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Addressing energy poverty in an integrated way.

An interdisciplinary characterisation of Spanish vulnerable households and proposal for implementing feasible technical and policy solutions

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Pour réussir dans le monde, retenez bien ces trois maximes: voir, c'est savoir; vouloir, c'est pouvoir; oser, c'est avoir[i].

"Barberine", Acte I, Scène IV, Alfred de Musset

[i] *To succeed in the world, remember these three maxims: seeing is knowing; where there is a will there is a way; to dare is to have.*

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Roberto Barrella

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Summary

Nowadays, energy is often recognised as a basic good for full human development and a strategic and geopolitical issue. Indeed, the lack of affordable energy makes people unable to live a decent life and adequately participate in society. Thus, addressing this energy deprivation by improving people's affordability and access to this essential good is one of the unsolved issues of the modern world. This should not be considered just an individual issue but as a society's duty of ensuring 'access to affordable, reliable and modern energy services', as stated in the 7th UN Sustainable Development Goal (SDG7).

In developed countries, energy vulnerability is an expression of the socio-economic issues of energy systems, where energy poverty would be an externalisation of these weaknesses. Moreover, energy deprivation could be identified as a manifestation of general poverty. Indeed, the former should be studied in connection with economic poverty since this position of energy vulnerability is closely linked to a low income level. However, energy poverty is also caused by specific factors such as high energy prices, low housing energy efficiency, and lack of information on energy end-use. These are particular conditions that may affect the capability of individuals or families to meet their domestic energy needs or access better market conditions. Therefore, addressing this issue in an integrated way would have massive benefits for individuals and society.

Based on this premise, this thesis aims to contribute to the literature on energy poverty in a developed country such as Spain within the European context. This scientific journey starts by exploring when and how this social issue was recognised in Europe and identifying the studies and policies that have attempted to define, measure and address energy poverty in Spain and some neighbour countries, i.e. the UK, France and Portugal. Therefore, the literature and policy gaps are identified, thus raising some outstanding and unaddressed queries that lead to the definition of the general scope of the thesis, which is to enhance the knowledge on the measurement and fight against energy poverty in the case study country within the EU framework. Thereafter, four sub-objectives are proposed to achieve the main one. Each of these goals is unpacked in one chapter of the thesis, which is structured to guarantee a consistent narrative that goes from the characterisation of households' energy needs to the assessment of the effectiveness of different policy solutions. Moreover, the results of the former study are used to propose novel energy poverty indicators and analyse the feasibility of alternative technological solutions to combat energy poverty in block dwellings.

Energy characterisation of Spanish households

This work proposes a bottom-up model to estimate the Spanish households' theoretical energy expenditures according to their characteristics, which was selected as a reference in the Spanish National Strategy against Energy Poverty 2019-2024 (SNSEP). Specifically, this model was developed to assess each Spanish household's Required ENergy Expenditure (RENE), i.e. the theoretical energy expenditure that a household would have to pay to meet its required energy needs, including thermal and electrical uses. The former services are estimated by applying the Required Thermal Energy

Expenditure (RTEE) sub-model, which relies on the Spanish building regulation and calculates the required costs for space heating/cooling and domestic hot water (DHW) preparation by considering basic household features (e.g. the climate zone of the residence locality, the dwelling's construction age and floor area, and the household size). The last two mentioned parameters, together with the household composition, are also included as inputs of the Required ELectricity Expenditure (RELE) sub-model, which estimates the annual domestic energy costs for electrical uses, i.e. lighting, electrical appliances and cooking.

The RENE model is proposed as a tool to enhance the 'energy diagnosis' in energy-poverty studies. In this sense, some of its direct and indirect uses are presented in this thesis. Regarding the primary applications, this thesis employs the model to analyse the 'winter energy needs' (space heating during winter and domestic hot water preparation throughout the year) at the provincial level. Moreover, this work carries out an energy characterisation of a sample of vulnerable families attended by a Spanish NGO, i.e. ECODES. Furthermore, the model's implementation into an energy-expenditures' assessment tool for vulnerable (and non-vulnerable) households is described. Beneficial results and insights were deducted from these model's applications:

- The RTEE mainly depends on the climate zone of the residence locality, the building thermal enclosure, the thermal systems' performance, and the dwelling and household size. In this sense, the national average required heating-and-DHW expenditure is €1,055 per year, but the average one in the coldest province (*León*) is six times higher than the warmest province's one (*Las Palmas*). Moreover, in cold climates, the thermal energy carrier's and system's election significantly impact the thermal energy burden.
- A Spanish household's RELE, averagely €624 per year (with a tariff without time discrimination), is mainly influenced by its size and composition. Regarding the latter, families with unemployed or retired people, pensioners for other reasons, and homemakers require more energy. On the other hand, three electrical appliances stand out as those with the highest electricity consumption: refrigerator, freezer, and kitchen stoves.
- 'External factors' that could also significantly affect the required domestic energy expenditures are the energy prices and taxation. These features are carefully analysed in this work (e.g. including a 'before tax' scenario for vulnerable consumers), giving the growing concern due to the current energy crisis.

A novel indicator to measure hidden energy poverty

This work presents a novel methodology to estimate the extent and depth of hidden energy poverty (namely, the HEP indicator), intended as an *underspending* issue. The proposed approach requires the application of two criteria. The former makes it possible to estimate the share of households with low absolute energy expenditure (energy *underspending*) by applying a threshold based on the RENE model. The latter criterion is based on an income threshold and filters (from the first sample) the families or individuals underconsuming because of an affordability issue, i.e. it identifies the share of households in hidden energy poverty (HEP extent). Moreover, the energy poverty gap (HEP depth) is calculated as the average difference between the absolute energy expenditure threshold and the actual energy expenditure of energy-poor households. Finally, this work analyses the sensitivity of results to the assumptions made for the two proposed thresholds, thus presenting an alternative 'adjusted to household's comfort strategy' scenario.

The application of this methodology to the Spanish case study shows some outstanding insights:

- Hidden energy poverty is a dimension of the overall phenomenon that cannot be overlooked. Indeed, in 2019, according to the HEP indicator, 25% of Spanish households were affected by this social issue. In the same year, the average 'energy poverty gap' per household was €374. Moreover, the national budget needed for a potential hidden-energy-poverty-eradicating policy was eight times higher than the budget earmarked for energy consumption subsidies.
- The residence region, household size and income level are critical determinants of the possibility of being energy poor. Respectively, households living in *Extremadura*, with more than four members and belonging to the first income decile, are the most vulnerable to this social issue.
- Moreover, the building age significantly influences this issue, i.e. families living in old dwellings have a higher HEP share than those residing in recently constructed housing. On the other hand, tenants and families/individuals living in rural areas are also particularly vulnerable to hidden energy poverty.

Techno-economic feasibility study of centralised air-water heat pumps to face energy poverty in Spain

The techno-economic feasibility of electrically (EHP) and gas-engine (GHP) driven centralised air-water heat pumps is studied to eventually consider them as alternative solutions for vulnerable households living in block dwellings. The novelty of this analysis lies both on the study of the use of centralised air-water heat pumps to meet the heating demand in a sector and a country where they are not commonly installed (i.e. the Spanish residential sector) and their evaluation as measures to fight energy poverty. In this sense, the two studied technologies have been investigated as a retrofit of the current heating system based on radiators, thus, the operation temperatures of the heat pumps are adapted to this configuration. Regarding the required hourly heating demand, an advanced version of the model presented in previous studies is applied, which also considers the thermal insulation level of the building. After that, two models are proposed to obtain the performance of the EHP: one for the best efficiency point and another for the off-design operation. On the other hand, two different devices are considered for the GHP study, having a design heating capacity of 75 kWth and 25 kWth (the latter is used to cover the peak of the demand). Moreover, an economic analysis is performed by using the levelised cost of heating (LCOH) method, allowing the author to compare the studied heat pumps with conventional technologies such as individual and centralised natural gas boilers.

According to the results of this work, the centralised air-water EHPs and GHPs can be considered promising systems to tackle energy poverty in Spanish vulnerable households living in block dwellings. Nevertheless, several caveats should be pointed out:

- Regarding the environmental and technical indicators, the results show an excellent performance of the EHPs compared with classical solutions such as decentralised and centralised condensing boilers fuelled by natural gas. On the other hand, the GHPs solution has worse seasonal performance but offers a better response to low temperatures. Although, it should be highlighted that GHPs' performance is calculated against primary energy (natural gas), whereas the EHPs' one is estimated against 'final energy' (electricity).
- Both technologies are very much economically competitive with a de-centralised natural gas boiler. However, measures to reduce the electricity bill in the centralised EHPs case would be highly recommended to lower their operation costs and make them competitive with centralised natural gas boiler solutions. On the other hand, less technological maturity has been detected in GHPs, both in terms of available sizes and refrigerants, which affects the techno-economic feasibility of these thermal systems.
- The parametric analysis shows that the performance indicators of EHPs vary broadly depending on the climate zone considered. Moreover, the heated floor area and the LCOH per unit floor area depend on the building's energy efficiency. On the other hand, for the same building insulation level, as the floor area increases, the system becomes more techno-economical feasible, but it shows worse environmental performance.
- The GHPs' parametric analysis shows that as the number of devices increases, the heating demand covered rises, and the LCOH decreases. Moreover, a second parametric analysis shows that (in the thesis' reference energy prices' scenario) it is more economically feasible to install a GHP in a colder climate.

Assessment of the effectiveness of the main policies against winter energy poverty in Spain

This thesis includes an evaluation of the effectiveness of some of the mitigating and structural energy poverty policies implemented in Spain and proposes alternative aids that would enhance the fight against this social issue in the country. This analysis is performed by applying the RTEE model to a socio-economic assessment of these two kinds of policies. Firstly, this work presents a winter energy poverty (WEP) impact analysis of the current Spanish Thermal Social Allowance (TSA) and proposes an alternative aid, i.e. the Thermal Energy Cheque (TEC). The latter is a cheque for vulnerable consumers whose amount depends on the household's 'winter energy needs'. Secondly, the national average RTEE is calculated under different housing retrofitting strategies implemented in 2030 (including building thermal-enclosure's low-cost retrofitting and thermal systems' replacement measures) to compare their impact on vulnerable households' thermal energy expenditures and WEP. Finally, this work compares the effectiveness and the national financial burden of different implementation scenarios of the analysed measures (mitigating or structural ones). Moreover, it estimates the ‘social cost’ of the retrofitting interventions, thus providing some policy insights, which can be summarised as follows:

- The implementation of the analysed structural measures would achieve a WEP reduction in 2030 between 12% and 37% with respect to the 2019 share, which is a higher impact compared to the one produced by heating allowances such as the current TSA and the proposed TEC. Indeed, the latter policies are estimated to reduce WEP by 1% and 11%, respectively.
- Concerning their national financial burden, the total levelised investment cost to implement the most WEP-effective structural-measures’ scenario (among the analysed ones, i.e. implementing both building thermal enclosure’s low-cost retrofitting and thermal systems’ replacement) is only 23% higher than the budget needed to apply the TEC in a single year.
- Heating allowances are necessary instruments to reduce the energy burden of vulnerable people in the short term. Nevertheless, these mitigating policies should be temporary solutions complemented by structural measures in the medium-long run. Eventually, this ‘rolling’ policy strategy could avoid cronifying energy poverty by improving the energy efficiency of vulnerable households at an affordable social cost.

Overall, this thesis aims to improve the identification and tackling of energy poverty in Spain and the EU. We are confident that the highlighted conclusions and policy recommendations may be helpful for the actors involved at the national and European levels to design and implement policies and strategies in an integrated way.

Resumen

Hoy en día, la energía se suele conceptualizar como un bien básico para el pleno desarrollo humano, así como una cuestión estratégica y geopolítica. De hecho, la falta de energía asequible hace que las personas no puedan llevar una vida digna ni participar adecuadamente en la sociedad. Por lo tanto, abordar esta privación de energía mejorando la asequibilidad y el acceso de las personas a este bien básico es una de las cuestiones sin resolver del mundo moderno. Esto no debe considerarse sólo como una cuestión individual, sino como un deber de la sociedad de garantizar 'el acceso a servicios energéticos asequibles, fiables y modernos', como se indica en el 7º Objetivo de Desarrollo Sostenible de la ONU (ODS7).

En los países desarrollados, la vulnerabilidad energética es una expresión de los problemas socioeconómicos de los sistemas energéticos, donde la pobreza energética sería una externalización de estas debilidades. Además, la pobreza energética podría identificarse como una manifestación de la pobreza general. De hecho, la primera debería estudiarse en relación con la pobreza económica, ya que esta posición de vulnerabilidad energética está estrechamente vinculada a un bajo nivel de ingresos. Sin embargo, la pobreza energética también está causada por factores específicos como los altos precios de la energía, la baja eficiencia energética de las viviendas y la falta de información sobre las implicaciones del uso final de la energía, que son condiciones particulares que pueden afectar a la capacidad de las personas o de las familias para satisfacer sus necesidades energéticas domésticas o para acceder a mejores condiciones de mercado. Por lo tanto, abordar esta cuestión de forma integrada tendría enormes beneficios tanto para los individuos como para la sociedad.

Partiendo de esta premisa, esta tesis pretende contribuir a la literatura sobre la pobreza energética en un país desarrollado como España en estrecha relación con el contexto europeo. Este recorrido científico comienza explorando cuándo y cómo se reconoció este problema social en Europa e identificando los estudios y políticas que han intentado definir, medir y abordar la pobreza energética en España y algunos países vecinos, es decir, Reino Unido, Francia y Portugal. A partir de este proceso de revisión, se identifican las lagunas en la literatura y en las políticas, planteando así algunas cuestiones pendientes que conducen a la definición del alcance general de la tesis, que es mejorar el conocimiento sobre la medición y la lucha contra la pobreza energética en el país del caso de estudio en el marco de la UE. A continuación, se proponen cuatro subobjetivos para alcanzar el objetivo principal. Cada uno de estos objetivos se desglosa en un capítulo de la tesis, que está estructurada para garantizar una narrativa coherente que va desde la caracterización de las necesidades energéticas de los hogares hasta la evaluación de la eficacia de las diferentes soluciones políticas, utilizando también los resultados del primer análisis para proponer nuevos indicadores de pobreza energética y analizar la viabilidad de soluciones tecnológicas alternativas para combatir la pobreza energética en viviendas en bloque.

Caracterización energética de los hogares españoles

Este trabajo propone un modelo bottom-up para estimar el gasto energético teórico de los hogares españoles en función de sus características, modelo que fue seleccionado como referencia en la Estrategia Nacional contra la Pobreza Energética 2019-2024 (ENPE). En concreto, este modelo se desarrolló para evaluar el Gasto Energético Requerido (RENE en su sigla inglesa) de cada hogar español, es decir, el gasto energético teórico que un hogar tendría que abonar para satisfacer sus necesidades energéticas requeridas, incluyendo tanto los usos térmicos como los eléctricos. Los primeros usos se estiman aplicando el submodelo de Gasto Térmico Requerido (RTEE en su acrónimo en inglés), que se basa en el Código Técnico de la Edificación (CTE) y calcula los costes requeridos para la calefacción/refrigeración de espacios y la preparación de agua caliente sanitaria (ACS) teniendo en cuenta características básicas del hogar y de la vivienda, como la zona climática de la localidad de residencia, la antigüedad de la vivienda y su superficie, y el tamaño del hogar. Los dos últimos parámetros, junto con la composición del hogar, se incluyen también como entradas del submodelo de Gasto Eléctrico Requerido (RELE en su sigla inglesa), que estima los costes anuales de energía doméstica para usos eléctricos, es decir, iluminación, electrodomésticos y cocina.

