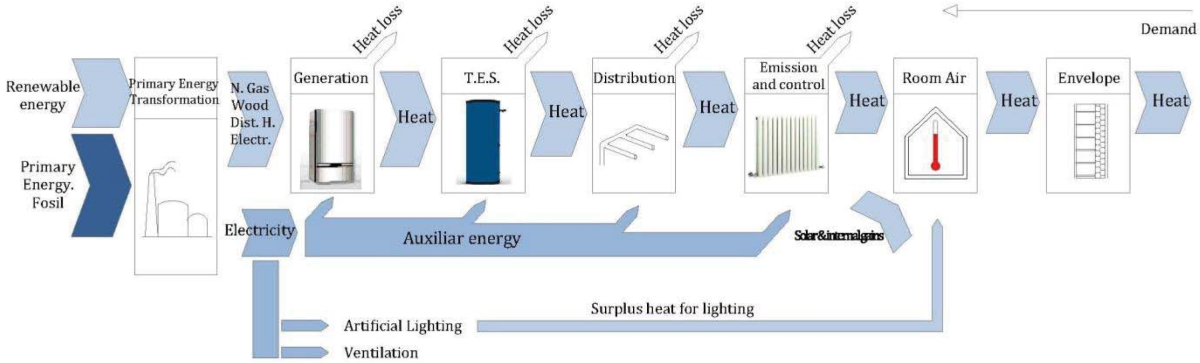


Fig. 8. 1. Energy supply chain for space heating in buildings (Adapted from [136])

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:

$$\psi_{simple} = \frac{Ex_{out}}{Ex_{in}} \qquad \text{Eq. 39}$$

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.

$$\psi_{rat} = \frac{Ex_{des,out}}{Ex_{in}} \qquad \text{Eq. 40}$$

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:

$$\psi_{rat} = \frac{Ex_{in}}{En_{out,i}} = \frac{F_{q,in,i}}{\eta_i} \qquad \text{Eq. 41}$$

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. 2.

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. 2. 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

LABURPENA

Azken kapitulu honetan, Doktorego – tesi honen ondorio nagusiak biltzen dira. Argitalpenak eta proposatutako lanak erakusten dira, baita metodologia bat proposatzen da lan hauek garatzeko. Gainera, gaur egun eskuragarriak diren argitalpenak (tesi honen fruituak direnak), baita idazteke daudenak ere, zerrendatzen dira.

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.

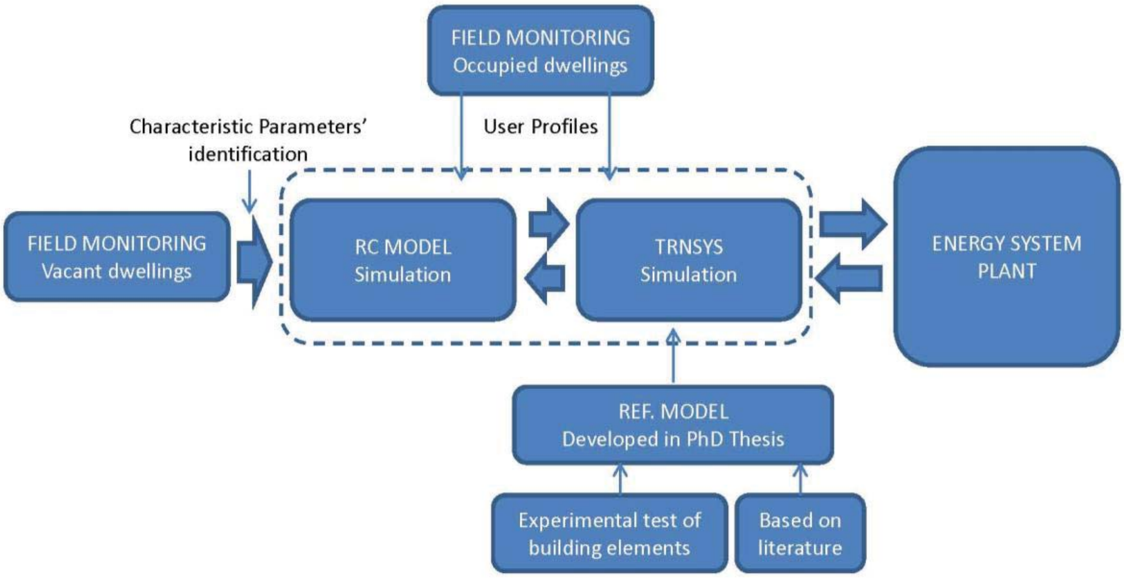


Fig. 9. 1. Interaction of monitoring studies, simulations and Energy System Plant

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.

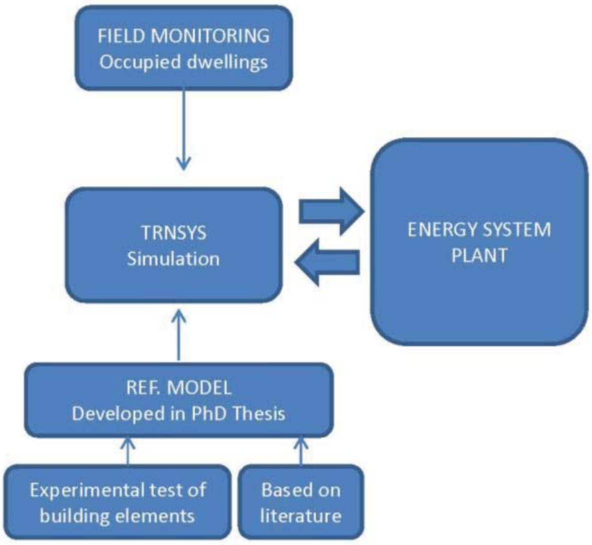


Fig. 9. 2. Workflow when the object of the test is the energy system itself

- 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.

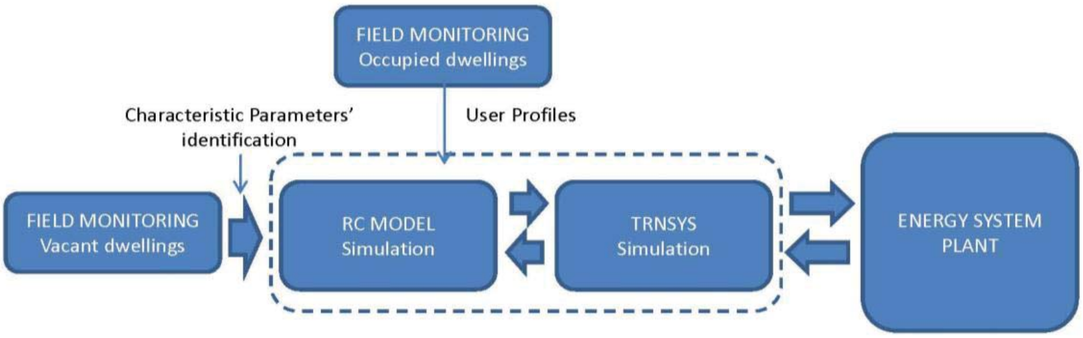


Fig. 9. 3. Workflow when the object of the test is the interaction between the energy system and a given building

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 / ERANSKINAK

Eranskinen aurkibidea / Index

1.1. Eranskina. Energia pobrezia. Literatura aztertzea
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.

1.2. Eranskina: Eraikinen euskal parkearen berotegi – efektuko gasen isuriak eta energia - kontsumoa

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. 1, distribution of GHG emissions by sectors in 2010 is depicted.

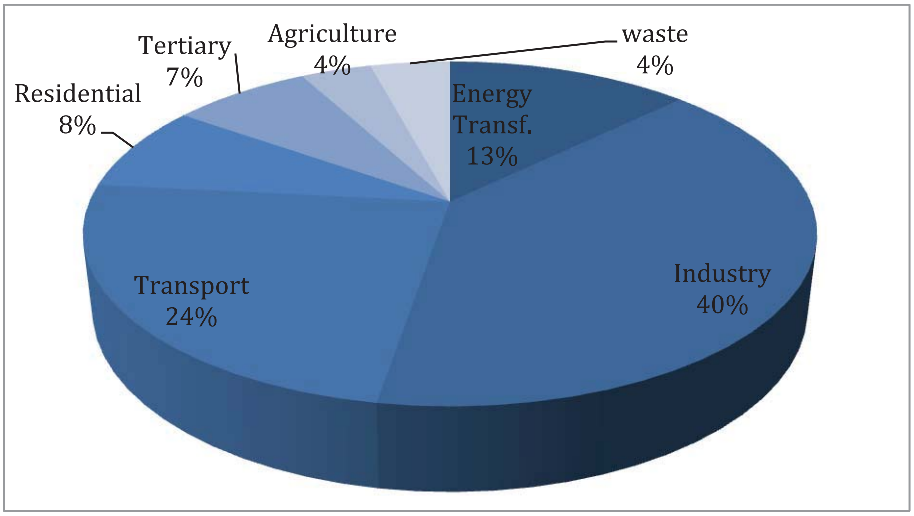


Fig. 2. 1. GHG emissions by sectors in the Basque Country in 2010 (EUSTAT, 2011)

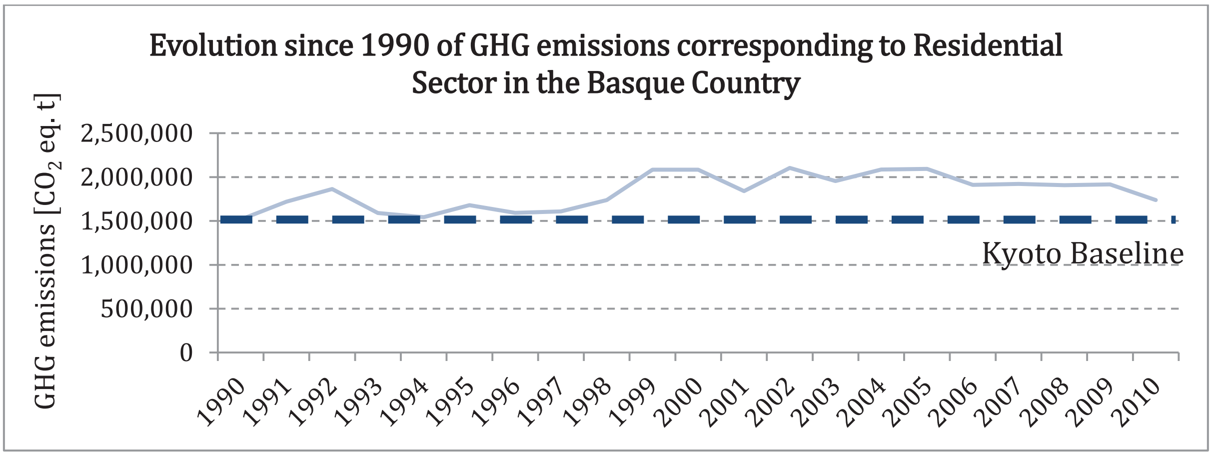


Fig. 2. 2. GHG emissions corresponding to Basque residential sector (EUSTAT, 2011)

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. 2.

As shown in Fig. 2. 2., 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. 3.

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.

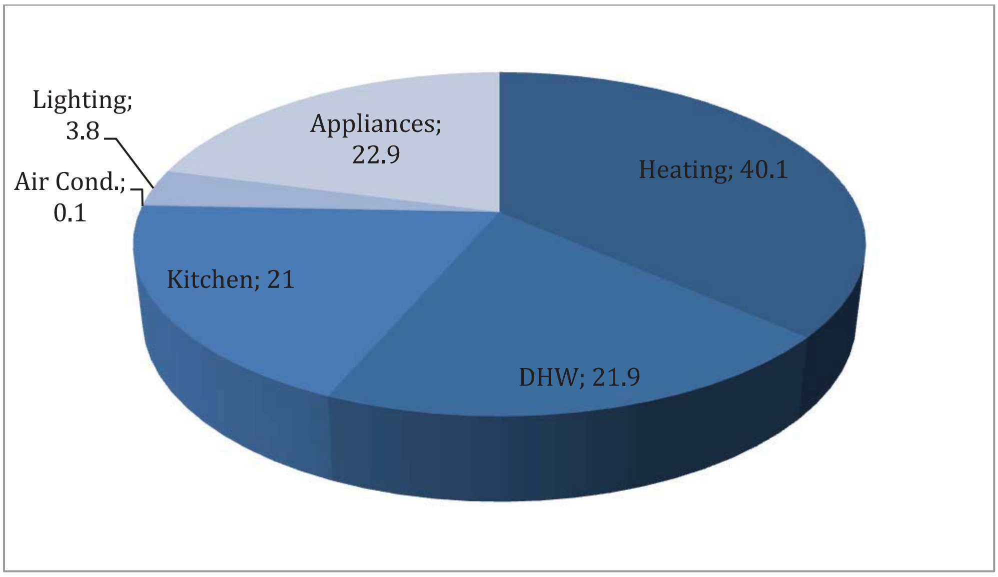


Fig. 2. 3. Energy consumption in Northern Atlantic Spain (2011 IDAE)

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. 3, 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. 4. 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.

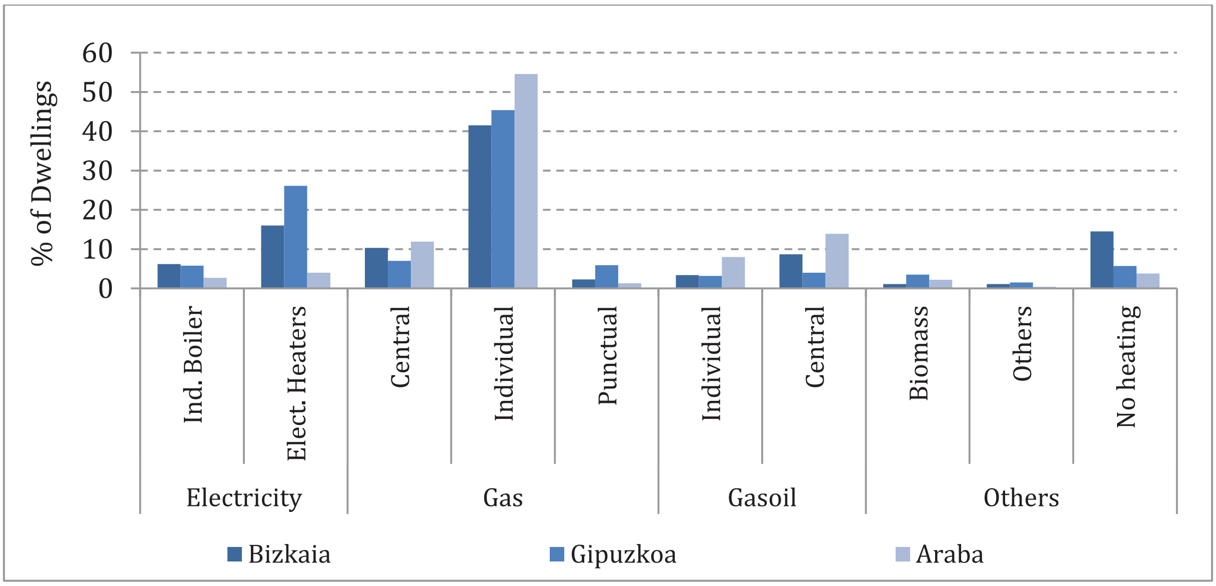


Fig. 2. 4. Heating systems (according to fuel) used in Basque dwellings (EUSTAT 2008)

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)

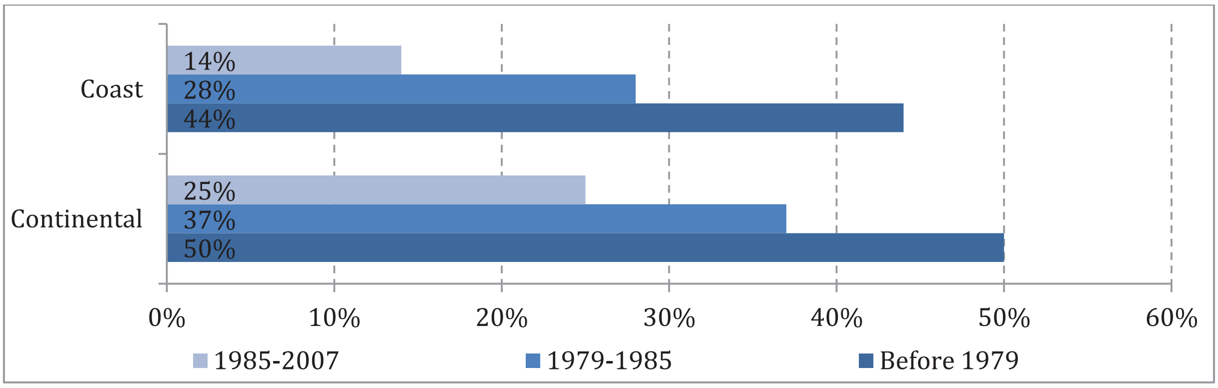


Fig. 2. 5 (Energy consumption in dwellings by construction year, 2012, EVE)

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. 5.

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. 6, where the evolution of the energy bill per year is depicted, based on data obtained from EVE.

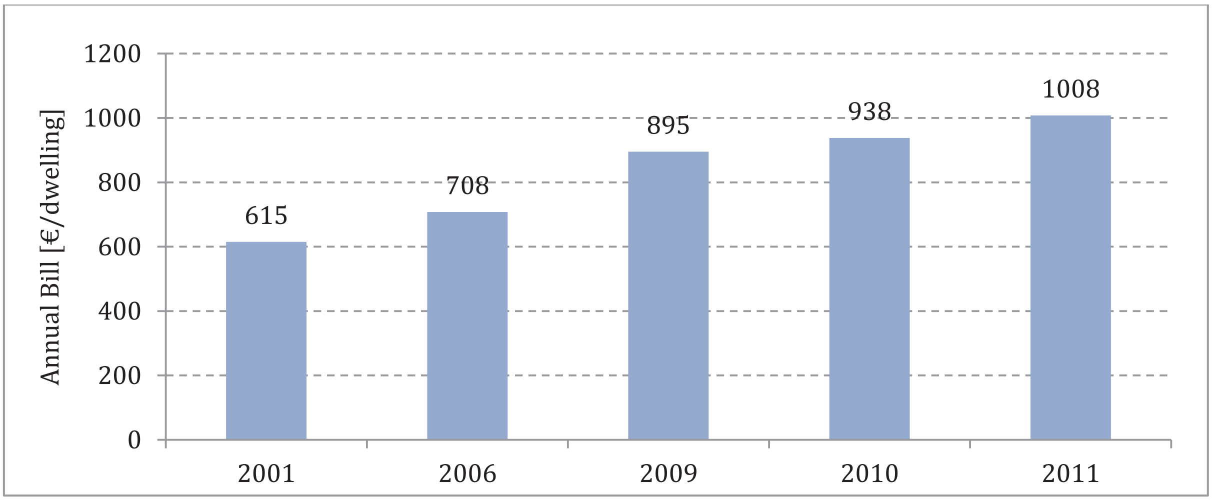
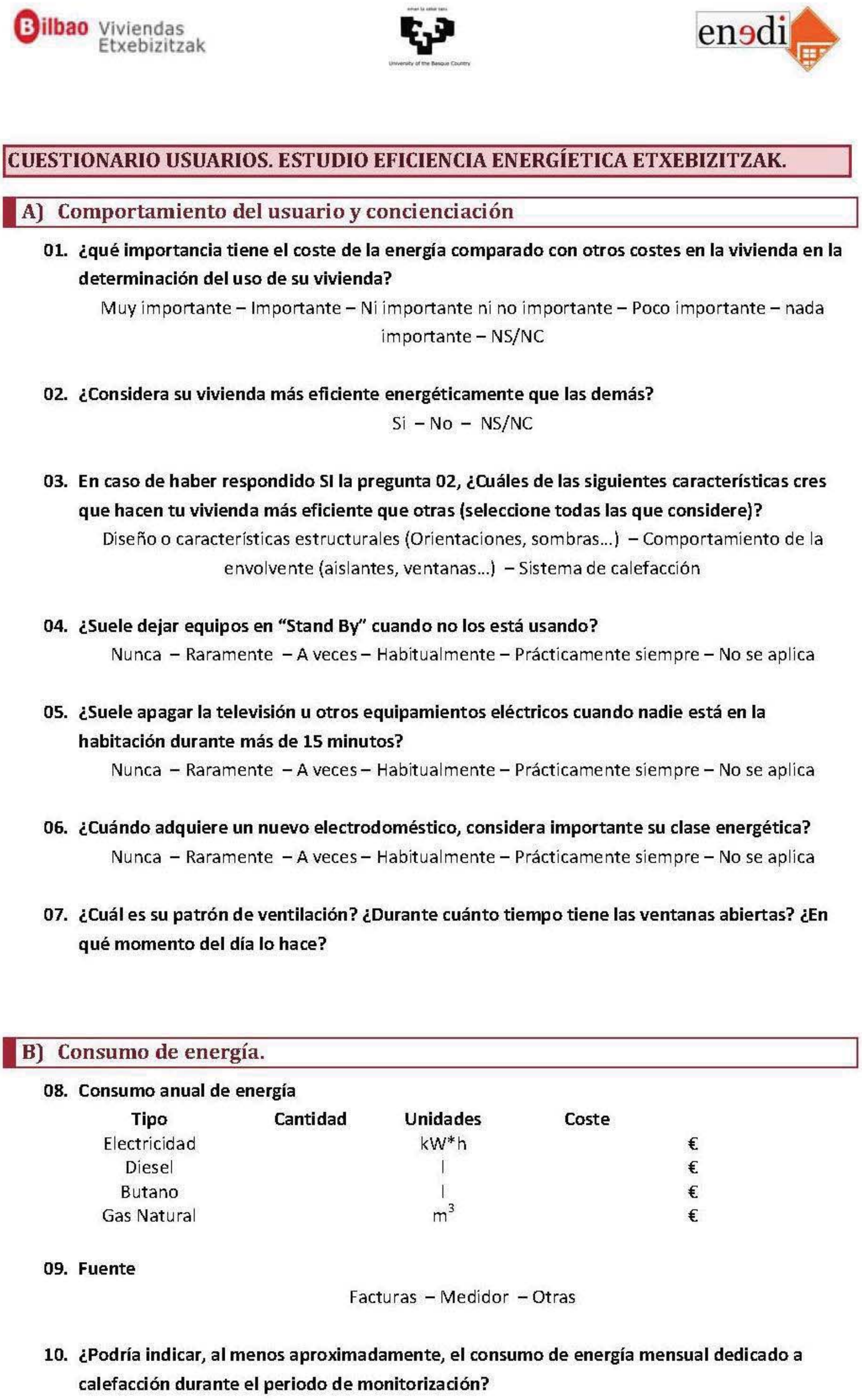


Fig. 2. 6. Annual energy expenses per dwelling (2012, EVE)

3.1. Eranskina: Galdeketa - orri txantiloia



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

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?

Si – 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

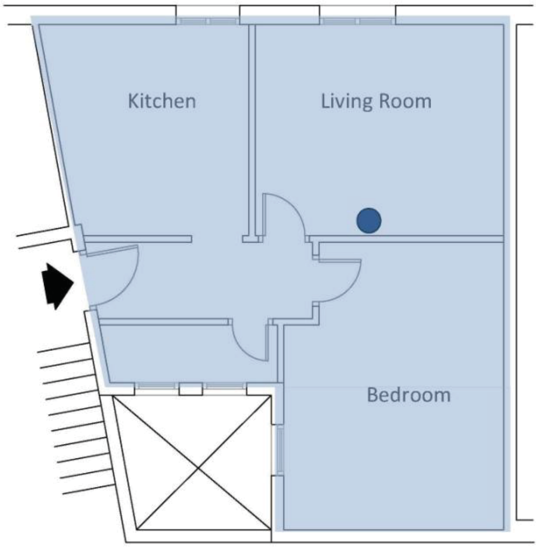
55. ¿Cómo cree que puede mejorarse el confort interior de su vivienda?

3.2. Eranskina: Landa – azterketaren neurketak

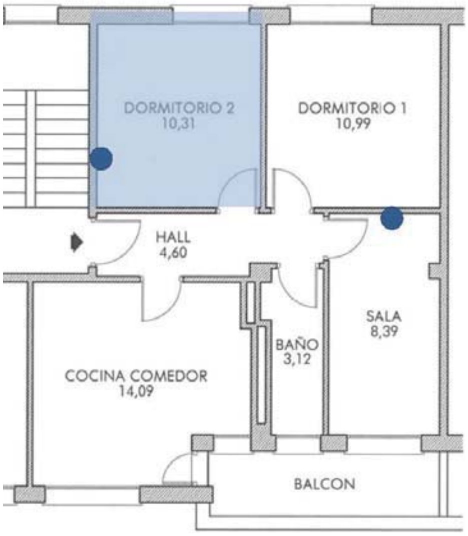
1 Etxebizitzen datu geometrikoak eta THen kokapena

Eranskinaren atal honentan etxebizitza bakoitzaren berotutako lekuen ezaugarri geometrikoak zein TH-en kokapena aurkesten dira.

