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DESIGN OF METHODOLOGIES AND EMPIRICAL APPLICATION FOR THE CHARACTERIZATION OF SOCIAL HOUSING AND APPROACH FOR ENERGY VULNERABILITY REDUCTION

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Contributions of the authors to each of the articles published in this PhD Thesis.

All the authors collaborated in the study and in the papers elaboration. A more precise description of the activities done by each author is described below.

Paper 1. *Energy poverty composite index in social housing, from a household energy poverty perspective*

Authors: Eva Llera-Sastresa, Sabina Scarpellini, Pilar Rivera-Torres, Juan Aranda, Ignacio Zabalza-Bribián and Alfonso Aranda-Usón

Eng. J. Aranda was the article coordinator, performed the empirical study, carried out the data analysis and wrote the paper. Dr. Scarpellini's contribution is specially focused on the theoretical background of the study. Dr. Llera, PhD co-director, designed the method. She is the corresponding author as well. Dr. Rivera-Torres designed the statistical experiments; and Dr. Alfonso Aranda-Usón contributed in the analysis of the energy installations and energy management; Finally, Dr. Zabalza, PhD co-director, focused on the building characterization.

Paper 2: *The mediating role of social workers in the implementation of regional policies targeting energy poverty*

Authors: Sabina Scarpellini, M. Alexia Sanz Hernández, Eva Llera-Sastresa, Juan Aranda, María Esther López Rodríguez

Dr. Scarpellini was the article coordinator and corresponding author, she designed the paper and the survey. Eng. J. Aranda designed the energy training tool and analysed the data from the survey, covering the technical analysis of the energy poverty causes and variables. Dr. Sanz Hernández gave the sociological point of view. Dr. Llera, PhD co-director, supported on the methodological approach. Finally, Dr. López Rodríguez contributed to the analysis of the existing aid schemes and regulatory policies in place.

Paper 3: *Building Energy Assessment and Computer Simulation Applied to Social Housing in Spain*

Authors: Juan Aranda, Ignacio Zabalza, Eva Llera-Sastresa, Sabina Scarpellini and Alfonso Alcalde.

Eng J. Aranda designed the study, established the parameters to be assessed, carried out the data analysis, coordinated the paper contributions and wrote the paper. Dr. Zabalza-Bribián, PhD co-director, worked on the building characterization. He is also the corresponding author. Dr. Llera's (PhD co-director) contribution is specially focused on the characterization of the energy user behaviour. Dr. Scarpellini is an expert in energy poverty in households and her contribution was specially focused on the theoretical background of the study. Finally, Alfonso Alcalde performed the simulations and the energy audits under the supervision of Dr. Zabalza and J. Aranda.

Paper 4: *Analysis of Energy Efficiency Measures and Retrofitting Solutions for Social Housing Buildings in Spain as a Way to Mitigate Energy Poverty*

Authors: Juan Aranda, Ignacio Zabalza, Andrea Conserva and Gema Millán.

Eng J. Aranda coordinated the author's contributions, analysed the theoretical background of the study, performed the economic analysis of all the energy efficiency measures and wrote the paper. Dr. Zabalza, PhD co-director, defined the methods and selected the case study for this paper. He is also the corresponding author. A. Conserva performed all the energy simulations with EnergyPlus calculation engine. Finally, G. Millan is the TRIBE project coordinator and her contribution was especially focused on the energy efficiency measures characterization.

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ABSTRACT

(Spanish follows)

Energy poverty is a common issue in social housing all over Europe, with a harder impact in Southern European countries. In Europe, the proportion of social housing is high, and such houses tend to be inhabited by below average-income households, which are particularly vulnerable to energy poverty. The first part of the research proposes a new methodological approach for defining an index for household energy vulnerability assessment. This method can be used to improve the management of social housing and the prioritise solution and mitigation actions towards energy poverty. After establishing a heuristic framework for household energy poverty – which stems from different causes such as income, characteristics of the residence, energy installations, and the energy-consumption habits of household members– multi-criteria analytical methods, based on the aggregation of indicators which reveal the conditions leading to energy poverty, have been applied, and effective means of intervention are proposed. The method is also applied to a sample of social houses and thus validated as a useful tool in decision-making processes which concern the management of social housing and from a household energy-poverty perspective.

Once the energy poverty has been characterized by the proper metrics, an assessment on the way it is tackled by society and public administrations has been carried out. The second part of this research work aims to provide a socio-political reflection of the role played by social workers in regional policies and of the real needs of households affected by energy poverty. The research also examines the impact of technical-specialised training on the ability of social workers to prevent and mitigate conditions of household energy poverty in Europe.

The adoption of a research-action-participation methodological framework and a training research approach has permitted the opinions of social workers to be collected through surveys, and their central role in implementing regional policies to be highlighted. The conclusions obtained have made possible the construction of a self-diagnosis and data-collection tool which increases the ability of social workers to mediate and implement urgent mitigation measures for energy impoverished households. In addition, regional policies which aim to mitigate household energy poverty are examined from the professional perspective of social workers.

Social housing buildings play an important role in energy poverty. Several social housing buildings were selected and analysed to check how the architecture, the equipment and the energy usage by the tenants influence the energy poverty of the occupants. Energy audits and energy computer simulations were carried out in a sample of buildings as a case study. Although it is well known that the actual energy consumption and simulated energy performance of a building usually differ, this gap widens in social housing, owing to the characteristics of these buildings and the consumption patterns of economically vulnerable households affected by energy poverty. The aim of this research work was to characterise the energy poverty of the households that are representative of those residing in social housing, specifically in blocks of apartments in Southern Europe. The main variables that affect energy consumption and costs are analysed, and the models developed for software energy-performance simulations (which are applied to predict energy consumption in social housing) are validated against actual energy-consumption values. The results demonstrate that this type of household usually lives at a temperature below the average thermal comfort level. It is noticed that a standard thermal comfort level may lead to significant differences between computer-aided energy building simulation and actual consumption data (which is 40%-140% lower than simulated consumption). This fact is of integral importance, as computer simulation is used to predict building energy performance in social housing.

Finally, the results obtained from the previous task were applied to the analysis of suitable energy efficiency measures that may be applicable to social housings to reduce the vulnerable households’ energy costs and to improve their thermal comfort levels. Social housing buildings are usually owned and managed by public institutions and usually share common characteristics and issues. Behavioural changes and energy retrofitting are interesting paths forward but some solutions do not fit well in this type of housing due to socioeconomic reasons and tenancy constraints.

The last part of the research makes a thorough analysis of possible energy efficiency measures in social housing buildings, characterizing them by energy and economic savings and investment tailored to a social housing case study, and proposing different methods of prioritization. A rational approach of behavioural and retrofitting solutions that best fit into this particular housing type is delivered, with the aim to increase the thermal comfort of the residents and mitigate the energy poverty issue. Results show that there is a wide range of domestic efficiency measures to be applied in this type of dwellings at none or low costs, bringing annual savings per average dwelling of about 55% of the initial energy costs, including measures both at domestic level, and at building level with a final aggregated payback of the investments to be about 1.5 years.

RESUMEN

La pobreza energética es un problema común en las viviendas sociales en toda Europa, con un impacto más fuerte en los países del sur de Europa. En Europa, la proporción de viviendas sociales es alta, y dichas viviendas tienden a estar habitadas por unidades familiares con ingresos por debajo de la media, que son particularmente vulnerables a la pobreza energética. La primera parte de la investigación propone un nuevo enfoque metodológico para definir un índice que permita realizar una evaluación de la vulnerabilidad energética de los hogares. Este método se puede utilizar para mejorar la gestión de la vivienda social y priorizar soluciones y acciones de mitigación de la pobreza energética. Se establece un marco heurístico para la pobreza energética de los hogares, que proviene de diferentes causas, como los ingresos, las características de la residencia, las instalaciones energéticas y los hábitos de consumo de energía de los miembros del hogar. Se aplican métodos analíticos multicriterio, basados en la agregación de indicadores que revelan las condiciones que conducen a la pobreza energética y se proponen medios efectivos de intervención. Esta metodología también se aplica a una muestra de hogares sociales y comunes y, por lo tanto, se valida como una herramienta útil en los procesos de toma de decisiones que se refieren a la gestión de la vivienda social desde una perspectiva de la pobreza energética de los hogares.

Una vez que la pobreza energética ha sido caracterizada a través de los parámetros adecuados, se lleva a cabo una evaluación sobre la forma en que la sociedad y las administraciones públicas la abordan. La segunda parte de este trabajo de investigación tiene como objetivo proporcionar una reflexión sociopolítica del papel desempeñado por los trabajadores sociales y las políticas regionales, así como de las necesidades reales de los hogares afectados por la pobreza energética. La investigación también examina el impacto que tiene la formación técnica especializada de los trabajadores sociales en la prevención y mitigación de las condiciones de pobreza energética en los hogares europeos.

La adopción de un marco metodológico de investigación-acción-participación y un enfoque de investigación en acciones de capacitación ha permitido recoger las opiniones de los trabajadores sociales a través de encuestas y resaltar su papel central en la implementación de políticas regionales. Las conclusiones obtenidas han hecho posible la construcción de una herramienta de autodiagnóstico y recopilación de datos que aumenta la capacidad de los trabajadores sociales para mediar e implementar medidas de mitigación urgentes para los hogares empobrecidos. Además, las políticas regionales que apuntan a mitigar la pobreza energética de los hogares se examinan desde la perspectiva profesional de los trabajadores sociales.

Los edificios de viviendas sociales juegan un papel importante en la pobreza energética. Para verificar cómo la arquitectura, el equipamiento y el uso de energía por parte de los inquilinos influyen en la pobreza energética de los ocupantes se seleccionan y analizan varios edificios de viviendas sociales. Se realizaron auditorías energéticas y simulaciones energéticas en una muestra de edificios como caso de estudio. Aunque está demonstrado que el consumo de energía real y el consumo energético simulado de un edificio suelen diferir, esta brecha se amplía en la vivienda social, debido a las características de estos edificios y los patrones de consumo de los hogares económicamente vulnerables afectados por la pobreza energética. El objetivo de este trabajo de investigación fue caracterizar la pobreza energética de un conjunto de hogares representativos de quienes residen en viviendas sociales en modo de alquiler, específicamente en bloques de apartamentos en el sur de Europa. Se analizaron las principales variables que afectan el consumo y los costes de la energía, así como los modelos desarrollados para las simulaciones energéticas por ordenador, que se aplican para predecir el consumo de energía en la vivienda social. Los resultados se validaron frente a los valores reales de consumo de energía de las viviendas simuladas. Los resultados demuestran que en este tipo de vivienda se encuentra generalmente a una temperatura por debajo del nivel de confort térmico promedio. Se advierte que tomar un nivel de confort térmico estándar para simulaciones puede generar diferencias significativas entre la simulación energética de la vivienda y los datos de consumo real, que está entre 40% y 140% por debajo del consumo simulado. Este hecho es de gran importancia, ya que la simulación energética por ordenador es una herramienta comúnmente utilizada para predecir el comportamiento energético de cualquier tipo de edificio.

Finalmente, los resultados obtenidos de la tarea anterior se aplicaron al análisis de medidas adecuadas de eficiencia energética que pueden aplicarse a las viviendas sociales para reducir los costes de la energía de los hogares vulnerables y mejorar sus niveles de confort térmico. Los edificios de vivienda social generalmente son propiedad de instituciones públicas y están gestionados directamente por la entidad pública propietaria. Muchas veces comparten características y problemas comunes. Los cambios de comportamiento de los usuarios y el ajuste de la fuente energética son mejoras interesantes, pero algunas soluciones no encajan bien en este tipo de viviendas debido a razones socioeconómicas y de régimen de propiedad.

La última parte de la investigación lleva a cabo un análisis exhaustivo de las posibles medidas de eficiencia energética en los edificios de viviendas sociales, caracterizando las medidas por el ahorro energético y económico y por la inversión necesaria adaptadas a un caso de estudio de vivienda social, y proponiendo diferentes métodos de priorización. Se ofrece un enfoque racional de priorización de las medidas de eficiencia que mejor se adaptan a este tipo particular de vivienda, con el objetivo de aumentar el confort térmico de los residentes y mitigar el problema de la pobreza energética. Los resultados muestran que existe una amplia gama de medidas de eficiencia para ser aplicadas en este tipo de viviendas con un coste nulo o muy bajo, lo que representa un ahorro anual por vivienda promedio de alrededor del 55% del coste inicial de la energía, incluyendo medidas aplicables a cada vivienda individual, y al edificio en su conjunto, con un periodo de retorno simple de las inversiones de aproximadamente 1,5 años.

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LIST OF ACRONYMS

COP: Coefficient of Performance

DHW: Domestic Hot Water

EC: European Commission

EE: Energy Efficiency

EU: European Union

GVI: Global Vulnerability Index

HVAC: Heating, Ventilation and Air Conditioning

IVI: Individual Vulnerability Index.

NGO: Non-Governmental Organisation

RD: Royal Decree

ZV: Zaragoza Vivienda

1 Introduction

1.1 Concept of energy vulnerability

In general terms most studies about relative poverty, such as energy poverty, use indicators based on monetary variables such as income or expenditure. In both cases a minimum value is set, below which people are classified as "poor". In the case of energy, many authors consider that an energy expenditure that exceeds 10% of a household's income gives rise to energy poverty situations (Boardman, 1991), (Tirado Herrero and Bouzarovski, 2015). In this case, the variable chosen for the definition of this problem is the percentage of energy expenditure with respect to household income and therefore its level of vulnerability or energy poverty will depend on the distribution of its expenditures.

At the Community level, the European Union Statistics on Income and Living Conditions (Central Statistics Office, 2016) currently provides standardized data to measure some of the aspects linked to energy poverty in Europe. It is, in fact, the EU reference source for comparative statistics on per capita income and social inclusion in the territory. From this source, it can be seen that the precariousness of households' fuel access is present throughout the EU and, in particular, in the Eastern and Southern areas. In 2011, for example, 9.8% of the households in the 27 Member States and 15.8% of households in the 12 European Union newer Member States could not afford adequate heating systems to maintain comfortable thermal conditions, and 8.8% of households in the 27 Member States and 17.1% of households in the 12 newer Member States were late in paying their bills. These data, which revealed the precariousness of access to certain resources by the most vulnerable households in the EU in terms of energy, were obtained mainly through the analysis of monetary indicators.

Given the problem raised here and the objectives pursued in this study that focuses on the relationship between the building characteristics of housing and the energy vulnerability of a household, it was deemed necessary to define a series of indicators that integrate both the factors inherent to housing and the energy equipment available into a single measurement system, as well as those factors that concern the family structure, and the energy consumption habits of its members.

One of the first issues to be addressed in order to determine the approach to the proposed analysis is the terminology. Currently, at European level, there is no unanimous opinion at the academic level about the definition to be adopted to delimit the term “energy vulnerability” in a household or the more commonly used term of “energy poverty”. European policy in this area has been fragmented to date to a certain extent, as a result of the subsidiarity of competences with the Member States which limits the scope of a defined European Union framework.

Given these considerations, the first phase of the work briefly analyses the literature available on the subject and the different definitions used for energy vulnerability and energy poverty, which are often used indistinctly.

In the definitions initially adopted at European level, following the pioneering publication of Boardman (Boardman, 1991), it was generally considered that a household is in a situation of energy poverty when it has to allocate more than 10% of its income to satisfy a sufficient thermal comfort to maintain the indoor temperature of between 18º and 21ºC (BERR-Department or Business Entreprise & Regulatory Reform, 2008). This criterion was subsequently debated and reviewed by different authors, such as Hills (Hills, 2012), who proposed to consider a household in a situation of energy poverty when the domestic energy costs that would have to be incurred to obtain a suitable level of thermal comfort would be above average, and provided that they had an income below the official poverty line (60% of the average income after deducting the non-energy expenses associated with housing).

Similarly, the International Energy Agency (IEA, 2011) states that a household is in a situation of "energy poverty" when it has excessive energy costs compared to the total household income. The definition provided by the IEA is very similar to that adopted by the Environmental Sciences Association (ACA) in one of the pioneering publications in Spain in the field (Herrero Tirado and López Fernández, 2012). At the European level, the EU's "Energy Poverty in the EU" report (Thomson and Snell, 2013) incorporated into the existing definitions the concepts of "cold home" or "energy debt" related to housing.

Based on the relative definition of energy poverty by Grevisse and Brynart (Grevisse and Brynart, 2011), this study adopts the definition by which a household is in a situation of energy poverty when it is unable to pay an amount of energy services sufficient to the satisfaction of their domestic thermal needs. The accreditation of the problem is introduced here by the competent body in social services that can classify the degree of vulnerability of the different households in terms of energy (Scarpellini et al., 2015).

As far as the definition of energy vulnerability is concerned, the analysis and definition of vulnerable energy consumers was addressed in the third energy package adopted by the EU in 2009 (Rab et al., 2011). Final consumers, whether individuals or companies, are considered to be vulnerable in their relationship with the energy service provider (mainly gas, electricity, etc.). This approach can also include other people in a household considering the joint needs of comfort, beyond the individual tenant. This is relevant to define the unit of analysis of this study that focuses on the household.

As pointed out by Bergasse et al., when households are to bear excessive costs for their energy supplies, they are undoubtedly in a situation of energy vulnerability (Bergasse et al., 2013). Therefore, they have to be protected as consumers due to their high degree of vulnerability in energy terms (Bouzarovski et al., 2012)) to avoid their social exclusion, and thus guarantee basic access to energy at reasonable and stable prices (Comité Económico y Social Europeo, 2013) in the EU. This approach by Bouzarovski, widely adopted in Europe, introduces the concept of "fuel shortage" for the thermal aspects of the phenomenon (Bouzarovski et al., 2012).

This consideration is, in fact, recognized in the third “Energy Package” of 2009 (Rab et al., 2011), whereby all EU member countries must take appropriate measures to protect vulnerable consumers. With regard to the protection of vulnerable consumers, Directive 2009/72/EC (European Parliament, 2009) on common rules for the internal market for electricity provides that Member States should be empowered to take appropriate measures to protect final customers and, in particular, to ensure adequate protection for vulnerable customers. In this respect, each Member State defines the concept of vulnerable customer and / or energy poverty and, if necessary, regulates the possible prohibition of electricity curtailment in critical seasons (Article 3.7). In the European context, the term vulnerable consumer can therefore adopt different meanings according to the transposition of the Directives into national laws.

Based on these considerations, this study considers an energy vulnerable household the one that is forced to spend an excessive part of its income to pay the energy bills of their home. In this case, the household is more exposed to any increase of domestic energy expenditure to supply its minimum needs.

There is unanimity in Europe today when it comes to classifying energy poverty in households as a preferential issue that the governments of member states must tackle and prioritize in order to avoid social exclusion by guaranteeing access to energy at reasonable and stable prices (European Economic and Social Committee, 2013). This problem has been recognized by the European Commission in the third

"Energy Package" in 2009 (Altan et al., 2015) and in the current "Winter Package" at the end of 2016 (EuropeanCommission, 2016). This problem is much more serious in Southern and Eastern Europe (Tirado Herrero and Bouzarovski, 2015). Although favourable weather conditions suggest that in southern Europe the situation is better, it is estimated that 16.6% of households in the Mediterranean area live in poor conditions of thermal comfort while the European average is four percentage points lower (Bouzarovski, 2011).

However, there is not a common agreement on the criteria for classifying households in and out of energy poverty. The main cause of energy poverty lies in the lack of household economic resources, which prevents them from meeting the minimum energy costs to ensure adequate thermal comfort conditions in their homes (Bergasse et al., 2013). This research does not tackle the possible causes of this lack of resources, but their consequences, and possible actions to mitigate situations of energy vulnerability in households. Through a methodological and empirical development, it is proposed to respond to different research questions that imply an advance in the scientific literature on energy policy, energy management of social housing buildings and characterization of vulnerable consumers from the energy point of view.

The study of the literature on household energy poverty policy shows how the volume of energy expenditure is often adopted to identify situations of need (Boardman, 2012) or other measures inherent to the thermal comfort situation (Dubois, 2012), (Li et al., 2014), a question relevant to the definition of aid to alleviate the problem (Chaudhuri and Ravallion, 1994).

Just as the macro analysis of energy poverty at the European level has been addressed by several authors (Liddell et al., 2012), (Moore, 2012), (Rosenow et al., 2013), the European empirical studies of European households in this situation are less abundant (Roberts, 2008), (Santamouris et al., 2013), (Tirado Herrero et al., 2014), (Scarpellini et al., 2015). The studies that measure the phenomenon have experienced some increase in recent years (Morrison and Shortt, 2008), (Pachauri and Spreng, 2011), (Rudge and Gilchrist, 2007), (Rudge, 2012) as well as those that analyse possible solutions (Boardman, 2004), (Darby, 2012), subsidy policies (Dartanto, 2013) and the relative efficiency of public funds for households in social exclusion (Copiello, 2016). In this field, some authors have identified the lack of uniformity among European and national statistical data as a limitation, as well as a shortage of data and a lack of surveys and specific methodology for measuring the phenomenon (Heindl, 2015).

Energy poverty is a multidimensional issue, and the degree of energy vulnerability of households is determined by a multiplicity of factors. This research uptakes the main results of an analysis undertaken using a large sample of households whose energy poverty situation was certified by the social services, and analyses the role of the four determinant factors leading to a situation of energy poverty. These four factors are the building characteristics, the energy equipment, the energy costs and the household structure and tenants habits.

Limited access to personal data has restricted the analysis of energy poverty to macro and micro levels, based on aggregate public data. As pointed out by Dubois and Meier (Dubois and Meier, 2015), identifying the problem and designing more effective solutions requires research on a local scale. Local level studies concluded that the characteristics of buildings and installations are a key factor, especially for low-income households, and local management can contribute to solving the problem globally. These studies share the same vision of the problem posed by energy poverty and also agree on the partial dimensions into which the problem can be broken down, e.g. the energy efficiency of buildings, the social characteristics of the household, the characteristics of the installations, the cost of energy, etc. (Monzón and López-Mesa, 2018), but lack a composite vulnerability index that integrates the characteristics of the home, the household’s consumption habits and the energy tariffs and establishes the household's degree of vulnerability. The design, creation and test of such composite index is one of the main objectives of this research.

The cases of energy poverty are not easy to identify and diagnose since there is no certifying body of this situation. Only families that request financial assistance and qualify for it are registered and potentially affected by this phenomenon. Data indicate that the problem is increasing in Spain (Tirado Herrero et al., 2014), (Tirado Herrero and Bouzarovski, 2015) because the effects of the economic crisis have been particularly severe among the most vulnerable social groups (IEA, 2016). Therefore, many households in this situation are served by regional social assistance services and NGOs that are in continuous contact with these households and can prove the situation of vulnerability, and even help with simple diagnoses and recommendations to improve the situation of thermal comfort of these households.

The process followed for the granting of emergency economic aid, including energy poverty, begins with the activation of social services in the face of an emergency situation. The social service staff assesses the situation in terms of type of home and magnitude of the problem and propose a type of assistance to the Administration, temporarily, that can cover part of the energy costs, as well as housing tenure. Therefore, these assistance services, both public and private, provide top-level information for the characterization and certification of cases of energy poverty in the homes they serve. Analysing what role social workers can play towards the mitigation of energy poverty and the tools and training needs that would help them on this task is another objective of this research.

Finally, although they are not the main cause of energy poverty, building characteristics and building equipment are key factors that contribute to reducing the degree of thermal comfort of households in a situation of energy poverty, as well as to increase their expenditures in energy to alleviate the deficiencies of buildings and equipment. For all of the above, residents in social housing are a representative sample on which to analyse the problem of energy vulnerability from their different perspectives.

From the standpoint of housing, energy modelling tools are a great deal to know details of building demand and consumption, as well as to propose solutions. Energy-simulation tools have been mainly applied when refurbishment of social housing is being analysed, as energy refurbishment has a greater social impact in those cases where residents are living with energy poverty (Santamouris et al., 2007). Despite the many improvements in computer-simulation techniques, the specificities of social housing still cause variations between the results obtained by computer simulation and the actual energy consumption in these dwellings, as some authors have pointed out (Tronchin and Fabbri, 2008), (Wang and Zhai, 2016), (Escandón et al., 2017), but the results do not coincide with the real consumption of this type of housing, thus limiting the application of these tools (Huedo et al., 2017). Ramos et al. state that the differences in energy performance are mainly related to specific social housing constraints (Ramos et al., 2015). Knowing the deviations and their causes may allow us to adjust the models to get closer to the actual energy performance situation of social housing buildings. This is another main objective of this research.

Long term solutions besides the incomes increase in households, necessarily means behavioural changes focused on a better use of the scarce energy resources by social housing tenants, and affordable energy refurbishment to be mainly held by the building property. The case of public social housing represents a special situation because residents have neither the awareness nor the economic capacity to undertake any serious investment on building retrofit and efficient equipment replacement (Healy and Clinch, 2004). In addition, often they are not the owners of the dwellings and are not entitled to make any major modification on the facilities, hindering any investment attempt. A combined effort of social building users and property is needed to carry out holistic energy saving actions that include awareness raising, efficient behavioural change, building energy refurbishment, use of more efficient energy equipment and energy control and management systems for both residents and building managers.

In line with previous case studies that refer to methodologies for prioritising actions for social housing refurbishment (Monzón and López-Mesa, 2017), this research aims at quantifying and analysing a high number of energy efficiency measures in buildings, and advice about the best way to filter out, order and prioritize energy saving actions in a representative sample of social housing dwellings in Spain, using energy simulation tools and economic criteria, unlike other tested systems like Mikucioniené et al. (Mikučionienė et al., 2014). The methodology proposed can be applied in similar cases of the same type of buildings and users.

The kind of solutions proposed to mitigate the problem of energy vulnerability in social housing have different approaches:

- Social solutions, through the involvement of public and private social assistance services to these households, to certify cases, identify problems, assist households in these issues and mediate in front of public administrations.
- Methodological solutions, through improvements in the use of energy simulation tools for this type of housing, and economical solutions through the optimization of energy sources and contracts for each case.
- Building solutions by characterizing the type of buildings most common in public social housing for rent, and the definition of proposals for improvement and refurbishment of these buildings.

The importance in developed societies of the energy poverty issue today, the right of citizens not only to decent housing, but also to decent living conditions, the interaction of these rights with those of energy supplying companies and the role that integration and social assistance policies must play in order to fill these gaps make it desirable to address the study of social housing from various points of view and make recommendations for improvement from different spheres of work: social, political and energy. In this combination of multidisciplinary perspectives to tackle the problem lies the innovative nature of this research work.

1.2 Background: Preliminary studies about energy vulnerability situation in public social housing for rent

Two preliminary studies about energy poverty in Aragon (2015) and in social housing in Zaragoza (2015) have been the basis of this Thesis research. The purpose of this section is to give an overview of the actions made and results obtained in these two studies where an overview of the situation of energy poverty in Aragon is given, and how this phenomenon affects public social housing in the city of Zaragoza (Aragon, Spain) through a sample of buildings analysed in 2015. The conclusions of these studies have been used eventually throughout this Thesis research.

1.2.1 Energy poverty in Aragon 2015

This section gives a brief description of the households in a situation of energy vulnerability in Aragon, resulting from the study carried out in 2015 by Scarpellini et al. commissioned by the Government of Aragon (Scarpellini et al., 2015).

The information was structured in the following relevant factors, responding to an analysis pattern that can describe the main causes of energy vulnerability in households:

- Household income.
- Household structure.
- Building characteristics.

- Equipment available in the house.
- Characteristics and user habits of households.
- Energy costs (Total energy bills per year).

Based on these variables, questionnaires were prepared covering a wide range of households, including urban and rural dwellings, social housing and regular housing, and vulnerable families being assisted by the local social services. Results show interesting findings summarised hereby.

With respect to the total members who live in the dwelling and make up the household, there is a great difference between the two models of analysed households (generic and assisted by social services). In general terms, most vulnerable households have a higher number of members. The number of households with more than four members is significant and the average number of people in the assisted households is 3.4, whereas general households are composed of fewer members, the majority of which are 2-3 members per household.

68% of vulnerable households show all members unemployed, compared to the generic household in which at least one member is employed (41.3%). In many cases there are two or more members unemployed (43.8%).

Focusing on the analysis of household income, it is also interesting to see the relationship between low income in households and the problem of energy poverty (indirectly proportional) as it was obvious to expect. Those households that have used social services to apply for emergency housing aid are in the most vulnerable group with annual gross income of less than 14,000 €/year, while the results obtained for the general type show that the majority of the households surveyed is situated in a volume of income of more than 35,000 €/year. It should be noted that these data should be analysed with caution, since the income figure refers to the total household, not the individual, so that the total number of household members, among whom the income should be distributed, must be taken into account for future analysis.

Regarding the factors related to the building characteristics, the year of construction is a relevant factor in the analysis of energy poverty, carried out in Aragon in 2014. The majority of vulnerable households live in a building built before 1970, most of which are block of apartments, and usually rented. On the other hand, generic housing usually corresponds to a building built between 1990 and 2010, with a percentage of single-family or semi-detached houses, owned in property.

In the analysis, it is important to remark the type of energy equipment in place in the analysed household sample. 41% of the respondents declare that they do not have heating (radiators). Among those with heating, 47% of them are individual systems while a minority (approximately 12%) corresponds to central heating systems.

As for the type of heating energy source, the most used is natural gas. However, it should be noted that more than half of the respondents said they have "alternative" heating systems like fuel catalytic stoves and electric heaters (43.2%) in addition of wood stoves or fireplaces (47.3%), particularly in rural areas.

Regarding the type of utility contract for the electricity supply, more than 50% of the cases declare not to know in detail the contract type. This indicates a general lack of knowledge and information in both samples, whether users of social services or general housing. In addition, a lower-than-expected proportion of social tariff option in the vulnerable households, and a higher use of the default regulated domestic tariff in this group is observed.

The following table provides detail data for the households in situation of energy poverty analysed in the study of 2015 for the municipality of Zaragoza.

Table 1. ***Main data on households receiving emergency aid for housing in the city of Zaragoza. (Source: Scarpellini et al. (2015))***

TOTAL HOUSEHOLD MEMBERS	Average members per dwelling	3.44	
EMPLOYED MEMBERS	Average employed members per dwelling	0.36	
GROSS INCOME	1=below 9,000 €/year	91	*78.45%*
	2= between 9,000 & 14,000 €/ year	17	*14.66%*
	3= between 14,000 & 19,000 €/ year	5	*4.31%*
	4=above 19,000 €/ year	3	*2.59%*
DWELLING SURFACE	Average dwelling m²	*67.75*	
NUMBER OF ROOMS	Average number of rooms	5.02	
YEAR OF CONSTRUCTION	1= prior to 1970	58	*51.79%*
	2=between 1970 & 1979	19	*16.96%*
	3= between 1980 & 1989	14	*12.50%*
	4= between 1990 & 1999	10	*8.93%*
	5= between 2000 & 2010	10	*8.93%*
	6= After 2010	1	*0.89%*

As shown above, 78.5% of the surveyed households in Zaragoza, receivers of emergency housing aids provided by the Zaragoza City Council, reported having an income of less than 9,000 euros per year, live in a house of approximately 70 m^2 on average, where half of the buildings were built prior to the year 1970. Pertaining energy costs and contractual conditions of electricity supply, the average highest monthly expenditure of these homes in Zaragoza is the one corresponding to the electricity supply, as shown in the following graph.

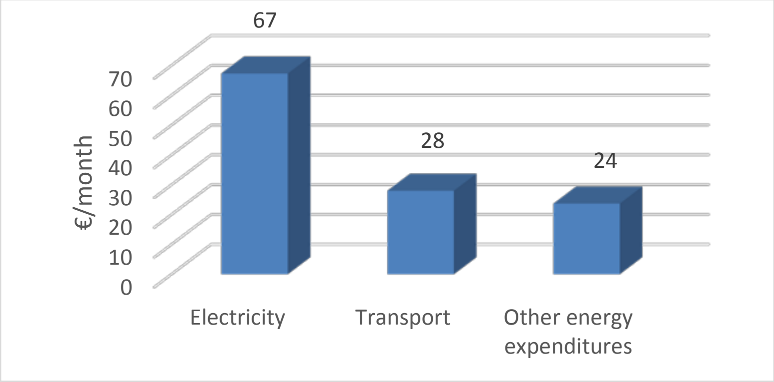

Figure 1. ***Monthly energy expenditure in households receiving emergency aid for housing in the city of Zaragoza. (Source: Scarpellini et al. (2015))***

Regarding the type of contract, it should be noted in the following figure, a significant percentage of households (24%) do not know in detail the type of tariff or terms of the electricity tariff, in line with the results obtained for all of Aragon.

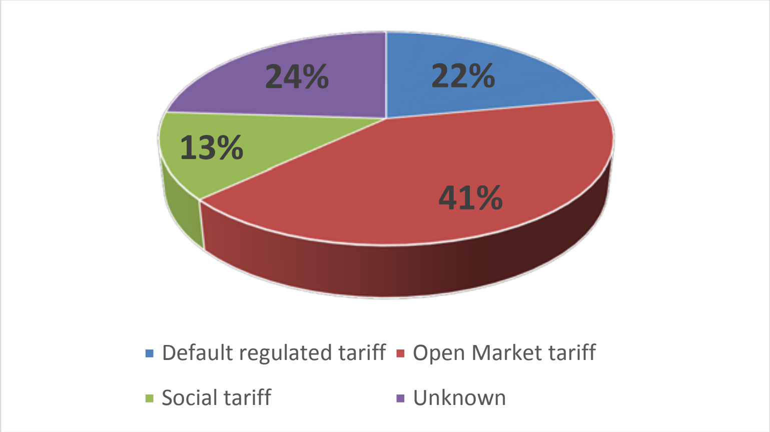

Figure 2. ***Type of electricity supply contract in households receiving emergency aid for housing in the city of Zaragoza. (Source: Scarpellini et al. (2015))***

The complexity of the energy bill and contractual issues and the lack of knowledge about the electricity market options for domestic sector hinder these vulnerable households to make the best tariff choice for their actual energy needs. This issue is aggravated by the fact that many social housing tenants that rent a dwelling with an existing supply contract, do not check that the contracted tariff is suitable for them, often paying supply capacity rights beyond their real needs, or not benefiting from hourly-discrimination tariffs. Having a high percentage in open-market tariffs (41%) prevent them from applying from special social tariffs that would entitle them to a bill discount due to low-income household.

1.2.2 Empirical analysis of social housing buildings in Zaragoza

This study was made in 2015 within the frame of the "Catedra Zaragoza Vivienda" of the University of Zaragoza[1]. The study was coordinated by Dr. Sabina Scarpellini, with the participation of Dr. Eva Llera, Dr Ignacio Zabalza, and the author of this thesis. This study followed on the previous one and focused on a thorough analysis of three social housing buildings for rent, hereinafter referred to 1, 2 and 3, managed by Zaragoza Vivienda in the city of Zaragoza. The aim was to relate the building and dwelling characteristics and equipment with the economic data of the households (incomes, energy expenditure, etc.) and the structure of the households (members, retired, children, employed, etc.)

The Municipal Social Housing Society "Zaragoza Vivienda" manages, promotes and builds the municipal stock of social housing for both purchase and renting in Zaragoza. The policy of its construction also responds to an intentional urban policy of the old quarter refurbishment, where around 40% of the society's dwellings are located. At present, it also has promotions in other neighbourhoods of the city such as Torrero or Goya Park aimed at facilitating access to housing for certain sectors of the population through different options based on renting.

Zaragoza Vivienda also has an administrative area in charge of the management of the housing stock and a social assistance team to support socially-vulnerable families. This service is always carried out in collaboration and continuous coordination with the other instances that intervene, namely the Municipal Centres of Social Services, Health Care Centres, Government of Aragon, district associations and other social entities. For this reason, it was of special interest to focus the present study on some of the buildings owned by this Municipal Society, very active in social area and paying special attention to the needs of its tenants. The houses managed in 2015 by this Municipal Society are detailed below:

Table 2*. Housing stock managed by the Zaragoza Municipal Housing Society "Zaragoza Vivienda" Z.V. (Source: Zaragoza Vivienda, Financial Statements and Auditing States 2015)*

Property status	Number of dwellings
Owned by Zaragoza City Council and Managed by Z.V.	68
Owned by Banking institutions and Managed by Z.V.	31
Privately Owned and managed by Z.V.	363
TOTAL dwellings managed by Z.V.	2,251
Total owned by Z.V.	1,789
Total managed but not owned by Z.V.	462

The Social Management Area of the Zaragoza Municipal Housing Society "Zaragoza Vivienda" works very closely with the technical accounting unit (management of renting bills) and property management (as the age of the housing stock increases the technical and economic effort that Zaragoza Vivienda must dedicate to this aspect). This is an additional reason that justifies the choice of buildings of this municipal society for this study, in order to raise possible palliative actions of the phenomenon of energy vulnerability in social housing.

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[1] https://catedrazaragozavivienda.wordpress.com

In the analysis of the households' energy vulnerability, the different study variables have been grouped by building case to study the variabilities in energy consumption due to the constructive characteristics of each building, as well as by level of income to see variations in each group and how the level of income affects the consumption of energy and household habits.

As for building characteristics, buildings 2 is different than building 1 and 3. 1 is taller (8 floors) while 2 and 3 are smaller buildings (3 floors). Building 2 is embedded between other buildings on the street, and somewhat smaller on average. Also the type of households is different in average, the occupancy of building 2 being shorter with little proportion of families. The following table summarizes the main building and resident parameters.

Table 3. ***Building and occupancy characteristics.***

Building number	**B1**	**B2**	**B3**
Number of dwellings	160	12	53
Number of blocks	11	1	5
Year of construction	1988	1988	1990
Orientation	All	North-South	North-South
Average dwelling surface (m^2)	68.2	55.6	74.8
Number of Floors	8	3	3
Usable floor surface (m^2)	1,644	220	1,395
Heating and hot water system	Individual gas boiler	Electric radiators + water tank	Electric radiators + water tank
Average occupancy per dwelling	3.9	2.7	4.1
surface per resident (m^2/person)	17.5	20.6	18.2
Refurbishment	No	Partial	No
Contracted power (kW)	3.5	5.6	4.4

In spite of building 2's apartments being the smallest (55 m^2), the ratio of m^2 per resident is the largest of all, with the lowest occupancy per dwelling (2.7 persons/dwelling). At the other end, building 1 has the largest apartment size (68.2 m^2), and the lowest ratio of m^2/person (17.5 m^2/person) with an average of almost 4 residents per dwelling. This ratio is an indicator of comfort and life standard because a low value of m^2 per person could show signs of overcrowding of residents, although a high value represents a risk of energy vulnerability due to the higher energy costs to maintain a larger surface heated.

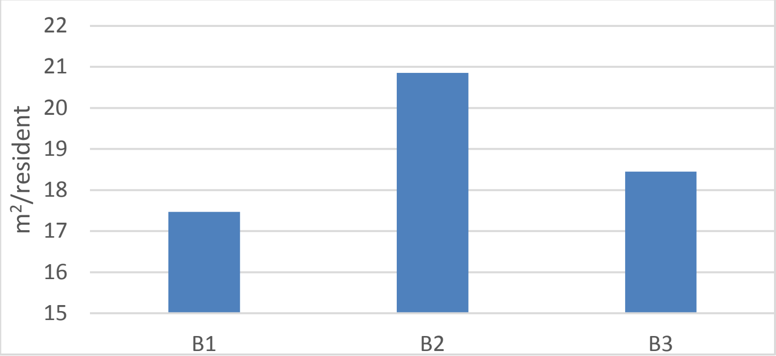

Figure 3. ***Ratio of available dwelling surface per person.***

Household income by income level shows that almost half of households have annual incomes below 9,000 € per year, and 80% do not reach 19,000 € per year. This is expected since it is social housing, and the criterion of access to these houses is mainly economic factors with or without social exclusion factors.

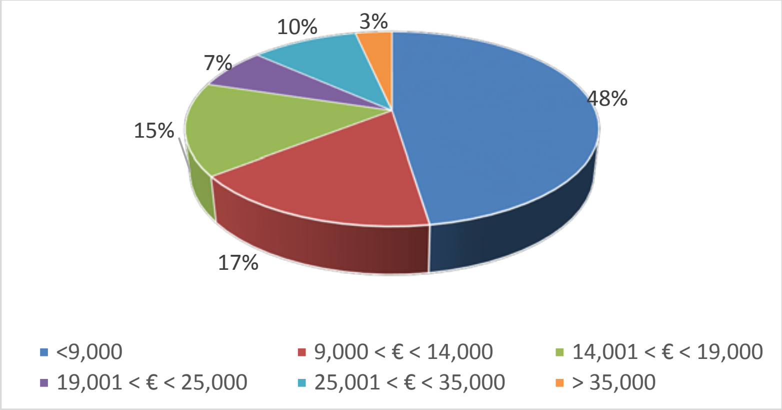

Figure 4. ***Distribution of households per level of annual gross income in €/year.***

The results of the analysis show an average income per household of 14,241 €/year. The factor that most affects the income is the ratio of the number of employed persons per total of residents in each household. The average is low in the whole sample, with 0.16 employed persons per household, but there are considerable differences between the buildings in the sample, being higher in 2 (0.18 employed people per household, mainly due to the lower number of residents per household), and lower in 3 (0.1 employed people per household).

It is observed that the number of employed persons per household has a direct correlation with the income level, as shown in the following figure. Therefore, the level of employability of household members is the main factor of vulnerability, and therefore, of energy poverty.

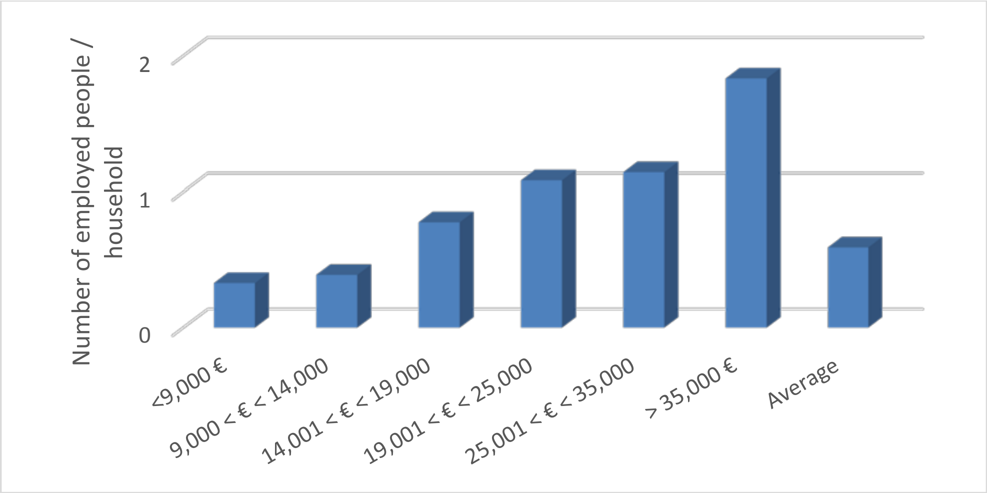

Figure 5. ***Average number of employed people per household as a function of income level.***

Going to detail the distribution of the average population per household in each building, it can be seen that building 2's households are mostly inhabited by elderly retirees and the number of children per household is very low (0.6 children per household), compared to buildings of families such as building 1 where there are almost twice as many children per household. For this reason, the number of employed residents in building 2 is low, but it does not affect income so much as it is supported by retirement pensions in many cases. In the case of building 3, the low income level is explained by unemployment rather than retirements, since the unemployment subsidy is not guaranteed for many long-duration unemployed. The distribution of activity per dwelling in each building is shown in the following graph, where a high correlation degree between employment level and income can be observed.