El modelo RENE se propone como una herramienta para mejorar el 'diagnóstico energético' en los estudios de pobreza energética. En este sentido, se presentan en esta tesis algunos de sus usos directos e indirectos. En cuanto a las aplicaciones directas, esta tesis emplea el modelo para analizar las 'necesidades energéticas invernales' (calefacción durante el invierno y preparación de agua caliente sanitaria durante todo el año) a nivel provincial y realiza una caracterización energética de una muestra de familias vulnerables atendidas por una ONG española (ECODES). Además, se describe la implementación del modelo en una herramienta de evaluación de los gastos energéticos de los hogares vulnerables (y no vulnerables). De estas aplicaciones del modelo se deducen valiosos resultados y conocimientos:

- El RTEE depende principalmente de la zona climática de la localidad de residencia, de las prestaciones de la envolvente edificatoria, del equipamiento térmico, del tamaño de la vivienda y del hogar. De hecho, el gasto medio nacional en calefacción y ACS es de 1.055 euros al año, pero el de la provincia más fría (León) es casi tres veces superior al de la segunda provincia más cálida (Cádiz) y seis veces superior al de la provincia más cálida (Las Palmas). Además, en los climas fríos, la elección del suministro para usos térmicos y del equipamiento tiene un alto impacto en la carga de energía térmica.
- El RELE de un hogar español, de 624 euros de media al año (con una tarifa sin discriminación horaria), está influenciado principalmente por su tamaño y composición. Respecto a esta última, las familias con desempleados o jubilados, pensionistas por otros motivos y trabajadores domésticos en general consumen más energía. Por otro lado, tres electrodomésticos destacan como los asociados a un mayor consumo de electricidad, como son el frigorífico, el congelador y la cocina.

- Los ‘factores externos’ que también podrían afectar significativamente al gasto energético doméstico requerido son los precios de la energía y la fiscalidad, que se analizan cuidadosamente en este trabajo (por ejemplo, incluyendo un escenario ‘antes de impuestos’ para los consumidores vulnerables) y cuya preocupación es creciente debido a la actual crisis energética iniciada en 2021.

Un nuevo indicador para medir la pobreza energética oculta

Se presenta una metodología novedosa para estimar el alcance y la profundidad de la pobreza energética oculta (indicador HEP, en su acrónimo en inglés), entendida como un problema de gasto insuficiente. El enfoque propuesto requiere la aplicación de dos criterios. El primero permite estimar la proporción de hogares con bajo gasto energético absoluto (gasto energético insuficiente) aplicando un umbral basado en el modelo RENE. El segundo, basado en un umbral de ingresos, filtra (de la primera muestra) a las familias o individuos que tienen un bajo consumo debido a un problema de asequibilidad, es decir, identifica la proporción de hogares en situación de pobreza energética oculta (extensión HEP). Además, la brecha de pobreza energética (profundidad HEP) se calcula como la diferencia media entre el umbral de gasto energético absoluto y el gasto energético real de los hogares en situación de pobreza energética. Por último, este trabajo analiza la sensibilidad de los resultados a las hipótesis realizadas para los dos umbrales propuestos, presentando así un escenario alternativo ‘ajustado a la estrategia de confort del hogar’.

La aplicación de esta metodología al caso de estudio español muestra algunas conclusiones destacadas:

- La pobreza energética oculta es una dimensión del fenómeno global que no puede pasarse por alto. De hecho, en 2019, según el indicador HEP, el 25% de los hogares españoles estaban afectados por esta problemática social. Ese mismo año, la ‘brecha de pobreza energética’ media por hogar era de 374 euros y el presupuesto nacional necesario para una posible política de erradicación de la pobreza energética oculta era ocho veces mayor que el presupuesto real destinado a los bonos sociales.
- La región de residencia, el tamaño del hogar y el nivel de ingresos son determinantes para la posibilidad de ser pobre energéticamente. Respectivamente, los hogares que viven en Extremadura, con más de 4 miembros y que pertenecen al primer decil de ingresos son los más vulnerables a este problema social.
- Además, la antigüedad del edificio influye significativamente en esta cuestión, es decir, los hogares que viven en viviendas antiguas tienen una cuota de HEP mayor que los que viven en viviendas de reciente construcción. Por otro lado, los inquilinos, por un lado, y las familias/personas que viven en zonas rurales, por el otro, también son especialmente vulnerables a la pobreza energética oculta.

Estudio de viabilidad tecno-económica de las bombas de calor aire-agua centralizadas para hacer frente a la pobreza energética en España

Se estudia la viabilidad tecno-económica de las bombas de calor aire-agua centralizadas accionadas por electricidad (EHP) y por motor de gas (GHP) para considerarlas eventualmente como soluciones alternativas para los hogares vulnerables que viven en viviendas en bloque. La novedad de este análisis radica tanto en el estudio del uso de las bombas de calor aire-agua centralizadas para satisfacer la demanda de calefacción en un sector y un país donde no están comúnmente instaladas, es decir, el sector residencial español, como en su evaluación como medidas de lucha contra la pobreza energética. En este sentido, las dos tecnologías estudiadas se han abordado como una rehabilitación del sistema de calefacción actual basado en radiadores, por lo que las temperaturas de funcionamiento de las bombas de calor se adaptan a esta configuración. En cuanto a la demanda horaria de calefacción requerida, se aplica una versión avanzada del modelo presentado en estudios anteriores, que considera también el nivel de aislamiento térmico del edificio. A continuación, se proponen dos modelos para obtener el rendimiento de la EHP: uno para el punto de máxima eficiencia y otro para el funcionamiento fuera de diseño. Por otro lado, para el estudio de la GHP se consideran dos equipos diferentes, con una potencia calorífica de diseño de, respectivamente, 75 kWt y 25 kWt, siendo este último utilizado para cubrir la punta de la demanda. Además, se realiza un análisis económico mediante el método del coste normalizado de calefacción (LCOH), que permite al autor comparar las bombas de calor estudiadas entre sí y con tecnologías convencionales como las calderas individuales y centralizadas de gas natural.

De acuerdo con los resultados de este trabajo, las EHPs y GHPs centralizadas de aire-agua pueden considerarse como sistemas prometedores para abordar la pobreza energética en los hogares españoles vulnerables que viven en viviendas en bloque. No obstante, hay que señalar varias advertencias:

- En cuanto a los indicadores ambientales y técnicos, los resultados muestran un excelente rendimiento de las EHPs en comparación con soluciones clásicas como las calderas de condensación individuales y centralizadas alimentadas por gas natural. Por otro lado, la solución de las GHPs tiene un peor rendimiento estacional, pero ofrece una mejor respuesta a las bajas temperaturas. No obstante, cabe destacar que el rendimiento de las GHPs se calcula en función de la energía primaria (gas natural), mientras que el de las EHPs se estima en función de la energía final (electricidad).
- Ambas tecnologías son más competitivas económicamente que una caldera de gas natural individual. Sin embargo, sería muy recomendable tomar medidas para reducir la factura eléctrica en el caso de las EHPs centralizadas para reducir sus costes de operación y hacerlas competitivas también frente a las soluciones de calderas de gas natural centralizadas. Por otro lado, se ha detectado una menor madurez tecnológica en las GHPs, tanto en términos de tamaños disponibles como de refrigerantes, lo que afecta a la viabilidad tecno-económica de este sistema térmico.

- El análisis paramétrico muestra que los indicadores de rendimiento de las EHPs varían ampliamente en función de la zona climática considerada. Además, la superficie calefactada y el LCOH por unidad de superficie dependen de la eficiencia energética del edificio. Por otra parte, para un mismo nivel de aislamiento del edificio, a medida que aumenta la superficie calefactada, el sistema es más viable desde el punto de vista técnico y económico, pero presenta un peor rendimiento medioambiental.
- En cuanto al análisis paramétrico de las GHPs, muestra que a medida que aumenta el número de aparatos, la demanda de calefacción cubierta también aumenta y el LCOH disminuye. Además, un segundo análisis paramétrico muestra que, en el escenario de precios energéticos de referencia, es más viable económicamente instalar una GHP en un clima más frío.

Evaluación de la eficacia de las principales políticas contra la pobreza energética invernal en España

Esta tesis incluye una evaluación de la efectividad de algunas de las principales políticas paliativas y estructurales implementadas en España para combatir la pobreza energética y propone ayudas alternativas que mejorarían la lucha contra esta problemática social en España. Este análisis se realiza usando el modelo RTEE para una evaluación socioeconómica de estos dos tipos de políticas. En primer lugar, este trabajo presenta un análisis del impacto de la pobreza energética invernal (WEP en su acrónimo en inglés) del actual bono social térmico español y propone una ayuda alternativa, el Cheque Térmico (TEC en su acrónimo en inglés), que es un cheque para consumidores vulnerables cuyo importe depende de las 'necesidades energéticas invernales' del hogar. En segundo lugar, se calcula el RTEE medio nacional bajo diferentes estrategias de rehabilitación de viviendas aplicadas en 2030 (incluyendo la rehabilitación exprés de la envolvente edificatoria y las medidas de sustitución de los sistemas térmicos) para comparar su impacto en el gasto de energía térmica de los hogares vulnerables y en la WEP. Por último, este trabajo compara la eficacia y la carga financiera nacional de los diferentes escenarios de aplicación de las medidas analizadas (paliativas o estructurales) y estima el 'coste social' de las medidas de rehabilitación, proporcionando así algunas recomendaciones políticas, que pueden resumirse como sigue:

- La aplicación de las medidas estructurales analizadas lograría una reducción de la WEP en 2030 de entre el 12% y el 37% respecto a la cuota de 2019, lo que supone un impacto mayor comparado con el producido por las ayudas a la calefacción, como el actual bono térmico y la propuesta de TEC. De hecho, se estima que estas últimas políticas reducen la WEP en un 1% y un 11%, respectivamente.
- En lo que respecta a la carga financiera nacional, el coste de inversión normalizado para aplicar el escenario de medidas estructurales más eficaces en cuanto a la reducción de la WEP (entre los analizados, es decir, un escenario con la rehabilitación exprés de la envolvente edificatoria y la sustitución de los sistemas térmicos) es solo un 23% superior al presupuesto necesario para aplicar el TEC en un solo año.

- Los subsidios de calefacción son instrumentos necesarios para reducir la factura energética de las personas vulnerables a corto plazo. No obstante, estas políticas paliativas deben ser soluciones temporales complementadas por medidas estructurales a medio y largo plazo. Finalmente, esta estrategia política progresiva podría evitar la cronificación de la pobreza energética al mejorar la eficiencia energética de los hogares vulnerables a un coste social asequible.

En general, este trabajo pretende contribuir a mejorar la identificación y el abordaje de la pobreza energética en España y en la UE. Confiamos en que las conclusiones destacadas y las recomendaciones políticas sean útiles para los agentes involucrados a nivel nacional y europeo para diseñar e implementar políticas y estrategias de manera integrada.

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Abbreviations

ACA	Association of Environmental Sciences
AELC	Actual ELectricity Consumption
AEMET	Meteorological State Agency of Spain (*Agencia Estatal de Meteorología*)
ATECYR	Spanish Technical Association of Air-Conditioning and Cooling (*Asociación Técnica Española de Climatización y Refrigeración*)
AROP	‘At Risk Of Poverty’ criterion
AROPE	‘At Risk Of Poverty or social Exclusion’ criterion
ASHPWH	Air source heat pumps water heaters
AT	After Tax
AVCO2	CO2 avoided ratio
BT	Before Tax
CCAA	Autonomous Communities (*Comunidades Autónomas*)
CCHP	Combined Cooling, Heat and Power
CDD	Cooling Degree Days
CENSUS	Population and Housing Census (*Censo de Población y Vivienda)*
CHP	Combined Heat and Power
COP	Coefficient of performance
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 2019
CTE	Spanish Technical Code for Building Construction (*Código Técnico de la Edificación de España*)
DHW	Domestic Hot Water
DS	Dwelling size [m^2]
ECODES	*Fundación Ecología y Desarrollo*
EEP	Energy Efficiency Parameter
EES	Engineering Equation Solver |
EHP	Electrically driven heat pump
EPAH	Energy Poverty Advisory Hub
EPC	Energy Performance Certificate
EPOV	EU Energy Poverty Observatory
EU	European Union
EUROSTAT	European Statistical Office
GDP	Gross Domestic Product
GHP	Gas engine driven heat pump
GWP	Global Warming Potential
HBS	Household Budget Survey
HDD	Heating Degree Days
HEP	Hidden Energy Poverty indicator
HHV	Higher Heating Value
HS	Household size (number of household members)
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation and Air Conditioning
IDAE	Spanish Institute for Energy Diversification and Saving (*Instituto para la Diversificación y Ahorro de la Energía*)
IPCC	Intergovernmental Panel on Climate Change (United Nations)
INE	Spanish National Statistics Institute (*Instituto Nacional de Estadística*)
LCOH	Levelised Cost of Heating

LPG	Liquefied Petroleum Gas
LTRS	Long-Term Strategy for Energy Renovation in the Building Sector[1]
MIS	Minimum Income Standard
NGO	Non-Governmental Organization
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Co-operation and Development
R2H	Renewable input to Heating demand ratio
RDL	Royal Decree-Law
RELC	Required ELectricity Consumption
RELE	Required ELectricity Expenditure (cooking, electrical appliances and lighting)
RENE	Required ENergy Expenditure
RTEE	Required Thermal Energy Expenditure (heating, cooling and DHW)
RWTEE	Required Winter Thermal Energy Expenditure (heating and DHW)
SCOP	Seasonal Coefficient of Performance (heat pumps)
SDG	Sustainable Development Goal
SECH	SECH Project (Development of detailed Statistics on Energy Consumption in Households)
SEER	Seasonal Energy Efficiency Ratio
SILC	Survey on Income and Living Conditions
SNSEP	Spanish National Strategy against Energy Poverty
SPAHOUSEC	SPAHOUSEC Project (Analysis of the Energy Consumption in the Spanish Households)
SPF	Seasonal Performance Factor
SW	Summer Severity Index
TEC	Thermal Energy Cheque
TLR	Tariff of Last Resort (natural gas)
TSA	Thermal Social Allowance
TUS	Time Use Survey
UK	United Kingdom
VAT	Value Added Tax
VPSC	Voluntary Price for Small Customer (electricity)
WACC	Weighted Average Cost of Capital
WHO	World Health Organization
WS	Winter Severity Index

[1] The new nomenclature introduced by the EU in 2021 is National Building Renovation Plans (NBRPs).

1. INTRODUCTION

1.1 Foreword

This thesis document presents the main contributions of four years of study and experience on the energy poverty issue in a developed country, i.e. Spain, within the European policy framework. What was firstly proposed as a research work on the feasibility of heat supply through cogeneration in Spanish vulnerable households became an interdisciplinary journey that has explored energy poverty characterisation, measurement and tackling in a just energy transition perspective.

Since the first interviews with my thesis' supervisors, i.e. the professors Dr. José Ignacio Linares and Dr. José Carlos Romero, the research has evolved through a process of scientific and personal growth culminating in this thesis manuscript that lays the foundations for a line of work open to new collaborations and further improvements. In this regard, this document is a starting effort to do my bit in the enhancement of knowledge and fight against energy poverty and to pave the way for future works.

Therefore, this thesis explores energy vulnerability from the characterisation of households' energy needs to the assessment of the effectiveness of different policy solutions, also using the results of the former to propose novel energy poverty indicators and analyse the feasibility of alternative technological solutions to combat energy poverty in block dwellings.

It is important to note that this research work also includes the fruit of different transdisciplinary debates and collaborations, i.e. the constant dialogue with the members of the Advisory Board and the Executive Committee of the Chair of Energy and Poverty and the multidisciplinary collaboration with the core research team of the same centre (in primis, the professors Dr. Eva Arenas and Dr. Efraim Centeno) and with the ENGAGER (Energy Poverty Action: Agenda Co-Creation and Knowledge Innovation) COST Action. In particular, the NGO *Fundación Ecología y Desarrollo* (ECODES) is the entity that most contributed to this work and made it possible to apply the research to the reality of vulnerable households in Spain.

1.2 Context

In a first approach to the issue, this section[2] defines the concept of energy poverty, taking into account its intimate connection with the phenomenon of poverty in general and the distinction between lack of access and lack of affordability.