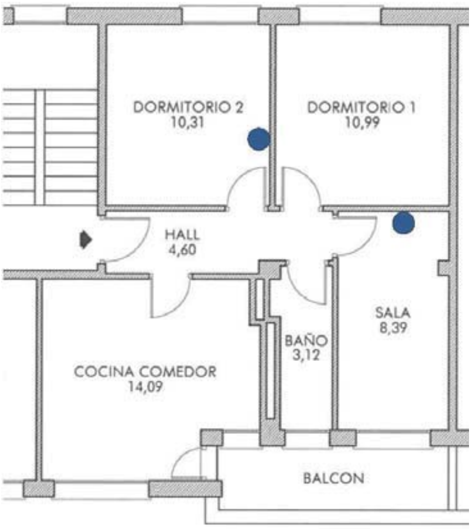
D1



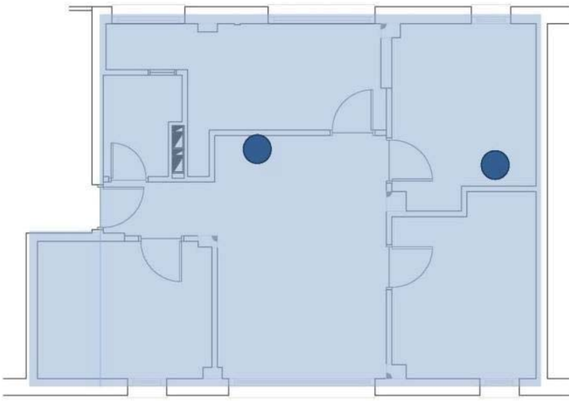
D2



D3

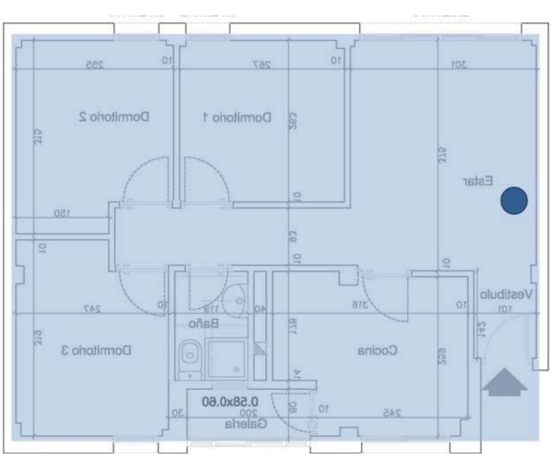


D4

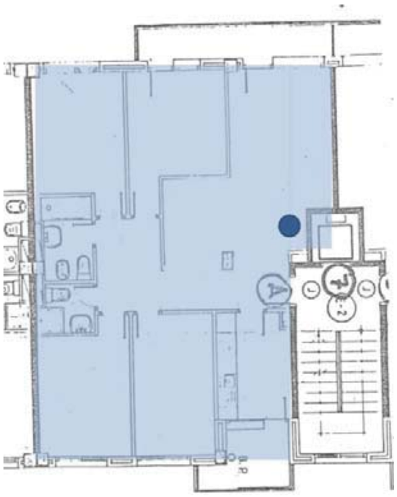


D5

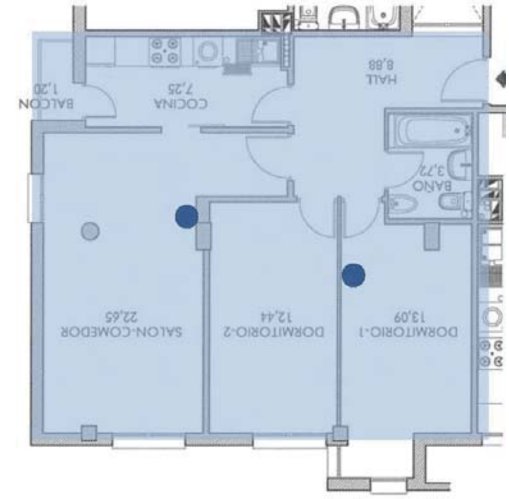
D6



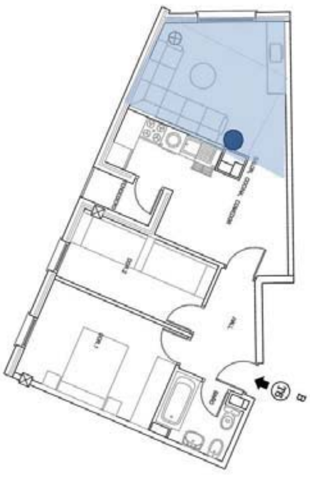
D7



D8



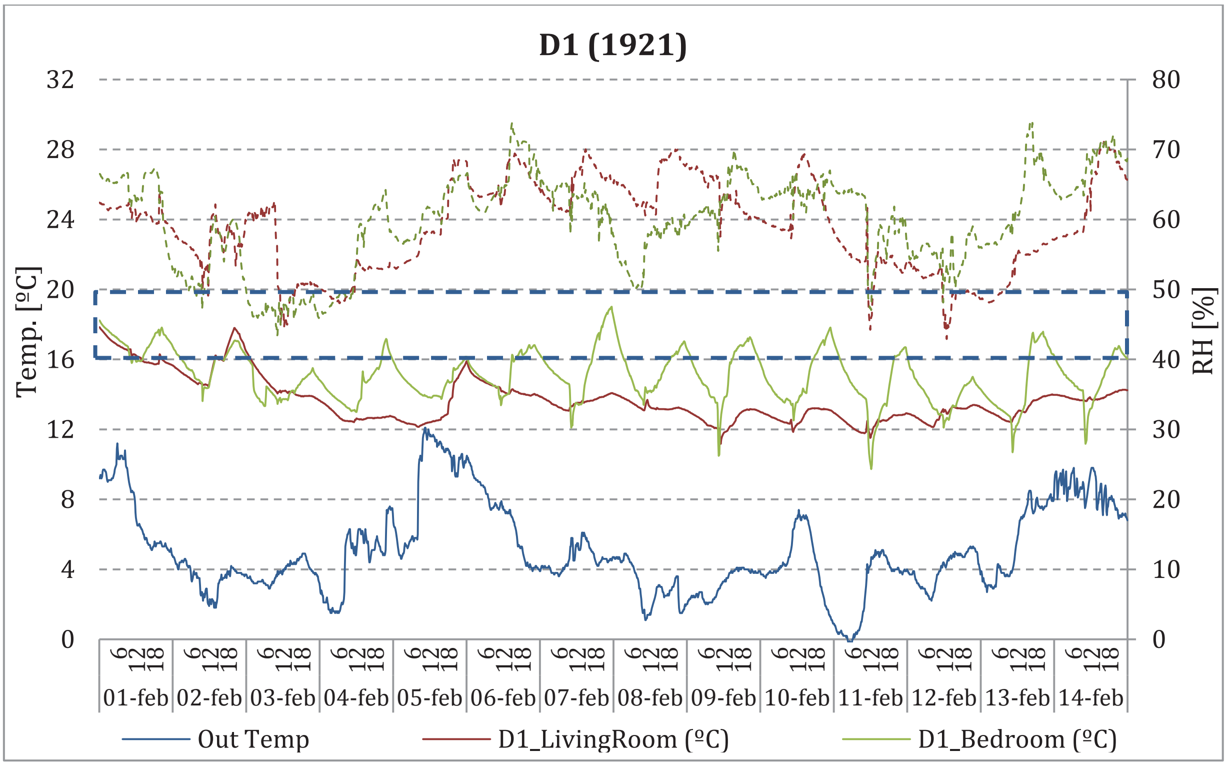
D9

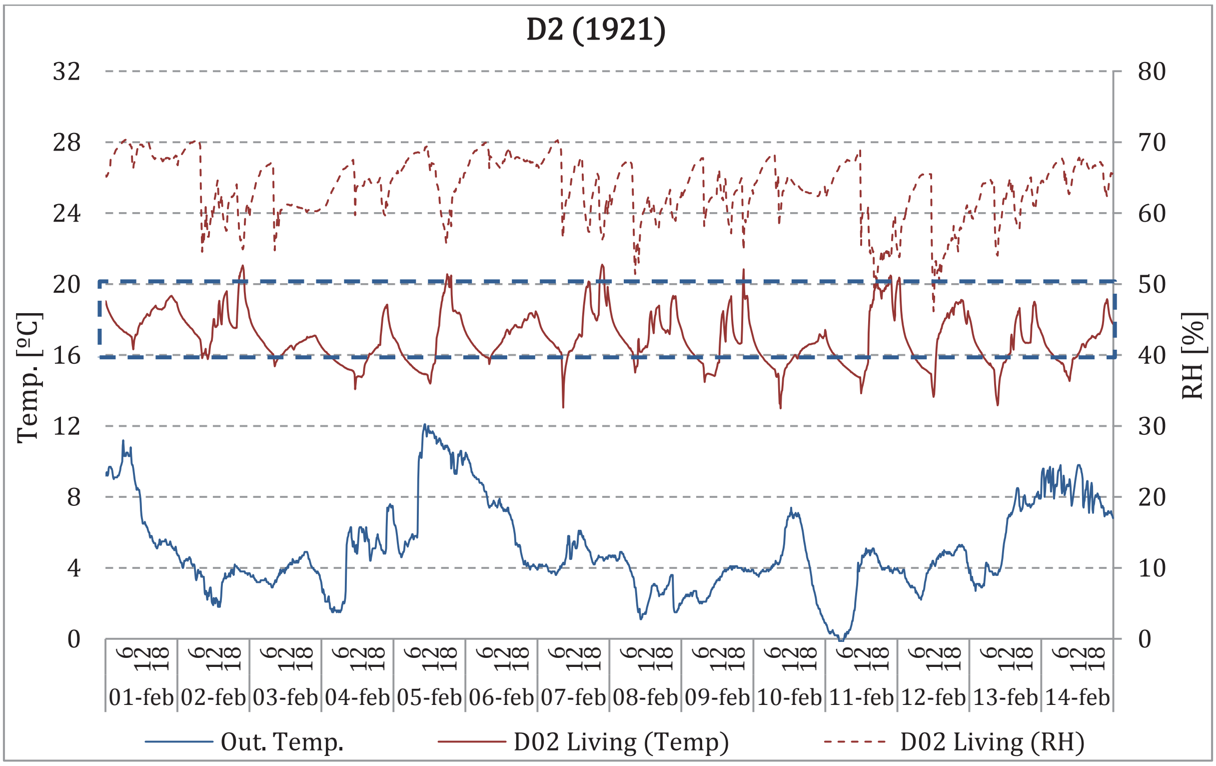


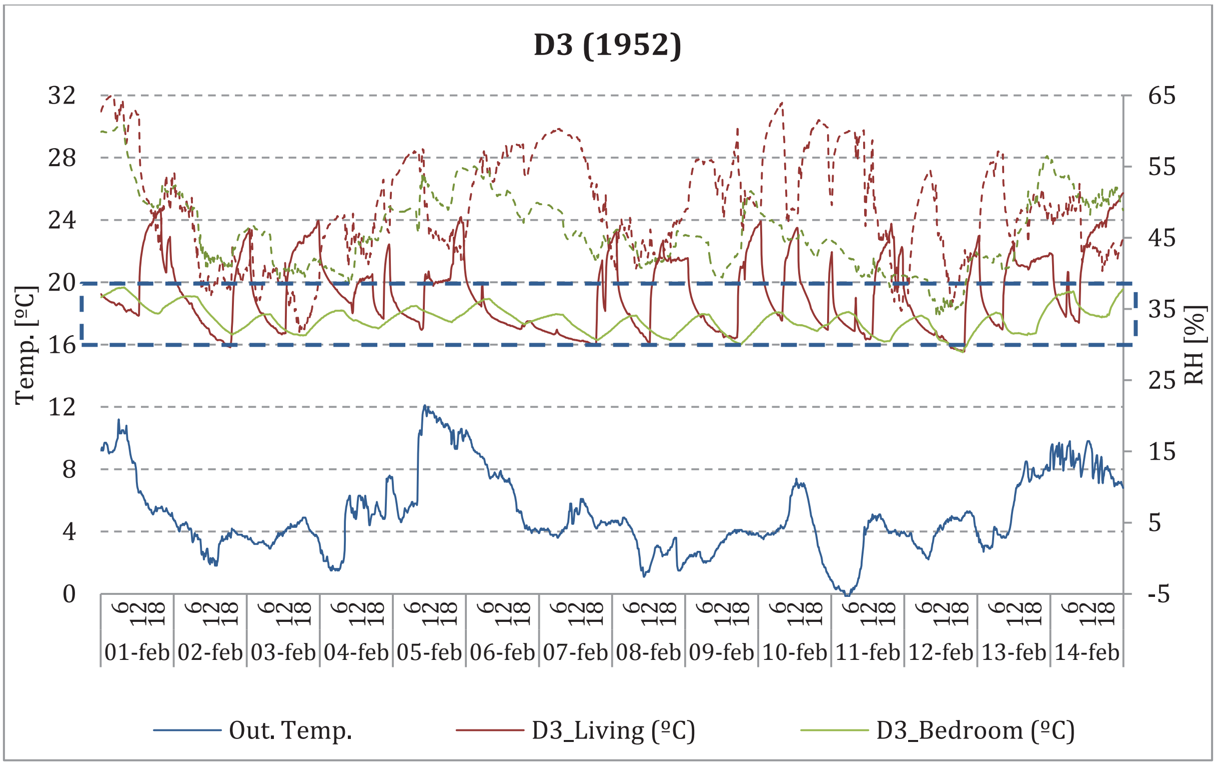
D10

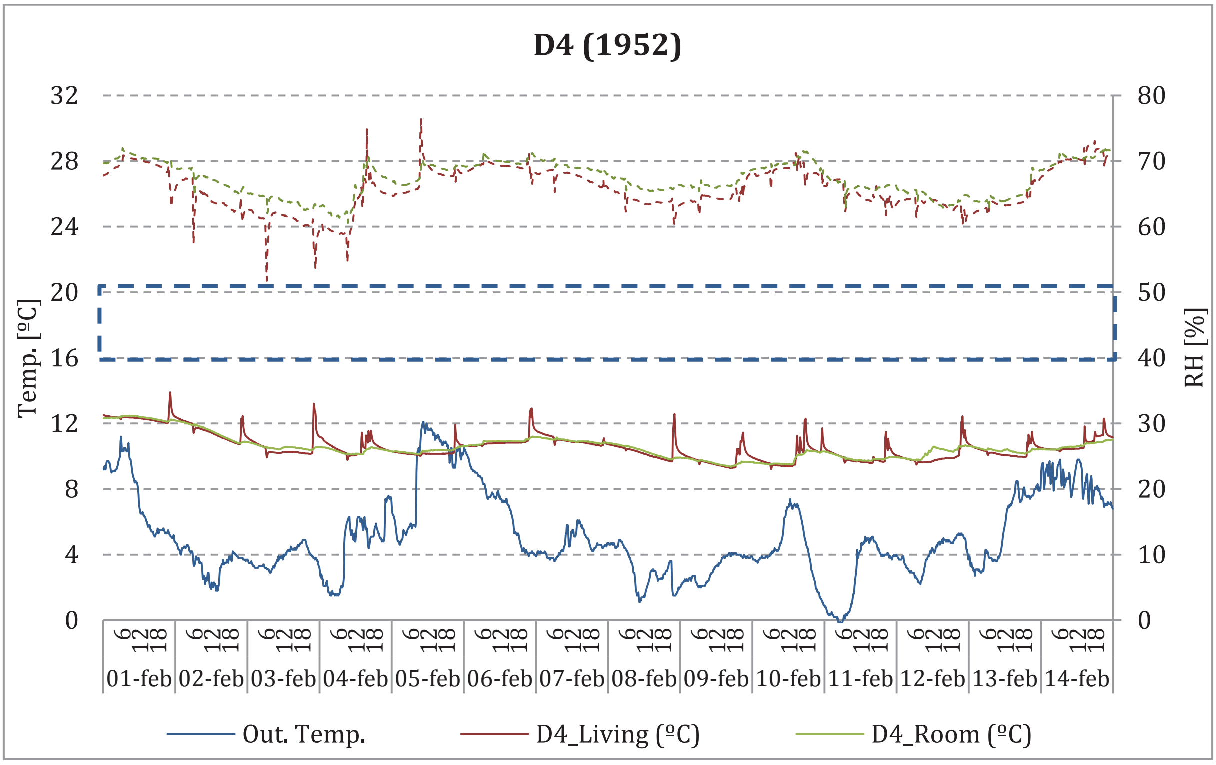
2 Neguan neurtutako datuak

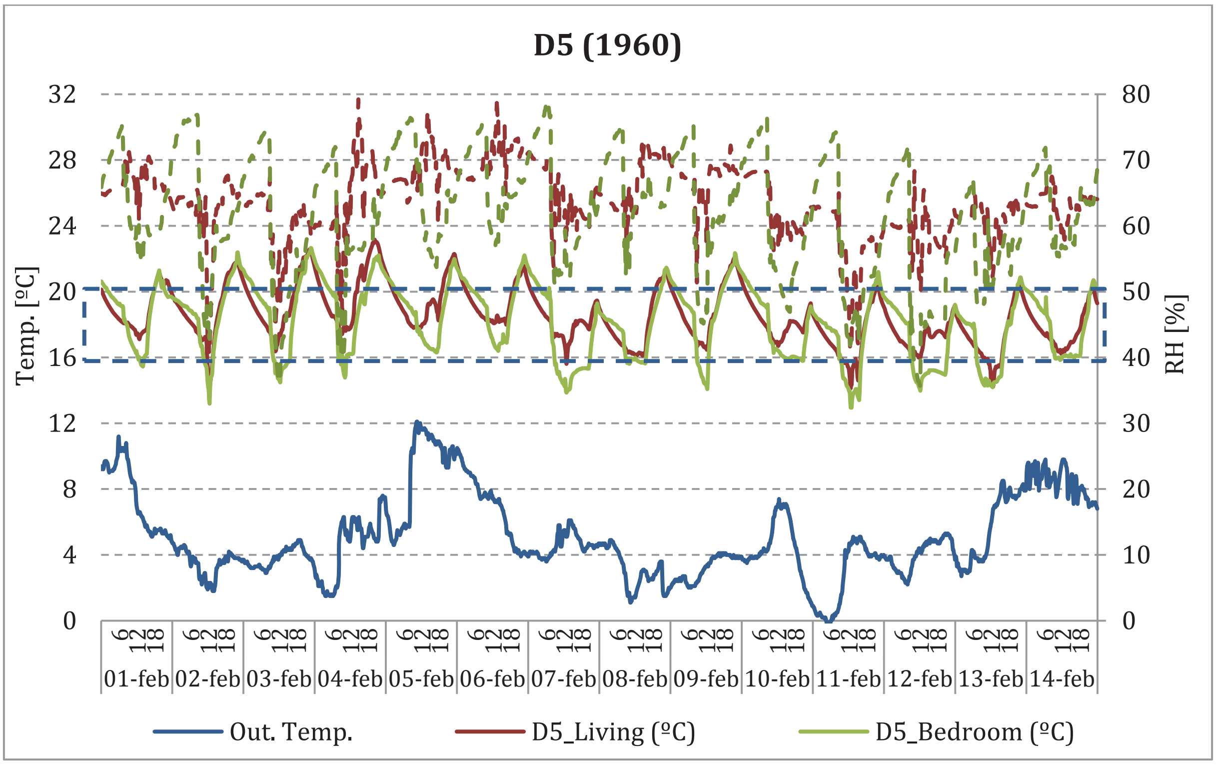
Atal honetan, etxebizitza bakoitzean neguko 15 eguneko epean neurtutako datuak (Tenperatura eta hezetasun erlatiboa) irudikatzen dira.

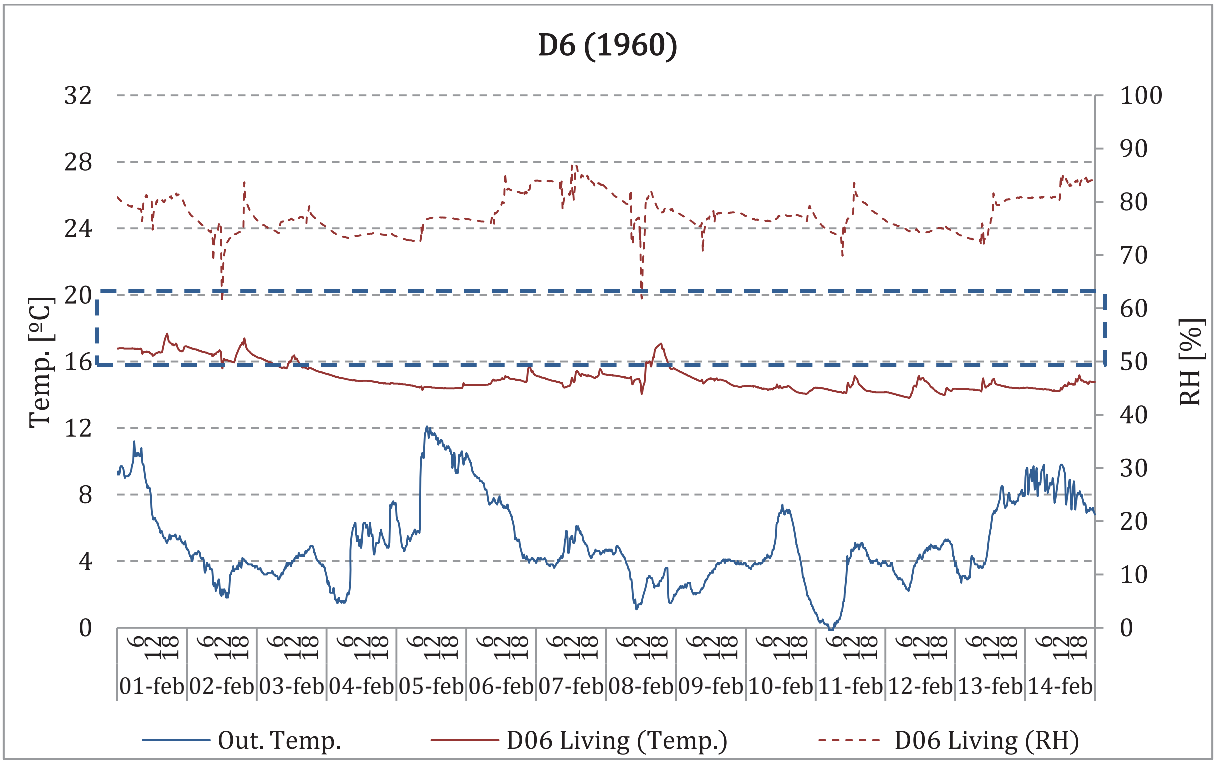

D1 (1921)

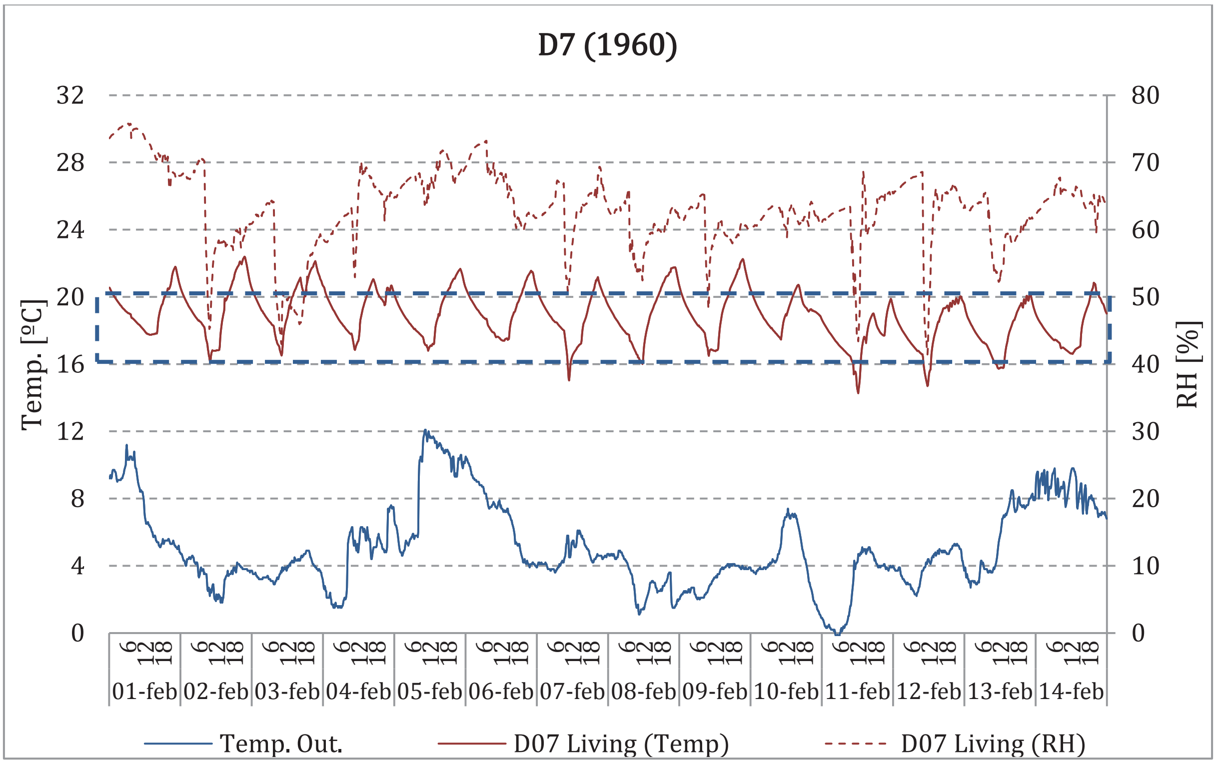

D2 (1921)

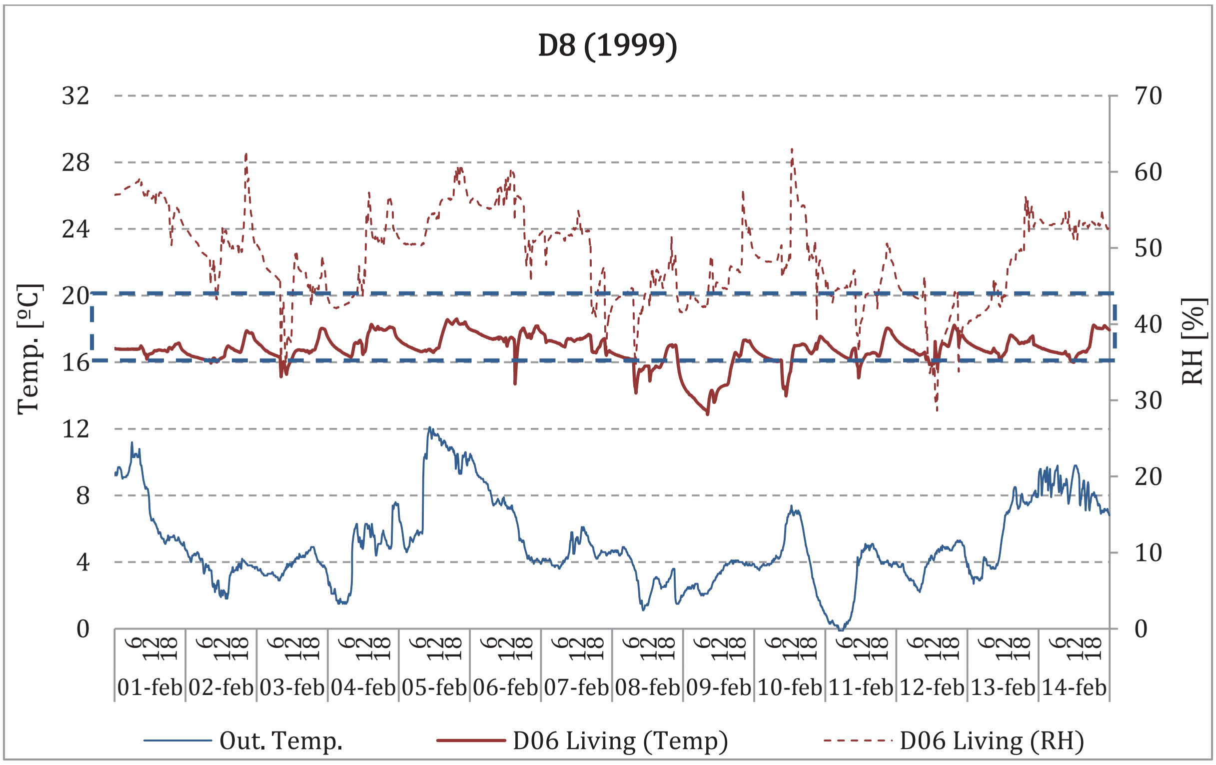

D3 (1952)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
65
55
45
35
25
15
5
-5
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D3_Living (ºC)
D3_Bedroom (ºC)

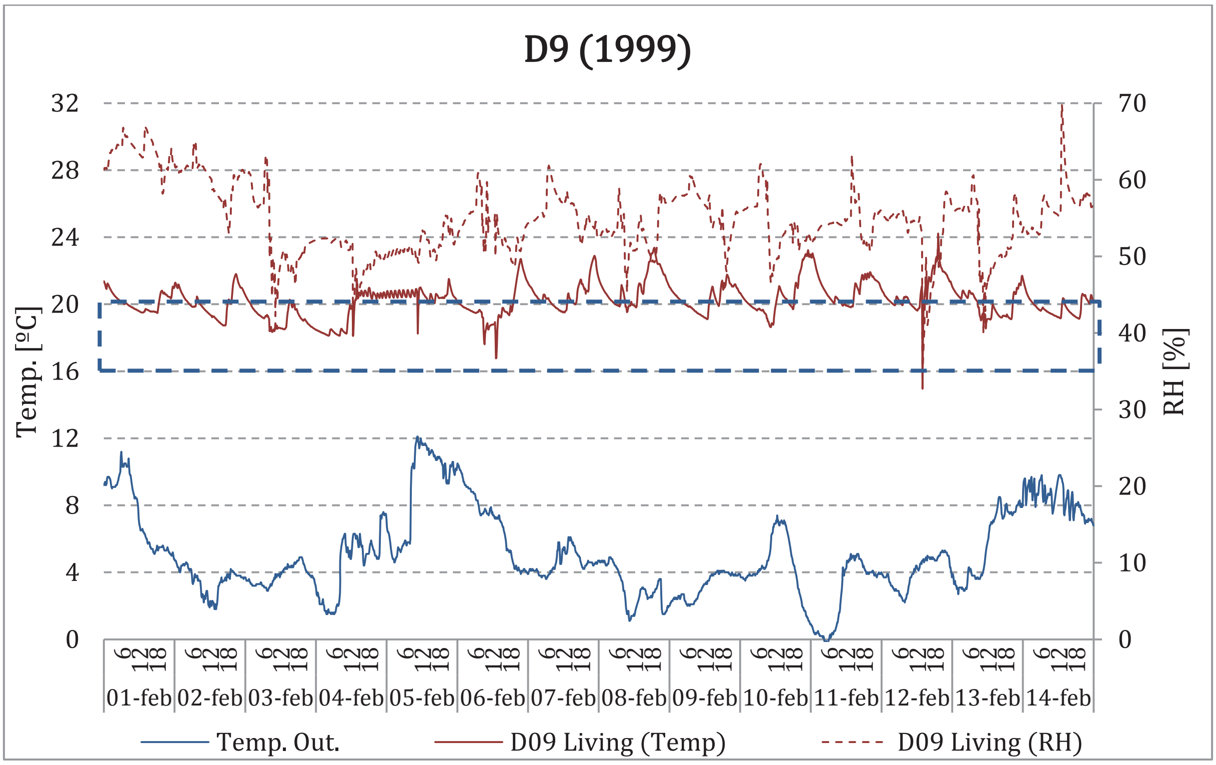

D4 (1952)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
80
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D4_Living (ºC)
D4_Room (ºC)

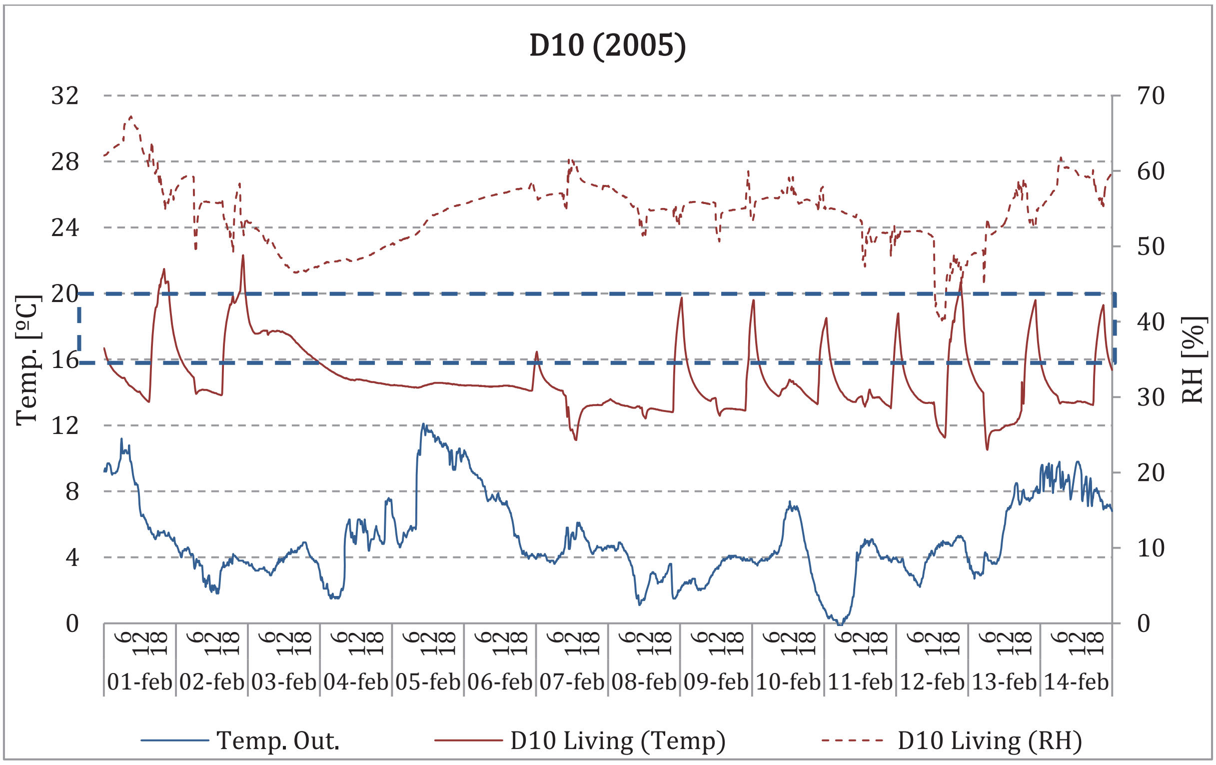

D5 (1960)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
80
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D5_Living (ºC)
D5_Bedroom (ºC)


D6 (1960)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
100
90
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
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)

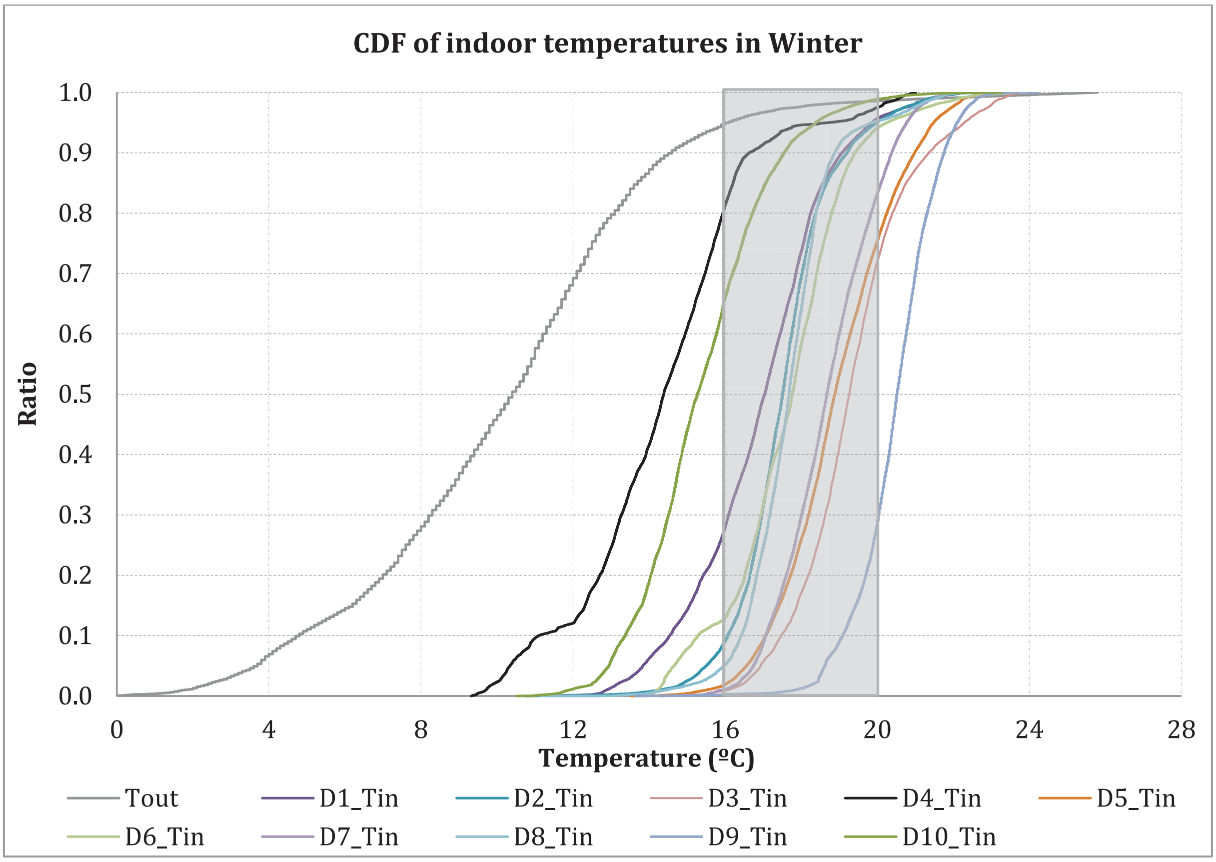

D8 (1999)
Temp. [ºC]
RH [%]
32
28
24
20
16
12
8
4
0
70
60
50
40
30
20
10
0
6
12
18
01-feb
02-feb
03-feb
04-feb
05-feb
06-feb
07-feb
08-feb
09-feb
10-feb
11-feb
12-feb
13-feb
14-feb
Out. Temp.
D06 Living (Temp)
D06 Living (RH)


D9 (1999)


D10 (2005)

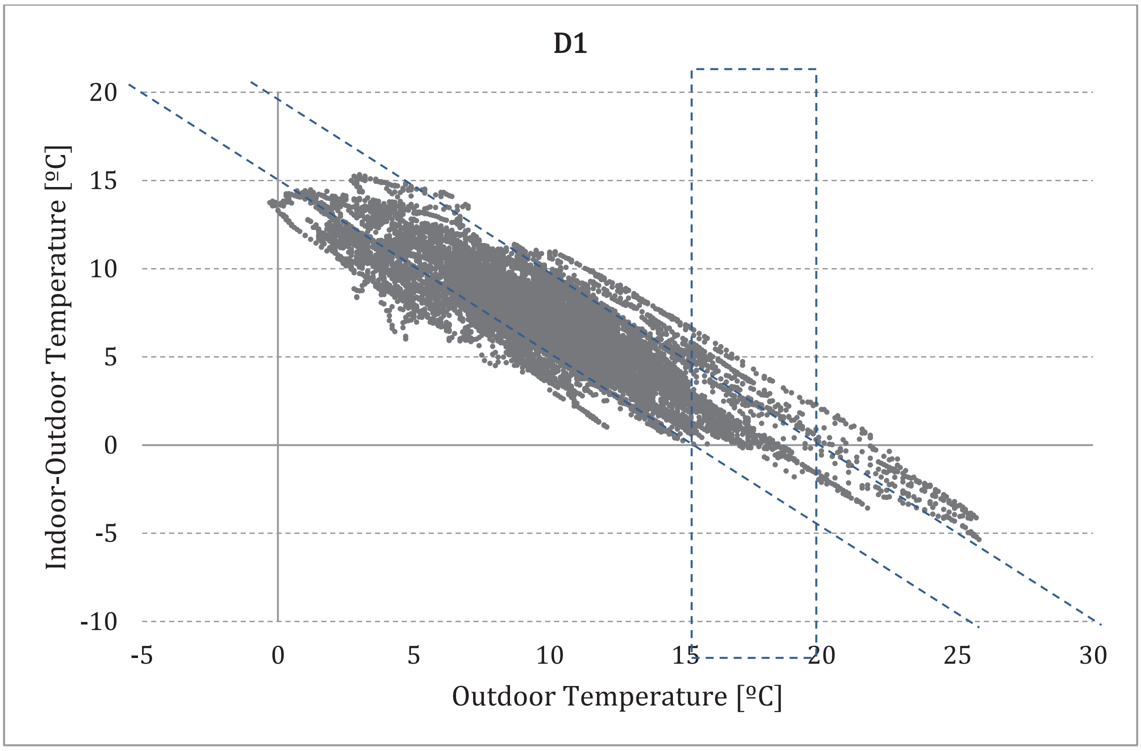
3 Neguko barne tenperaturaren banaketa funtzioak

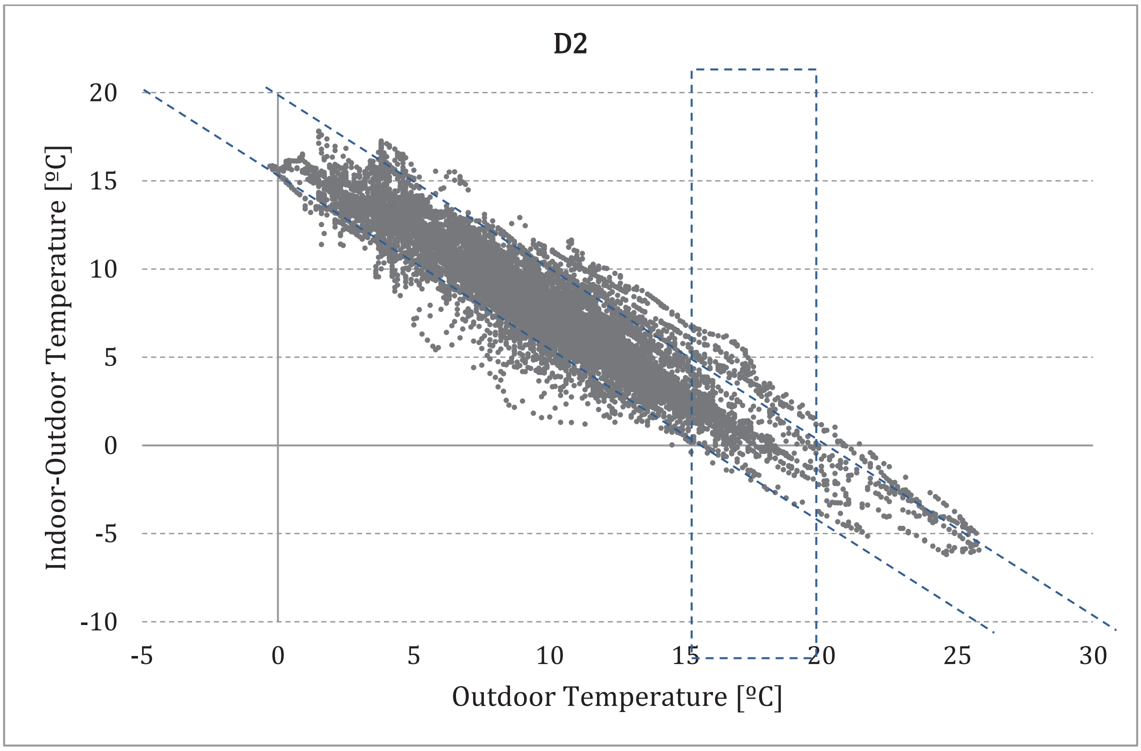
Aztertutako etxebizitza guztietan negualdian neurtutako tenperaturen banaketa funtzioak hurrengo grafikoan irudikatzen dira.