The income factor is key to analyse the causes of energy vulnerability because its scarcity proportionately affects the income vs consumption ratio, but it can also alter the behaviour factor reducing the minimum energy consumption that is necessary to keep minimum thermal comfort levels.

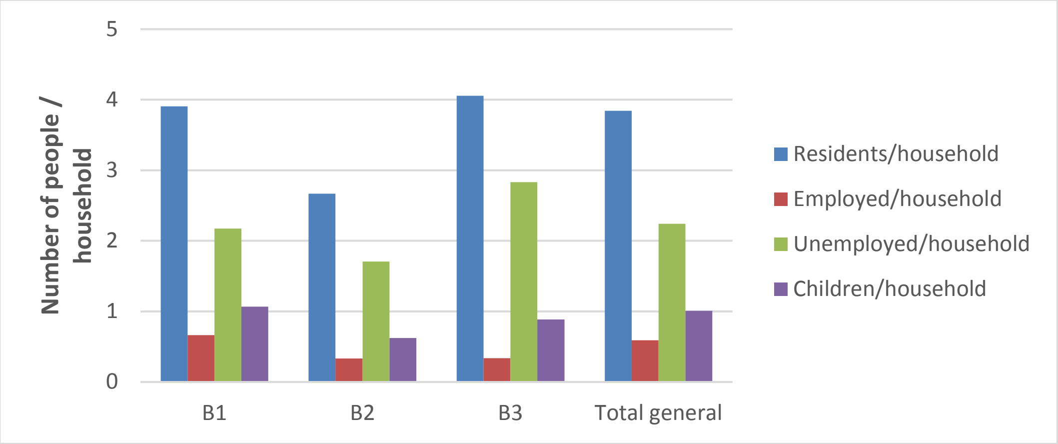

Figure 6. ***Average employed and total number of people per dwelling at each building.***

There are several main factors affecting the consumption of energy in a dwelling:

a) Building envelope. The highest energy consumption of a home is heating, followed by use of appliances, DHW and lighting. In this type of homes there are hardly any refrigeration consumption beyond fans, which is very low energy consumption. The heating consumption is the additional contribution of heat necessary to cover up the balance of external losses and internal and external gains. Larger heat losses occur through the building envelope by thermal conduction through the building materials. There are also losses due to infiltration of air and humidity.

The conduction losses are directly proportional to the temperature rise between the exterior and the interior, the surface in contact with the exterior and the transmittance of the materials. In order to reduce these losses little can be done about external temperature, or the geometry of the building once built, so that the only parameter to play with is the transmittance of the materials, improving their properties (increasing their thermal resistivity) through an action of energy refurbishment. These actions are interesting to reduce the consumption of heating but are also expensive to be faced by families with low incomes, or on a rental basis.

b) Heating and hot water system. The most efficient systems are based on efficient centralized boilers and well isolated distribution systems. On the other hand, the most efficient generation systems are based on high coefficient of performance (COP) heat pumps or low temperature gas or biomass condensing boilers. In the case of the sample buildings, the available heating systems are highly inefficient because they are individual heating systems and DHW and frequently based on electrical consumption by Joule effect.

- Buildings 2 and 3: heating systems and DHW are individual electric resistance.
- Building 1: heating system and DHW is provided by individual gas boiler.

The gas system is more efficient than the electric system in terms of primary energy (primary energy conversion factor to final energy of 1.07, vs 2.3 for electric energy), and cost-based (average price of kWh of gas 0.06 €/kWh, average price of kWh of electricity 0.15 €/kWh). However, this only affects building 1, where many boilers are the original since the construction of the building (year 1990). Hence, this equipment is old and low-performing compared to the current low temperature and condensation boilers.

c) Income level: A higher level of income induces a higher consumption, to reach high levels of comfort, but once an adequate comfort level is achieved, higher income levels do not translate into increasing consumption. Household annual incomes above 20,000 €/year seem to have no more increasing energy costs in €/month, the minimum being 56 €/month while the maximum is below 60 €/month. The average is 57 €/month. The difference in energy expenditure between more and less wealthy households are larger in winter than in summer.

As the size of the dwelling and the number of people living together is also important, the monthly expenditure per m^2 and person has been calculated according to income level. The result obtained is almost constant but slightly decreasing, varying between 0.23 €/m^2 and person of the lowest incomes and 0.17 €/m^2 and person of the highest incomes. This is because higher-income households usually live in bigger apartments and have more members in average.

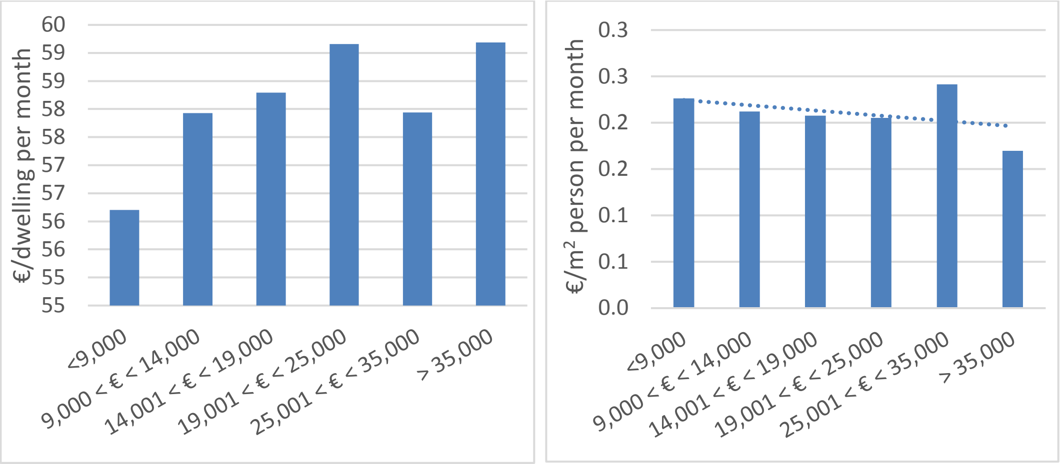

Figure 7. ***Monthly energy expenditure per household in €/dwelling (left) and monthly energy expenditure per m^2 and person (right) as a function of income.***

Monthly energy expenditure per building and source of energy are shown below. Only building 1 shows gas consumption, to be added to the electricity costs. In this case, the consumption of gas is dedicated to the heating service in winter and domestic hot water all year long, subtracting this demand from the electricity consumption.

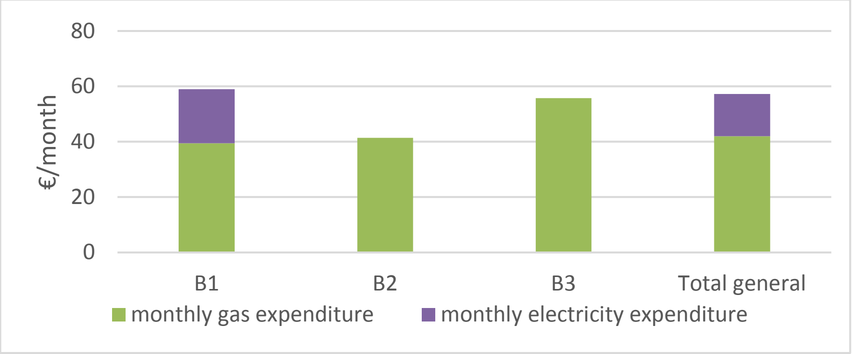

Figure 8. ***Monthly energy expenditure per energy source at each building in €/month.***

Gas is a more economic fuel than electricity for heating and domestic hot water DHW. However, the addition of both energy sources consumption shows that building 1 has the highest consumption of the three buildings on average, and significantly higher than building 2. Building 2 dwellings are smaller with lower occupancy, and this may explain part of the difference in consumption, since more surface to heat means more heating energy. However, the difference still exists when the energy consumption per m^2 is compared. Occupancy is a more explanatory factor than surface.

The reason for this difference is not to be found in the type of thermal energy conversion equipment, but in the characteristics of the building itself.

The most efficient building is building 2 as it has lower thermal losses than 1 because it is a smaller building, more compact, and better sheltered with neighbouring buildings at both sides. This reduces the exposure area with the exterior. On the other hand, building 2 apartments are smaller and have had energy refurbishments in year 2014. The transmittances on different surfaces in both buildings in W/m^2K are in the following table and show the differences of both buildings, much more favourable for the building 2.

Table 4. ***Thermal transmittance of some elements in the buildings sample.***

Transmittance value (W/m^2K)	Windows	Walls	Roof
Building 1	5.7	0.71	0.55
Building 2	3.2	0.3	0.2
Building 3	5.7	0.52	2.51

One important difference is in glazing. Those of building 2 are double-glazing with wooden frame and casement window, which are much more efficient than the building 1's simple glazing on sliding aluminium frame with thermal bridges and with non-hermetic closure.

Other factors that affect the individual consumption of each dwelling in building 1 are the orientation of each dwelling and the height, since in the same block there are floors facing north and others facing south. The highest floors with a north orientation will tend to consume more to ensure the same thermal comfort conditions.

The ratio of revenues dedicated to the payment of average energy bills for each building is shown below. The average of the dwelling sample is 7.6% and is strongly conditioned by the largest sample size of building 1 (80% of the dwellings in the sample). This ratio is lower than building 3 and higher than building 2. Although the level of income has a major influence in this ratio, a similar level of income between buildings 1 and 2 brings different results, mainly due to energy costs. Better insulation reduces energy vulnerability in low-income households. Building 3's higher ratio is due to the lowest average income level.

Taking a ratio greater than or equal to 10% as a limit of risk or energy vulnerability, the average number of households is not at risk, but building 1 households are more likely to fall into this situation (7.8 %) than those in 2 (5.1%). An energy refurbishment similar to the one made in building 2 in 2014 would be advisable to reduce this vulnerability. This recommendation also applies to building 3, to a greater extent.

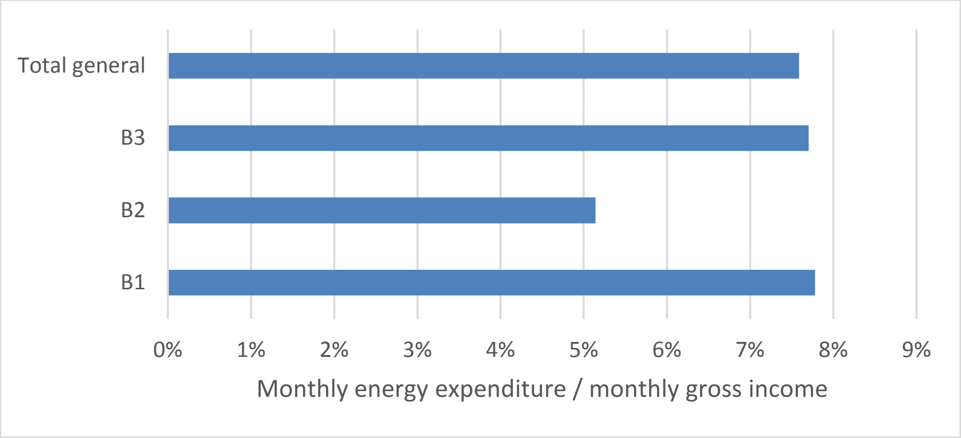

Figure 9. ***Average ratio of monthly incomes and energy expenditure per building.***

The percentage of households with a vulnerability index equal to or greater than 10% of energy expenditure is 26%, distributed in building 3 (26% of households) and 1 (31% of households), and 2 (20% of households) as shown in figure 10.

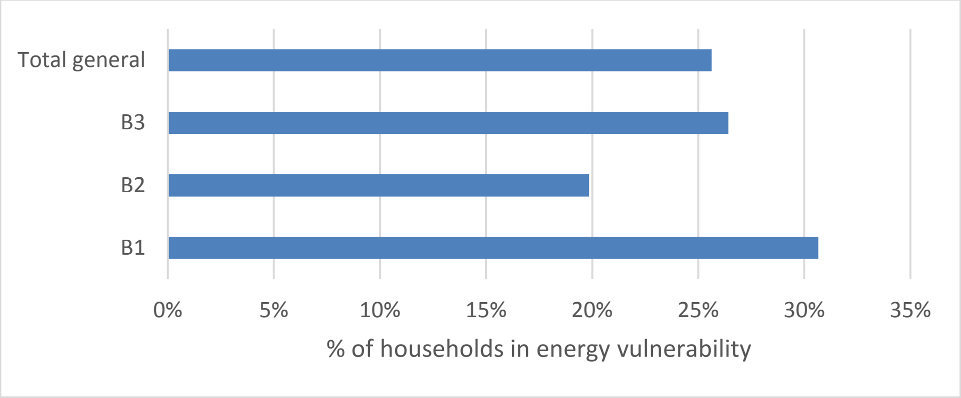

Figure 10***. Percentage of households above the energy vulnerability index limit of 10%.***

In figure 11, it is observed that households with incomes below 9,000 €/year are vulnerable to an average consumption (11% of income for energy expenditure), logically due to low incomes, while this vulnerability index falls to 7.1% for the next level of income and successive. The average is 7.6% of incomes dedicated to cover energy expenditures.

The distribution of vulnerable households by income level clearly shows how the entire energy vulnerability affects the lowest level of household income as 97% of households with this level of incomes spend more than 10% of their incomes for energy bills while only 3% of the next income level (from 9,000 € to 14,000 €) are in this situation. Therefore, the main vulnerability factor is household income, although the greater efficiency of building 2 protects residents from the risk of energy vulnerability.

In addition, households adjust their energy consumption to their financial capabilities, thereby affecting the level of comfort, which is not constant. Figure 8 shows how the monthly energy consumption in each household increases with the level of income, being practically constant from income above 20,000 €/year. This income level corresponds approximately to 3% of income dedicated to pay the energy bills.

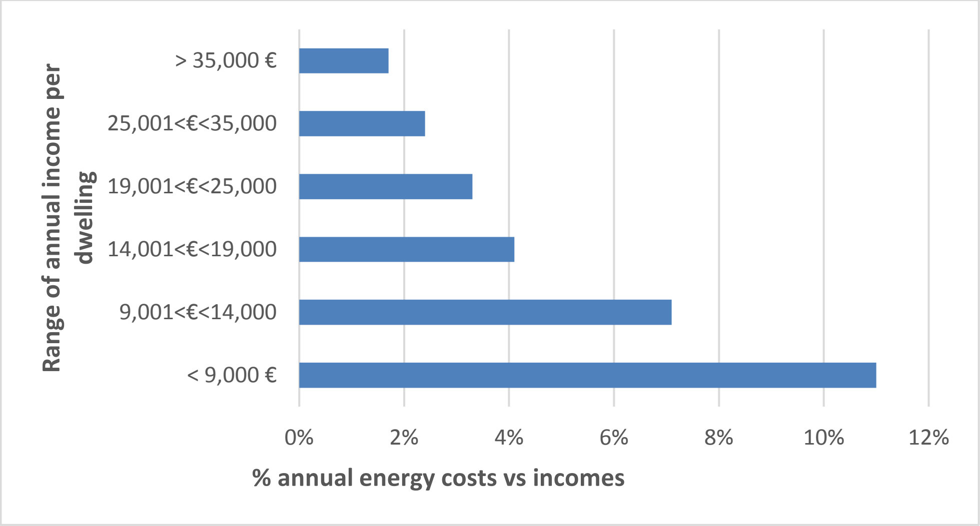

Figure 11. ***Ratio of incomes dedicated to pay for energy bills as a function of level of annual income.***

The case of building 2 is illustrative in this sense. Many of its residents are seniors without children under their care. Their thermal comfort needs in winter are smaller and, many of them, choose to keep a heated room instead of the whole dwelling. This fact, added to better thermal insulation and better enclosures of the building, results in a much lower energy consumption.

The conclusion of this qualitative analysis can be summarised in the following bullet points:

- Total annual household income is the most influential factor of energy vulnerability in the sample of households. Most vulnerable households are classified in the lowest level of disposable income.
- The average income dedicated to the payment of energy costs per household in the sample is 7.6%. By buildings, this ratio varies between 7.8% of building 1 and 5.1% of building 2, despite having similar average incomes. The difference is due to the greater energy efficiency of building 2 envelope after an energy refurbishment and dwelling smaller size.
- 26% of the households analysed invest more than 10% of their income in energy expenditure. It could be said that these homes are in a situation of energy vulnerability.
- Household income is correlated with the number of employed persons in the household, with an average of 0.6 employed residents per household. In vulnerable households, this ratio reaches only 0.3. Therefore, the level of employment seems to be an important factor of energy vulnerability.
- Energy consumption is strongly affected by the purchasing power of families, as well as by the type of residents. Households with more purchasing power tend to consume more energy to improve thermal comfort to a sufficient level. Households with more children tend to consume more energy.
- Energy consumption is mainly defined by heating in winter. For this reason, poorly insulated buildings with poor enclosures tend to consume much more than others of similar size but better insulation. Insulating a building can reduce the energy cost-to-income ratio by half, as can be seen in the averages of the newly renovated building 2, compared to the other two.
- Gas consumption for heating is economically more efficient than electricity heating consumption with electric resistance heaters. Only building 1 has gas heating and DHW, but the boilers are individual, old and not efficient (seasonal performance about 76%). The bad insulation in this building hides any benefits derived from the use of a more efficient thermal energy source.

1.3 Main objectives of this Thesis and thematic unit

The general purpose of this research is to generate a multidisciplinary and empirical methodological contribution for the analysis of the variables that influence the energy vulnerability of households, and for the definition and dimensioning of actions in the design and physical maintenance of social housing. Housing is considered as one of the axes of social welfare.

Although the proposed methodology is applicable in social housing located anywhere, it has been applied to a case study: the social housing of the city of Zaragoza (Spain), due to the greater accessibility of data and large representativeness of the social housing sample at national level.

The contribution consists on the joint application of quantitative, qualitative and simulation methodologies that have not been applied in an integrated way to date. It also consists of an empirical contribution in terms of the number of households analysed and the range of variables applied that will provide an integral view of the household as a unit of analysis in terms of its vulnerability index from the energy point of view. These heterogeneous variables try to analyse the problem of energy poverty from different perspectives: building and equipment, consumption habits and household structures, which affect in one way or another the energy poverty.

The overall objective is divided into 5 specific objectives with different analyses and methodologies in each case, which are explained below. Each specific objective is addressed in a separate chapter.

Objective 1: Creation and integration of the significant variables that affect energy poverty into a weighted multi-criterion index of energy vulnerability.

The objective is to create a multivariate index that incorporates a number of aspects that influence the energy vulnerability of households and which includes aspects of housing and building, energy aspects and use of equipment, and socioeconomic aspects of households as a structure of homes and habits of energy use. This objective includes the application of the index to social housing, as well as to samples of households in certified energy poverty situation and in normal housing.

Objective 2: Analysis of social aspects of energy vulnerability in households, certification and mediating role of social services in cases of energy poverty.

The involvement of public and private social assistance services aims to obtain first-hand information on cases of energy poverty, and the verification and certification of these cases, which open the door to the granting of public aid and other palliating mechanisms. The Inclusion of social services for the attention of households in energy poverty and NGOs as a mediating vehicle between social housing management bodies, public authorities and mechanisms for granting aid to households at risk of social exclusion is part of the objective. Public and private social assistance takes an active role in the problem as a source of first-hand information gathering, certifying cases of energy poverty and the first palliative level of extreme cases of energy poverty.

Objective 3: Study of building characteristics in social housing. Application of energy simulation in this type of cases and analysis of this type of computerized simulations applied to homes with risk of energy vulnerability.

The aim is to establish a series of performance metrics for each building, and a comparison of buildings in a sample of social housing to identify inefficiencies in the building, heating equipment or usage habits. The methodology followed to reach this objective is based on a complete empirical analysis of two social housing buildings representative of this type of construction in Spain. The data will be collected in an energy audit carried out in houses representative of each building. Data on enclosures, enclosures, temperatures, surfaces, thermal transmittance and heating and DHW equipment will be taken. Monthly consumption data and invoice types will also be collected. These data will be complemented by the habits of consumption, specified by the residents of the houses analysed.

It is also intended to simulate the energy behaviour of these buildings and compare it with the actual behaviour in order to validate the simulation tools in this type of dwellings, and to provide calibration keys and simulation improvements in case of finding important differences. The methodology to be followed is based on the use of an energy simulation tool where the buildings based on plans and projects will be modelled, and the data collected in the energy audits will be introduced to compare the actual and simulated consumption and to find out the root causes.

Objective 4: Selection and characterization of measures to improve buildings and equipment especially targeted to households in situations of energy poverty and social housing managers. Proposal of solutions and palliative actions for social housing from the point of view of the buildings.

The aim is to evaluate measures to improve social housing buildings. The main problems tackled are the fact that residents in this type of housing are usually neither homeowners nor usually have the economic ability to undertake expensive housing refurbishment or changes of efficient equipment. However, the advantage is that there is a centralized and efficient management by the public entity in charge of these social housing buildings, which in the case of the study has shown great collaboration and recognition for the issues of energy poverty.

The research is structured in 4 main chapters, namely 2, 3, 4 and 5, according to the objectives described above. Each one contains an introduction, a methodology description, and an exposition of the main results obtained. Then, the corresponding published article full text follows. Details and final conclusions are available in the article main text.

2 Energy vulnerability composite index in social housing, from a household energy poverty perspective

2.1 Introduction

The objective of this chapter is the integration of energy vulnerability variables in a multi-criteria index of energy vulnerability in social housing.

Due to the heterogeneity of the variables under study it is not possible to directly establish a single aggregate criterion that allows to consolidate a metric of energy vulnerability in households, which in turn takes into account the most significant variables that help to evaluate and classify households according to their degree of vulnerability. The work has consisted in the selection and application of a multi-criteria methodology that allows the selection of variables by their degree of significance, normalize the variables to unify the units and weigh their contribution to be aggregated into a complete vulnerability index. This index has evaluated the homes of the initial sample of social housing, as well as a larger group of houses at risk of vulnerability, as well as a larger sample of non-vulnerable households belonging to the entire Autonomous Community of Aragon, proving from this the adequacy of the multi-criteria methodology for household vulnerability that allows comparisons of household samples from different and heterogeneous criteria and draw conclusions.

For the definition of the study background in this section, it is considered of interest to extend the analysis of the energy vulnerability from the energy behaviours of the households, understood as a consequence of the building characteristics of the house, the different habits for electrical appliances use, lighting, air conditioning and temperature of the dwelling as well as the analysis of consumption (Becker et al., 1981) and the type of contracting and tariffs that the household has for energy supplies.

The energy behaviour within the dwelling concerns all the members who occupy it, which are, therefore, also an integral part of this study. It is considered of interest in this area to analyse both the demand for energy according to the building characteristics of the dwelling, the use of the available equipment, as well as those individual and family activities that imply energy consumption in the daily life of all household members (Yu et al., 2011). In addition, the peculiarities inherent to the economic cost of energy supply and their contracting typology are added.

In this context, it is of particular interest to have primary data and a suitable methodology to proceed with the energy characterization of households that are in certain conditions to alleviate and / or prevent the problem of vulnerability in a territory (Brunner et al., 2012), (Howden-Chapman et al., 2012) and to take the appropriate measures according to the level of vulnerability in which each household is.

Going into the analysis of the different methodologies adopted by the authors for the studies carried out in this field, Brunner et al. applied the qualitative research to data obtained through 50 interviews in households of the Austrian capital (Brunner et al., 2012) from the procedures and techniques of theoretical sampling (Strauss and Corbin, 1990). Devaliere also carried out a quantitative empirical study in France in 2010 on samples from 40 households in 2 territories (Devalière, 2010) and on the empirical analysis carried out in Greece by Santamouris et al., the 598 households in the sample were classified into two types according to their income, with advances in energy consumption characteristics in a time series (3 years studied in 2 periods) (Santamouris et al., 2014). These results were amplified in the sample size and number of variables analysed by the empirical study carried out in Aragón (Scarpellini et al., 2015) , in which more than 650 households were analysed in a situation of vulnerability and energy poverty through different quantitative and qualitative methodologies.

In general terms, the studies analysed do not offer methodologies that provide an integrated index of the vulnerability of the households including the characteristics of the dwelling, the habits of consumption and the household structure, as well as the questions related to the energy costs.

For this reason, it is deemed interesting to make a contribution in methodological terms offering a dual approach, quantitative and qualitative, in order to integrate a series of variables into a joint index that allows to measure the level of vulnerability of households in terms of energy. This composite index to assess the level of vulnerability of households combines heterogeneous factors such as building characteristics, available energy equipment, tenants' habits and the tariff and contractual conditions of energy supplies.

2.2 Methodology

The methodology used for the establishment and measurement of this index is based on the selection of significant variables of each aspect, obtaining information for a specific sample of households, and the application of the analytical hierarchy process methodology (Saaty, 2008), better known as multi-criteria analysis. This analysis allows a relative check on how each group of variables influences the energy vulnerability of the households in the sample (social housing), and compare it with other samples or populations, such as vulnerable households outside social housing.

The main groups of variables affecting energy vulnerability where dwelling characteristics, equipment, energy expenditure and household structure. A normalized individual vulnerability index (IVI) ranging from 0 (not vulnerable) to 1 (highly vulnerable) was calculated per household and per group of variables in a sample of 351 social housing households. Additionally, a global composite vulnerability index (GVI) was calculated using as weights the result of an expert panel with 65 experts in focused interviews.

2.3 Summary of the main results

The results applied to the social housing sample show a low overall vulnerability rating, despite the low average income of the households, whereas the global vulnerability rating (taking all four factors into consideration) for the whole sample is moderate. The relative impact of the building characteristics (0.18) is very low due to the homogeneity and good maintenance level of the public social housing stock in the sample. Bills and household structure reflect values of 0.33 and a wider variability range due to the differences among household habits and structure.

The composite index was also applied to a sample of 615 certified energy impoverished households and to a sample of generic 1,340 regular households. Results reveal that social houses are less vulnerable from the building standpoint, and more from the energy expenditure point of view. The reason is the type of energy and type of tariffs, of social housing tenants that do not adapt the former resident’s contract to their own real needs. Social housing and certified vulnerable consumers have household structures and habits that affect negatively their risk for energy poverty. The GVI of the samples does not present substantial differences.

The result of this study has been included in an article submitted to the journal "Sustainability", with the following reference:

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Article

Energy Vulnerability Composite Index in Social Housing, from a Household Energy Poverty Perspective

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Abstract: In Europe, the proportion of social housing is high, and such houses tend to be inhabited by below average-income households, which are particularly vulnerable to energy poverty. This article proposes a new methodological approach for defining an index for household energy vulnerability assessment. This method can be used to improve the management of social housing. After establishing a heuristic framework for household energy poverty–which stems from different causes such as income, the characteristics of the residence, energy installations, and the energy-consumption habits of household members–multi-criteria analytical methods, based on the aggregation of indicators which reveal the conditions leading to energy poverty, have been applied, and effective means of intervention are proposed. The method is also applied to a sample of social houses and thus validated as a useful tool in decision-making processes which concern the management of social housing from a household energy-poverty perspective.

Keywords: energy poverty; social housing; indicators; energy management; socioeconomics

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1. Introduction

Insufficient access to modern energy services and the lack of energy security are still important limitations to the development of poor regions [1,2] and they also affect certain social sectors in developed countries; people in these sectors struggle to afford the costs of the energy that is required for their material and social development [3–6].

The EU has demonstrated its concern for this important problem; a significant number of particularly vulnerable households in the Union have insufficient access to energy resources [6–11].

Energy poverty has, in fact, been declared a grave problem, as it is directly related to some of the Union's priority policies concerning poverty [12,13], healthcare [14–16], and energy efficiency [17,18]. European countries have launched numerous national, regional, and local initiatives to evaluate the problem posed by energy poverty, especially in those southern and eastern countries where the problem is most acute [7,19–21].

In this context, social housing has been at the centre of several studies on the impact of the rehabilitation of residential buildings on energy consumption [22–25], and the effect of improved energy installations [26–28]. Social housing tends to be inhabited by low-income households, and the buildings are often energy-inefficient.

The inadequate building features of the dwellings not only increases the energy vulnerability of the households, but is also a factor in exacerbating the relative degree of energy poverty (relative energy poverty index) suffered by vulnerable households [29–32]. However, Walker et al. [33] and others have demonstrated that the rehabilitation of the building is often not enough to solve the problem, as other factors such as the energy-consumption habits of household members [34–37], the socio-economic profile of the household [38,39], the characteristics of energy installations, and the cost of energy supply [40,41] also play a part.

Given that most social housing within the EU is publicly owned, energy vulnerability and the prevention and mitigation of household energy poverty are, to a large extent, a public concern. The application of a composite energy vulnerability index is thus a necessary tool for decision-making processes, and is also of interest when designing energy installations, when retrofitting residential buildings, and when approaching energy management from the perspective of household energy poverty.

Although it is generally accepted that the accurate identification and evaluation of the causes of energy poverty constitute the first step in solving the problem [8,42,43], no specific multi-criteria methodology for managing social housing has been developed to date. The specialised literature on energy and building has put forward interesting ideas concerning social housing [28,31,34,44–47], but an integrated analysis of household energy poverty and the management of social housing is still lacking.

Therefore, after establishing a heuristic framework for household energy poverty, the main target of the research presented in this paper is to define a multi-criteria index for the aggregation of the different factors that contribute to household energy poverty, and to define their relationship with the management of social housing and the implementation of efficient palliative measures.

The energy vulnerability index defined in the empirical stage of this research was subsequently tested on a sample of social housing, and these houses were characterised according to this index. This exercise, which is a key contribution of the present paper, aimed to assess the validity of the index as a tool in decision-making processes in the context of managing social housing.

The development of the tool constitutes, in itself, an important contribution to the generation of composite indexes that can be used to evaluate household energy poverty. The results of using the tool prove that it is highly relevant for policy makers at the local level and for public housing managers, and can be applied to mitigate and prevent the energy vulnerability of households.

The first section reviews the relevant bibliography and the background for this study. This is followed by the methodology applied when developing the energy vulnerability index and the case study, which concerns a sample of social housing in a northern Spanish city. Finally, the results and conclusions are summarised.

2. Background

Following Boardman's pioneering publication [48], according to which a household can be regarded as being in energy poverty if its members must use more than 10% of their income to cover its energy needs, other definitions and criteria have been suggested, such as the notion of 'thermal comfort' [49], a 'cold home', and 'energy debt' [11]. The International Energy Agency [50] considers that a household is energy impoverished if it has to spend an excessive proportion of its total income on energy expenses.

Based on Grevisse and Brynart [51], this study considers that a household suffers from energy poverty if the members cannot afford to pay for enough energy to satisfy basic domestic needs. On the other hand, it is considered that energy vulnerability expresses the risk of households falling into a situation of energy poverty. Through the use of the right indicators, energy vulnerability can be used as a relative index of energy poverty. Energy vulnerability can, therefore, be regarded as a spending pressure on the household income.

Energy vulnerable households, although not officially in energy poverty, are more exposed to a potential increase in energy costs/basic needs and, therefore, to becoming energy poor as a cause of a rise in energy prices [5], a decrease in household income [52], an increase in energy needs [11], and the inability to invest in increasing the residence's energy efficiency [53] or to switch to cheaper energy sources [54], as some examples.

As pointed out by Bergasse et al. [55], households that need to use an excessive proportion of their income to cover their energy needs are energy vulnerable and at risk of social exclusion [20,56]. These households need protecting and require guaranteed access to energy at stable and reasonable prices [57], as is implicitly assumed in different public policies, such as additional consumer protection measures, the implementation of financial aid packages, the launch of information campaigns, and the promotion of energy efficiency measures [51,58].

This is also recognised in the Third Energy Package issued in 2009 [59], which compels EU countries to implement the necessary measures to protect vulnerable consumers. In this regard, Directive 2009/72/CE, concerning common rules for the internal market in electricity, leaves the jurisdiction and responsibility for adopting these measures which protect consumers, especially the most vulnerable ones, to the member states. Each state must, therefore, adopt its own definition of vulnerable customer and/or energy poverty and define measures which aim to protect vulnerable households from having their energy supply cut off at critical periods (art. 3.7). In the European framework, therefore, the definition of what constitutes a vulnerable consumer can be variously formulated in the different national regulations.

Although such measures as one-off money handouts and cheaper tariffs can be a short-term solution, tackling energy poverty in the long term requires confronting the underlying structural problems–for instance, low household incomes and energy-inefficient homes. The maintenance of comfortable temperatures is more costly in terms of energy in low-quality housing [19], and for this reason, measures that aim to improve the energy efficiency of homes have historically been among the most effective in reducing energy consumption.

In addition, it is not rare to find households that, although inhabiting homes with similar characteristics, have very different energy consumption profiles. According to Santamouris et al. [46], energy consumption is directly related to the socioeconomic profile of the household and the use that its members make of the energy facilities; and this is a key factor, along with the characteristics of the energy tariffs being applied, in determining energy costs [60,61]. Although the low energy efficiency of buildings may not be the main factor behind energy poverty, improving energy efficiency can go a long way to helping low-income households avoid energy poverty.

For these reasons, it is considered necessary to approach the analysis of household energy vulnerability from the perspective of a comprehensive household energy profile, which should include the building characteristics of the home, the way in which different electrical appliances–lights, air-conditioning, heating, etc.—are used, as well as consumption habits and tariffs.

At all times, we should take into consideration that energy poverty is a multidimensional issue, and that the degree of energy vulnerability of households is determined by a multiplicity of factors. The present paper embraces the main results of an analysis undertaken using a large sample of households whose energy poverty situation was certified by the social services [40], and analyses the role of the four determinant factors leading to a situation of energy poverty. These four factors are as follows:

1. The dwelling characteristics of the home related to the energy needs [31,62].
2. The performance of the energy installation and of home appliances. The use of inefficient heating and air-conditioning devices to achieve comfortable temperature conditions leads to high energy costs [63,64].
3. The cost of energy. Low-income households are more vulnerable to high energy prices, and high energy prices may compromise the household finances, resulting in a vicious circle [65–67].
4. The characteristics and consumption habits of household members [16,34,68,69].

Once the concept of energy vulnerability has been established, a quantitative analysis of the position of households in terms of energy vulnerability can be approached. This quantitative analysis requires primary data and a sound analytical methodology. In turn, the results of the quantitative analysis may be used to suggest solutions and palliative measures [8,42].

However, identifying and measuring energy poverty in this way faces an additional difficulty, which is inherent to the specific nature of the problem. We must take into consideration that energy poverty is a private domestic concern, which has a different character in different regions and which is prone to changing sharply over time; it is also a socially sensitive issue, as expectations concerning energy services are highly subjective.

Limited access to personal data has restricted the analysis of energy poverty at macro- and micro-levels, based on aggregate public data. As pointed out by Dubois and Meier [6], identifying the problem and designing more effective solutions requires research on a local scale.

Focusing on the methodology applied by other studies carried out at the local level, Brunner et al. [8], undertook a qualitative analysis based on 50 interviews in Vienna. The subjects had been selected from a larger population by sampling [70]. In France, Devalière [71] undertook a quantitative analysis of 40 households in two different regions. Santamouris et al. [12], located in Greece, divided the 598 households in the sample into two groups according to income; in this case, consumption was tracked over three years, divided into two periods. An empirical study carried out in Aragón [40] was larger both in terms of the size of the sample and the number of variables: the study involved the multi-method analysis of over 650 poverty vulnerable and poverty impoverished households.

These previous studies concluded that the characteristics of buildings and installations are a key factor, especially for low-income households, and local management can contribute to solving the problem globally. As suggested by the report “Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures” [72], social housing is at the centre of multiple initiatives since social-housing dwellers may be particularly vulnerable to energy poverty [52,54].

These studies share the same vision of the problem posed by energy poverty and also agree on the partial dimensions into which the problem can be broken down (e.g., the energy efficiency of buildings, the social characteristics of the household, the characteristics of the installations, the cost of energy, etc.), but lack a composite vulnerability index that integrates the characteristics of the home, the household’s consumption habits, and the energy tariffs, and that establishes the household’s degree of vulnerability.

This is why our methodological proposal is important: it offers a double, quantitative and qualitative, approach that is capable of integrating different variables in a composite index which can be used to measure the degree of energy vulnerability of households.

The methodology, as described in the following section, has been applied to a sample of rental social homes located in several publicly owned buildings.

3. Methodology

The characterisation of energy vulnerability must be based on the previously noted factors that determine energy poverty and on the conceptual framework that we have established:

1. The dwelling characteristics of the home.
2. The performance of the energy installations.
3. The cost of energy.
4. The characteristics and habits of household members.

In order to design the composite index, different variables related to energy poverty were selected and allocated to one of the four key factors, as presented in Table 1. In this way, each key factor is represented by a relatively wide array of variables.

Table 1. Classification of variables using the four key factors.

Variable	Description of Variable	Factor
Dwell 1	Geographical area in which the building is located	Dwelling characteristics
Dwell 2	Environment surrounding the building (urban/rural)	Dwelling characteristics
Dwell 3	Year of construction of the building	Dwelling characteristics
Dwell 4	Ownership	Dwelling characteristics
Dwell 5	Type of residence	Dwelling characteristics
Dwell 6	Size	Dwelling characteristics
Dwell 7	Number of rooms	Dwelling characteristics
Instal 1	Is the home equipped with heating equipment?	Energy installations
Instal 2	Main type of heating in use	Energy installations
Instal 3	Is the home equipped with air conditioning?	Energy installations
Ebill 1	Voltage supplied	Energy bill
Ebill 2	Is the voltage supplied known by household members?	Energy bill
Ebill 3	Electric tariff applied	Energy bill
Ebill 4	Is the electric tariff applied known by household members?	Energy bill
Ebill 5	Energy expense	Energy bill
Ebill 6	Expense of other energy sources	Energy bill
Househ 1	Social service aid	Characteristics of the household
Househ 2	Household income	Characteristics of the household
Househ 3	Number of household members	Characteristics of the household
Househ 4	Number of minors in the household	Characteristics of the household

An integrated analysis of the information provided by these variables results in a composite index of energy vulnerability. The first step in this analysis is to establish measurements with which to evaluate the effect of these variables on vulnerability.

From an energy consumption-based perspective, Bouzarovski [7] put forward different measurement options:

- Directly measuring household energy consumption (heating, lighting, refrigeration, etc.) and comparing it to a given standard.
- Analysing variations in energy consumption profiles across the consumer population, both in relative and absolute terms.
- Compiling subjective perceptions of household energy consumption and supply.

Owing to the difficulties and costs associated with carrying out systematic energy audits in all the homes under scrutiny and the difficulties in tackling subjective information, the second option was chosen. It is considered that household energy consumption is defined by the previously selected set of variables; the value scored by each variable is compared to two extreme standard values, which represent the total energy poverty and no energy poverty.

A statistical analysis of the sample of Aragonese households compiled by Scarpellini et al. [40] revealed the most likely value for each variable in energy impoverished and energy non-impoverished households.

This process defines two theoretical household standards: a household that is totally energy vulnerable would score energy poverty-indicative values in all twenty variables, whereas a zero-vulnerability household would score non-energy poverty indicative values in all twenty variables.

In this way, assessing the degree of energy vulnerability of a given household, the variables of which are known, is undertaken by comparing this household and the two standards. In other words, assessing vulnerability is reduced to evaluating three alternative scenarios using an integrated analysis of different variables, some of which may conflict with each other. This is a multi-criteria analysis problem.

As noted, a qualitative approach is proposed, according to which the concept of energy vulnerability is represented by a structural model in which the four key factors are the first level of analysis and the broken-down variables are the second level of analysis. The most suitable methodology is, therefore, the Analytic Hierarchy Process (AHP).

This methodology was originally devised by Saaty [73] and is one of the most commonly used multi-criteria decision-making tools. It has been widely applied for different energy management purposes [74–76], including the energy management of buildings [77]. The process is based on the decomposition of a complex problem into different levels with a target at the top of the structure, criteria and sub-criteria at different levels and sublevels of the hierarchy, and decision alternatives at the bottom.

The different elements on each level are pairwise compared in order to evaluate their relative preference with regard to the elements in the level above. The application of the Saaty 1–9 scale is a useful exercise, regardless of whether information is qualitative or quantitative. A value of 1 indicates equal importance for the variables being compared, 3 moderately more important, 5 strongly more important, 7 very strongly more important, and 9 extremely more important. The scores 2, 4, 6, and 8 indicate intermediate values.

In order to compare pairs within a given level, a matrix is created using the result of the comparison of element i with element j in the position a_{ji}, as follows in Figure 1:

$$A = \begin{bmatrix} a_{11} a_{12} & \cdot & a_{1n} \\ a_{21} a_{22} & \cdot & a_{2n} \\ \cdot \quad \cdot & \cdot & \cdot \\ a_{n1} a_{n2} & \cdot & a_{nn} \end{bmatrix}$$

Figure 1. Structure of a pairwise comparison matrix.

Once the weight vector is known, it is multiplied by the weight coefficient of the element above (which was used as a comparison criterion). The process is repeated upwards until reaching the top of the hierarchy.

The method calculates and aggregates its own vectors until the final vector, made up of the weight coefficient of all alternatives, is obtained. The elements of this final vector reflect the relative importance of each alternative with regard to the target indicated at the top of the hierarchical structure.

A critical stage of the methodology is the assignation of relative importance values to each variable and factor—that is, the relative preference of each criteria with regard to the elements in the level above.

For the first issue, and given the lack of specific data, all variables were considered to have equal importance for the corresponding key factor.

However, it was obvious that factors had a different impact on the degree of vulnerability of households, and it was decided that a specific methodology should be used to manage subjectivity and assign different weights to each.

This was achieved by asking 65 technicians and professionals with direct or indirect experience in the management of energy poverty in Aragón to evaluate (on a scale of 0 to 10), within the framework of a semi-structured interview, the significance of each of the factors considered relevant to energy poverty.

The relative weight of each factor was calculated on the basis of the average values presented in Table 2:

Table 2. Evaluation of the four factors (in percentages) for the multi-criteria methodology (Source: authors' own).

	Average	**Relative Importance for Vulnerability**
Dwelling	7.18	26%
Installations	8.17	30%
Bill	7.74	28%
Household	4.48	16%

Figure 2 shows the frequency of answers and the average value for the four key factors:

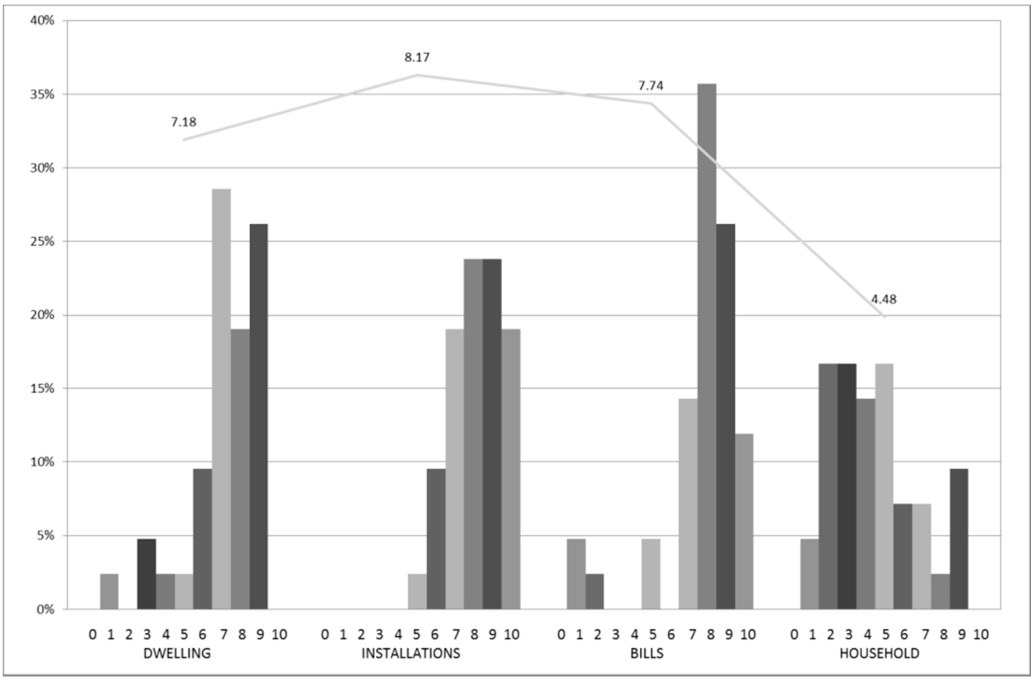


Figure 2. Qualitative analysis of the relevance of the four key factors concerning energy poverty, according to the experts (Source: authors' own).