The concepts of energy poverty and vulnerability are impossible to deal with and understand without linking them to the concept of general poverty and vulnerability. Vulnerability is a human condition related to a person's probability or risk of suffering a certain harm, in such a way that two dimensions of vulnerability can be pointed out: an anthropological one, directly related to the fragility of the human being, and a social vulnerability, the latter being understood as ‘the condition of special fragility in which certain environments or socio-economic situations place the people who suffer them’ [1]. In this sense, energy vulnerability would be an expression of this socio-economic vulnerability applied to the new rules of the energy system, where energy poverty would be a manifestation of its weakness [2]. Thus, the relationship between general poverty and energy poverty is two-way. The latter should be studied in connection with poverty in general, since this position of energy vulnerability is closely linked to a low level of income. On the other hand, energy poverty is also related to specific factors such as high energy prices and low dwelling’s energy efficiency, particular features of the energy system and individuals or families that may affect their capability of meeting domestic energy needs or their competitiveness to access better market conditions [3].

Poverty in general, far from being a new problem, is a circumstance that has been present, to a greater or lesser extent, in (almost) all societies throughout history, and this new form of poverty, i.e. energy poverty, is closely related to ‘general poverty’ and to the not so recent concept of social exclusion. In resource-abundant societies, poverty is both a thermometer of the solidarity of their members towards each other and an expression of inequality. The maturity of the solidarity bond between individuals in the same society determines their social perception of poverty, the poor and their role in society. This bond is based on the concern of individuals to provide society with fair structures that ensure the equal participation of all members in the creation and distribution of social benefit. In less affluent societies, poverty both an expression of inequality between members, resulting from intra-community lack of solidarity, and a question of justice between different countries. In this sense, another distinction that should be made is between absolute and relative poverty, in other words, between poverty and inequality, the latter being defined by the UN as ‘the state of not being equal, especially in status, rights, and opportunities’ [4].

Energy poverty is characterised by the inability of a significant number of people and households around the world to access adequate and sufficient energy services for a full

[2] This section uses some of the work carried out for the publication of the Chapter ‘La pobreza energética en España’ in Informe España 2019, written by the author and other scholars, and edited by *Cátedra José María Martín Patino de la Cultura del Encuentro* of Comillas Pontifical University.

material and social life, in accordance with their needs and at a reasonable price, i.e. which is not disproportionate to the income they have available to purchase other, equally necessary, goods. Energy poverty is a new type of poverty insofar as society, which, due to its economic, technological, political and social evolution, has turned energy (and energy services) into an essential good for social participation. Indeed, energy has become an indispensable vehicle, channelling relations between individuals and society and between some States and others. This ‘new poverty’ arises in the heart of a globalised world, with a transnational organisation that modifies the ways in which people relate to each other and communicate, as well as the ways in which they travel and move around. A liquid society in Bauman's expression, which coexists with the creation of new risks [5] and with the inability of national welfare institutions to protect and provide security for people immersed in problems created at another level, i.e. the global level [6]. Risks that cannot be faced individually, as the dynamics of exclusion that must be fought against in order to counteract them is a progressive and continuous process of loss of the capacities necessary to do so. Such coordinates shape a phenomenon, namely energy poverty, which as a multidimensional issue, with a markedly structural and dynamic character, shares if possible more characteristics with social exclusion than with poverty, with a very powerful capacity to generate new processes of social exclusion and reinforce old ones.

The upsurge of political concern about poverty in this new form is driven by social but also environmental motives. Energy is reconceptualised as a basic good for full human development, and as a strategic and geopolitical good, the lack of which makes societies dependent, and the misuse of which seriously compromises the sustainability of the planet and the human species. Thus, the energy transition responds to the needs of sustainability as well as to the needs of competitiveness and leadership in the management of the energy market. On the other hand, there is no doubt that ‘access to energy’ plays a fundamental role in the eradication of poverty in general [7], and that tackling this type of poverty by improving people's affordability and access to this basic good can offer great opportunities in this sense. The strategic dimension places multiple and diverse social actors in the same direction, providing the opportunity to harmonise logics as disparate as business and social services, for the benefit of the most vulnerable. To this end, the restoration of social links, cooperation and networking, and a sense of social justice, are more than ever essential for the eradication of all types of poverty and exclusion. A possible step in this direction would be the proclamation of access to energy as a fundamental right of all people [8], a recognition that has not yet taken place [9], but which is being increasingly vehemently demanded by various European entities committed to the fight against poverty. In this regard, the European Anti-Poverty Network (EAPN) advocates at least proposing the relevant legal reforms to prohibit the disconnection of vulnerable consumers [10].

1.2.1 Sustainable Development Goal 7

In 2015, the General Assembly of the United Nations (UN) adopted the Sustainable Development Agenda [11] that sets 17 Sustainable Development Goals [12]. The 7th goal

(SDG7) set the following global objective: ‘Ensure access to affordable, reliable, sustainable and modern energy for all’. In order to achieve this, the five sub-objectives set the targets for energy affordability and reliability, renewable energy and energy efficiency [12]:

- ‘7.1: By 2030, ensure universal access to affordable, reliable and modern energy services.
- 7.2: By 2030, increase substantially the share of renewable energy in the global energy mix.
- 7.3: By 2030, double the global rate of improvement in energy efficiency.
- 7.A: By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.
- 7.B: By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support.’

Hereafter there are some figures on the 7.1 sub-goal progress to give an idea of the global magnitude of this challenge. In this regard, Fig. 1. 1 shows the percentage of access to electricity in the world by country. It can be seen that this problem has a very specific geographical incidence: Central America, South Asia and Africa, where the levels of access to electricity are worrying. In the rest of the world, marked in yellow on the map, the incidence of the lack of access is marginal (although it should not be neglected in certain specific cases, e.g. informal settlements [13]).

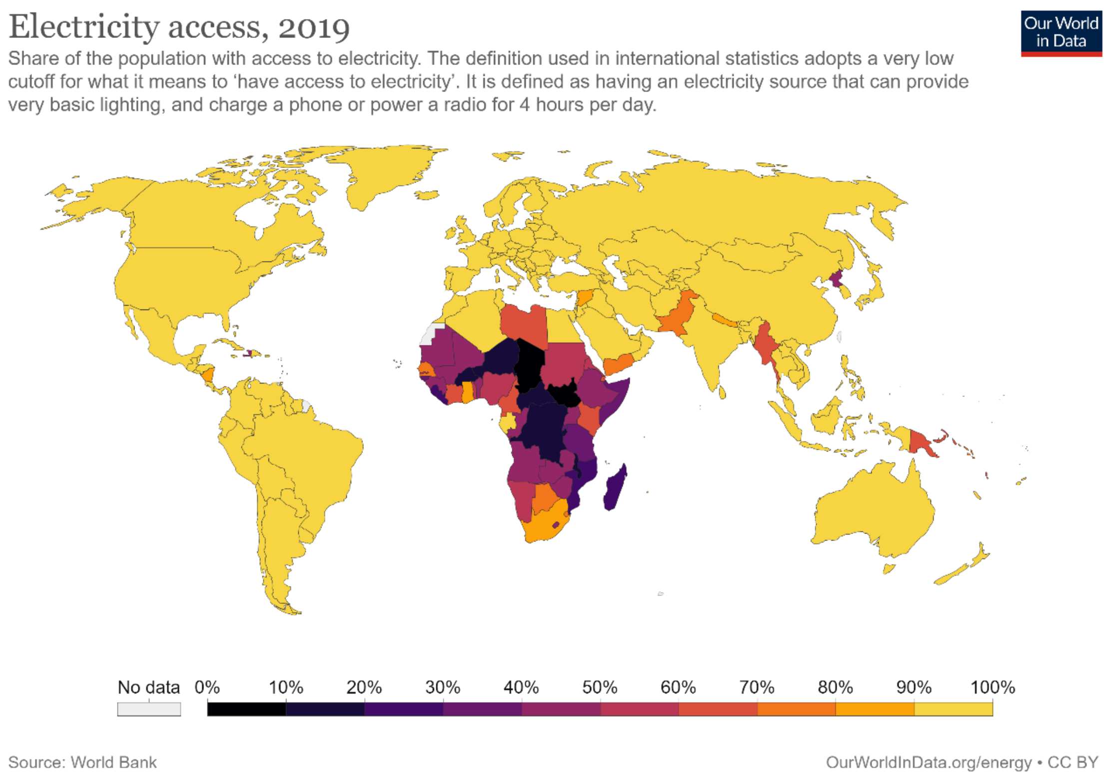

Fig. 1. 1. Percentage of the population with access to electricity in the world in 2019 by country (OurWorldInData.org from World bank's data [14]*)*

Although the challenge is enormous, there are some hopeful signs. In absolute numbers, the last available data (2019 [15]) saw the number of people in the world without access to electricity falling below 800 million (759 million people), which meant around 390 million people more with access to electricity compared to 2010. Nevertheless, the UN target is to reach full access by 2030 (SDG7.1.1), which will not be achieved following the current trend. On the other hand, in the same year, there were still 2.6 billion people without access to clean cooking, thus showing a much smaller relative improvement with respect to 2010 (3 billion people). Therefore, according to the UN projections, neither the SDG7.1.1 nor the SDG7.1.2 would be achieved by 2030 if no important improvement will be carried out.

On the other hand, the progress towards the achievement of 7.2-7.B subgoals can be summarised as follows [15].

- Share of total final energy consumption from renewable energies: from 16.4% in 2010 to 17.1% in 2018.
- Primary energy intensity: from 5.6 MJ/USD in 2010 to 4.8 MJ/USD in 2018.
- International financial flows to developing countries in support of clean energy: from 10.6 USD billion in 2010 to 14 USD billion in 2018.

Although some progress has been made towards all SDG7 sub-targets, there is still much to be done to ensure global access to affordable, reliable, sustainable and modern energy.

1.2.2 Energy poverty in developed countries

While it is clear from Sections 1.2 and 1.2.1 that the global energy poverty issue reflects real situations of material and social deprivation, about which there is growing concern in society, defining and identifying this issue is not a simple task. In this sense, the first definitions of energy poverty in developed countries were proposed in the UK in the early 1980s [16] and further investigated by Dr. Brenda Boardman in the early 1990s [17]. That pioneering work focused on identifying the problem of 'affordable warmth', i.e. the economic ability of British households to ensure adequate warmth in winter. In the last three decades, however, the concept has been broadened and now encompasses all energy uses in the home (domestic energy poverty [18]). More recently, a transport affordability issue was identified in developed countries as transport energy poverty or transport poverty [19]. However, this thesis focuses only on the former issue. One interesting definition of domestic energy poverty was provided by the European Economic and Social Committee in its opinion on energy poverty in the context of liberalisation and the economic crisis [20] (proposed again in the opinion on 'For coordinated European measures to prevent and combat energy poverty' [21]): 'the difficulty or inability to ensure adequate heating in the dwelling and to have access to other essential energy services at a reasonable price'.

The former definition is related to energy poverty in developed countries. But what about developing countries, what is the reality of energy poverty like there? The answer to this question opens up a divide in the very definition of the issue. While energy poverty in developed countries has to do with what has come to be called 'energy affordability issue', i.e. the ability of a household to meet its energy needs at an affordable price, in developing countries the problem is even more acute [22]. As shown in Section 1.2.1, in many of these countries, a large percentage of the population has no technical access to modern forms of energy, especially electricity. For this reason, the reality of energy poverty in these regions of the world focuses on the accessibility to modern and clean energy (sometimes referred to as 'universal energy access').

This thesis focuses on the Spanish case study within the EU framework. Thus, the main topic is energy poverty in a developed country, i.e. an energy affordability issue. While Section 1.2.1 shows some global statistics on 'universal energy access', there are not global estimations of the share of households in domestic energy poverty. Indeed, this issue cannot be interpreted by a single metric or approach. Therefore, multidimensional studies covering both its measurement and policy frameworks, such as this work, are needed to enhance the knowledge and the fight against this social scourge.

1.3 Objectives

1.3.1 General objectives and motivation

In 2016, the EU commission launched the EU Energy Poverty Observatory (EPOV), which was an European project that had the aim of providing 'a user-friendly and open-access resource' to promote 'public engagement on the issue of energy poverty, disseminate information and good practice, facilitate knowledge sharing among stakeholders, as well as support informed decision making at local, national and EU level' [23].

Following the EPOV's guidelines, in early 2018, the Comillas Pontifical University (based in Madrid, Spain) created the Chair of Energy and Poverty [24], [25]. This research centre develops its academic work in two directions: (1) carrying out a bottom-up interdisciplinary research on energy poverty and (2) serving as a meeting point to facilitate contact and collaboration between entities and people involved in the fight against this social scourge.

One year later, in the same country, the first National Strategy against Energy Poverty (SNSEP) [26] was published to pave the way for an integrated approach to energy poverty in Spain . However, for an effective application of the policies proposed in the strategy, an in-depth study was pointed out as necessary to analyse the multiple dimensions of this social issue (especially the one related to the attainment of households' energy needs) and to guide the legislator in the implementation of efficient measures to tackle energy poverty.

Within this context, the first general aim of this thesis is to characterise the energy reality of the vulnerable households in Spain and to critically review the energy poverty indicators traditionally used by proposing alternative ones. In parallel to the aforementioned objective, this work aims to analyse and propose feasible technical and regulatory solutions that tackle households' energy precariousness.

1.3.2 Specific objectives

Having introduced the general thesis' objectives, the sub-objectives proposed to achieve the main ones are as follows.

A. *Energy characterisation of Spanish households*.
The first phase aims to determine the required energy expenditure needed to 'attain a socially and materially necessitated level of domestic energy services' [2]. The proposed approach is a theoretical bottom-up modelling based on local climate's features and the characteristics of dwelling and households' members.
B. *Critical review and proposal of energy poverty indicators*.
The first aim of this second phase of the thesis is to provide a critical review of energy poverty metrics in the light of the lessons learned in the process of characterisation of households' energy needs carried out in the first stage. Starting from that, the second sub-goal is to propose improvements in the calculation of these indicators, as well as alternatives to them, when appropriate.
C. *Analysis of the technical-economic feasibility of alternative solutions for heating and energy efficiency in vulnerable households*.
Based on the hourly heating demand modelling, it is proposed to evaluate the thermal systems that could efficiently meet that demand, thus reducing low-income households' energy expenditure in a technical-economic feasible way. The methodology proposed for the economic assessment is the levelised cost of heating one due to its capacity to integrate both the investment and the annual expenditure in the same calculation.
D. *Evaluation and proposal of policies to tackle energy poverty.*
This last step of the thesis introduces an assessment of the current energy poverty policies in Spain that focuses especially, but not exclusively, on heating allowances and energy efficiency programs in vulnerable households. This critical evaluation is carried out to subsequently recommend specific policy proposals based on previous analyses, as well as to estimate their impact on energy poverty in the country.

1.4 Structure

This research work is structured as follows. After the current Chapter 1, which introduces the thesis' topic and objectives, Chapter 2 reviews the state of the art by analysing the main literature and policy regulation concerning this issue in Spain and other representative European countries.

Chapter 3 introduces the bottom-up model proposed to estimate the Spanish households' required energy expenditure according to their characteristics. Moreover, some direct applications are presented to evaluate the model and extrapolate the results at provincial (NUTS3[3] [27]) and national level.

Then, Chapter 4 contributes to the energy poverty indicators' literature by proposing a novel methodology to estimate the share of households with low absolute energy

[3] Spain is a regional state, and the regions are further divided in provinces (second level of administrative division).

expenditure for lack of affordability, i.e. households in hidden energy poverty. This new metric is applied to the Spanish case study but it is intended to be replicable for other national and local contexts.

In Chapter 5, a technical-economic feasibility analysis is carried out for two kinds of air-water heat pumps (electrical and thermally driven) as a structural measure to fight energy poverty in Spain. Furthermore, these two technologies are compared with conventional thermal systems to test their economic competitiveness.

Thereafter, Chapter 6 assesses the effectiveness of household heating allowances (both current and alternative ones) and energy efficiency interventions in Spain. In particular, their impact on thermal energy services' affordability and winter energy poverty are analysed to suggest some policy recommendations.

Finally, Chapter 7 points out the thesis' main contributions, conclusions and future work.