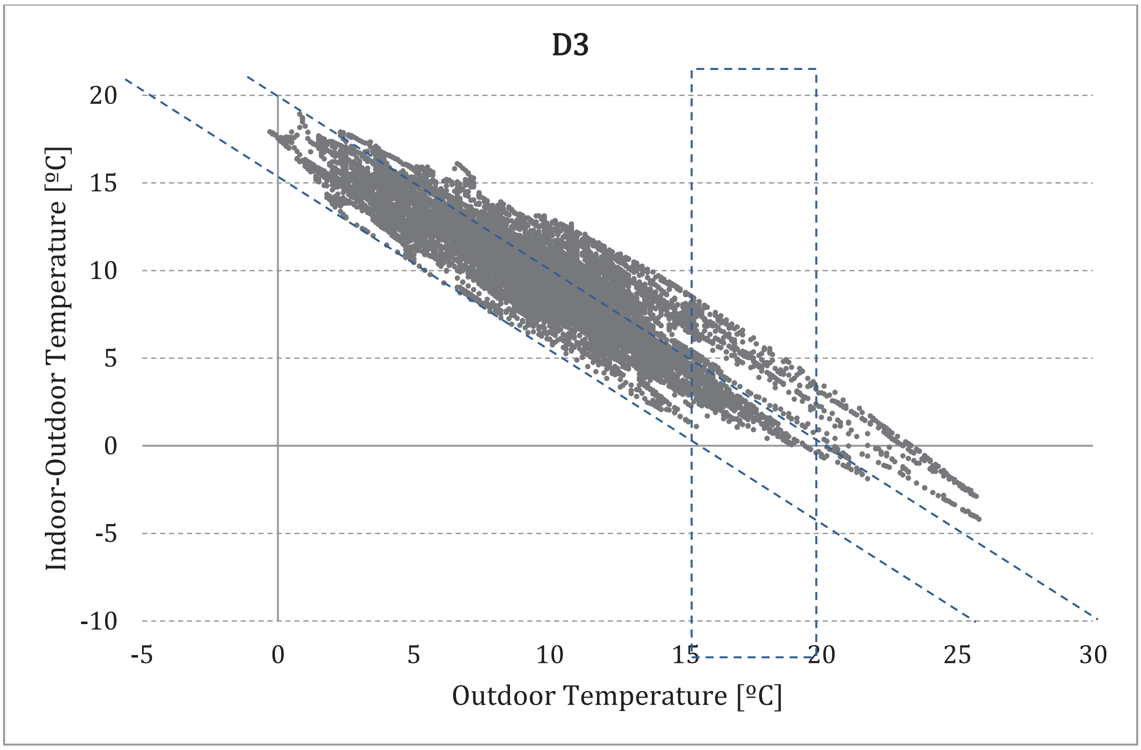


4 Barne - kanpo Vs kanpo tenperatura negualdian

Etxebizitza bakoitzaren barne eta kanpo tenperaturen arteko diferentzia kanpo tenperaturaren aurka hurrengo grafikoetan irudikatzen dira.






D3
Indoor-Outdoor Temperature [ºC]
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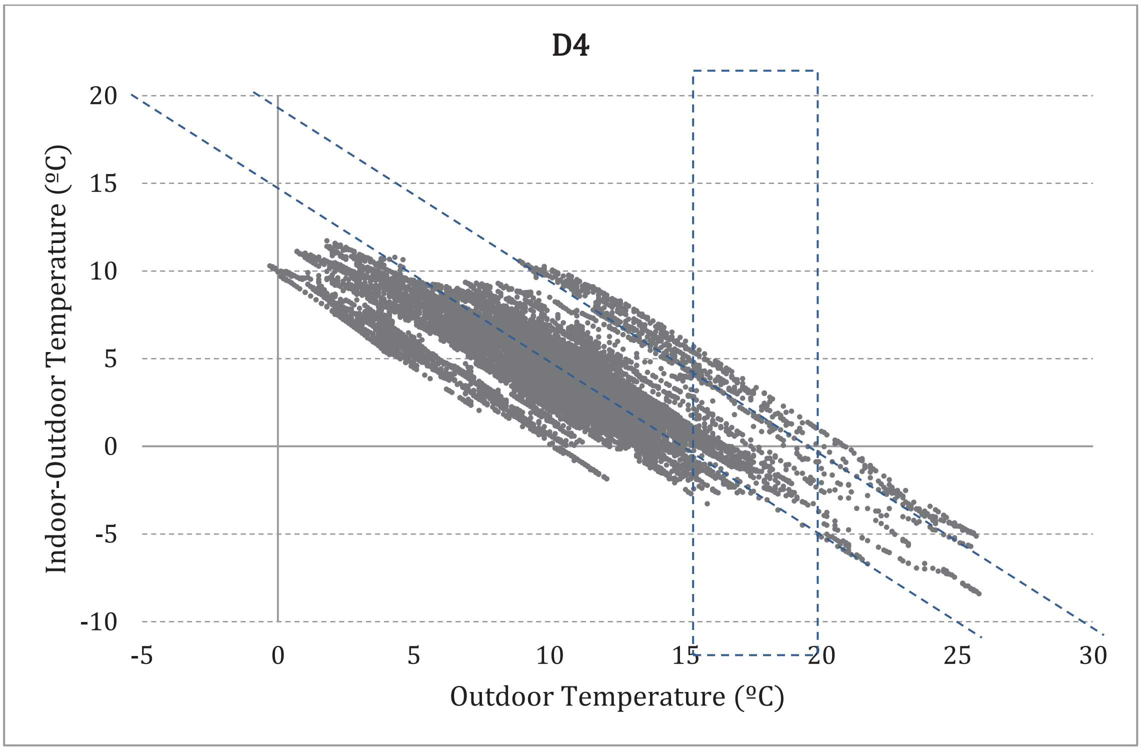
30
Outdoor Temperature [ºC]


D4
Indoor-Outdoor Temperature (ºC)
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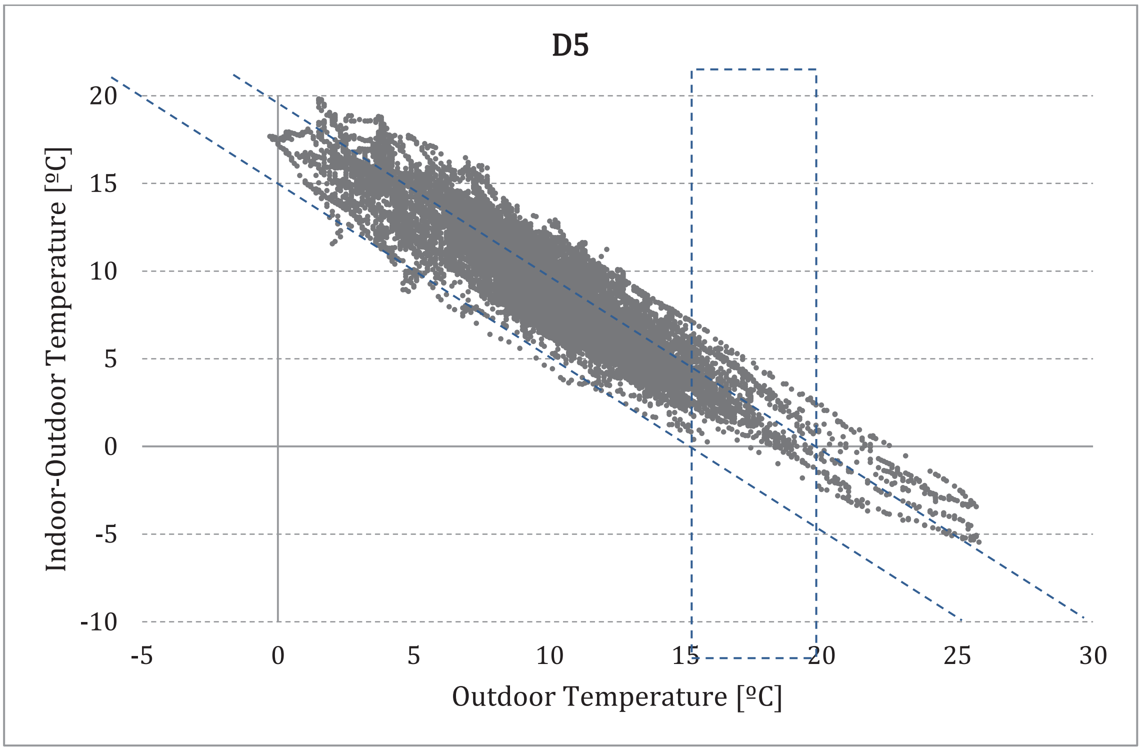
30
Outdoor Temperature (ºC)


D5
Indoor-Outdoor Temperature [ºC]
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-5
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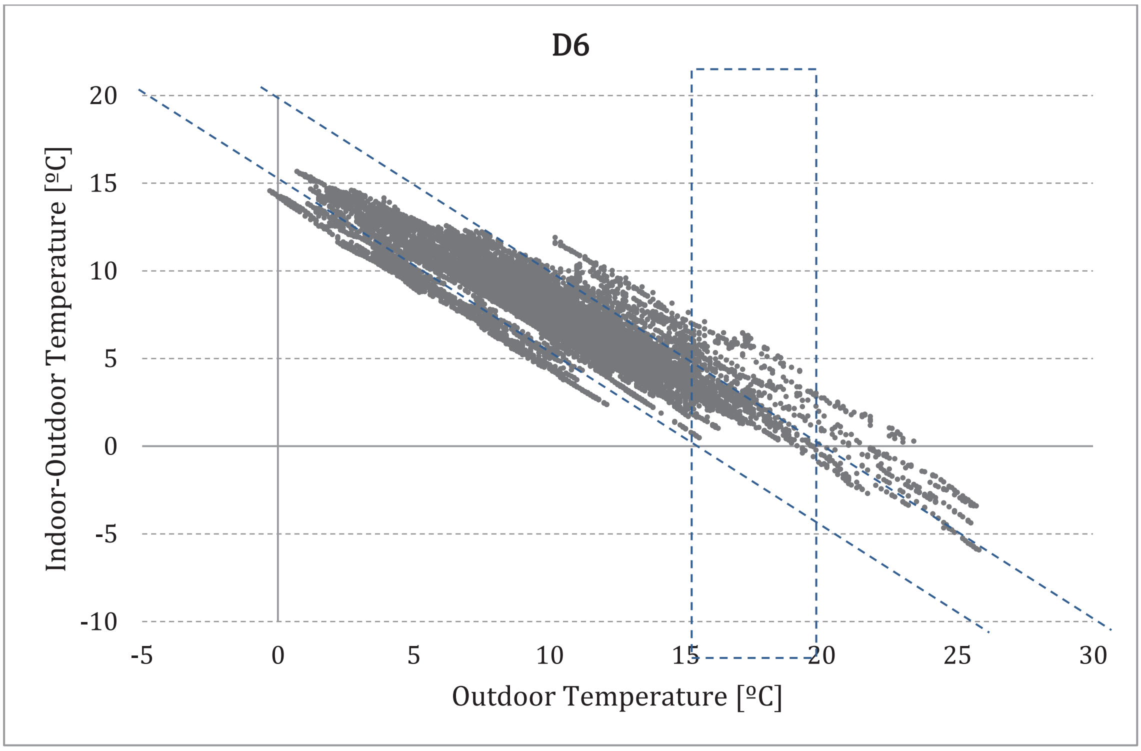
20
25
30
Outdoor Temperature [ºC]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Indoor-Outdoor Temperature [ºC]
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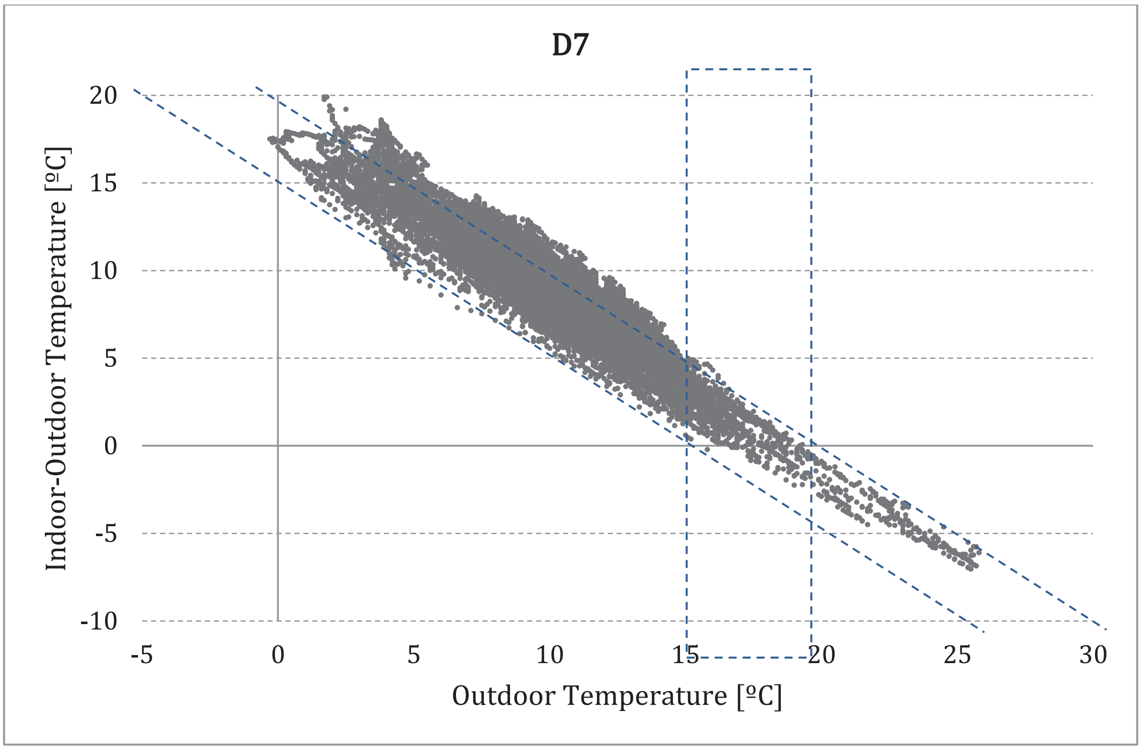
Outdoor Temperature [ºC]


D7
Indoor-Outdoor Temperature [ºC]
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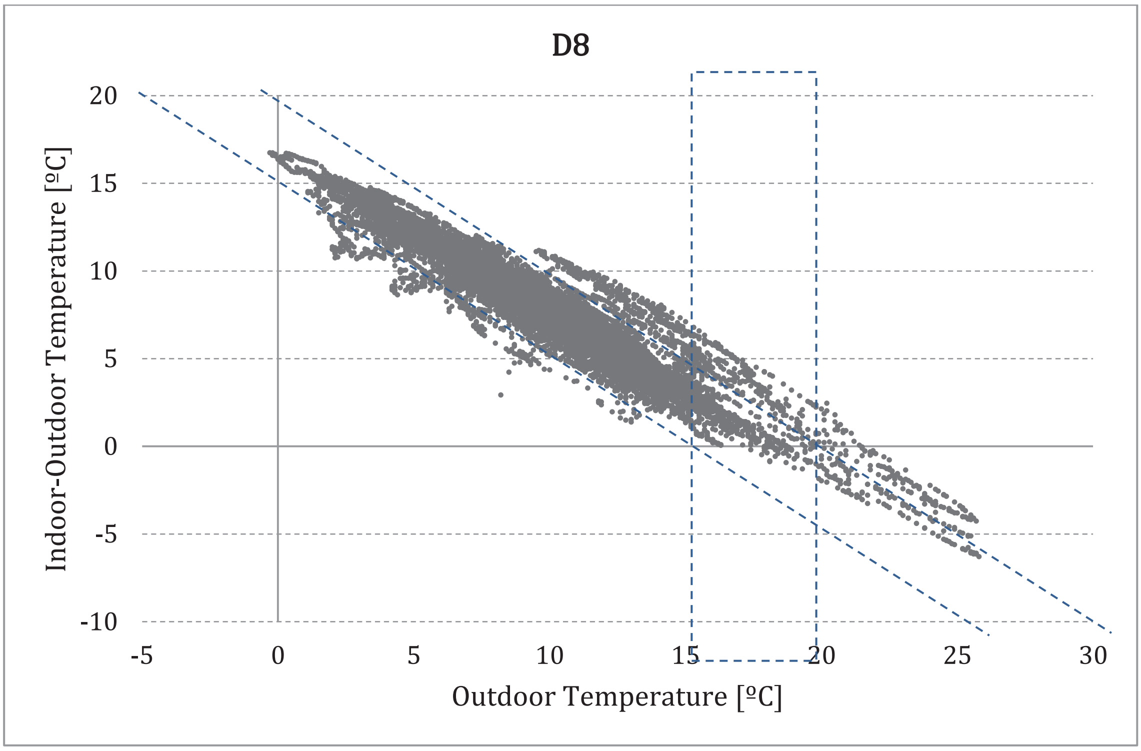
Outdoor Temperature [ºC]


D8
Indoor-Outdoor Temperature [ºC]
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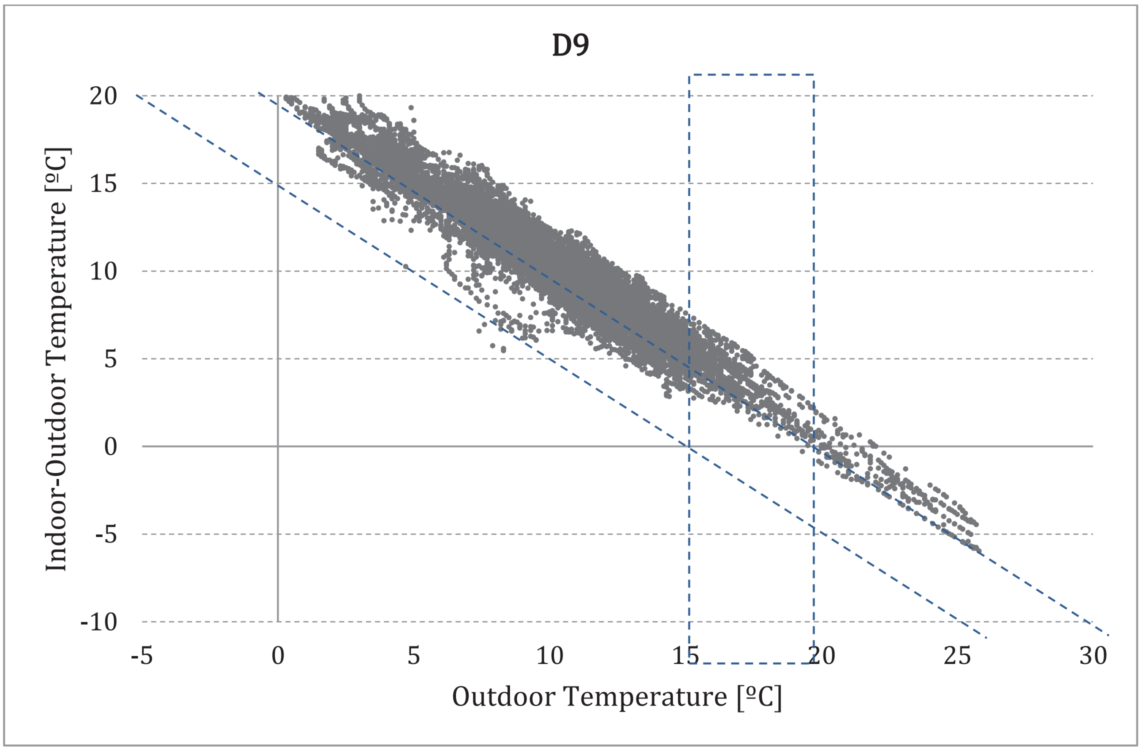
Outdoor Temperature [ºC]


D9
Indoor-Outdoor Temperature [ºC]
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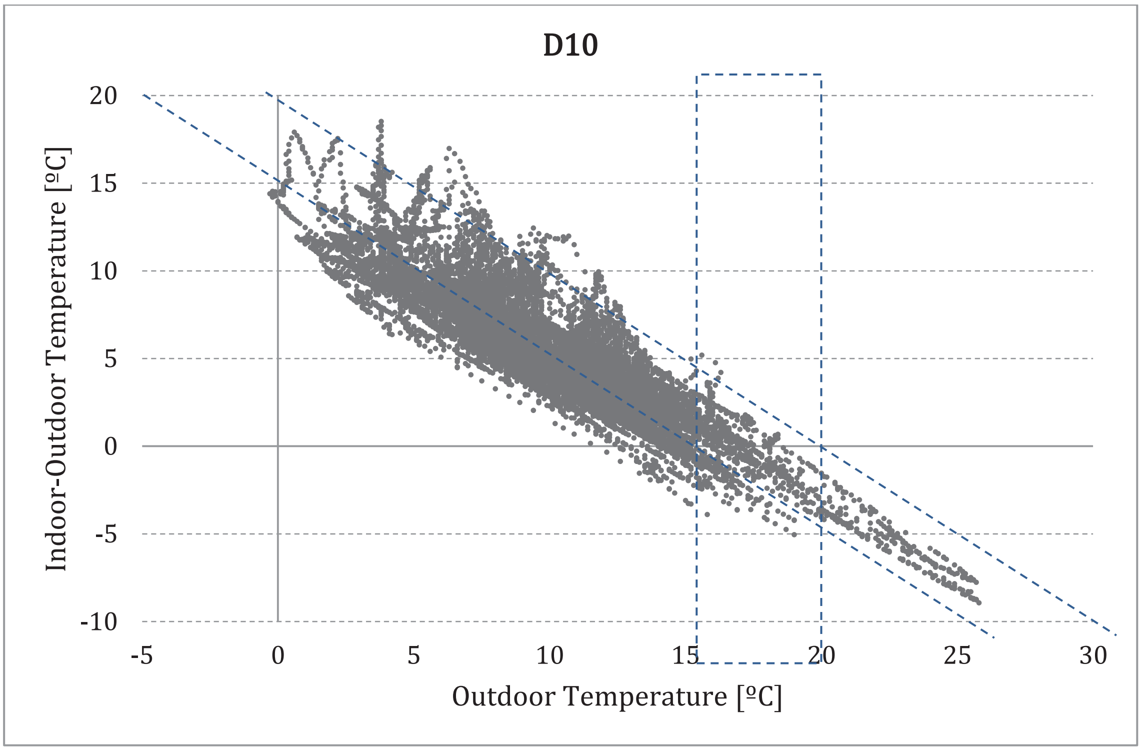
20
25
30
Outdoor Temperature [ºC]


D10
Indoor-Outdoor Temperature [ºC]
20
15
10
5
0
-5
-10
-5
0
5
10
15
20
25
30
Outdoor Temperature [ºC]

3.3. Eranskina: Gizarte etxebizitzaren portaera termikoaren analisia

- 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.

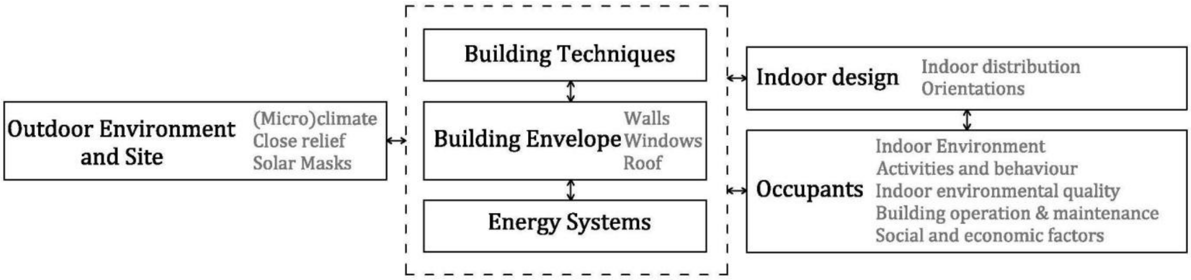


Fig. 1. Subsystems for investigation.

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 43^{o} 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.

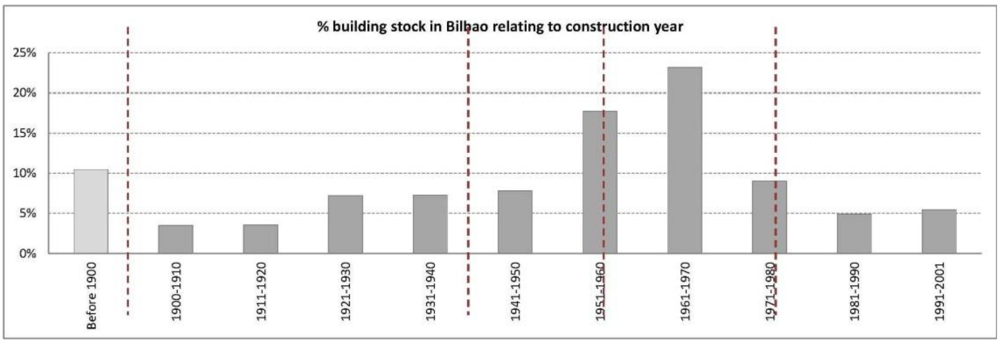


Fig. 2. Building stock in Bilbao in relation to construction year (Building Stock: 10044, year 2001, INE)

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

$$\mathrm{U_i} = \frac{1}{R_{in} + R_i + R_{out}}$$	**eq. 1**
$$\mathrm{C} = \sum \rho_i \cdot c_{p,i} \cdot e_i$$	**eq. 2**

Where:

R_{in}: is the internal surface thermal resistance (0.13 m^{2}K/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 m^{2}K/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

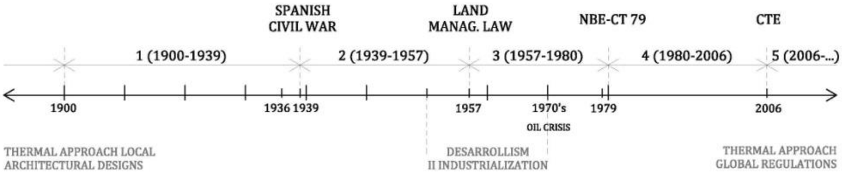
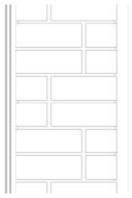
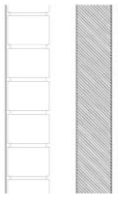
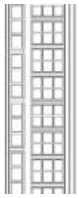
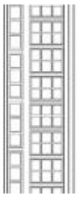
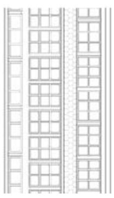
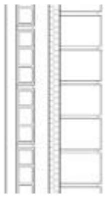
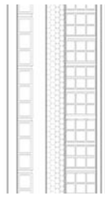


Fig. 3. Construction periods during twentieth century in Bilbao (Spain)

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/m^2.K] C[kJ/ m^2.K]	Constructive Section (in-out)	Period	U [w/m^2.K] C[kJ/ m^2.K]	Constructive Section (in-out)	Perio d
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. (m²)	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)

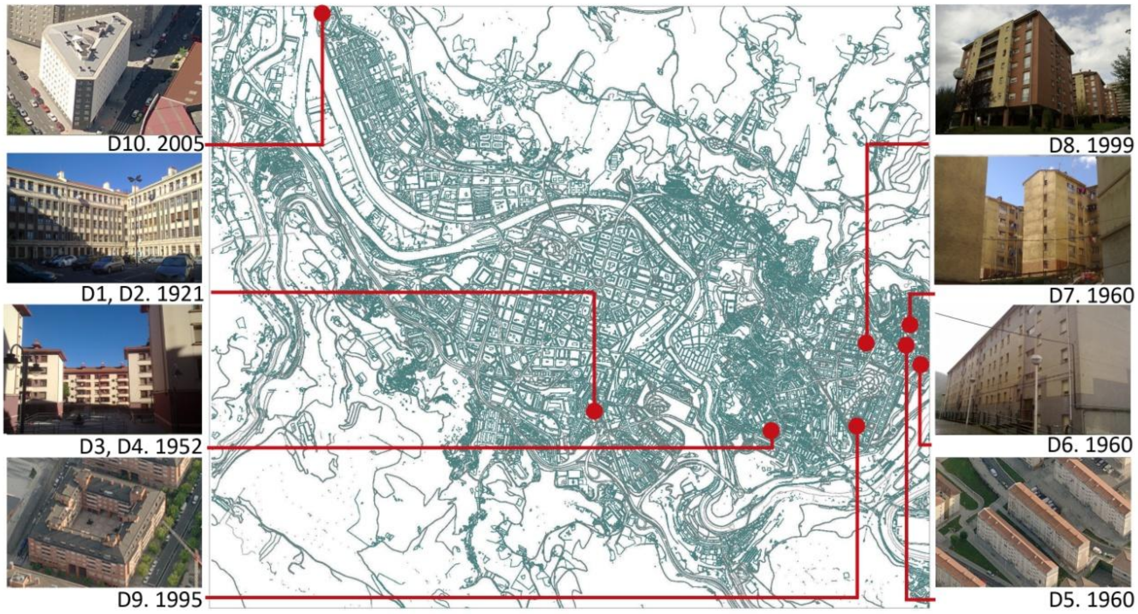


Fig. 4. Location of the ten case-studies.

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 ±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. 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]

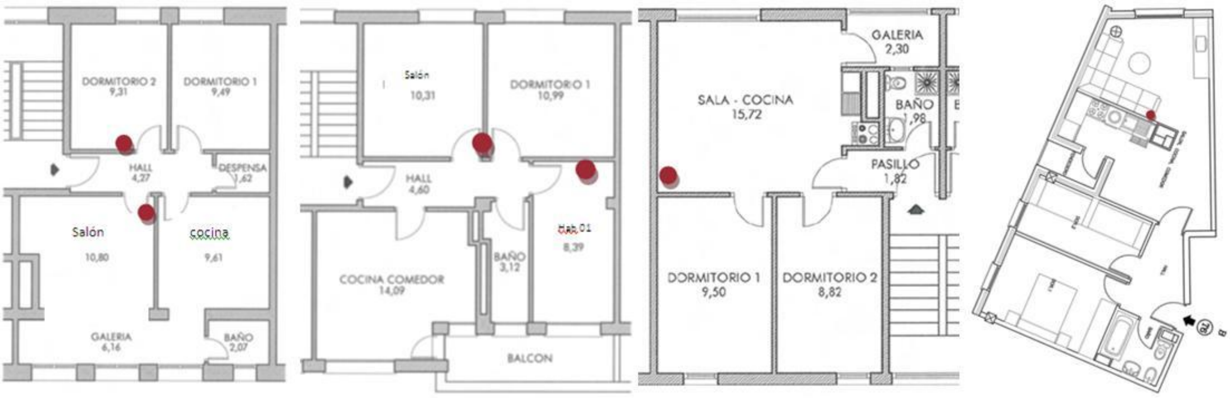


Fig. 5. Layout of some case studies (D1, D3-D4, D6 and D10).

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	m^2 (heated area)	Consumpt. [kWh/m^2.year]	Corrected Consumpt. [kWh/m^2.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.

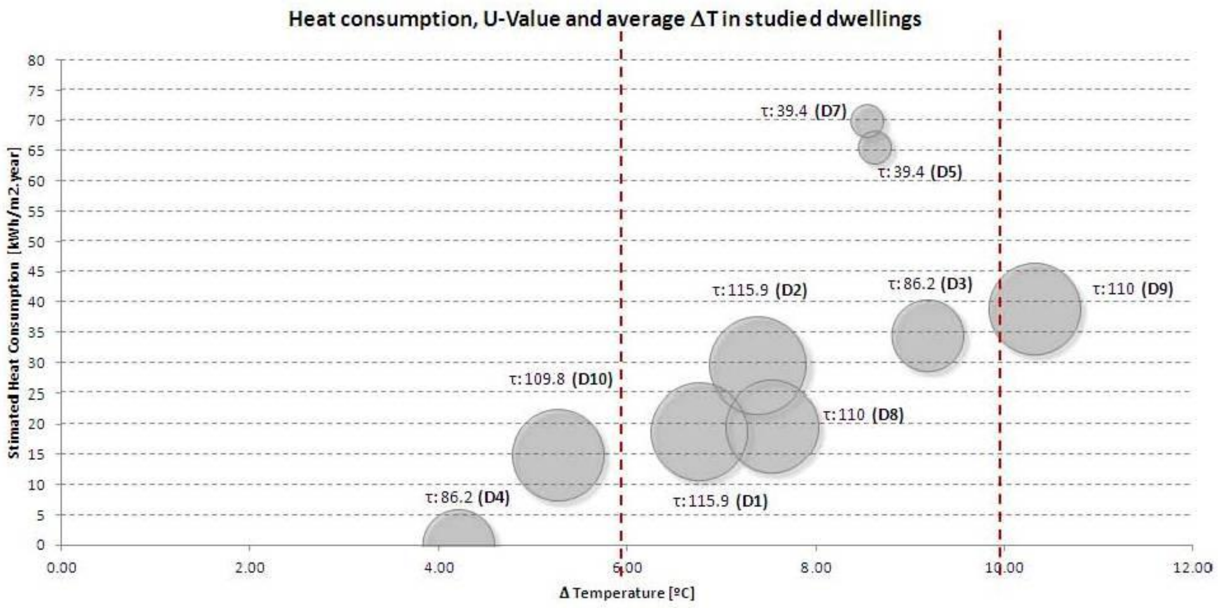


Fig. 6. Energy performance of the dwellings. Relation between yearly energy consumption per square meter of heated area, time constant and average ΔT. (Non available heating consumption data in D6) Outdoor Average: 10.17

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.

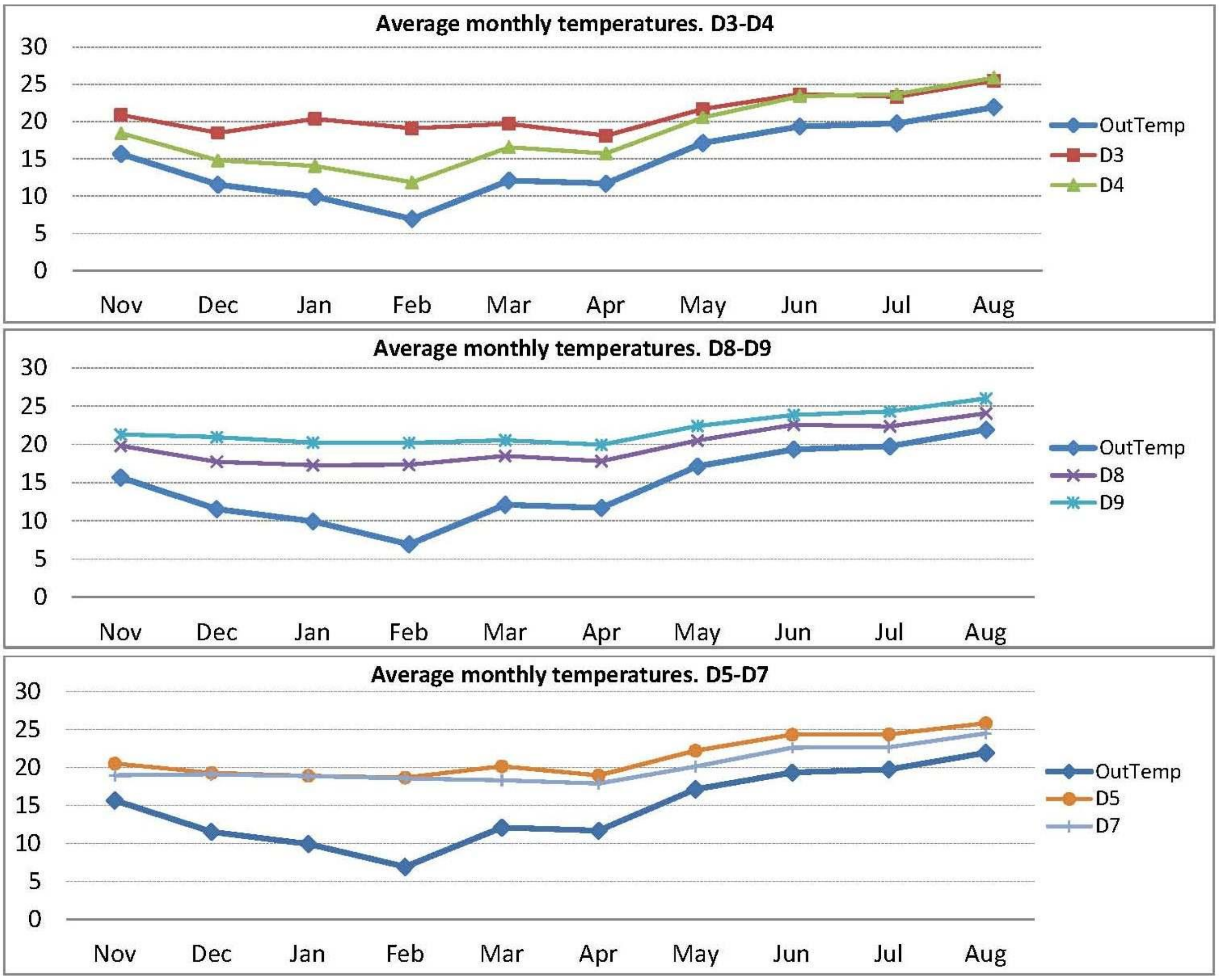


Fig. 7. Comparison of the monthly average temperatures in some studied dwellings.