However, the obtained value for the rated household will be relative to the individual assessment and cannot, therefore, be directly compared with those of other households. Obtaining a vulnerability index requires that the weight vectors be normalised to an absolute scale. In each analysis, the analytical values will thus be normalised to a linear scale, zero-vulnerability having a value of 0 and total vulnerability a value of 1. This system allows for an absolute value to be assigned to each household; the closer to 1 the value is, the more vulnerable the household.

The values thus obtained will be the ultimate composite index of energy vulnerability.

The following section presents and examines the results of applying the described methodology to a sample of households.

The application of the AHP to the evaluation of the degree of vulnerability of a household, using the structural model illustrated in Figure 3, results in a vector with three elements, the aggregate value of which is 1. The value of these elements determines the position of the household under scrutiny with regard to the two standards.

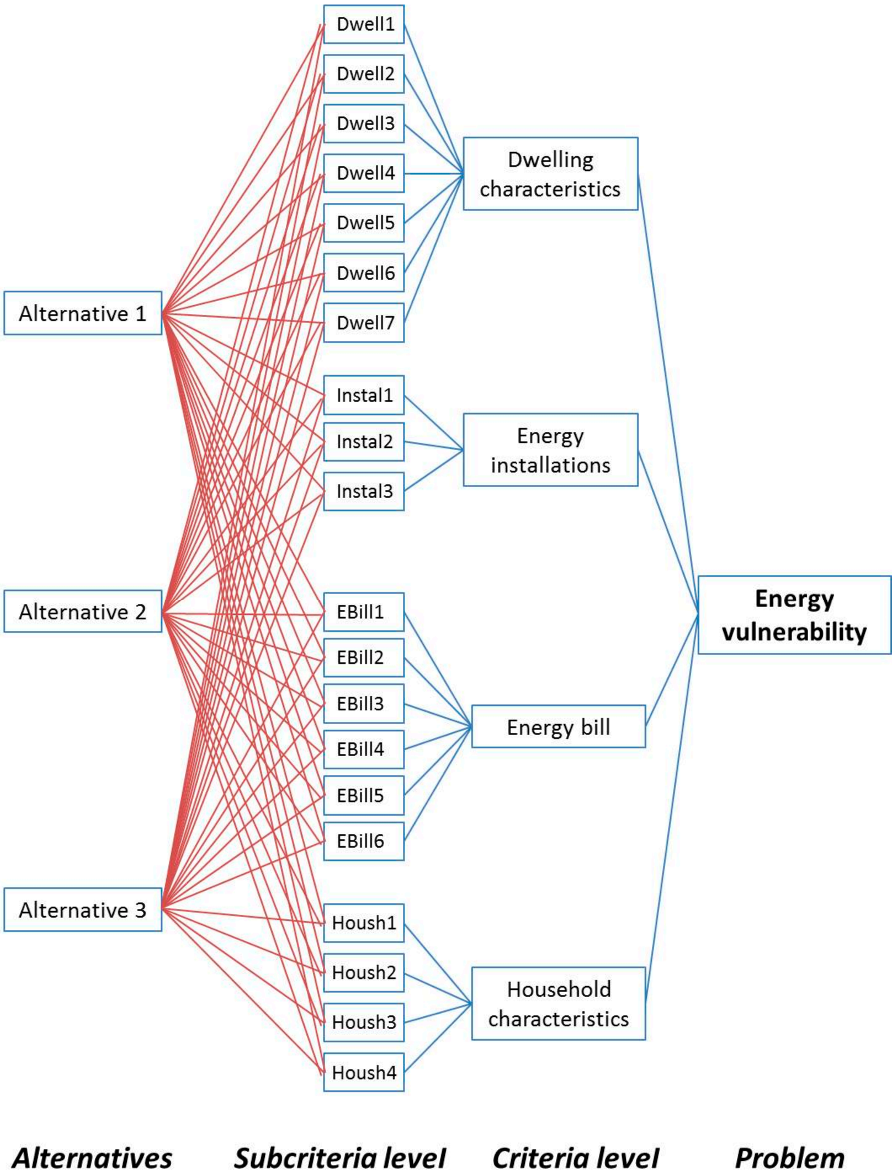


Figure 3. Structure of the decision problem.

4. Case Study

The sample under analysis includes 351 households living in social housing. Homes are located in Zaragoza, Spain, and are owned by the public agency Sociedad Municipal Zaragoza Vivienda. The sample is considered representative of rented social housing in the region.

The homes under analysis are located in three apartment blocks that were built in three different districts of the city of Zaragoza between 1990 and 1995. Their size is between 50 and 75 m^2, and the number of rooms varies. The flats are equipped with individual electrical or gas heating systems. These flats are largely allocated on the basis of economic criteria; over half of the households under scrutiny have an annual income below €9000 and 80% have an annual income below €19,000. Up to 26% of these households must dedicate over 10% of their income to pay their energy bills. The profile of the subject households in terms of the age and characteristics of household members varied greatly.

As a preliminary stage to our analysis, a comprehensive database was compiled using information on the apartment blocks under examination; the staff and management of the municipal agency that owns the buildings actively cooperated and participated in this process. Combining this information with other primary and estimated data compiled by the research team allowed for values to be allocated to the 20 selected variables.

As described in the previous section, the subject households were evaluated individually and compared to two standard households as though they were three different alternatives in a hierarchical analytical process. It must be made clear that most variables were nominal quantitative variables, and thus in order to facilitate the comparison in a multi-criteria analysis setting, they had to be transformed into discrete quantitative variables. Both these variables and the rest were categorised in order that the minimum value coincided with the most probable value in zero vulnerability households and the maximum value coincided with that in total vulnerability households.

The first step in the hierarchy analysis process is the design of the pairwise comparison matrixes of the three alternatives for each of the selected criteria. This is undertaken for each factor (criteria) which, as previously noted, is in turn defined by n-variables (sub-criteria). In this way, each factor needs n 3 × 3 matrixes.

As an example of how we can use this methodology, we can calculate the final vector for the factor or criteria 'Dwelling characteristics' for one household. According to Table 1, this factor is defined by seven variables:

- Dwell 1: Geographical area in which the building is located.
- Dwell 2: Environment where the building is located (urban/rural).
- Dwell 3: Year of construction of the building.
- Dwell 4: Ownership.
- Dwell 5: Type of residence.
- Dwell 6: Size.
- Dwell 7: Number of rooms.

The second row of Table 3 reflects the value of these variables for these households, while the first and third express the value for total- and zero-vulnerability households, respectively.

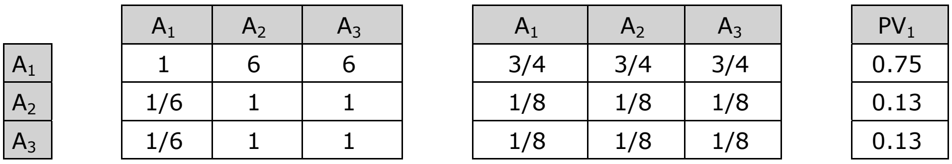
Table 3. Alternatives to be considered in the calculation of the decision problem 'Vulnerability according to the dwelling characteristics'.

Alternatives		Dwell 1	Dwell 2	Dwell 3	Dwell 4	Dwell 5	Dwell 6	Dwell 7
A1	Totally vulnerable household	3	1	1	3	1	4	5
A2	Subject household	1	1	0	2	0	2	1
A3	Zero vulnerability household	1	0	0	1	0	1	1

Given that quantitative information is available, the pairwise comparison matrixes can be based on a comparison of the value with the pair of alternatives. These will form the basis of the priority vector for each criterion, which will form the column of the alternative priority matrix for that problem.

Figures 4–10 represent the Alternative Comparison Matrix (ACM), the normalised comparison of alternatives matrix (NCM), and the priority vector (PV) for each of the seven sub-criteria (variables) that define the criterion (factor).

In the matrixes, the elements of the comparison are presented as fractions in order to demonstrate that the reciprocal comparison axiom is maintained. Obviously, the values of the diagonal that indicates the priority of each criterion with regard to itself equal 1.



	A_1	A_2	A_3
A_1	1	6	6
A_2	1/6	1	1
A_3	1/6	1	1

A_1	A_2	A_3
3/4	3/4	3/4
1/8	1/8	1/8
1/8	1/8	1/8

PV_1
0.75
0.13
0.13

Figure 4. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell1.

	A_1	A_2	A_3
A_1	1	1	5
A_2	1	1	5
A_3	1/5	1/5	1

A_1	A_2	A_3
4/9	4/9	4/9
4/9	4/9	4/9
0	0	0

PV_2
0.44
0.45
0.09

Figure 5. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell2.

	A_1	A_2	A_3
A_1	1	5	5
A_2	1/5	1	1
A_3	1/5	1	1

A_1	A_2	A_3
5/7	5/7	5/7
1/7	1/7	1/7
1/7	1/7	1/7

PV_3
0.71
0.14
0.14

Figure 6. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell3.

	A_1	A_2	A_3
A_1	1	5	6
A_2	1/5	1	5
A_3	1/6	1/5	1

A_1	A_2	A_3
3/4	4/5	1/2
1/7	1/6	3/7
1/8	0	0

PV_4
0.68
0.24
0.08

Figure 7. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell4.

	A_1	A_2	A_3
A_1	1	5	5
A_2	1/5	1	1
A_3	1/5	1	1

A_1	A_2	A_3
5/7	5/7	5/7
1/7	1/7	1/7
1/7	1/7	1/7

PV_5
0.71
0.14
0.14

Figure 8. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell5.

	A_1	A_2	A_3
A_1	1	6	7
A_2	1/6	1	5
A_3	1/7	1/5	1

A_1	A_2	A_3
3/4	5/6	1/2
1/8	1/7	2/5
1/9	0	0

PV_6
0.71
0.22
0.07

Figure 9. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell6.

	A_1	A_2	A_3
A_1	1	8	8
A_2	1/8	1	1
A_3	1/8	1	1

A_1	A_2	A_3
4/5	4/5	4/5
0	0	0
0	0	0

PV_7
0.80
0.10
0.10

Figure 10. ACM (**left**), NCM (**centre**), and PV (**right**) for sub-criterion Dwell7.

This results in seven priority vectors which form each of the seven columns of the alternative priority matrix (APM) that is shown in Figure 11:

$$\mathrm{APM} = (\mathrm{VP}_1\ \mathrm{VP}_2\ \mathrm{VP}_3\ \mathrm{VP}_4\ \mathrm{VP}_5\ \mathrm{VP}_6\ \mathrm{VP}_7) \tag{1}$$

	Build1	Build2	Build3	Build4	Build5	Build6	Build7
A_1	0.75	0.45	0.71	0.68	0.71	0.71	0.80
A_2	0.13	0.45	0.14	0.24	0.14	0.22	0.10
A_3	0.13	0.09	0.14	0.08	0.14	0.07	0.10

Figure 11. Alternative priority matrix APM for the decision problem 'Vulnerability according to the dwelling characteristics.

The second step consists of constructing the criteria priority vector (CPV) according to a pairwise criteria comparison matrix. As previously noted, given the impossibility of establishing the relevance of the different explicative variables, it is assumed that no substantial difference exists between them, and therefore, all the criteria comparison elements are equal to 1. The CPV is based on this matrix; this vector has one element for each of the sub-criteria that define the level immediately below, and a value which equals the unit divided by the number of sub-criteria.

In our example, the CPV is a vector with seven identical elements as shown in Figure 12, the value of which is divided by seven, resulting in 0.14.

$$\mathrm{CPV} = (\mathrm{PV}_1\ \mathrm{PV}_2\ \mathrm{PV}_3\ \mathrm{PV}_4\ \mathrm{PV}_5\ \mathrm{PV}_6\ \mathrm{VPV}_7) \tag{2}$$

Dwell1	Dwell2	Dwell3	Dwell4	Dwell5	Dwell6	Dwell7
0.14	0.14	0.14	0.14	0.14	0.14	0.14

Figure 12. Criteria priority vector (CPV) for the decision problem 'Vulnerability according to the dwelling characteristics'.

Finally, Figure 13 displays the Global Priority Vector (GPV) that is attained by multiplying the CPV by the APM.

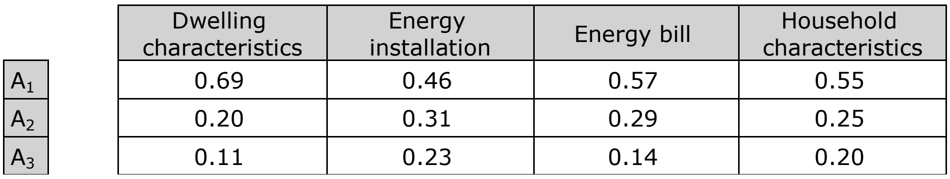
$$\mathrm{GVP} = \mathrm{CPV} \times \mathrm{APM} \tag{3}$$

	Dwelling characteristics
A_1	0.69
A_2	0.20
A_3	0.11

Figure 13. GPV for the decision problem 'Vulnerability according to the dwelling characteristics'.

It should be observed that this final vector is made up of the weight coefficients of each of the alternatives, which in turn indicate the relative relevance of the three households considered with regard to the decision problem. In this case, the decision problem is the need to classify the energy vulnerability of the households on the basis of the dwelling characteristics. It is to be noted that the sum of the three coefficients equals 1. The result of the test indicates that, based on the dwelling characteristics, the household under examination (alternative A2) presents an intermediate degree of energy vulnerability, but is closer to zero-vulnerability coefficients than to total vulnerability coefficients.

If we apply the same process to the three remaining factors, we obtain the global priority vectors for the corresponding decision problems as summarised in Figure 14.

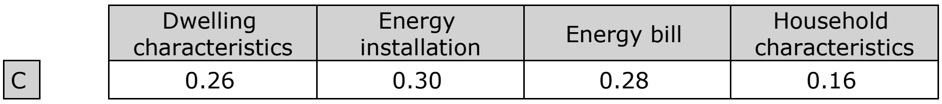


	Dwelling characteristics	Energy installation	Energy bill	Household characteristics
A_1	0.69	0.46	0.57	0.55
A_2	0.20	0.31	0.29	0.25
A_3	0.11	0.23	0.14	0.20

Figure 14. GPVs for the decision problems 'Vulnerability according to the different factors'.

Each column in the GPV can be considered the individual vulnerability indicators (IVI) of the three households with regard to each factor.

The problem presented in Figure 3 can be solved using the relevance factors calculated and presented in Table 2, considered a coefficient vector C whose elements can be seen in Figure 15:



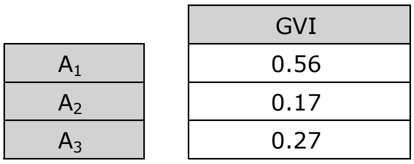
	Dwelling characteristics	Energy installation	Energy bill	Household characteristics
C	0.26	0.30	0.28	0.16

Figure 15. Coefficient vector (C).

The elements on each row i of the GPV (Figure 14) and those of the coefficient vector (Figure 15) are used to calculate the Global household Vulnerability Indicator (GVI):

$$\mathrm{GVI} = \sum \mathrm{GPV_i} \times \mathrm{C_i} \tag{4}$$

Figure 16 shows the result for the three alternatives of the decision problem:



	GVI
A_1	0.56
A_2	0.17
A_3	0.27

Figure 16. Global household vulnerability indicator.

At this stage, all the values obtained for the subject household are normalised (values in the row A2 in Figure 14), ranging from a value of 0 (zero vulnerability) to 1 (total vulnerability), in order to obtain a vulnerability index for each criterion, as well as a global one. The results are shown in Table 4.

Table 4. Vulnerability indexes based on the factors and the global vulnerability index in the household used as an example.

IVI Regarding Dwelling Characteristics	IVI Regarding Energy Installation	IVI Regarding Energy Bill	IVI Regarding Household Characteristics	GLOBAL VULNERABILITY
0.16	0.35	0.35	0.15	0.25

Applying these evaluation factors allows for the definition of a global energy vulnerability index based on the values of individual criteria. However, it may be mentioned that this global index is highly sensitive to weight coefficients and that it conceals the specific information supplied by relative vulnerability indexes.

For descriptive purposes, the vulnerability ranges set in Table 5 (within the [0, 1] interval) will be used:

Table 5. Vulnerability ranges.

	VI
Low	0–0.25
Moderate	0.25–0.50
High	0.50–0.75
Very high	0.75–1

Based on the previous calculations, the household used as an example rates low on the vulnerability scale in general, but its rating is moderate when only the installation and energy bill-related variables are considered.

The use of a composite index made up of the four individual vulnerability indicators is proposed.

This method was applied to the 351 households in the sample, resulting in a group of indexes. These are represented in Figure 17.

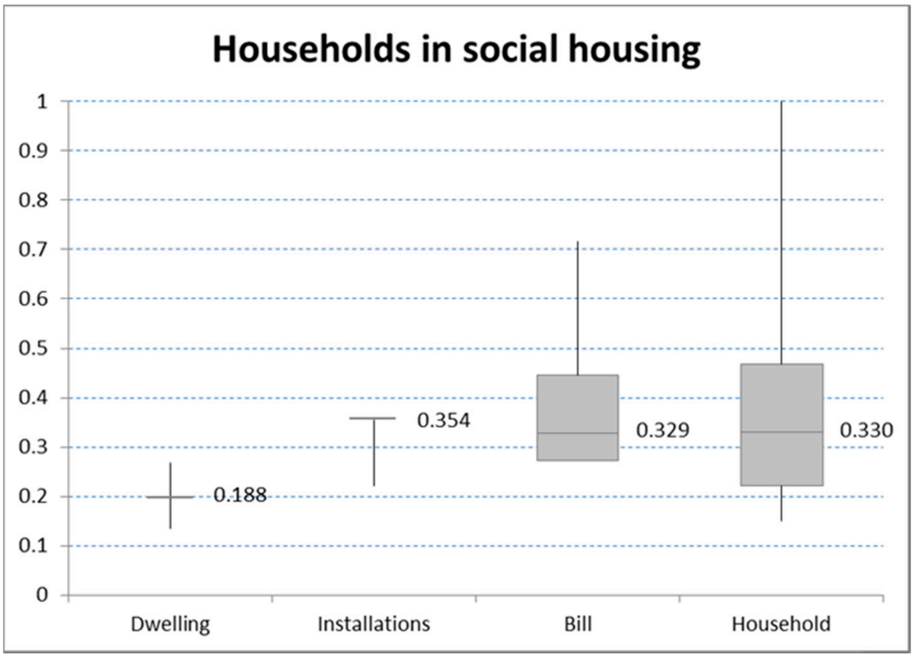


Figure 17. Distribution of the elements in the composite index for the subject sample of social houses.

Using box plots, we can identify the mean of all the sample values and graphically illustrate the interval in which the most common, and, therefore, most representative, values of the sample fall.

The similarities between the buildings under examination in terms of dwelling characteristics and energy installations are reflected in the almost negligible range of values presented by the first two indexes. Taking these factors into consideration, the sample households score a low overall vulnerability rating, whereas the global vulnerability rating (taking all four factors into consideration) for the whole sample is moderate.

The values recorded using the variables concerning energy bills and household habits, however, present a much wider range.

The application of this multi-criteria methodology indicates that the households under examination do not score high energy vulnerability ratings, despite the low average income of the households.

This positive result is, to a large extent, due to the good building characteristics of the dwellings. In contrast with other studies that deal with low-income households, this factor has little impact on the overall index because all the buildings under consideration are homogenous and are publicly owned, and thus, they are adequately maintained.

In order to demonstrate the consistency of the method and the indexes generated with it, the indexes for two additional samples were calculated: a sample of 615 certified energy impoverished households was used to establish the conceptual framework of the study (results in Figure 18); and a sample of 1340 households in Aragón (results in Figure 19), the data for which were collected in the preliminary phase of the study undertaken by Scarpellini et al. [40]. (For more details on this study, see [78]).

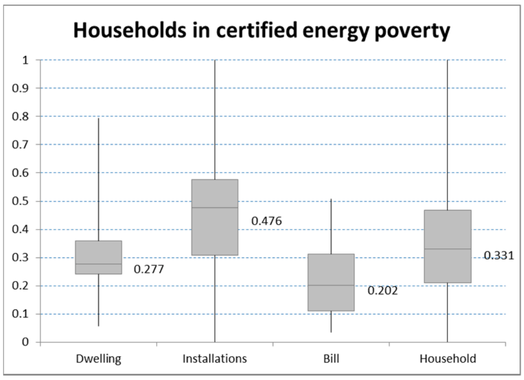


Figure 18. Distribution of the elements of the composite index for the additional samples.

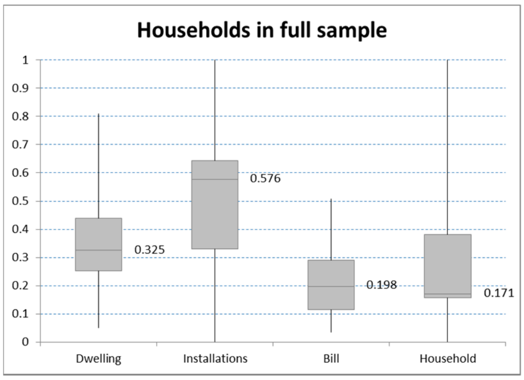


Figure 19. Distribution of the elements of the composite index for the 'Households in full sample'.

The mean and the variability range of the values concerning the characteristics of the home match those presented by certified energy impoverished households (in both cases, the households are at risk of falling below the poverty threshold); the subjects in both samples are more vulnerable than those in the third sample.

A comparison of the vulnerability indexes of the social houses in our sample (Figure 17) with the values calculated for the two other samples (Figures 18 and 19) indicates that the social houses are the least vulnerable in terms of architectural characteristics and energy installations.

However, the social houses are markedly more vulnerable than the other two samples in terms of energy bills. In any case, the close match of the mean calculated for this factor with that calculated for the installations suggests that this is a consequence of the kind of energy used by these installations.

Considering these results, the only actions that the public agencies can take in order to reduce the energy vulnerability of these households is to intervene in energy supply contracts, which is beyond their jurisdiction (energy supply contracts are bilateral agreements between the utility company and the customer), or to lead public campaigns to raise awareness.

Finally, these indicators also point to the source of energy poverty in the subject households, which, given the similarity of the results concerning the building, installation, and tariff characteristics, lies in the profile of the household. The difference between the installation and the bill indexes may be due to the need to excessively constrain energy consumption in response to low income levels.

Energy efficiency in buildings and installations is not a major cause of energy poverty in the social houses in the sample. Priority should be given to actions that aim to reduce the difference between the installation and energy bill-related vulnerability indexes. The vulnerability index concerning energy bills suggests that the implementation of improved energy contracts would reduce the risk of energy vulnerability in these households.

Using this methodology to study individual households may assist in decision-making processes and also facilitate a prediction of the effect of a given change in the variables on the household's energy vulnerability rating.

As presented in Figure 20, the global vulnerability index in the three samples does not present substantial differences.

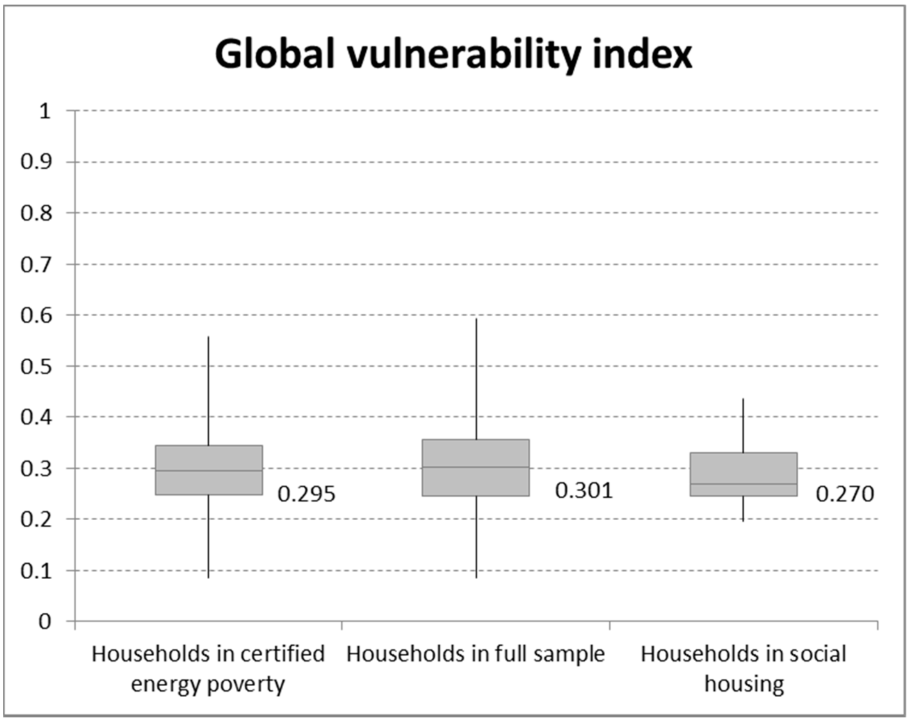


Figure 20. Distribution of global vulnerability index in the three samples.

We may conclude that the information provided by a single index is, therefore, partial and incomplete, and that it contributes to concealing the causes of household energy poverty. In addition, the use of a single index wastes the interesting information provided by partial indexes, which is enormously useful, for instance, for the management of social housing. On the other hand, the proposed composite index can be used to evaluate whether a specific household falls within a given vulnerability typology range.

5. Conclusions

The EU has adopted numerous initiatives in order to evaluate the problem posed by energy poverty at local, regional, and national levels, and to define the most effective palliative actions. The most effective measures to prevent or mitigate household energy poverty, however, are those targeted at the household level. For these measures to be effective, frameworks need to be put into place to guarantee that information on consumption is kept private and to develop methodologies with which to examine the problem from all its different angles.

Within the framework of the debate on the relationship between household energy poverty and energy vulnerability associated with the buildings in which these households live, this study has defined the most significant factors for household energy poverty. This has led to the determination of a series of indicators which are accessible to the public agencies and which are used to generate a composite index of energy vulnerability. This index is a tool that can be used to holistically manage social housing from the perspective of energy poverty. The index considers the four key factors for energy poverty (aside from the socio-professional position of household members): the characteristics of the building, the characteristics of the energy installation, the energy bill, and the energy habits of household members.

The proposed methodology achieves three goals. Firstly, it can be used to assign a relative weight to different indicators of household energy vulnerability. Secondly, the resulting index is a heuristic tool, which can increase our understanding of how attributes, and combinations of attributes, can lead to similar degrees of vulnerability. Thirdly, it reveals new data with which to design and monitor action in more efficient ways.

The household vulnerability index proposed, understood as a heuristic tool, offers a new insight into the causes and structure of vulnerability among populations with a similar level of exposure. This makes it a very useful tool for decision-making processes concerning the management of household energy poverty in social housing, e.g., the rehabilitation of buildings, maintenance, or the management of energy supply.

These results are not free of limitations, especially regarding the size of the sample and the number of data variables. Similarly, the lateral nature of the study leaves many questions open: for instance, the evolution of a sample over several years and the possibility of analysing larger samples which include homes of different types and located in different climatic areas.

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Conflicts of Interest: The authors declare no conflict of interest.

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3 The mediating role of social workers in the implementation of regional policies targeting energy poverty

3.1 Introduction

The objective of this chapter is to analyse the social aspects of the energy vulnerability in households, and the role that public social workers and NGOs play to mitigate the urgent issues of energy poverty cases in Spain. For a more comprehensive approach, an introduction to the regulatory framework in Spain and more particularly in the region of Aragon is carried out then.

With regard to the regulatory framework applicable in Aragon and the city of Zaragoza for the assistance of households in situations of social exclusion due to energy poverty, this analysis refers to the aids provided by public social services in charge of attending these situations and, more specifically, the so-called emergency aid.

Law 5/2009 on social services in Aragón establishes the content of the social services Catalogue as public nature benefits, and regulates two types of service: economic and technology services (article 37.2a) for emergency situations provided by local authorities. The aforementioned Act of 2009 (article 37) refers to economic benefits for emergency situations and defines them as monetary contributions whose purpose is "c) Cover or alleviate the economic consequences of situations of social urgency."

This Act was developed through Decree 143/2011 of the Government of Aragon. It regulates the social services of the Autonomous Community of Aragon, and contains all the benefits of the public system aimed at addressing the possible needs of people living in the region in terms of social service access, social integration, adequate coexistence, basic needs, personal autonomy and social participation. This social services Catalogue establishes the definition and determines its nature, essential or complementary, as well as the applicable regime for its acceptance, deployment and extinction. It determines, in particular, the requirements which the beneficiaries have to meet, the management and provision centres, the quality standards to be adjusted and, finally, their free or, if not, the degree of participation in the financing of the service or payment conditions of the market price.

Decree 143/2011 of the Government of Aragon (Article 2.1.1) specifically defines emergency aid, indicates the population for whom it is intended, the nature of the benefit, the type of need, the form of access and the applicable regime. In this sense, the Decree determines, the name, definition, nature, target population, addressed needs, managing centre and the funding regime, for each of the benefits. It incorporates both the applicable benefits contained in the Catalogue of social services of Aragon and the set of regulation elements, including access requirements, the participation scheme in financing of the service and the quality standards to be applied.

In summary, emergency aid for general situations are extraordinary single-payment economic benefits intended to solve situations of necessity, at the time they occur, affecting persons or families who are deprived from essential living means. It is designed as a complementary benefit and it is directed, among others, to the following cases:

- Impossibility to continue in the use of the usual residence, and in particular, the payment of rents to preserve the right to use it.

- Lack of economic means to preserve the habitability conditions or to acquire the basic equipment of the usual residence.

These Aids are framed in the Concerted Plan of Basic Benefits of Social Services in Local Corporations of the Ministry of Health, Social Services and Equality and are executed through the Autonomous Communities. In the case of Aragón the aids is managed by the Aragonese Institute of Social Services (IASS in Spanish) and Local Entities. The applicable regime to this benefit is regulated by Decree 48/1993 of the Government of Aragón, about Modalities of Economic Benefits of Social Action, regulated by Law 4/1987.

The aids most directly related to this study, are aimed at individuals, unemployed, low incomes and elderly people living in Aragon who are in economic and / or social need and are not covered by other protection systems. The beneficiaries should have an annual income below 1.25 times the Public Income Indicator for Multiple Effects (IPREM in Spanish) for grants and subsidies, increased by 20% for every additional household member. These aids are regulated by Decree Law 3/2015 of the Government of Aragon, about Urgent Measures for Social Emergency in the Field of Social Economic Benefits, Energy Poverty and Access to Housing.

In summary, the urgent aids related to housing in Aragon refer to situations of necessity and aim at covering those expenses in a household related to maintenance and conservation of the usual residence such as rent and mortgage payments, payment of debts in avoidance of evictions, necessary repairs to ensure habitability, the acquisition of basic furniture and essential household appliances, Community expenses and, finally, the electricity, gas, diesel and fuelwood expenses that concern our analysis.

In the case of the Aragon Region, once the competences in social services and the emergency aid scheme available for housing in socially excluded households have been analysed, those households that are eligible to receive specific emergency aid for the payment of energy supplies (electricity and / or fuel) are considered under energy poverty, according to the assessment made by the social services of the Local Authorities competent in the territory.

Households in a situation of energy vulnerability are considered to be those that have economic deficiencies according to two criteria:

a) Households declared as unable to reduce consumption expenditure after all measures suggested have been applied

b) Households having proved that the tariffs they have contracted for the energy supply correspond to the social tariff modality available in the regulations in force. It could therefore be the case that a vulnerable consumer is not included in a situation of general energy poverty but at a specific moment could not face the energy bills of his dwelling.

The latest regulation in force in Aragon is Law 9/2016 about Energy Poverty Mitigation in Aragon. This law aims at adopting measures to palliate and reduce domestic energy poverty in Aragon in an environment of purchasing power decrease due to the long economic downturn, an increase in energy supply costs and the problems identified with the existing social aids. As in the precedent regulations, Law 9/2016 determines urgent aids of essential services like energy supply at home, where the beneficiary has to prove compliance with the requirements of the law and the Administration, by means of the Social Service have to explicitly assess and accept the aids.

This regulation focuses on vulnerable and very vulnerable social groups, classifying vulnerability as a function of incomes per household and risk of social exclusion. Factors considered for social exclusion are gender violence, victim of terrorism or natural disasters, and disability degree higher than 33%. Economic factors include large family status, mortgage payment failure, unemployed or elderly with mortgage liabilities and low incomes.

Low income criterion is set as a comparison with the IPREM official index that is updated yearly. 2017's value is 538 €/month (Annual State's budget 29/06/2017). According to this index, people's annual incomes should be between 1 and 2 times the IPREM index, to be considered vulnerable. For extreme vulnerability total annual incomes should be below the IPREM index. Extreme vulnerability status can be obtained upon request and should be certified by the Government's Social Services and it extends until the conditions giving place to this vulnerability status disappear. In these extreme cases energy bills can be covered up to 100% while in usual vulnerability cases bills are covered from 50% to 75%.

Utilities warning of the consequences of a payment failure should inform the faulty client about the provisions and aids available in this law. In the same way, utilities having payment failures should notify the Public Administration Social Services and wait for their consent before stopping any energy supply, especially in winter. For this purpose, bilateral agreements between the local district administrations and the utilities have been reached to avoid energy curtailments in vulnerable households that default. Once social services assess every particular situation and agree to grant the aids, the utility commits to keep the energy supply service while aids are being processed. In this case, the faulty bills are directly payed from the social service to the utility. If the energy cut down had already been executed before the social aids has been processed, there will be an immediate request to the utility to resume the energy supply. In this case, aids will cover the unpaid bills but not necessarily the utility resuming costs.

The social discount rate system (Social tariff or "Bono social" in Spanish) has also been reformed recently to avoid situations in which non vulnerable consumers benefited from discount rates while the opposite situation could also happen. The social discount rate concept is maintained, enabling retailers to offer energy discount rates in regulated supply contracts for domestic users and maximum supply power below 10 kW. Discounts are not social aids from Public Administrations but an electricity market compensation meant for vulnerable consumers. The systems is managed by retailers and utilities and the program costs are part of the regulated electricity system cost to be sustained by consumers in their bills.

Modifications to the social discount rate system affect the eliciting requirements to be considered vulnerable. The domestic vulnerable consumer figure is regulated in the new Royal Decree 897/2017. Three levels of vulnerability are described as follows:

- Vulnerability level for a 25% discount eligibility. All large size families (3 or more dependent children), minimum wage retired people, or any individual with annual incomes below 1.5 x IPREM (below 2 x IPREM if 1 child and below 2.5 x IPREM if 2 children).

- Severe vulnerability level for a 40% discount eligibility. Large size families (3 or more dependent children) with total income below 2 x IPREM, minimum wage retired people with total income below 1 x IPREM, or any individual with annual incomes below 0.75 x IPREM (below 1 x IPREM if 1 child and below 1.25 x IPREM if 2 children).

- Severe vulnerability level certified by social services and categorised as high social exclusion risk. This includes extreme vulnerable consumers assisted by social services where energy bills are already covered by 50% or more. In this case, the social discount rate system adds on the social service aids provided by local and regional governments to cover the full unpaid bill amount.

All utilities and retailers should provide means for consumers to apply for the social discount rate by any means (telephone, fax, website, or post) and are entitled to receive the applications, check eligibility criteria, grant or deny the discount and revise the eligibility criteria at least once every two years.

3.2 Methodology

The proposed methodology consists of obtaining interviews and surveys of social workers from the Government of Aragon and several NGOs for the direct collection of information from these households and their situation. The result of the analysis of this information and its conclusions is relevant to the proposal of solutions in the political and social level to mitigate situations of vulnerability.

In collaboration with the Government of Aragon, the University of Zaragoza, Endesa and the CIRCE Foundation, a training programme on energy costs and energy efficiency in households was designed and implemented for social workers and NGOs that assist vulnerable residents in social housing throughout the region of Aragon. A computer tool was created to evaluate areas of risk for energy vulnerability, in order to help social workers assess the possible causes of this situation in each household. Data were collected from households, as well as the opinion of the trained social assistants, who act as mediators between vulnerable households and Administration for the implementation of palliative measures to help this target group.

3.3 Summary of the main results

Results indicate that social workers are aware of the problem related to energy poverty and that they consider more active action should be taken, especially those social workers who work in rural areas and for NGOs. In summary, most participants (86%) agree that vulnerable homes should not have their supply cut off. They also reach consensus about agree that the problem posed by energy poverty cannot be solved by means of urgent ad hoc measures, but rather by further-reaching decisions, which are beyond their power to implement.

In a large proportion, the common feeling is that energy poverty is underestimated by policy makers and they think there is a lack of sufficient coordination among different public administrations and NGOs.

The tool created to assess risk of energy vulnerability in households permitted to collect data about households attended by social services. The average dwelling is badly insulated flat in a block of apartments, but rather big in size, where less than a third had been refurbished. Electric heating is used by 30%. The total average monthly energy expense is 270 €, which seems too high given the income of these households; a significant percentage (46%) has an income of below 900 € net for the whole household. As a result, 15% of households claim to have been given a cut-off notice, but state that emergency aid prevented the electricity being cut off.

The main measures that can be highlighted to improve the energy poverty intervention at regional level are:

- To create coordination units which facilitate communication and cooperation between agents (public services and NGOs) and contribute to the maximisation of available resources.

- To offer social workers specific training as a key agent.

- To implement specific policies in order to prevent the gap between exclusion and inclusion from widening even more-

- To increase the volume of social housing and to implement a specific refurbishment investment program to prevent the energy poverty in households in rural and urban areas.

- To define progressive levels of subsidies depending on the level of energy vulnerability or poverty and the situation of the households.

- To define a participative national model to design the main rules for energy poverty, within which all agents, including utility companies and the media, are represented and directed by national, rather than regional, authorities.

The result of this study has been compiled in an article presented in the journal "Energy Policy". The publication data is the following:

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The mediating role of social workers in the implementation of regional policies targeting energy poverty

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ABSTRACT

This paper aims to provide a socio-political reflection of the role played by social workers in regional policies and of the real needs of households affected by energy poverty. The paper also examines the impact of technical-specialised training on the ability of social workers to prevent and mitigate conditions of household energy poverty in Europe.

The adoption of a research-action-participation methodological framework and a training research approach has permitted the opinions of social workers to be collected through surveys, and their central role in implementing regional policies to be highlighted. The conclusions obtained have made possible the construction of a self-diagnosis and data-collection tool which increases the ability of social workers to mediate and implement urgent mitigation measures for energy poverty.

Finally, regional policies which aim to mitigate household energy poverty are examined from the professional perspective of social workers.

1. Introduction

Over the last few years, the European Union (EU) has adopted different initiatives to evaluate energy vulnerability at local, regional and national level, in an attempt to protect citizens from energy poverty (Bouzarovski et al., 2012) and prevent social exclusion by guaranteeing access to energy for reasonable and stable prices (European Economic and Social Committee, 2013). These issues were recognised in the Third Energy Package in 2009 (Eikeland, 2011), in which EU member states are directed to adopt the appropriate measures to protect consumers, and partially addressed in the so-called "winter package" at the end of 2016 (European Commission, 2016).

As pointed out by Bergasse et al. (2013), when households have to spend an excessive proportion of their income on energy, they are considered to be in a position of energy vulnerability, which may lead to a deterioration in living standards and have a negative effect on overall socioeconomic development. National public policies among EU members are, however, fragmented, both in terms of the definition of energy poverty and of the assessment and definition of prevention and mitigation measures.

This fragmentation is also linked to the different incidence of household energy poverty in different European countries. Energy poverty is a much more serious problem in Southern and Eastern Europe (Healy and Clinch, 2002; Sergio Tirado Herrero and Bouzarovski, 2015), especially in the Mediterranean region, where it is estimated that 16.6% of the households do not generally live in conditions of thermal comfort. The European average is approximately 4% lower (Bouzarovski, 2011).

European policies on the matter are patchy, owing to the fact that specific measures have been implemented by individual member states; this has limited the scope of EU-wide policies. Furthermore, a comprehensive understanding of energy poverty in each country depends on the availability of primary data, and some authors pointed out that a holistic perspective on everyday energy practices in low-income households that are undergoing energy poverty is needed at local and national level (Howden-Chapman et al., 2012; Brunner et al., 2012).

The first obstacle to analysing energy poverty is related to defini-

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tion: there is no unanimously accepted EU-wide academic definition of household energy vulnerability or energy poverty.

The earliest European definitions, which follow pioneering publication of Boardman (1991), established that a household suffered from energy poverty if it had to use over 10% of its income to meet basic energy expenses, which were those conducive to maintaining a temperature at home that varied between 18 and 21 °C (BERR, 2001; Rudge, 2001). This definition was later challenged and revised by different authors, who distinguished between electricity consumption and the use of combustion-based heating systems (Morrison and Shortt, 2008; Rudge, 2012; J. Hills, 2012) suggested that a household is in a situation of energy poverty when the costs of attaining sufficient thermal comfort are above average, provided that household income is under the poverty threshold (60% of the median income after deducing non-energy related housing expenses).

The International Energy Agency (IEA - IEA - International Energy Agency, 2011) established that a household is in a situation of energy poverty when the energy-related costs bear too heavily on the total income. This definition is very similar to that put forward by Tirado-Herrero et al. (2012) in one of the earliest Spanish publications on this subject. On the other hand, the report 'Energy Poverty in the EU' (Thomson and Snell, 2013) incorporated the concepts of the 'cold home' and household 'energy debt' into existing definitions.

Based on the relative definition of energy poverty provided by Grevisse and Brynart (2011), it seems appropriate for this study to adopt a definition according to which a household is in a position of energy poverty when it cannot afford the services conducive to satisfying recognised household needs. The definition, therefore, introduces the need for a mediating agent which can 'classify' households in terms of energy vulnerability on behalf of the relevant public social services (Scarpellini et al., 2015).

Given the differences in definition, we may question what model is accepted by public agencies in a European context, what role is being played by social workers involved in detecting, certifying and mitigating energy poverty in households, and finally what methods are being used for the detection and assessment of energy poverty in households The results presented in this article are based on these three research questions, and are focused in the context of a Spanish region characterised by the presence of active cooperative movements for energy poverty prevention (Scarpellini et al., 2014).