2. BACKGROUND: ASSESSING AND ADDRESSING ENERGY POVERTY

There are several definitions of energy (or fuel) poverty in the literature. The first official definition of fuel poverty was given in the British Warm Homes and Energy Conservation Act 2000 (WHECA) [28]: 'a person is to be regarded as living in fuel poverty if he is a member of a household living on a lower income in a home which cannot be kept warm at reasonable cost'. In the first UK Fuel Poverty Strategy (2001) an energy poor household was defined as 'one which needs to spend more than 10% of its income on all fuel use' (excluded mobility and transport needs) 'and to heat its home to an adequate standard of warmth'[29]. This definition, derived from the pioneering study of Boardman [17], has been used as the official energy poverty indicator in the UK from 2001 to 2013, when the UK Fuel Poverty Strategy was revised and a new energy poverty metric was introduced [30][4]. Since then several studies have been carried out in the EU and some Member States (MS) have provided official definitions of energy poverty. A summary of these definitions is shown in Table 2. 1 [31]. At the EU level, according to the description in recital 59 of the Directive (EU) 2019/944, households in energy poverty are unable to afford 'essential energy services to guarantee a decent standard of living and citizens' health', such as 'adequate warmth, cooling, lighting and the energy to power appliances', 'due to a combination of low income, high energy expenditure and poor energy efficiency of their homes' [32]. In 2022, the European Parliament has been debating on an EU official definition of this social issue. In this regard, the Amendments 14-300 [33] to the Social Climate Fund (described in Section 2.4.2) propose to define energy poverty as the 'situation in which households are unable to access essential energy supply needs, so as to guarantee basic levels of comfort and health, such as cooling, as temperatures rise, and heating as a result of an insufficient level of income, high-energy prices and which, if applicable, may be aggravated by having an energy inefficient dwelling' (Amendment 42 to Article 2 – paragraph 1 – point 1). The essential energy services mentioned in that document are intended as the ones 'to guarantee basic levels of comfort and health, a decent standard of living, including adequate heating and cooling, lighting, and energy to power appliances, in the relevant national context, existing social policy and other relevant policies, as a result of an insufficient disposable income' (Amendment 150 to Article 2 – paragraph 1 – point 2). On the other hand, Amendment 150 proposes to identify energy poor households as the one 'in the lowest income deciles whose energy costs exceed twice the median ratio between energy costs and disposable income after deduction of housing costs'[5]. Regarding the case study of this thesis, the Spanish Government officially defined energy poverty (in the National Strategy against Energy Poverty (SNSEP) [26]) as the situation in which a household cannot meet its energy needs

[4] In 2019, a new change was proposed in the reference metric by introducing the 'Low Income Low Energy Efficiency' indicator (LILEE) [203]

[5] The Energy Poverty Advisory Hub (EPAH), described in Section 2.2.4, transmitted its opinion on this energy poverty definition to the DG Energy. The author of this thesis participated to the internal discussion on this topic carried out in CENSE, research centre of NOVA School of Science and Technology, based in Lisbon (Portugal).

'as a result of insufficient income and which, in some cases, may be aggravated by energy inefficient housing' [26].

Another crucial point that should be addressed to understand and tackle energy poverty is the identification and categorization of vulnerable consumers. In this regard, the European parliament stated in the Directive (EU) 2019/944 that 'each Member State shall define the concept of vulnerable customers which may refer to energy poverty and, inter alia, to the prohibition of disconnection of electricity to such customers in critical times' [32]. In this sense, the Spanish Ministry of the Ecological Transition defined the figure of the vulnerable consumer as 'the consumer of electricity or thermal utility who is in a situation of energy poverty, being able to benefit from support measures established by the administrations' [26]. This definition relates vulnerability directly to energy poverty, thus creating a circular connection. Moreover, it is not reflected in the actual social tariff's identification of vulnerable consumers. Indeed, the latter only depends on income and household composition while energy poverty is a multidimensional issue. In this sense, it is important to distinguish the two definitions and characterize the energy needs of all households, with particular attention to the most vulnerable groups.

Moreover, to properly tackle energy poverty and understand the needs of these households, it is necessary to characterise the relation between energy and monetary poverty. A study carried out in Spain [34] identified six household groups, according to energy and monetary poverty thresholds: energy and monetary poverty (G1), monetary poverty (G2), energy poverty (G3), vulnerability to energy and monetary poverty (G4), vulnerability to poverty (G5) and absence of energy and monetary poverty (G6). Fig. 2. 1 shows a representation of this classification. As seen in this figure, while monetary poverty and energy expenditure are represented in two orthogonal axes, the six defined groups cover the whole map of scenarios with intermediate situations.

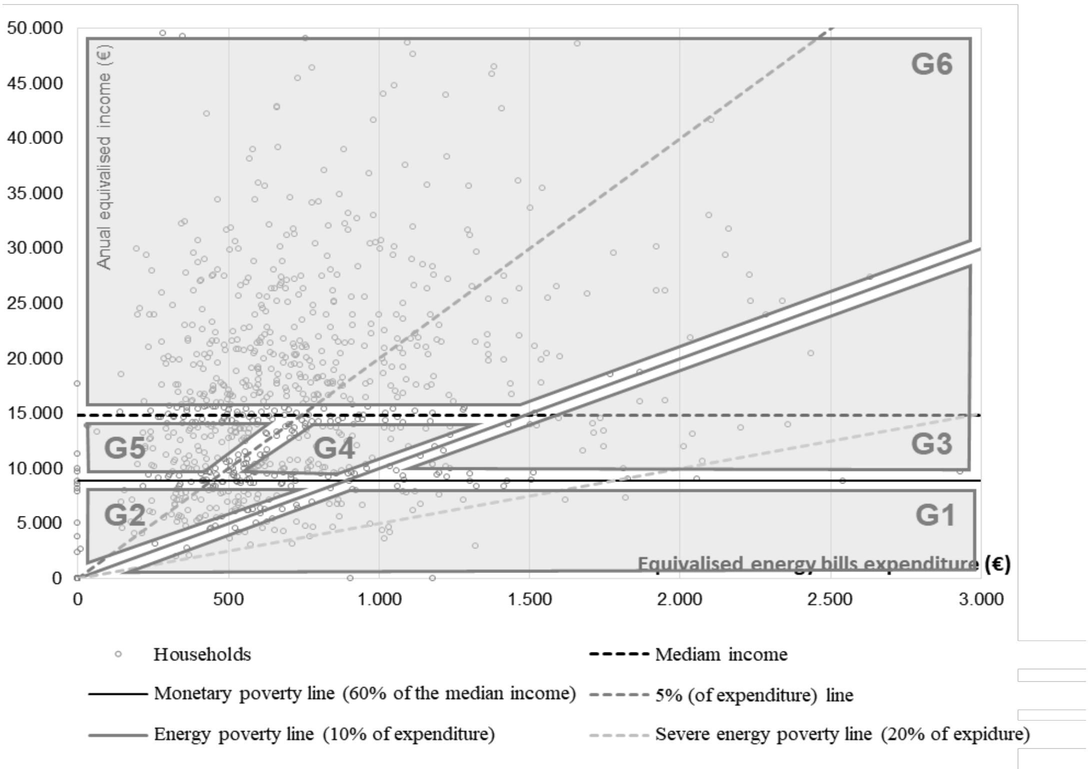

Fig. 2. 1. Characterisation of energy poverty (reprinted from [34]*)*

Eventually, energy poverty could be considered as ‘a subset of poverty’ that ‘must be viewed in the context of overall poverty’ [35]. At the same time, leading researchers such as Boardman and Hills agree that ‘fuel poverty should be considered a unique form of poverty, distinct from other types of poverty, and requiring tailored solutions’ [36]. As shown in Table 2. 1, there is no clear consensus on the definition of energy poverty. However, all the ‘energy poor’ share a common problem: ‘the inability to attain a socially and materially necessitated level of domestic energy services’ [2].

The main causes of this social scourge have historically been identified as high energy prices, low income and low energy efficiency in housing [37]. As detected by the 17th Bulletin on Social Vulnerability of the Spanish Red Cross [38], another problem that worsens the situation of energy poverty in households is the lack of basic information about their energy consumption, the tariffs they can contract or the assistance mechanisms they can access. In the numerous studies developed in recent years [37], [31], [39], [40] there is a broad consensus in identifying energy poverty as a complex problem that requires an in-depth study covering different issues: (1) the energy and socio-economic characterization of vulnerable households, (2) the identification of the most appropriate metrics to quantify the share of energy poor, (3) the study of measures to be taken to tackle energy poverty and (4) the implementation of these measures through efficient energy policies.

This chapter presents a review of the state of the art of the abovementioned topics, following a path that goes from the characterisation of households’ energy needs to the implementation of measures and policies to tackle energy poverty. After analysing the methodologies proposed to characterise households' energy needs (Section 2.1), a critical review of the main existing energy-poverty indicators is carried out (Section 2.2). The state of the art of active/passive measures and policies implemented to tackle energy poverty are presented, respectively, in Section 2.3 and Section 2.4. In the light of the abovementioned state of the art, the research gaps are pointed out at the end of each section in order to highlight shortcomings in research and support the potential contributions of the thesis.

Table 2. 1. Energy poverty definitions in European countries [31] [41]

MS	Definition
Austria	'A household is considered energy poor if its income is below the at-risk-of poverty threshold and, at the same time, it has to cover above-average energy costs.' [42]
Belgium	Energy poor: Households spend too high a proportion of their disposable income on expenditure for energy. [43]
Cyprus [official]	'Energy poverty may relate to the situation of customers who may be in a difficult position because of their low income as indicated by their tax statements in conjunction with their professional status, marital status and specific health conditions and therefore, are unable to respond to the costs for the reasonable needs of the supply of electricity, as these costs represent a significant proportion of their disposable income.' [41]
England [official]	Fuel poor: Households whose energy expenditure are above the national average, and after paying that expenditure their income results below the official poverty line (60% of median income). [44]
France [official]	'A person in a fuel poverty situation is a person who has particular difficulties in his/her home in obtaining the energy supply necessary to meet basic needs because of the inadequacy of his/her resources or living conditions.' [45]
Ireland [official]	'Energy poverty can be described as a situation whereby a household is unable to attain an acceptable level of energy services (including heating, lighting, etc.) in the home due to an inability to meet these requirements at an affordable cost.' [46]
Italy [official]	Energy poverty: 'difficulty for buying a minimum basket of energy goods and services, or condition where access to energy services implies a diversion of resources (in terms of expenditure or income) higher than socially acceptable' [47]
Northern Ireland [official]	'A household is in fuel poverty if, in order to maintain an acceptable level of temperature throughout the home, the occupants would have to spend more than 10% of their income on all household fuel use.' [35]
Portugal	Energy poverty: 'inability to maintain housing with an adequate level of essential energy services, due to a combination of low income, low housing energy performance and energy costs' [48]
Romania [official]	Energy poverty: 'impossibility of the vulnerable consumer to meet their minimum energy needs for the optimal heating of the home during the cold season' [49]
Scotland [official]	Fuel poor: A household, in order to maintain a satisfactory heating regime, it would be required to spend more than 10% of its income (including Housing Benefit or Income Support for Mortgage Interest) on all household fuel use. [50]
Slovakia [official]	Energy poverty: Inability of a household to secure a socially- and materially-necessitated level of energy services in the home. [51]
Spain [official]	Energy poverty is the situation in which a household finds itself in a situation in which its basic energy supply needs cannot be met as a result of an insufficient level of income and which, where appropriate, may be aggravated by having an inefficient energy house. [26]
Wales [official]	'Fuel poverty is defined as having to spend more than 10% of income (including housing benefit) on all household fuel use to maintain a satisfactory heating regime. Where expenditure on all household fuel exceeds 20% of income, households are defined as being in severe fuel poverty.' [52]

2.1 Characterisation of households' energy needs

This section[6] reviews the methodologies and approaches proposed to characterise households' energy needs. In this regard, the residential energy needs can be classified in two main categories: electricity demand and thermal energy demand, whose main modelling literature is presented in Sections 2.1.1.1 and 2.1.1.2. The Eurostat's Household Energy Consumption Statistics Manual (MESH) [53] proposes methodologies and guidelines for the compilation and analysis of energy consumption statistics in European households.

Regarding the thesis' case study, it is worth considering that the case of Spain is quite complex, as it covers a very broad framework of climatic conditions, housing types (in terms of construction age and characteristics) and multiple socio-demographic dimensions. The SECH-SPAHOUSEC project [54] developed energy statistics in the Spanish residential sector using methodologies summarised in the MESH. This project carried out a survey with both phone and face-to-face interviews to analyse the equipment, consumption and energy behaviour in the Spanish residential sector and crossed the results with measurements of energy consumption. The combination of different methods and sources of information made it possible to determine the domestic energy consumption for the Spanish case, aggregated by service, use, climate macrozone (Mediterranean, Continental and Atlantic) and type of housing [54]. This statistical estimation, which is partially updated annually [55], has been the residential energy demand reference for several subsequent studies. Considering this statistical approximation of the structure of domestic energy consumption [55], heating accounts for the largest share of total consumption in Spanish households (42% in 2018), followed by consumption in household appliances and lighting (32%) and DHW consumption (17%). Moreover, the Spanish Institute for Energy Diversification and Saving (IDAE) [56] analysed the evolution of electricity consumption in Spain between 2010 and 2016. The data from the abovementioned study show that the average electricity consumption in Spanish households has been gradually decreasing from 3,645 kWh in 2010 to 3,355 kWh in 2016 and this reduction could be partially justified by the energy efficiency improvements made in those years. On the other hand, between 2016 and 2018, the same institute carried out a statistical analysis of the natural gas consumption in Spanish households with individual heating systems (SPAHOUSEC II [57]), which continued the research previously carried out for the Spanish residential sector [54]. The most significant result was that the climatology and the typology of the dwelling are the main factors influencing natural gas consumption. Another main reference for domestic energy expenditure's statistical studies in Spain is the Spanish Household Budget Survey (HBS) [58], which reports the income and expenditure of a sample of Spanish households that

[6] This section uses some of the work carried out for the papers 'The dark side of energy poverty: who is underconsuming in Spain and why?', 'Does cash money solve energy poverty? Assessing the impact of household heating allowances in Spain', 'Modeling and analysis of electricity consumption in Spanish vulnerable households', published by the author and several scholars. It also includes quotations from the mentioned articles. See the list of published work for further details.

statistically represent the entire population. This survey can be used to characterise the energy expenditures and income levels in Spanish residential sector.

2.1.1 Modelling households' energy needs

Residential energy demand has been modelled in the literature by using two alternative approaches, i.e. top-down or bottom-up. The former modelling approach 'works at an aggregated level, typically aimed at fitting a historical time series of national energy consumption or CO_2 emissions data' [59]. On the other hand, in the latter modelling approach the household's energy consumption is determined by using the house's characteristics and the type of domestic appliances, as well as the features of the household's members. The bottom-up approach [60], [59] has been pointed out as the most suitable one for supporting energy saving and energy efficiency policy planning [61], [62], [63], and to carry out energy poverty analyses [64], [65]. Therefore, this section and the following ones are mostly focused on the studies that applied the bottom-up modelling approach.

The analysed literature on modelling domestic energy needs suggests that building characteristics (age, building type and energy efficiency), location of the dwelling, household consumption patterns [66] and socio-demographic variables, such as household size and composition, are key parameters to define a required energy consumption[7] [67]. The studies carried out in the UK [68], Ireland [64] and Netherlands [30,31] stand out for the integrated approach applied which, in the British case, has led to an official national model, i.e. the Building Research Establishment Domestic Energy Model (BREDEM) [71]. The BREDEM established a methodology to estimate energy requirements for several end uses (lights, appliances, cooking, DHW, heating and cooling) using two kinds of input parameters: 'variable' parameters, which vary with the month of the year (e.g. external temperature), and constant parameters, which have the same value throughout the year (e.g. number of occupants). Raaij and Verhallen [69] conducted research relating personal, environmental and behavioural factors of household energy use. One of the conclusions of this study was that consumers are not always aware of the energy costs related to some of their household behaviour and this fact can lead to both lack of comfort and waste of energy. Other remarkable examples of research on this topic are the following ones. Brouner et al. [70] concluded in an investigation that thermal consumption is mainly determined by the structural characteristics of the dwelling (age, building type and 'building quality'), while electricity consumption is more related to the household composition and income level. Salari and Javid [72] studied the annual electrical and thermal (specifically, natural gas) energy consumption of 168,046 US households for the period between 2010 and 2012 based on a multivariate analysis model. That work determined that five variables' groups can explain residential energy

[7] It is important to notice that the energy demand models analysed in this thesis are primarily intended for applications to domestic energy poverty ('affordability issue') in industrialised countries such as Spain, which may differ from the modelling of basic energy needs used in studies on the 'accessibility issue' in developing countries [67].

consumption in the US: socio-demographic composition of the household, building characteristics, location of the dwelling, temperature and energy price.