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.

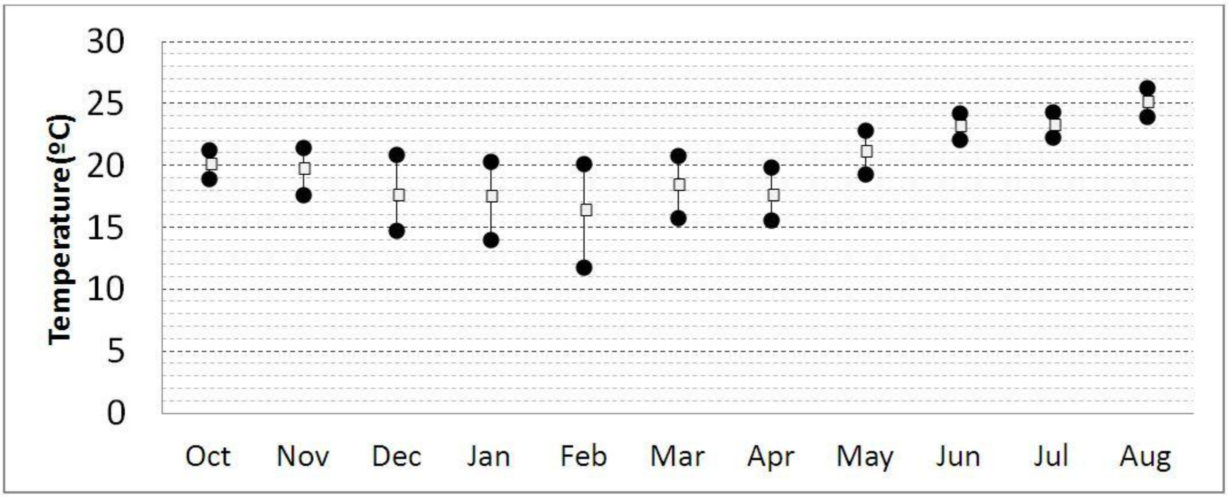


Fig. 8.Maximum, average and minimum monthly indoor temperatures for the 10 studied dwellings.

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).

		Winter Period (Dec-Mar)		Spring Period (Apr-May)		Summer Period (Jun-Aug)	
	C (kJ/ m^{2}K)	Diurnal Range (8-20h) (Δt_i)	Nocturnal Range (20-8h) (Δt_i)	Diurnal Range (8-20h) (Δt_i)	Nocturnal Range (20-8h) (Δt_i)	Diurnal Range (8-20h) (Δt_i)	Nocturnal Range (20-8h) (Δt_i)
(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.

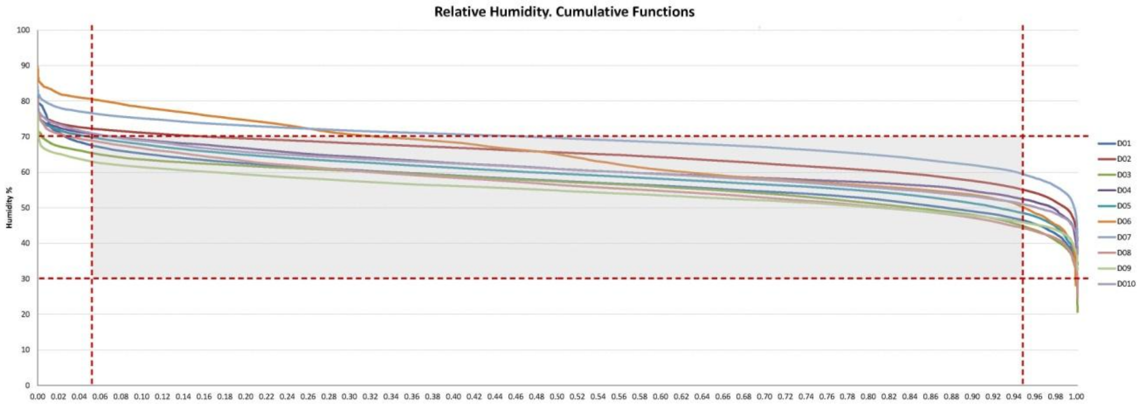


Fig. 9.Relative Humidity in the Dwellings. Cumulative Distribution Function.

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.

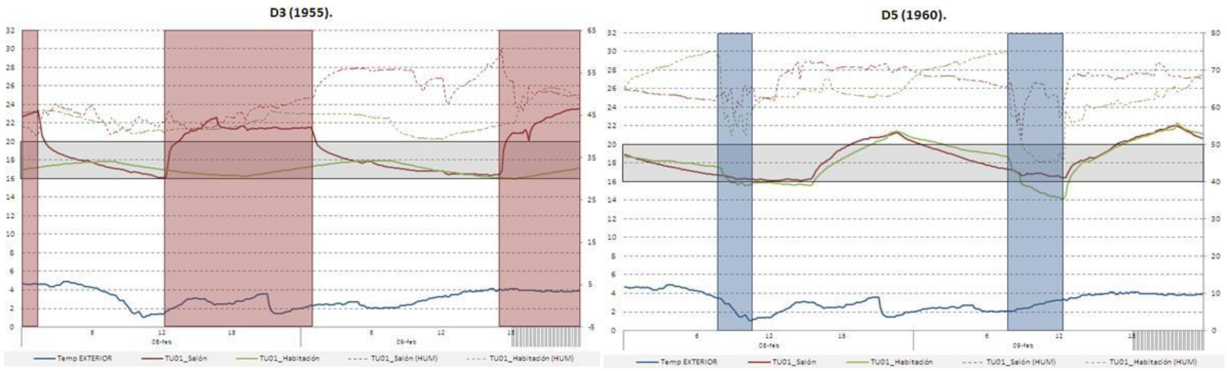


Fig. 10. 48-h analysis. Identification of heating system activation (left graph) or opening windows (right graph)

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.

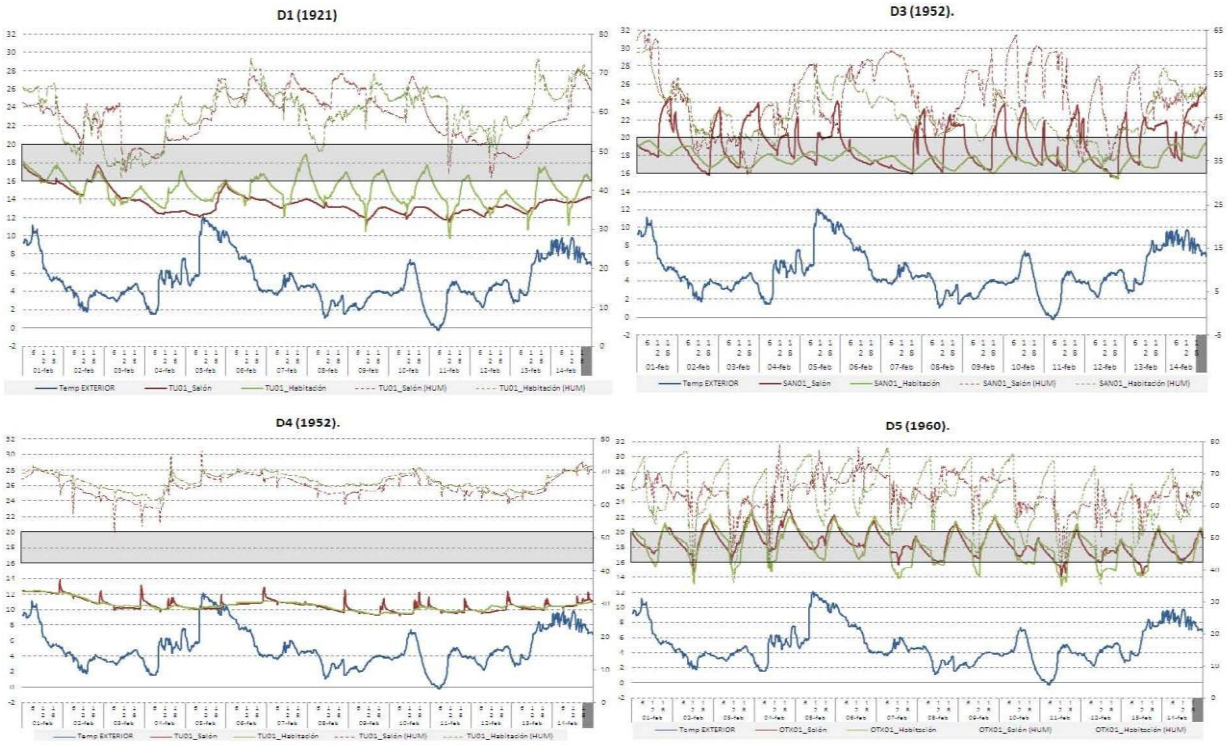


Fig. 11. Indoor RH and Temperature and outdoor temperature for D1, D3, D4 and D5 dwellings during 15-day period in winter.

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)

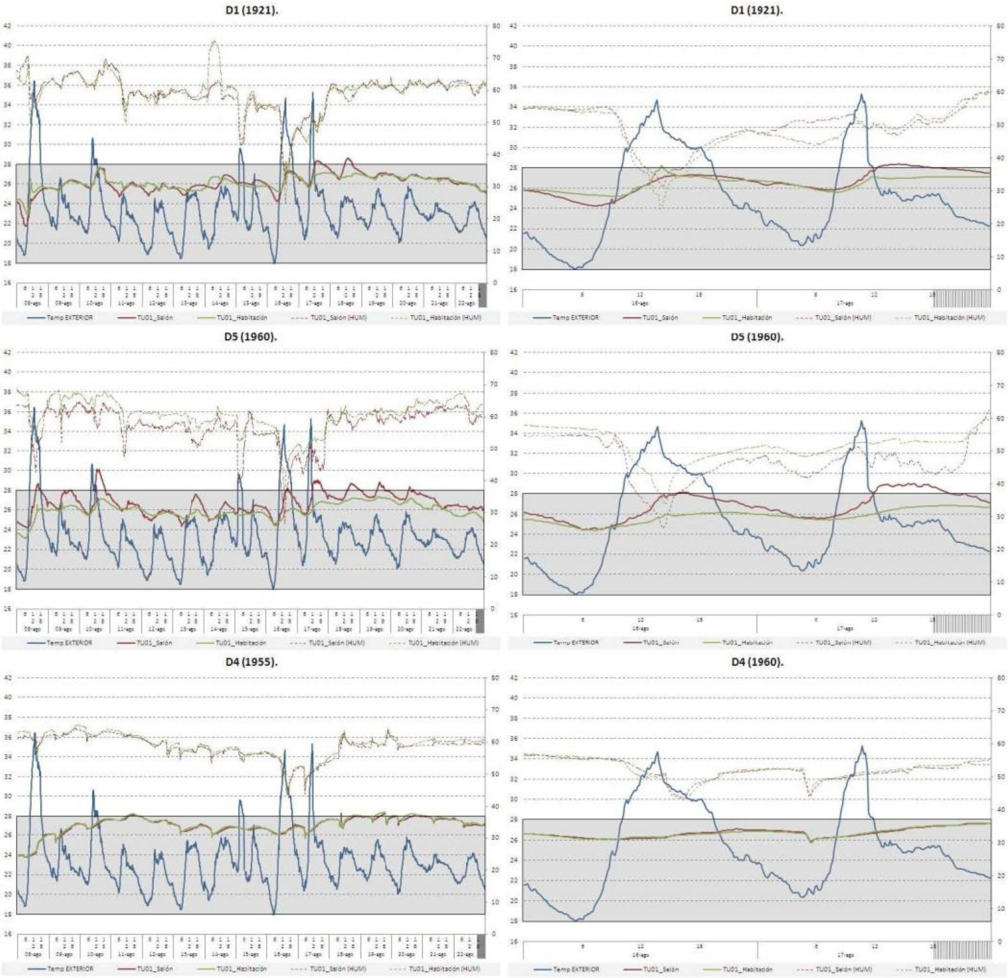


Fig. 12. 15-day and 48-hour period (the hottest period) analyses for D1, D4 and D5 in summer.

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.

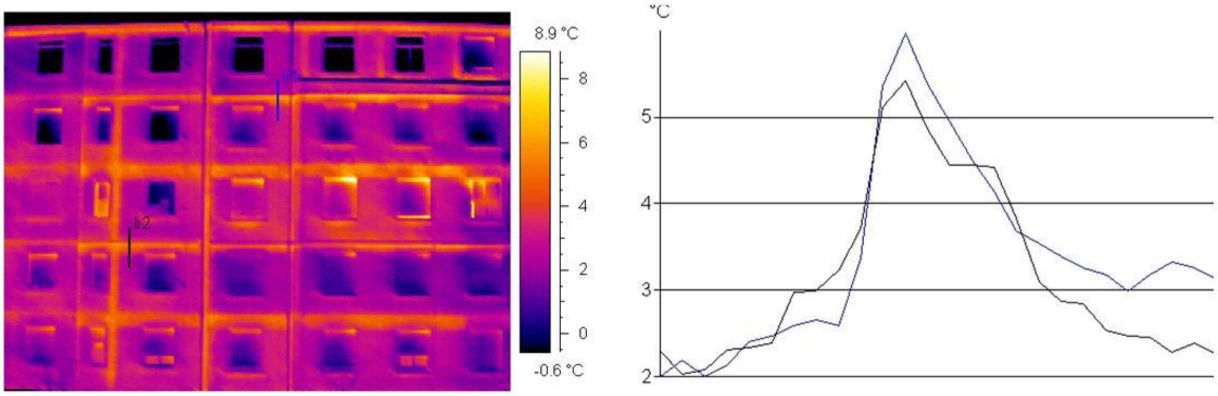


Fig. 13. Temperature profile in the slab face thermal bridge of dwelling D2.

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.

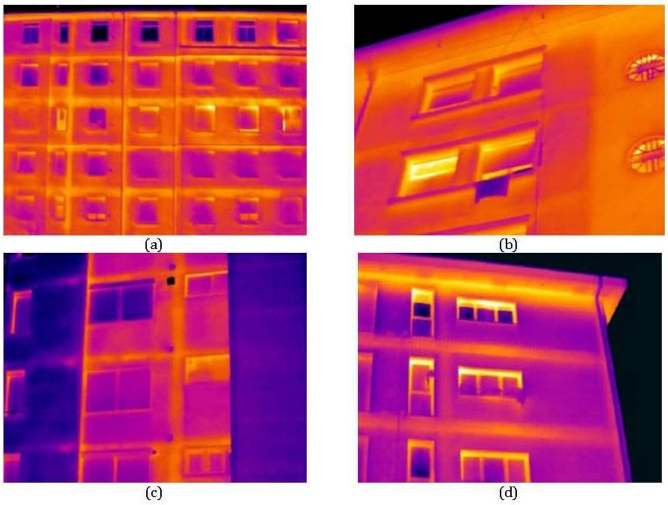


Fig. 14. Thermographs of some buildings studied (a) D2; (b) D3; (c) D5; (d) D8.

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.

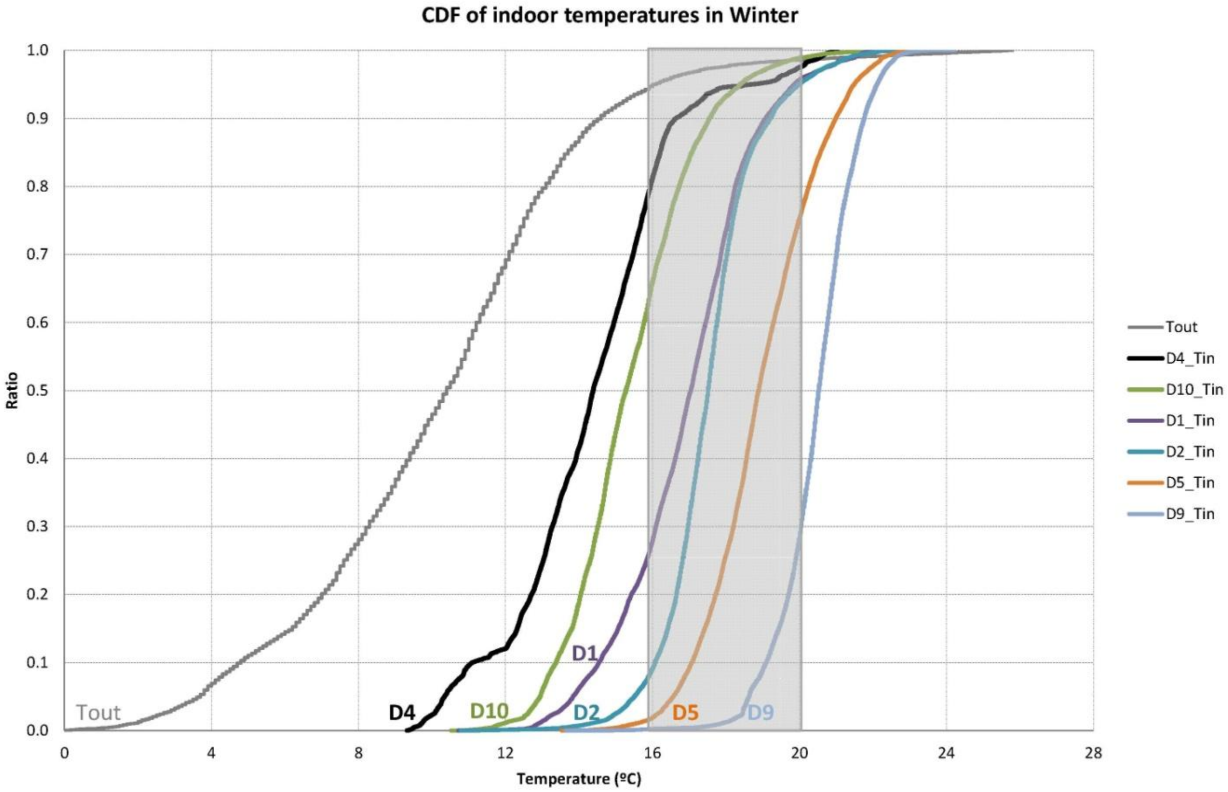


Fig. 15. Cumulative Distribution Function of 6 studied dwellings in winter (D4, D10, D1, D2, D5 and D9).

	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.

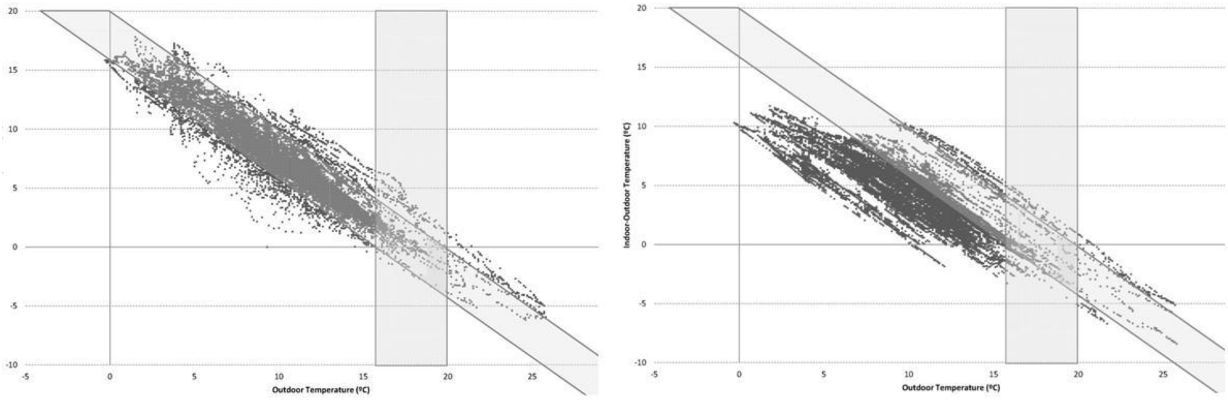


Fig. 16. Indoor-Outdoor temperature against outdoor temperatures in wintertime. (D2 and D4).

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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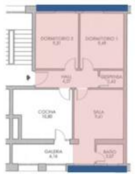
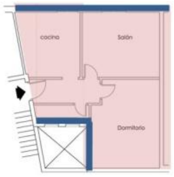
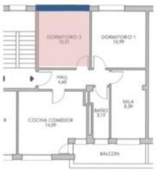
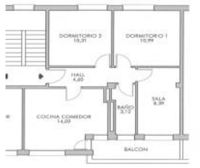
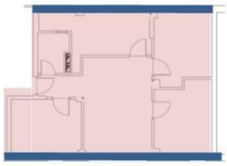
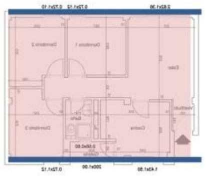
10 Appendix

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**

	m^2 façade (of heated area)	EF		m^2 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= m^2 heated area /m^2 façade of heated area)

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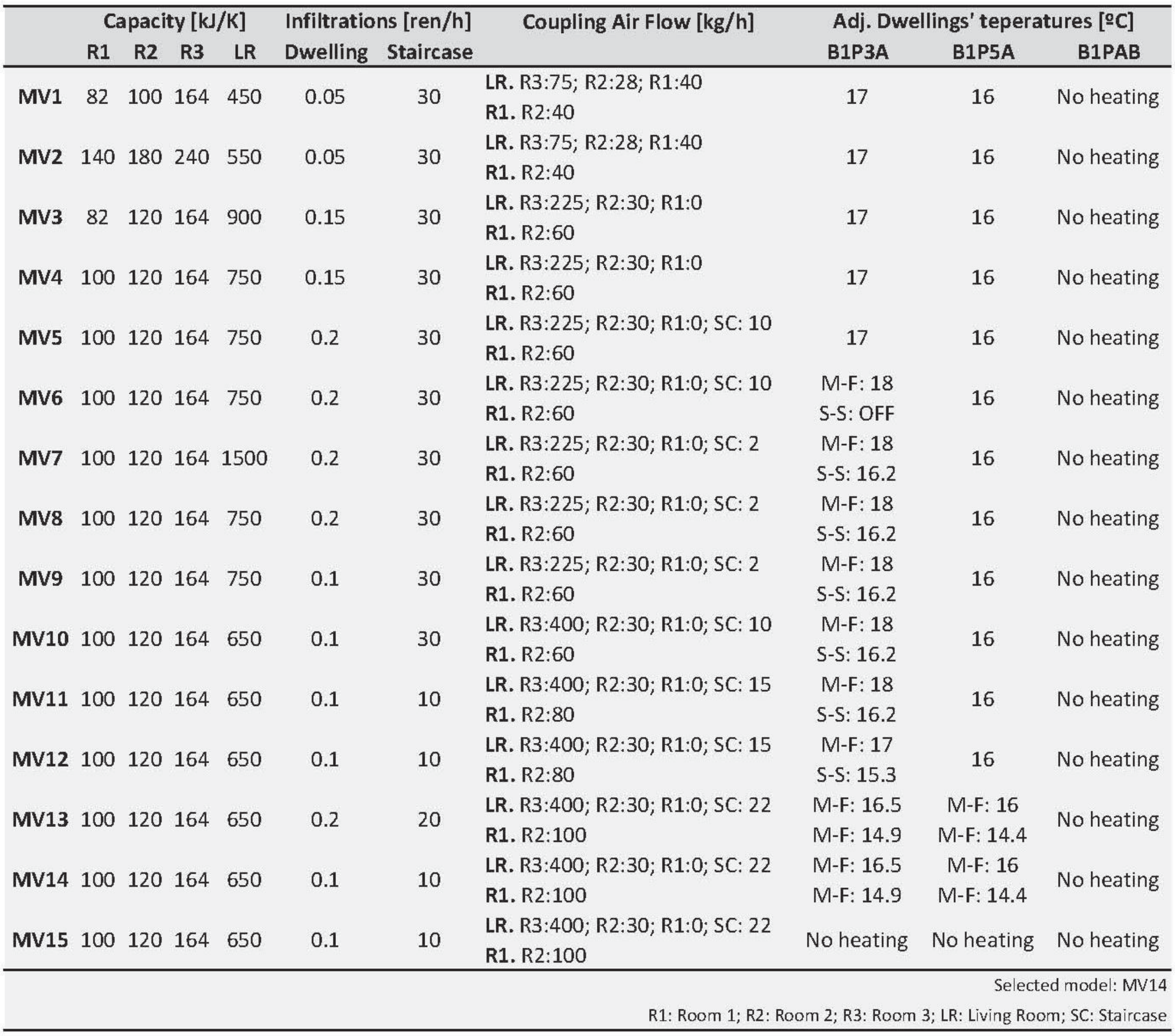
5.1. Eranskina: Ereduen parametroen konbinazioa



	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. Aztertutako azken 15 ereduen parametroen konbinazioa

5.2. Eranskina: Baliozkotutako ereduaren emaitzen analisia

Egokitutako eredu baten hondarrak neurtutako datuen eta ereduak emandakoen arteko diferentziak dira. Grafikoak aztertzean egindako hondarren analisi kualitatiboaz gain, analisi kuantitatibo sinplea garatu zen ere. Beraz, eredu bakoitzeko hondarren balio absoluen batezbestekoa, hondarren balio errealen batezbestekoa, eta nodo bakoitzaren eta etxebizitza osoaren datuen desbiderapen tipikoa zein banaketa normala aztertu ziren.

		Hondarren analisia			
		Batezbestekoa (Balio absol)	Batezbestekoa (Balio err)	Desbiderapen tipikoa	Banaketa normala
V1	***Etxebizitza***	***0.45***	**0.11**	***0.53***	***0.41***
	Gela 1	0.44	- 0.08	0.52	0.56
	Gela 2	0.38	0.04	0.49	0.46
	Gela 3	0.76	- 0.70	0.55	0.90
	Egongela	0.57	0.03	0.68	0.48
V2	***Etxebizitza***	***0.44***	**0.11**	***0.52***	***0.42***
	Gela 1	0.42	- 0.09	0.50	0.57
	Gela 2	0.38	0.04	0.48	0.47
	Gela 3	0.75	- 0.71	0.54	0.91
	Egongela	0.54	0.02	0.65	0.49
V3	***Etxebizitza***	***0.54***	**0.41**	***0.53***	***0.22***
	Gela 1	0.46	0.29	0.50	0.28
	Gela 2	0.49	0.37	0.49	0.22
	Gela 3	0.51	- 0.29	0.54	0.71
	Egongela	0.58	0.24	0.66	0.36
V4	***Etxebizitza***	***0.51***	**0.34**	***0.52***	***0.25***
	Gela 1	0.43	0.06	0.53	0.46
	Gela 2	0.43	0.25	0.49	0.31
	Gela 3	0.49	- 0.29	0.52	0.71
	Egongela	0.55	0.23	0.64	0.36
V5	***Etxebizitza***	***0.62***	**0.54**	***0.53***	***0.15***
	Gela 1	0.46	0.18	0.54	0.37
	Gela 2	0.50	0.39	0.50	0.22
	Gela 3	0.45	- 0.10	0.53	0.58
	Egongela	0.65	0.46	0.64	0.24
V6	***Etxebizitza***	***0.59***	**0.51**	***0.51***	***0.16***
	Gela 1	0.43	0.17	0.52	0.37
	Gela 2	0.47	0.37	0.47	0.21
	Gela 3	0.44	- 0.13	0.50	0.60
	Egongela	0.61	0.42	0.63	0.25
V7	***Etxebizitza***	***0.50***	**0.36**	***0.49***	***0.23***
	Gela 1	0.42	0.11	0.51	0.41
	Gela 2	0.43	0.30	0.46	0.26
	Gela 3	0.43	- 0.26	0.46	0.71
	Egongela	0.50	0.22	0.58	0.35

		Hondarren analisia			
		Batezbestekoa (Balio absol)	Batezbestekoa (Balio err)	Desbiderapen tipikoa	Banaketa normala
V8	***Etxebizitza***	***0.52***	**0.37**	***0.51***	***0.23***
	Gela 1	0.43	0.11	0.53	0.41
	Gela 2	0.45	0.30	0.48	0.26
	Gela 3	0.47	- 0.25	0.51	0.69
	Egongela	0.55	0.24	0.63	0.35
V9	***Etxebizitza***	***0.44***	**0.18**	***0.50***	***0.36***
	Gela 1	0.43	- 0.08	0.52	0.56
	Gela 2	0.37	0.10	0.47	0.41
	Gela 3	0.56	- 0.45	0.50	0.81
	Egongela	0.52	0.04	0.62	0.48
V10	***Etxebizitza***	***0.45***	**0.22**	***0.51***	***0.33***
	Gela 1	0.43	- 0.06	0.52	0.55
	Gela 2	0.38	0.13	0.47	0.40
	Gela 3	0.53	- 0.39	0.51	0.78
	Egongela	0.54	0.09	0.64	0.44
V11	***Etxebizitza***	***0.43***	**0.16**	***0.50***	***0.37***
	Gela 1	0.43	- 0.09	0.51	0.57
	Gela 2	0.37	0.08	0.47	0.43
	Gela 3	0.56	- 0.46	0.50	0.82
	Egongela	0.53	0.03	0.62	0.48
V12	***Etxebizitza***	***0.44***	**0.21**	***0.50***	***0.34***
	Gela 1	0.43	- 0.07	0.51	0.55
	Gela 2	0.37	0.10	0.47	0.41
	Gela 3	0.54	- 0.42	0.50	0.80
	Egongela	0.53	0.09	0.62	0.44
V13	***Etxebizitza***	***0.56***	**0.48**	***0.49***	***0.17***
	Gela 1	0.42	0.12	0.51	0.41
	Gela 2	0.42	0.29	0.46	0.26
	Gela 3	0.44	- 0.16	0.50	0.63
	Egongela	0.59	0.41	0.62	0.25
V14	***Etxebizitza***	***0.39***	**0.16**	***0.46***	***0.36***
	Gela 1	0.45	- 0.27	0.46	0.72
	Gela 2	0.34	- 0.02	0.43	0.51
	Gela 3	0.55	- 0.47	0.46	0.84
	Egongela	0.50	0.11	0.59	0.43
V15	***Etxebizitza***	***0.85***	**0.83**	***0.60***	***0.08***
	Gela 1	0.48	0.27	0.55	0.31
	Gela 2	0.59	0.55	0.52	0.15
	Gela 3	0.50	0.19	0.60	0.38
	Egongela	0.93	0.86	0.74	0.12

7.1. Eranskina: Irizpide ekonomikoak, energetikoak eta ingurugiroari lotutakoak

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.

$$S_{7.f.r.w.} = \eta_{HS} \cdot \left(ED_{7.0.0.0.} - ED_{7.f.r.w.}\right) \cdot C_{N.G.} \quad \text{Eq. 44}$$

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.

$$PP_{Simple} = \frac{I[€]}{S[€/year]} \quad \text{Eq. 45}$$

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.

$$DPP = \frac{-ln\left(1 - \frac{r \cdot I}{S_n}\right)}{ln(1 + r)} \quad \text{Eq. 46}$$

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:

$$NPV = -I + \sum_{n=0}^{LS} \frac{S_n}{(1+r)^n} \quad \text{Eq. 47}$$

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.

$$NPV = -I + \sum_{n=0}^{LS} \frac{S_n}{(1+r^*)^n} = 0 \quad \text{Eq. 48}$$

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	[tCO2]	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	[tCO2]	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	[tCO2]	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	[tCO2]	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.