In general, energy poverty in Spain is being addressed through the implementation of emergency measures which aim to avoid households being cut off, and through the provision of necessary financial resources to those households who cannot afford to pay their energy bills. Data indicate that the problem is increasing in Spain (S. Tirado Herrero et al., 2014; S. Tirado Herrero et al., 2016) because the effects of the economic crisis have been particularly severe among the most vulnerable social groups (OECD, 2016).

Based on this premise, and after the next section, which will provide the background for the research presented in this paper, our aim is to analyse a regional energy poverty-policy model from the perspective of the social agents responsible for certifying energy impoverishment. These agents are key to ensuring that the model is efficacious, flexible and capable of responding to urgent energy-related needs. The empirical results obtained and the training scheme which was designed for the relevant social workers led to the development of a self-diagnosis tool, which was used in the certification of energy impoverishment; this will be presented along with our discussion of the regional policies currently in place. Finally, the main conclusions will be summarised.

2. Bacground

Energy poverty should not be interpreted in isolation from the overall processes of impoverishment and growing inequality that can be observed presently in countries such as Spain (Moretón, 2015; Bellver, 2015; García Escalera, 2015). In fact, during the last decades, the poverty characterised by the progressive, and chronic, impoverishment of the middle layers of society has increased specially in Latin America (Kliksberg, 1995; Barbeito and Lo Vuolo, 1992), but also affects European middle classes (Laparra and Casado, 2013). For this reason, this paper is focused on the role played by social workers in dealing with poverty (Laparra and Casado, 2013), and the problem is addressed using an interdisciplinary approach which incorporates a socio-political perspective.

An examination of the relevant literature in this field reveals that energy poverty is often identified on the basis of the proportion of overall income used to meet energy costs (Boardman, 2012), or other measurements based on comfort criteria (Roberts, 2008; Walker and Day, 2012), and the identification of households that are suffering energy poverty (Dubois, 2012; Li et al., 2014) is considered relevant to the design of appropriate mitigation measures (Chaudhuri and Ravallion, 1994).

The macro-analysis of energy poverty on a European-wide scale (Liddell et al., 2012; Moore, 2012; Rosenow et al., 2013; Heindl, 2015) and regional scale (Fahmy, Gordon, and Patsios, 2011; R. Walker et al., 2013), has received a fair amount of attention in this decade. In recent years, more attention has been paid to the measurement of the phenomenon (Morrison and Shortt, 2008; Pachauri and Spreng, 2011; Waddams Price et al., 2012; Rudge, 2012; Heindl, 2015), as well as to possible solutions (Boardman, 2004; Darby, 2012; European Economic and Social Committee, 2012; Guertler, 2012; Saunders et al., 2012; Sergio Tirado Herrero and Ürge-Vorsatz, 2012), subsidy policies (Dartanto, 2013) and the efficiency of public funds earmarked to help households living under conditions of social exclusion (Copiello, 2016).

In the recent years, the household-focused studies are increasing among the academics (Roberts, 2008; Devalière, 2010; Mathew Santamouris et al., 2013; Mathew Santamouris et al., 2013; S. Tirado Herrero et al., 2014; Scarpellini et al., 2015). In this field, some authors have identified the lack of uniformity among European and national statistical data as a limitation, as well as a shortage of data and a lack of surveys and specific methodology for measuring the phenomenon (Heindl, 2015). According to Santamouris et al. (2007), energy consumption is directly related to the socioeconomic profile of the household and the habits of its members. Energy tariffs has been pointed out as well in determining energy costs in energy poverty situations (Yu et al., 2011; Majcen et al., 2015).

When we look closely at the analysis of preventive or palliative proposals, Grevisse and Brynart (2011) provide a synthesis of the measures undertaken in the European Union, differentiating between the activities aimed at consumer protection and those designed to avoid disconnection of energy supply. The inadequate building features of dwellings has been analysed as a relevant factor in increasing the relative degree of energy poverty in households (Bahaj and James, 2007; Sdei et al., 2015; Terés-Zubiaga et al., 2013; Jenkins, 2010) Additionally, social housing has been a subject of some authors because it may be particularly related to energy poverty (John Hills, 2012; Li et al., 2014).

Nevertheless, despite growing interest of academics, there are still many aspects to be explored about energy poverty in households as the dissemination of information, which has recently been analysed by Bartiaux et al. (2016), or the role of social workers dealing with energy-impoverished households in the EU, that is the main subject of this paper. It means to discern what role social workers – regardless of whether they work for a public social service or a private NGO - play in the mitigation of energy poverty and the management of the specific funds available in some regions for the palliation of this problem.

In this context, the analysis presented in this paper is based on a regional case study and also aims to propose a specialised energy training initiative specifically designed to advance the results of the mediating role played by social workers, with the ultimate purpose of improving institutional responses to the needs of impoverished households.

3. Case study and methodology

The case study is the region of Aragón, in northern Spain. Aragon has been among the first regions to entrust social workers with the task of certifying cases of energy poverty (Scarpellini et al., 2015).

In 2015, the region had a population of 1,317,847, spread across 731 municipalities (over half the region's inhabitants live in the capital). Social exclusion and poverty rates in the region (17.7%) are well below the national average (28.6%). Territorially and demographically, the region presents the following figures (CESA, 2016): population loss (−1.6‰ in 2015), low population density (25 p/km^2), an increasingly aged population (and, in consequence, a high dependence rate; 56% of the population is economically inactive), and a negative migratory balance (75% of the municipalities have fewer inhabitants than in 2005).

The region has adopted a policy of territorialising social policies, and thus promoted proximity to vulnerable subjects, which has been fostered by the EU in recent decades (Hamzaoui, 2005). In this way, council-based policies (regulated by the Local Administrations Act[1]) have been complemented by district-wide social services[2] and also by private NGOs which, during the worst episodes of the economic crisis have gone a long way to mitigating the shortcomings of the public system (see Fig. 1).

The regional Social Services Act[4] establishes the catalogue of public social benefits and divides these into services, economic subsidies and technological assistance. This Act, was further developed by a decree[5] that regulated urgent subsidies which are, in essence, one-off monetary handouts which aim to ensure families do not lose their primary residence, adequate living conditions are maintained and, finally, electricity and other energy expenses are covered.

As previously noted, in the Region monitoring situations of energy poverty is the responsibility of social workers employed by the local administration. For this reason, almost all district and local councils have enacted specific regulations with which to ensure that the energy needs of vulnerable homes are met. In 2014, 2015 and 2016, several bilateral agreements were signed with the main utility companies in the region, in order to facilitate the management of outstanding energy bills and thus the protection of vulnerable households.

These agreements are legally binding, according to the Mitigation of Energy Poverty Act[6] which sets out the need to certify energy vulnerability in economic terms[7] and coordinate agents and those affected by energy poverty, in order to improve detection, measurement, regulation and mitigation, after the model adopted in other areas (for instance, mitigation of child poverty).

Thus, whenever social workers detect that household is in danger of having the power supply cut off, they carry out an assessment of the specific case in order to establish whether the person/family is/are in danger of social exclusion, and whether they are entitled to receive an economic subsidy which could be used to pay the energy bill. The utility company are informed of the situation, and the possibility of continuing or reconnecting the energy supply, following the relevant agreement, is contemplated.

In any case, the mitigation measures that are eventually implemented in order to tackle energy poverty revolve around the social worker, as illustrated in Fig. 1.

The following figure illustrates the evolution of subsidies provided by public agencies and social NGOs; 85% of the aid was granted to households in the regional capital (Zaragoza), and 89% in urban areas (Fig. 2).

Another interesting aspect is the involvement of social NGOs in tackling energy poverty, as illustrated in Table 1.

As the table clearly illustrates, after the signing of the agreements with utility companies in late 2014 and 2015, and the changes to local rules that regulated the management of these subsidies, the proportion of aids provided by NGOs dropped, while that provided by public agencies increased – a change in comparison to the trends detected in 2013 and 2014. Previously, aid provided by private NGOs was twice that provided by public bodies, whereas now the situation is the opposite.

Although they are limited by political and administrative caveats, social workers are assessing an increasing number of households and their lack of specific training could limit their ability to assess the problem adequately and, importantly, to suggest preventive, as opposed to simply palliative, measures, as well as to detect potential fraud.

With these premises, a specific training programme was designed and carried out at regional level, to explore in deep the issue of energy poverty and to develop new measures with which to tackle it (reflection/action) in collaboration with social workers.

3.1. Specialised training

The training programme of 20 3-h sessions was made possible by the cooperation of private and public entities.[8] There were 169 attendees, 77.5% of whom were social workers for local administrations which are responsible for providing urgent aid to vulnerable households. Workers affiliated with social NGOs constituted 21.9% of the attendees.

In general, the training programme was positively received (the average score was 7.98/10) and the involvement of the social workers was highly satisfactory, as illustrated by the Fig. 3.

Importantly, the attendees largely declared that their professional activity would benefit from the programme (7.98/10). This generated some debate and difference of opinion between those attendees who are in direct contact with energy-impoverished households and in charge of managing the emergency mitigation measures – those who regard the training programme as highly beneficial for their daily work – and those attendees not in direct contact with the households (educators, NGO workers, etc.), who generally consider the content of the programme as not applicable to real settings. Despite this difference of opinion, the need for this sort of training initiative is clear, as demonstrated by the fact that all available places were taken and that many attendees requested information on future programmes. The aspects that the attendees appreciated most were the sections on electric plans/tariffs and billing and information on the source of the energy costs incurred by the households with which they were working.

During the sessions, participation instruments were implemented in order that social workers were able to offer their points of view on the social challenge posed by energy poverty. Similarly, a specific survey was elaborated, in order to compile the data necessary for an in-depth analysis of the perspectives of professionals about energy poverty in the region.

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[1] Ley 7/1985 Reguladora de las Bases del Régimen Local.

[2] After the central government transferred responsibility for social services to the regional governments in 1996, social policies have become institutionalised and professionalised within the framework of this district-based system of social policies (Decreto 4/2005, de 11 de enero, del Gobierno de Aragón).

[4] Ley 5/2009, de 30 de junio, de Servicios Sociales en Aragón

[5] Decreto 143/2011, de 14 de junio, del Gobierno de Aragón.

[6] Ley 9/2016 of the 3rd of November: Mitigation of Energy Poverty Act of the Region of Aragón (Ley de Reducción de Pobreza Energética de Aragón).

[7] The threshold is established with reference to the so called "IPREM", an income indicator which is currently set at a gross €532/month. The vulnerability threshold is set at 2xIPREM/month.

[8] In spring 2016, the Regional Government presented a training programme that specifically addressed the issue of energy poverty. The programme was directed at those social workers who dealt with vulnerable households. The initiative was funded by Fundación Endesa (affiliated with the main electricity company in the region) and implemented by a research centre specialising in energy matters (CIRCE), in cooperation with the regional institute of social services and the University of Zaragoza. For more information, visit: www.fcirce.es/vulnerabilidadenergetica (accessed November 2016).

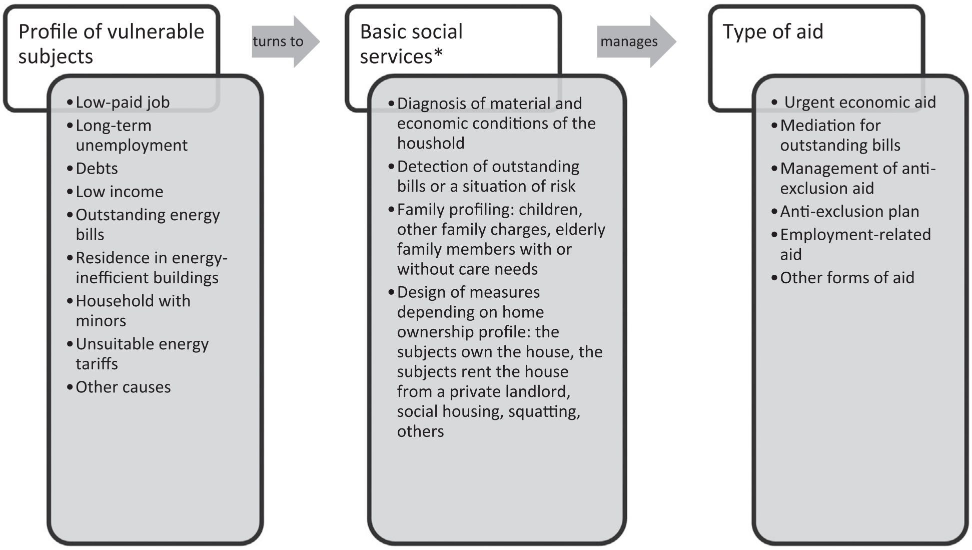

Fig. 1. Basic outline of the process involved in granting emergency economic aid[3] in situations of certified energy poverty.

Fig. 2. Evolution of the aid granted in situations of certified energy poverty.

The first part of the survey (Table 2) aimed to characterise, identify and classify the professionals completing the questionnaire, while the second section included eleven questions which touched on key topics concerning household energy vulnerability and poverty (answers were structured according to a Likert scale, with scores ranging from 0 to 10: 0 being totally disagree with the statement and 10 totally agree). Table 3 summarises the questions and the main results. At this stage, the analysis is purely statistical-descriptive.

During the training course, the attendees were provided with a self-diagnosis tool with which, using 208 variables, they identified four aspects which determine energy poverty: architectural characteristics, household facilities, energy costs and habits of household members. This information is summarised in the following table.

The tool, which was available online, aims to help social workers play a mediating role with energy-impoverished households which are entitled to assistance, as well as detect vulnerable households and present possible mitigation measures. The methodology, which was specifically designed to be used within the framework of the training programme, is based on statistic-descriptive and qualitative analysis. The specific topics under analysis are divided into four different fields. As such, results are measured depending on their potential impact on the households' energy vulnerability.

4. Main results

The main aim of this paper was to analyse, from a socio-political perspective, the relative position of social workers in the context of the regional-institutional setting and simultaneously to collect the opinion of the social workers about the energy poverty at regional level. To this goal, the empirical analysis was carried out using a sample of 108 valid observations – 80% publicly employed social workers and 20% NGO-employed workers. This proportion of participants is thought to be representative of the distribution of social workers in the region (70% in urban contexts and 30% in rural contexts), which is close to the distribution of the population (62% urban and 38% rural). 90% of the participants declared that they had attended households living in conditions of energy poverty. 85% of participants were women aged 42.6 on average (40% were under 41).

Results indicate that social workers are aware of the problem related to energy poverty and that they consider more active action should be taken, especially those social workers who work in rural areas and for NGOs. 67% of participants agree that households with no income should have access to free electricity, but they also agree that the amount of electricity supplied in this way must be limited. Although no agreement exists concerning this limit, most agree that the electricity bill should depend on income, as illustrated by the answers in the Table 3.

In summary, most of participants (86%) agree that vulnerable homes should not have their supply cut off in winter. This is the highest-scoring variable (8.3/10), with almost half of the participants ticking 'totally agree'. This indicates a clear consensus among social workers, who openly stand against cutting off the electric supply (Aragon is a relatively cold region, where buildings are often poorly constructed and energy inefficient). This tallies with their close involvement and commitment to current mitigation policies. However, most participants agree that the problem posed by energy poverty cannot be solved by means of urgent ad hoc measures, but rather by farther-reaching decisions, which are beyond their power to implement, but are the responsibility of regional governments, utility companies, national governments and even European institutions.

In order to gain a deeper understanding of the issue, social workers were asked about their subjective perceptions of the visibility of the problem at regional level; 90% claimed that energy poverty is not regarded as a relevant problem, which stands in sharp contrast to their everyday interactions with families who can barely afford to cover basic needs (housing, food, etc).

It is also worth underlining that NGO-employed workers think that their response to the problem has been more efficient and flexible than that of publicly employed social workers (66% agree with an average score of 6.3/10). Similarly, public- and NGO-employed social workers differ concerning whether the public and private agencies are sufficiently coordinated. Only 43% of all participants think that sufficient coordination exists, with an average score of 5.1/10 (6/10 among

Table 1
Public-Private sources of energy poverty-related aids for households in situations of certified energy poverty.

	2011		2012		2013		2014		2015		2016 (forecasted)		2017 (estimated)	
	Subsidies (Euros)	%	Subsidies (Euros)	%	Subsidies (Euros)	%	Subsidies (Euros)	%	Subsidies (Euros)	%	Subsidies (Euros)	%	Subsidies (Euros)	%
Public Social Services	131,493.58	*100%*	144,558.98	*100%*	191,928.16	*33.7%*	368,456.14	*31.3%*	635,760.00	*54.8%*	695,421.00	*68.8%*	726,081.3	*79.0%*
NGOs	n.a.		n.a.		377,191.34	*66.3%*	807,445.31	68.7%	524,839,45	*45.2%*	314,903.67	*31.2%*	192,721.04	*21.0%*
TOTAL	131,493.58		144,558.98		569.119,50		1,175,901.45		1,160,599.45		1,010,324.67		918,802.34	
Variation			*9.94%*		*293.69%*		*106.62%*		*−1.3%*		*−12.95%*		*−9.06%*	

NGO-employed social workers).

The crucial role played by social workers is unquestionable. Their on-the-ground experience seems adequate argument to continue supporting a system which emphasises attention being paid to rural areas. The perspective of social workers is invaluable concerning the real dimension of energy impoverishment as an indicator of poverty, and also concerning the multiple variables that can lead to energy impoverishment and, therefore, the best ways to improve the aid system.

Finally, half of the participants (51%) disagree that social movements in Aragón have exhibited sufficient awareness of or concern about the issue of energy poverty.

4.1. Characterisation of households

The provision of social workers with a specific tool during the training programme helped to get to the root of the problem and increase the efficiency of their assistance. In addition, the tool allowed the characterisation of 55 energy-impoverished households.

34 cases correspond to flats in apartment blocks. The flats have an average of 6 rooms and are 100 m^2. Insulation is generally poor. The average temperature is 20 °C in winter and 24 °C in summer, which leads to high energy expenses. Only one-third are occupied by tenants, and less than one out of three had been recently refurbished. Heating and water heating systems are described in the Fig. 4.

We may stress the use of inefficient heating systems, such as electric or gasoil heaters, which made up 30% of the heating and water-heating systems in use. In addition, 40% of homes have inefficient lighting systems, and the kitchen appliances are largely electrical.

Half of the households are billed according to a PVPC tariff (a regulated tariff designed for private consumers), while one-third have a free-marked tariff and 9 do not know the terms of their contract. Of those consumers billed according to a PVPC tariff, 7 have been granted a social tariff (social discount for vulnerable consumers). This suggests that more of the households under examination may be entitled to a social tariff, but members of these households do not know how to or are, simply, unaware of the terms of their contracts. The average energy supply in dwellings is 3.6 kW, which is reasonable. The average consumption in winter and summer is illustrated in the following figure (Fig. 5).

The total average monthly energy expense is €270, which seems too high given the income of these households; a significant percentage (46%) has an income of below €900 net for the whole household. As a result, 15% of households claim to have been given a cut-off notice, but state that emergency aid prevented the electricity being cut off.

On the other hand, the data collected thought the tool has contributed to gain a new perspective on the real dimension of the problem posed by energy poverty. Generally, a household is considered to be energy impoverished when the energy-related expenses take over 10% of the total income (Tirado-Herrero et al., 2014). These statistical data are interesting on a macro level, but they are clearly at odds with the number of households which were in a situation of certified energy poverty and, as such, were granted emergency subsidies. This sort of inconsistency underlines the fact that macro-level analysis, norms, mitigation measures and the real needs of households must converge.

4.2. The mediating role of social workers

Social workers are the central link in the detection and certification of occasional or chronic situations of energy poverty in households in the analysed regional model. They are the mediators who are responsible for verifying the household's (in)ability to meet the energy

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[3] In some cases the case is first handled by a private NGO, which generally provides a one-off emergency handout and puts the case in the hands of the basic social services.

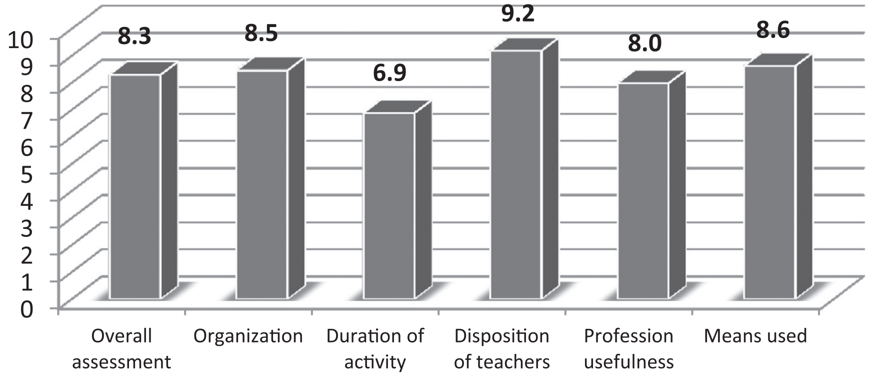

Fig. 3. Participants' assessment of different aspects of the energy training programme.

Table 2
Sections of the Energy Training tool.

Buildings characteristics	**Household equipment**
Potential problems in the architectural characteristics of the primary residence. Isolation and ventilation. Energy efficiency issues. – *Possible low cost measures on envelope improvement.* – *Possible low cost measures on passive gains* – *Possible measures in humidity control and ventilation* – *Etc.*	Potential problems in the household facilities. Recommend energy-saving measures. – *Possible savings in equipment maintenance and renewal.* – *Possible savings in high efficiency equipment replacement.* – *Possible savings in optimal use of the equipment* – *Etc.*
Energy costs	**Household habits**
Potential problems with billing. Advice on revising energy tariff/plan, or applying for social billing. – *Possible shift to more economic energy sources.* – *Possible measures in energy supply optimisation* – *Ratio energy expenses* vs *income* – *Meet conditions to apply for aids and subsidies.* – *Time discrimination tariffs.* – *Etc.*	Potential problems caused by household habits. Advice on good practice. – *Possible measures in automatic regulation* – *Possible measures in training and awareness of energy consumption drivers.* – *Possible measures in seeking advice from social services and consumer organizations.* – *Etc.*

expenses necessary to maintain reasonable living comfort standards, and activating the social-mitigation mechanisms in place.

The use of the proposed self-diagnosis tool led to the conclusion that the casuistic of energy poverty is varied, and that the emergency aid provided by administrations and ONGs, although effective in solving occasional episodes, cannot solve the underlying problem, which has long-term structural causes. In any case, specific training initiatives are useful for social workers, especially concerning irregularities in consumption and billing; social workers can propose more appropriate tariffs and encourage good consumption practices in order to minimise consumption.

In the case study under analysis, the public network is spread over the whole territory and aims to reach all households and municipalities. This ability to extend mitigation measures to the whole territory has contributed to shifting the burden of social action from private to public agencies.

Social workers, in contrast, emphasise the shortcomings of the system. Although the powers and responsibilities of social workers have increased, no investment has been made in order to develop the support network, although some measures have been undertaken which have improved their working conditions. The regional government's support of training initiatives such as that described in this paper is a good example of this.

The initial phase of this research (data-collection), and the evaluation of the results of the energy training programme described, demonstrates that the adequate preparation of professionals needs specific and comprehensive training initiatives: for example, to teach them how to manage technical energy supply/billing issues.

As demonstrated by our analysis, local regulations can hamper the operation of social services and their coordination with the relevant NGOs. The changes in the normative framework in 2014 immediately brought about a transformation in the provenance of emergency funds; before this change, two-thirds of the funds allocated originated from NGOs, whereas now 70% of the funds are provided by public agencies (see Table 1). The previous regulations limited the assistance that could be provided, not only in relation to the amount of money but also the number of outstanding bills; those limits were removed in 2014.[9]

In Spain, in 2016 court rulings[10] have contributed to the debate on the role that social agents and utility companies must play, emphasising the legal vacuum that exists concerning the scope of social responsibility and access to a basic service. This leaves the most vulnerable sectors of society totally unprotected.

4.3. *Specific measures*

The main measures that can be highlighted to improve the energy poverty intervention at regional level are:

- To create coordination units which facilitate communication and cooperation between agents (public services and ONGs) and contribute to the maximisation of available resources: currently, coordination occurs spontaneously and informally and is largely based on personal relationships between social workers, especially in areas which the public network does not reach.
- To offer social workers specific training and a diagnosis tool with which to make their work more effective. Training and tools will also contribute to increase their knowledge of the underlying causes of energy poverty as a key agent.

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[9] Ordenanza Ayuntamiento de Zaragoza, 2014

[10] Recently, a High Court ruling declared that the social tariff regime set out in article 45.4 of Ley 24/2013, de 26 de diciembre, is incompatible with Directive 2009/72/CE, set out by the European Parliament and the Council on 13 July 2009, concerning common rules for the internal market in electricity.

Table 3
Results of the survey carried out on social workers who deal with energy poverty.

Cod variable	Questions	Results
A.1	Should utility bills (electricity, gas, etc.) vary according to income?	70% agree. Average 6.7
A.2	In Aragón, energy poverty poses a grave problem because there are many households which cannot afford to pay their electricity or gas bills	90% agree. Average 8
A.3	In households with no income, electricity should be free, up to a limit	67% agree. Average 6.4
A.4	In Aragón vulnerable households should not have their energy supply cut off in winter	86% agree. Average 8.3
A.5	Public social services in the Region adequately support energy-vulnerable households	65% agree. Average 6.2
A.6	Public aid should also be made available to energy-vulnerable community of owners in the Region	74% agree. Average 6.9
A.7	Public and private agencies are sufficiently coordinated in the provision of aid aimed at covering outstanding energy bills	43% agree. Average 5.1
A.8	Household energy poverty is being adequately prioritised by Regional politicians	54% disagree. Average 4.1
A.9	Household energy poverty is being adequately prioritised by Regional media	55% disagree. Average 4.2
A.10	Regional social movements are the most committed social agent with regard to energy poverty	50% agree. Average 5.7
A.11	Private agencies and NGOs have been more responsive to the problem than the public sector in the Region	66% agree. Average 6.3

NOTE: Level of agreement is calculated as percentage of answers scoring 5 or above. Level of disagreement calculated as percentage of answers below 5.

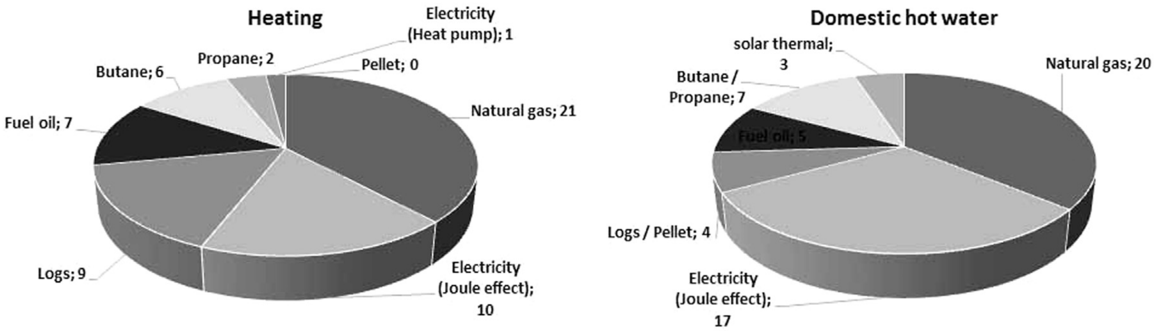

Fig. 4. Distribution of dwellings according to energy source for heating and DHW.

- To implement specific policies in order to prevent the gap between exclusion and inclusion from widening even more; the boundary between impoverishment and poverty must be regarded as a red line. On the other hand, public policies have previously been too disperse, which has led to coordination problems and regional inequality.
- To increase the volume of social housing and to implement a specific refurbishment investment programme to prevent the energy poverty in households in rural and urban areas.
- To define progressive levels of subsidies depending on the level of energy vulnerability or poverty and the situation of the households.
- To define a participative national model to design the main rules for energy poverty, within which all agents, including utility companies and the media, are represented and directed by national, rather than regional, authorities.

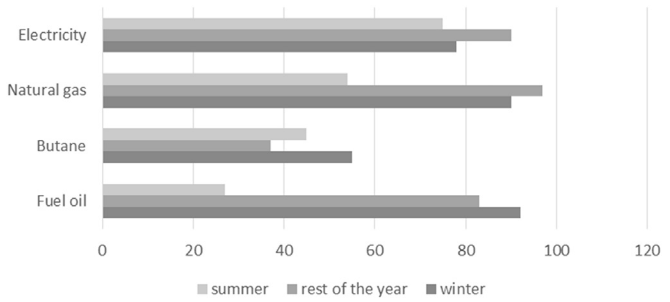

Fig. 5. Energy consumption of the households under examination in winter, summer and throughout the rest of the year (euros).

5. Conclusions and policy implications

The case study of a Spanish region has demonstrated that the problem of energy poverty should not be treated locally without the adequate coordination with the national and European regulation, which only postpones achieving a solution for the underlying structural causes.

The model indicates that the initiative is progressively shifting from private to public (local) agents when the Administration increases the activities in this field; the efficiency of the model strongly relies on spontaneous, informal and even improvised relationships between the different agents. However, it is useful for solving occasional emergencies but it does not reach the root of the problem.

While the dichotomy between public and private responsibility goes unresolved, the sustainability of public aid policies, which are largely funded by the social services, will be uncertain. The national legal vacuum (which stems from European directives) has to some extent been corrected at regional level.

Urban and rural households have different problems, and for this reason policies should take into consideration such variables as strength/weakness of social capital, community support strategies, population ageing, the state of conservation of residential buildings and the optimisation of energy resources through the use of traditional systems (for instance, exploitation of nearby forest resources for heating). In any case, although the policies in place seem to be shifting from trying to prevent inequality to the management of poverty and social exclusion, the reasons for the structural discrimination of persons and territories remain unchallenged.

Policies must, therefore, be redefined in order to go beyond the local level, and they must take into consideration structural factors and the restructuring of social aid. The diagnosis of the problem, however, must remain close to the territory, which is where the central role of social workers stands out.

In this context, it is important that regulations take into consideration the mediating role played by social workers at a local level and the present study has contributed to underline their role in energy poverty prevention– an aspect which has been paid little attention to date. In the model under analysis, social workers are responsible for detecting, diagnosing and assisting energy-impoverished households.

A social worker is not an expert on energy consumption and insulation, but rather is the public agent with the best first-hand knowledge of the real problems faced by vulnerable households and of the issues with the buildings in which these families live. As suggested, training can provide the basic knowledge that they need in order to identify the causes of the vulnerability of the households with which they work. It is, therefore, necessary to adapt the normative framework to their work and to provide them with better tools to carry out their duties.

The role of social workers as certifying agents is well attuned to the territorial model in place, and that it should be extended to other European regions, since it can be implemented by both public social services (it efficiently covers rural regions) and private (NGO) networks. This is not to say that the model cannot be improved, and this is especially true in relation to the territorial inequalities caused by the diversity of socio-demographic and contextual (urban/rural settings) conditions present in the region.

This study aimed to answer several questions and to increase our knowledge of energy poverty in European households from the point of view of the social workers who deal with the problem first-hand. The limitations of our analysis are obvious, beginning with the small size of the sample and the limitation to one region. This means that there are future challenges: larger samples need to be analysed, and comparative studies should be undertaken, which will include territories in different countries which have different socio-demographic characteristics and assistance models.

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4 Building energy assessment and computer simulation applied to social housing

4.1 Introduction

The objective pursued in this chapter is the analysis of building typology of public social housing through computer energy simulations.

The building characteristics in some public social housing in Spain have been analysed by means of a case study. The application of energy simulation in this type of cases and the analysis of this type of computerized simulations applied to homes with risk of energy vulnerability takes a great part of the study.

A case study was carried out by taking accurate data of two buildings of Zaragoza Vivienda, which were carried out an energy audit and an evaluation of the living conditions of the houses. Thanks to the data taken, it is possible to analyse how the behaviour of the residents within the same building characteristics influences the final consumption of the home, but to a much lesser extent than the type of building, the envelope and the air conditioning equipment available. The type of energy used and contract also affect in a significant way both the conditions of thermal comfort and the use that families make of energy, and not so much to the consumption, since this comes mainly determined by the economic capacity of the families. Therefore, the possible improvements in buildings and equipment will not have a strong effect on the reduction of consumption but on the improvement of housing conditions.

On the other hand, building energy simulation tools were used to simulate and predict the consumption of the houses of each building, finding very significant differences between the consumption estimated by simulation and the actual one extracted from utility bills. In this section the possible causes that originate this gap have been studied, obtaining as a conclusion that the main cause is the limited use of heating equipment by this type of social housing residents, compared to other average users. This factor must be taken into account when modelling user profiles in a climate simulation programme of a social housing building.

4.2 Methodology

The methodology consisted on an empirical analysis of a number of public social housing households on rental tenure. For this analysis, every type of variable was obtained from different means. Building and equipment was obtained from the building management company. Energy costs, household structure and other habits were collected by means of surveys in combination with onsite visits.

On the other hand, this data was applied to the modelling of households in energy simulation software. The validation of results was made against actual energy consumptions for the period observing large differences.

To find the reasons for these differences, a sensitivity analysis was performed on climatic data, inaccuracy of data, software-based parameters and default average user profiles. Where no accurate model adjustment could be made due to the lack of reliable data, ranges of factor variations were calculated to assess the impact of the inaccuracy.

4.3 Summary of the main results

The main results of the energy audit applied to the two social housing buildings highlight the problem of energy precariousness in winter, where the energy consumptions are the highest. Tenants' consumption is mainly driven by their disposable incomes rather than by comfort criteria, and some of them live below the thermal comfort standards.

The most efficient building had the effects of a recent envelope refurbishment hindered by the higher cost of the energy consumption, due to the electric heating, whereas the building with gas individual heating showed lower energy poverty index, understanding this index as a ratio of incomes dedicated to cover the energy bills. In the same line, many residents have inappropriate supply tariffs and an excess of unused contracted power, having a direct impact on their energy bills.

The software simulations done reflected a large deviation between predicted energy consumption and actual energy bills, where simulated consumption was 40% to 149% higher. Adjustments were made in a variety of model variables to calibrate the models. Improvements in climatic data for the analysed year were made. Building material characteristics were corrected with real transmittance measurements. Other suspicious factors were proven not to affect much, like the number of residents above two persons.

The user profiles in social housing turned out to be the main contributor to the differences as standard comfort conditions cannot be assumed in this group. Adjustment of comfort hypothesis and assumptions is needed when using computer simulation in social housing. It was found that the assumed user profiles were the major cause of deviation as residents in social housing often live below thermal comfort conditions. According to the simulations carried out, in order to achieve some convergence between the simulated heating consumption and the actual consumption, it would be necessary to adjust the annual hours of heating from 1,405 to a range between 564 hours and 445 hours depending on the building type. This adjustment would mean setting 3.5 daily hours for heating in winter, or a longer time but restricting heating to the living room.

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Building Energy Assessment and Computer Simulation Applied to Social Housing in Spain

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Abstract: The actual energy consumption and simulated energy performance of a building usually differ. This gap widens in social housing, owing to the characteristics of these buildings and the consumption patterns of economically vulnerable households affected by energy poverty. The aim of this work is to characterise the energy poverty of the households that are representative of those residing in social housing, specifically in blocks of apartments in Southern Europe. The main variables that affect energy consumption and costs are analysed, and the models developed for software energy-performance simulations (which are applied to predict energy consumption in social housing) are validated against actual energy-consumption values. The results demonstrate that this type of household usually lives in surroundings at a temperature below the average thermal comfort level. We have taken into account that a standard thermal comfort level may lead to significant differences between computer-aided energy building simulation and actual consumption data (which are 40–140% lower than simulated consumption). This fact is of integral importance, as we use computer simulation to predict building energy performance in social housing.

Keywords: social housing; energy audit in buildings; building computer simulation; energy poverty

1. Introduction

For most EU member states, there is a general consensus nowadays that energy poverty in households is a top priority which should be addressed to avoid social exclusion. This issue has been tackled by ensuring that most citizens can access energy at stable and affordable prices [1]. Indeed, the European Commission in the recent "Winter Package" (2016) [2] has acknowledged this issue. The issue of energy poverty is more severe in Southern and Eastern Europe [3]. Despite more favourable climatic conditions in Southern Europe, 16.6% of households in the Mediterranean region live in conditions characterised by poor thermal comfort; in contrast, the European average is 4% lower [4].

Owing to its importance for policy-formulation purposes, energy poverty has been defined by many authors [5]. The International Energy Agency [6] states that a household is in a situation of "energy poverty" when it has to pay energy costs which are excessive compared to the total household income. The definition provided by the International Energy Agency (IEA) is very similar to that adopted by the Environmental Sciences Association (ACA) in a pioneering Spanish publications [7]. Energy poverty is a particular type of poverty which is principally determined by various factors [8]: the ratio of minimum annual energy expenditure to income in a household [9], the energy efficiency of buildings [10], and finally the (more subjective) perception of comfort level in the dwelling [11].

Authors such as Rudge [12] establish this adequate level of comfort in a dwelling as an indoor temperatures ranging between 18 °C and 21 °C in winter, and a constant humidity level ranging between 20% and 80% of relative air humidity. Comfort level is affected by the clothing of the residents, the air speed and the level of physical activity and can only be expressed statistically by means of psychometric diagrams, due to the subjective nature of this parameter [13].

These definitions include a subjective component, such as the thermal comfort level or satisfactory living conditions. To solve this issue, Grevisse and Brynart [14] define "energy poverty" as the inability of a household to meet its certified energy needs. In this case, the subjective component means that an assessment and certification by a competent Public Body is necessary, as this body can confirm and classify the degree of vulnerability of the different households in terms of energy [8]. In Spain, this evaluation and certification is provided locally by regional Public Social Services.

Based on the fundamental contribution by Boardman [15], we applied the following information in our study: the use of 10% of net income to sufficiently meet energy needs is used as an index to detect households living with energy poverty. This figure was also applied by Taylor [16], who introduced into the debate the definition of "energy poverty" [17]. This threshold of 10% of annual net income being used to cover basic energy expenditure is a clear and measurable limit, and has been used in this present study to identify energy poverty in social housing.

Certain structural aspects of the global energy system help to sustain energy poverty, according to Sovacool [18]. In general terms, a higher number of cases of energy poverty may occur among groups living in social housing, mainly due to the lower average level of income of these households. The influence of energy poverty on social housing has been studied by several authors in different countries, cities and climate zones such as in Australia [19], the United Kingdom [20,21], the Netherlands [22], and in several areas of Spain [10,23,24].

Social housing is also a useful area of study in terms of examining the usage habits of the residents, specifically the comfort temperature target or the heating schedules. These users' patterns make them different from the average urban households of European cities, according to Teres-Zubiaga et al. [10] and Hui Ben and Steemers [25]. The report "Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures" by the European Commission [26] indicated that social housing has been the main focus of several initiatives, perhaps because of the high level of energy poverty of its occupants (this is in line with the conclusions reached by Hills [9] and Li et al. [27]).

Energy-simulation tools have been mainly applied when refurbishment of social housing is being analysed, as energy refurbishment has a greater social impact in those cases where residents are living with energy poverty [11]. Despite the many improvements in computer-simulation techniques, the specificities of social housing still cause variations between the results obtained by computer simulation and the actual energy consumption in these dwellings, as Tronchin and Fabbri [28], Wang and Zhai [29] and Escandón et al. [30] have pointed out. These differences may not be of great import in, for example, the energy certification of buildings, where the object of the study is a building which is generally compared to a reference building with similar characteristics, geometry, occupancy, use, and which is built in areas with the same climatic conditions. However, these differences are very important when simulation is carried out to assess the energy savings and benefits associated with building refurbishment and related investments [31], or to define the priorities of public bodies providing subsidies for social housing based on the buildings' energy performance [32]. Ramos et al. [33] state that the differences in energy performance are mainly related to specific social housing constraints. Efficient technologies alone cannot fix the problem, unless these technologies are adequately combined with an understanding of sociological aspects [34].

Energy simulation is a widely extended tool which is used to assess energy performance in a building; it could also be used to evaluate energy poverty. However, using the simulation results with predetermined user profiles to assess the root causes of energy poverty, or to note energy-efficient refurbishment measures, may lead to important errors [31].

This study analyses the application of energy-simulation tools to a sample of social housing in Spain. The main contribution of this article lies in the comparative analysis of real patterns of energy consumption in social housing. This analysis was undertaken to identify the variables that influence the level of energy poverty of these households and the causes of deviations in the data (computer simulations vs actual data). The obtained results can be used to improve the accuracy of the energy-performance simulations of a building of social houses: a characterisation of users' patterns in buildings, where most of the households are somehow affected by energy poverty, can thus be undertaken [35].

The article comprises two analyses. The first is an empirical analysis of energy-consumption patterns and energy-poverty assessment in a sample of social housing in Spain. The second analysis focuses on the use of energy-simulation tools to assess energy poverty (applied to the same sample). We will also take into account the limitations of these tools when studying social housing in Spain, and make recommendations based on our in-depth study of the issue of energy poverty.

2. Methodology

Cases of energy poverty are associated with households in the present study. For our purposes, the household is the analytical unit with which we aim to tackle energy poverty. This approach is in line with that of Webb et al. [36].

Buildings play a major role in energy demand. For each specific climate, the energy demand of a building is related to the construction of the building and depends on factors such as materials, insulation, as well as the building's geometry and the level of exposure to wind and sun radiation. Fully dedicated social housing building units are considered in the analysis. To discriminate energy poverty cases, a threshold of 10% of total annual income being used to satisfy energy needs, as postulated by Boardman [15], was applied here. This index is easy to calculate using the available data and allows us to consider the relationship between excessive energy costs and household net income.

The first step for this study involved setting the selection criteria used to search for social housing samples. Buildings had to be homogenous in terms of their age, construction, maintenance and management, function and the climate of their setting. Two blocks of fully dedicated social housing apartments were selected (noted as buildings A and B). They are located in the city of Zaragoza (Spain) and are of public ownership; they are managed by the municipal company "Zaragoza Vivienda", which reports to the Zaragoza City Council. Both buildings are subject to the same climatic conditions, were built at the same time in 1988, and are close to the average municipal housing stock age (from 1985). They have the same maintenance policy since they are publicly owned, and are used for the same purpose (public social housing for rent).

Two types of complementary and comparative analyses were performed in the present study: an empirical analysis which was used to analyse energy poverty in the sample based on actual energy consumption data, and an energy-performance simulation which was used to validate this approach as a tool with which to assess energy poverty.

2.1. Empirical Analysis

An empirical analysis of the data for each building was undertaken to characterise the energy consumption associated with this type of social housing. Four main types of variables have been studied: building envelope and geometric characteristics, energy-consuming equipment, energy sources and energy consumption, and household structure and consumption patterns (Table 1).

The public company managing the buildings provided data on building materials and construction details, refurbishments carried out to date and the precise dimensions of the various floors and rooms (Subsections 1 and 2 in Table 1).

A survey addressed to the building residents, which included socio-economic questions, was designed and distributed to all households. The questionnaire included questions about the household structure, residents' employment and social situations, energy usage habits, the residents' schedules and the intensity of use of the energy-consuming elements (Subsections 3 and 4 in Table 1).

In total, 36 households out of 160 participated in the survey in building A, and 8 out of 12 participated in building B. The obtained sample was validated against the following criteria:

- The different occupancy levels of the dwellings had to be taken into account, to permit us to study the effects of family structure and occupancy. The sample includes between two and six dwellings for each occupancy level (from one to seven people).
- The different orientations of the buildings and the types of dwelling in each building were accounted for. Building B has three floors with four different types of dwellings per floor: two north facing and two south facing. The sample includes two dwellings of each type, distributed over three floors.