2.1.1.1 Domestic thermal energy demand

Focusing on thermal energy needs (the most relevant ones in the EU residential sector[8] [73]), vulnerable households tend to use heating or cooling installations sparingly to reduce their energy bills [30], often living in unhealthy conditions [74]. These circumstances usually affect the household's wellbeing [75] and health [76], [77]. Heating and cooling thermal-comfort-performance-gaps have been assessed for the Portuguese case-study to identify, on one hand, households who are under-consuming energy due to low income (hidden energy poverty) and, on the other hand, families with a high level of energy consumption ('energy or fuel obesity') [78]. In a different study, the annual heating requirements of Italian households have been calculated (with a regional breakdown) by taking into account the number of municipalities belonging to the different climate zones [65]. That work found that energy poverty in Italy is mainly related to the geographical dimension, thus suggesting a rational basis for planning effective strategies. In the UK, the BREDEM [71] defined an acceptable level of heating 'in terms of the temperature of a dwelling, the extent to which the dwelling space is heated and the number of hours that the occupants spend within the dwelling and require heating'. Moreover, in the UK, a 'satisfactory heating regime for pensioners, long-term sick and disabled households' was defined as follows: 'the adequate standard of warmth is achieved at a higher temperature for these groups' (from 21°C to 23°C, depending on the country) [79].

At EU level, Eurostat sets the winter and summer comfort base temperatures for the calculation of the Heating Degree Days (HDDs) and Cooling Degree Days (CDDs), respectively, at 18°C and 21°C [80]. Regarding the thesis' case study, the Institute for Energy Diversification and Saving (IDAE) [81] established correlations to determine thermal energy demand in the winter and summer periods in specific terms (kWh/m^2). The IDAE correlations are based on the climatic zones into which Spain is divided, the age, energy efficiency and typology of the dwelling (single-family or block). The winter climate zone is identified by a letter, from A to E, in order of increasing winter severity (WS), or in other words from the warmest to the coldest one. The letter α is used in Canary Islands to identify the warmest zones. The summer climate zone is identified by a number from 1 to 4, in order of increasing summer severity (from the coolest to the hottest). After processing this basic information, it is possible to obtain the annual thermal demand (heating and cooling) to maintain certain comfort conditions in the house: the values recommended by the regulation are 17ºC (winter) or 27ºC (summer) at night and 20ºC (winter) or 25ºC (summer) during the day. In addition to the thermal demand for air-conditioning, the thermal demand for the preparation of domestic hot water (DHW) has to be considered. The annual demand for DHW can be calculated following the procedure set out in [82], [83], [84]. The official references for setting the baseline requirements of

[8] In EU households, heating and domestic hot water account for 79% of total final energy use [73].

both calculations (HVAC and DHW) is the Spanish Technical Code for Building Construction (CTE) [83], [84] and the 'Reference climate descriptive document' [85]. The former sets the base temperature for the calculation of the HDDs and CDDs at 20°C and the DHW set-point temperature at 60ºC.

The characterisation of Spanish domestic thermal energy demand has been analysed in previous research such as [86], [87]. These studies proposed a 'model to determine the hourly thermal energy demand profile of a location in mainland Spain' based on the CTE requirements. Moreover, a study commissioned from the Spanish Green Building Council and Conama foundation [88] analysed the theoretical energy demand for residential heating in the various Spanish provinces. That work was carried out by expanding the results of a previous study [89] based on the CTE regulation and using the Census to characterise the Spanish building stock. On the other hand, some studies proposed a different methodology that considers the adaptive comfort model criterion [90], [91]. According to these studies, this method 'assesses the occupants' ability to adapt to climate, so it enables considering Spanish climatic diversity'.

2.1.1.2 Domestic electricity demand

According to the literature, the electricity demand (lighting, electrical appliances and often cooking [92]) can be controlled by taking certain measures, but the consumers perceive this as necessary and difficult to replace by other alternatives [93]. Indeed, one of the main conclusions of [93] is that the electricity consumption has an income short-term elasticity close to zero. A study of 2011 [93] analysed the determinants of the electricity demand of Spanish households, defining the hierarchy of importance of the different factors included in the HBS. From the results of the abovementioned study, it can be assumed that the size of the household (number of members) and of the dwelling (m^2) are the variables that most influence the electricity bill of a household. According to the reports by Eurostat and IDAE mentioned in the introduction of Section 2.1.1, household energy consumption, particularly the electricity one, is strongly dependent also on household composition.

A research study carried out for the Spanish residential sector [94] used the data taken from the Spanish Time-Use Survey (TUS) to elaborate an average load profile of residential electricity consumption in Spain according to the household size and a series of appliances' electrical load profiles. That work [94] was inspired by previous studies on the relation between households' activities and electricity consumption [95], and an analysis of the consumption of electrical energy for lighting [96]. All of the research works mentioned so far use a bottom-up approach, defined in the introduction of Section 2.1.1. On the other hand, other studies such as [97] explored the use of an artificial neural networks system-based model for load and energy profile prediction in the residential sector by involving the following households' parameters: income level, occupancy and occupant-related activities. Other works have also validated the electrical-load models proposed by comparing them with actual electricity consumption data (measured or obtained from surveys) from national databases [98] or specific case studies.

2.1.2 Discussion and literature gaps

From the analysis of the literature it can be concluded that the modelling of household energy expenditures has to consider not only the structural characteristics of the building, but also the household composition and other socio-demographic variables that may have a great influence on their energy burden. Taking these aspects into account, it is worth considering that the case of Spain is somewhat complex, as it covers a very wide range of climatic conditions, types of dwellings (in terms of years of construction and residential areas) and there are multiple socio-demographic dimensions. Indeed, to the best of the author's knowledge, no comprehensive model of the theoretical/required thermal energy and electricity expenditures in the Spanish residential sector have been proposed and applied to vulnerable households. Moreover, the studies carried out so far in Spain have analysed the variation of thermal energy or electricity consumption with household's characteristics and behaviour, but most of them have not validated it with field investigations.

In this sense, the Spanish National Strategy against Energy Poverty 2019 – 2024 (SNSEP) [26] (see Section 2.4.5) highlighted the need to deepen the knowledge on the theoretical energy expenditure of different consumer types in Spain, with the intention of having a reference for vulnerable households. However, the strategy only mentions the concept of the reference required thermal expenditure (heating and DHW) that is related to the 'average household'. Therefore, the SNSEP expressed the need to characterise both the real and required energy expenditures of Spanish households. Accurate knowledge on the relationship between household features and energy consumption could be used not only for the implementation and the monitoring of effective policies to optimise energy consumption, but also for a better characterisation of energy poverty in the country (as mentioned in the SNSEP).

2.2 Energy poverty indicators

To understand the energy poverty extent and depth in a country it is necessary to quantify the number of energy poor households. Several indicators have been proposed in the literature to estimate the share of households affected by energy poverty [99]. These metrics could be classified into three main groups: (1) indicators based on income-expenditure data (objective indicators); (2) self-reported (subjective) indicators (both included in the characterisation of [31] and [100]); and (3) 'direct approach' indicators (mentioned, for example, in [100]), which monitor parameters such as the indoor temperature or humidity. The following sections[9] describe the approach and metrics proposed for these three indicator categories. The most commonly used indicators from

[9] These sections use some of the work carried out for the paper 'The dark side of energy poverty: who is underconsuming in Spain and why?', published by the author, José Carlos Romero, José Ignacio Linares, Eva Arenas, María Asín and Efraim Centeno in the journal Energy Research & Social Science. They also include quotations from the mentioned article.

the first two categories (the ones that have been officially recognised both at EU and single country level) are shown in Table 2. 2.

Table 2. 2. The most commonly used energy poverty indicators in the two officially recognised groups

Group	Indicator	References
Objective approach	10%	Boardman, 1991 [17]
	LIHC	Hills, 2012 [30]
	2M	Isherwood, Hancock, 1979 [101]; Boardman, 1991 [17]
	MIS	Moore, 2009 [102] [103]
Subjective approach	Inability to keep the house adequately warm	Gordon et al., 2000 [104]
	Arrears on utility bills	
	Dwellings with leakages & damp walls	

2.2.1 Income/expenditure or objective approach

Within the first group, the traditionally used indicator is the so-called 10% indicator. According to the definition by Boardman [17], used as official reference in the UK until 2013, members of a household are considered to be fuel poor if ‘they are required to spend more than 10% of their income to maintain an adequate standard of warmth’ [105]. This threshold represented, in the early 90s, ‘the actual average share of energy spending among the 30 percent poorest households in Great Britain as well as roughly twice the median share of actual energy spending for all households’ [106]. A recent study summarized the application method of the 10% indicator in a very practical way [107]. This metric uses a ratio of theoretical energy expenditure and household income. The theoretical energy expenditure is derived from energy price and a modelled energy consumption that considers the following parameters: the size of the dwelling and household, the house energy efficiency and the types of energy utilities. Energy poor households are those with a ratio ‘theoretical-energy-expenditure/income’ greater than 1:10 (10%).

The 10% indicator is simple to define and calculate, easy to understand, and relatively versatile [108]. On the other hand, the 10% metric has several disadvantages [109]: (1) it is extremely sensitive to energy prices; (2) the 10% threshold were referred to the socio-economic scenario in the UK in the early 90s and cannot be justified on the actual UK scenario or, even more, on other countries' setting; (3) there is no reference to the income threshold of the household, thus false positives such as high-income households could be included. In 2012, Hills [30] proposed a new metric called Low income/High cost indicator (LIHC) that substituted the 10% indicator as official energy poverty metric in the UK [44]. According to the original Hills definition [30], 'households should be counted as fuel poor if:

a) They had required fuel costs that were above the median level; and

b) Were they to spend that amount they would be left with a disposable income below the official poverty line.'

These two complementary conditions have been expressed mathematically as, respectively, in Eq. (2.1) and Eq. (2.2):

$$[Household\ energy\ expenditure] > [Median\ energy\ expenditure] \tag{2.1}$$

$$[Household\ income] - [Household\ energy\ expenditure] < 60\%\ [Median\ household\ income] \tag{2.2}$$

A recent study carried out in Spain [108] proposed using Eq. (2.3) instead of Eq. (2.2):

$$[Household\ income] - [Household\ energy\ expenditure] < 60\%\ [Median\ household\ income - Mean\ energy\ expenditure] \tag{2.3}$$

Unlike the Eq. (2.2), in Eq. (2.3) the two terms are consistent with each other, both calculating the difference between income and expenditure. For this reason, the second method can be considered more appropriate. To use the LIHC indicator, two different thresholds have to be defined: the median equivalent income, after housing and energy expenditure, and the national median-equivalent-energy-expenditure. The calculation of the energy-expenditure standard in the UK is currently carried out using the BREDEM model [71], described in Section 2.1.1. The LIHC indicator considers both energy expenditure and income of households but several limitations can be pointed out [103]: (1) the equivalisation of energy expenditure involves a complex and non-transparent calculation; (2) the energy-expenditure threshold does not consider the energy efficiency of housing and makes it difficult to identify those households that can improve their energy-poverty-related situation by reducing their energy expenditure; (3) the relative thresholds make it difficult to separate causes and consequences of energy poverty and can generate both false positives or false negatives [110].

In contrast to the doubly-relative character of the LIHC, the original definition of 2M threshold, mentioned in [111], defined 'households with high fuel expenditure as those spending more than twice the median on fuel, light and power' [101]. Several scholars have adopted this metric to analyse and quantify energy poverty. The median score has been considered 'particularly useful for measuring and monitoring aspects of deprivation' [111]. The 2M indicator detects those households having abnormally high energy expenditure [112]. On the basis of the studies that analysed in depth this metric [109], [113], four possible definitions of the 2M threshold can be presented:

- Double the median household energy-expenditure;
- Double the average household energy-expenditure;
- Double the median share of household energy-expenditure in income;
- Double the average share of household energy-expenditure in income.

In the abovementioned studies, several limits on the application of the 2M have been identified: (1) difficulties in investing the 2M with normative meaning; (2) income and expenditure do not follow the same trend; (3) there are not good arguments why 2M is an appropriate threshold. A 2014 study [109] proposed that, to gain in acceptability, the 2M could be linked to 'adequate energy services'.

On the other hand, a Spanish study [108] carried out a vulnerability analysis based on an econometric methodology proposed by Legendre in 2015 [114]. This study identified four main variables that can increase the probability of a household to be energy poor: income level, configuration of household, tenure status of the housing and occupation of the main breadwinner. The analysis of energy consumption considered the configuration of household (household composition) and the occupation of the main breadwinner but it should be complemented by an analysis of the household income level. However, defining and measuring an adequate household-income-level is not an easy task. In this sense, there are two main methodologies that have been used in the literature to characterize 'overall' poverty [115]: 'indirect approach'[116], which defines inputs necessary to achieve a certain level of wellbeing; 'direct approach'[117], which focus on the 'actual standard of living of people'(outcomes). The former measures poverty in terms of income, the latter in terms of consumption. Several studies on living standard conditions have been carried out but no single standard has emerged. The Organisation for Economic Co-operation and Development (OECD) identified three main equivalence scales that assigned a value in proportion to household needs [118]: 'OECD equivalence scale', 'OECD-modified scale', and 'Square root scale'. The value is commonly dependent on the size of the household and the age of its members but differs depending on the scale used. For the calculation of the equivalent income in Spanish households, the main energy poverty reports carried out in Spain [39], [40], [119] applied the 'OECD-modified scale' [120], which is the one recommended in the Eurostat guidelines. This scale assigns a value of 1 to the household breadwinner, of 0.5 to each additional adult member, and of 0.3 to each child. These values can be applied to the minimum living costs, which cover all the cost items other than housing and energy costs. In the literature, the income level that allows households to meet the minimum living costs is called Minimum Income Standard (MIS) [121]. The main technical difficulty in this calculation is represented by the uncertainty in the determination of an objective minimum income [108]. A study of 2013 [122] identified three main contentions that should be considered in determining household income: (1) whether or not to consider the housing cost in the measure; (2) 'what benefits should be included as disposable income'; (3) 'whether income should be equivalised'. To take into account the third point, it is necessary to categorize the income standard depending on the household composition.

In line with the above-mentioned approach, an alternative measure of the ability of household to afford energy expenditure was proposed by Moore in 2012 [103]. This methodology is based on the definition of a Minimum Income Standard (MIS) 'needed by different household types in different locations to participate in society'. This new metric was inspired by a research carried out at the Loughborough University and the University of York [121]. According to the MIS-based indicator, a household is considered energy poor if Eq. (2.4) occurs.

$$\begin{aligned} &Actual\ household\ energy\ expenditure \\ &\qquad > Net\ household\ income - Housing\ costs \\ &\qquad - Minimum\ living\ costs\ (MIS) \end{aligned} \tag{2.4}$$

On the other hand, a study published in 2018 [108] proposed a MIS-based energy poverty indicator for Spanish households that uses the following Eq. (2.5).

$$\begin{aligned} &[Actual\ household\ energy\ expenditure] \\ &\qquad > [Net\ household\ income] - [Housing\ costs] - [MIS_{eq.} \\ &\qquad - Average\ energy\ expenditure \\ &\qquad - Average\ housing\ costs] \end{aligned} \tag{2.5}$$

As can be deduced from Eqs. (2.4) and (2.5), the minimum living costs ($MIS_{eq.}$ in Eq. (2.5)) cover all items other than housing and energy expenditure. The drawback of this methodology lies precisely in the difficulty in objectively determining the MIS. This metric requires a complex previous calculation of the different income items necessary to meet the household needs. Nevertheless, several studies identified various advantages in using the MIS [31]. The two main improvements introduced by the MIS indicator are the following ones: (1) the MIS equivalisation of household incomes is more accurate compared to the OECD scale [123]; (2) the MIS-based indicator results 'robust when measuring objective income-based energy poverty', especially if combined with a sensitivity analysis [108].