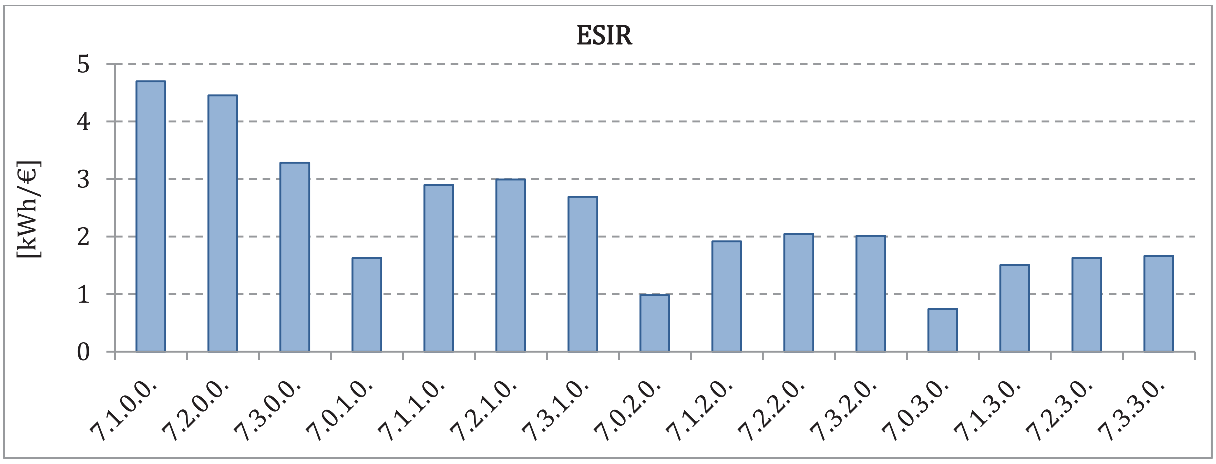


Fig. A.7.1. 2. ESIR

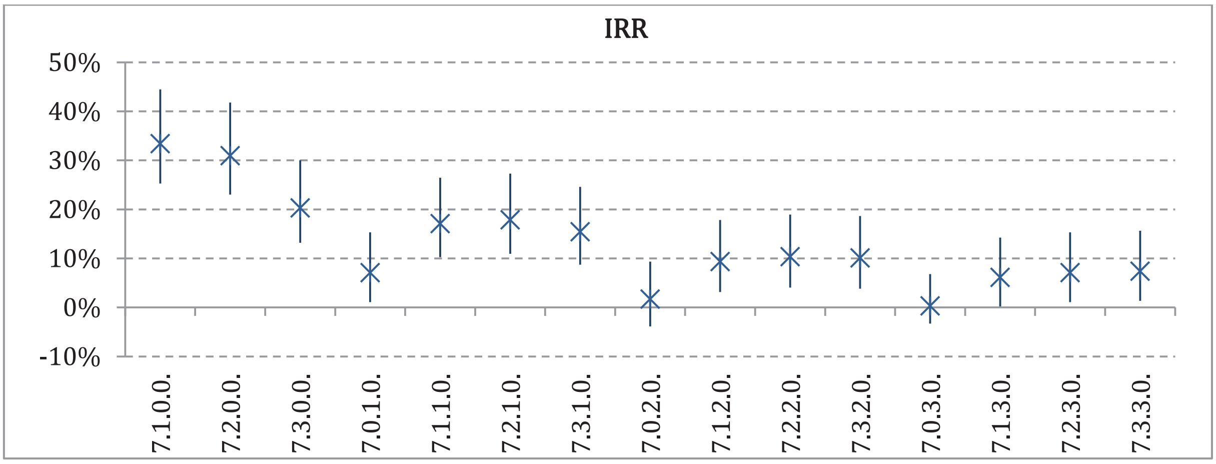


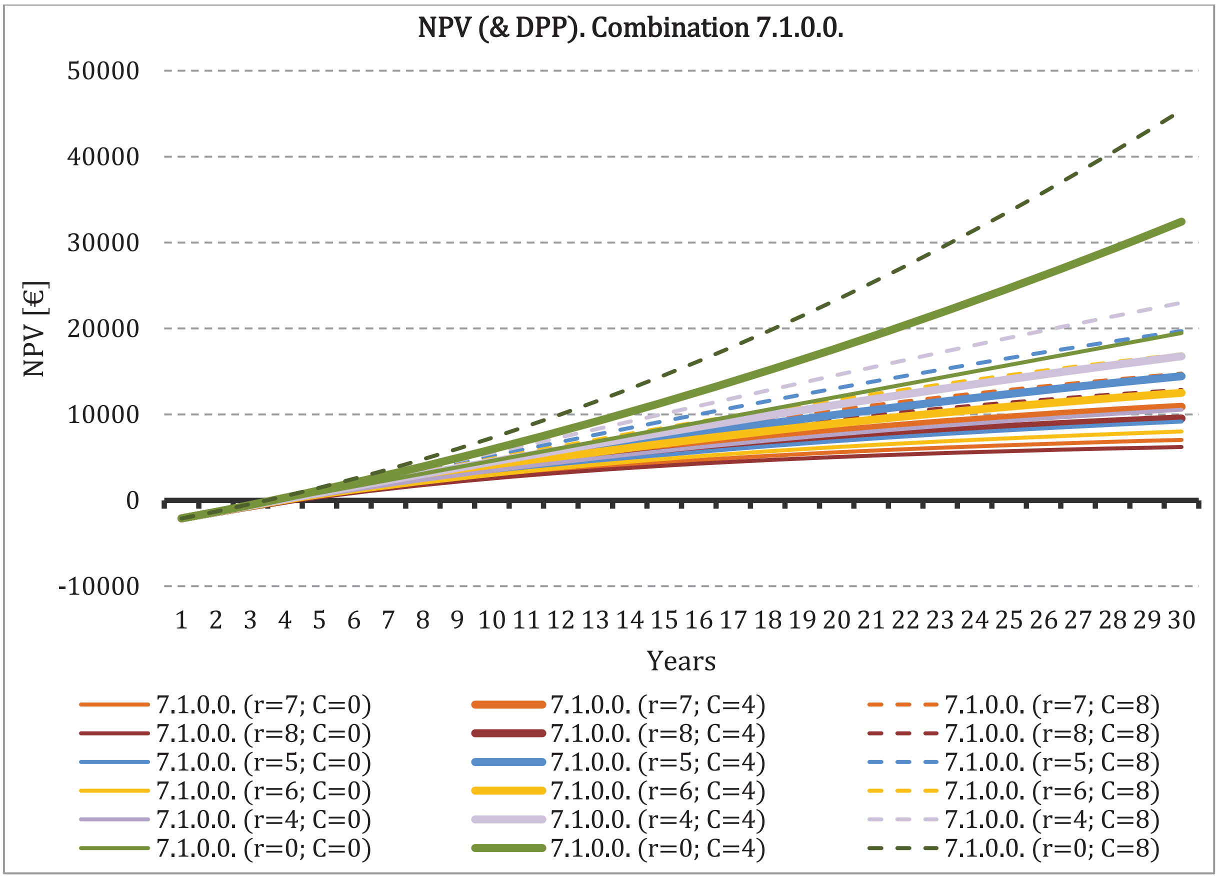
Fig. A.7.1. 3 Maximum, minimum and average IRR values

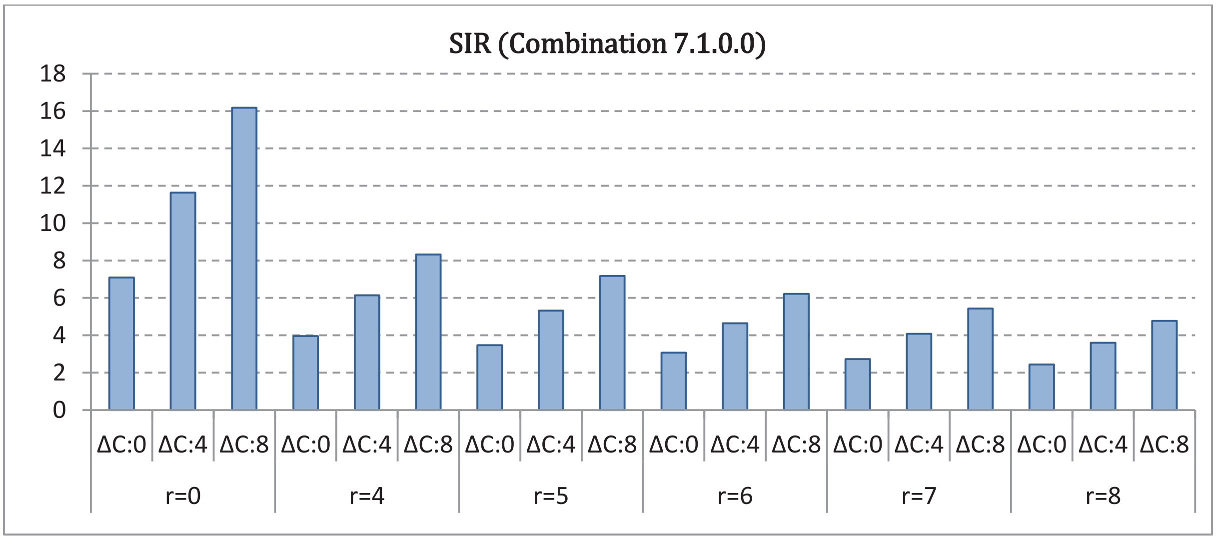
Economic values for each assessed scenario are presented in the following charts. Mentioned values are presented in two graphs and one table for each model. The first graph depicts the NPV during the considered lifespan (30 years). Moreover, this graph also depicts the depreciated payback period (DPP) 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/€

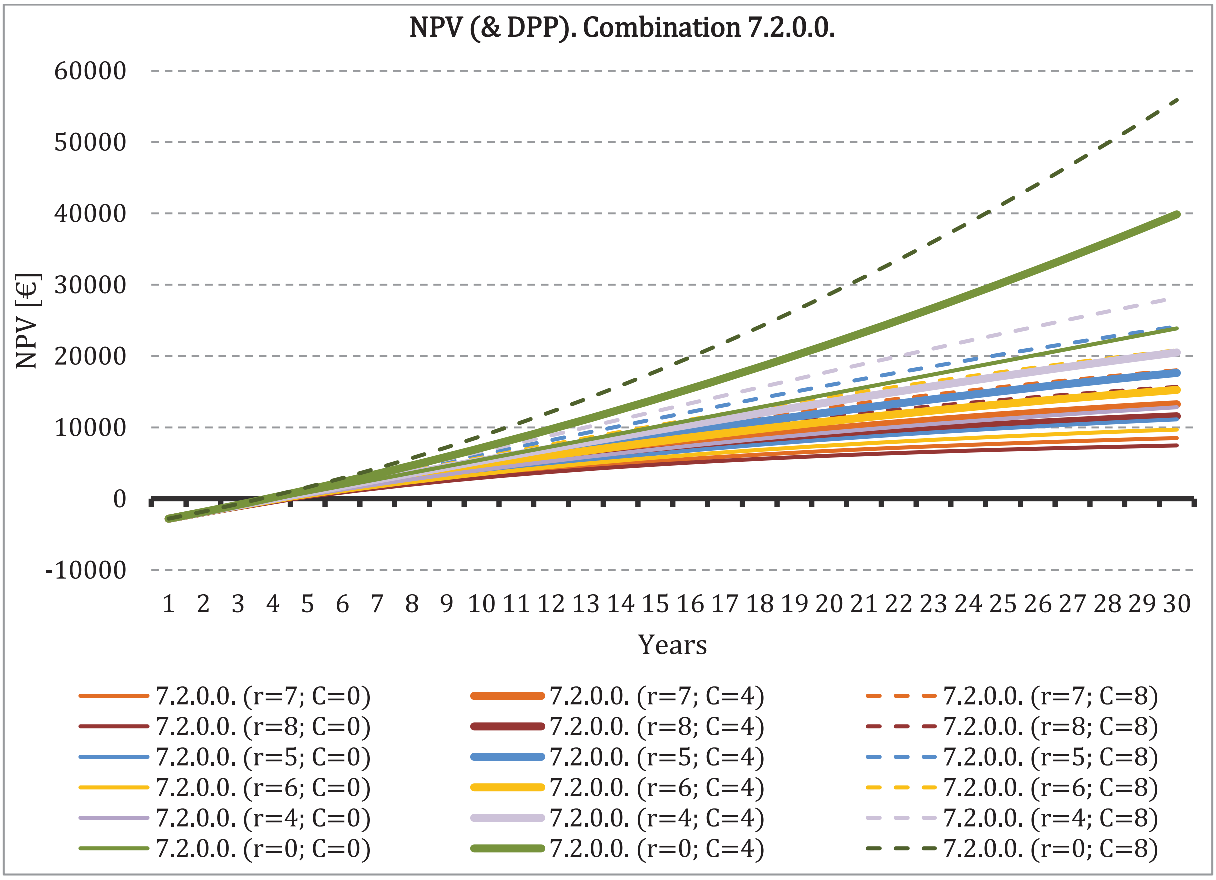


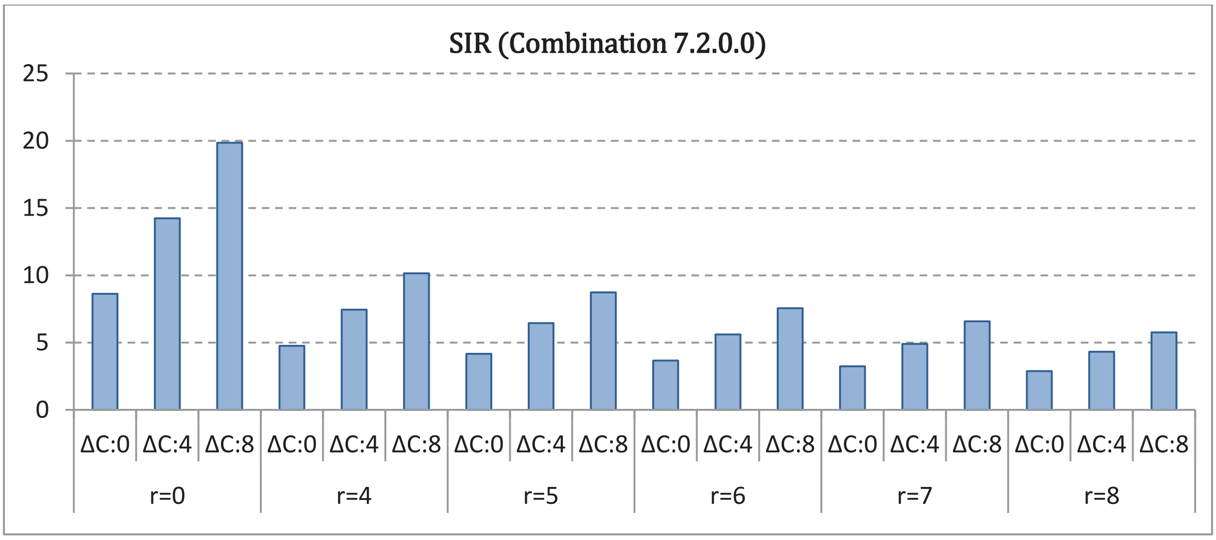


IRR 7.1.0.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	35.32%	30.11%	28.87%	27.66%	26.46%	25.29%
ΔC:4	40.24%	34.85%	33.56%	32.30%	31.07%	29.85%
ΔC:8	44.49%	38.94%	37.61%	36.32%	35.04%	33.79%

- **Combination 7.2.0.0.**

ESIR: 4.45 kWh/€

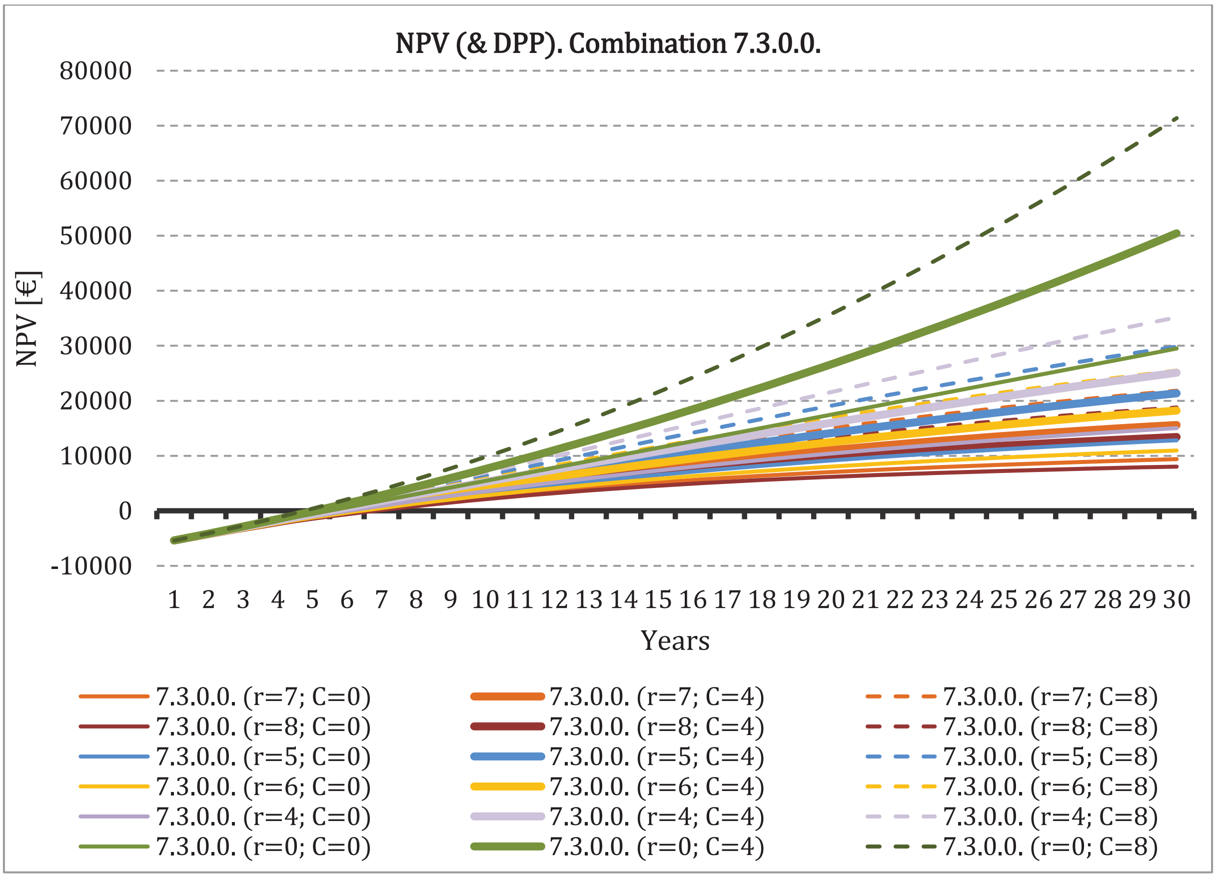


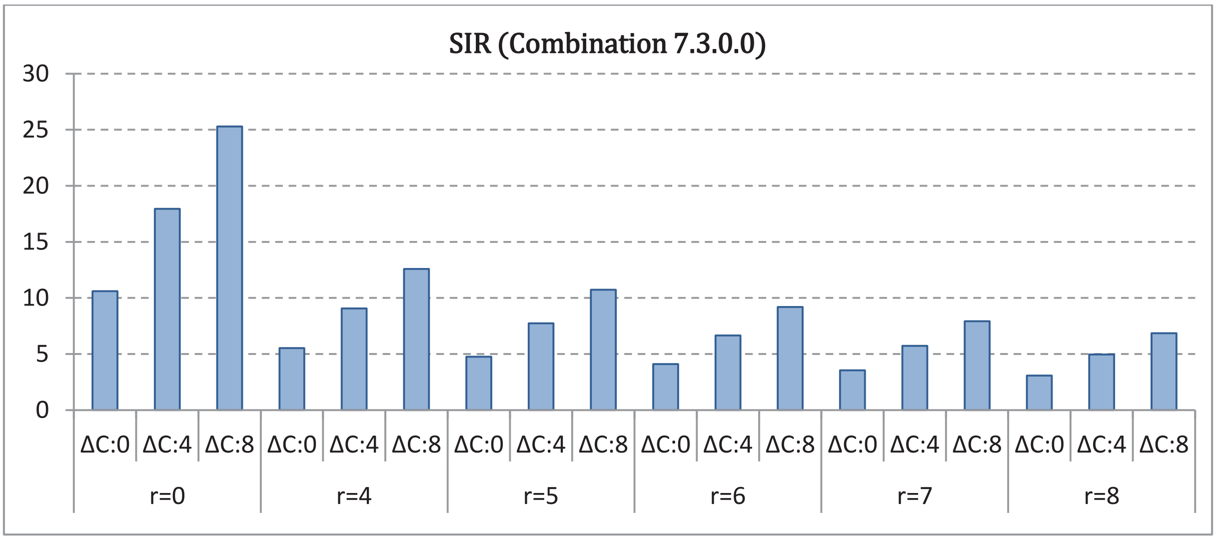


IRR 7.2.0.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	32.86%	27.75%	26.53%	25.34%	24.17%	23.02%
ΔC:4	37.67%	32.37%	31.11%	29.88%	28.66%	27.47%
ΔC:8	41.79%	36.33%	35.04%	33.76%	32.51%	31.28%

- **Combination 7.3.0.0.**

ESIR: 3.28 kWh/€

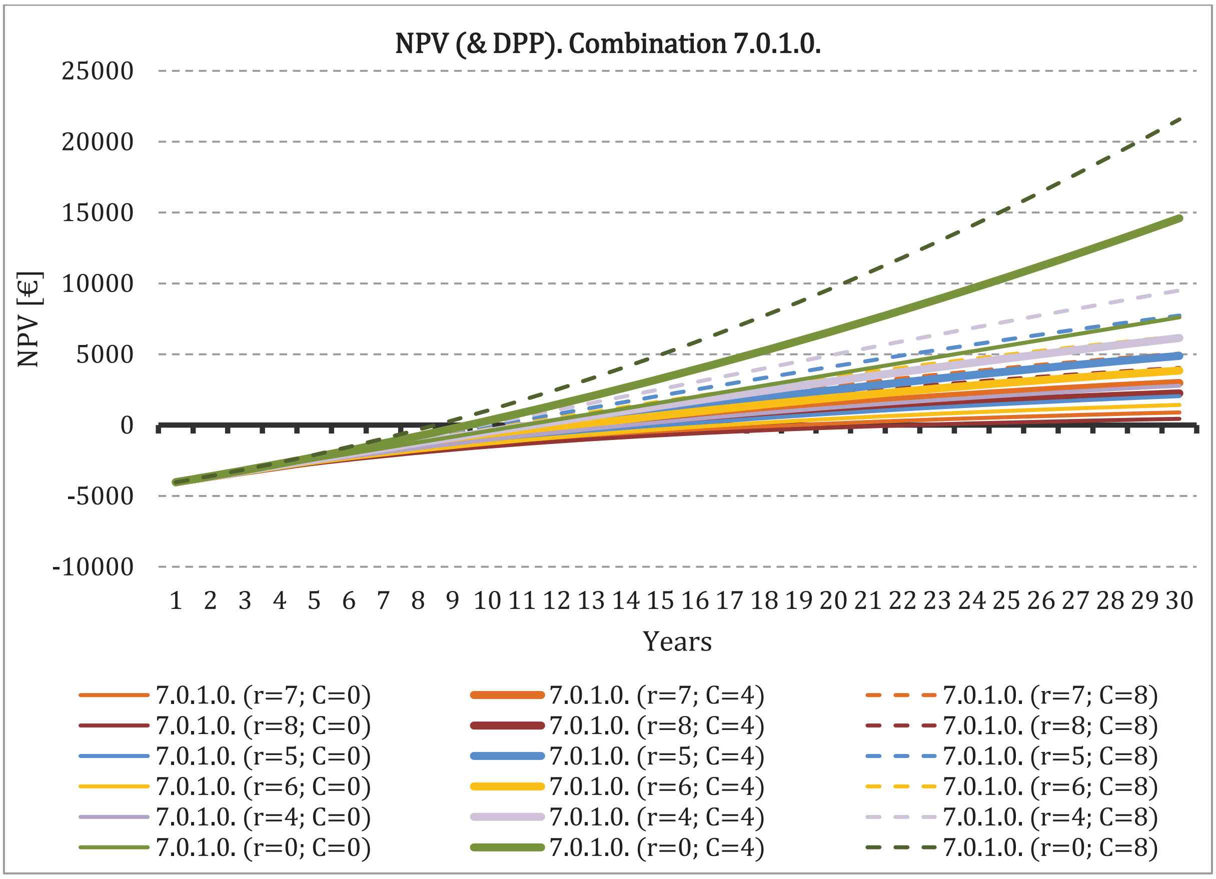


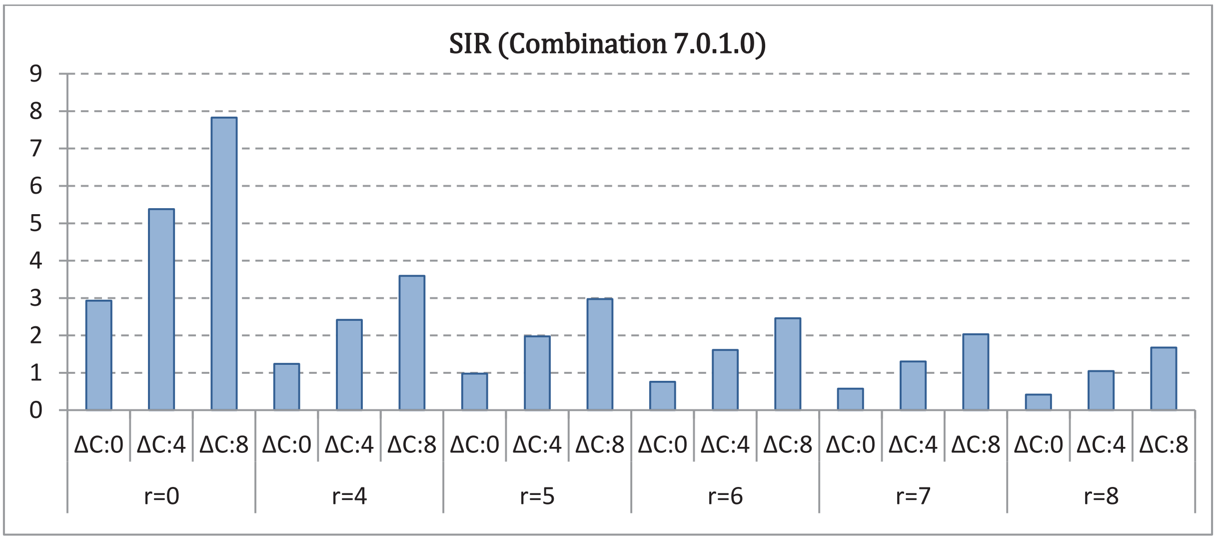


IRR 7.3.0.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	22.24%	17.54%	16.42%	15.32%	14.25%	13.19%
ΔC:4	26.51%	21.65%	20.49%	19.35%	18.24%	17.14%
ΔC:8	30.00%	25.00%	23.81%	22.64%	21.50%	20.37%

- **Combination 7.0.1.0.**

ESIR: 1.63 kWh/€

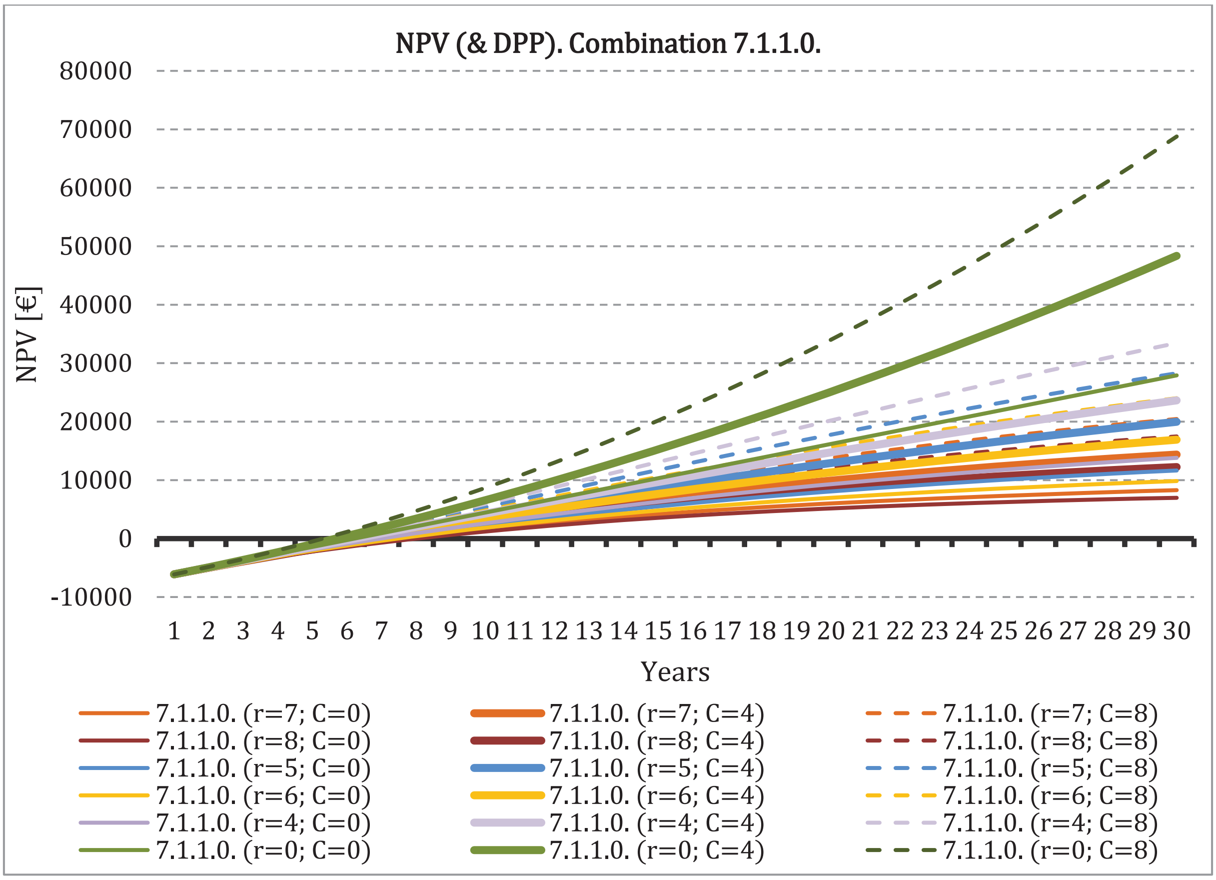


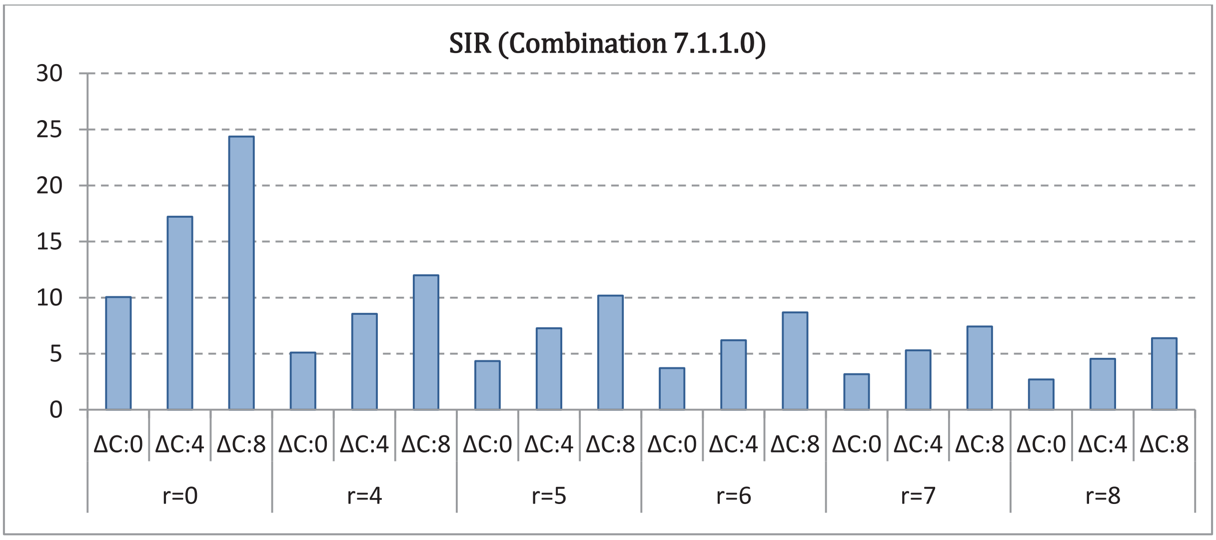


7.0.1.0.	**r=0**	**r=4**	**r=5**	**r=6**	**r=7**	**r=8**
ΔC:0	9.17%	4.97%	3.97%	2.99%	2.03%	1.08%
ΔC:4	12.70%	8.37%	7.34%	6.32%	5.33%	4.35%
ΔC:8	15.32%	10.88%	9.83%	8.79%	7.77%	6.78%

- ## Combination 7.1.1.0.