Table 1. Household information inquired.

(1) Building characteristics	**(2) Equipment characteristics**
- Surface area - Envelope materials and quality - Refurbishments undertaken to date	- Household equipment HVAC and DHW systems - Other energy-consuming elements
(3) Energy supply and consumption per year	**(4) Household structure and consumption habits**
- Type of energy-supply contract (utilities) - Energy consumption invoiced per year and type of energy invoiced	- Frequency of equipment use - Intensity of equipment use - Number of residents - Employment situation of each resident - Annual net income

In addition, a detailed energy audit of two dwellings was carried out for each building analysed to confirm and extend the available data for the dwellings. This audit included a visit to the dwellings to measure and collect data on the indoor temperature, relative humidity, thermal transmittance of the building envelope and details relating to the residents' energy-consumption habits such as their schedules, their usage of HVAC equipment, as well as the number and type of household appliances.

2.2. Energy Simulation

Energy simulations using computer tools and reputable commercial databases were carried out on these social housing buildings. The EnergyPlus calculation engine was used along with the DesignBuilder V4.7 (Stroud, Gloucestershire, UK) interface [37]. The characteristics of the building and its enclosures, the equipment of the building and an average-user profile were modelled based on survey data and data supplied by the management company. Three different user profiles were created, according to the most common schedules registered: Families with 4 members, adults working full-time; families with 4 members, adults unemployed; and families with 2 members, adult(s) working part-time.

Finally, the simulation model was validated by comparing simulation results with actual energy consumption. Significant differences were noted, and, on this basis, we revised the model input parameters to fine-tune the model. A sensitivity analysis that included several model parameters was completed to assess the margin of error when using inaccurate input data. The user profiles and thermal comfort levels [38,39] received most attention, and we took into account the type of housing analysed.

Figure 1 summarises schematically the methodology followed in this study.

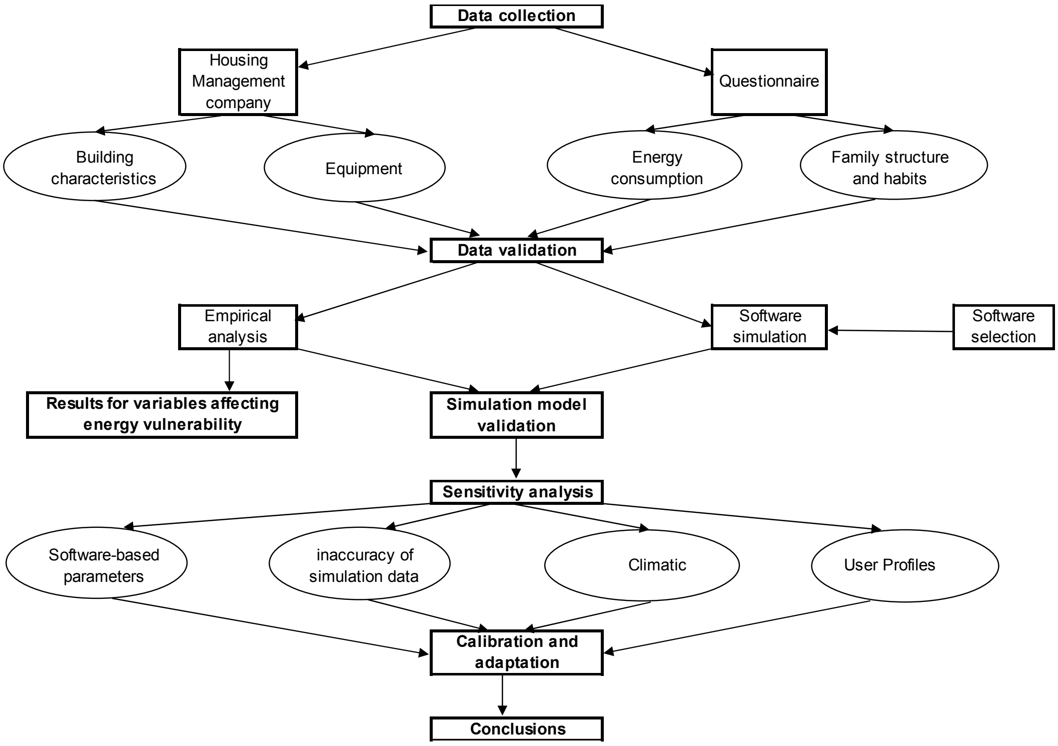

Figure 1. Flow chart depicting the buildings' energy performance methodology.

3. Case Study

Social housing in Spain has particular characteristics, both in terms of the buildings themselves and in their maintenance. A large percentage of these residential buildings were built prior to the implementation of the first energy-efficiency regulations in buildings [30]. As few major retrofitting works have been carried out, these buildings usually have little or no insulation. Owing to the mild winter climate of the region and the poor gas-grid development at the time of construction, heating systems are individual and usually run on electricity. Public social housing, which constitutes a small proportion of the total social housing stock [40] is well maintained and managed by the public authorities (usually municipal); there is no evidence that private social housing undergoes regular maintenance or building upgrades owing to the low rent of this type of housing.

Two buildings have been chosen for this study because they are homogeneous and representative of social housing in the city of Zaragoza (Aragon region of Spain); they also present interesting differences, mainly in relation to their size and HVAC equipment. The two buildings consist of individual apartments for residential use, with levels of occupancy generally ranging between one and seven people on low income. The dwellings are between 40 and 70 m^2. The buildings were built in 1988; at that time, few energy-efficiency criteria were contained in the regulations [41]. All the dwellings are in the same climatic zone (mild Mediterranean). Building A is a group of blocks with 160 dwellings over eight floors, while building B consists of a single block of twelve dwellings over three floors. Another relevant difference is the individual heating system that runs on gas boilers in building A, and electric resistance radiators in building B.

Many family units have been subject to detailed attention by public social services, and, in some cases, they have received additional emergency aid to cover the minimum expenses of housing (mainly rent), and energy expenses, as well as other basic needs.

The climate in Zaragoza is dry and continental Mediterranean with very low rainfall, mild winters and hot summers. The average temperature is 15.5 °C. The registered number of annual Heating Degree Days (HDD), using a reference temperature of 15 °C [42], is 1177 HDD (Degree days calculated using www.degreedays.net). The average wind speed is 19 km/h. The predominant wind is cold and dry, blowing in a Northwest–Southeast direction [43].

Table 2 describes the building characteristics, which are relevant from an energy-performance point of view.

Table 2. General data of the buildings and residents.

Building Data	Building A	Building B
Number of dwellings	160	12
Number of blocks	11	1
Build year	1988	1988
Orientation	All	N-S
Sample of dwellings/total number of dwellings	36/160	8/12
Average dwelling size (m^2)	68.5	55
Number of floors on ground level	8	3
Useable surface on each floor (m^2)	1644	220
Average number of occupants per dwelling	3.7	2.8
Surface area per occupant (m^2/person)	18.5	28.5
Building refurbishment	No	partial
Other buildings surrounding the building	No	East and West

From the point of view of construction quality, both buildings have no thermal insulation, but both comply with the Basic Norms of Buildings in force in the year of construction [41]. Transmittances values of the main enclosing areas are shown in Table 3, along with the limits of the current building regulations CTE DB HE1 [44] corresponding to the climatic zone D3 ("D" indicates the winter-weather severity on a scale from A to E and "3" indicates the summer weather severity on a scale of 1 to 4). Looking at the value of the transmittances, building B exhibits better enclosure quality. A recent refurbishment of building B improved insulation, and adapted it to the aforementioned regulation.

Table 3. Comparison of thermal-transmittance measurements of various enclosing areas of buildings A, B, B renewed and value required by current regulations CTE DB-HE1, in W/m^2K.

Type of Enclosure	Thermal Transmittance (W/m^2K)			
	Building A	Building B	Building B, Renewed	CTE DB-HE1
External walls	0.71	0.5	0.27	0.6
Internal walls	2.44	0.47	0.47	0.6
Bottom floor	1.12	0.5	0.33	0.4
Roof	0.51	1.18	0.19	0.4
Windows	5.7	3.17	3.17	2.7
(glazing type)	(single glazing 6 mm)	(double glazing 4-6-4)	(double glazing 4-6-4)	(-)

As for the structure of the households in each building, there was a higher level of average occupancy in building A than in building B. There was more average living space per person in building B (28.5 m^2/person) than in building A (18.5 m^2/person) despite the smaller size of the average dwelling.

A similar average level of income was noted for households in both buildings, as shown in Table 4. The level of income was slightly above the "poverty threshold" established in Spain at €7961/year for a one-person household, according to the 2015 Living Conditions Survey by the National Institute of Statistics [45]. The income level is also below the "poverty line" for four-person households in Spain (€16,719/year), and well below the average income of households in Zaragoza, which is €24,336/year [46]. However, a few relatively high values strongly distort this distribution, as 38% of the households in building A and 25% in building B are living below the poverty line [45].

Table 4. Average socio-economic characteristics of households in Buildings A and B.

Household Average Data	Building A	Building B
Average annual income (€/household)	€10,471	€11,663
Number of employed people per household	0.7	0.4
Number of children per household	1.3	0.8
Number of retired people per household	0.6	0.9

Energy poverty is a type of economic poverty that affects the basic consumption of households. The main cause of energy poverty is a lack of economic resources, as has been noted in Scarpellini et al. [8]. The number of employed household members significantly affects the energy consumption of households: it is higher in building A (0.7 employed per household vs 0.4 in building B), but it should be noted that those employed in building A earned lower average wages.

Regarding the equipment, neither of the two buildings has summer cooling systems, and residents use natural and mechanical ventilation to improve their thermal comfort at home. This lack of cooling equipment is common to all social housing in Southern Europe [47]. The demand for heating takes place over longer periods, carries more health risks and produces a greater sense of dissatisfaction in its absence than an absence of cooling. In addition, there are alternative solutions to a lack of cooling equipment, such as ventilation during cooler hours, limiting thermal gains with curtains and blinds, and the potential to act on parameters such as "activity", "clothing", and "humidity" with evaporative coolers, and the "speed of air" using fans. Therefore, although there is a demand for cooling in both buildings, no consumption derived from cooling was considered.

For heating and Domestic Hot Water (DHW), building A has 24-kW individual gas condensing boilers, with a rated throughput of between 87.8% and 92.8%, depending on the type, and a variable operating schedule which is set individually by each user. These boilers are gradually replacing the original gas boilers with a nominal throughput of 72%. Each dwelling has a central thermostat that regulates the heating, and manual valves to open and close the radiators of each room. During the energy audit, it was possible to verify that the lack of maintenance produced lime deposits in the valves that impeded the correct operation of the valves. The gas supply is individual and may also be used in the kitchen, although most of the residents have electric glass-ceramic cookers. The rest of the energy consumption is related to electrical equipment.

Building B has individually-manoeuvrable resistance electric-heating systems. The DHW is provided by individual electric-resistance tanks of between 30 and 70 L capacity. In addition, households own a variety of portable electric-heating apparatus. This led to a larger electrical power-supply capacity in building B, where the average is in 5.6 kW of contracted power compared to the average 3.5 kW in building A. This increased the fixed energy costs of residents in building B for the same energy consumption.

4. Results and Discussion

4.1. Energy Poverty: An Empirical Analysis

Average actual energy consumption per month has been evaluated for 2015. As can be observed in Figure 2 and Table 5, a higher energy consumption per dwelling was detected in building A. Energy consumption in building A was 47% greater than in building B because of the larger dwelling size (25%) and the partial envelope refurbishment that had been undertaken in building B. However, the energy cost for those dwelling in building B was 18% higher than for those residents of building A. Whereas only electricity was consumed in building B, building A's thermal demand (66%) was met by natural gas. The average energy price (fixed cost and tax included) of the gas-electricity combination in building A is €0.11/kWh, while in building B the electricity price is €0.2/kWh. These costs (especially the electricity costs) are among the highest in the European Union according to Bouzarovski [48], owing to the excessively regulated electricity sector in Spain. Therefore, there is a strong link between the source of the energy used in a dwelling and its cost, especially since electricity is indispensable but economically inefficient for thermal purposes when compared to other energy sources, such as natural gas or biomass [49].

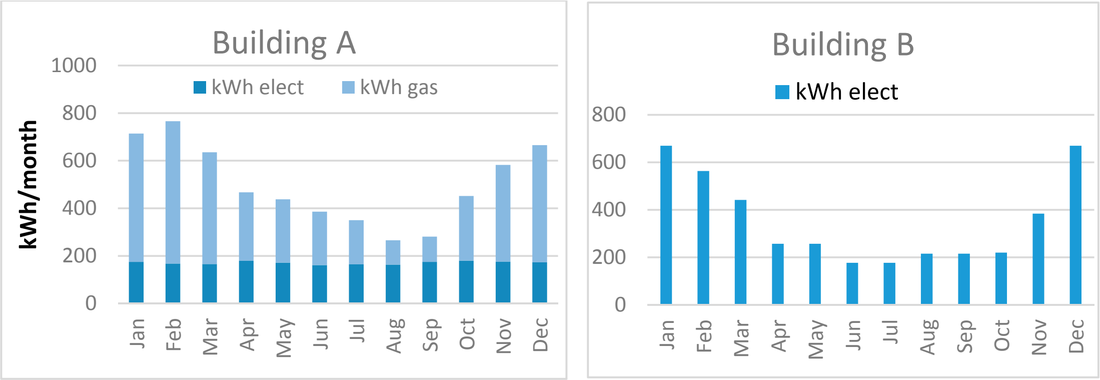

Figure 2. Average monthly energy consumption (kWh/month) in the average dwelling of the analysed buildings A (**left**) and B (**right**).

Table 5. Average actual energy consumption and cost ratios of households in buildings A and B.

Household Average Energy Data	Building A	Building B
Annual energy consumption per household (kWh/year housing)	6003	4249
Annual energy cost per household (€/year housing)	642	779
Annual energy consumption per surface (kWh/m^2 year)	87.6	77.5
Annual energy cost per m^2 (€/m^2 year)	9.37	14.1
Real thermal transmittance of facades (W/m^{2}K)	0.71	0.91
Contracted power per housing (kW)	3.52	5.6
Equivalent hours of electricity usage per household (h/year)	592	712
Average overall cost of energy consumed (€/kWh)	0.11	0.20
Income percentage dedicated to energy costs (%)	6.1%	6.7%

In terms of energy consumption per useable area, building B presents a lower ratio than building A: 77.5 kWh/m^2 year compared to 87.6 kWh/m^2 year. This ratio reflects the better energy performance of building B. It is more efficient because it is a more compact building, with a lower height and a smaller glazed area. In this building, half of the windows are composed of double-glazing and PVC-framed windows, which are much more efficient than the single-glazed aluminium frame windows of building A. However, the difference in energy consumption of these buildings is not as great as might be expected: we should take into account that the thermal-transmittance values are higher than the design values in building B. External wall insulation level is a key factor in a building's energy demand performance [50]. In building B, the measured thermal transmittance of the outer walls (0.91 W/m^{2}K) was much higher than the refurbishment target value (0.27 W/m^{2}K) and even higher than the measured value in building A (0.71 W/m^{2}K).

If we compare these energy-consumption figures with those of an average dwelling in a Mediterranean climatic zone in Spain (121.45 kWh/m^2 year, according to the Institute for Diversification and Energy Saving (IDAE) [51]), these social houses use between 39% and 57% less energy, although there is no evidence for better energy performance (see Table 6).

The average dwelling in building A consumes less energy than an average four-person household in Spain, with 4.4 kW of electrical contracted power and an annual energy consumption of 3900 kWh (only electricity) [8]; this is similar to the level of consumption of building B. Indeed, the unit cost for the electricity consumed (€/kWh) is similar in all cases, since the contracted power savings (fixed costs) are masked by the higher electricity consumption.

Table 6. Comparison between the electrical consumption and economic cost in a household of four people in the buildings analysed and in an average reference home.

Household	Power (kW)	Electricity Consumption (kWh/year)	Cost (€/year)	Electricity Average Price (€/kWh)
Building A	3.8	2020	€435	€0.22
Building B	5.6	3695	€771	€0.21
Reference home in Spain [50]	4.4	3900	€826	€0.21

A survey conducted by Scarpellini et al. in 2014 [8] on a sample of social housing in Aragon revealed that, in general, people at risk of energy poverty, are largely unaware of energy-supply contract types or details. In fact, the majority (70%) of people in this type of housing had the standard regulated tariff for domestic consumers (PVPC: Precio de Venta a Pequeño Consumidor. Regulated electricity tariff for domestic sector in Spain), and paid a fixed charge for a high contracted power, that they did not need. Only 15% of the households in building B requested a reduction in their contracted power to adapt the supply to their needs and thus reduce electricity costs. This result is in line with the low level of social tariff applications by social housing residents: thus, not many residents benefit from discounts for vulnerable households, according to another survey of social housing residents in the same region of Aragon, by Scarpellini et al. (2017) [52].

Energy poverty may often be caused by a combination of the energy performance of the building (thermal envelope-demand and equipment-consumption), the energy source used and the dwelling size. In the case studies presented, the dwellings of building B are more efficient (13% lower relative consumption) and are smaller (25% smaller on average), but the energy costs per dwelling are 18% higher. Although the energy-consumption habits can be improved through training and user feedback programmes [53,54], improving the heat-generation systems and redesigning energy tariffs should be a priority in these households, before proposing expensive solutions to refurbish the thermal envelope. The increase in electricity prices in many European countries has aggravated the vulnerability of many low-income and energy-inefficient households [55]. In these cases, the use of natural gas for heating systems presents some beneficial results [56]. Providing a more diversified range of primary energy sources can also contribute to alleviate energy-poverty status [57].

Residents in building A spent on average 6.1% of their income on energy costs, whereas an average household spent between 2% and 4%. Owing to the higher energy costs of building B, this indicator rises to 6.7%. Figure 3 indicates the ratio of annual energy costs versus the annual income, disaggregated by income levels. Most of the households whose income vs energy cost ratio exceeded 10% have annual incomes lower than €9000/year, which demonstrates that income is the greatest factor for energy poverty.

Any energy renovations should ensure improvement occurs in three fundamental areas. In order of importance, these are: energy poverty, energy consumption of buildings, and mitigation of climate change [58]. As reported by Teli et al. [59], the savings derived from energy refurbishment in social housing are much lower than those in standard housing. The most significant result of energy refurbishment is the social benefit achieved by the improvement of the thermal comfort conditions in the refurbished dwelling, as this increases health and life quality of the residents, as noted by Ormandy and Ezratty [60]. Investments may consider building-envelope retrofitting and heating-equipment replacement, but only the former translate into energy-poverty alleviation and indoor-comfort improvements [61]. These investments should be undertaken by the public entity that owns the dwellings [31], and the improvements should be included in a holistic programme of refurbishing and improving social housing, as noted by Swan et al. [62].

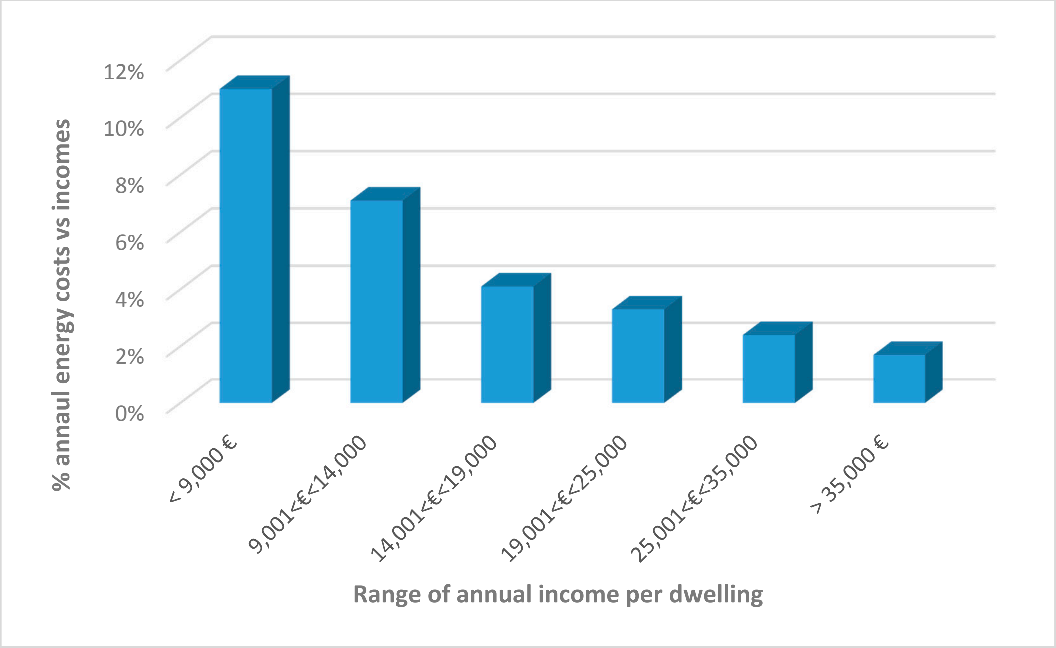

Figure 3. Ratio of annual energy costs and annual income distributed by income level (€/year) of the households.

4.2. Energy Simulation Results

Computer-aided energy simulation has proven to be a fast, economic and accurate method of predicting energy consumption in a building and assessing the benefits of building refurbishment [63,64]. The energy simulation of the building begins with modelling the geometry and composition of the thermal envelope of the buildings, as well as the building's internal zoning (using the engine tool EnergyPlus). The internal zones are divided into habitable zones separated by adiabatic walls and non-habitable common zones separated by internal partitions. The vertical enclosure in building A is composed of exterior walls, whereas building B also has two walls that are shared with the neighbouring buildings, as can be noted in Figure 4.

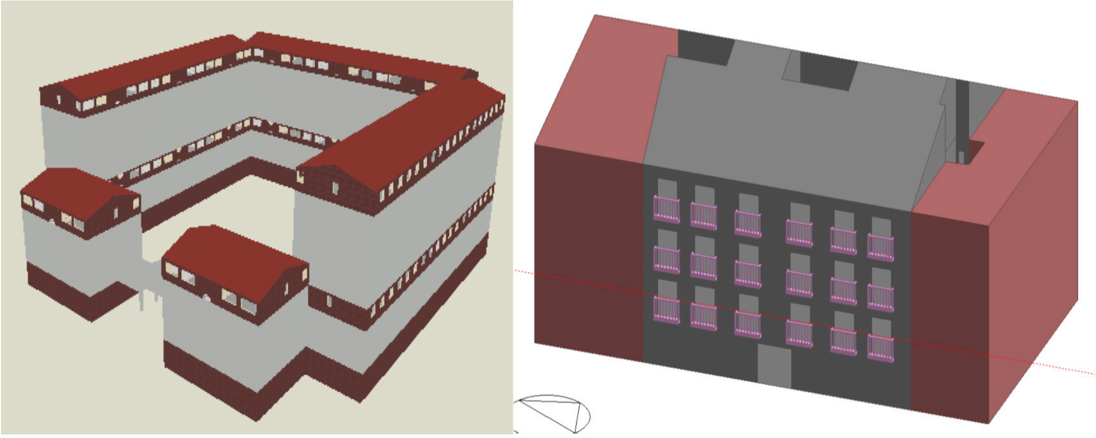

Figure 4. 3D model of: building A (**left**); and building B (**right**).

After the modelling of the building installations and equipment, an average user profile was modelled, defining a temperature set-point for heating (20 °C) during the winter and a temperature set-point for cooling (26 °C) during the summer. The summer target temperature did not involve any additional energy consumption because there are no cooling systems in either of the buildings. No precise data is available for setting the ventilation rate. In both buildings, a value of 1.5 ac/h (including leaks) was considered. This value is quite common in this type of building, although it is more than twice the reference value for energy certification of existing buildings in Spain (0.63 ac/h according to Royal Decree 235/2013 [65]). Moreover the value considered was higher than the average ventilation rates for renovated buildings, ranging from 0.35 to 1.01 ac/h in the study published by Ramos et al. [66].

The heating-user profile was developed based on questionnaires and interviews conducted with residents. In both buildings, the heating schedule is set manually by residents, and we presumed that there is no consumption of energy when residents are away from home. Based on the information provided in the interviews, there is no night-time heating consumption, and all heating systems are turned off from 11:00 p.m. to 7:00 a.m.

According to the average user profile defined in the Methodology, the heating is used for 59.5 h per week from November to March, which equals 1358 h per year. During these hours, the heating systems are available, but are not necessarily being used at full capacity. In Figure 5, the results of the simulation for building A (disaggregated by energy uses and sources) are depicted, taking into account this heating-user profile. The consumption of illumination and electrical appliances (there is a presumption of continued occupancy) is almost constant throughout the year. Likewise, the consumption for DHW varies little throughout the year, although the data has a slight U-shape owing to the different water-inlet temperature throughout the year. Electricity consumption represents 32% of the total annual energy consumption and DHW 23%. Heating consumption is the most significant, accounting for 45% of total annual energy consumption, but it presents significant monthly variations, accounting for up to 73% of total consumption in December and January.

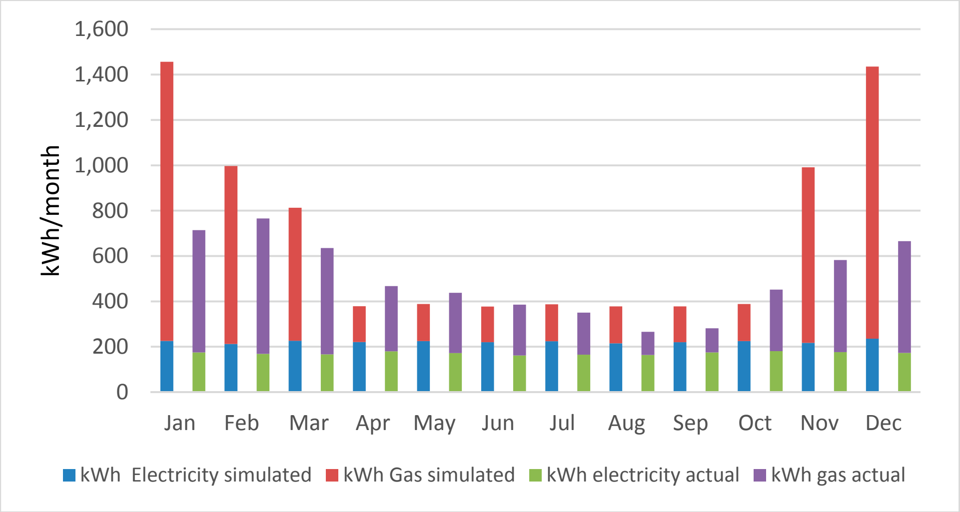

Figure 5. Monthly average for simulated and actual final energy consumption (kWh/month) per dwelling in building A.

4.3. Validation of Results

4.3.1. Simulation-Model Validation

Since actual energy consumption data are available, the simulation model was validated by comparing simulated and actual data. Table 7 compares annual simulated energy consumption versus actual energy consumption. In building A, simulated consumption is 39% higher than actual consumption (6003 kWh/year). This difference occurs for both electricity (30% higher) and gas

(44% higher). The most noticeable difference between simulated and measured consumptions can be found in relation to heating, where the difference is as high as 131%.

Table 7. Comparison of simulated and actual consumption in the average dwelling in building A, in kWh/year.

Energy Consumption	Simulated Consumption (kWh/year)	Actual Consumption (kWh/year)	Change (%)
Electricity	2669	2056	30%
DHW + others	1920	2309	−17%
Heating	3779	1638	131%
TOTAL	8368	6003	39%

Upon examination of the monthly distribution of consumption depicted in Figure 5, we can note that the difference between actual and simulated consumption (excluding the winter months) is relatively low. This difference is greater in April and October when the simulation considers that the heating is turned off but actually it is on for some time during the coldest days. Therefore, the biggest difference between actual and estimated consumption is in relation to heating consumption during the winter months, from November to March. The lower the outside temperature, the greater this difference becomes.

Similar trends were noted when we compared simulated and actual consumption for building B (see Table 8 and Figure 6). However, in this case, the difference between yearly simulated and measured consumption was 149%—even higher than in building A. The main source of difference is again the heating consumption.

Table 8. Comparison of simulated and actual consumption in a dwelling of building B, in kWh/year.

Energy Consumption	Simulated Consumption (kWh/year)	Real Consumption (kWh/year)	Change (%)
Others	6604	2980	122%
Heating	3994	1268	215%
TOTAL	10,598	4249	149%

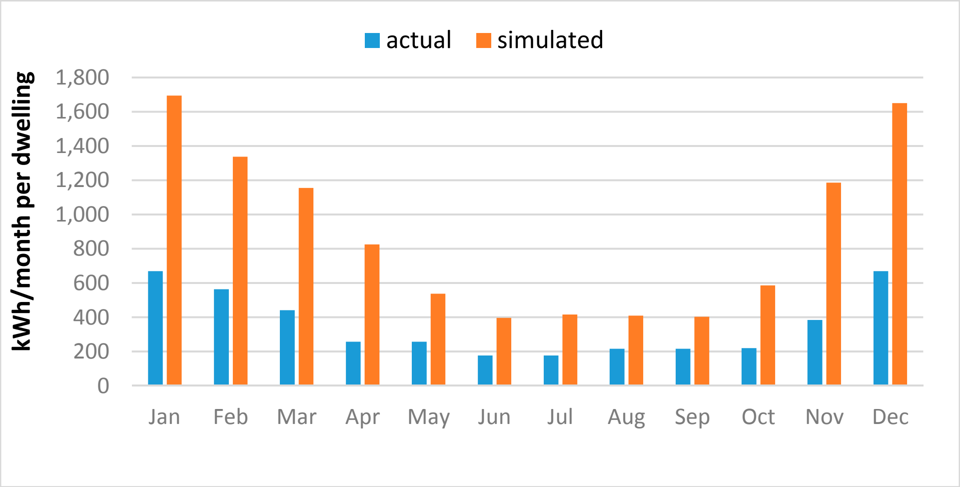

Figure 6. Monthly average of simulated and actual final energy consumption (kWh/month) per dwelling in building B.

Silva and Ghisi [67] found differences of 43.5% between simulation and actual consumptions in an uncertainty analysis of the behaviour of generic users (not necessarily vulnerable users) and included additional physical parameters. The difference noted in their study of 43.5% is similar to that noted for building A in our study. We may conclude that the model requires adjustments be made to the input parameters to accurately describe the energy performance of social housing. A sensitivity analysis for the variables used in the model follows here.

4.3.2. Sensitivity Analysis for the Parameters of the Simulation Model

Reasons for the significant differences between simulated and actual results can be ascertained. Some of them are related to the constraints of using a software-simulation tool (geometry, climatic model, etc.). Others may be explained by inaccuracy in relation to the hypothesised data for unknown variables such as air tightness. In addition, household structure and user profiles are difficult to simulate. A sensitivity analysis for the modelling design parameters is proposed here:

- Modelling of geometries and volume loses precision when flexibility, speed and ease of use of the design software are prioritised. One of the disadvantages is the inability to introduce curved geometric shapes, or include the consumption of certain specific equipment besides HVAC, as Herrando et al. [68] has noted in a previous study on tertiary buildings.
- Air tightness, which significantly affects the consumption of heating [69], is unknown and has not been measured accurately. In addition, it is also dependent on the user factor—e.g., different and variable ventilation times in each dwelling. Moreover, the effect of natural ventilation on heating consumption differs according to the thermal inertia of the building [70]. To better study the effect of air changes per hour, 1, 1.5 and 2 ac/h were simulated for building B in winter. In Figure 7, it can be observed that shifting from 1 to 1.5 ac/h requires an additional 16% in heating power whereas for a shift from 1.5 to 2 ac/h the increase is 12%. A higher increase in total energy demand was noted during the coldest months.
- Energy consumption was relatively unaffected by occupancy above two members, but this influence was noted as significant for one-person households. This significance is clear from the actual-to-simulated consumption differences for building B throughout the year: over one-third of the dwellings in this building are occupied by just one person. As shown in Figure 8, for occupancy levels above two people, significant variations in the annual consumption per dwelling are not observed, and thus we can posit that this variable is not particularly relevant.
- Materials and transmittance data are usually directly taken from technical data sheets and drawings of buildings. However, in this study, we found that these values can vary significantly with respect to the actual measured values, owing to documentation errors, the quality of the execution of the work, or simply owing to material deterioration. In the case of building B, the difference between the theoretical thermal transmittance of the outer wall (0.5 W/m^2K) and the actual value (0.91 W/m^2K) was 0.4 W/m^2K. Measured values have been used in the simulation.
- The climate model in the simulation depends on the climatic zone, and does not take into account local or annual variations. The climate data used by the simulation software are based on hourly values for the year 2002, compiled in a .epw format file [37], but the year of the analysis is 2015. To illustrate the margin of error for the climate, Figure 9 depicts the difference in average temperatures between these two years (2002 and 2015) in Zaragoza.

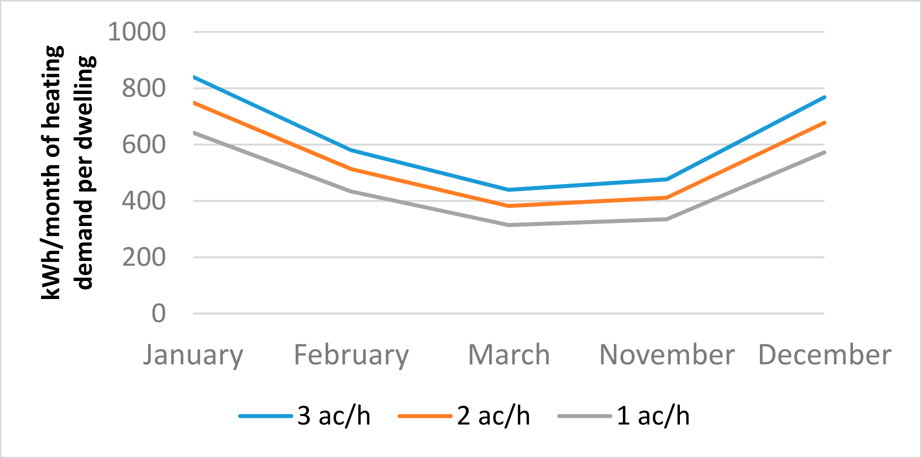

Figure 7. Monthly heating demand (kWh per month) for several levels of air changes per hour for a dwelling in building B.

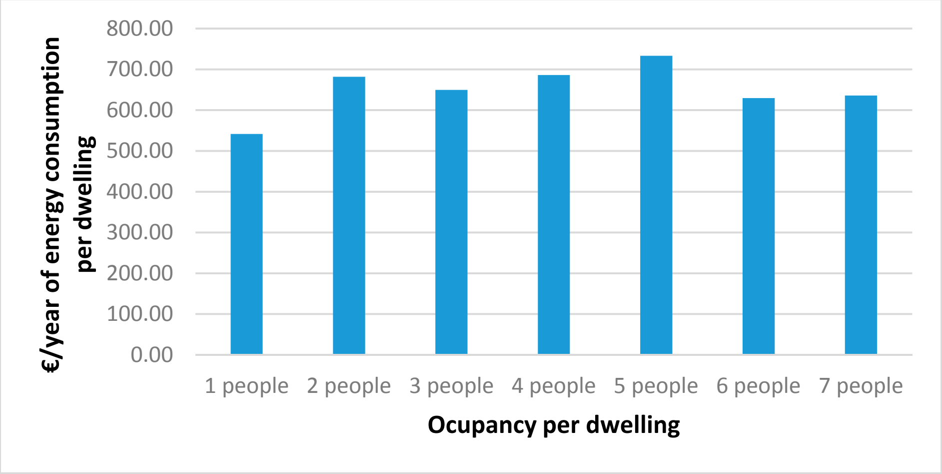

Figure 8. Average annual energy cost per occupancy level (€/year): Building A.

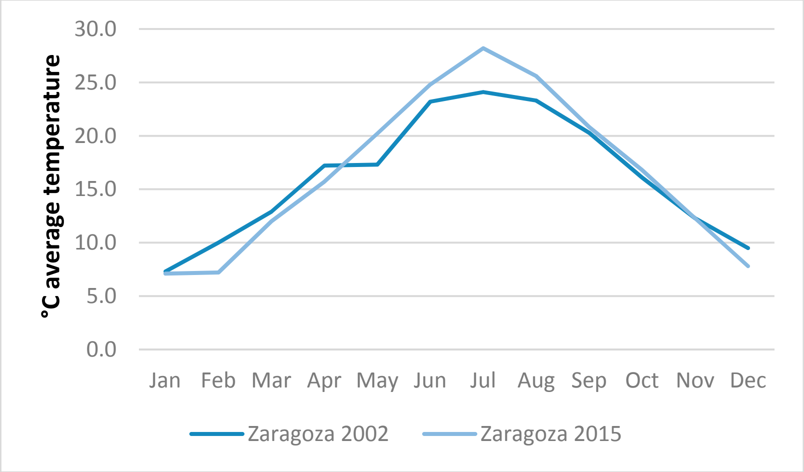

Figure 9. Average daily temperature in Zaragoza (°C) in the reference year 2002 and in year 2015.

In general, 2015 was 0.4 °C warmer than 2002. However, the temperature distribution indicates that there was an average increase of 2.1 °C in summer 2015 and a decrease of 1.1 °C in winter 2015, resulting in greater thermal discomfort in summer, and higher consumption of heating in winter; with respect to the data obtained in the simulation, this is important because the difference between these data and the actual consumption data is very significant. These deviations would result in a 7.7% increase in the heating consumption obtained by means of simulation.

To illustrate dependence on a specific type of climate, a type "A" dwelling was simulated in three different European climates. The first dwelling is located in Athens (Greece), where there is a warm Mediterranean climate; the second is located in Zaragoza (Spain), where a Continental Mediterranean climate exists; and the last dwelling is located in Stockholm (Sweden), where there is a Continental Northern Atlantic climate. Figure 10 indicates the heating demand in kWh for the core winter months in the year of reference (2002). Keeping the user profiles and the other parameters constant, it can be observed that the house in Athens requires 37% less heating than the house in Zaragoza; during the same period in Stockholm, 136% more heating is needed than in Zaragoza. This difference is greater in the coldest months than in the mildest ones.

- The household structure is another relevant factor. Households with children or elderly people, who have higher care requirements and spend longer at home, would imply higher energy consumption [71]. In the case under study, 60% of the households are households with children (mainly living in building A), and 45% of those families surveyed report elderly people living at home. However, the level of influence of this factor could not be calculated in the present study since households with a higher number of residents are usually larger in size, and size seems to be of more relevance to increased energy consumption than occupancy.

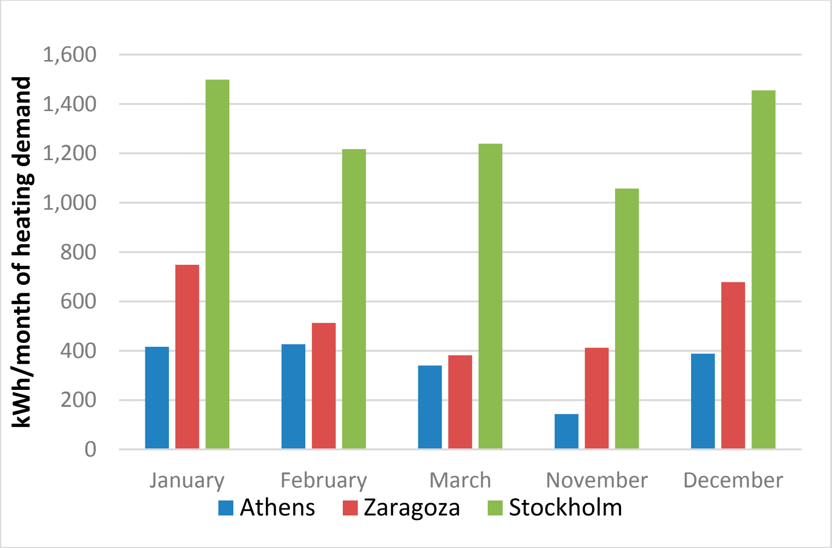

Figure 10. Heating demand (kWh per month) for a type-A dwelling in three different European climates.

The aforementioned variables that affect energy-simulation results do not explain by themselves the significant differences between simulation and actual consumption. New simulations with adjusted parameters were run and the main differences persisted. A more significant factor must thus explain those differences.

4.3.3. Adjustment and Fine-Tuning of model User Profiles

The reasons for the deviations may be related to the uses and habits of the tenants in social housing, many of whom are at risk of energy poverty. These consumption patterns of energy-poor households are similar across Europe, and this has been noted by Kolokotsa and Santamouris [72]. The economic constraints placed on these households reduce the residents' energy use, affecting the conditions of comfort negatively.

These economic limitations primarily affect the target setpoint temperature values for comfort and the hours the heating equipment is operated. The greatest differences in heating have been attributed to the heating profiles declared by the residents (which were then applied in simulations): these differ significantly from the actual, measured profiles. The interviews demonstrate that tenants usually apply acceptable set-point temperature values but reduce the number of hours of heating, or the number of heated rooms, which eventually reduces the comfort conditions. The higher cost of electricity-powered heating in building B makes this building's residents even more vulnerable than those of building A, and this explains the higher difference between simulated and real consumptions in building B when compared to building A.

Figure 11 shows how the monthly energy expenditure per household increases with the level of income to a point where the energy needs are supposed to be fully covered and there is not any additional energy consumption.

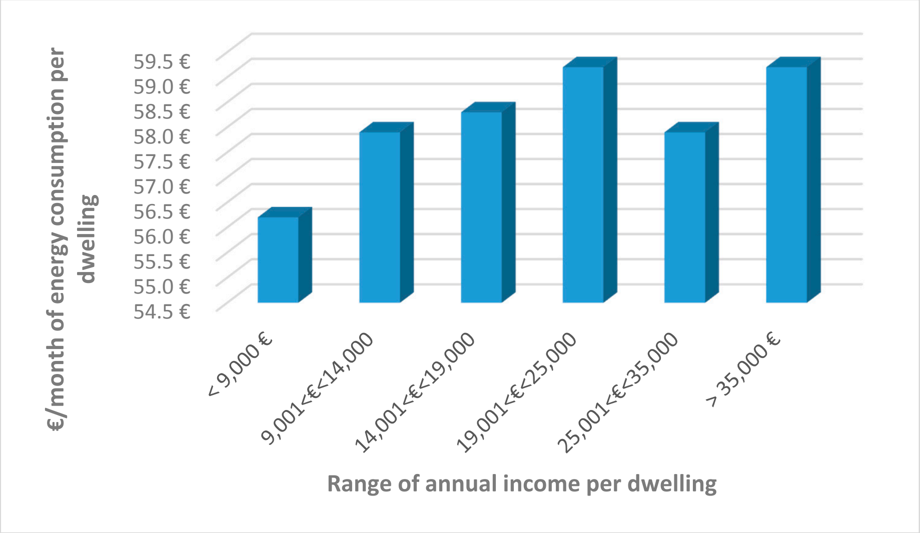

Figure 11. Monthly energy expenditure in €/month per household versus annual income levels: Building A.

According to the simulations carried out, to achieve some convergence between the simulated heating consumption and the actual consumption, it would be necessary to adjust the annual hours of heating from 1405 to 564 h in the case of building A and to 445 h in the case of building B. This adjustment would mean setting 3.5 daily hours for heating in building A and less than three daily hours for building B in winter. However, common practice is not to reduce the overall heating hours but rather to keep smaller areas warm for longer. This result is in line with the observations of Santamouris et al. [73], who studied a sample of 50 households in Athens.