As shown in the above paragraphs, among the objective indicators, the 'traditional' metrics have been usually based on a disproportionate expenditure approach, which quantifies the so-called 'measured energy poverty' [124]. This term refers to households whose energy expenditure is considered too high compared to their income, i.e. households that spend too much of their disposable income on energy. On the other hand, low-income households often apply coping strategies to reduce their consumption [125], [126], [127], [128], such as 'switching on heating only in one room, wearing more clothes or slipping under the duvet even during daytime' [125]. Energy spending reduction was identified in [126] as the primary strategy adopted by households to cope with the lack of financial resources. The term 'hidden energy poverty', introduced by Meyer et al. [124], refers to circumstances of '(self-)imposed restriction' of energy consumption, which are the most difficult to detect through existing administrative metrics and energy poverty indicators. Thus, this 'hidden face' of energy poverty has not been sufficiently reflected in measurement and policies [124], [18].

2.2.1.1 Existing Hidden Energy Poverty indicators

To the author’s knowledge, the following are the most relevant European[10] studies on measuring hidden energy poverty (i.e. HEP indicators), which can be classified into two categories according to the kind of energy expenditure threshold proposed.

A. HEP indicators based on relative energy-expenditure thresholds

The energy expenditure thresholds used in the four studies described hereafter are 'relative' because they are based on the median or average values of similar households in the corresponding country.

- Meyer et al. [124] presented a methodology that fixes a relative energy expenditure threshold and eliminates households having equivalised disposable income excluding housing costs belonging to the five higher deciles and the ones living in ‘well-insulated’ dwellings.
- The EU Energy Poverty Observatory (EPOV) (see Section 2.2.4) introduced, among its primary metrics, the M/2 indicator, which is an underconsumption index that estimates ‘the share of households whose absolute energy expenditure is below half the national median’ [129]. That indicator is a proxy to identify households that might be in hidden energy poverty. However, the underconsumption circumstance detected in those households could be due to different reasons: high energy efficiency standards, physiological and occupation-related habits or cultural behaviour, ecological awareness, etc.
- A recent study carried out for Italy [130] is aligned with the ‘triple threshold’ approach (energy expenditure, income and energy efficiency) used in [124], being the expenditure threshold set as the mean energy expenditure of similar households[11] . On the other hand, the second and third constraints are set according to, respectively, both the conditions of absolute and relative poverty[12], and the building construction period.

[10] Europe is the geographical area where the energy poverty literature is most extensive and diverse [18].

[11] Here similar households are households with the same size (number of persons) and living in the same climate zone (while in [124] the second condition refers to the dwelling size).

[12] The relative poverty threshold is based on the International Standard of Poverty Line. Whereas absolute poverty ‘identifies as poor a household with a consumption expenditure lower than or equal to the monetary value of a basket of goods and services considered essential to avoid severe forms of social exclusion’.

- Karpinska and Śmiech [131] analysed hidden energy poverty in eleven Central and Eastern European countries by considering multiple factors of exposure to this social issue, including housing parameters and location, households' composition, and regional characteristics.

B. HEP indicators based on absolute energy-expenditure thresholds

The HEP indicators using an absolute energy-expenditure threshold identify as energy poor the households whose actual energy expenditures are below their required or modelled energy expenditures. Hereafter are some examples of the application of this approach.

- Antepara et al. [132] analysed hidden energy poverty in three southern European countries (Portugal, Spain, and Greece[13]) by using an underconsumption criterion based on modelled energy costs, thus introducing an absolute energy expenditure threshold. These modelled energy expenditures, assessed following the methodology presented by Papada and Kaliampakos [133], were characterized by considering twelve input variables, e.g. income, energy price, or building energy performance. Specifically, in [133], expenditures for heating and cooling were modelled based on the requirements to achieve thermal comfort at home, while the rest of the energy uses (domestic hot water, cooking, lighting and electrical appliances) were estimated using Greek statistics.

- Papada and Kaliampakos [134] applied the same energy cost model to introduce a new indicator for the Greek case study, i.e. the 'Degree of Coverage of Energy Needs', which assesses the ratio of actual energy expenditure to required energy expenditure.

- In another southern European country, i.e. Italy, Faiella and Lavecchia [135] applied the absolute energy approach only to a single energy service. Specifically, they estimated the share of households in hidden energy poverty as the one whose total expenditure, net of the 'minimum heating expenditure' (absolute energy expenditure threshold), falls below the relative poverty threshold.

Table 2. 3 summarizes the main characteristics of the HEP indicators proposed in the abovementioned studies.

[13] It has to be noted that, in the Portuguese and Spanish case studies, the indicator was applied to a single geographical area, i.e. Évora (PT) and Basque Country (ES).

Table 2. 3. A brief review of the methodology and results of the main HEP indicators proposed in Europe (from [136]*)*

Authors and references	**Countries**	**Database**	**Energy expenditure threshold**	**Definition of energy poor**	**Results (extent)**	**Results (depth)**
Meyer et al. [124]	BE	EU-SILC	Relative	• Actual energy expenditures < half the median expenditure of similar households • Equivalised disposable income excluding housing costs belonging to the five lower deciles • Dwelling being not well-insulated	3.4% (2011) 4.6% (2013) 3.9% (2015)	1140 €/yr (2011) 1123 €/yr (2013) 919 €/yr (2015)
EPOV [129]	EU member states + UK	HBS	Relative	Actual energy expenditures < M/2 (M= National median energy expenditure)	EU average: 14.6% (population, 2015)	-
Betto et al. [130]	IT	HBS	Relative	• Actual energy expenditure < mean expenditure of similar households (HEP1, HEP2) • Total expenditure < relative poverty threshold (HEP1, HEP2) • Absolute poverty (HEP2) • Dwelling being not well-insulated (HEP2)	HEP1: 10.1% (2018) HEP2: 2.3% (2018)	-
Karpinska and Śmiech [131]	Eleven Central and Eastern European countries	EU-SILC	Relative	[Household income − Estimated Household housing costs] < 60% Median (Household income - Estimated housing costs)	Average: 23.6% (2017)	(see [131])
Antepara et al. [132]	PT, ES, EL	Primary surveys	Absolute	• Actual energy expenditures < (Equivalised modelled energy expenditure) / 2 • Disposable income belonging to the five lower deciles	EL: 8.3% (2015) Évora (PT): 8.3% (2014) Basque country (ES): 16.3% (2018)	-
Papada and Kaliampakos [134]	EL	Primary survey	Absolute	DCEN[a] = Actual energy expenditure / Required energy expenditure < 0.8	45% (2015)	-
Faiella and Lavecchia [135]	IT	HBS	Absolute	(Total expenditure - Required heating expenditure) < Relative poverty threshold	11.7% (2014-2016)	550–600 €/yr (2014-2016)

2.2.2 Subjective approach

Subjective metrics, such as the ones shown in Table 2. 2, are based on self-reported or third parties assessments that qualify the ‘indoor housing conditions, and the ability to attain certain basic necessities relative to the society in which a household resides’[100]. The sources used to evaluate these subjective indicators are usually the national or European surveys on living conditions (e.g. EU-SILC) [137]. These metrics are based on the pioneer work supported by the Joseph Rowntree Foundation in 2000 [104]. This study introduced a subjective measure of deprivation that includes energy-poverty-related problems such as heating lack, presence of damp in the house and utility disconnections. Healy and Clinch applied this methodology to British and Irish households in order to derive a composite measurement of fuel poverty [138].

The ‘Inability to keep home adequately warm’ indicator is based on question ‘Can your household afford to keep its home adequately warm?’. The ‘Arrears on utility bills’ metric is based on question ‘In the last twelve months, has the household been in arrears, i.e. has been unable to pay on time due to financial difficulties for utility bills (heating, electricity, gas, water, etc.) for the main dwelling?’[139]. The ‘Dwellings with leakages & damp walls’ indicator [100] is a proxy of ‘difficulties with achieving adequate warmth and coolth’. The most widely accepted is the declared inability of a household to maintain an adequate temperature in winter.

The subjective indicators showed some limits due to the subjective interpretation of the reality. Nevertheless, these could be meaningful metrics to suggest to the politicians to implement structural measures such as the housing energy-retrofitting in case of a high share of people unable to adequately heat their homes.

2.2.3 Direct approach

The direct approach aims to assess if households are achieving adequate levels of energy services (usually the thermal energy ones, i.e. HVAC and DHW) through in-situ measurements. This is probably the most effective way to verify if a household is living in a comfortable environment, although it commonly does not ensure that the rest of the non-thermal energy needs are effectively covered. On the other hand, the direct approach is the most time-consuming and expensive methodology because of the necessity to carry out measurements in housing. As mentioned in Section 2.1, focusing on the thesis’ case study, the IDAE published a report [57] that presents a bottom up analysis of gas consumption in Spanish households. The consumption estimation is carried out by cross-checking of in-situ measurements (600 households), telephone surveys (4400 households) and consumption data from energy companies. This study could be very useful to compare the measured-heating-consumption with the required one and define energy poverty and vulnerability thresholds.

Although there have been several developments on the front of the energy-consumption measurement, this metric has rarely been used to quantify the number of energy poor [100] and has never been employed at the European scale [140]. A housing survey was carried out in five urban areas of England, measuring the living room and bedroom temperature for two weeks to one month across winter [141]. This study compared the collected data points with the single data of the English House Condition Survey (EHCS). A similar survey carried out in Ireland [142] concluded that 'not all those who are defined in the study as fuel poor can be classified as enduring thermal discomfort'. A study of 2015 reviewed the state of the art concerning the energy demand and indoor environmental comfort of low income households in Europe [143]. Two important conclusions regarding air conditioning can be derived from the abovementioned work: (1) low quality heating equipment affects adversely the winter indoor-environmental-quality of households; (2) high temperatures during summer creates discomfort and heat stress. The latter statement could be a symptom of a no adequate cooling equipment.

On the other hand, as mentioned in Section 2.1.1.1, there is no consensus on the definition of a thermal comfort range in housing. However, the most plausible technique seems to be to use regulatory standards to legitimise the studies carried out and support them with proposals for energy efficiency policies.

2.2.4 EU Energy Poverty Observatory (EPOV)

It is estimated that 33.8-82.3 million people [144] in the EU (6.6-16.2 % of population) are experiencing energy poverty. In this context, in 2016 the European Union created the EU Energy Poverty Observatory (EPOV) [145]. One of the fundamental objectives of the Observatory was to make a proposal for methodologically consistent indicators across Member States. To achieve this, four main indicators were selected, as well as a battery of secondary indicators. The primary energy poverty indicators are classified according to the type of methodology used: subjective approach (Arrears on utility bills; Inability to keep home adequately warm) or objective approach (Low share of energy expenditure in income (M/2), High share of energy expenditure in income (2M)). Therefore, it can be shown that there is a context of analysis that opts for two very different strategies, but these approaches share something fundamental: the sources of the data are usually surveys conducted at national and EU (in the case of the SILC) level. The other fundamental role of the EPOV was working as a network that 'facilitates knowledge sharing and co-production among Member States and relevant stakeholders'.

In 2020, the Energy Poverty Advisory Hub (EPAH) replaced the EPOV as the EU official energy poverty entity. This new hub aims to monitor and tackle energy poverty at the local level. Particularly, it 'aims to provide direct support, training, and information to local authorities and civil society organisations and identify and promote local actions to tackle energy poverty.' In 2022, the EPAH published a report that aims to bring energy poverty research into local practice [146]. In order to do that, the study reviews the existing energy poverty indicators both at national and local scale, and provides some recommendations to bridge the gap between the theoretical analysis and the policy actions.

2.2.5 Spanish case study

Within Axis 1 of the SNSEP (described in Section 2.4.5), the Spanish Government chose four indicators as those thatwould be monitored periodically to analyse the evolution of the phenomenon in our country. Specifically, they chose the four primary indicators proposed by the EPOV (see Section 2.2.4) and, since 2019, they have been monitoring their results yearly. The latest results, referred to 2020, are shown in Table 2. 13.

The reference sources for the indicators' calculation are the HBS [58] for the objective approach and the Survey on Income and Living Conditions (SILC) [147] for the subjective approach. Therefore, the indicators are calculated on a sample of the population and elevated to the whole of the citizenship using statistical factors provided by the Spanish National Statistics Institute (INE).

From an unofficial perspective, since the publication in 2012 of the first report on energy poverty in Spain carried out by the Association of Environmental Sciences (ACA) [148], there have been several studies that have continued to work on the reality of poverty linked to energy [149], [150], [119]. Researchers from the ACA [39] and the research centre Economics for Energy [40] characterised the problem in an integrated way using different indicators applicable to the Spanish case.

2.2.6 Discussion and literature gaps

Analysing the review of energy poverty indicators presented in this section, it is possible to denote that the task of measuring energy poverty is a complex issue. Indeed, energy poverty is a multidimensional social reality that can hardly be captured in a single metric. It is important to understand that each indicator is identifying a particular reality or dimension of this issue. Specifically, there are four main dimensions that have emerged in the above classification:

- *Disproportionate expenditure*: households that are in energy poverty due to energy overspending in relation to their income.
- *Underspending*: households in energy poverty because they do not meet minimum energy needs.
- *Arrears in utility bills*: households accumulating energy debts, a potential symptom of energy poverty.
- *Inadequate temperature*: households in energy poverty due to inability to maintain the dwelling at an adequate temperature (commonly related to the winter season).

Regarding the objective dimensions, i.e. *Disproportionate expenditure* and *Underspending*, the 'traditional' metrics introduced in Section 2.2.1 are usually focused on the former issue, thus estimating the so-called 'measured energy poverty'. On the other hand, the circumstances of '(self-)imposed restriction' of energy consumption have not been adequately addressed both in official indicators and policies. This explains the term assigned to this dimension, i.e. 'hidden energy poverty'.

Particularly, in the studies mentioned in Section 2.2.5 and, in general, in all works concerning Spain, this 'hidden face' of energy poverty is not considered or the proposed metric does not include a characterisation of the households' required energy expenditure. Therefore, this in an unexplored path and a new research could enhance the knowledge on this energy poverty dimension, thus improving both the identification and assistance to household in hidden energy poverty.

2.3 Active and passive measures for vulnerable households

As highlighted in this chapter's introduction, one of the main causes of energy poverty is the low energy efficiency in housing. Vulnerable households usually live in old buildings with poor energy efficiency [151]. In Spain, several NGOs have carried out micro interventions (energy saving in lighting and micro passive-measures) campaigns to improve energy efficiency in housing [152], often financed by energy companies [153]. A study carried out in Spain [154] classified the different energy efficiency measures applicable in housing's retrofitting interventions according to the building component/equipment affected:

- Thermal enclosure: passive measures to improve the building's thermal enclosure.
- HVAC: active measures to improve the heating and air conditioning equipment (heating/cooling).
- DHW: Domestic Hot Water equipment renovation.
- Lighting: interventions on lighting system.
- Electrical Devices: energy saving and replacement of electrical appliances.
- Renewable Energy Sources and others: installation of micro plants for self-consumption, electrical (photovoltaic), thermal (solar thermal) or both (cogeneration).

Ultimately, to reduce energy consumption and consequently cut down the energy expenditure of vulnerable households, two main typologies of structural interventions can be carried out: active and passive measures. The former ones are applied to the active systems of the house/building, such as the HVAC equipment. The latter aim to improve the housing thermal insulation. The following sections describes both kinds of measures with a special focus on an efficient type of active systems', i.e. aerothermal heat pumps, whose technoeconomic and environmental analysis is presented in Chapter 5.