ESIR: 2.90 kWh/€

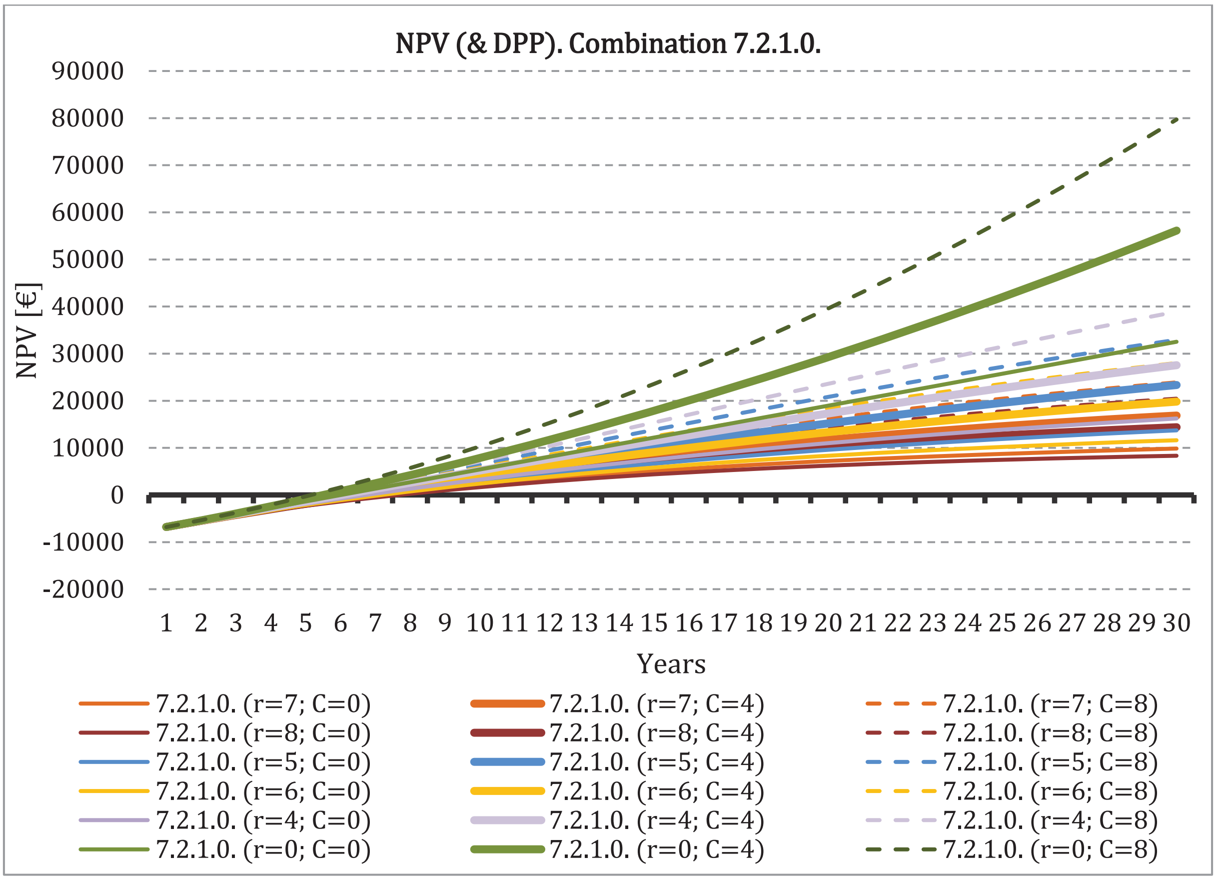


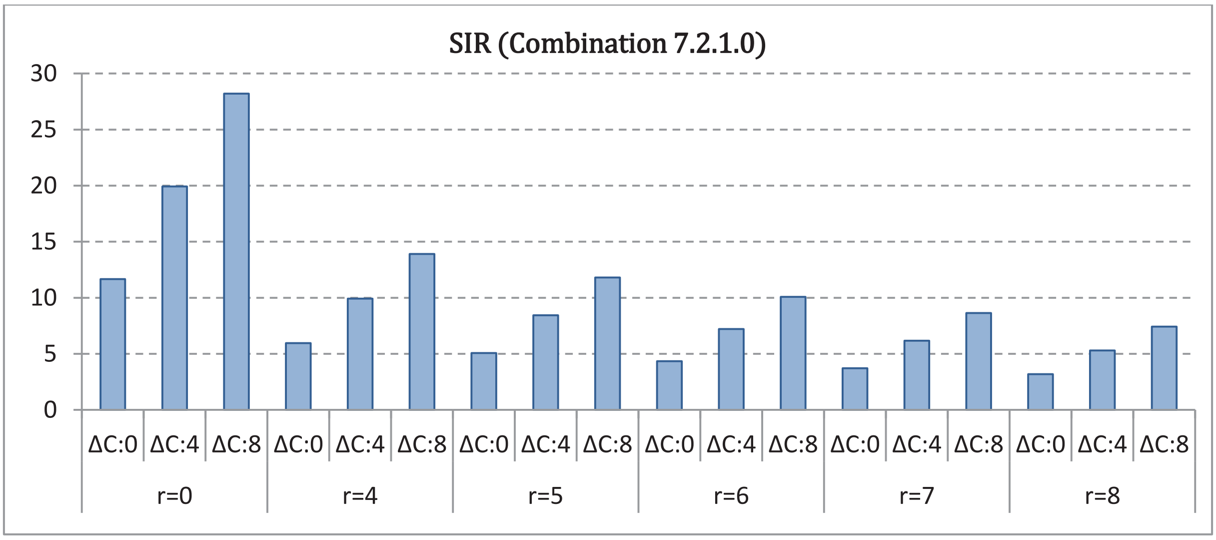


7.1.1.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	19.07%	14.49%	13.40%	12.33%	11.28%	10.25%
ΔC:4	23.17%	18.43%	17.30%	16.20%	15.11%	14.04%
ΔC:8	26.45%	21.59%	20.43%	19.30%	18.18%	17.09%

- **Combination 7.2.1.0.**

ESIR: 2.99 kWh/€

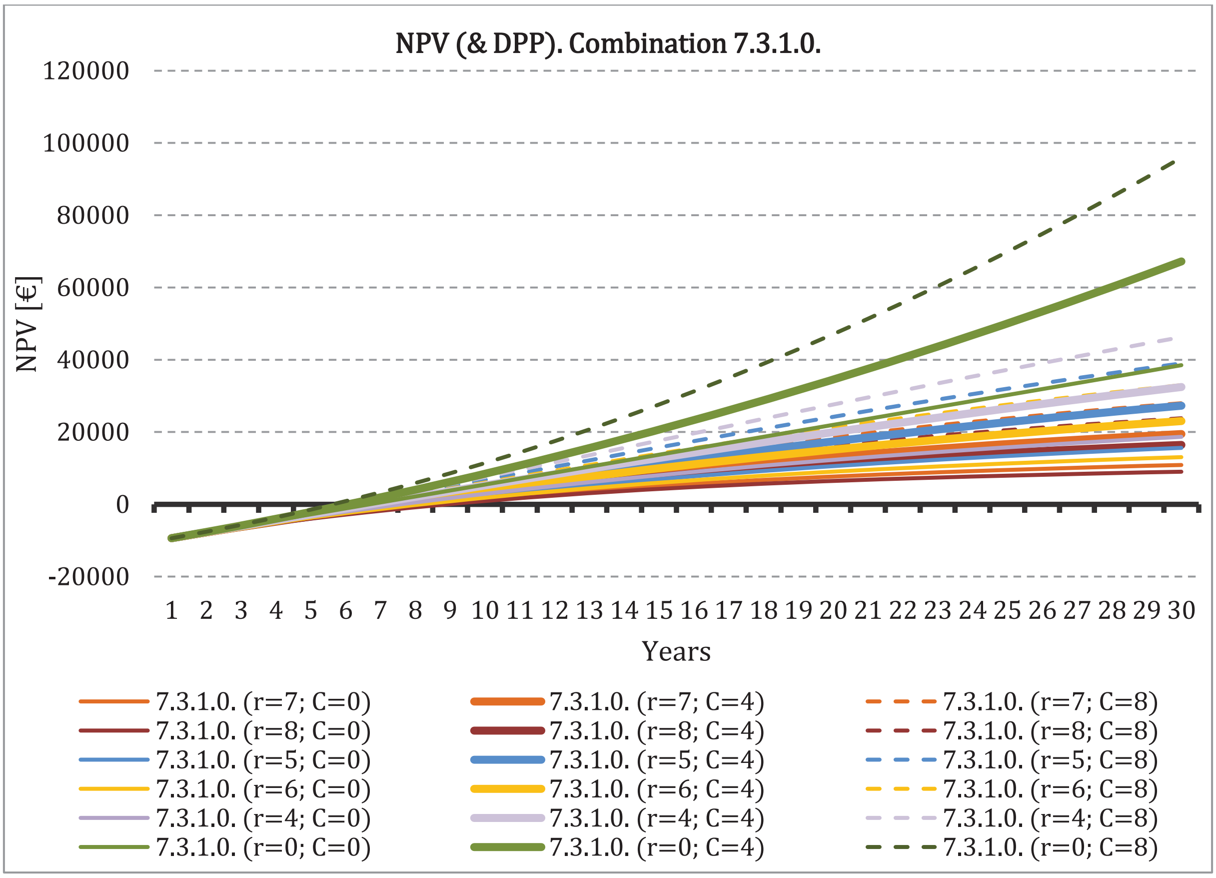


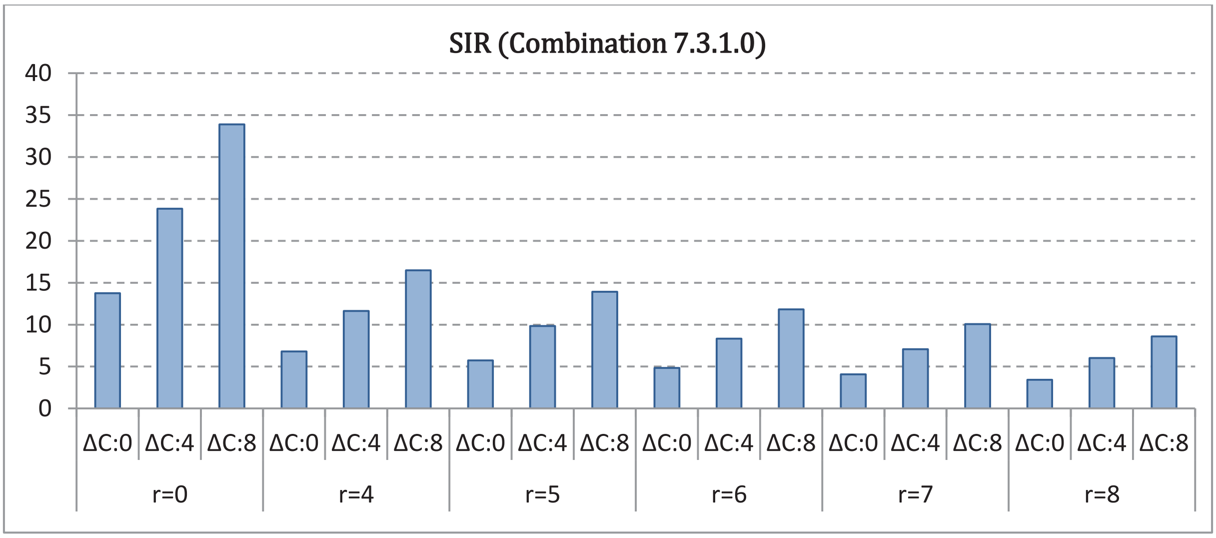


7.2.1.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	19.84%	15.23%	14.13%	13.05%	12.00%	10.96%
ΔC:4	23.98%	19.21%	18.07%	16.96%	15.86%	14.79%
ΔC:8	27.31%	22.42%	21.25%	20.11%	18.98%	17.88%

- **Combination 7.3.1.0.**

ESIR: 2.69 kWh/€

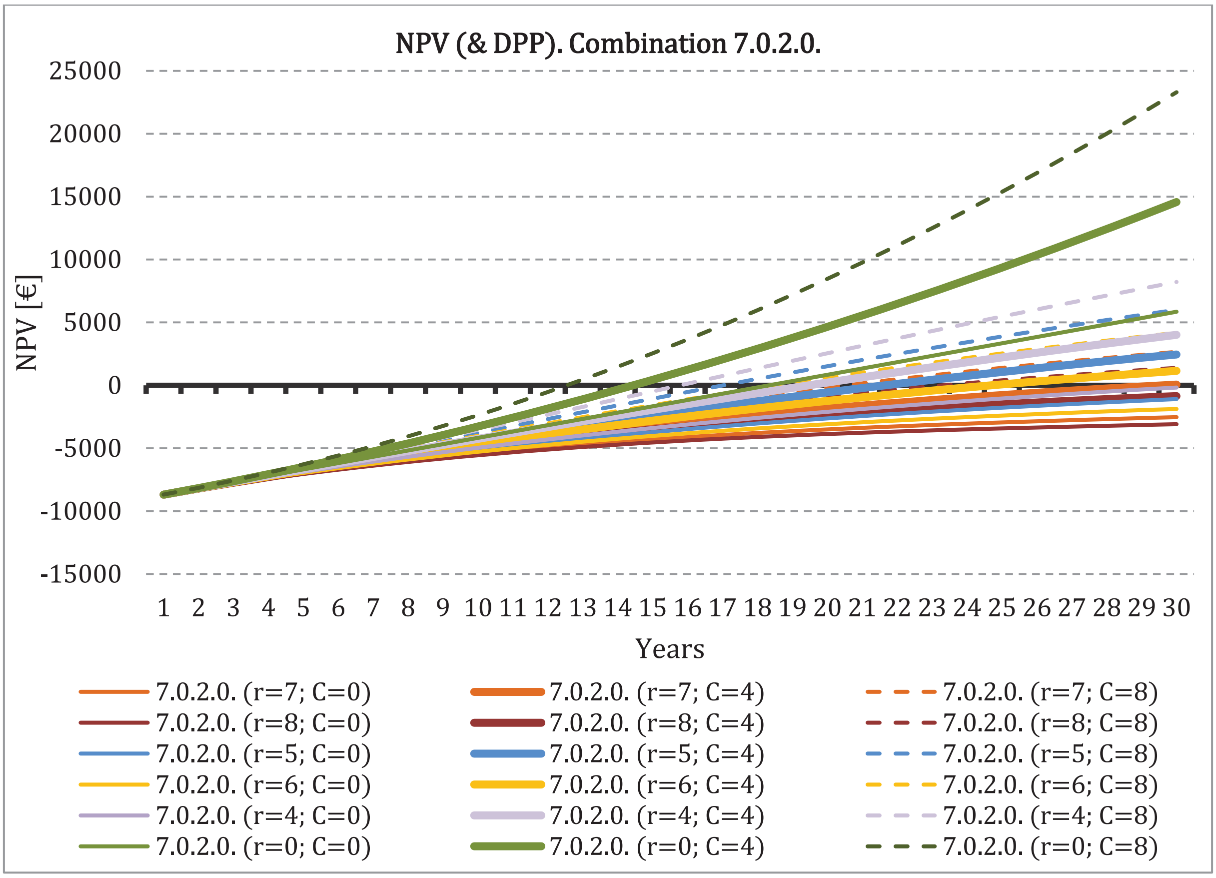


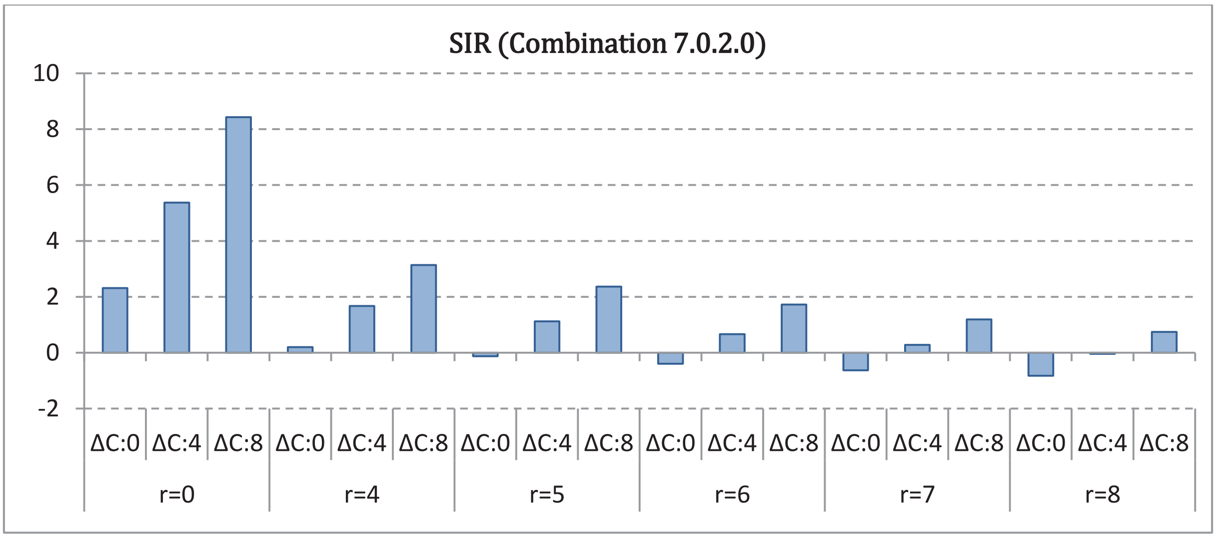


7.3.1.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	17.43%	12.91%	11.84%	10.78%	9.74%	8.73%
ΔC:4	21.43%	16.76%	15.65%	14.56%	13.49%	12.44%
ΔC:8	24.61%	19.82%	18.68%	17.56%	16.46%	15.38%

- ## Combination 7.0.2.0.

ESIR: 0.98 kWh/€

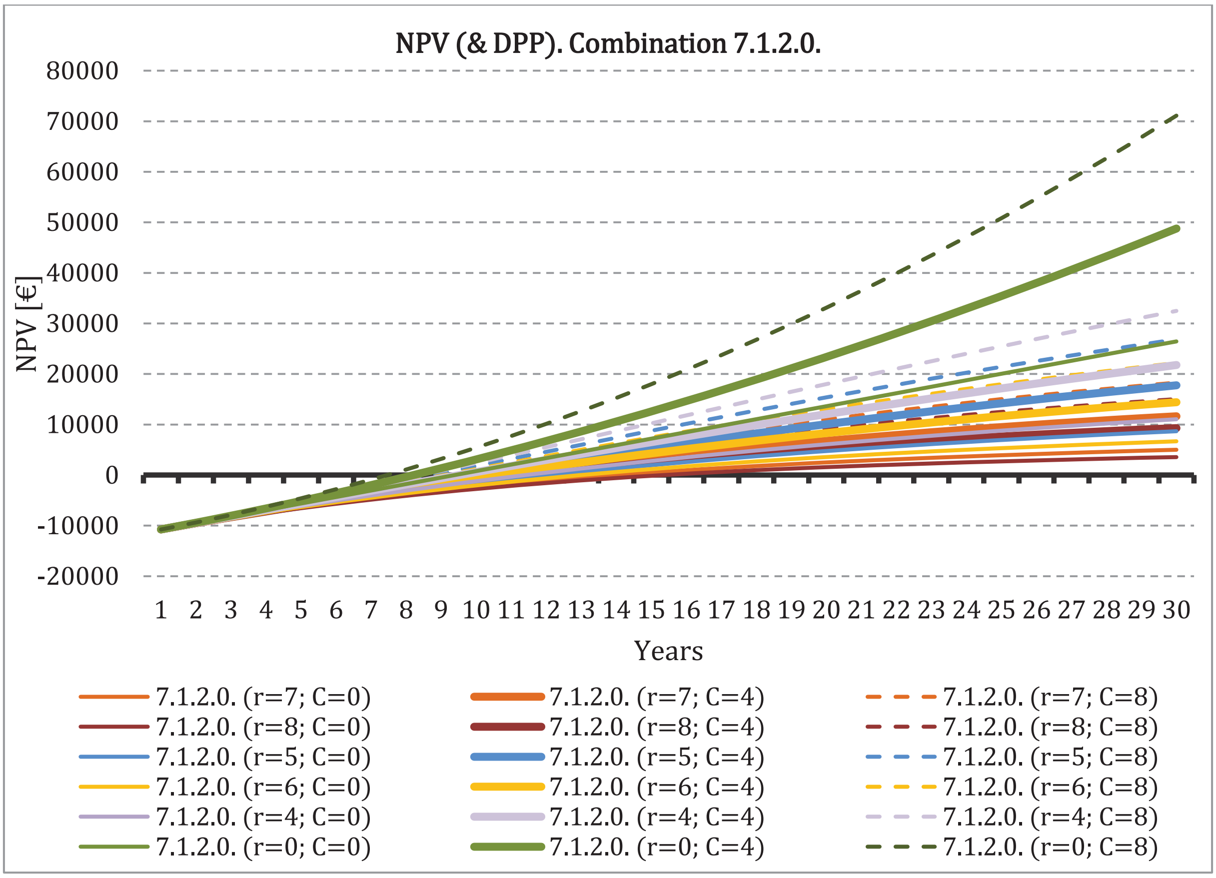


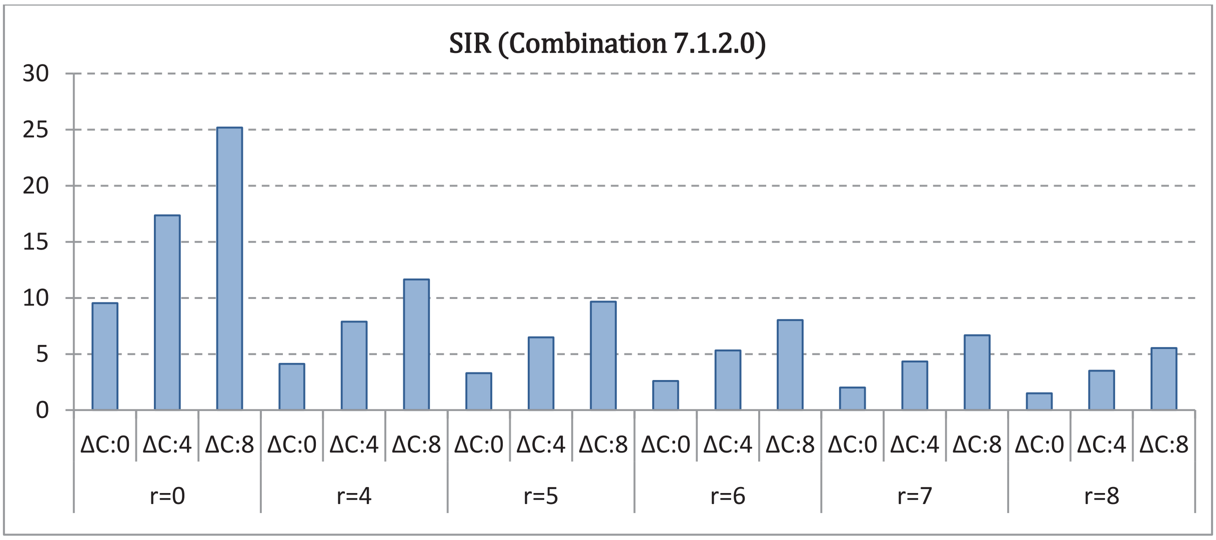


7.0.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	3.83%	- 0.16%	- 1.11%	- 2.05%	- 2.96%	- 3.86%
ΔC:4	7.06%	2.95%	1.97%	1.00%	0.06%	- 0.87%
ΔC:8	9.33%	5.13%	4.13%	3.14%	2.18%	1.23%

- **Combination 7.1.2.0.**

ESIR: 1.92 kWh/€

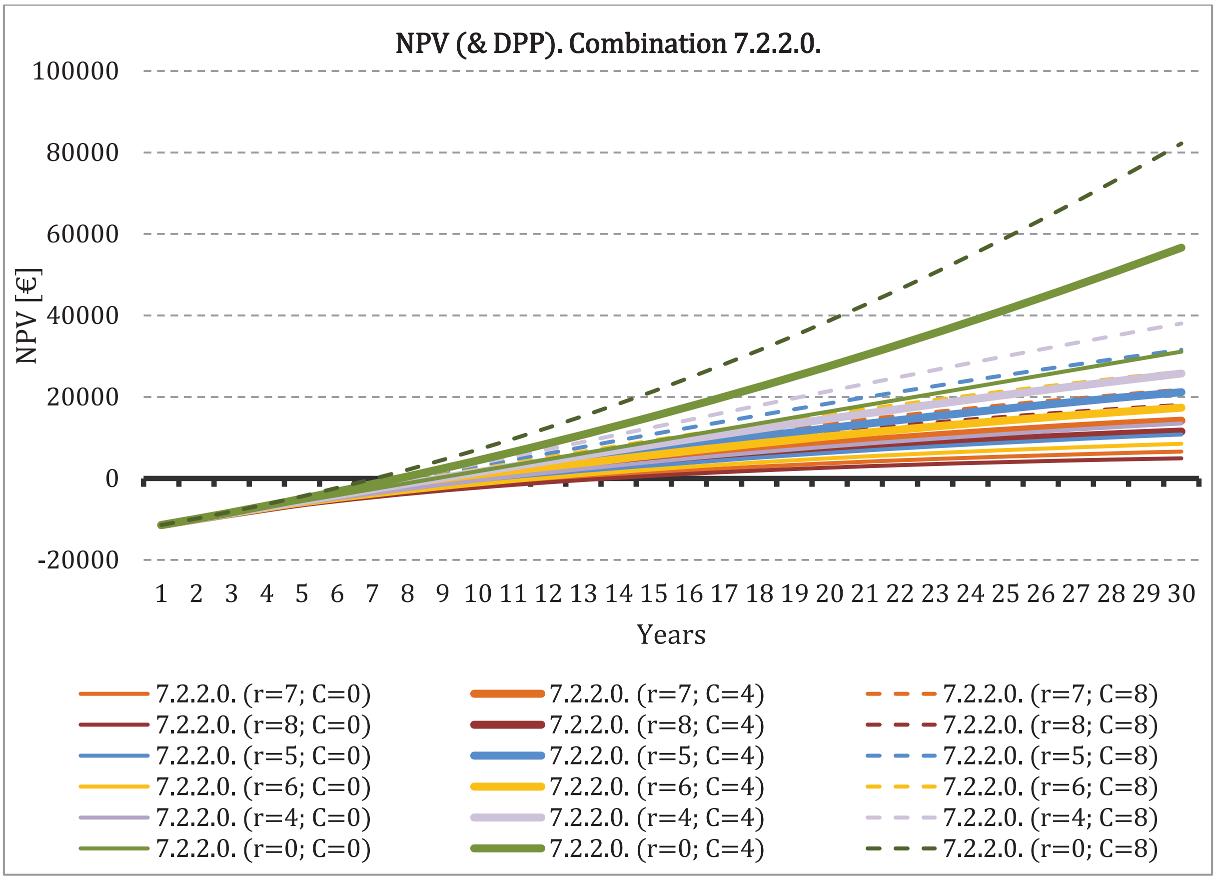


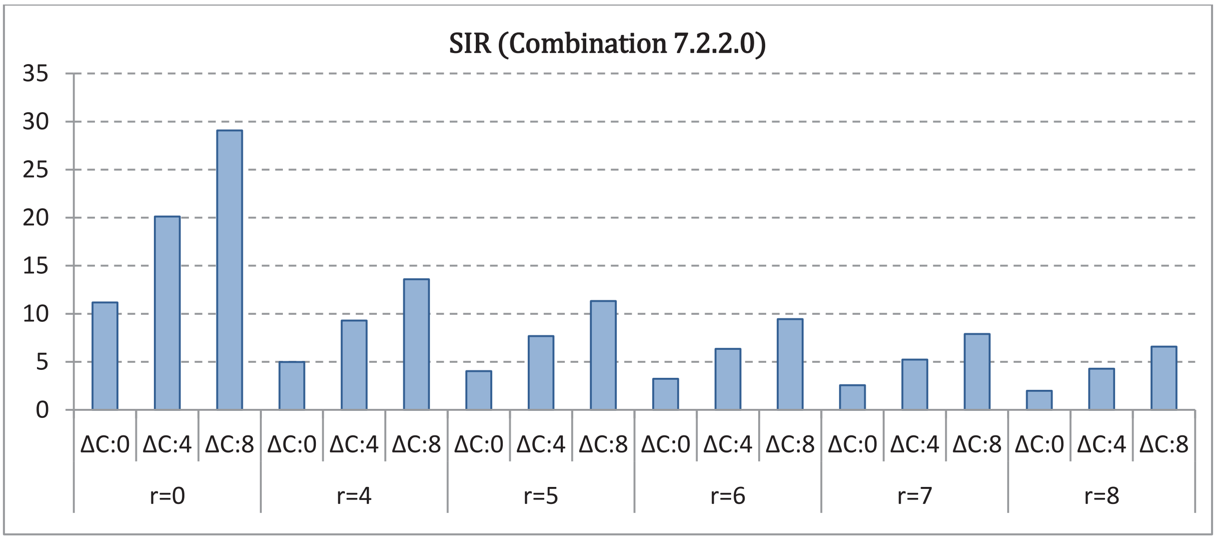


7.1.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	11.41%	7.12%	6.10%	5.10%	4.12%	3.15%
ΔC:4	15.07%	10.64%	9.59%	8.55%	7.54%	6.54%
ΔC:8	17.84%	13.30%	12.23%	11.17%	10.13%	9.11%

▪ Combination 7.2.2.0.

ESIR: 2.05 kWh/€

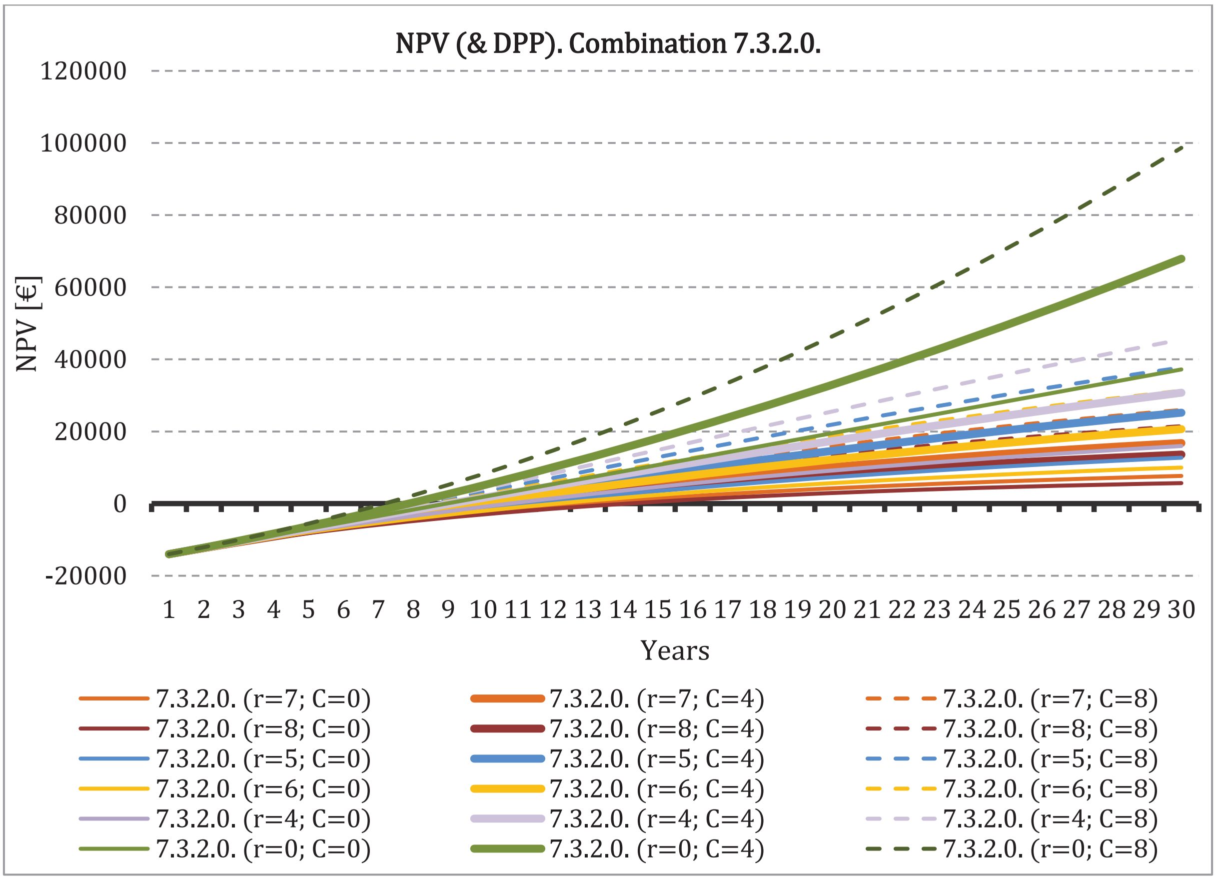


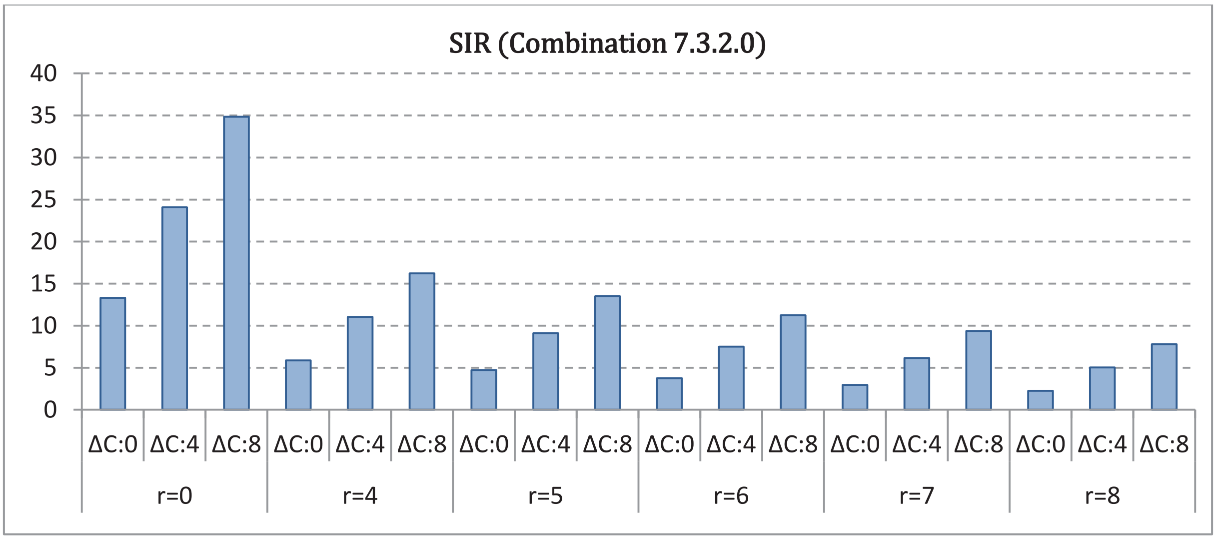


7.2.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	12.40%	8.07%	7.04%	6.03%	5.04%	4.07%
ΔC:4	16.11%	11.65%	10.59%	9.54%	8.52%	7.51%
ΔC:8	18.95%	14.38%	13.29%	12.22%	11.17%	10.14%

- **Combination 7.3.2.0.**

ESIR: 2.01 kWh/€

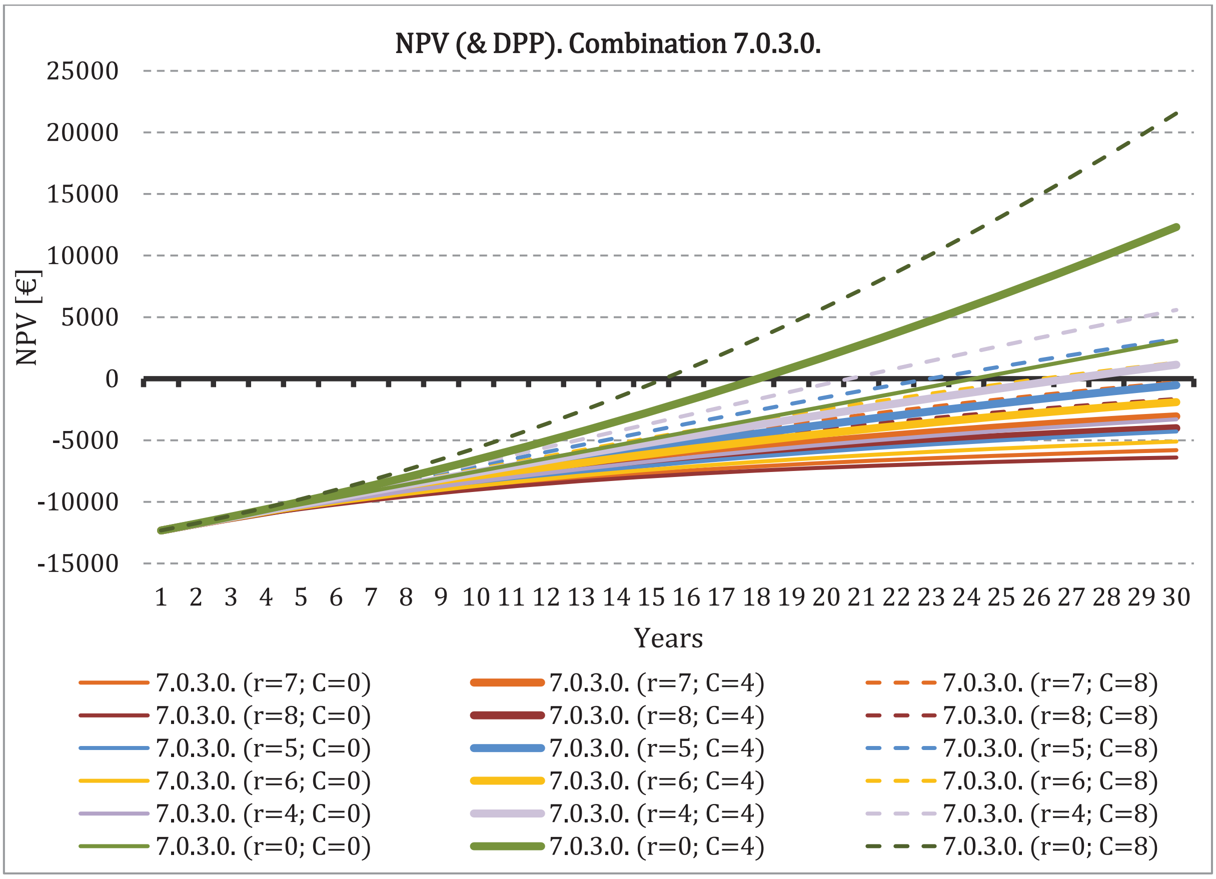


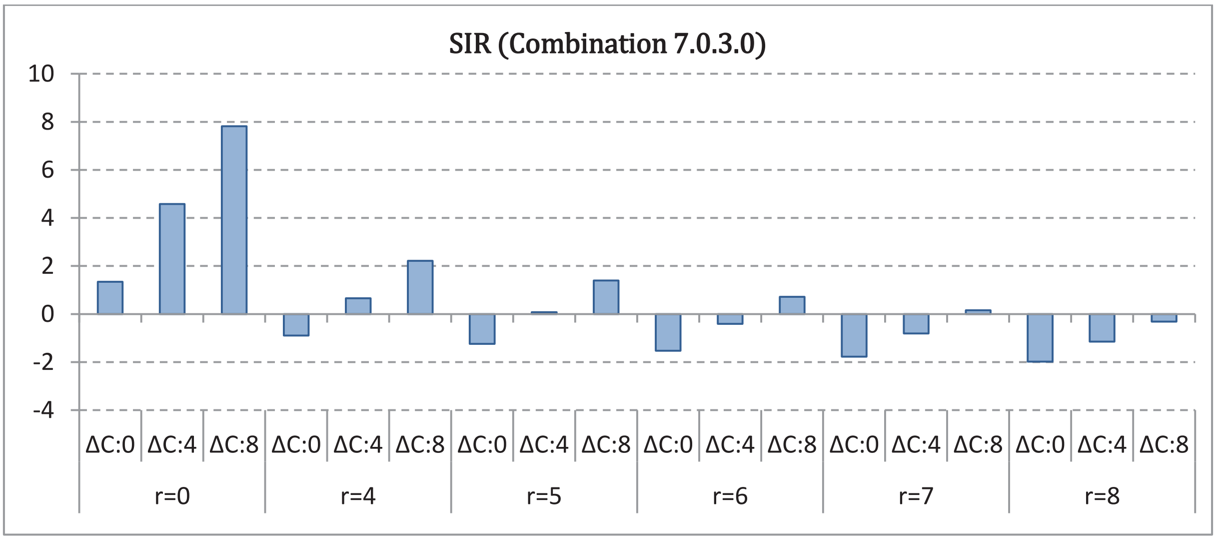


7.3.2.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	12.14%	7.83%	6.80%	5.80%	4.81%	3.84%
ΔC:4	15.85%	11.39%	10.33%	9.29%	8.27%	7.27%
ΔC:8	18.67%	14.10%	13.02%	11.95%	10.90%	9.88%

- ## Combination 7.0.3.0.