Energy poverty affects thermal comfort in dwellings; this is clear. Figure 11 allows for the straightforward identification of the simulated comfort level. It demonstrates the number of hours for which a home in building A is maintained at a given temperature during the period 1 November to 31 March for both situations: with heating and without heating (limited to the actual consumption).

Figure 12 shows that, without heating, the indoor temperature is not higher than 14 °C 75% of the time. When the heating system in the houses is on, cold hours are reduced to 33% of the winter season but the temperature hardly reaches 20 °C (considered to be the temperature required to achieve thermal comfort). In summary, according to the measured data for the dwellings under study, the use of the heating system increases the indoor temperature but the dwellings do not reach the desired comfort level.

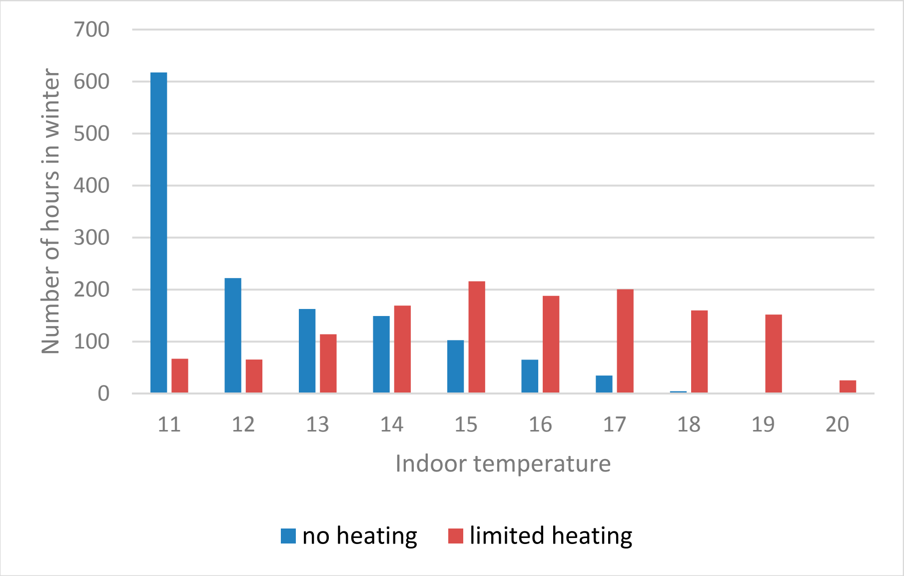

Figure 12. Number of hours and the indoor temperature for a dwelling in building A in winter, with and without heating (limited to actual figures of consumption).

5. Conclusions

This paper corroborates the hypothesis that the main cause of energy poverty is a level of income insufficient to satisfy the primary energy needs of a household. However, for a given income level, there are other factors that contribute to increase the impact of energy poverty on households. Building characteristics are not necessarily the most relevant factors when it comes to energy poverty. The structure of households and the behaviour of residents also play an important role. The cost of energy is considered relevant, mainly for electricity. In addition, the supply-contract typology does not always enable the optimisation of tariffs to the actual needs of social housing tenants.

Based on this analysis of the energy consumption and the household behaviour in situations of energy poverty, it was observed that users make proper use of the facilities, practise efficient ventilation and disconnect the systems when they are not in use, or when they are not at home. The greatest expenditure of energy was on heating, which social housing tenants underused; thus, they are prevented from achieving minimum indoor comfort conditions of 20 °C.

The optimisation of contracts and energy tariffs, as well as the diversification and shift to more affordable energy sources for heating, as opposed to Joule heating, are the most straightforward recommendations for those living in social housing to palliate energy poverty. Dwellings with only an electricity supply have energy costs which are almost double that of homes using natural gas for DHW and heating, even in cases of buildings which are more energy efficient.

Energy poverty translates into lower levels of thermal comfort in the affected households. The difference between pre-determined and actual user profiles and habits is the main cause of the deviations between the actual and the simulated energy consumption in social housing. We suggest that the standard comfort temperatures (21 °C) is not correct for energy-vulnerable households. In the analysed households, the simulated heating schedule should be significantly reduced, to between 3 and 3.5 h of heating service per day in winter season, to match the actual heating consumption in the social housing sample under study.

It should be noted that any improvement in the building envelope would not fully translate into real energy savings, but it would contribute to improve the thermal comfort conditions of those living in social housing, and thus would have a positive social impact quite separate from economic savings. The main reason is that those living in households suffering from energy poverty already live below standard comfort conditions: improvements to energy performance are likely to improve the residents' thermal comfort by bringing the temperature closer to the standard level rather than driving down their already-low energy expenditure.

The obtained results contribute to improve the simulation tools for measuring energy poverty and social housing. These results can also be used to support decision-making processes concerning the management of household energy poverty in social housing—e.g., in relation to building refurbishment, maintenance, and energy-supply management.

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5 Analysis of energy efficiency measures and retrofitting solutions for social housing buildings in Spain as a way to mitigate energy poverty

5.1 Introduction

This chapter consisted basically on the consolidation of a database of energy efficiency measures in residential building, the characterization based on expected savings calculated with energy simulation tools, the calculation of the investment required, the filtering and selection of measures, and the classification from an economic point of view (investment level and payback), taking into account the property situation of public social housing for rent, the type of building equipment and the habits of use of the residents. To keep consistency, all suggested energy efficiency actions were simulated in a real building case study to obtain the simulated savings. The implications of energy simulations on social housing derived from the previous chapter were taken into account to correct the obtained data. Also, care about savings cross effects of measures applied simultaneously on the same energy demand was taken and results treated to avoid the issue.

5.2 Methodology

The methodology proposed for the achievement of this objective is based on studying the most appropriate measures of refurbishment and energy efficiency for the optimization of energy consumption and that at cost, better adapted to social housing cases. To do this, it will be necessary to select and apply different criteria to those of other dwellings since the objective is not only to obtain the greatest possible savings but the improvement of thermal comfort at reasonable costs. The methodological approach is also part of the consolidation of a database of energy efficiency measures in residential building, which will be filtered according to several criteria and analysed from an economic (cost-benefit) point of view, and social (improvement in the thermal comfort of homes). A prioritization metric based on the best cost-benefit ratio will be established on the type of buildings typical of the social housing in Zaragoza.

5.3 Summary of the main results

The results obtained include a series of recommendations for prioritization and implementation of measures by residents and by property ownership. From a list of 250 catalogued energy efficiency measures in buildings (available in annex 2) from the TRIBE project, financed by the European Commission’s H2020 programme, 100 were selected as applicable in a social housing case study building for rent. Then, behavioural and no cost measures were prioritised for immediate benefits at no cost. The rest were divided in two groups according to whether they should be implemented by tenants and those by the building property.

The efficiency measures had been assessed in terms of investment and expected savings, using energy efficiency software and the current average energy prices for domestic tariffs. Two thirds of measures lay on the tenant’s responsibility. Prioritising by fastest payback gives better result in terms of economic savings than using the lowest investment criteria. This criterion leaves off expensive envelope insulation improvements that provides savings on gas, at a much lower cost than electricity.

Energy savings calculated for standard residents had to be corrected with real social housing tenants' consumption, which is 28% lower. Lower consumption implies longer paybacks. Also, the cross-effect of the implementation of several measures affecting the same energy demand had to be considered, since the potential for new additional savings decrease as measures are implemented and decrease consumption. A new check was needed to reject those measures where the longer payback exceeds the lifespan.

On top of the behavioural saving measures, the final recommendation limits the list of investment-needed measures to 9 measures, with a total investment per dwelling of 780 €, and savings of 157 €/year, to be added to the 353 €/year of the no-cost measures. Total energy savings are up to 55% of the original annual energy costs. Most of the measures involve electricity savings as a consequence of the faster return of a more expensive energy source. On the other hand, only 7% of the selected measures are under the property responsibility, making the beneficiary of the measures the main actor in energy savings. The distribution of measures per saving category shows that nearly half of the measures deal with the efficient use and selection of electrical devices, while envelope improvement measures look less attractive for return investment.

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Article

Analysis of Energy Efficiency Measures and Retrofitting Solutions for Social Housing Buildings in Spain as a Way to Mitigate Energy Poverty

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Abstract: Energy poverty is a common issue in social housing all over Europe, with a harder impact in Southern European countries. Social housing buildings play an important role in energy poverty. They are usually owned and managed by public institutions and usually share common characteristics and issues. Behavioural changes and energy retrofitting are interesting paths forward but some solutions do not fit well in this type of housing due to socioeconomic reasons. This paper makes a thorough analysis of possible energy efficiency measures in social housing buildings, characterizing them by energy and economic savings and investment and proposing different methods of prioritization. A rational approach of behavioural and retrofitting solutions that best fit into this particular housing type is delivered, with the aim to increase the thermal comfort of the residents and mitigate the energy poverty issue. Results show that there is a wide range of domestic efficiency measures to be applied in this type of dwellings at none or low costs, bringing annual savings per average dwelling of about 510 €/year (55% of initial energy costs) including measures both at domestic level, and at building level with a final aggregated payback of the investments to be about 1.5 years.

Keywords: social housing; energy poverty; energy efficiency; building retrofit; energy saving measures

1. Introduction

Energy vulnerability is a common risk in social housing due to the low income level of the families that fall back on this type of social service [1]. Bergasse et al. [2] define energy poverty as the level of a household income below the minimum energy costs that are necessary to achieve a satisfactory living condition within a dwelling. Hence, energy poverty is a global issue [3] that can be considered a particular case of poverty, and it is basically determined by several factors, such as a low ratio of income and annual energy expenditure, the building energy efficiency and other behavioural and occupant attitudes to achieve a given level of comfort [4].

There are two ways of addressing the issue of energy poverty. One way is by reporting energy poverty cases to assess their eligibility for public aids meant to help families to temporarily cover their energy costs, mainly in winter. Social workers play an important role in identifying and certifying energy poverty issues as stated by Scarpellini et al. [5] and Llera et al. [6]. This is a short-term temporary solution, but the issue remains unsolved and will likely turn up again next winter season.

The second way is by finding corrective solutions to their unaffordable energy consumptions, by reducing their energy expenditure while keeping, or even increasing, their thermal comfort level. This approach provides a solution to the energy vulnerability issue and reduce social and health inequalities [7] joining the benefits of sustainable energy policy with low-income housing policy [8]. This is a long-term definitive solution, which implies acting in the elements, systems and activities that consume energy in a dwelling. The cost of this second way has to be put against the cost of maintaining continuous palliative aids to vulnerable households and the inherent economic charges to the National Public Health System due to tenants' health problems, air pollution and other environmental burdens [9].

A natural source of improvement is the compulsory adaptation to more environmentally stringent policies as Directive 2010/31/EU [10] is being transposed and applied to existing buildings that are subject to major renovation. This level of changes is definitely too slow, especially when social welfare and health are concerned. Social housing renewal would also take too long and, thus, retrofitting current buildings seems to be the best path forward [11].

The main energy consumptions in a residential dwelling are thermal energy for heating and domestic hot water (DHW), and electricity for lighting and home appliances. Among them, the largest is usually the energy consumption for heating. This is particularly an issue in Southern Europe, despite more favourable climatic conditions due to the poorer insulation of the buildings [12], the inefficiency of the heating equipment in use and the lack of knowledge about efficient energy use at home [13]. This issue has been particularly acknowledged in the "Winter Package" by the European Commission [14], and by authors including Tirado-Herrero and Bouzarovsky [15]. Energy-vulnerable households face not only a problem of comfort but a problem of health [16].

Spain's social housing system relies mainly on freehold tenure [17], with a short amount of publicly owned buildings [18]. A freehold tenure means a permanent and absolute tenure of the property with freedom to dispose of it at will, as opposed to a leasehold in which the property reverts back to the owner after the lease period has expired. This paper focuses on the second type, which plays a crucial role in offering low-cost, affordable access to a house for vulnerable families [19]. This type of social housing in Spain is a particular kind of housing that share common characteristics that make it homogeneous to some extent, and, for the purpose of this study: they are usually urban blocks of individual apartments owned by a Municipality, and being managed by the owning Public Body or by a subcontracted public or private company [20]. Apartments are allocated to families at an advantageous rent according to a number of requirements, among which are low level of incomes and risk of social vulnerability [21]. Buildings are usually well maintained but often they are old and built with poor construction materials and standards [22].

The case of public social housing represents a special situation because residents have neither the awareness nor the economic capacity to undertake any serious investment on building retrofit and efficient equipment replacement [23]. In addition, often, they are not the owners of the dwellings and are not entitled to make any major modification on the facilities, hindering any investment attempt [23]. In this case, a combined effort of social building users and property is needed to carry out holistic energy saving actions.

This paper quantifies and analyses a high number of energy efficiency measures in buildings, and recommendations about the best way to filter out, order and prioritize energy saving actions in a representative sample of social housing dwellings in Spain, using energy simulation tools and economic criteria, unlike other tested systems like Mikucioniené et al. [24]. The methodology proposed can be applied in similar cases of the same type of buildings and users. In the same way, limitations of these tools to evaluate the implementation of the recommended set of measures are described and results are reviewed and corrected accordingly.

2. Methodology

Computer-aided energy simulation is an interesting tool to assess the effect on energy performance of different possible efficiency measures due to the low cost, high accuracy and great versatility of this method, as illustrated by Altan et al. [25]. The methodology proposed is based on the characterization of a number of possible energy efficiency measures by means of energy simulation tools, and the right selection and priority setting based on economic terms for this type of buildings in a real representative case study, similar to the procedure followed by Sadineni et al. [26] and Ascione et al. [27]. The methodology presented is an alternative to the one presented by Tan et al. [28], but focusing in immediate effects at the possible lowest cost, to address the urgent issue of families undergoing energy poverty issues. It prioritizes economic factors on top of purely environmental (similar to Pombo et al. [29]) since the perceived economic benefits are key drivers of action by most decision makers, and energy poverty is mainly an economic problem [30]. A single dwelling has been taken as the analysis unit since this is the unit of most energy poverty studies, in line with Walker et al. [31].

The methodological approach is divided in three steps that eventually converge: on the one side the social housing dwellings for the case study are chosen, characterised and the energy performance evaluated. On the other hand, the energy efficiency measures for buildings are identified, filtered, simulated in the case study building, and evaluated economically. Finally, the energy efficiency measures are prioritized before making the final selection proposal according to different criteria. Final checks and corrections have to be made in terms of real consumption data versus average user profiles based on thermal comfort assumptions, and due to cross saving effects of implementing different measures that affect the same energy consumptions.

In the first step of the methodology, a building with 160 dwellings in the city of Zaragoza (Spain) was selected among a sample of 300 social housing buildings due to the larger number of dwellings and the representability of this type of dwellings in the sample. Two sources of information were sought to gather the necessary data for the energy modelling of the building:

- Construction materials and characteristics of the building, provided by the owner of the building, the municipal company “Zaragoza Vivienda” (Sociedad Municipal “Zaragoza Vivienda”. www.zaragozavivienda.es).
- User profiles gathered from onsite visits and energy bills supplied by a representative sample of 36 dwellings. Comfort temperatures and HVAC schedules were gathered. Three different user profiles were defined under the premise of keeping thermal comfort conditions during the HVAC scheduled hours. These profiles are described in the following epigraph. The annual energy bills of the 36 dwellings were also collected to calculate real consumption average data and correct the simulated results associated to the three user profiles previously defined.

With these values, a building energy performance simulation was done, assessing a yearly thermal demand and an average consumption for eight of the building dwellings using the three user profiles created. The apartments chosen for the simulation were among those visited, and were equally distributed around the four orientations to account for this factor in the energy consumption, as depicted in Figure 1. The representative dwelling of the building is then composed as an average of the eight. In this case, the EnergyPlus calculation engine was used, through the DesignBuilder V4.7 interface [32].

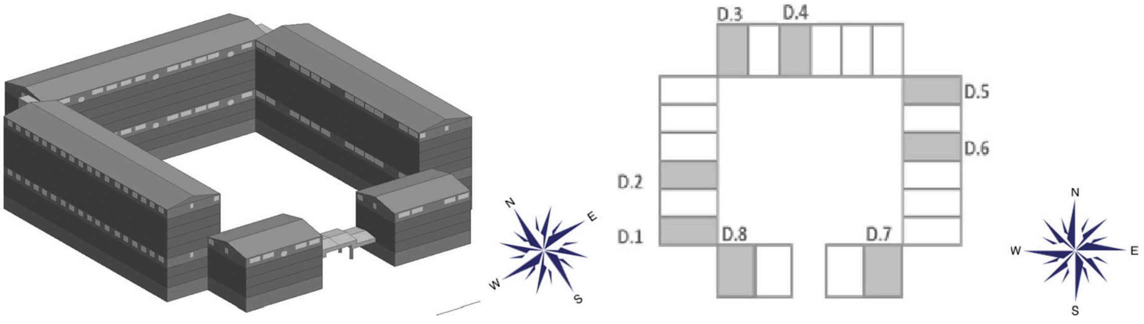


Figure 1. Overview of the building and location of the simulated dwellings in the building.

The second step of the methodological approach followed in this paper consisted on the compilation of energy efficiency measures applicable to existing buildings. This was done in the frame of the TRIBE project "TRaIning Behaviours towards Energy efficiency: play it!", co-funded by the European Union's 2020 research and innovation programme. In total, 250 energy efficiency measures were identified in all the previous categories and were collected in the TRIBE website [33]. These measures were the result of a holistic energy efficiency assessment in several building types. The different measures were classified according to the energy consumption categories as described below:

- Envelope (E): These are refurbishment measures applicable to the building envelope to reduce the thermal demand, such as adding insulation, thermal bridge breakages, waterproofing, reducing air infiltrations, etc.
- HVAC (H): Heating and ventilation system improvements.
- DHW (D): Domestic Hot Water supply savings and improvements.
- Lighting (L): Indoor lighting savings and improvements.
- Electrical Devices (ED): These measures refer to the better use of more suitable and efficient equipment for home appliances and other common domestic electrical devices. Many behavioural and no cost measures also deal with the efficient use of electrical devices and are contained in this category.
- RES and others (O): Self generation and consumption by means of renewable sources, as well as other type of measures are included.

Measures are codified by using the above designation in brackets, followed by "L" for long term measures or "S" for short term measures, and the correlative number of the action.

Of the total set of 250 measures, only measures applicable to residential blocks of apartments were chosen. In the sample of 300 social housing buildings analysed in this study, no cooling systems were observed in any dwelling. In addition, in the literature review, the existence and use of active cooling systems in this kind of buildings are extremely rare, due to the lower disposable incomes. In these buildings, natural cross ventilation, mainly at night, is the most widely used technique for cooling. Although this is an effective technique it does not usually completely meet the cooling demand, so thermal comfort conditions are not achieved during many summer days. For all these reasons, measures related to cooling systems were dismissed in this study. Similar equivalent measures were also eliminated to avoid redundancy such as the different insulation materials for insulation improvement, or glazing types in the installation of more efficient glazing. Those measures dealing with the design concept of the building were discarded as well as those that were deemed inapplicable in a typical social housing building, ending with a preliminary list of 100 measures.

The third step of the methodology was devoted to assess which energy efficiency measures apply to the case study building. The preliminary measures selected were simulated in the case study using EnergyPlus to obtain annual energy savings, both thermal and electrical for the whole building and per dwelling. Measures were simulated one by one while keeping the rest of the building inputs, user profile and conditions unchanged. Some behavioural measures or many involving recommendations for an efficient use of electrical devices such as kitchen elements could not be simulated in the energy performance software. In this case, savings were taken from other literature sources, averages and manufacturer estimations. Consequently, a significant uncertainty level has to be considered in the assessment of some behavioural measures.

Savings were calculated in kWh/year per dwelling and m^2, and in €/year per dwelling and m^2 using an average energy price of 0.045 €/kWh for gas and 0.14 €/kWh for electricity, according to the average tariff provided by the collaborating residents of the building.

An estimation of investment needed was also made using solution providers' datasheets, commercial catalogues and construction products databases such as BEDEC [34]. A simple payback was calculated for every measure as a ratio of investments versus annual savings in years of investment return, and then compared with the expected lifetime of the implemented action.

The preliminary 100 measures were then distributed by implementation ownership, separating those that correspond to the property of the building (public entity and management service company) and the dwelling tenants. Generally, flats are rented empty with no furniture or user devices that are catered for by the tenants. EE actions related to the building, the external envelope and the HVAC equipment maintenance belongs to the property. This was the situation of the building under analysis. However, this may vary depending on the renting conditions and policies set by the social housing authorities. At each case, the right screening criteria should be applied.

Although not investing in EE also has a cost in terms of extra energy consumed and environmental impacts [35], energy vulnerable families are extremely sensitive to large expenditures, hindering the implementation of many of the above list of measures. They would only undertake no or low investment measures, whereas those involving building equipment and envelope should be promoted by the building property or the management company. Related analysis shows a willingness to pay for energy-saving measures by apartment tenants if the benefit is noticeable [36]. However this may not apply in the case of social housing as low-income tenants who are not home owners are usually less engaged in energy efficiency, as stated by Robison and Jansson-Boyd [37]. Since the level of investment that can be covered by each actor was unknown, they were quizzed about the right level of expenditure per dwelling that each side felt reasonable. Residents claimed that the total aggregated investment should not exceed 500 € in 10 years, whereas the owning property had plans to gradually invest as much as 5000 € per dwelling in a 10 year plan. These were the top budget thresholds proposed for each side.

The next step consisted on an assessment over the most suitable set of practices and measures proposed, based on two different criteria:

- Lowest investment, due to the limited resources available, not only by the apartments' tenants, but also by the housing managing companies. According to this criterion, EE measures by residents and by property would be taken starting by the lowest cost until the delimited budget is reached.
- Lowest payback, as a ratio of savings provided per economic unit invested. In this case, EE measures would be undertaken starting by the lowest payback until the allocated budget is depleted.

To quantify the optimum budget range for resident and property's investment in EE, the savings–investment exponential model proposed by Valero [38] was used to determine the maximum achievable accumulative savings derived from the investments and the elasticity of the savings as a function of investment for the set of preliminary measures. The model was developed starting from the characterized EE measures sorted by decreasing payback. Savings were calculated in total value for the whole lifespan of the applied EE measure. The accumulated savings and accumulated investments were then worked out and represented graphically, obtaining the savings–investment curve. Finally, the best fit exponential curve was derived.

$$\mathrm{S(I)} = \mathrm{S_M} \times (1 - \mathrm{e}^{-\varepsilon^{*}\mathrm{I}})$$

where

- $\mathrm{S(I)}$: Accumulated savings for an accumulated investment I, in €/dwelling;
- I: Accumulated investment in €/dwelling;
- $\mathrm{S_M}$: Maximum achievable savings for the total investment I, in €/dwelling; and
- ε: Saturation coefficient of the curve ($€^{-1}$/dwelling).

The prioritization criteria and the proposed classification is a relevant result of this analysis focusing energy efficiency in social housing. Nevertheless, two important aspects of the results seriously affect the final performance of the building and need a closer look. These aspects were analysed as well:

- Cross-savings of EE measures that are applied simultaneously affecting the same consumption. Total savings of a set of measures have to be simulated together and savings will be lower than the addition of savings, thus increasing the overall payback.
- Real consumptions of the dwellings versus simulated consumptions. Actual energy consumptions turn out to be lower than the simulated energy consumptions. Hence, EE measure implementation bring along lower economic savings than expected, extending the payback period of the investments.

Finally, an extension of the results to the full public Spanish social housing system is done to become aware of the potential of energy sustainability at a national level.

A flow chart of the methodology is depicted in Figure 2.

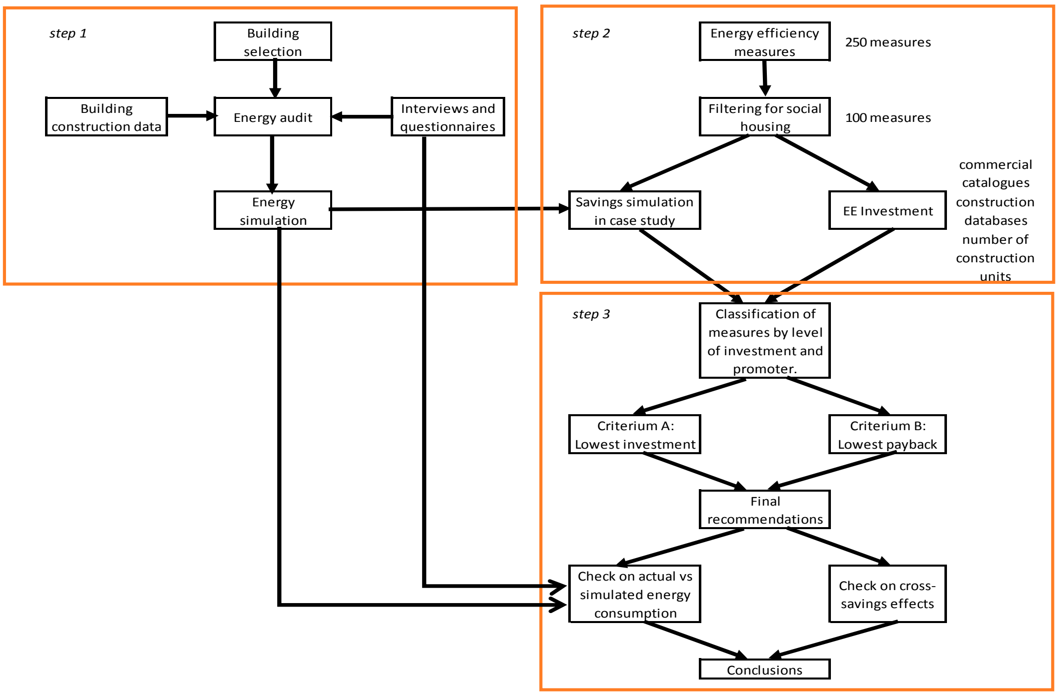


Figure 2. Methodology flowchart.

3. Case Study

A social housing building that represents generic social housing buildings has been chosen to test the different EE measures, recommendations and retrofitting in it. The building chosen for this analysis is situated in the city of Zaragoza (Spain) and is fully dedicated to social housing. This building is being managed by the public company "Zaragoza Vivienda". This is a square-shape building containing 160 similar dwellings of about 74 m^2 each in eight floors over ground level.

The case study building was built in 1988 and commissioned in 1990. This is in line with the average age of the social housing building sample, from 1985. It was built with no energy efficiency criteria, under the building regulation in force at the time of construction [22]. It is subjected to a mild Mediterranean dry climate of warm long summers with average temperatures of 25 °C, and short mild winters with average temperatures of 10 °C. The registered annual Heating Degree Days (HDD) using a reference temperature of 15 °C are 1177 HDD, and the annual Cooling Degree Days (CDD) for a reference temperature of 28 °C are 113 CDD (degree days calculated by means of www.degreedays.net). It corresponds to the Spanish climatic zone D3 ("D" indicates the winter weather severity on a scale from A to E and “3” indicates the summer weather severity on a scale from 1 to 4, according to section HE1 in CTE [39]. A1 corresponds to the mildest weather.). The average wind speed is 19 km/h at 20 m high, the predominant wind is cold and dry, in the northwest–southeast direction [40].

There is an important gap for the quality of the envelope with respect to today’s minimum requirements in Spain [39], as shown in Table 1. Windows are sliding aluminium frame single glass with thermal bridges showing theoretical transmittances two times larger than today’s construction standards for glazing surfaces. These types of building practices were common at the time of this building construction.

Table 1. Comparison of thermal transmittance of the enclosures of the case study building according to building design values and the value required by current regulations CTE DB-HE1 [39], in W/m^{2}K.

Type of Enclosure	**Thermal Transmittance (W/m^{2}K)**	
	Building Case Study	**CTE DB-HE1**
External walls	0.71	0.6
Internal walls	2.44	1.2
Bottom floor	1.12	0.4
Roof	0.51	0.4
Windows	5.7	2.7
(glazing type)	(single glass 6 mm)	(-)

Energy costs are covered by each household with its own resources that may be completed with social bonus and/or other social aids aimed at mitigating energy poverty. In addition, families also pay the social rent, which is a very favourable rate compared with market housing costs and also depends on the family incomes and conditions. For vulnerable households, the main difference between house renting costs and energy costs is that social renting is managed by the local Social Services that may be open to study the situation with the family in case of payment default, whereas the energy supply is managed by private utilities and the failure of payment may result in an energy supply cut [41]. Recently, after RDL 7/2016 [42] and especially in winter time, utilities are not allowed to cut down the energy supply and they must keep the supply while the social services would certify the energy vulnerability [5] and temporarily take up partially or totally the incoming energy invoices.

Apartments have an average occupancy of 3.7 persons per dwelling. They are fitted with individual 24 kW individual gas boilers for DHW and heating and have no cooling systems. The user profile taken corresponds to an average occupancy of three tenants per dwelling, staying at home from 18:00 to 09:00 on weekdays, and all day long on weekends. The average winter set point temperature is 21 °C. Hot water consumption is assumed to be 30 L/day per tenant, with delivery temperature of 55 °C. Heating schedule is from November to March, from 00:00 to 22:00 Table 2 summarizes the heating and DHW demand data for an average dwelling.

For electrical devices and lighting, three different family profiles have been defined, each one with different occupancy profiles and electrical device use schedules:

- “Working”: Family composed of four members, two adults who work during the weekdays and two children that go to the school. Total lighting hours: 2586 h/year.
- “Part-time”: Family composed of two members who work part time on weekdays. Total lighting hours: 2553 h/year.
- “Not-working”: Family composed of four members, two adults, from which just one of them works on weekdays while the other one is usually at home, and two children that go to school. Total lighting hours: 2804 h/year.

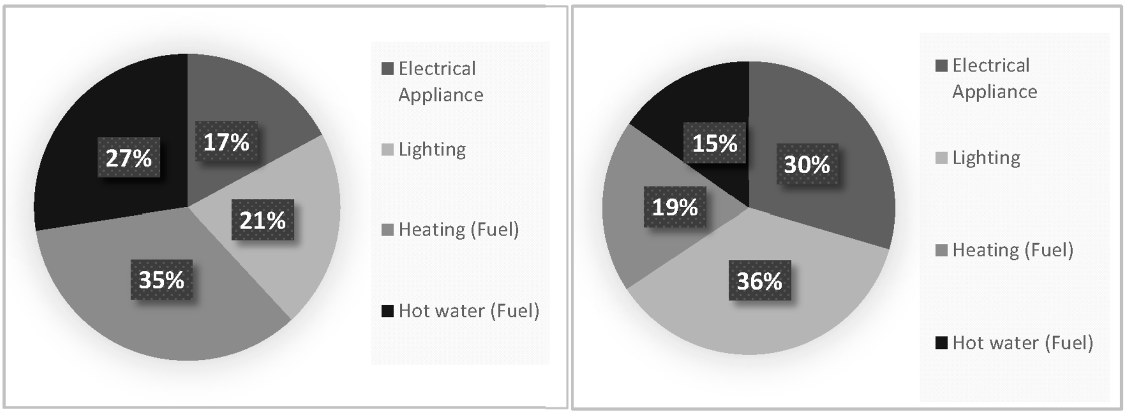
For each of the aforementioned profiles, a specific schedule has been defined for the weekends, which is alternated randomly with other schedule of no occupancy (representing the family leaving the house for the weekend).

Table 2. Heating and DHW equipment and user profile.

System	Main Characteristics	
Heating	Type of system	Individual atmospheric conventional boiler
	Fuel	Natural gas
	Temperature set point (°C)	21 °C
	Heating capacity (kW)	24 kW
	Heating system seasonal efficiency (%)	72.2%
	Working temperature (°C)	70–80 °C
	Heating distribution network	Monotubular copper installation
	Heating distribution in the dwelling	Steel plate radiator in every room
	Schedule	November to March from 12 a.m. to 10 p.m.
Cooling	No cooling system available in the dwellings	
Ventilation	Type	Natural
	Relative humidity set point (%)	40–60%
Domestic Hot Water	Type of system	Same boiler as heating
	Delivery temperature (°C)	55 °C
	Average daily consumption (L/day tenant)	30 L/day per tenant

4. Results and Discussion

The simulated energy consumption per dwelling and year is 95.8 kWh/m^2, around 900 €/dwelling, where heating and DHW account for 62% of the annual energy, although they only represent 34% of the energy expenditure (gas consumption) due to the lower natural gas cost with respect to electricity. The large difference of gas and electricity energy costs explains why electricity is two thirds of the total energy costs of these dwellings, as reflected in Figure 3.



(**a**) (**b**)

Figure 3. Simulated energy consumption and cost share for the building in: kWh/year (**a**); and €/year (**b**) per type of demand.

The result of this screening for the applicable 100 EE measures by implementation owner was the following:

- Behavioural change and no investment measures, based on real-time operation of buildings and devices [43], to be implemented by residents: 45 measures.
- Measures requiring investment by the residents: 21 measures.
- Measures requiring investment by the property: 33 measures.

The energy saving categories are evenly distributed with predominance of those involving the optimal use of electrical devices and improvements in the building envelope, according to Figure 4.

According to some recent studies, most of the energy efficiency measures implemented in non-profit housing involve the replacement of DHW and HVAC systems [44].

In the case study, envelope, HVAC and DHW measures involve savings in gas consumption as heating and DHW is supplied by means of individual natural gas boilers. Most of the measures in the other categories affect the consumption of electricity.

Most measures report savings lower than 50 €/year and require investments lower than 1000 €. This is mainly the case for the EE measures attributed to the residents. Non-investment EE measures have been removed from Figure 5.

Regarding measure category, envelope-concerning measures require the highest investments with modest savings, whereas lighting measures involve the lowest investment for acceptable savings. Many electrical devices measures mean no investment as depicted in Figure 6.

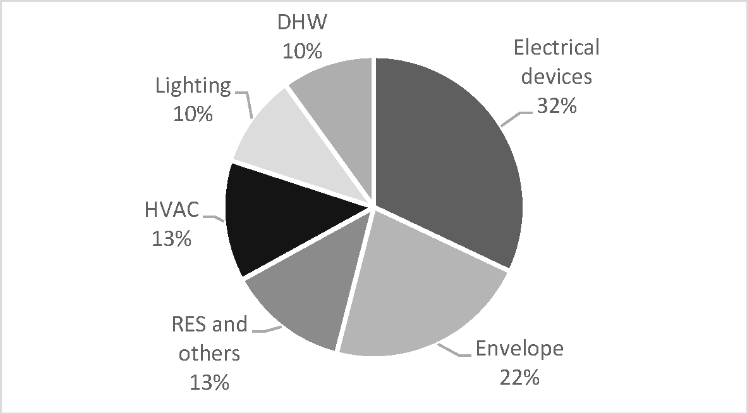


Figure 4. Distribution of measures by energy saving category.

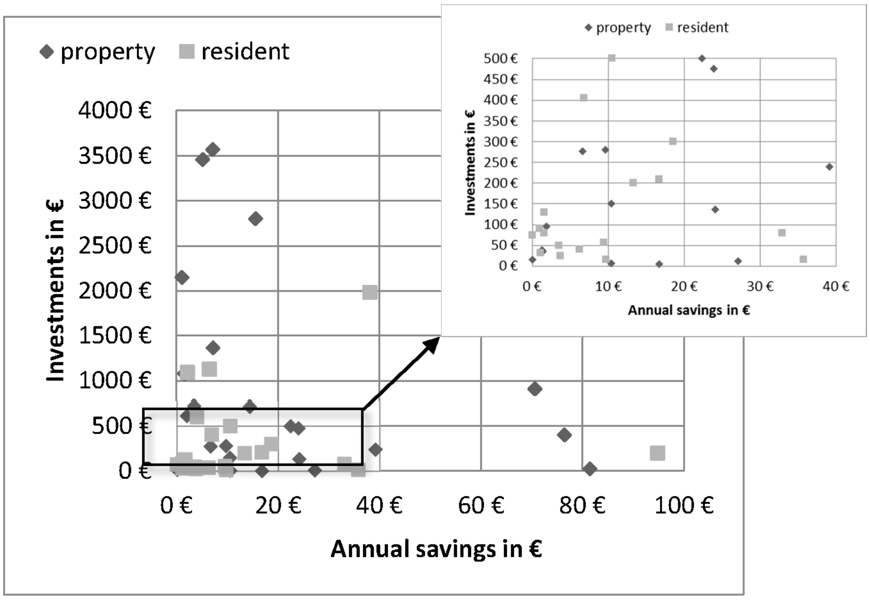


Figure 5. Total investment vs. annual savings per dwelling of every EE measure according to the implementation owner.

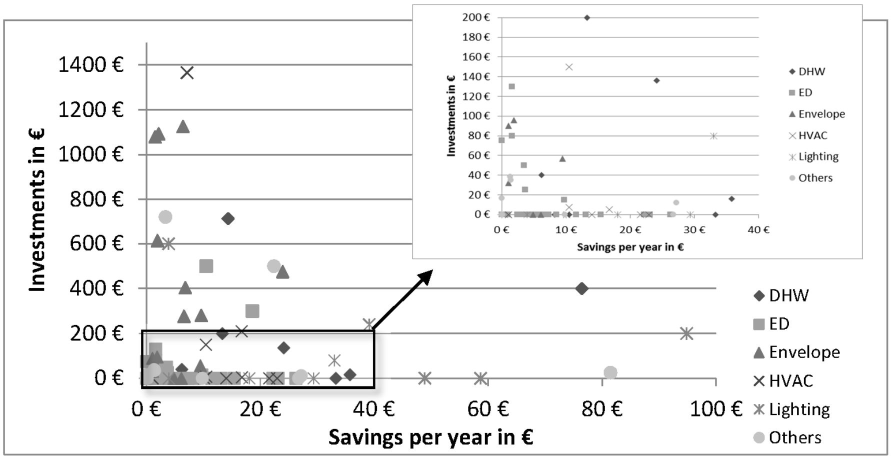


Figure 6. Total investment vs. annual savings per dwelling of every EE measure according to the measure category.

4.1. Prioritization Criteria for EE Actions

The results show that two thirds of the measures lay on the tenants' responsibility. In a context of social housing, residents are likely to be very sensitive to large investment expenditures to undertake many of the proposed EE actions. Hence, a prioritization criterion should be the necessary level of investment to implement each measure, starting by those measures that require no investment or just entail a user behavioural change and followed by the fastest and lowest price measures in order to allow for the maximum number of EE measures to be implemented with a limited budget. This budget is the maximum amount of money that the implementing owners are willing to spend on EE in a given time. This question was posed to the residents and to the property for a period of 10 years and the average answer by the 36 questioned flat tenants was around 500 € and for the building management company (property) 5000 €/dwelling.

Most of the EE measure's lifespan are above 10 years with a mean of 16 years. Only measures related to annual maintenance have shorter lifespan, often just one year.

To obtain the fastest results at no cost, the behavioural and no investment measures should be prioritized. Almost half of the measures are within this category. They are grouped by type of measure in Table 3, and then sorted by decreasing annual expected savings. The percentage of savings is calculated with respect to the total simulated dwelling energy consumption per year in kWh.

Table 3. List of zero investment and user behavioural measures grouped by type of measure and sorted by annual savings in aggregated €/dwelling.

Type of Measure	Number of Measures	Savings per Year	
		Energy Saving (%)	Cost Saving (€/Dwelling)
Electrical devices	25	22%	186 €
Lighting	5	17%	159 €
HVAC	6	23%	71 €
Others	5	11%	65 €
DHW	4	17%	53 €

These EE measures, in general, cover all possible categories of energy efficiency, but more than half refer to the optimal usage of electrical devices usually available in residential households, as shown in Figure 7. These measures are easy to implement and involve almost no investment but their implementation is rather unpredictable, since their success is based on the residents' knowledge and skills, habits, technology used, awareness and their willingness to collaborate [45], despite the fact that they are the greater beneficiaries of the savings achieved. The measures individually contribute little to the overall energy consumption reduction, but due to the immediate results and the need of no investment, they should be the first to be implemented to obtain fast savings to mitigate extreme energy poverty cases.

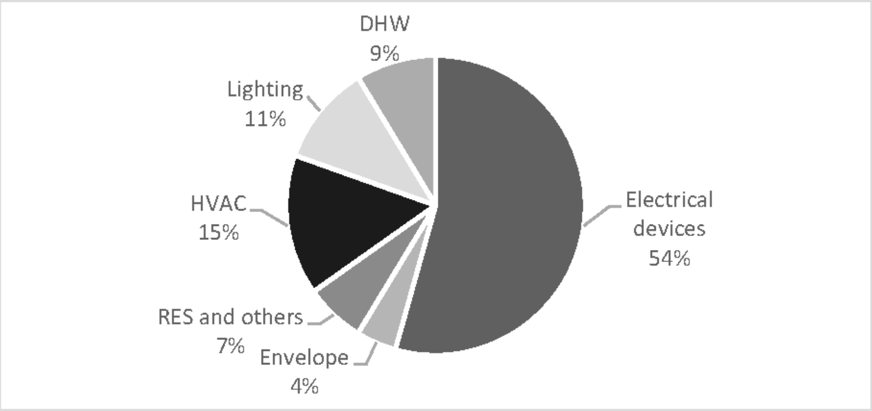


Figure 7. Distribution of non-investment measures by energy saving category.

To achieve further savings, some investments should be made, either by the residents or by the building property. At this point, a question arises about the criteria to prioritise the implementation of EE measures. The usual criteria is the economic simple payback since this metric ensures the maximum return in savings for a given investment and hence, the inclusion of the best EE investments. However, given the low economic resources of the residents of this type of building, and to ensure a higher number of EE measures for a given budget, it is proposed to consider the advantages of using the lowest investment as a criteria to sort out EE measures.

With this latest criteria, on the side of the residents, the 500 € budget would give room for 10 EE measures obtaining a total saving of 104 €/year per dwelling, no cross-effect considered. The list of low investment EE measures to be implemented by the residents is shown in Table 4.

Table 4. List of resident low investment EE measures sorted by lowest investment per dwelling.

Code	EE Measure Description	Energy Saving (%)	Payback (Years)	Lifespan (Years)
EDS35	Decalcify home appliances	1%	1.5	1
DS8	Installation of taps with flow reduction (faucet aerator)	11.8%	0.4	15
EDS1	Use of multiple power strips with switch and/or programmable plugs	0.4%	6.8	10
ES9	Substitution of roller tape guide	0.3%	30.6	30
DS10	Installation of low-flow showerheads	2.1%	6.5	10
EDS24	Repair refrigerator door seals	0.4%	14.3	10
ES1	Use silicone, putty or draught excluder to reduce air infiltrations through windows and doors	3.1%	6	10
EDS30	Promote the use of solar chargers	0%	9403	2
LL2	Installation of electronic ballast	3.5%	2.4	15
EDS16	Use a toaster oven or microwave instead of the oven	0.2%	50	5

EE measures being rejected by this sorting criteria relate to the purchase of expensive more efficient equipment and appliances. However, it can be observed that some of the prioritised measures have longer estimated payback than lifespan.

On the side of the property, there are 19 EE measures within a limited budget of 5000 €/dwelling. The total accumulated savings sum up 373 €/year per dwelling, no cross-effect considered. They are shown in Table 5 where, again, payback periods exceed solution life expectancy in many cases.

Table 5. List of property low investment EE measures sorted by lowest investment per dwelling.