2.3.1 Passive measures: energy retrofitting of the thermal enclosure

A report that analysed in depth the first category of measures and their application to vulnerable households is the one financed by the Naturgy Foundation in 2017 [91]. This study proposed an 'express housing retrofit' comprising a series of low-cost measures (i.e. low-cost building retrofit) that can be applied to the thermal enclosure of vulnerable households. They calculated the energy saving resulting from the application of the low-cost building retrofit in a modelled building. The calculation, based on the adaptive comfort criterion [90], was carried out in four Spanish cities (*Barcelona, La Coruña, Madrid* and *Sevilla*). An elaboration of the report results [155] showed that the reduction in thermal energy demand was inversely proportional to the winter climate zone, ranging from 57% (*Madrid*, zone D) to 68% (*Sevilla*, zone B). Therefore, these studies showed that even a modest investment in the energy efficiency of homes (approx. 4,500 €) can lead to considerable energy savings. Another report carried out by the ACA [148] pointed out the additional benefits of building energy retrofitting in the Spanish households: (1) it makes it possible to reduce the greenhouse gases emissions; (2) it generates employment in the building sector, one of the most affected by the 2008 economic crisis and with the highest number of unemployed; (3) it improves the indoor environment quality, reducing exposure of household members to chronic diseases.

2.3.2 Active measures

Examples of active energy-efficiency-measures are the replacement of the HVAC equipment (heating/cooling) or the installation of micro-grids for self-consumption. The replacement of old boilers by modern condensing ones is one of the easiest measures to be implemented. However, the new condensing boilers may not respect the normative on primary energy established by the Spanish Technical Code for Building Construction (CTE). In particular, according to the regulation, the preparation of DHW cannot be considered exclusively with a boiler or electric water heater. Indeed, 60 to 70% of the energy must be on-site renewable (solar thermal, PV or aerothermal) or solid biomass [84]. The CTE also limits the maximum amount of non-renewable primary energy consumption in HVAC and DHW systems. Overall, the CTE encourages renewable energy solutions either in new buildings or as part of existing buildings' refurbishments.

Technical guides carried out by the IDAE and the Spanish Technical Association of Air-Conditioning and Cooling (ATECYR) [81], [82], [156], [157] make it possible to calculate the energy saving due to a replacement of an HVAC and/or DHW equipment. However, an analysis of state-of-the-art technology has to be carried out to optimize the type and size of the new equipment. Among the proposed technologies, current aerothermal heat pumps provided with speed variator (inverter models) are able to enhance the efficiency at partial loads. Under certain conditions (oversizing might be necessary in extreme winters), such technology can constitute a feasible measure [158]. In this regard, Section 2.3.2.1[14] analyses the state of the art of the performance assessment of aerothermal heat pumps, which are promising technologies to replace inefficient boilers in existing buildings.

[14] This section uses some of the text mentioned in the paper 'Feasibility study of a centralised electrically driven air source heat pump water heater to face energy poverty in block dwellings in Madrid (Spain)', published by the author, Irene Priego, José Ignacio Linares, Eva Arenas, José Carlos Romero and Efraim Centeno in the journal Energies. It also includes quotations from the mentioned article.

On the other hand, the installation of cogeneration (combined heat and power, CHP, or combined cooling, heat and power, CCHP) plants in buildings/districts requires an adequate technical-economic feasibility study. A Spanish study [86] developed a methodology to optimize the size and configuration of an Organic Rankine Cycle (ORC) cogeneration plant for district heating/cooling. This paper showed that the profitability of the abovementioned plant increases with the size and 'the operation in CCHP mode is only worth in locations with high summer severity and in full load operation'. This study was updated in 2017 [87]. In the latter paper, the authors optimized the size of the ORC cogeneration plant for all Spanish provinces, calculating the primary energy savings and avoided CO_2 emissions.

2.3.2.1 Aerothermal heat pumps and coupling with the heating demand

The CTE recently included heat pumps as a renewable solution to supply thermal services to buildings, especially domestic hot water [84]. In spite of this, the use of heat pumps for heating purposes is far away from the common practice in Spain. Conversely, space heating from heat pumps is usually a by-product of cooling services, using the so-called reversible heat pumps. This situation is even considered by the European Union [10], which penalises reversible heat pumps when counting renewable energy due to the fact they are usually designed to operate in cooling mode.

Curve fitting from actual machines is a common methodology to model the behaviour of heat pumps. Thus, Underwood et al. [159] developed a model based on refrigerant-side variables, which makes it suitable to performance analysis of heat pumps in service. Indeed, this type of model is used when the focus is on the model of the entire system building-heat pump. For instance, Lohani et al. [160] integrated correlation curves of coefficient of performance (COP) for ground and air source heat pumps in a software of building modelling which lacked of heat pump models. In some cases, e.g. [161], the curve fitting is based on the theoretical behaviour of Carnot efficiency, compared with actual performance. These models are used in order to identify key performance parameters in a site, as carried out by Vieira et al. [162].

Physical models of heat pumps are based on energy and heat transfer equations of the different components. The key components are the heat exchangers, which are modelled using the effectiveness-number of transfer units' method or the equivalent logarithmic mean temperature difference method [163]. These methods usually take into account the single phase and phase change zones. So, Fardoun et al. [164] established a quasi-steady state model based on an iterative procedure for the heat exchangers. In this sense, Patnode [165] developed a model of heat exchangers based on Dittus-Boelter correlation that is able to obtain the overall heat transfer coefficient as a function of the mass flow rate. These types of models are the base of rules and standards that determine the COP of air source heat pumps water heaters (ASHPWH) as correlations of water temperature and air dry and wet temperature [166]. Other studies used dynamic models, usually based on commercial software as TRNSYS. This type of analyses might pursue the improvement of the control strategies in the operation of heat pumps [167], or the coupling with the thermal inertia of the building [168]. In short, dynamic models are useful when the seasonal performance is sought [169].

On the other hand, the hourly heating load, required as an input data to simulate the behaviour of the heat pump, can be calculated using hourly average data or load predictions. Xu et al. [170] carried out a case study using data recorded along two years of operation of a data centre, evaluating the performance of the combined cooling, heat and power (CCHP) system, performing also transient modelling. An analysis of the heat meter readings obtained on an hourly basis along one year was performed by Gadd et al. [171] aiming to provide heat load patterns. Whereas, Bacher et al. [172] attempted to develop a method to predict the space heating thermal load in a dwelling using measured data from actual houses in combination with local climate measurements and weather forecasts. Noussan et al. [173] proposed a thermal demand model built up using heat measurements taken every 6 minutes along several years of operation. Energy Plus software from the U.S. Department of Energy [174] has been used by a number of researchers to determine the thermal load, namely Wood et al. [175] and Michopoulos et al. [176], for their investigation related to the use of biomass in space heating. Other authors used regression analysis to obtain thermal energy demand prediction methods [177] or autoregressive with exogenous time and temperature indexed model [178]. In this sense, nonlinear autoregressive models with exogenous inputs were selected by Powell et al. [179] as the best methodology based on artificial neural networks.

In order to obtain the thermal energy demand profile on an hourly basis, the degree-day method has also been used as for example Büyükalaca et al [180], who estimated the energy needs in a building in Turkey by calculating the heating and cooling degree-days using variable-base temperatures. Also, Martinaitis et al [181] performed an exergy analysis of buildings based on the degree-days method. By other hand, the errors in the degree-day method that may affect the building energy demand analysis have been analysed by Layberry [182]. Carlos et al. [183] combined solar radiation data with the degree-day method and several different simplified methodologies for building energy performance assessment are compared for winter. In Spain, the winter climatic severity index is defined from the winter degree-days and solar radiation measurements [184]. This index is used to determine the thermal energy demand and it allows the division of the country into climatic zones in order to establish the building energy performance regulations [185]. This thermal energy demand modelling is also suitable to assess the performance of other thermal devices for the evaluated scenario.

2.3.3 Discussion and literature gaps

Some of the abovementioned studies carried out for the Spanish case study analyse the techno-economic feasibility of power plants for district heating/cooling, which supply energy to villages/cities. However, regarding the case study of this thesis, i.e. Spanish vulnerable households, it could be more appropriate to verify the profitability of alternative technologies such as heat pumps, which could be installed in buildings or blocks of buildings.

Electrically driven aerothermal heat pumps have been more commonly considered for their high average performances and the future perspective of a renewable-based electricity generation [186]. However, at low temperature, they suffer a great loss of capacity, which usually makes it necessary to equip them with a back-up system (e.g.

natural gas boiler) that penalises their consideration as renewable energy. In order to solve this problem, an alternative solution could be using a thermal engine driven by natural gas [187], [188]. The thermal engine allows the heat it generates to be used as an auxiliary heater or to produce domestic hot water. Its low electricity consumption makes it a good option to provide these services in places with an unstable or absent grid connection. On the other hand, one of the main disadvantages is that it is a less developed technology than the electrically driven heat pump, so the number of available models is much smaller. Moreover, the use of the thermal engine ensures higher efficiency at low temperatures, but has a lower COP than would be obtained with an electric motor (although to make a fair comparison it would be necessary to find the COP of the latter with respect to the primary energy to produce the electrical energy).

For all the above, it could be interesting to assess and compare the performance of air source heat pumps water heaters (ASHPWH), electrically or gas driven. This new study should also take into account the economic feasibility of these two alternative solutions when applied to vulnerable households. Indeed, the economic comparison of these two technologies is even more important in the thesis' case study, considering the current and future changes in the Spanish energy and residential sector.

2.4 Energy poverty policies

In the context of the SDG7 described in Section 1.2.1, once the potential beneficiaries are identified (Section 2.2), it is necessary to design energy poverty policies in an integrated way that includes a broad set of mitigating and structural strategies: financial support, disconnection safeguards, consumer engagement and energy efficiency [189].

Energy consumption subsidies (financial support) characterise the regulation of many jurisdictions. They can be found in developing countries and transition economies, but also in most developed countries. The theoretical justification behind the introduction of such subsidies lies in the role of energy as an enabler of basic services, such as hygiene, cooking and home heating. These essential services may not be accessible to all citizens if energy is charged at prices that reflect the full costs, so the regulator introduces an energy consumption subsidy [190] for certain categories of users. Beyond this justification, subsidies can also be seen as a mechanism for redistributing economic resources within the citizenry [191], especially in contexts where there is a significant share of poverty [192]. However, subsidies for energy consumption have been criticised by many experts and institutions in recent decades. The design of a subsidy scheme is a very complex task and, in many cases, design flaws lead to inefficiencies and sub-optimal situations from an economic point of view. These subsidies could be classified according to several characteristics. A proposal of this classification is presented below (based on [191]).

- The first distinction to be made is between direct and indirect subsidies. Since the customer of the energy service is the final target of consumption subsidies, it is possible to define as direct any subsidy that is provided directly to the consumer, acting on the price of the service. On the other hand, there are indirect subsidies, which act on the costs underlying the price of the energy service and provide economic support to the active agents along the supply chain.

- The second distinction, which can be applied within the group of direct subsidies, is between explicit and implicit subsidies. Explicit subsidies involve the calculation of a price for the energy service that reflects the costs incurred and the subsequent application of discounts on that price. Implicit subsidies, on the other hand, materialise through measures that prevent the transfer of actual costs to the price of energy, resulting in an overall under-pricing of the energy service.
- Another very relevant distinction between the different designs of energy consumption subsidies is between targeted and untargeted subsidies. Untargeted subsidies provide financial support to all or a majority of energy consumers (e.g. all residential consumers), without differentiating between their needs. Targeted subsidies, on the other hand, have a targeting strategy that identifies the beneficiaries of subsidies through different mechanisms ([191], [193], [194]).
- Energy consumption subsidies can also be distinguished according to their financing strategy: (1) Funding through the general state budgets; (2) cross-subsidising, whereby the economic imbalance generated by the subsidy is covered by additional charges on the tariff of consumers who do not benefit from the subsidy; (3) subsidies 'without financial coverage', which stem from a structural lack of funding or are a decision of the regulator.
- The last design element discussed in this section is the 'mode of delivery' of the subsidy to beneficiaries. There are basically two alternatives, transfer/payment in cash and transfer/payment in-kind. The former provides for a transfer of money from the subsidy administrator to the consumer. A transfer in kind, on the other hand, takes the form of discount on the energy service tariff that are applied to the beneficiaries' bills.

Giving the case study of the thesis, the following sections mostly focus on direct explicit targeted subsides. The improvement of information on these subsidies is also included in this review.

Another category of measures to protect vulnerable consumers and alleviate energy poverty is protection against disconnection, usually due to non-payment or late-payment of bills. Clearly, each jurisdiction has specific legislation that regulates the disconnection of users from the electricity or gas grids in case of non-compliance with the terms of the contract, establishing a detailed protocol for action. The focus of this section within the country-by-country analysis is not on these protocols, but on the specific rules that may exist on the disconnection of consumers in vulnerable situations, identifying some design elements of these protection schemes, i.e. targeting strategy; duration of protection from disconnection; imposing limits on consumption/power during the protection phase; seasonality of safeguards; financial treatment of debts.

On the other hand, this chapter also describes those energy efficiency policies that have or may have an impact on vulnerable households, i.e. those related to the pursuit of efficiency improvements in vulnerable households, especially through retrofitting of dwellings or replacement of equipment. In order to facilitate the comparison of energy efficiency measures implemented in the different countries included in this analysis, a classification according to the aspect or element of the household that is to be improved through them is proposed:

- Energy saving support: financial support or material deliveries (e.g. energy saving micro-kits) for small energy saving interventions in the home (weather stripping, light bulbs, etc.).
- Aid for the renovation of the thermal enclosure: financial aid for the renovation of the thermal enclosure of the dwelling (windows, roofs, etc.).
- Aid for the replacement of equipment: financial aid or delivery of material for the replacement of thermal equipment (air-conditioning systems, DHW, etc.) or electrical equipment (lighting, electrical appliances, etc.) in the dwelling.

In addition to the above measures, which focus on direct action in households, two additional measures are included in this description:

- Improvement of information: provision of information and training for the improvement of energy efficiency in the home (direct energy saving actions, management and processing of grants, etc.).
- Establishment of energy efficiency standards in dwellings: obligation to have an energy efficiency certificate that accredits a certain level in order to be able to rent a dwelling (that should be complemented with aids for not wealthy landlords and the prohibition of increasing the rent to the current tenants for a certain time).

Finally, the COVID-19 pandemic and the measures that different governments have taken to address it have had a very significant impact on vulnerable households [195], [196], [197]. In addition, in 2021-2022, the energy price crisis is expected to exacerbate the situation of energy poverty, which could have been partially alleviated by the measures implemented by governments [198], [199]. However, these exceptional measures have been temporary, so only a few that have had a significant impact on the case study of this thesis will be mentioned.

Therefore, the following sub-sections analyse the mitigating and structural policies implemented in the UK and in three selected EU Member States, i.e. France, Portugal and Spain, which are framed in the EU policy context (Section 2.4.2). The UK was the first European country that introduced policies to address energy poverty, thus, given its trajectory, it can be considered a good reference of consolidated political framework; France stands out for its commitment in recent years in the fight against this issue [200] and the introduction of an energy voucher for vulnerable households [201], which partially inspired the energy cheque proposal presented in Section 6.2.1; Portugal was selected for the significant similarities with the thesis' country case study[15].

[15] Moreover, Portugal was the country selected for the author's PhD International Exchange, which was carried out between January and April 2022.

2.4.1 United Kingdom

As mentioned before, the UK is the European country that first investigated and tackled energy poverty. Based on research carried out by Dr Brenda Boardman in the early 1990s, the first fuel poverty strategy in the UK was adopted in 2001 [29]. Since then, the UK Government has been adopting several policies to address this social scourge [202]. In 2015, the national strategy underwent a major change with the adoption of a new indicator for energy poverty (see Section 2.2.1). In 2019, a new change was proposed in the reference metric, which became known as 'Low Income Low Energy Efficiency' (LILEE) [203]. Thus, according to this new indicator, a household would be in fuel poverty if its disposable income, discounting household energy costs, placed it below the poverty threshold and, in addition, it resided in a dwelling with an energy rating of D or worse energy performance certificate (EPC). In February 2021, the most recent strategy in the fight against fuel poverty in the United Kingdom was published, entitled: 'Sustainable warmth: protecting vulnerable households in England' [204].

Currently, the governments of the four UK countries apply different metrics to estimate the number of energy poor households [205]. However, for ease of comparison, Table 2. 4 shows the macroeconomic and socio-demographic variables and the incidence of energy poverty in the UK according to the EPOV metrics. Of the four main indicators of the European Observatory, disproportionate expenditure (2M) has the highest incidence in the UK. This indicates that the energy inefficiency of British households is having a major impact on energy poverty in the country.