ESIR: 0.74 kWh/€

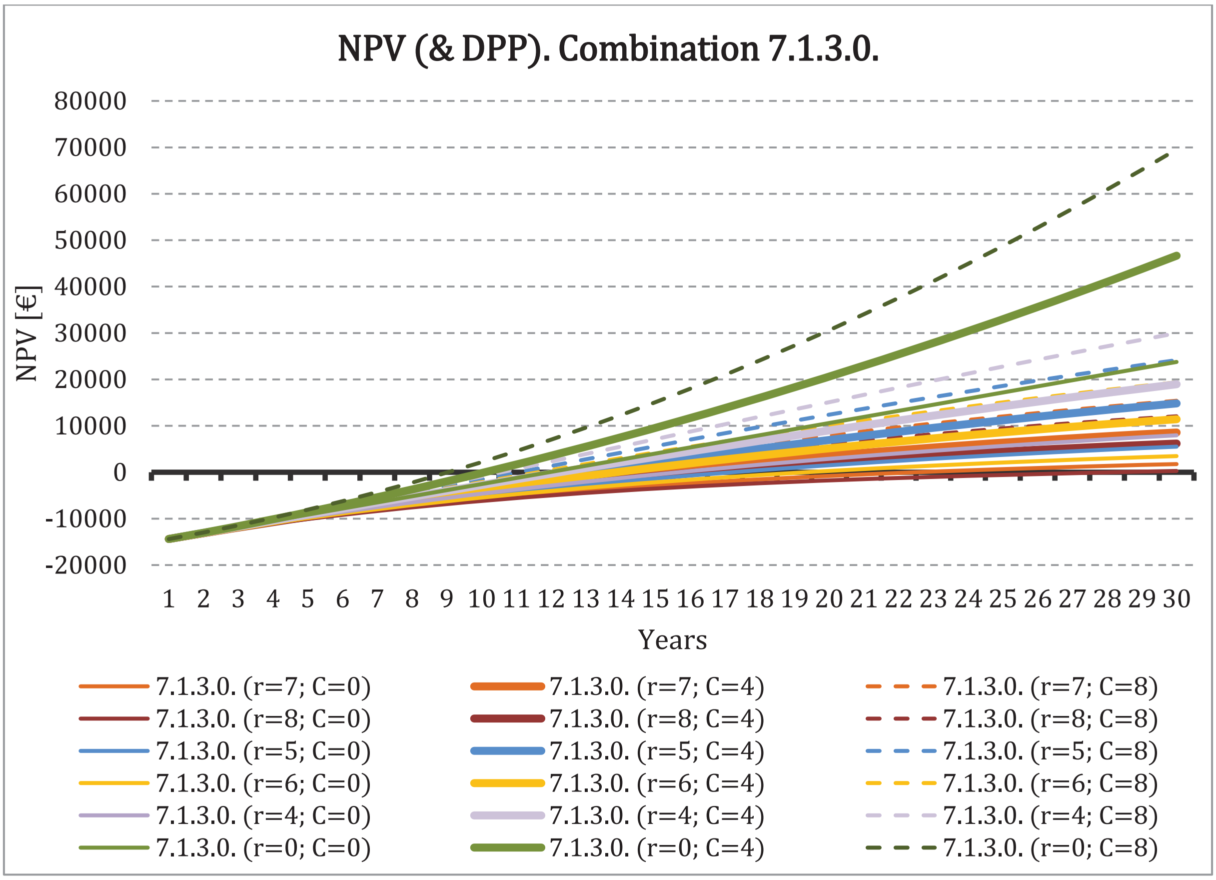


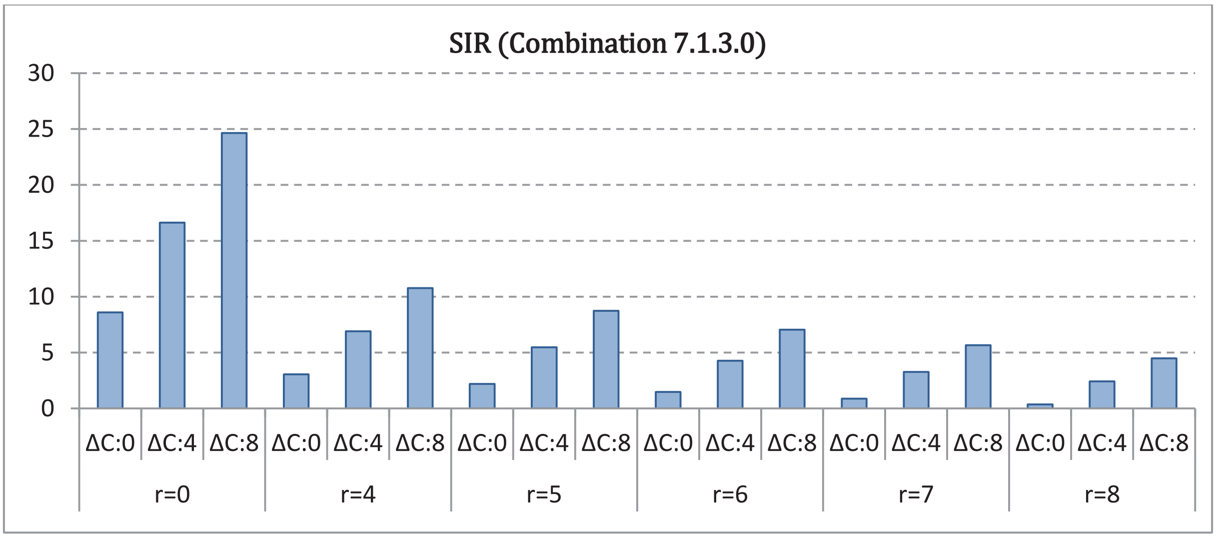


7.0.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	1.55%	- 2.35%	- 3.28%	-	-	-
ΔC:4	4.67%	0.64%	- 0.32%	- 1.26%	- 2.18%	- 3.09%
ΔC:8	6.80%	2.69%	1.71%	0.75%	- 0.19%	- 1.11%

- **Combination 7.1.3.0.**

ESIR: 1.51 kWh/€

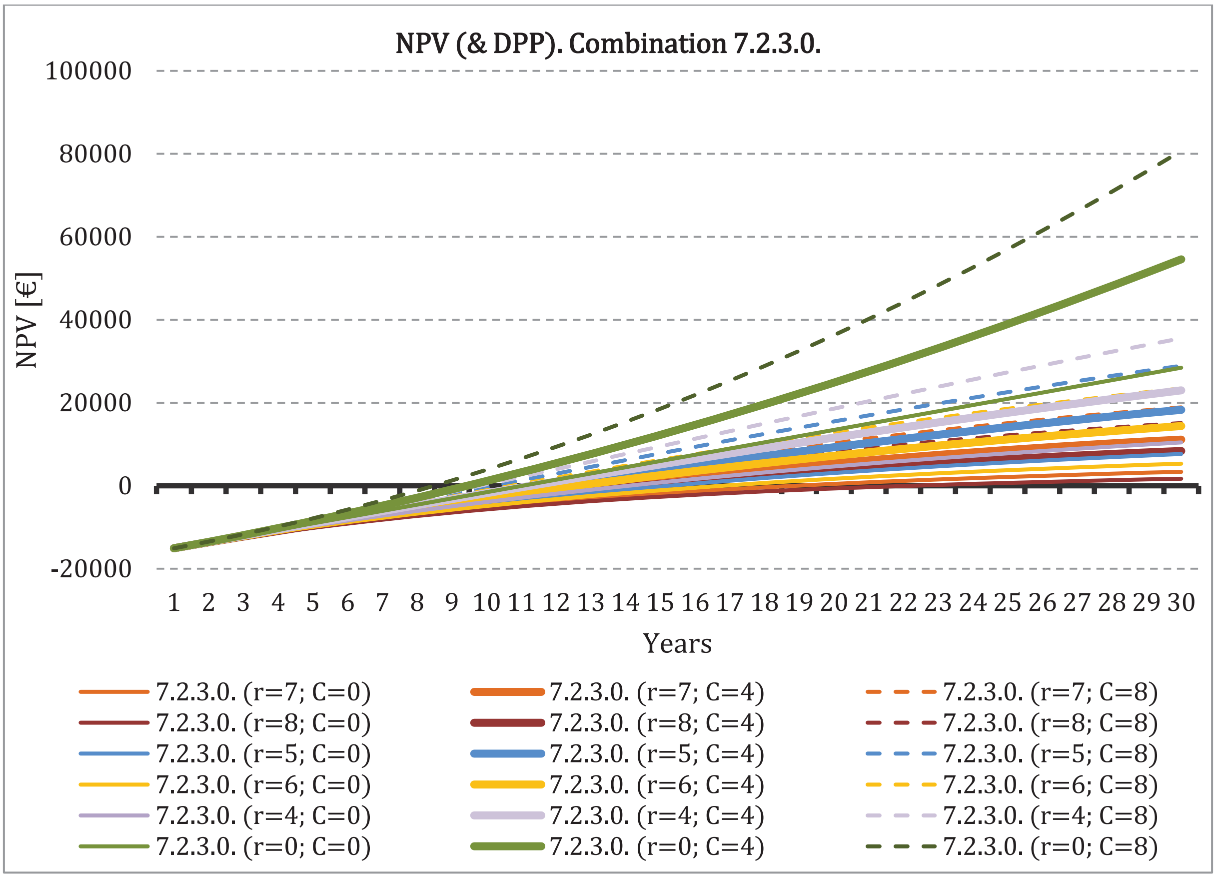


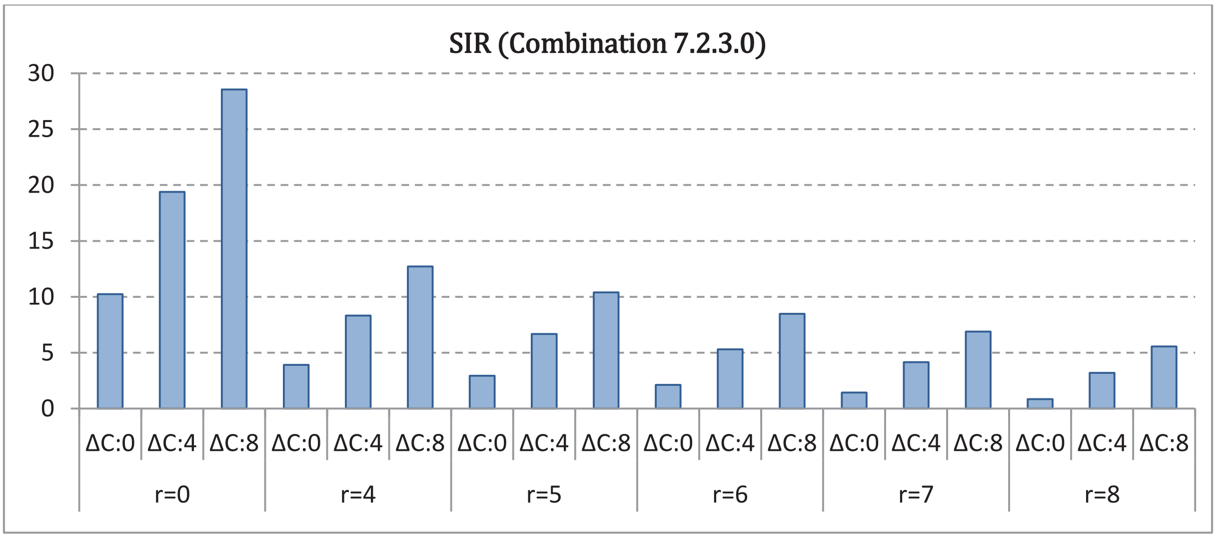


7.1.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	8.22%	4.06%	3.07%	2.09%	1.14%	0.20%
ΔC:4	11.70%	7.40%	6.38%	5.37%	4.39%	3.42%
ΔC:8	14.25%	9.85%	8.81%	7.78%	6.77%	5.79%

- ## Combination 7.2.3.0.

ESIR: 1.63 kWh/€

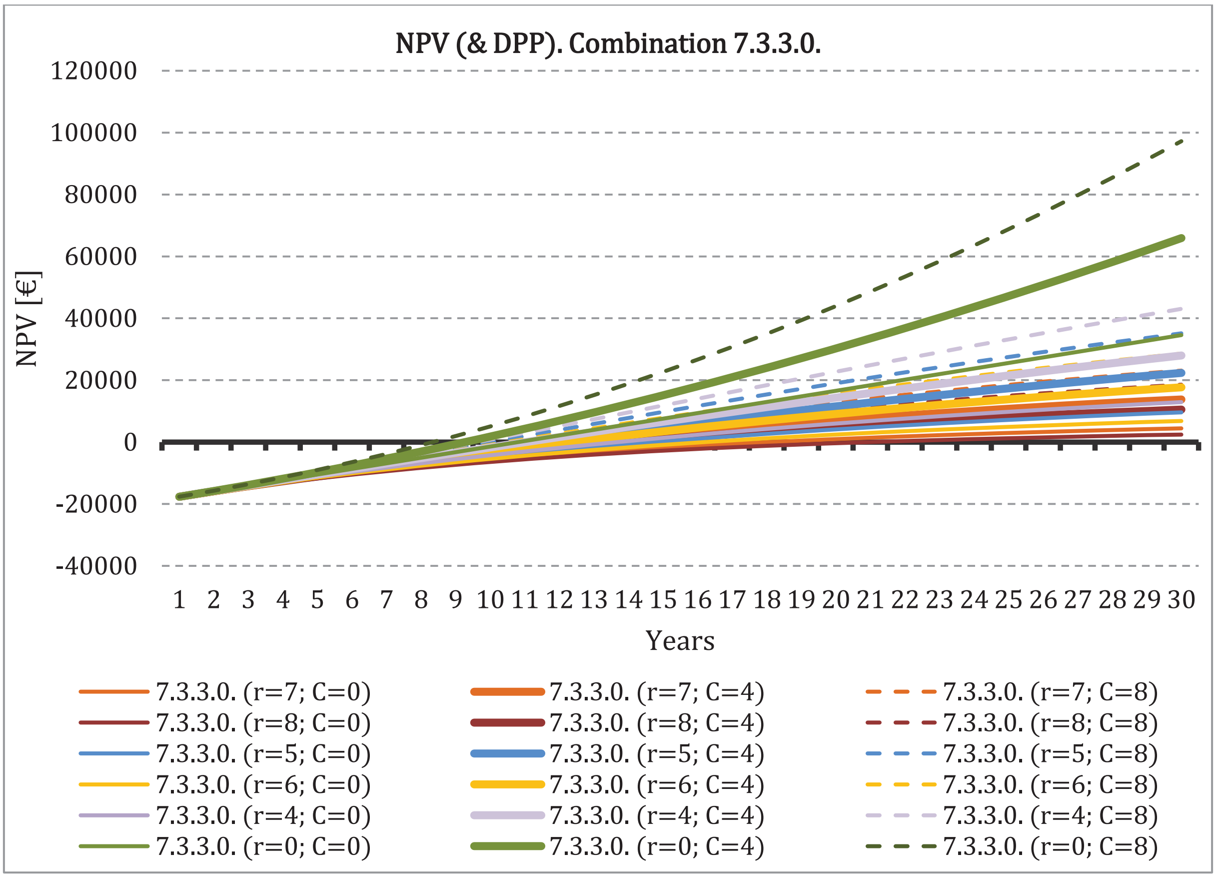


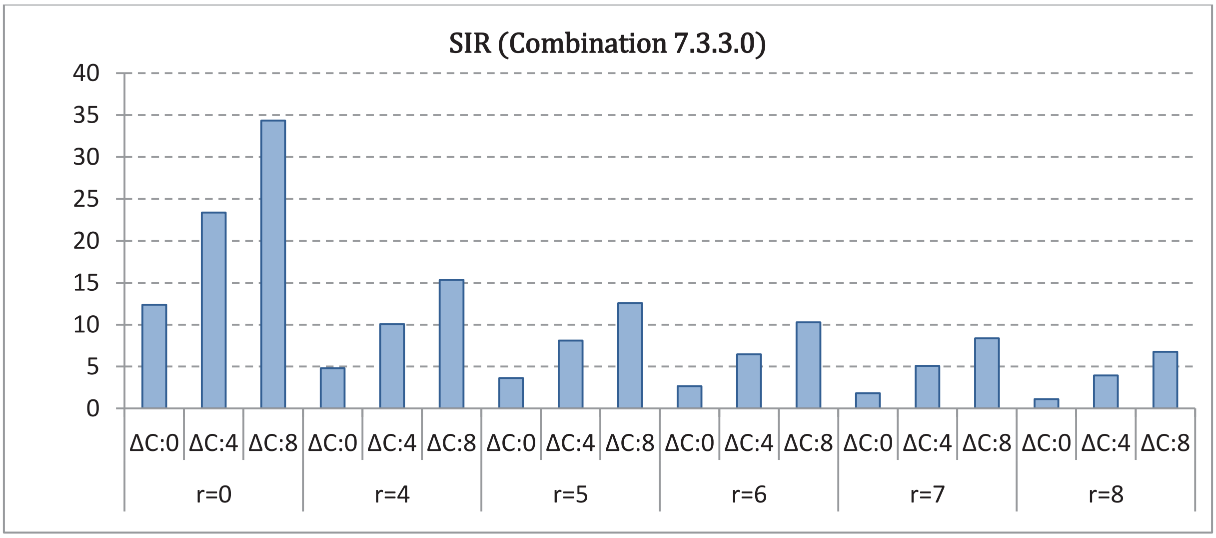


7.2.3.0.	r=0	r=4	r=5	r=6	r=7	r=8
ΔC:0	9.18%	4.98%	3.98%	3.00%	2.04%	1.09%
ΔC:4	12.71%	8.38%	7.35%	6.33%	5.34%	4.36%
ΔC:8	15.33%	10.89%	9.84%	8.80%	7.79%	6.79%

- **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%

8.1. Eranskina: Ikuspegi exergetikoa gizarte etxebizitzaren sistema energetikoa aztertzeko

- *"The exergy approach for evaluating and developing an energy system for a social dwelling",* “Energy and Buildings” aldizkarian argitaratuta 2012ko abenduan (Vol 55, pag 693 - 703) [53]

8.2. Eranskina: Gizarte etxebizitzaren sistema energetikoaren analisi exergetiko iragankorra

- *"Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement",* “Energy and Buildings” aldizkarian argitaratuta 2013ko Irailean (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:

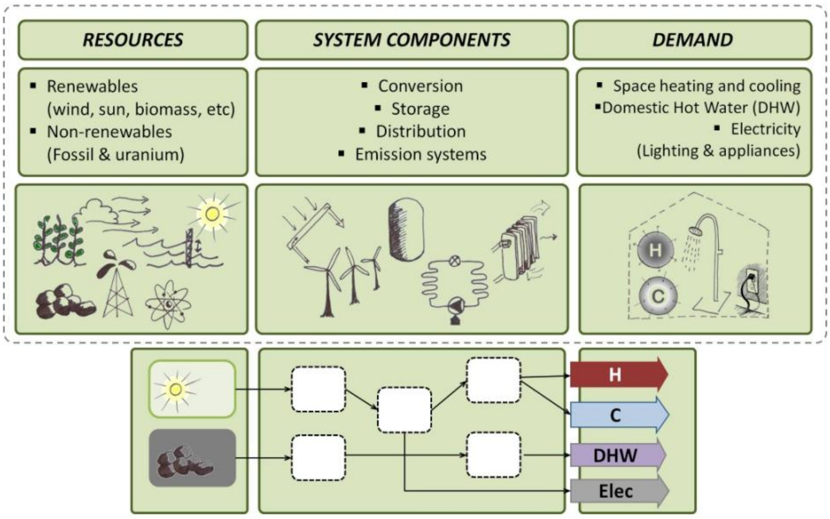


Fig. 1. Analysis framework consisting of demand, energy system components and energy resources

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. 1/36th 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/m^2 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.

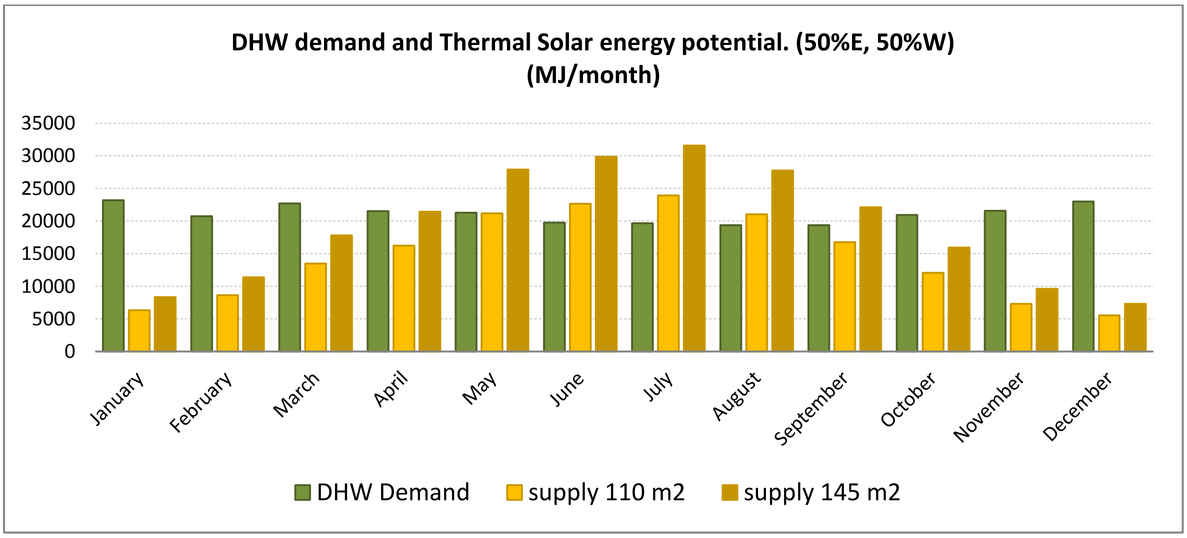


Fig. 3. DHW demand and Thermal Solar energy potential (It represents the DHW demand for the whole building of 36 dwellings)

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).

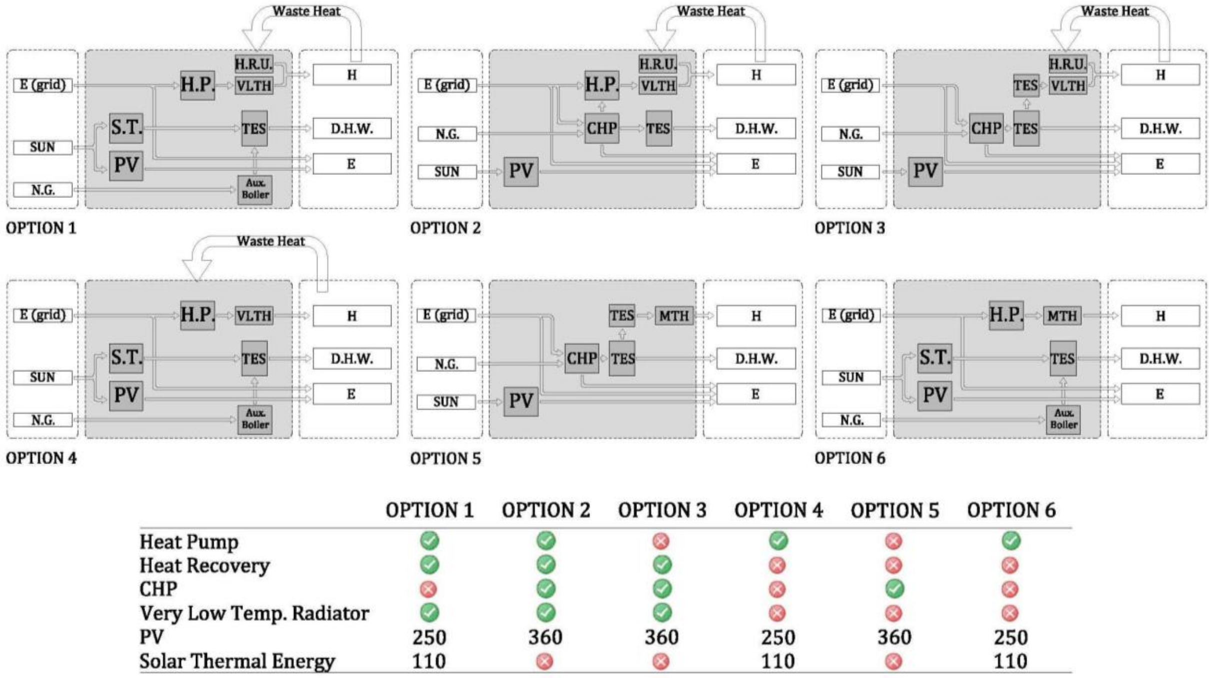
4.2 Options considered.

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.

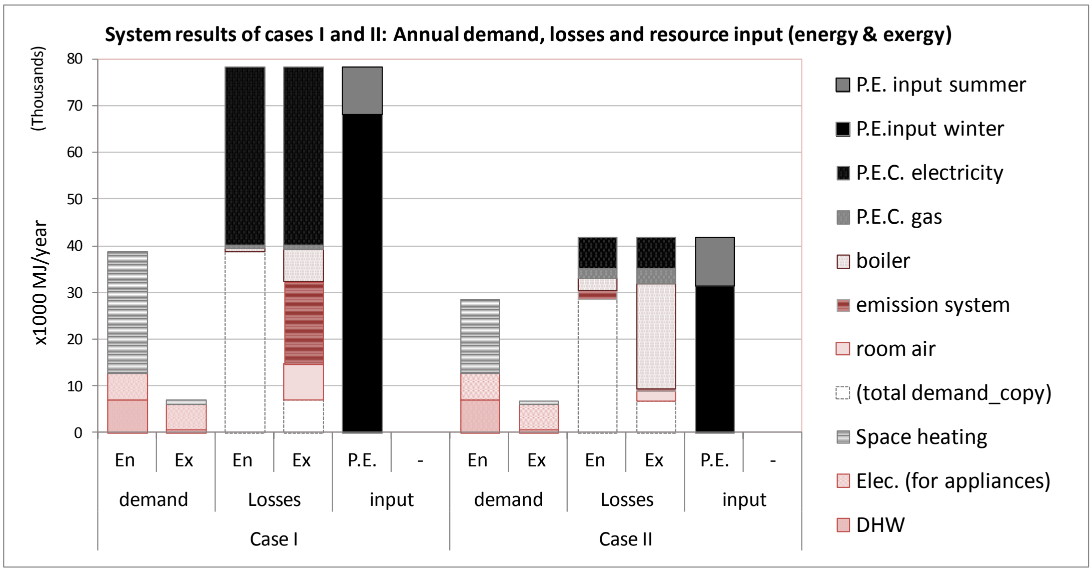


Fig. 5. Annual results of Case I and Case II: energy and energy demand, energy and exergy losses of the various system components and primary energy input (energy equals exergy in this case)

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).

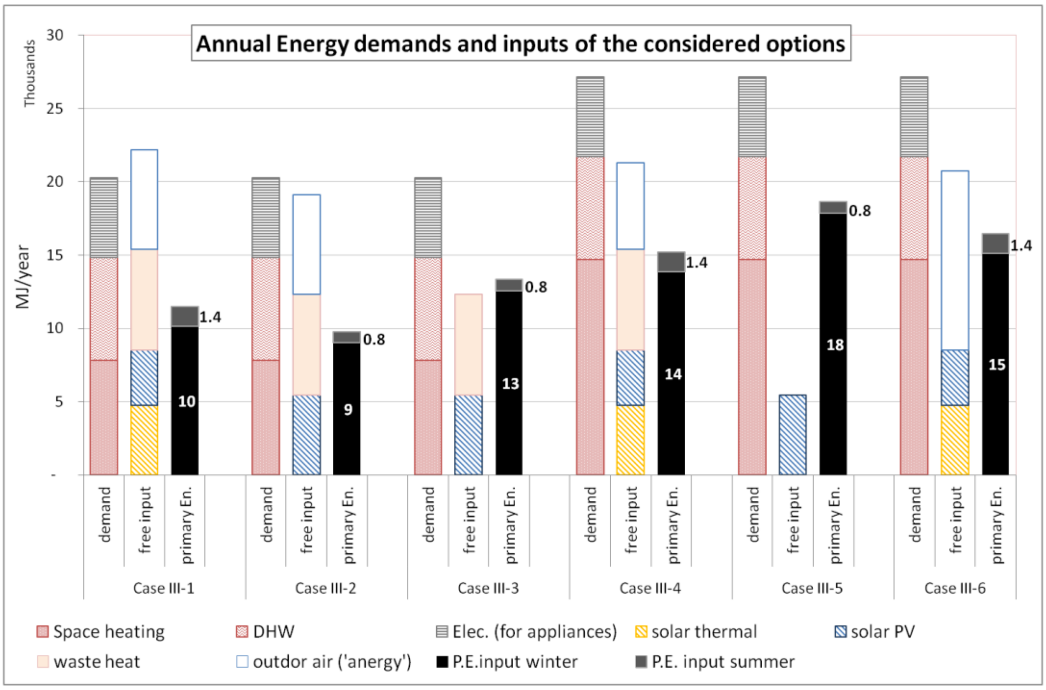


Fig. 6: Results Case III options 1-6: Annual energy demands (=system output) and energy inputs.

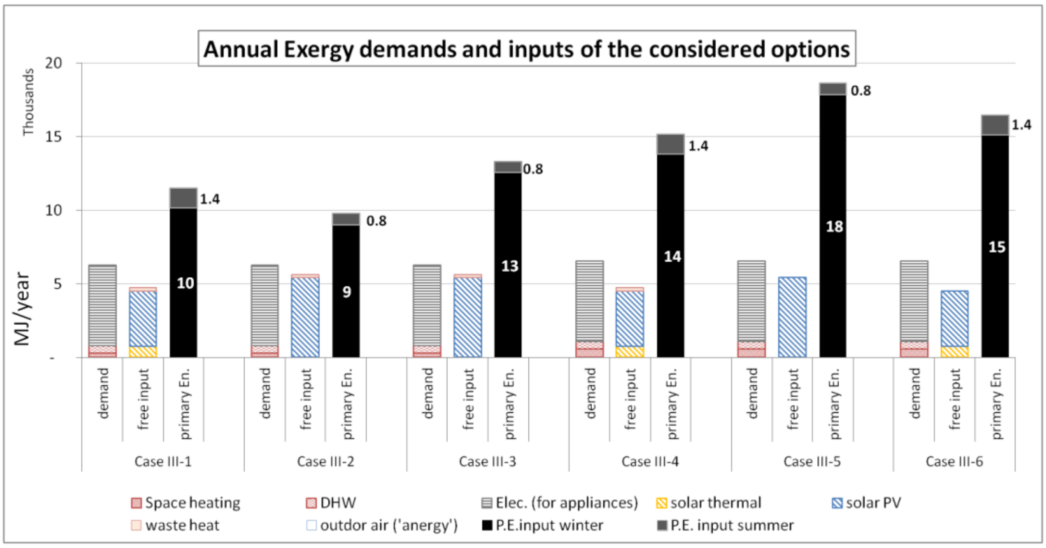


Fig. 7: Results Case III options 1-6: Annual exergy demands (= output) and exergy inputs.

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.

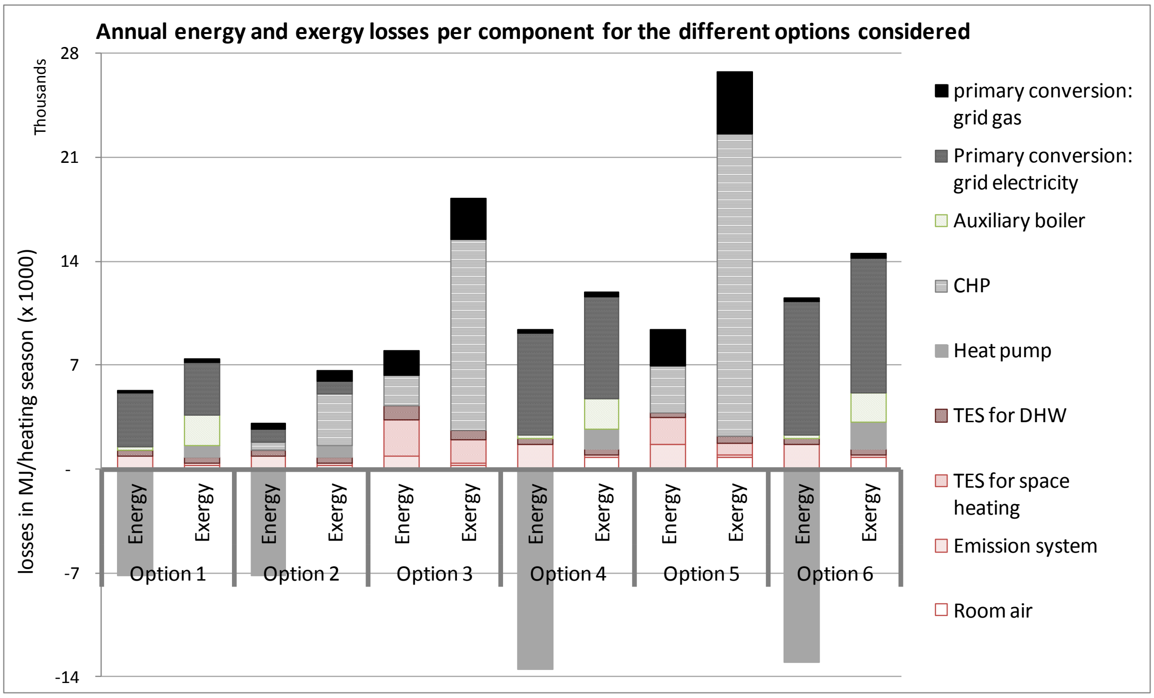


Fig. 8 Energy and exergy losses per energy system component, for each of the improved options considered (according to steady state evaluation of the heating season).

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.