Code	EE Measure Description	Energy Saving (%)	Payback (Years)	Lifespan (Years)
HS9	Adding or repairing boilers insulation	6%	0.3	15
HS7	Analysis of the combustion and maintenance of heating boilers	3%	0.7	1
OS4	Sensitizing of occupants through workshops	5%	0.4	-
OS3	Inspection and maintenance of lifts	0%	465.3	1
OS7	Create reminders and promotional materials to raise awareness	15%	0.3	2
OL6	Installation of an ICT system	0%	25.2	20
OL5	Installation of a Building Energy Management System (BEMS)	0%	29.1	20
ES10	Maintenance of wood and aluminium windows frame	1%	51.5	1
DS3	Adding or repairing DHW distribution systems	8%	5.7	15
HS24	Installation of thermostatic radiator valves	3%	14.4	20
LL11	Installation of manual potentiometric switches	4%	6.1	10
EL29	Application of an appropriate solar reflectance coating for the external walls	2%	41.9	10
EL26	Improve insulation in thermal bridge areas	3%	29.2	30
DL6	Installation of Drain Water Heat Recovery (DWHR) systems	25%	5.2	30
ES2	Seal air leaks located in all cavities presented in the building	8%	19.9	15
OL7	Installation of smart meters	2%	22.3	15
EL6	Adding or increasing internal insulation in roofs	1%	319.8	30
DL5	Change from an individual to a collective DHW system	5%	49.8	30
OL3	Installation of direct traction electric lifts	0.4%	216	15

Actions out of budget include efficient window replacement, envelope insulation improvement, efficient low temperature heating equipment, ventilated façade and other high-cost measures.

When applying the traditional payback criterion, results change significantly in some cases. For the resident side, the number of measures under budget goes down from 10 to 7 but increasing the savings per year from 104 €/dwelling to 193 €/dwelling. The new list of EE measures by decreasing payback is represented in Table 6. The only difference when compared with Table 4 is LL4, replacing incandescent lamps by fluorescent lamps, with a high investment but providing significant savings, and with better payback than LED lighting replacement (not selected due to redundancy). In all cases, the payback in years is shorter than the expected measure lifespan. In this case, no measure's estimated payback exceeds the expected lifespan.

In the case of the property low investment measures, the new list sorted by lowest payback and meeting the maximum affordable budget goes down from 19 to 10 EE measures, but the amount of accumulated annual savings increases by 38% from 373 €/dwelling to 605 €/dwelling (Table 7). The main difference is the inclusion of measures OL1 and OL2 dealing with the installation of renewable solar sources that bring in very interesting savings despite the high installation cost. An important check to be done is that all measures' estimated payback stays below the expected lifespan. It is not the case for the last measure, about sealing air leaks, whose payback (20 years) exceeds the estimated lifespan of the investment (15 years). This measure should be deleted from the list or replaced by the following in the list. However, the rest of the analysed measures' payback turns out to be longer than the estimated lifespan. Hence, the recommendation is to stop the measure deployment at this point, resulting in a total property investment of 4424 €/dwelling and total annual savings of 581 €/dwelling, which means an overall payback of 7.6 years. The kind of actions under the property's responsibility can be easily deployed by means of an ESCO business model as illustrated by Yi et al. [46].

Table 6. List of resident low investment EE measures sorted by lowest payback in years.

Code	EE Measure Description	Energy Saving (%)	Payback (Years)	Lifespan (Years)
DS8	Installation of taps with flow reduction (faucet aerator)	11.8%	0.4	15
EDS35	Decalcify home appliances	1%	1.5	1
LL4	Replacement of incandescent lamps by Compact fluorescent lamps (CFLs)	10.2%	2.1	15
LL2	Installation of electronic ballast	3.5%	2.4	15
ES1	Use silicone, putty or draught excluder to reduce air infiltrations through windows and doors	3.1%	6	10
DS10	Installation of low-flow showerheads	2.1%	6.5	10
EDS1	Use of multiple power strips with switch and/or programmable plugs	0.4%	6.8	10

Table 7. List of property low investment EE measures sorted by lowest payback in years.

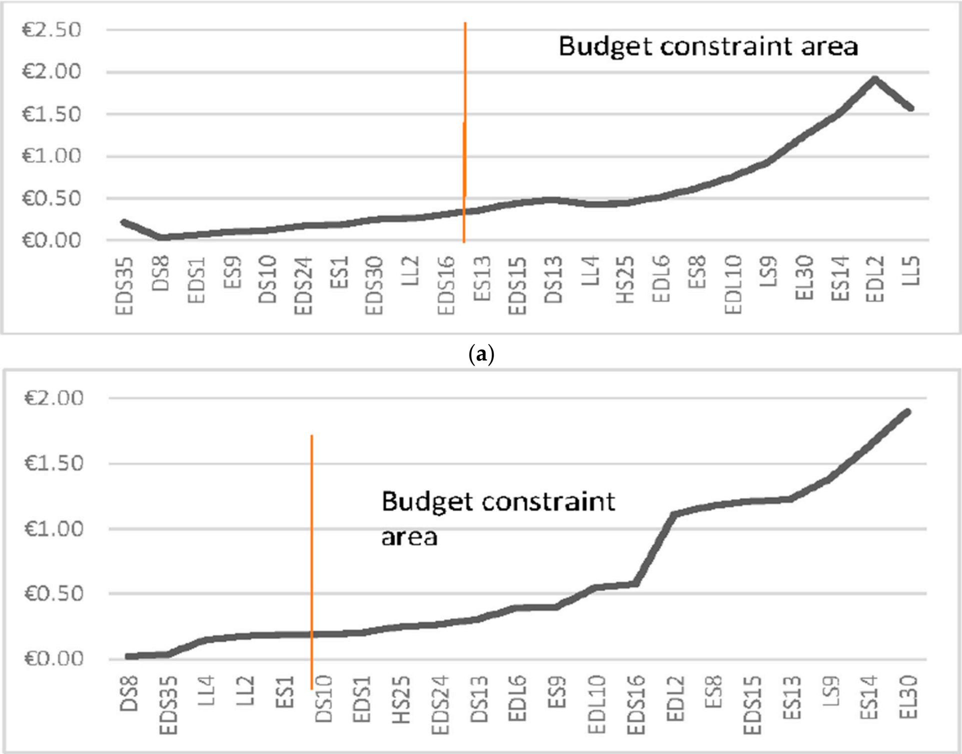
Code	EE Measure Description	Energy Saving (%)	Payback (Years)	Lifespan (Years)
OS7	Create reminders and promotional materials to raise awareness	15%	0.3	2
OS4	Sensitizing of occupants through workshops	5%	0.4	-
HS7	Analysis of the combustion and maintenance of heating boilers	3.5%	0.7	1
DL6	Installation of Drain Water Heat Recovery (DWHR) systems	25.3%	5.2	30
DS3	Adding or repairing DHW distribution systems	8%	5.7	15
LL11	Installation of manual potentiometric switches	4.2%	6.1	10
OL2	Installation of photovoltaic panels	25.9%	10.5	20
OL1	Installation of solar thermal panels for DHW	23.3%	12.9	20
HS24	Installation of thermostatic radiator valves	3.4%	14.4	20
ES2	Seal air leaks located in all cavities presented in the building (Rejected)	7.9%	19.9	15

On the other hand, measure OS4, sensitizing occupants through workshops, is a necessary measure to enable the resident's awareness and involvement in the energy vulnerability mitigation [47]. This measure is to be promoted by the management entity, which, in the case of public social housing in Spain, is the property of the buildings.

In other words, although most of the EE measures recommended match both sorting criteria, the payback sorting option is best as the resulting measures are more optimal and enable larger energy and economic savings.

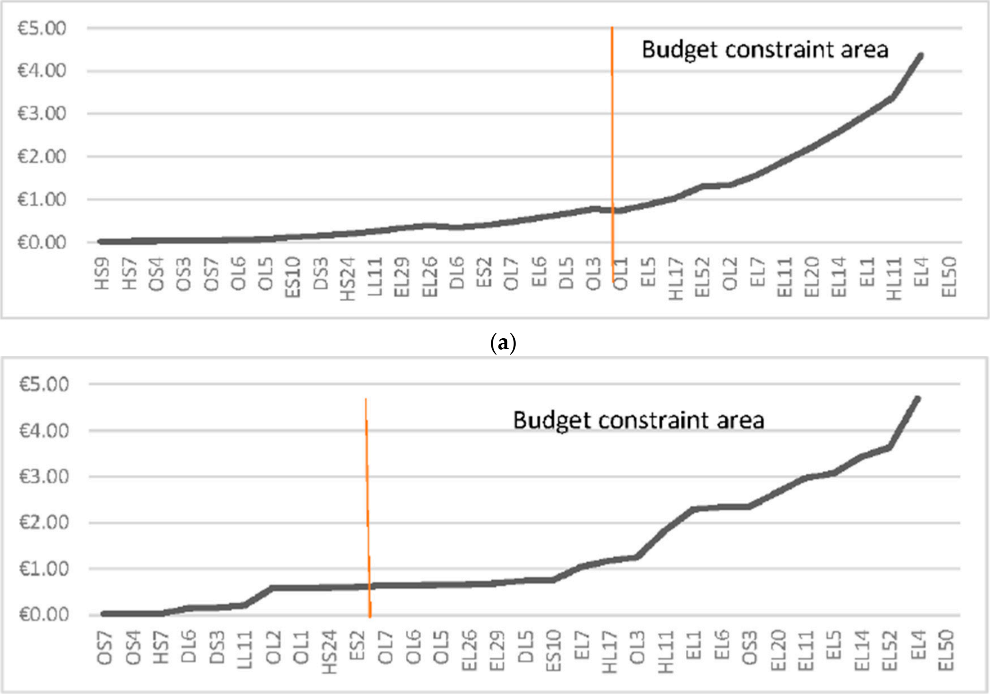
Looking at the cost per kWh saved per year in an average dwelling, as can be seen in Figure 8, the cost of the marginal EE measure meeting the resident budget constraints is 0.3 €/kWh saved following the lowest investment criterion, and 0.2 €/kWh by the lowest payback.

For property owned EE measures, the marginal EE measure shows a cost of 0.77 €/kWh of annual savings if sorted by lowest investment. This cost goes down to 0.61 €/kWh if sorted by payback (Figure 9). In both cases, the best results are obtained by the lowest payback sorting option.



(b)

Figure 8. Cost per kWh of annual energy savings of the accumulated resident EE measures by each sorting criterion: (**a**) by lowest investment; and (**b**) by lowest payback.



(b)

Figure 9. Cost per kWh of annual energy savings of the accumulated property EE measures by each sorting criterion: (**a**) by lowest investment; and (**b**) by lowest payback.

4.2. Sorting Model Based on Savings–Investment Curves

The sorting methodology is independent of the budget constraints, but, in the case there was no budget restrictions, a question that remains is what the most appropriate budget would be to invest in energy efficiency, as the higher the budget the more EE measures that can be implemented but the lower the payback of the additional investments. A suitable way to deal with this issue is by using the savings–investment exponential model proposed by Valero [38].

Looking first at the resident EE measures that imply a level of investment, the maximum achievable saving is around 4500 €/dwelling and the saturation coefficient $\varepsilon = -0.0017$ €$^{-1}$/dwelling. It can be seen that from 1800 €/dwelling of accumulated investment there is no significant improvement in savings. The budget restriction in this case is placed far below, at 500 €/dwelling, the investment saturating level of 1800 €/dwelling (Figure 10). Above this threshold, an increase in investment brings along decreasing absolute savings.

Doing the same exercise for property owned EE measures, the savings–investment curve in Figure 11 shows a maximum achievable accumulated saving of nearly 14,000 €/dwelling, and a saturation coefficient of $\varepsilon = -0.00026$ €$^{-1}$. The elasticity grade in this case is lower and the savings–investment curve saturates at an optimum investment level of 9600 €. Again, the level of 5000 € is appropriate, as it is below this saturating investment level.

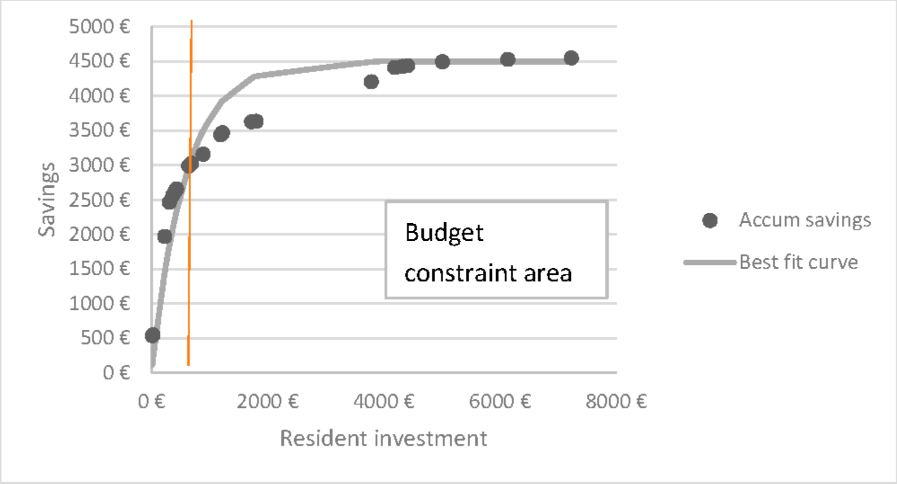


Figure 10. Savings–Investment curve for resident EE measures.

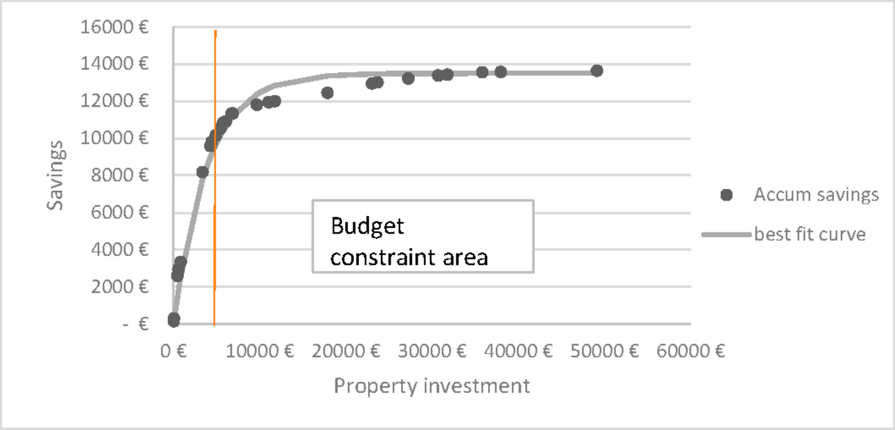


Figure 11. Savings–Investment curve for property EE measures.

4.3. Simulated versus Real Energy Savings

In total, the 100 EE measures for this social housing building are distributed in 45 behavioural change recommendations, seven low investment measures to be done by the residents and nine by the property, while 39 are rejected for budget constraints or larger payback than lifespan (Figure 12). This distribution shows that 68% of the applicable measures and 84% of the selected measures are under the tenants' responsibility, becoming the key players to drive consumption down. To ensure that all households are in the position of taking active action towards energy efficiency, programmes offering modest economic aids or loans to be paid back by means of energy savings could be of great help.

The calculations done so far are all based on energy simulations on an average dwelling. Nevertheless, the actual consumption may differ from the simulated consumption. Therefore, some corrections need to be done to obtain more realistic saving forecasts from the implementation of the selected EE measures and calculate the real payback of the investments.

Real consumption data from actual utility billing were collected and a weighted average in terms of dwelling size and orientation was estimated to compare with the simulated consumption of the average dwelling. Results per type of energy and dwelling can be seen in Table 8.

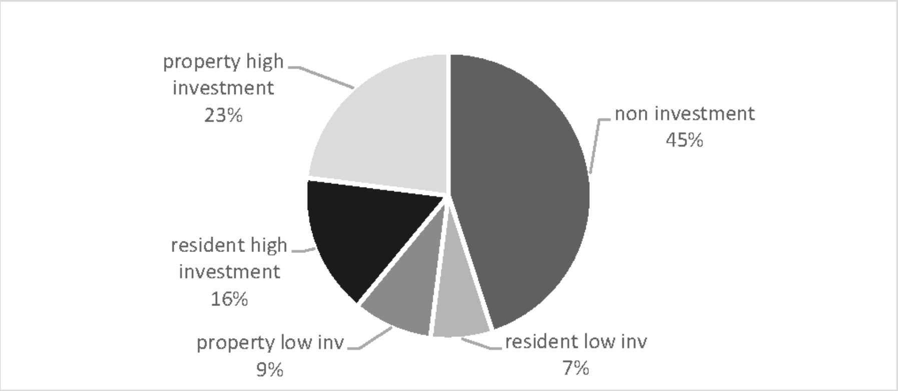


Figure 12. Distribution of measures by level of investment and by deployment owner.

Table 8. Difference of energy consumption for simulated and real consumption in kWh/year per dwelling.

Type of Energy	Simulated Energy Consumption (kWh/Year)	Real Energy Consumption (kWh/Year)	Difference (%)
Electricity	2669	2056	23%
Gas	5699	3947	31%
Total	8368	6003	28%

The real energy consumption is about 30% lower than the simulated energy, and will presumably have an effect on the expected savings, as already identified in some studies such as Teli et al. [48]. This gap between simulated and actual consumption is due to several factors:

- Degradation of the materials and building with time: The simulation has been done with project data thermal transmittances that may have changed along time. The lack of insulation in the building and the good maintenance may diminish this factor. The measurements taken on the walls of the building analysed showed little change with respect to the theoretical values of Table 1.
- Climatic differences of the database reference year (2002) and the billing year (2015): This difference is 1.1 °C colder in winter 2015 with respect to 2002, which should have increased

the actual consumption by 7.7%. This factor though, has been corrected by using 2015 heating degree days (1147 HDD) and the same seasonal temperature profile of year 2002, according to the simulation software features [32].

- Level of occupation of dwellings: Although this should be a relevant factor, looking at the annual energy expenditure per household with respect to occupancy, there are no trend lines. Only single-occupant dwellings may show some differences in consumption, but the number of apartments in this situation is just 11% of the sample.
- Lower usage of heating, DHW and electric devices than an average resident, due to the issue of energy poverty in the building, as corroborated by Teres-Zubiaga et al. [49]: The lack of economic resources and the fear of a power cut in the case of non-payment force many of these families to sacrifice thermal comfort, either by setting lower target indoor temperatures or reducing the number of heating hours. This is, in fact, a true issue in social housing and the error versus standard comfort temperatures considered in the simulated user profiles may be significant. This factor does not only affect thermal comfort in social housing but it could have serious impacts on tenants' health as exposed by Maqbool et al. [50]. The simulated user profiles based on the tenants' habits information and the real usage models can deviate to some extent, as reported by Silva et al. [51] and Herrando et al. [52].

This last factor jeopardizes the calculated savings of the different EE measures that will be around 30% lower than initially calculated, affecting the payback in the same way. Electricity saving measures become more interesting as the correction factor is lower (23% vs. 31%) but especially due to the much higher cost of the electricity with respect to gas. The high cost of electricity in many European countries is a serious issue for energy poverty since many social housing buildings in Southern Europe run only on electricity, aggravating the problem of energy affordability for many economically vulnerable households.

Applying the actual average consumption correction factors for gas and electricity, the real savings obtained decrease for each measure versus the calculated saving, as represented in Table 9. Total savings achieved in the case of the implementation of the 61 EE measures go down about 30% ending in 1000 €/dwelling per year. The total payback time increases one year to almost five years for the full set of measures.

Table 9. Summary of savings including the correction of the actual social housing annual energy consumption.

Type of Measure	Number of Measures	Investment (€/Dwelling)	Calculated Annual Savings (€/Dwelling)	Calculated Payback (Years)	Real Annual Savings (€/Dwelling)	Real Payback (Years)
Resident no investment	45	-	534 €	-	410 €	-
Resident low investment	7	433 €	193 €	2.2	144 €	3
Property low investment	9	4424 €	581 €	7.6	449 €	9.8
Total	61	4857 €	1308 €	3.7	1003 €	4.8

The second correcting factor for the energy saving estimations is the saving cross-effect of several EE measures implemented together and affecting the same demand. This is specially the case of gas savings as they involve only heating and DHW. Acting on envelope and on boiler equipment simultaneously maximizes the absolute savings achieved by the combination of both measures together but their individual saving contribution of each measure cannot be added to each as the investments do. Hence, the payback of the joint measures increases.

However, some EE measures have additional impacts on savings (such as using microwave instead of oven, decalcifying home appliances or switching off unused equipment). These measures represent independent savings and do not interfere with other measures. The sequence in which they are implemented does not affect the final savings. Usually measures with additional impacts are behavioural and imply electrical savings when using home appliances efficiently. A total of 31 EE measures can be classified as providing additional savings.

The remaining EE measures show cross-effects to some extent. Savings achieved by the previously deployed measures on a given demand (lighting, HVAC, and DHW) will diminish the capacity of obtaining the expected savings of a cross-effect measure as it acts on declining consumptions.

EE measures have been classified by providing additional or cross-effect savings and by the demand they serve (lighting, heating, DHW and others) and, in the case of the latest, the expected savings have been calculated on the decreasing demand, giving the results shown in Table 10. For this calculation, it has been assumed that measures have been implemented in declining payback order, starting by the no investment measures, followed by the resident low investment measures and finishing with the property investment measures.

Table 10. Summary of savings including the correction of the cross-effect annual energy savings.

Type of Measure	Number of Measures with Additional Savings	Number of Measures with Cross-Effect Savings	Investment (€/Dwelling)	Real Annual Savings (€/Dwelling)	Corrected Annual Savings (€/Dwelling)	Corrected Payback (Years)
Resident no investment	29	16	-	410 €	352.8 €	-
Resident low investment	2	5	433 €	144 €	97.4 €	4.4
Property low investment	0	9	4424 €	449 €	153.6 €	28.8
Total	31	30	4857 €	1003 €	604 €	8

The final payback period is up to eight years, which is still acceptable for investments in the residential sector. However, the convenience of implementation has to be checked again on a one to one basis, calculating the new paybacks and comparing them with the expected lifetime of each measure. Measures ES1 and DS10 now do not comply with the payback criteria and should be turned down, leaving the list with just 5 measures (DS8, EDS35, LL4, LL2 and EDS1) and a total investment lower than 400 € per dwelling and a total annual saving of 92.3 €/dwelling, with a payback of just 4.3 years.

In the case of the property low investment measures, there are more that do not comply with the payback criteria, limiting the applicable list to four measures (OS7, OS4, HS7 and DL6).

The summary savings are given in Table 11, where 55% of savings with respect to initial energy costs have been achieved at very low cost (780 €/dwelling), shared by the beneficiary resident (336 €/dwelling) and the property (444 €/dwelling). The list of EE measures to implement may be incremented if some of the selected measures, especially those pertaining to behavioural aspects, do not apply in some cases or are already implemented. This way, new low cost measures in the list may become applicable. On the other hand, many of these energy savings might not translate into economical savings but into further margin to increase consumption for the same energy cost, in an attempt to improve the thermal comfort of these energy vulnerable households and enhance their life standards.

Table 11. Summary of savings of the selected measures to be applied by residents and property and corrected by real consumption and cross-effect savings.

Type of Measure	Number of Measures	Investment (€/Dwelling)	Corrected Annual Savings (€/Dwelling)	Corrected Payback (Years)	Energy Savings (%)
Resident no investment	45	-	353 €		38%
Resident low investment	5	336 €	92.3 €	3.6	10%
Property low investment	4	444 €	64.5 €	6.9	7%
Total	54	780 €	510 €	1.5	55%

Seventy per cent of the selected measures involve electricity savings as a consequence of the faster return of a more expensive energy source. On the other hand, only 7% of the selected measures are under the property responsibility, making the beneficiary of the measures the main actor in energy savings. The distribution of measures per saving category shows that nearly half of the measures deal with the efficient use and selection of electrical devices, while envelope improvement measures look less attractive for investment (Figure 13).

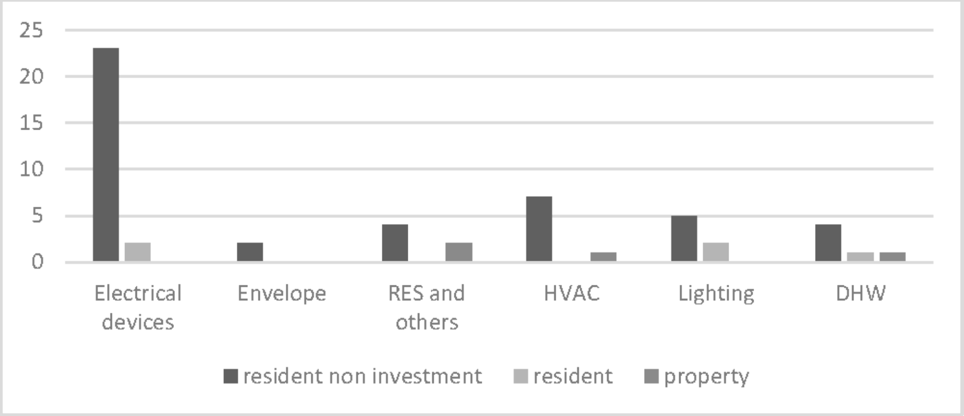


Figure 13. Distribution of final selected measures per saving category in number.

5. Conclusions

Building refurbishment is a secure investment to minimise the problem of recurrent energy poverty in households. Energy savings can contribute to both reducing the energy cost burden for vulnerable consumers and increasing their level of thermal comfort. However, due to the dwelling tenancy system, a collaborative measure implementation plan between residents and building owner or manager has to be designed, to avoid redundant measures and maximise the result of the combined investment.

When selecting the best energy efficiency options from a list of opportunities, the characteristics of the residential buildings and the typology of vulnerable households have to be considered. About 100 EE measures have been found applicable in a representative social housing building in Spain, and 64 of them have no investment or lower than 100 € per dwelling.

It is recommended to start by the non-investment measures, since the return on these measures is immediate in time. For these measures, the prioritization criterion should be the increasing amount of energy savings expected.

For the necessary investments, a budget threshold is necessary to share the investments between the beneficiary tenants and the property. Residents of social housing are often affected by energy vulnerability and their investment capacity is usually low. However, 70% of the EE measures lay on their side. Hence, their involvement and commitment is crucial.

To make sure that the budget threshold is correctly set, the savings–investment exponential curves can be used to calculate the maximum savings attainable by the implementation of sequential investments in energy efficiency. These curves also help to determine the limit at which further investment do not significantly contribute to get extra energy savings.

The sorting criterion based on lowest payback yields better saving results for the same investment budget than it does the sorting by lowest investment. The aggregated annual saving for non-investment measures is 534 €/dwelling while the aggregated annual savings of measures within budget limits is 774 €/dwelling with a simple payback of 6.3 years. When correcting with actual consumptions, savings get reduced to 410 €/dwelling for non-investment measures, and 593 €/dwelling with a payback of 8.2 years.

Energy simulation tools have proven to be affordable, fast and convenient to assess the energy saving potential of each measure implemented in a building. However, the real saving values are usually 20–30% lower than the simulated results, mainly because simulated demand is calculated to meet standard thermal comfort conditions which are not always met in this type of housing due to their economic limitations. Furthermore, the cross-effect of the simultaneous implementation of energy efficiency savings addressing the same energy saving category is significant and should be taken into account when assessing payback periods.

The results of the study prove that, with minimum investment levels, shared by flat tenants and building property, a considerable amount of savings can be obtained (up to 55% of the initial energy consumption). The deployment priority to be followed is first the non-investment measures and then the lowest payback measures, but always using actual consumption data and taking into account the cross-effect of simultaneous measures affecting the same energy demand. Even though the implementation of EE measures might not bring the desired economic benefit, a more intangible social benefit may be attaint in the form of increased levels of comfort for the households.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

CDD	Cooling Degree Days
DHW	Domestic Hot Water
EE	Energy Efficiency
ESCO	Energy Service Company
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
RES	Renewable Energy Sources

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6 Conclusions

Energy poverty is a particular case of poverty that affect negatively the thermal comfort of vulnerable households. Although the main cause is the lack of incomes to sufficiently cover the energy needs, other factors also contribute like the type of building where they live, the equipment used to satisfy the energy demand and the household structure and energy consumption habits.

From a broader perspective, the EU has adopted numerous initiatives in order to evaluate the problem posed by energy poverty at local, regional and national levels, and to define the most effective palliative actions. The most effective measures to prevent or mitigate household energy poverty, however, are those targeted at household level. For these measures to be effective, frameworks need to be put into place to guarantee that information on consumption is kept private and to develop methodologies with which to examine the problem from all its different angles.

An initial objective of the research dealt about the study of the energy poverty in Spain attending at the variables that affect the energy vulnerability of households, and the application of these variables to the empirical analysis of real households in situations of energy vulnerability. From the empirical analysis carried out in three public social housing buildings for rent in the city of Zaragoza, some interesting conclusions confirm that the total annual household income is the most influential factor of energy vulnerability in the sample of households. Most vulnerable households are classified in the lowest level of disposable income. The average annual income dedicated to the payment of energy costs per household in the sample is 7.6%, below the threshold of 10% that is taken to highlight energy poverty cases. Better insulated buildings and smaller size apartments show better results, although there is no clear difference with occupancy levels above two persons.

26% of the households analysed invest more than 10% of their income in energy expenditure. It could be said that these homes are in a situation of energy vulnerability. On the other hand, household income is correlated with the number of employed persons in the household, with an average of 0.6 employed residents per household. In vulnerable households, this ratio reaches only 0.3. Therefore, the level of employment is the main factor of energy vulnerability.

Energy consumption is strongly affected by the purchasing power of families, as well as by the type of residents. Households with more purchasing power tend to consume more energy to improve thermal comfort. In addition, Households with more children tend to consume more energy.

Energy consumption is mainly defined by heating in winter. For this reason, poorly insulated buildings with poor enclosures tend to consume much more than others of similar size but better insulation. Building insulation can reduce the energy cost-to-income ratio by half.

Gas consumption for heating is economically more efficient than electricity consumption for electric resistance heaters, even in the case of poor insulation or old and non-efficient heating boilers. Buildings relying only on electricity for heating show higher cost-to-income ratio and lower thermal comfort conditions.

The first main objective of this research was the integration of the significant variables into a weighted multi-criterion index of energy vulnerability. Within the framework of the debate on the relationship between household energy poverty and energy vulnerability associated with the buildings in which these households live, this study has defined the most significant factors for household energy poverty. This has led to the determination of a series of indicators which are accessible to the public agencies and which are used to generate a composite index of energy vulnerability. This index is a tool that can be used to manage social housing holistically from the perspective of energy poverty. The index considers the four key factors for energy poverty (aside from the socio-professional position of household members): the characteristics of the building, the characteristics of the energy installation, the energy bill, and the energy habits of household members.

The proposed methodology achieves three goals. Firstly, it can be used to assign relative weight to different indicators of household energy vulnerability. Secondly, the resulting index is a heuristic tool, which offers a new insight into the causes and structure of vulnerability among populations with a similar level of exposure. Thirdly, it reveals new data with which to design and monitor action in more efficient ways. This index is a tool that can be used to holistically manage social housing from the perspective of energy poverty, e.g., the refurbishment of buildings, the maintenance policies, or the management of energy supply.

The results applied to the social housing sample of 351 households show a low global vulnerability rating (taking all four factors into consideration), despite the low average income of the households, whereas the global vulnerability rating for the whole sample of households (including non-social housing) is moderate. The relative impact of the building characteristics is very low due to the homogeneity and good maintenance level of the public social housing stock in the sample. Bills and household structure reflect higher impact values and a wider variability range due to the differences among household habits and structure.

The composite index was also applied to a sample of 615 certified energy impoverished households, and to a sample of generic 1340 regular households. Results reveal that social houses are less vulnerable from the building standpoint, and more from the energy expenditure point of view. The reason is the type of energy and type of tariffs, of social housing tenants that do not adapt the former resident's contract to their own real needs. Social housing and certified vulnerable consumers have household structures and habits that affect negatively their risk for energy poverty. The global composite vulnerability index of the samples does not present substantial differences among housing samples

A second objective of the research consisted on analysing the social aspects of energy vulnerability in households, and the certification and mediating role of public social services in cases of energy poverty. Generally, vulnerable consumers address the local public authorities in their home country in the search of public aids and economic support. For this reason, it was deemed important to tackle the energy poverty issue from a different perspective and analyse the mediating role of social workers in the implementation of regional policies targeting energy poverty. The case study of the energy poverty in a Spanish region has demonstrated that this problem should not be treated locally without the adequate coordination with the national and European regulation, which only postpones achieving a solution for the underlying structural causes.

The efficiency of the assistance model strongly relies on spontaneous, informal and even improvised relationships between the different agents. However, it is useful for solving occasional emergencies but it does not reach the root of the problem.

While the dichotomy between public and private responsibility goes unresolved, the sustainability of public aid policies, which are largely funded by the social services, will be uncertain. The national legal vacuum (which stems from European directives) has to some extent been corrected at regional level.

Urban and rural households have different problems, and for this reason policies should take into consideration such variables as strength/weakness of social capital, community support strategies, population ageing, the state of conservation of residential buildings and the optimisation of energy resources through the use of traditional systems (for instance, exploitation of nearby forest resources for heating). In any case, although the policies in place seem to be shifting from trying to prevent inequality to the management of poverty and social exclusion, the reasons for the structural discrimination of persons and territories remain unchallenged.

Policies must, therefore, be redefined in order to go beyond the local level, and they must take into consideration structural factors and the restructuring of social aid. The diagnosis of the problem, however, must remain close to the territory, which is where the central role of social workers stands out.

In this context, it is important that regulations take into consideration the mediating role played by social workers at a local level and the present study has contributed to underline their role in energy poverty prevention– an aspect which has been paid little attention to date. In the model under analysis, social workers are responsible for detecting, diagnosing and assisting energy-impoverished households.

A social worker is not an expert on energy consumption and building insulation, but he is rather the public agent with the best first-hand knowledge of the real problems faced by vulnerable households and of the issues with the buildings in which these families live. As suggested, training can provide the basic knowledge that they need in order to identify the causes of the vulnerability of the households with which they work. It is, therefore, necessary to adapt the normative framework to their work and to provide them with better tools to carry out their duties.

The role of social workers as certifying agents is well attuned to the territorial model in place, and it should be extended to other European regions, since it can be implemented by both public social services (it efficiently covers rural regions) and private networks (NGO). This is not to say that the model cannot be improved, and this is especially true in relation to the territorial inequalities caused by the diversity of socio-demographic and contextual (urban/rural settings) conditions present in the region.

Once analysed the social implications at regional level, efforts shift the focus to the analysis of determinant factors that affect energy poverty besides economic precariousness, such as the building, the household structure and the energy consumption habits. The objective pursued was the study of building characteristics in social housing, the application of energy simulation in this type of cases and the analysis of this type of computerized simulations applied to homes in risk of energy vulnerability. In order to make energy assessments in social housing building, computer simulations tools are applied with significant differences between actual and simulated energy consumptions.

Building characteristics are not necessarily the most relevant factors when it comes to energy poverty. The structure of households and the behaviour of residents also play an important role. The cost of energy and the type of supply-contract are considered relevant, mainly for electricity. The greatest expenditure of energy in the cases analysed was on heating, which social housing tenants underused in a great extent; thus many are prevented from achieving minimum indoor comfort conditions of 21ºC.

The optimisation of contracts and energy tariffs, as well as the diversification and shift to more affordable energy sources for heating, as opposed to Joule heating, are the most straightforward recommendations for those living in social housing to palliate energy poverty. Dwellings with only an electricity supply have energy costs which are almost double that of homes using natural gas for DHW and heating, even in cases of buildings which are more energy efficient.

Energy poverty translates into lower levels of thermal comfort in the affected households. The difference between pre-determined and actual user profiles and habits is the main cause of the deviations between the actual and the simulated energy consumption in social housing. The standard comfort temperature (21ºC) is not appropriate for energy-vulnerable households. In the analysed households, the simulated heating schedule should be significantly reduced, to between 3 and 3.5 hours of heating service per day in winter season, to match the actual heating consumption in the social housing sample under study, despite of the longer heating schedule reported by tenants.

It should be noted that any improvement in the building envelope would not fully translate into real energy savings, but it would contribute to improve the thermal comfort conditions of those living in social housing, and thus would have a positive social impact quite separate from economic savings. The main reason is that those living in households suffering from energy poverty already live below standard thermal comfort conditions: improvements to energy performance are likely to improve the residents' thermal comfort by bringing the temperature closer to the standard level rather than driving down their already-low energy expenditure.

The obtained results may contribute to improve the simulation tools for measuring energy poverty in social housing. These results can also be used to support decision-making processes concerning the management of household energy poverty in social housing – e.g. in relation to building refurbishment, maintenance, and energy-supply management.

The last objective of the research was set to make a proposal of solutions and palliative actions for social housing from the point of view of the buildings. The next step was focused on taking these results to carry out an analysis of energy efficiency measures and retrofitting solutions for social housing buildings as a way to mitigate energy poverty using energy simulation tools. The analysis was made in a social housing building where 250 possible energy efficiency measures were assessed from an economic point of view.

Results show that building refurbishment is a secure investment to minimise the problem of recurrent energy poverty in households. Energy savings can contribute to both reducing the energy cost burden for vulnerable consumers and increasing their level of thermal comfort. However, due to the dwelling tenancy system, a collaborative measure implementation plan between residents and building owner or manager has to be designed, to avoid redundant measures and maximise the result of the combined investment.

When selecting the best energy efficiency options from a list of opportunities, the characteristics of the residential buildings and the typology of vulnerable households have to be considered. About 100 energy efficiency measures have been found applicable in a representative social housing building in Spain, and 64 of them have no investment or lower than 100 € per dwelling.

It is recommended to start by the non-investment measures, since the return on these measures is immediate in time. For these measures, the prioritization criterion should be the increasing amount of energy savings expected.

For the necessary investments, a budget threshold is necessary to share the investments between the beneficiary tenants and the property. Residents of social housing are often affected by energy vulnerability and their investment capacity is usually low. However, 70% of the energy efficiency measures lay on their side. Hence, their involvement and commitment is crucial.

To make sure that the budget threshold is correctly set, the cumulated savings–investment exponential curves can be used to calculate the maximum savings attainable by the implementation of sequential investments in energy efficiency. These curves also help to determine the limit at which further investment do not significantly contribute to get extra energy savings.

The sorting criterion based on lowest payback yields better saving results for the same investment budget than it does the sorting by lowest investment. The aggregated annual saving for non-investment measures is 534 €/dwelling while the aggregated annual savings of measures within budget limits is 774 €/dwelling with a simple payback of 6.3 years. When correcting with actual consumptions, savings get reduced to 410 €/dwelling for non-investment measures, and 593 €/dwelling with a payback of 8.2 years.

Energy simulation tools have proven to be affordable, fast and convenient to assess the energy saving potential of each measure implemented in a building. However, the real saving values are usually 20–30% lower than the simulated results, mainly because simulated demand is calculated to meet standard thermal comfort conditions which are not always met in this type of housing due to their economic limitations. Furthermore, the cross-effect of the simultaneous implementation of energy efficiency savings addressing the same energy saving category is significant and should be taken into account when assessing payback periods.

The results of the study prove that, with minimum investment levels, shared by flat tenants and building property, a considerable amount of savings can be obtained (up to 55% of the initial energy consumption). The deployment priority to be followed is first the non-investment measures and then the lowest payback measures, but always using actual consumption data and taking into account the cross-effect of simultaneous measures affecting the same energy demand. Even though the implementation of energy efficiency measures might not bring the desired economic benefit, a more intangible social benefit may be attaint in the form of increased levels of thermal comfort for the households.

6.1 Main scientific contributions of this thesis

The summary of the main contributions of this PhD to the state-of-the-art in the field of energy poverty is:

- The proposal and validation of an energy poverty composite index in social housing, from a household energy poverty perspective that enables to consider several factors in a single index such as building type, household structure, energy expenditure and house hold incomes.

- The identification of training needs and resources to boost the role played by social workers to help vulnerable users to mitigate energy poverty issues, not only by issuing economic aids but also by empowering them to give advice and recommendations about domestic energy consumptions through training programmes and fast assessment tools.

- An in-depth empirical analysis based on real and simulated data of the main variables and factors that affect social housing tenants in Spain, from building characteristics, heating, ventilating, and air conditioning (HVAC) equipment, energy consumption patterns and household structure.

- An assessment of the use of building energy simulation tools in the case of social housing, with the identification of the main factors of divergence between real and simulated consumptions and the quantification of the impact that behavioural aspects have in this difference due to the limitations in energy consumption caused by the economic constraints of these vulnerable households.

- An economically-efficient methodology for the prioritization and deployment of energy efficiency measures, with a systematic approach for collaboration between vulnerable residents of rented social housing and public building managing entities to maximise the impact of the measures in both energy expenditure and thermal comfort improvement.

6.2 Future research directions

As energy poverty is a broad, multidisciplinary and complex problem, many open issues should be addressed to add on to this study and complete the work done so far. The future research steps should go in the following directions:

- Enlarge the geographical scope of the analysis. The future study should comprise a larger geographical area covering other regions, not only in Spain but in other European countries, so as to observe the influence of the climate, the local culture and the architectural differences. Local regulations and public palliative aid systems may also have a great impact on energy vulnerability in social housing.

- Extend the case study sample size. The study is based on real data of several social buildings in Zaragoza. These buildings are representative of public social housing in Spain and offer a variety of architectural characteristics, equipment and households but a larger sample may reveal more interesting insights.

- Make an analysis of the evolution of the sample over time. Extract similar data in the same sample some years later would put in perspective the evolution of the variables under analysis, and the status of the dwelling tenants referred to external economic factors, regulation developments and possible building improvement actions.

- Extend the number of variables used in the analysis. Some socio-demographic variables such qualification, immigration, employment, etc. would permit to study how society and exclusion risk factors may also affect the energy poverty problem.

- Enlarge the analysis from public social housing for rent in block of apartments in urban areas to other type of social housing, mainly private housing and rural areas with different type of buildings.

Extending the sample to give response to the above limitations would provide a better and a more complete picture of the energy poverty issue, enabling the possibility to carry out comparative analysis between public and private social housing, rural and urban buildings and other geographical and climatic areas. This analysis requires costly and hard data gathering campaigns that remain open for further study in the future.

6 Conclusiones

La pobreza energética es un caso particular de pobreza que afecta negativamente al confort térmico de los hogares vulnerables. Aunque la causa principal es la falta de ingresos económicos para cubrir suficientemente las necesidades energéticas, otros factores también contribuyen, como el tipo de edificio donde viven, los equipos utilizados para satisfacer la demanda de energía, la estructura del hogar y los hábitos de consumo de energía.

Desde una perspectiva más amplia, la Unión Europea ha adoptado numerosas iniciativas para evaluar el problema planteado por la pobreza energética a nivel local, regional y nacional, y para definir las acciones paliativas más eficaces. Sin embargo, las medidas más efectivas para prevenir o mitigar la pobreza energética de los hogares son las dirigidas a nivel de los hogares. Para que estas medidas sean eficaces, se deben establecer marcos que garanticen que la información sobre el consumo se mantenga confidencial y que permitan desarrollar metodologías con las que examinar el problema desde todos sus ángulos.

El estudio inicial de la investigación trató sobre el análisis de la pobreza energética en Aragón atendiendo a las variables que afectan la vulnerabilidad energética de los hogares, y a la aplicación de estas variables al análisis empírico de hogares reales en situaciones de vulnerabilidad energética. A partir de este análisis empírico llevado a cabo en tres edificios públicos de viviendas sociales en alquiler en la ciudad de Zaragoza, algunas conclusiones interesantes confirman que el nivel de ingreso anual total del hogar es el factor más influyente de vulnerabilidad energética en la muestra de hogares. Los hogares más vulnerables se clasifican en el nivel más bajo de ingresos disponibles, por debajo de 9.000 €/año, donde se encuentran el 97% de los hogares vulnerables con ratios de gasto energético por encima del 10% de los ingresos. El ingreso anual promedio dedicado al pago de los costes de energía por hogar en la muestra es del 7,6%, por debajo del umbral del 10% que se toma para resaltar los casos de pobreza energética. Los edificios mejor aislados y los apartamentos de menor tamaño muestran mejores resultados, aunque no hay una diferencia clara con niveles de ocupación superiores a dos personas.

El 26% de los hogares analizados invierte más del 10% de sus ingresos en gasto de energía. Se podría decir que estos hogares se encuentran en una situación de vulnerabilidad energética. Por otro lado, el ingreso familiar se correlaciona con el número de personas empleadas en el hogar, que en la muestra alcanza un promedio de 0,6 residentes ocupados por hogar. En hogares vulnerables, esta proporción llega solo a 0,3. Por lo tanto, el nivel de empleo parece ser uno de los principales factores de vulnerabilidad energética.

El consumo de energía se ve fuertemente afectado por el poder adquisitivo de las familias, así como por el tipo de residentes. Los hogares con mayor poder adquisitivo tienden a consumir más energía para mejorar el confort térmico hasta un límite superior. Además, los hogares con más hijos tienden también a consumir más energía.

El mayor consumo de energía en los hogares viene dado principalmente por la demanda de calefacción en invierno. Por esta razón, los edificios mal aislados tienden a consumir mucho más que otros de tamaño similar pero con mejor aislamiento. El aislamiento del edificio puede reducir a la mitad la relación entre el coste de la energía y los ingresos.

El consumo de gas para calefacción conlleva un menor coste económico que el consumo de electricidad para los calentadores basados en resistencias eléctricas, incluso en el caso de un aislamiento deficiente o calderas de calefacción viejas y no eficientes. Los edificios que dependen solo de la electricidad para la calefacción muestran un mayor índice de vulnerabilidad (ratio de ingresos dedicados a los gastos energéticos) y peores condiciones de confort térmico.

El primer objetivo de esta investigación fue la integración de las variables significativas en un índice ponderado de vulnerabilidad energética múlti-criterio. En el marco del debate sobre la relación entre la pobreza energética de los hogares y la vulnerabilidad energética asociada a los edificios en los que viven estos hogares, este estudio ha definido los factores más importantes para la pobreza energética de los hogares. Esto ha llevado a la determinación de una serie de indicadores que son accesibles a las agencias públicas y que se utilizan para generar un índice compuesto de vulnerabilidad energética. Este índice es una herramienta que se puede utilizar para gestionar la vivienda social de manera integral desde la perspectiva de la pobreza energética. El índice considera los cuatro factores clave para la pobreza energética (además de la posición socio-profesional de los miembros del hogar): las características del edificio, las características de los equipamientos energéticos, la factura energética y los hábitos de consumo de energía de los miembros del hogar.

La metodología propuesta permite lograr tres objetivos. En primer lugar, puede utilizarse para asignar un peso relativo a diferentes indicadores de vulnerabilidad energética de los hogares. En segundo lugar, el índice resultante es una herramienta heurística que puede ofrecer una nueva percepción de las causas y la estructura de la vulnerabilidad entre las poblaciones con un nivel de exposición similar. En tercer lugar, revela nuevos datos con los cuales diseñar y monitorizar acciones de mejora, de manera más eficiente. Este índice es una herramienta que se puede usar para gestionar holísticamente la vivienda social desde la perspectiva de la pobreza energética, como por ejemplo, para la rehabilitación de edificios, el mantenimiento o la gestión del suministro de energía.

Los resultados aplicados a la muestra de viviendas sociales de 351 hogares muestran una baja calificación de vulnerabilidad global (considerando los cuatro factores), a pesar del bajo ingreso promedio de los hogares, mientras que la calificación de vulnerabilidad global para toda la muestra completa de hogares (incluyendo los que no son vivienda social) es moderada. El impacto relativo de las características edificatorias del edificio es muy bajo debido a la homogeneidad y el buen nivel de mantenimiento del parque público de viviendas sociales en la muestra. Las facturas y la estructura del hogar reflejan valores más altos de impacto y un rango de variabilidad más amplio debido a las diferencias entre los hábitos y la estructura del hogar de la muestra.

El índice compuesto también se aplicó a una muestra de 615 hogares en situación de pobreza energética certificada, y a una muestra de 1340 hogares genéricos normales. Los resultados revelan que las viviendas sociales son menos vulnerables desde el punto de vista del edificio, y más desde el punto de vista del gasto de energía. La razón es el tipo de energía y el tipo de tarifas de los inquilinos de viviendas sociales que no suelen adaptar el contrato del antiguo residente a sus propias necesidades reales. La vivienda social y los consumidores vulnerables certificados tienen estructuras y hábitos en el hogar que afectan negativamente a su riesgo de pobreza energética. El índice global de vulnerabilidad compuesta de las muestras no presenta diferencias sustanciales entre muestras.

Un segundo objetivo de la investigación consistió en analizar los aspectos sociales de la vulnerabilidad energética en los hogares y la función de certificación y mediación de los servicios sociales públicos en los casos de pobreza energética. Generalmente, los consumidores vulnerables se dirigen a las autoridades públicas locales en su país de origen en la búsqueda de ayudas públicas y apoyo económico. Por esta razón, se consideró importante abordar el tema de la pobreza energética desde una perspectiva diferente y analizar el papel mediador de los trabajadores sociales en la implementación de políticas regionales dirigidas a la pobreza energética. El estudio de caso de la pobreza energética en una región española ha demostrado que este problema no debe tratarse localmente sino en coordinación con la regulación nacional y europea, ya que solo alivia temporalmente el problema sin buscar una solución para las causas estructurales subyacentes.

La eficiencia del modelo de asistencia depende en gran medida de relaciones espontáneas, informales e incluso improvisadas entre los diferentes agentes. Aunque se muestra útil para resolver emergencias ocasionales, no llega a la raíz del problema.

Si bien la dicotomía entre la responsabilidad pública y privada queda sin resolver, la sostenibilidad de las políticas de ayuda pública, que en gran medida son financiadas por los servicios sociales, es incierta. El vacío legal nacional (que se deriva de las directivas europeas) se ha corregido en cierta medida a nivel regional.

Los hogares urbanos y rurales tienen problemas diferentes, y por esta razón las políticas deben tomar en consideración variables como la fuerza o debilidad del capital social, las estrategias de apoyo comunitario, el envejecimiento de la población, el estado de conservación de los edificios residenciales y la optimización de los recursos energéticos mediante el uso de sistemas tradicionales (por ejemplo, explotación de recursos forestales cercanos para calefacción). En cualquier caso, aunque las políticas vigentes parecen estar cambiando desde intentar prevenir la desigualdad hacia la gestión de la pobreza y la exclusión social, las razones para la discriminación estructural de las personas y los territorios siguen sin ser cuestionadas.

Las políticas deben, por lo tanto, ser redefinidas para ir más allá del nivel local, y deben tomar en consideración los factores estructurales y la reestructuración de la ayuda social. El diagnóstico del problema, sin embargo, debe permanecer cerca del territorio, que es donde se destaca el papel central de los trabajadores sociales.

En este contexto, es importante que las reglamentaciones tomen en cuenta el papel de mediación desempeñado por los trabajadores sociales a nivel local y el presente estudio ha contribuido a subrayar su papel en la prevención de la pobreza energética, un aspecto al que se le ha prestado poca atención. En el modelo analizado, los trabajadores sociales son responsables de detectar, diagnosticar y ayudar a los hogares empobrecidos en términos de energía.

Un trabajador social no es un experto en consumo de energía y aislamiento de edificios, sino es más bien el agente público con el mejor conocimiento de primera mano de los problemas reales a los que se enfrentan los hogares vulnerables y los problemas con los edificios en los que viven estas familias. Como se sugiere, la capacitación puede proporcionar el conocimiento básico que necesitan para identificar las causas de la vulnerabilidad de los hogares con los que trabajan. Por lo tanto, es necesario adaptar el marco normativo a su trabajo y proporcionarles mejores herramientas para llevar a cabo sus tareas.

El papel de los trabajadores sociales como agentes certificadores está en sintonía con el modelo territorial vigente, y debería extenderse a otras regiones europeas, ya que puede ser implementado tanto por los servicios sociales públicos (cubre eficientemente las regiones rurales) como por las redes privadas (ONGs). Esto no quiere decir que el modelo no pueda mejorarse, y esto es especialmente cierto en relación con las desigualdades territoriales causadas por la diversidad de condiciones sociodemográficas y contextuales (entornos urbanos / rurales) presentes en la región.

Una vez analizadas las implicaciones sociales a nivel regional, los esfuerzos de la investigación cambian el enfoque al análisis de factores determinantes que afectan la pobreza energética añadidos a la precariedad económica, como los edificios, la estructura del hogar y los hábitos de consumo de energía. El objetivo perseguido es el estudio de las características del edificio en el que se encuentran las viviendas sociales, la aplicación de la simulación energética en este tipo de casos y el análisis de este tipo de simulaciones por ordenador, aplicadas a hogares en riesgo de vulnerabilidad energética. Para realizar evaluaciones energéticas en edificios de vivienda social, se aplican herramientas de simulación dando como resultado diferencias significativas entre los consumos de energía reales y los simulados.

Las características del edificio no son necesariamente los factores más relevantes cuando se trata de la pobreza energética. La estructura de los hogares y el comportamiento de los residentes también juegan un papel importante. El gasto en energía y el tipo de contrato de suministro se consideran relevantes, principalmente en el caso de la electricidad. El mayor gasto de energía en los casos analizados es la calefacción, que los inquilinos de viviendas sociales infrautilizan en gran medida. Este hecho les impide, en muchos casos, alcanzar condiciones mínimas de temperatura de confort interior de 21ºC.

La optimización de los contratos y las tarifas energéticas, así como la diversificación y el cambio a fuentes de energía más asequibles para la calefacción, a diferencia de la calefacción por resistencia eléctrica, son las recomendaciones más directas para quienes viven en viviendas sociales a la hora de paliar la pobreza energética. Las viviendas con solo suministro de electricidad tienen costes de energía que son casi el doble que los de aquellas que usan gas natural para agua caliente sanitaria y calefacción, incluso en los casos de edificios que son más eficientes en términos de energía.

La pobreza energética se traduce en menores niveles de confort térmico en los hogares afectados. La diferencia entre los hábitos y perfiles de usuario predeterminados y reales es la causa principal de las desviaciones entre el consumo de energía real y el consumo de energía simulado en la vivienda social. La temperatura de confort estándar en simulaciones energéticas (21ºC) no es aplicable para los hogares vulnerables. En los hogares analizados, los horarios de calefacción simulados deberían reducirse significativamente, a entre 3 y 3,5 horas de servicio de calefacción por día en la temporada de invierno, para que coincida con el consumo de calefacción real en la muestra de vivienda social en estudio, pese a que los residentes confirman un uso mucho más extenso.

Cabe señalar que cualquier mejora en la envolvente del edificio no se traduciría en un ahorro real de energía, sino que contribuiría a mejorar las condiciones de confort térmico de las personas que viven en viviendas sociales, y por lo tanto tendría un impacto social positivo bastante separado del ahorro económico. La razón principal es que las personas que viven en hogares que padecen pobreza energética ya viven por debajo de las condiciones estándar de confort térmico. Por tanto, es probable que las mejoras en el rendimiento energético mejoren el confort térmico de los residentes al acercar la temperatura al nivel estándar en lugar de reducir su bajo gasto de energía.

Los resultados obtenidos pueden contribuir a mejorar el uso de las herramientas de simulación para medir la pobreza energética en la vivienda social. Estos resultados también se pueden utilizar para respaldar los procesos de toma de decisiones relacionados con la gestión de los hogares en la vivienda social, por ej. en relación con la restauración de edificios, el mantenimiento y la gestión del suministro de energía.

El último objetivo de la investigación fue establecer una propuesta de soluciones y acciones paliativas para la vivienda social desde el punto de vista de los edificios. Este paso se centró en el uso de los resultados del estudio anterior para llevar a cabo un análisis de medidas de eficiencia energética y soluciones de rehabilitación para edificios de viviendas sociales como una forma de mitigar la pobreza energética, utilizando herramientas de simulación de energía. El análisis se realizó en un edificio representativo de viviendas sociales en España, donde se evaluaron 250 posibles medidas de eficiencia energética desde un punto de vista económico.

Las conclusiones muestran que la restauración de edificios es una inversión segura para minimizar el problema de la pobreza energética recurrente en los hogares. El ahorro de energía puede contribuir tanto a reducir la carga del gasto energético para los consumidores vulnerables como a aumentar su nivel de confort térmico con un gasto similar. Sin embargo, debido al sistema de tenencia de la vivienda, se debe diseñar un plan de implementación de medidas de colaboración entre los residentes y el propietario o gerente del edificio, para evitar medidas redundantes y maximizar el resultado de la inversión combinada.

Al seleccionar las mejores opciones de eficiencia energética de una lista de oportunidades, se deben considerar las características de los edificios residenciales y la tipología de los hogares vulnerables. Se han encontrado aproximadamente 100 medidas de eficiencia energética aplicables al edificio representativo analizado, y 64 de ellas no tienen inversión o es inferior a 100 € por vivienda.

Se recomienda comenzar por las medidas que no requieran inversión, ya que el resultado de estas medidas es inmediato en el tiempo. Para estas medidas, el criterio de priorización debe ser la cantidad creciente de ahorro de energía esperado.

Para las inversiones necesarias, se necesita un umbral de presupuesto para compartir las inversiones entre los arrendatarios beneficiarios y la propiedad. Los residentes de viviendas sociales a menudo se ven afectados por la vulnerabilidad energética y su capacidad de inversión suele ser baja. Sin embargo, el 70% de las medidas de eficiencia energética caen bajo su responsabilidad. Por lo tanto, su participación y compromiso es crucial.

Para asegurarse de que el umbral del presupuesto esté establecido correctamente, pueden usarse las curvas exponenciales ahorro-inversión para calcular el máximo ahorro posible mediante la implementación de inversiones secuenciales en eficiencia energética. Estas curvas también ayudan a determinar el límite a partir del cual una inversión adicional no contribuye significativamente a obtener un ahorro de energía adicional.

El criterio de clasificación basado en el retorno de la inversión más bajo (payback) produce mejores resultados de ahorro para el mismo presupuesto de inversión que la clasificación por menor inversión de las medidas. El ahorro anual agregado para medidas sin inversión es de 534 €/vivienda, mientras que el ahorro anual agregado de medidas con inversión dentro de los límites presupuestarios es de 774 €/vivienda con una amortización simple de 6,3 años. Al corregir con los consumos reales respecto a los simulados, los ahorros se reducen a 410 €/vivienda para medidas no relacionadas con la inversión, y 593 €/vivienda con una amortización de 8,2 años.

Las herramientas de simulación de energía han demostrado ser asequibles, rápidas y adecuadas para evaluar el potencial de ahorro de energía de cada medida implementada en un edificio. Sin embargo, los valores de ahorro reales suelen ser un 20-30% más bajos que los resultados simulados, principalmente porque la demanda simulada se calcula para cumplir con las condiciones de confort térmico estándar que no siempre se cumplen en este tipo de viviendas debido a sus limitaciones económicas. Además, el efecto cruzado de la implementación simultánea de medidas de eficiencia energética que abordan la misma categoría de ahorro de energía es significativo y debe tenerse en cuenta al evaluar los períodos de amortización.

Los resultados del estudio demuestran que, con niveles mínimos de inversión, compartidos por los inquilinos y la propiedad del edificio, se puede obtener una cantidad considerable de ahorro (hasta el 55% del consumo inicial de energía). La prioridad de implementación que se debe seguir es primero las medidas que no son de inversión y luego las de retorno más corto, siempre utilizando los datos de consumo reales y teniendo en cuenta el efecto cruzado de las medidas simultáneas que afectan la misma demanda de energía. Aunque la implementación de medidas de eficiencia energética podría no brindar el beneficio económico deseado, se puede lograr un beneficio social más intangible en forma de mayores niveles de confort térmico para los hogares de vivienda social.

6.1 Aportaciones científicas

El resumen de las principales contribuciones de esta tesis doctoral al estado del arte en el campo de la pobreza energética es:

• La propuesta y validación de un índice compuesto de pobreza energética en la vivienda social, desde una perspectiva de pobreza energética de los hogares que permite considerar varios factores, como tipo de construcción, estructura del hogar, gasto de energía e ingresos de la vivienda, en un solo índice.

• La identificación de necesidades y recursos de capacitación para impulsar el papel de los trabajadores sociales como primer nivel de ayuda a los usuarios vulnerables para mitigar los problemas de pobreza energética, no solo mediante la emisión de ayudas económicas sino también capacitándoles para brindar consejos y recomendaciones sobre el consumo de energía doméstica a través de programas de formación y herramientas de evaluación rápida del desempeño energético en hogares.

• Un análisis empírico en profundidad basado en datos reales y simulados de las principales variables y factores que afectan a los inquilinos de viviendas sociales en España, desde las características del edificio, los equipos de climatización y ventilación, los patrones de consumo de energía y la estructura del hogar.

• Una evaluación del uso de herramientas de simulación energética de edificios en el caso de viviendas sociales, con la identificación de los principales factores de divergencia entre los consumos reales y simulados y la cuantificación del impacto que tienen los aspectos de comportamiento en esta diferencia debido a las limitaciones en el consumo de energía derivadas de las limitaciones económicas de estos hogares vulnerables.

• Una metodología efectiva para la priorización y despliegue de medidas de eficiencia energética económicamente viables, con un enfoque sistemático de colaboración entre residentes vulnerables de viviendas sociales alquiladas y entidades administradoras de edificios públicos para maximizar el impacto de las medidas tanto en el gasto energético como en la mejora del confort térmico.

6.2 Líneas de investigación futuras

Como la pobreza energética es un problema amplio, multidisciplinar y complejo, se deben abordar muchos temas abiertos a agregar a este estudio y completar el trabajo realizado hasta el momento. Los pasos de investigación futuros deben ir en las siguientes direcciones:

- Ampliar el alcance geográfico del análisis. El futuro estudio debería comprender un área geográfica más amplia que abarque otras regiones, no solo en España sino en otros países europeos, para observar la influencia del clima, la cultura local y las diferencias arquitectónicas. Las regulaciones locales y los sistemas públicos de ayuda paliativa también pueden tener un gran impacto en la vulnerabilidad energética en la vivienda social.
- Ampliar el tamaño de muestra del caso de estudio. El estudio se basa en datos reales de varios edificios de vivienda social en Zaragoza. Estos edificios son representativos de la vivienda pública social en España y ofrecen una variedad de características arquitectónicas, equipos y hogares, pero una muestra más grande puede aportar un conocimiento más amplio.
- Hacer un análisis de la evolución de la muestra a lo largo del tiempo. Extraer datos similares de la misma muestra algunos años más tarde pondría en perspectiva la evolución de las variables bajo análisis, y el estado de los inquilinos de la vivienda en referencia a factores económicos externos, desarrollos normativos y posibles acciones de mejora de los edificios.
- Extender la cantidad de variables utilizadas en el análisis. Algunas variables sociodemográficas como la cualificación, la inmigración, el empleo ... permitirían estudiar cómo la sociedad y los factores de riesgo de exclusión también pueden afectar al problema de la pobreza energética.

- Ampliar el análisis de viviendas sociales públicas de alquiler en bloques de apartamentos ubicados en áreas urbanas a otros tipos de vivienda social, principalmente viviendas privadas y áreas rurales con diferentes tipos de edificios.

Ampliar la muestra para dar respuesta a las limitaciones anteriores proporcionaría una mejor y más completa imagen del problema de la pobreza energética, permitiendo realizar análisis comparativos entre viviendas sociales públicas y privadas, edificios rurales y urbanos y otras áreas geográficas y climáticas. Este análisis requiere costosas campañas de recolección de datos que permanecen abiertas para un futuro estudio.

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8 Annex

8.1 Annex 1: Table of variables for energy vulnerability assessment in households.

Building characteristics and envelope		
Variable	**Type of Variable**	**Units**
Year of construction	Quantitative	Years
Number of years living in this housing	Quantitative	Years
Surface	Quantitative	m^2
Total number of rooms	Quantitative	Number
North facade orientation	Qualitative	Yes/No
Building height	Quantitative	Number
Average winter temperature	Quantitative	ºC
% Surface openings in facades	Quantitative	% of m^2
Total number of windows	Quantitative	Number
Average summer temperature	Quantitative	ºC
Rented accommodation	Qualitative	Yes/No
Users Home Owners	Qualitative	Yes/No
Housing renovated in last 10 years	Qualitative	Yes/No
Double windows, double glazing	Qualitative	Yes/No
Window frame type	Qualitative	
Type door window	Qualitative	
Housing apartment block	Qualitative	Yes/No
Block of apartments	Qualitative	Yes/No
Awnings or sunscreens	Qualitative	Yes/No
Photovoltaic generation	Qualitative	Yes/No
Centralized heating	Qualitative	Yes/No
Gas heating boiler	Qualitative	Yes/No
Propane heating boiler	Qualitative	Yes/No
Heating boiler diesel	Qualitative	Yes/No

Heating stoves conventional electric	Qualitative	Yes/No
Heating stoves electricity low consumption	Qualitative	Yes/No
Heating pump	Qualitative	Yes/No
Heating stove / butane / propane	Qualitative	Yes/No
Heating stove / wood / fireplace	Qualitative	Yes/No
Individual heating stove / pellets	Qualitative	Yes/No
Heating installation Year Community	Quantitative	Years
Year of installation Heating Gas Boiler Individual	Quantitative	Years
Installation year Propane Heating boiler	Quantitative	Years
Heating Boiler Installation year Individual diesel	Quantitative	Years
Heating Stoves year conventional power plant	Quantitative	Years
Year of installation electric heating stoves	Quantitative	Years
Installation year pump heating cooling / heating	Quantitative	Years
Heating installation year stove /butane / propane	Quantitative	Years
Year of installation heating wood stove/fireplace	Quantitative	Years
Heating installation year individual pellet stoves	Quantitative	Years
Air conditioning central air conditioning	Qualitative	Yes/No
Individual air conditioned splits	Qualitative	Yes/No
Number of individual air conditioned split	Quantitative	Number
Year of installation central air conditioning	Quantitative	Years
Year of installation air conditioned splits	Quantitative	Years
Community individual use level for hot water	Qualitative	Yes/No
Oil-fired boiler hot water	Qualitative	Yes/No
Gas boiler hot water	Qualitative	Yes/No
Hhot water heater butane / propane	Qualitative	Yes/No
Hot water electrical heater	Qualitative	Yes/No
Hot water boiler pellets	Qualitative	Yes/No
Hot water solar collectors	Qualitative	Yes/No

Year of installation of shared hot water facility	Quantitative	Years
Year of installation oil-fired boiler hot water	Quantitative	Years
Year of installation gas hot water boiler	Quantitative	Years
Year of installation butane / propane hot water	Quantitative	Years
Year of installation of hot water electric heater	Quantitative	Years
Year of installation pellet hot water boiler	Quantitative	Years
Year of installation of solar hot water collectors	Quantitative	Years
% of heated surface	Quantitative	% of m^2
Lifts	Qualitative	Yes/No
Common leisure areas	Qualitative	Yes/No
Fuel central heating	Qualitative	Text
Number of neighbours	Quantitative	Number of dwellings
Common shared services monthly fee	Qualitative	€

Building Equipment and appliances

Variable	**Type of Variable**	**Units**
Refrigerator / freezer	Qualitative	Yes/No
Freezer	Qualitative	Yes/No
Furnace	Qualitative	Yes/No
Microwave	Qualitative	Yes/No
Ceramic plate cooker	Qualitative	Yes/No
Induction plates	Qualitative	Yes/No
Cooking gas	Qualitative	Yes/No
Washing machine	Qualitative	Yes/No
Dryer	Qualitative	Yes/No
Dishwasher	Qualitative	Yes/No
Conventional bulbs / halogen	Qualitative	Yes/No
Light bulbs / LED	Qualitative	Yes/No
Television	Qualitative	Yes/No

Number of refrigerator / freezer	Quantitative	Number
Number of freezer items	Quantitative	Number
Number of furnace	Quantitative	Number
Microwave number of	Quantitative	Number
Number of ceramic or plates	Quantitative	Number
Number of induction plates	Quantitative	Number
Number of gas cooker	Quantitative	Number
Number of washing machines	Quantitative	Number
Number of dryers	Quantitative	Number
Number of dishwashers	Quantitative	Number
Number of conventional bulbs / halogen	Quantitative	Number
Number of light bulbs / LED	Quantitative	Number
Number of items television	Quantitative	Number
Plug regulator in the water heater	Qualitative	Yes/No
Heating time programmer	Qualitative	Yes/No

Energy expenditure and assistance

Variable	**Type of Variable**	**Units**
Electricity supplier	Qualitative	
Contracted power	Quantitative	kW
Type of contract	Qualitative	
Digital smart meter	Qualitative	Yes/No
Electric contract on behalf of the property owner	Qualitative	Yes/No
Flat rate tariff	Qualitative	Yes/No
Average expenditure winter - electricity	Quantitative	Euros
Average expenditure winter - gas	Quantitative	Euros
Average expenditure winter - butane	Quantitative	Euros
Average expenditure winter - propane	Quantitative	Euros
Average expenditure winter - oil	Quantitative	Euros
Average expenditure winter - pellets	Quantitative	Euros

Average expenditure winter - firewood	Quantitative	Euros
Average expenditure winter - others	Quantitative	Euros
Community average expenditure winter - heating control	Quantitative	Euros
Average expenditure summer - electricity	Quantitative	Euros
Average expenditure summer - gas	Quantitative	Euros
Average expenditure winter - butane	Quantitative	Euros
Average expenditure winter - propane	Quantitative	Euros
Average expenditure summer – diesel	Quantitative	Euros
Average expenditure summer - pellets	Quantitative	Euros
Average expenditure summer - firewood	Quantitative	Euros
Average expenditure summer – others	Quantitative	Euros
Average expenditure summer - community heating control	Quantitative	Euros
Average expenditure - electricity rest	Quantitative	Euros
Average expenditure - gas rest	Quantitative	Euros
Average expenditure summer - butane	Quantitative	Euros
Average expenditure summer - propane	Quantitative	Euros
Average expenditure rest – oil	Quantitative	Euros
Average expenditure rest - pellets	Quantitative	Euros
Average expenditure rest - firewood	Quantitative	Euros
Average expenditure rest – others	Quantitative	Euros
Average expenditure rest - central heating	Quantitative	Euros
Net income per month average	Quantitative	Euros
Total energy expenditure relative to income	Quantitative	**%**
Perceive the Aragonese Insertion Income	Qualitative	Yes/No
Euros per month	Quantitative	€/month
Perceive other public financial aid	Qualitative	Yes/No
Euros per month	Quantitative	€/month
Social services aid request	Qualitative	Yes/No

Social services request (please specify)	Qualitative	
Aid applied for social services	Quantitative	€/month
Aid received social services	Quantitative	€/month
Aid request NGO	Qualitative	Yes/No
Aid request NGO (specify)	Qualitative	
NGO aid requested	Quantitative	€/month
NGO aid received	Quantitative	€/month
Aid request family and friends	Qualitative	Yes/No
Aid requested family and friends	Quantitative	€/month
Aid received family and friends	Quantitative	€/month
Aid request bank	Qualitative	Yes/No
Bank aid request (please specify)	Qualitative	
Bank or aid requested	Quantitative	€/month
Aid received bank	Quantitative	€/month
Others aid request	Qualitative	Yes/No
Others aid request (specify)	Qualitative	
Aids requested to others	Quantitative	€/month
Aid received others	Quantitative	€/month
Outages in the last year	Qualitative	Yes/No
Number of power outages in the last year	Quantitative	Number
Gas outages in the last year	Qualitative	Yes/No
Number of gas outages in the last year	Quantitative	Number
Rental assistance received	Qualitative	Yes/No
Number of rental assistance	Quantitative	€/month
Family structure and habits		
Variable	**Type of Variable**	**Units**
Floor number	Quantitative	Level
Number of people living at home are:	Quantitative	Number
Family home	Quantitative	Yes/No

Shared housing	Quantitative	Yes/No
Nationality of household maintainer	Quantitative	
Number of women	Quantitative	Persons
Number of men	Quantitative	Persons
Number of children under 16 years	Quantitative	Persons
Number of over 65s	Quantitative	Persons
Number of active people (working)	Quantitative	Persons
Number of unemployed persons	Quantitative	Persons
Number of persons studying	Quantitative	Persons
Number of retired persons	Quantitative	Persons
Number of persons doing full time housework	Quantitative	Persons
Use level for centralized heating	Quantitative	0-10
Heating use level for city gas boiler	Quantitative	0-10
Use level for propane heating boiler	Quantitative	0-10
Using individual diesel heating boiler	Quantitative	0-10
Use level for conventional electric heating stoves	Quantitative	0-10
Use level for low power electric heating stoves	Quantitative	0-10
Use level for heat pump	Quantitative	0-10
Use level for heating stove / butane / propane	Quantitative	0-10
Use level for heating stove / wood / fireplace	Quantitative	0-10
Use level for individual heating stove / pellets	Quantitative	0-10
Use level for central air conditioning	Quantitative	0-10
Use level for individual devices (air conditioned split)	Quantitative	0-10
Community single use level for hot water use	Quantitative	0-10
Use level for oil-fired boiler hot water	Quantitative	0-10
Gas boiler hot water use	Quantitative	0-10
Using hot water heater butane / propane	Quantitative	0-10
Use level for hot water electric heater	Quantitative	0-10

Use level for hot water pellet boiler	Quantitative	0-10
Using hot water solar collectors	Quantitative	0-10
Refrigerator / freezer use	Quantitative	0-10
Freezer use	Quantitative	0-10
Use level for oven	Quantitative	0-10
Use level for microwave	Quantitative	0-10
Use level for ceramic or plates	Quantitative	0-10
Using induction plates	Quantitative	0-10
Use level for gas cooker	Quantitative	0-10
Use level for washing machine	Quantitative	0-10
Use level for tumble dryer	Quantitative	0-10
Use level for dishwasher	Quantitative	0-10
Using conventional bulbs / halogen	Quantitative	0-10
Using low consumption bulbs / LED	Quantitative	0-10
Use level for TV	Quantitative	0-10
We feel ok with the temperature we have at home in winter	Quantitative	0-10
We feel ok with the temperature we have at home in summer	Quantitative	0-10

8.2 Annex 2: List of energy efficiency measures, TRIBE Project.

CODE	ENERGY EFFICIENCY MEASURE DESCRIPTION
ES1	Use silicone, putty or draught excluder to reduce air infiltrations through windows and doors
ES2	Seal air leaks located in all cavities presented in the building
ES3	Close windows and doors when HVAC systems are operating
ES4	Manage properly the opening of windows and doors for natural ventilation
ES5	Periodic and suitable cleaning of windows glass
ES6	Correct use of external solar shading
ES7	Correct use of internal solar shading
ES8	Improve insulation of roller shutter box
ES9	Substitution of roller tape guide
ES10	Maintenance of wood and aluminium windows frame
ES11	Adding a low Emissivity (E) window film
ES12	Adding a solar control window film
ES13	Put foil behind radiators to avoid heating the wall
ES14	Maintenance of room surfaces
EL1	Adding or increasing external insulation in walls
EL2	Adding or increasing internal insulation in walls
EL3	Adding insulation in air chambers of walls through injection
EL4	Installation of a ventilated façade
EL5	Adding or increasing external insulation in roofs
EL6	Adding or increasing internal insulation in roofs
EL7	Adding or increasing external insulation in floors
EL8	Adding or increasing internal insulation in floors
EL9	Installation of efficient windows (double glazing with aluminium frames with thermal break)
EL10	Installation of efficient windows (double glazing with wood frames)
EL11	Installation of efficient windows (double glazing with PVC frames)
EL12	Installation of efficient windows (low-E double glazing with aluminium frames with thermal break)
EL13	Installation of efficient windows (low-E double glazing with wood frames)
EL14	Installation of efficient windows (low-E double glazing with PVC frames)
EL15	Installation of efficient windows (solar control double glazing with aluminium frames with thermal break)

EL16	Installation of efficient windows (solar control double glazing with wood frames)
EL17	Installation of efficient windows (solar control double glazing with PVC frames)
EL18	Installation of efficient windows (triple glazing with aluminium frames with thermal break)
EL19	Installation of efficient windows (triple glazing with wood frames)
EL20	Installation of efficient windows (triple glazing with PVC frames)
EL21	Installation of double windows
EL22	Convert balconies into galleries
EL23	Build a greenhouse
EL24	Installation of a green roof
EL25	Use of appropriate materials for increasing the thermal inertia of the exposed surfaces to radiation
EL26	Improve insulation in thermal bridge areas
EL27	Installation of false ceiling to reduce internal height
EL28	Application of an appropriate solar reflectance coating for the roof
EL29	Application of an appropriate solar reflectance coating for the external walls
EL30	Application of an appropriate solar reflectance coating for the internal walls
EL31	Improvement of the percentage of transparent envelope
EL32	Substitution of transparent for opaque insulated envelope
EL33	Installation of solar tubes
EL34	Build a trombe wall
EL35	Installation of basement windows
EL36	Installation of revolving doors
EL37	Create entrance vestibule with two doors
EL38	Installation of an air-barrier system
EL39	Adding a electrochromic window film
EL40	Installation of fixed external systems for solar shading (louvres)
EL41	Installation of fixed external systems for solar shading (overhangs)
EL42	Installation of mobile external systems for solar shading (louvres)
EL43	Installation of mobile external systems for solar shading (shutters)
EL44	Installation of flexible external systems for solar shading (awnings and blinds)
EL45	Installation of internal solar shading (curtains and blinds)
EL46	Installation of solar shelf
EL47	Use of argon in chambers of double and triple glazing
EL48	Automatic control of mobile and flexible external devices

EL49	Use of Phase Change Materials (PCMs)
EL50	Installation of a green wall
EL51	Convert courtyards into atriums
EL52	Convert traditional in electric blinds to avoid thermal bridges
EL53	Installation of transpired air collectors for ventilation preheating
HS1	Turning off air conditioning systems when rooms are empty
HS2	Upgrade and maintain the filters of the HVAC system
HS3	Adjust the temperature of the thermostat properly
HS4	Adding or repairing HVAC distribution system insulation
HS5	Verify the appropriate operation of timers of the ventilation system
HS6	Use of free-cooling
HS7	Analysis of the combustion and maintenance of heating boilers
HS8	Replacement of the refrigerants fluids in heating and cooling equipment
HS9	Adding or repairing boilers insulation
HS10	Proper operation of the regulatory systems of the temperature of the heating and cooling equipment
HS11	Cleaning the radiator surfaces
HS12	Place the condenser unit in a ventilated area without solar radiation
HS13	Installation of a programmable thermostat
HS14	Purge radiators at the beginning of the heating season
HS15	Use ceiling fans instead of air conditioning when possible
HS16	Relocate thermostats to appropriate areas
HS17	Avoid using personal heaters in air-conditioned spaces
HS18	Turn off kitchen and bath fans immediately after use
HS19	Cleaning heat exchangers of chillers
HS20	Installation of dampers on flue gas ducts
HS21	Installation of motion sensors for HVAC systems
HS22	Installation of humidity sensors
HS23	Installation of an efficient destratification fan system
HS24	Installation of thermostatic radiator valves
HS25	installation of a radiator booster
HL1	Installation of a condensing boiler
HL2	Installation of a biomass boiler
HL3	Installation of an evaporative condenser
HL4	Installation of heat recovery in the ventilation air
HL5	Installation of Variable Frequency Drives (VFDs) on motors
HL6	Installation of high efficient motors for fans and pumps

HL7	Installation of a wireless room energy control system
HL8	Installation of a desiccant dehumidification system
HL9	Installation of pollutant detectors
HL10	Installation of earth-air heat exchangers
HL11	Installation of radiant floor heating
HL12	Installation of radiant ceiling cooling
HL13	Installation of an absorption cooling system
HL14	Installation of Variable Refrigerant Flow (VRF) system
HL15	Installation of micro-cogeneration boilers
HL16	Replace V-belts with cogged or synchronous belt drives
HL17	Installation of a low temperature boiler
HL18	Replacement of electric radiators or unit heaters by heat pumps
HL19	Installation of electronic expansion valves (EEVs) in the cooling equipment
HL20	Installation of modulating burners and oxygen sensors
HL21	Replacement of diesel and fuel oil per natural gas
HL22	Convert the constant volume system to a Variable Air Volume (VAV) system
HL23	Install small modular boilers
HL24	Convert the primary/secondary chilled water plant to variable flow primary
HL25	Installation of a thermally active building system (TABS)
HL26	Installation of aerothermal energy
HL27	Installation of zoning valves with time and temperature controls
HL28	Installation of air curtains
HL29	Installation of a gas powered heat pump
HL30	Eliminate reactive power with the installation of capacitor banks
DS1	Lower the DHW temperature set-point
DS2	Adding or repairing tank insulation
DS3	Adding or repairing DHW distribution systems
DS4	Maintenance and inspection of DHW pumps
DS5	Installation of a timer for the DHW recirculation pump
DS6	Installation of a timer for the DHW boiler
DS7	Installation of mixing valves in the outlet of the DHW tank
DS8	Installation of taps with flow reduction (faucet aerator)
DS9	Adding or repairing water heaters insulation
DS10	Installation of low-flow showerheads
DS11	Use shower instead of bath
DS12	Fix dripping taps
DS13	Installation of thermostatic taps
DS14	Installation of motion sensor faucets

DS15	Limit shower length to 5–7 minutes
DS16	Cleaning the DHW tank to avoid sediments
DS17	Disconnect the DHW tank in case it is not working for more than three days
DS18	Wash hands with cold water instead of warm water
DL1	Substitution of instant system for accumulation system
DL2	Installation of a hot water return circuit
DL3	Installation of heat recovery in the condensers of the air conditioning system
DL4	Installation of a CO_2 heat pump
DL5	Change from an individual to a collective DHW system
DL6	Installation of Drain Water Heat Recovery (DWHR) systems
DL7	Replace existing DHW system with heat pump water heaters
LS1	Change to task lighting method when required
LS2	Change to accent lighting when required
LS3	Cleaning and maintenance of lamps and luminaires regularly
LS4	Reduce the number of lamps
LS5	Reduce the number of luminaires
LS6	Turn off lighting in unused rooms or zones
LS7	Appropriate orientation of the work place
LS8	Lighting zoning through manual switches
LS9	Programming different scenarios for the same place
LS10	Turn off the luminaires close to windows when there is enough daylighting
LS11	Optimized interior security lighting
LS12	Place floor lamps and hanging lamps in corners
LL1	Installation of program warm-start ballast
LL2	Installation of electronic ballast
LL3	Replacement of conventional halogen lamps by Infrared Reflective Coating (IRC) halogen lamps
LL4	Replacement of incandescent lamps by Compact fluorescent lamps (CFLs)
LL5	Installation of Lighting Emitting Diode (LED) lamps
LL6	Replacement of fluorescent tubes by others with less diameter
LL7	Replacement of standard fluorescent tubes by triphosphorous fluorescent tubes
LL8	Installation of more efficient luminaires with suitable light distribution
LL9	Installation of presence detectors in sporadic use zones
LL10	Installation of time delay switches in sporadic use zones
LL11	Installation of manual potentiometric switches
LL12	Installation of programmable timer switches

LL13	Installation of daylighting sensors (on/off)
LL14	Installation of daylighting sensors (dimmer)
LL15	Reduce lamps wattage or illuminance where there is over-illumination
EDS1	Use of multiple power strips with switch and/or programmable plugs
EDS2	Set the energy saving mode of the electrical equipment
EDS3	Turning off the screen of the monitor
EDS4	Adjusting the brightness of the TV or monitor screen to a medium level
EDS5	Using the desktop screen in a proper way
EDS6	Using the screensaver in a proper way
EDS7	Use and manage properly the energy consumption of printers and photocopiers
EDS8	Turning off the TV
EDS9	Set the economic program of the washing machine
EDS10	Set the economic program of the dishwasher
EDS11	Set the economic program of the oven
EDS12	Set the appropriate temperatures of refrigerator and freezer
EDS13	Unplug battery chargers when their use is not necessary
EDS14	Use of networking printers
EDS15	Use pressure cookers
EDS16	Use a toaster oven or microwave instead of the oven
EDS17	Turning off communal equipment at the end of the day
EDS18	Air dry dishes instead of using the dishwasher’s drying cycle.
EDS19	Wash only full loads of dishes and clothes
EDS20	Turn off the oven or the electric cooker before finishing
EDS21	Air dry clothes
EDS22	Regularly defrost manual defrost refrigerators and freezers
EDS23	Cover liquids and wrap foods stored in the refrigerator
EDS24	Repair refrigerator door seals
EDS25	Match the size of the pan to the heating element
EDS26	Use a covered kettle or pan or electric kettle to boil water
EDS27	Use the washing machine with cold water
EDS28	Cleaning of the backside of the fridge
EDS29	When cooking on the range, use pot lids to help food cook faster
EDS30	Promote the use of solar chargers
EDS31	Using hand cleaners instead of electrical ones
EDS32	Try to optimize the delivery of print jobs or photocopies
EDS33	Remove refrigerators from places next to heat sources
EDS34	Print only necessary documents

EDS35	Decalcify home appliances
EDS36	Use dishwasher instead of hand wash of dishes
EDS37	Install coffee machines with thermal jug
EDS38	Ironing efficiently
EDS39	Defrost food naturally instead of using microwave
EDS40	Disconnect the fridge in case it is not working for long times
EDS41	Dry hair naturally
EDL1	Purchase of Energy Star label devices
EDL2	Purchase of A+++ electrical appliances
EDL3	Purchase of laptops instead of desktop computers
EDL4	Purchase of monitors with LCD screen
EDL5	Purchase double-sided copiers and printers
EDL6	Purchase bithermic washing machines
EDL7	Purchase bithermic dishwashers
EDL8	Install vending machine misers
EDL9	De-lamp vending machines
EDL0	Purchase of induction plates
EDL11	Consider the use of a common laundry instead of in-unit washing machine
OS1	Pressing one button to call the lift in case there are several ones
OS2	Use stairs instead of lifts
OS3	Inspection and maintenance of lifts
OS4	Sensitizing of occupants through workshops
OS5	Wear adequate clothing
OS6	Optimization of the conditions of the electric bill
OS7	Create reminders and promotional materials to raise awareness
OS8	Move the furniture or objects that block the natural light
OS9	Remove furniture from the front of HVAC terminal units
OS10	Implementation of a compressed work schedule
OS11	Allow employees to work from home on alternate days
OL1	Installation of solar thermal panels
OL2	Installation of photovoltaic panels
OL3	Installation of direct traction electric lifts
OL4	Installation of mechanisms of selective manoeuvre for several lifts
OL5	Installation of a building energy management system (BEMS)
OL6	Installation of an ICT system
OL7	Installation of smart meters
OL8	Installation of Geothermal Heat Pump (GHP)

OL9	Installation of micro wind turbines
OL10	Hire a qualified company to conduct an energy audit of the building
OL11	Installation of an Energy Storage System (ESS)
OL12	Installation of fuel cells
OL13	Integration of hybrid Photovoltaic Thermal hybrid solar collectors (PVT)