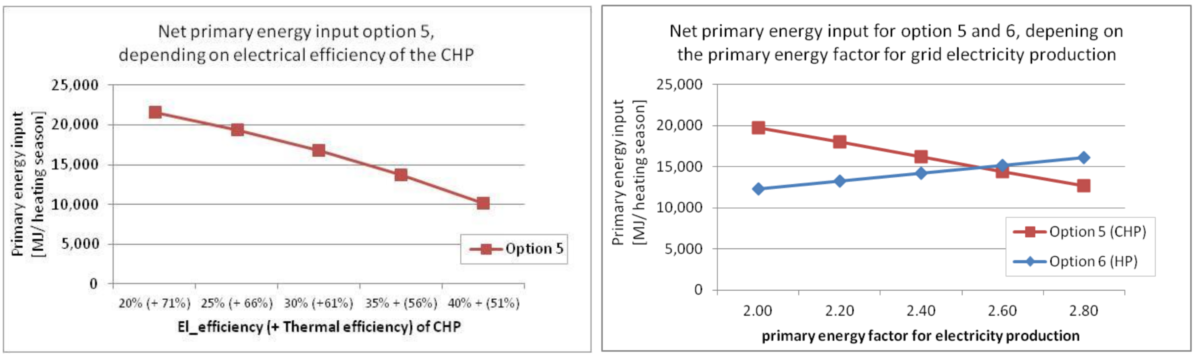


Fig. 9. (a): Sensitivity of the net primary energy input of option 5 to the electrical efficiency of the CHP (left graph), and (b): Sensitivity of the net primary energy input of options 5 and 6 to the primary energy factor for electricity from the national grid (right graph).

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/m^2K 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**
$T_{air,sp} = \left(T_{op,sp} - 0.5 \cdot T_{mean\_surf}\right) \cdot 2$	**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 (^oC 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.

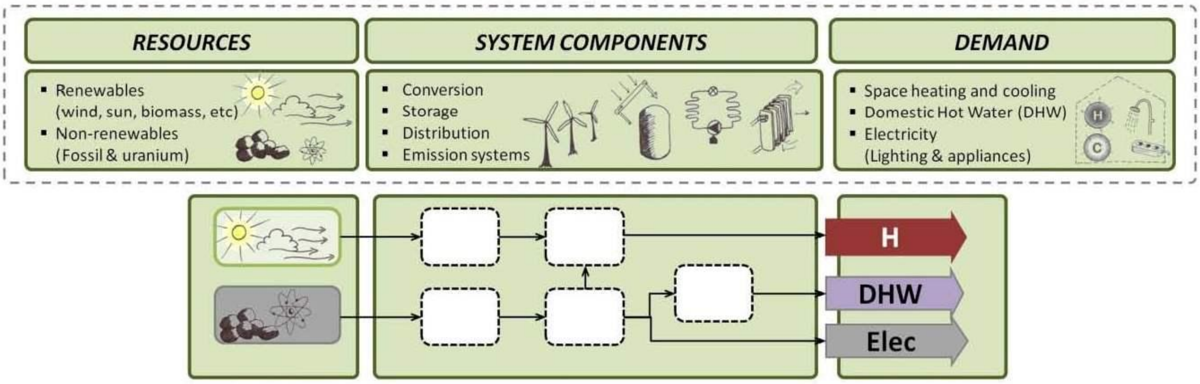


Fig. 1. Scheme of the energy chain

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.

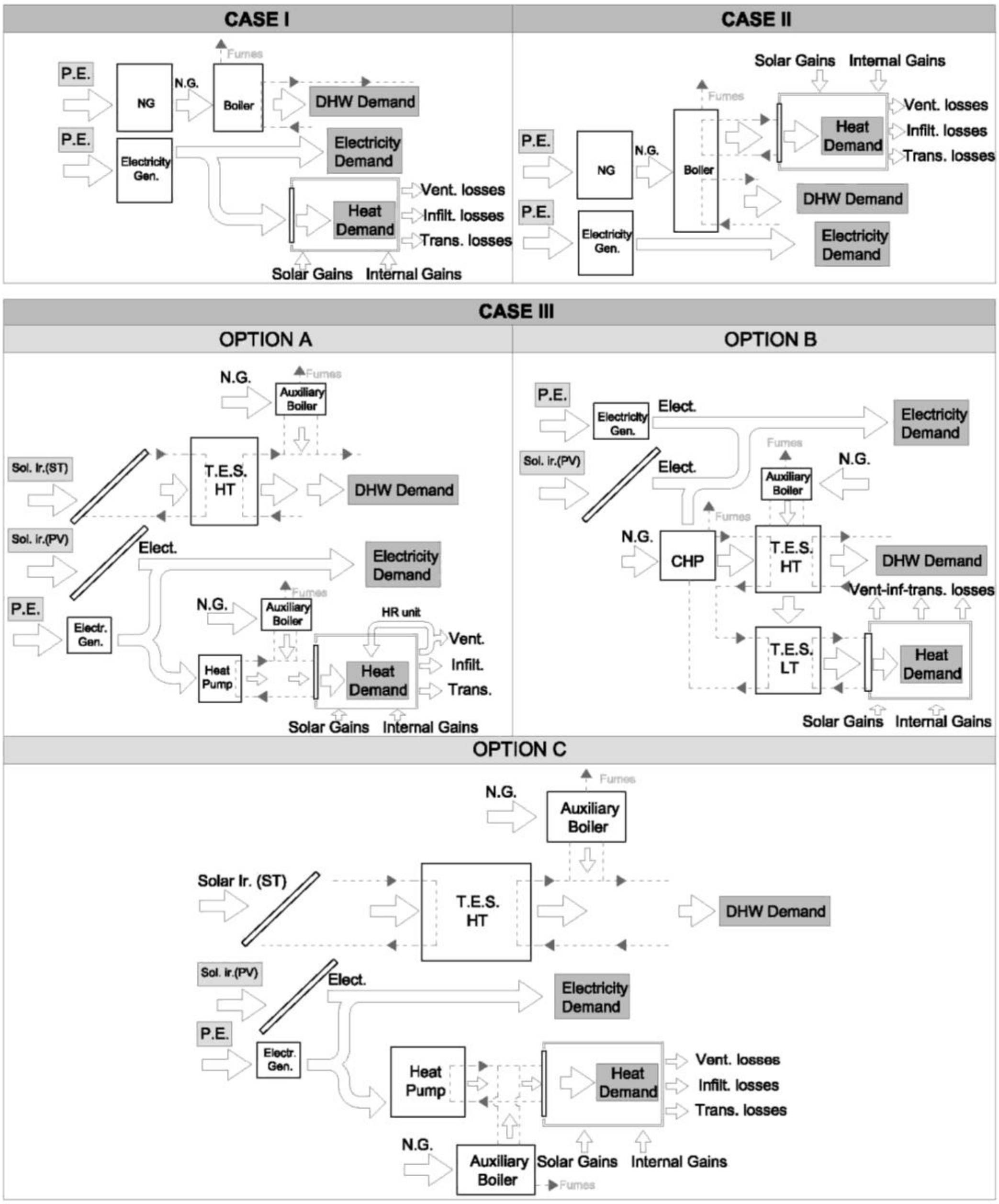


Fig. 3 Detailed schemes of the reference cases (Case I and II) and the improved options selected (Case III, options A, B and C).

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.

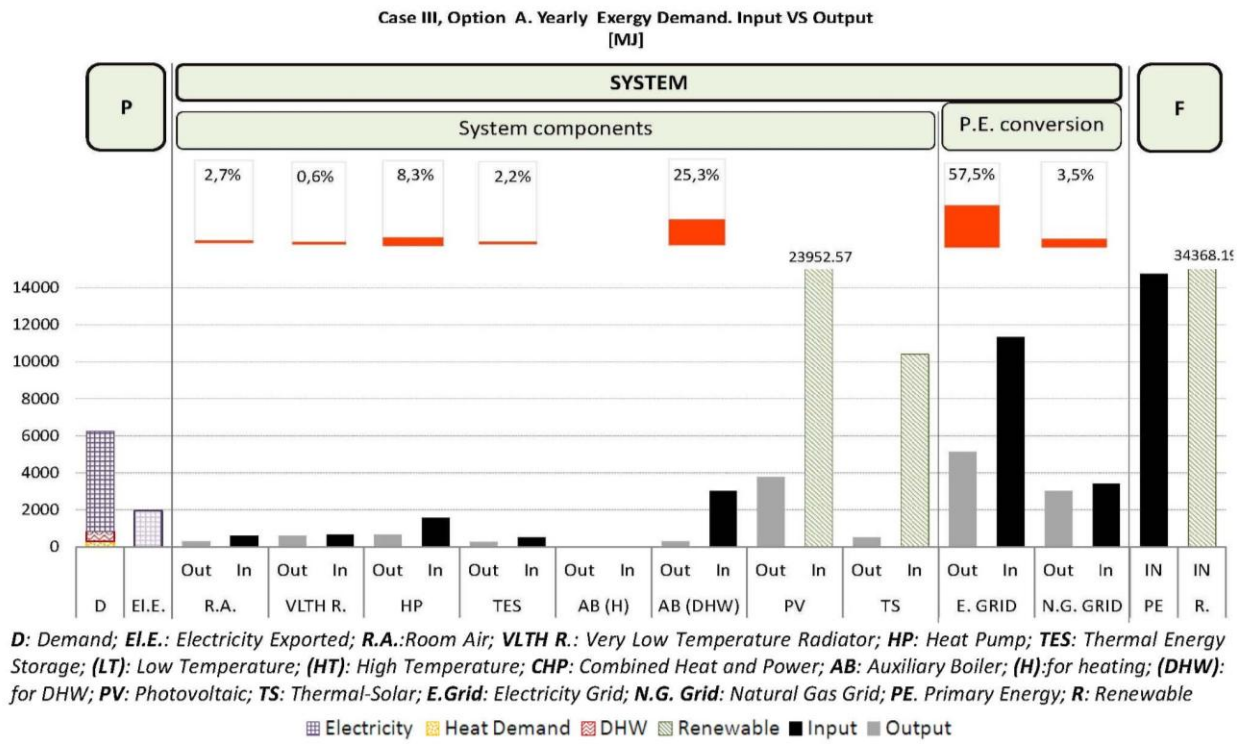
4.2.2 Detailed results of Cases III (A, B, C)

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.

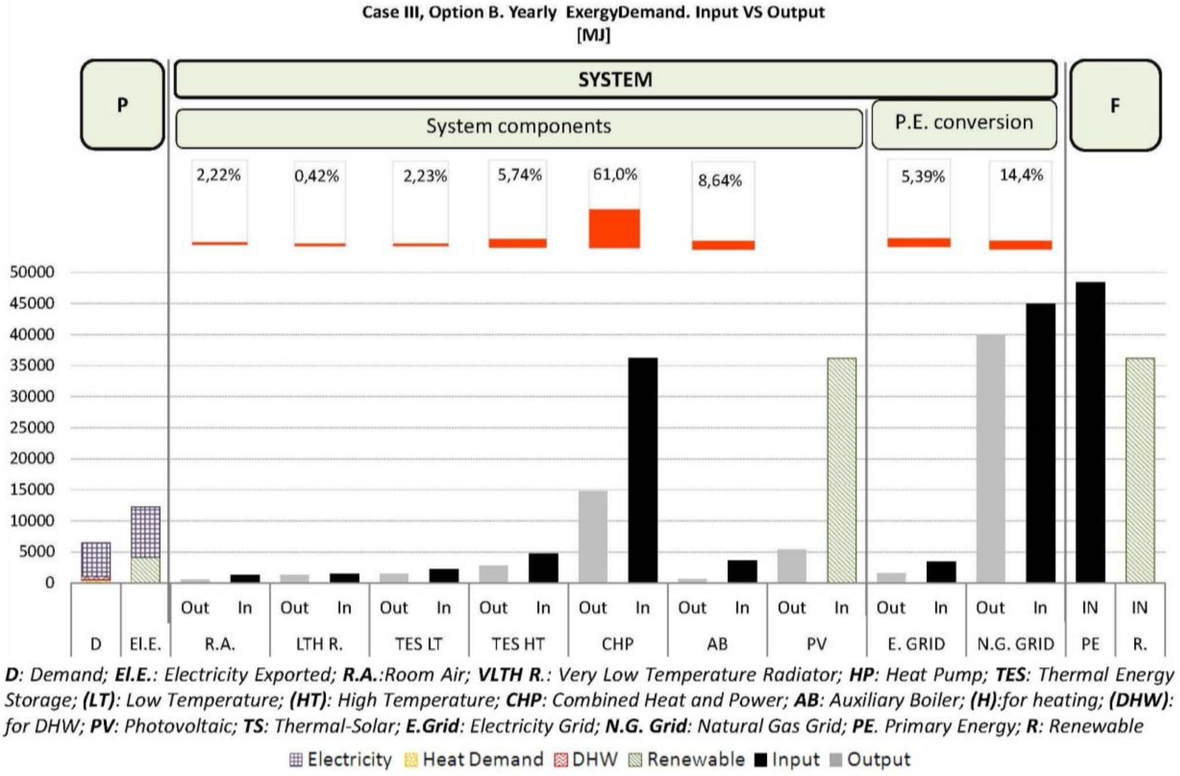
	OPTION A				OPTION B				OPTION C			
	Outp En (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Outp EN (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η (Ψ) [–]	L (D) [MJ/y]	Outp En (*Ex*) [MJ/y]	Inp EN (*Ex*) [MJ/y]	η [–]	L (D) [MJ/y]
Comp.												
Room Air	7560 (308)	7560 (598)	- (0.52)	- (290)	14375 (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)



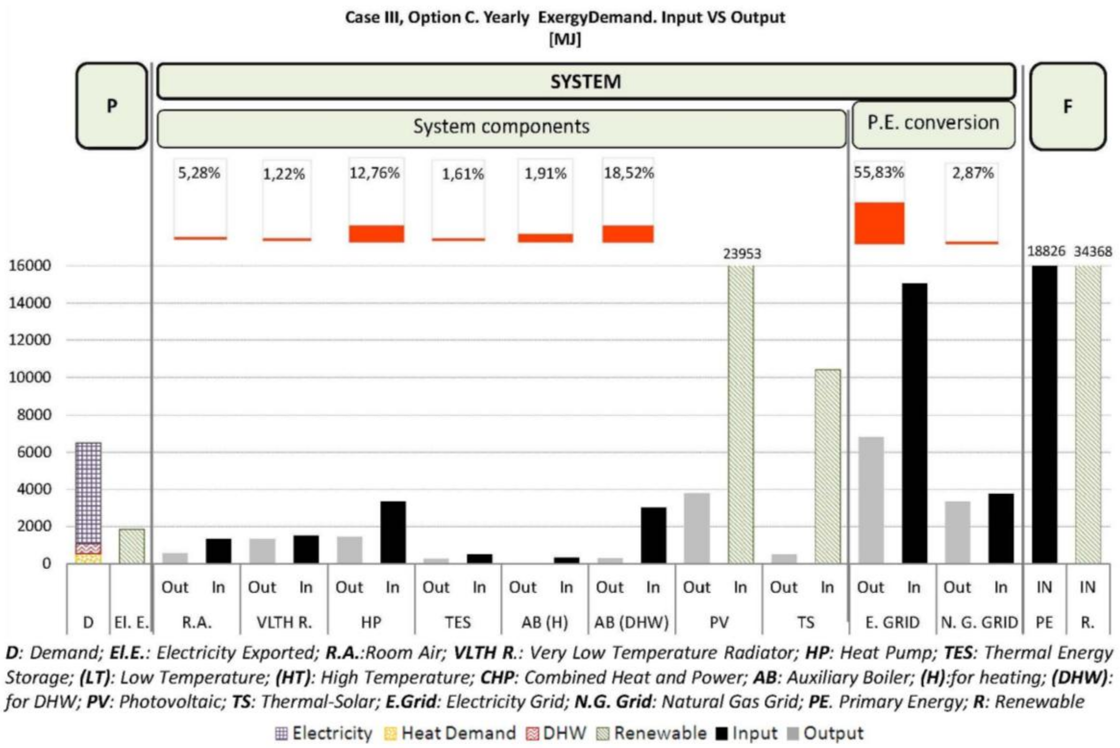
D: *Demand;* ***El.E.***: *Electricity Exported;* ***R.A.***:*Room Air;* ***VLTH R.***: *Very Low Temperature Radiator;* ***HP***: *Heat Pump;* ***TES***: *Thermal Energy Storage;* ***(LT)***: *Low Temperature;* ***(HT)***: *High Temperature;* ***CHP***: *Combined Heat and Power;* ***AB***: *Auxiliary Boiler;* ***(H)***:*for heating;* ***(DHW)***: *for DHW;* ***PV***: *Photovoltaic;* ***TS***: *Thermal-Solar;* ***E.Grid***: *Electricity Grid;* ***N.G. Grid***: *Natural Gas Grid;* ***PE***. *Primary Energy;* ***R***: *Renewable*

Fig. 4. Detailed analysis of the input and output in each component of the system. (Case III-Option A)



D: *Demand;* ***El.E.***: *Electricity Exported;* ***R.A.***:*Room Air;* ***VLTH R.***: *Very Low Temperature Radiator;* ***HP***: *Heat Pump;* ***TES***: *Thermal Energy Storage;* ***(LT)***: *Low Temperature;* ***(HT)***: *High Temperature;* ***CHP***: *Combined Heat and Power;* ***AB***: *Auxiliary Boiler;* ***(H)***:*for heating;* ***(DHW)***: *for DHW;* ***PV***: *Photovoltaic;* ***TS***: *Thermal-Solar;* ***E.Grid***: *Electricity Grid;* ***N.G. Grid***: *Natural Gas Grid;* ***PE***. *Primary Energy;* ***R***: *Renewable*

Fig. 5. Detailed analysis of the input and output in each component of the system. (Case III-Option B)



***D**: Demand; **El.E.**: Electricity Exported; **R.A.**:Room Air; **VLTH R.**: Very Low Temperature Radiator; **HP**: Heat Pump; **TES**: Thermal Energy Storage; **(LT)**: Low Temperature; **(HT)**: High Temperature; **CHP**: Combined Heat and Power; **AB**: Auxiliary Boiler; **(H)**:for heating; **(DHW)**: for DHW; **PV**: Photovoltaic; **TS**: Thermal-Solar; **E.Grid**: Electricity Grid; **N.G. Grid**: Natural Gas Grid; **PE**. Primary Energy; **R**: Renewable*

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).

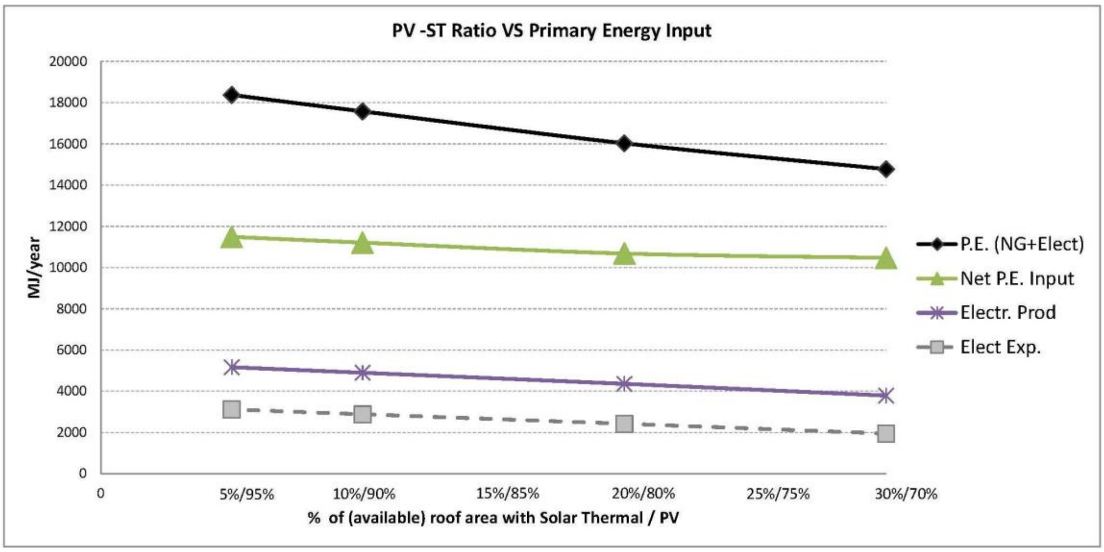


Fig. 7. ST-PV Ratio Vs Primary Energy input

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.

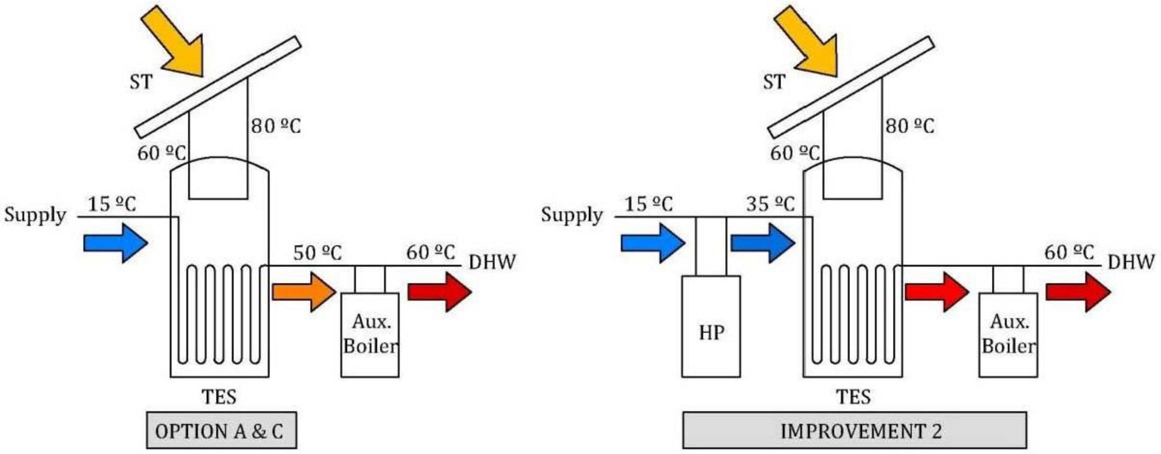


Fig. 8. Scheme of the 2nd improvement. The left picture depicts the system in option A and C, and right picture depicts the improvement.

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)

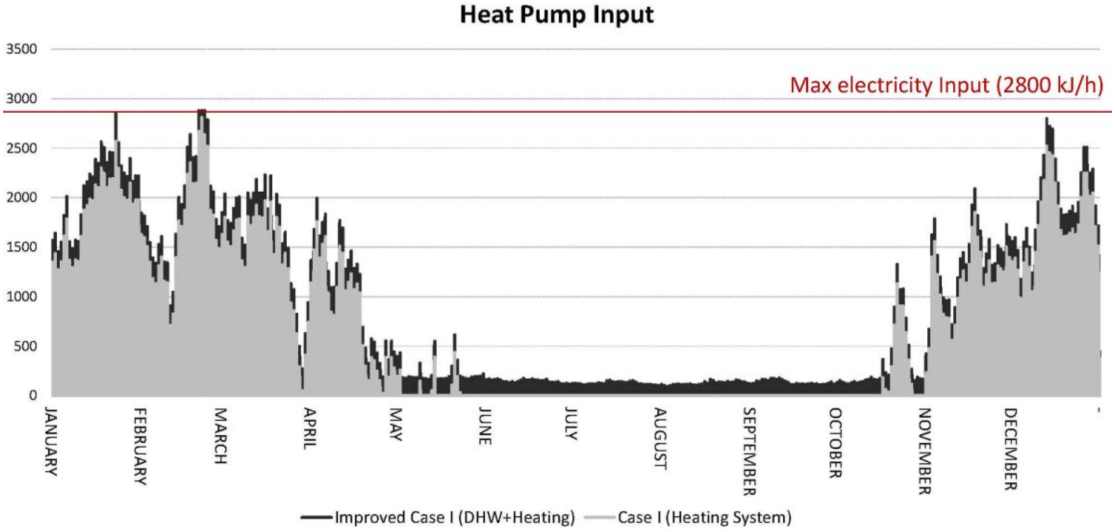
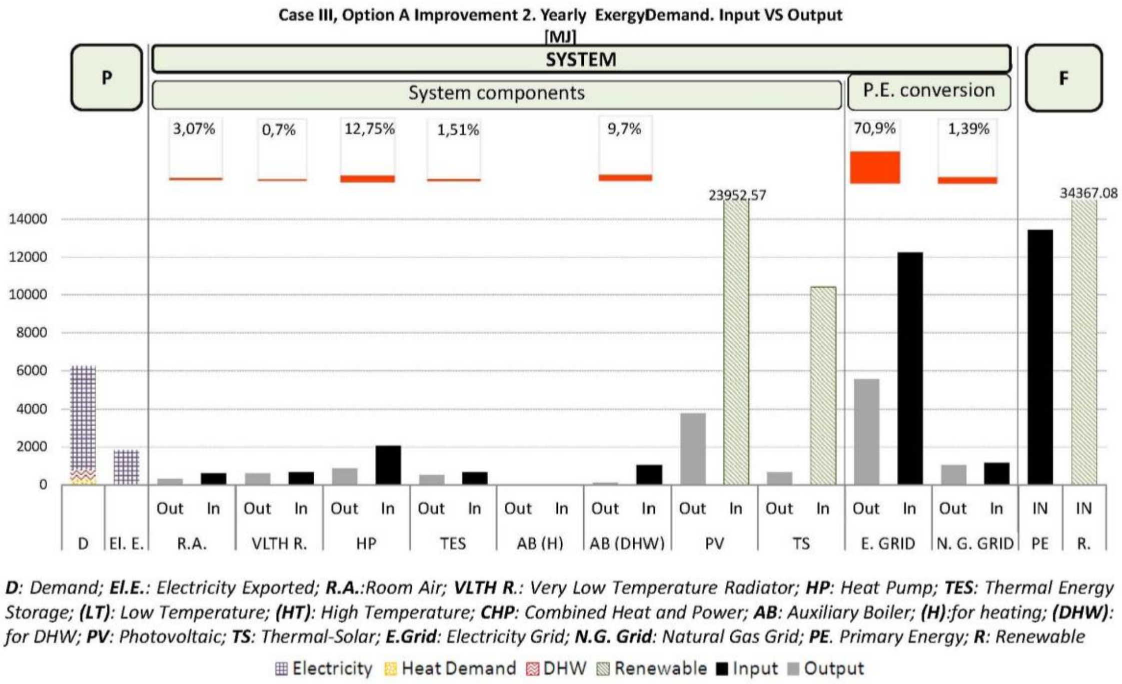


Fig. 9. Heat Pump input (Case I, in grey, Improved Case I, in Black)

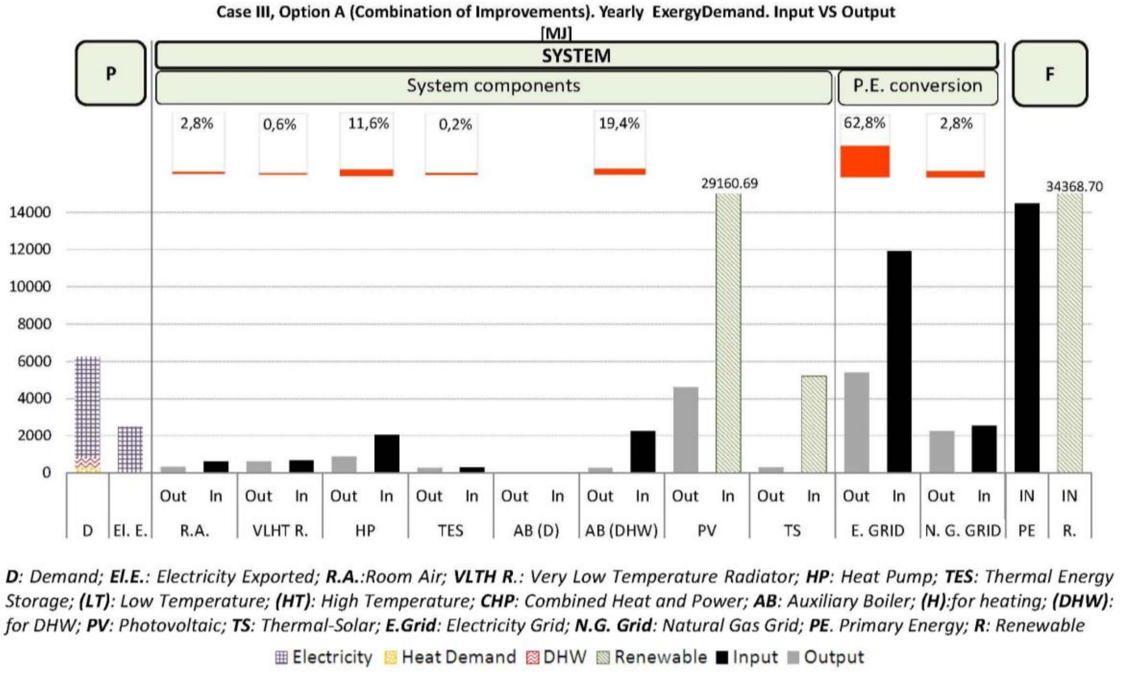
This significantly reduced use of the auxiliary boiler results in a reduction of the net P.E. input of more than 10%, from 10470MJ/year to 9361 MJ/year, as shown in Table 5. A detailed scheme of the improved system demand, component exergy losses and primary energy input is shown in Fig. 10.



D: *Demand;* ***El.E.***: *Electricity Exported;* ***R.A.***:*Room Air;* ***VLTH R.***: *Very Low Temperature Radiator;* ***HP***: *Heat Pump;* ***TES***: *Thermal Energy Storage;* ***(LT)***: *Low Temperature;* ***(HT)***: *High Temperature;* ***CHP***: *Combined Heat and Power;* ***AB***: *Auxiliary Boiler;* ***(H)***:*for heating;* ***(DHW)***: *for DHW;* ***PV***: *Photovoltaic;* ***TS***: *Thermal-Solar;* ***E.Grid***: *Electricity Grid;* ***N.G. Grid***: *Natural Gas Grid;* ***PE***. *Primary Energy;* ***R***: *Renewable*

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



D: *Demand;* ***El.E.***: *Electricity Exported;* ***R.A.***:*Room Air;* ***VLTH R.***: *Very Low Temperature Radiator;* ***HP***: *Heat Pump;* ***TES***: *Thermal Energy Storage;* ***(LT)***: *Low Temperature;* ***(HT)***: *High Temperature;* ***CHP***: *Combined Heat and Power;* ***AB***: *Auxiliary Boiler;* ***(H)***:*for heating;* ***(DHW)***: *for DHW;* ***PV***: *Photovoltaic;* ***TS***: *Thermal-Solar;* ***E.Grid***: *Electricity Grid;* ***N.G. Grid***: *Natural Gas Grid;* ***PE***. *Primary Energy;* ***R***: *Renewable*

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.

7 Acknowledgements

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Sabine Jansen and Peter Luscuere greatly acknowledge the financial support of Agentschap NL.

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		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

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).

$$\mathrm{T_{op}} = \frac{\mathrm{T_{air}} + \mathrm{T_{mean\_surface}}}{2}$$	**eq. A. 1**
$$\mathrm{T_{air,sp}} = \left(\mathrm{T_{op,sp}} - 0.5 \cdot \mathrm{T_{mean\_surf}}\right) \cdot 2$$	**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.

• $\mathrm{If\ T_{out}} < -5^{o} C \rightarrow T_{\mathrm{sup}\_DHW} = 1.8$ • $\mathrm{If\ T_{out}} \geq -5^{o} C \rightarrow T_{\mathrm{sup}\_DHW} = \left(2 \cdot \mathrm{T_{out}} + 15.4\right)/3$	**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:

- $\text{If } T_{in} < 23^{o}C \rightarrow T_{vent} = T_{HR}$
- $\text{If } T_{in} \geq 23^{o}C \rightarrow T_{vent} = T_{out}$

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.:

$Q_{CHP,output}$

$$\begin{aligned} &\text{If } \mathrm{Q_{TESHT,\,inp}} < 10800kJ \rightarrow Q_{CHP,outp} = Q_{TESHT,inp} \\ &\text{If } \mathrm{Q_{TESHT,\,inp}} \geq 10800kJ \rightarrow Q_{CHP,outp} = 10800kJ \end{aligned} \qquad \textbf{eq. A 6}$$

$$\mathrm{Q_{CHP,\,inp}} = \mathrm{Q_{CHP,\,outp}} / \eta_{CHP,Q} \qquad \textbf{eq. A 7}$$

$$\mathrm{E_{CHP,\,outp}} = \mathrm{Q_{CHP,inp}} / \eta_{CHP,E} \qquad \textbf{eq. A 8}$$

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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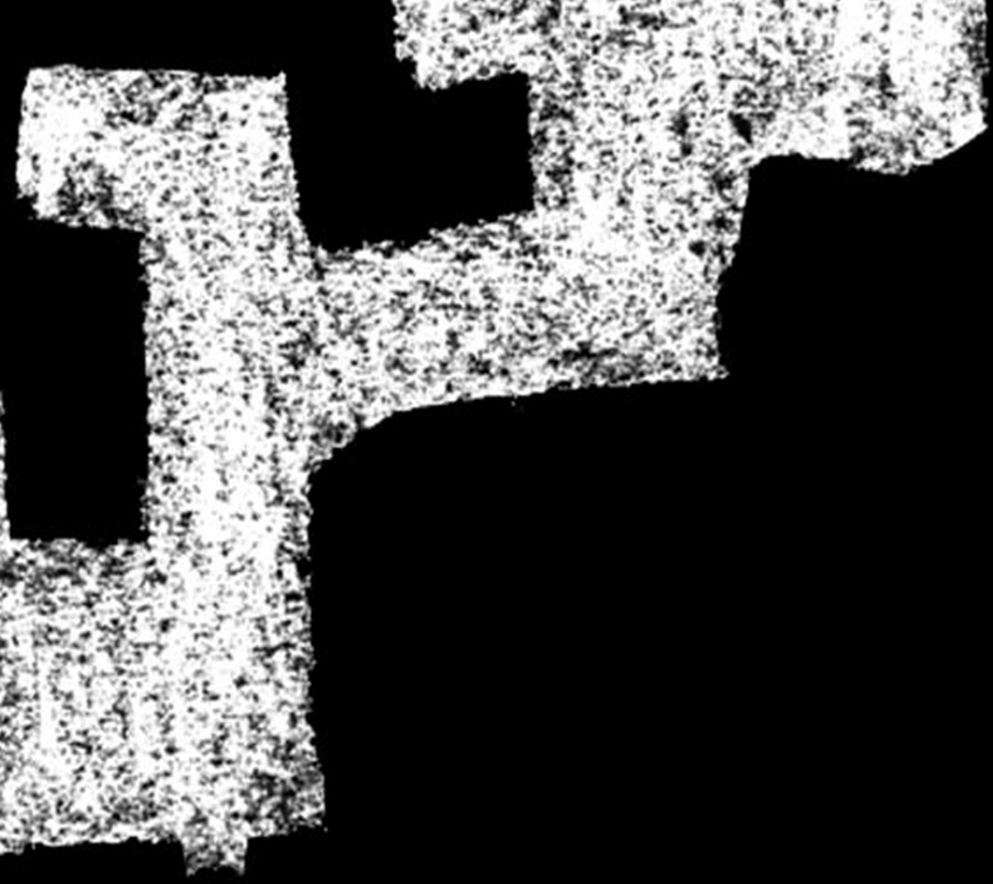

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Energy in Buildings

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