Table 2. 4. Context data of the UK, 2019

Indicator	**Population**	**Households**	**GDP**	**GDP per capita**	**Average income**	**% unemployment**	**GINI (1)**	**AROPE (2)**	**% EP**
Data	66.8M	29.5M	2,477,097M€	37,868 €	Median net equivalent income: €21,464 (2018)	3.90%	35.1 (2017)	23.1% (2018)	- 2M: 18.8% (households, 2015) - M/2: 9.2% (households, 2015) - Winter inadequate temperature: 5.4% (population, 2018) - Arrears in bills: 5.4% (population, 2018)
Source	World Bank	Eurostat	SFO	SFO	Eurostat	OECD	World Bank	Eurostat	EPOV

(1) Inequality indicator

(2) Percentage of population at risk of poverty or exclusion

2.4.1.1 Subsidies and additional protection measures in the UK

Among other analyses contained in the 2021 UK Fuel Poverty Strategy [204], it summarises the main policies in place in the fight against this social issue. The following is a brief description of the most relevant programs related to subsidies and additional protection tools:

- Warm Home Discount: This is a discount on the electricity and/or gas tariff for a certain amount (around €160[16]) that low-income households and pensioners can benefit from. It is a single discount to be made during the winter period on either the electricity or gas bill. The fact of receiving this benefit does not condition the other two mentioned below.
- Winter Fuel Payment: This is an automatic direct transfer of an amount ranging from €114 to €342 to pensioner households to help cover winter heating bills.
- Cold Weather Payment: This is an additional payment to vulnerable households when the average temperature in their area is zero degrees Celsius or below for 7 consecutive days. If this occurs, they receive €28.5 for each 7-day period of very cold weather between 1 November and 31 March.
- Energy Price Cap: This is a price cap calculated by the regulator (Ofgem) that limits the default tariffs that a supplier can apply. This includes the standing charge and the price per kWh of electricity and gas. It applies to consumers who are on a regulated or predetermined tariff.
- Priority Services Register: This is a free support service for vulnerable consumers offered by suppliers and distributors.
- Action in the event of non-payment: If a bill has not been paid after 28 days, the supplier may contact the consumer to inform them of the possibility of disconnecting the gas or electricity supply. Before disconnecting the consumer, the supplier must offer them the following options:
    - Agree a payment plan with the supplier. Such a plan will cover the debt plus an amount for current use.
    - 'Fuel Direct' scheme: This is an automatic deduction of a fixed amount from the current welfare benefit that the vulnerable consumer is receiving to cover the debt, plus an extra amount for current usage.
    - Pre-payment meters: If a payment plan cannot be agreed with the supplier, the supplier may choose to install this device. Once installed, there are emergency aids (credits) in case of difficulty in recharging.

[16] The conversion pounds-euros took the following refence: £1 = €1.1402 (https://www.bankofengland.co.uk/boeapps/database/Rates.asp?Travel=NIxAZx&into=GBP), 10th March, 2020.

- Disconnection procedure: If no agreement can be reached with the supplier to pay the debt, the supplier can apply to a court for a court order to enter the home and disconnect the supply. If the court grants the court order, the supplier may proceed with the disconnection. It must give seven days' notice in writing. The supplier does not need a court order to disconnect a meter outside the home.
- Reconnection procedure: To reconnect, payment of the debt, the reconnection fee and the administrative costs must be paid. Once this amount is covered, the supplier must reconnect the consumer within 24 hours.

Table 2. 5 provides summarised and categorised information on these policies in the country.

Table 2. 5. Summary of subsidies and additional protection measures in the UK, 2019

Measure	**Type**	**Requirements**	**Application**	**Financing**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Benefit ratio (1)**	**Beneficiary ratio (2)**
Warm Home Discount	Explicit direct subsidy with administrative guidance	Households with social benefits Pensioners	Through suppliers	Obligated participating suppliers (a): 397M€.	- Transfer in kind: Discount on energy bill (Electricity/natural gas, 160€)	2.2M	0.016%	7.5%
Winter Fuel Payment	Explicit direct subsidy with administrative guidance	- Older people (>65)	Automatic	PGE: 2250M€.	- Transfer in cash: Transfer (114€ - 342€)	8.2M	0.091%	27.8%
Cold Weather Payment	Explicit direct subsidy with administrative guidance	- Households on social benefits- Low-income households- Pensioners- Unemployed- Persons with disabilities	Automatic	PGE: Variable	- Transfer in cash: Transfer (€28.5 per 7-day period of very cold weather)	3.6M	N/A	12.2%
Energy price cap	Maximum energy price	Consumers with a predetermined tariff.	National regulator (Office of Gas and Electricity Markets-OFGEM)	N/A	According to consumption, location, type of contract and season (summer/winter)	11M (Default Tariff Price Cap) and 4M (Prepayment Meter Price Cap)	N/A	37%

Measure	**Type**	**Requirements**	**Application**	**Financing**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Benefit ratio (1)**	**Beneficiary ratio (2)**
Prepayment meter principles (PPM)	Consumer protection with prepayment meters	Household consumers	Through suppliers	N/A	Credits negotiated with the supplying company	N/A	N/A	N/A
Prohibition of supply cuts	Consumer protection against disconnection	Vulnerable groups	Through suppliers	N/A	Prohibition of cutting	N/A	N/A	N/A
Priority Services Register (PSR)	Additional protection for vulnerable consumers	Vulnerable groups	Through energy supplier or network operator	N/A	Individualised advice	N/A	N/A	N/A

(1) Budget of the measure / GDP

(2) No. beneficiaries / No. households

2.4.1.2 Energy efficiency policies in the UK

In relation to programs promoting or supporting energy efficiency in the UK households, those of most relevance are highlighted below:

- Green Homes Grant - Voucher schemes: this scheme, which was launched in September 2020, offers low-income homeowners in England up to €11,402 to implement energy efficiency and low carbon heating measures in their homes. It is estimated to achieve savings of up to €684 per year on energy bills.
- Green Homes Grant - Local Authority Delivery: The main aim of the scheme is to raise the energy efficiency rating of low income and low energy rated homes (those with D, E, F or G), including poorer quality homes off the gas grid.
- Energy Company Obligation: This policy obliges large energy suppliers to provide energy efficiency and heating measures to energy poor households across Britain. Since the start of the programme in 2013, 2.8 million measures have been installed in over 2.1 million homes. Eligible households benefiting from these measures can save up to €342 a year on their energy bills compared to an identical household that does not benefit from them.
- Home Upgrade Grant: This is an ambitious scheme approved in 2020 and due to start rolling out in 2022. It is the replacement for the 'Green Homes Grant'. Endowed with around €1.5 billion in total, it aims to help with €171m to improve the worst performing off-gas grid homes in England.
- Minimum Energy Efficiency Standards: The 2015 regulations require private landlords renting F or G-rated properties to upgrade their properties to a minimum energy efficiency rating of band E. Moreover, if they are unable to obtain sufficient external funding, they are required to make a financial contribution of up to €3991 including VAT. This is a first step towards achieving a minimum C rating for these dwellings by 2030.

Table 2. 6 summarises these measures including their main characteristics.

Table 2. 6. Summary of energy efficiency programs in the UK

Measure	**Type**	**Requirements**	**Application**	**Funding**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Non-recoverable funds ratio (1)**	**Additional percentage (2)**
Green Homes Grant - Voucher Schemes	Aid for the rehabilitation of the enclosure / Aid for the replacement of equipment	Low-income households and low energy rating (D or worse)	Online form	Central government	Up to €11,402 /household	79,400 households (Mar 2021)	N/A	100%
Green Homes Grant - Local Authority Delivery	Aid for the rehabilitation of the enclosure / Aid for the replacement of equipment	Low-income households and low energy rating (D or worse)	Through local authorities	Local authorities	Improvement of one level in the energy rating of the dwelling	17,556 households (Aug 2021)	N/A	100%
Energy Company Obligation	Aid for the rehabilitation of the enclosure / Aid for the replacement of equipment	Specific to each company. Generally: Be a beneficiary of the 'Warm Home Discount'; housing rated E or worse; meet the requirements of the local authorities.	To suppliers	Energy companies	Actions to replace equipment and/or energy renovation of the dwelling	2.1M households	N/A	N/A
Home Upgrade Grant	Aid for the rehabilitation of the enclosure / Aid for the replacement of equipment	N/A	Through local authorities	Central government	Actions to replace equipment and/or energy renovation of the dwelling	Total budget: 150 M	N/A	N/A
Minimum Energy Efficiency Standards	Efficiency Regulations	N/A	N/A	N/A	Improvement of one level in the energy rating of the dwelling	All	N/A	N/A

(1) Non-repayable financing / Total investment (in the case of vulnerable households or in the general case if there is no difference)

(2) (Vulnerable household’s benefit - Non-vulnerable household’s benefit) / Non-vulnerable household’s benefit

2.4.2 European Union

In 2018, around 34 million Europeans (7.6% of the EU population) were unable to afford to keep their homes adequately warm [206]. Two years earlier, the European Commission published the 'Clean Energy for All Europeans package' [207], [208], [209] in order to facilitate the energy transition. The document set the Energy Union as a priority and pursues three main goals: (1) 'Putting energy efficiency first'; (2) 'Achieving global leadership in renewable energies'; (3) 'Providing a fair deal for consumers'. In 2018 the European Commission came to a political agreement [210] that sets the targets for energy efficiency (32.5 %), renewable energy (32 %) and electricity market for 2030. In 2019, the Council of ministers of the EU defined the remaining sections of the 'Clean energy for all Europeans package' [211]. Two of the main intentions of the package were to reduce energy bills and tackle energy poverty.

In this policy framework, the regulation (EU) 2018/1999 [212] established several obligations for the Member-States' integrated national energy and climate plans. Specifically for energy poverty, the EU countries should: (1) asses the number of energy poor; (2) in case of a significant number of energy poor, carry out specific policies and set targets for the reduction of energy poverty in the country; (3) report information on progress towards the national energy-poverty-reduction targets. All this information has to be shared with the EU Energy Poverty Observatory (EPOV), presented in Section 2.2.4. A detailed report of energy poverty polices in Member States was presented in 2019 [189]. On the other hand, the most recent report of the EPOV on the energy poverty framework in Member States was published in 2020 [144]. Furthermore, in the same year, the EU Commission published a Recommendation Document on energy poverty [213], which summarizes the EU legislative framework and points out some guidelines for the analysis [206] and fight against energy poverty.

From the energy efficiency perspective, the Directive (EU) 2018/844 [214] sets the targets for energy performance of building, taking into account that 50% of EU's final energy consumption is used for air conditioning (heating/cooling), of which 80% is used in buildings. According to this European directive, the renovation in the residential sector would be needed at an average rate of 3%/year to achieve, cost-effectively, the EU's energy efficiency targets. Regarding the EU climate change plans, in 2021, the European Commission presented the amendments and actions of the European Green Deal climate initiatives. In particular, they announced the climate target plan to reduce net greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels) under the new Fit for 55 package [215]. Parallelly, they proposed the establishment of a Social Climate Fund to mitigate the potential regressive impacts of the climate plans [216]. This is expected to provide €72.2 billion for the period 2025-2032 in the EU budget from the new Emissions Trading System in order to support European vulnerable households during the transition. Moreover, among the monitoring requirements for Member States, they are required to include: '(a) detailed quantitative information on the number of households in energy poverty; (b) when applicable, detailed information on progress towards the national indicative objective to reduce the number of households in energy poverty'.

2.4.3 France

France is one of the most active Member States in terms of research and policy addressing energy poverty. Comprehensive studies on energy poverty in France started to be published in 2008, and the French Energy Poverty Observatory now facilitates the definition, monitoring and measurement of energy poverty in the country.

In terms of indicators, France performs better than the EU average on subjective indicators. In 2018, only 5.0% of French people reported that they could not keep the home adequately warm, while the corresponding EU average is 7.3%. Similarly, for 2018, 6.4% of the population could not pay their utility bills on time due to financial difficulties, while the respective EU average is 6.6%. On the other hand, the performance of expenditure-based indicators is mixed. The proportion of households spending more than twice the average share of their income on energy (2M) is 15.0%, which is lower than the EU average. In contrast, 19.5% of French households spend less than half the average value. Based on these values, it seems that the main dimension of energy poverty in France is the underspending one.

Overall, France can be taken as a reference in the EU because of its political leverage and its commitment in recent years in the fight against energy poverty [200]. Table 2. 7 summarises some macroeconomic, demographical and energy poverty features for this country. The mitigating and structural measures implemented by the French Government during the last years are summarised in Sections 2.4.3.1 and 2.4.3.2.

Table 2. 7. Context data of France, 2019

Indicator	Population	Households	GDP	GDP per capita	Average income	% unemployment	GINI (1)	AROPE (2)	% EP
Data	67.2M	30M (1)	2,426,312M€	36,075 €	Equivalent median net income: 22,583€.	8.70%	32.4 (2018)	17.9%	- 2M: 15% (households, 2015) - M/2: 19.5% (households, 2015) Winter inadequate temperature: 5% (population, 2018) - Arrears in bills: 6.4% (population, 2018)
Source	World Bank	Eurostat	World bank	World bank	Eurostat	OECD	World Bank	Eurostat	EPOV

(1) Inequality indicator

(2) Percentage of population at risk of poverty or exclusion

2.4.3.1 Subsidies and additional protection measures in France

Between 2004 and 2017, the social tariffs of electricity and gas have been the national financial measures to help low-income households pay their bills. These were discounts on the bill cost related to energy consumption. In 2018, the French Government replaced the social tariffs scheme with the Energy Voucher (*Chèque énergie*) [217], which is an annual cheque ('transfer/payment in cash') for vulnerable households[17] supporting the payments of energy bills and retrofitting investments. This aid is assigned according to the household income level and number of members. This measure is particularly interesting for comparison with the heating allowances in the thesis case study (see Sections 2.4.5.1 and 6.2.1). Currently, French vulnerable consumers can use the energy voucher in three different ways: (1) online, in a specific website of the French Ministry for the Ecological Transition [201]; (2) by requesting for an automatic deduction of the voucher amount from their bills; (3) by sending the energy voucher to their supplier by post. The average amount of the Energy Voucher in 2018 was €150, while the French Energy Poverty Observatory [218] estimated that the average energy poverty gap per household would vary from €526 to €735, depending on the method used. The Energy Voucher has been revalued in 2019 by €50 [201] for all beneficiaries, so reaching the total average amount of €200. Nevertheless, as mentioned before, the Energy Voucher is assigned only according to income level and the household size, thus not taking into account the climate zone, which was pointed out as one of the main parameters to consider in the analysis of energy poverty in France [218].

In addition to the Energy Voucher, there is another subsidy policy coordinated by the different national government's departments, i.e. the Housing Solidarity Fund (*Fonds de solidarité logement*), which provides financial assistance to people who find it difficult to pay their housing-related expenses (bills, rents, etc.). From the perspective of cut-off protection measures, in France, energy suppliers are prohibited from disconnecting households during the winter period (November-March, *Trêve hivernale*) from electricity and natural gas supply.

The main features of these mitigating measures are set out in Table 2. 8.

[17] The Energy Voucher is not a bank cheque, so it cannot be cashed at a bank or used for expenses others than energy supply ones.

Table 2. 8. Summary of subsidies and additional protection measures in France, 2019

Measures	**Type**	**Requirements**	**Application**	**Funding**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Benefit ratio**	**Beneficiary ratio**
Chèque énergie	Explicit direct subsidy with administrative guidance	Socio-economic (income and household composition)	Automatic	PGE: 850M€.	- Transfer in cash: Cheque (48€-277€)	5.8M	0.035%	19.3%
Trêve hivernale	Consumer protection against disconnection	-Main residence (limited power) -Consumers covered by the Chèque énergie (no power limit)	Automatic	N/A	No interruption of electricity, heating or gas supply to persons or families in a main residence.	N/A	N/A	N/A
Fonds de solidarité logement	Explicit direct subsidy with administrative guidance	Vulnerable tenants or owners	Through a social worker	Departments	Help with the payment of invoices	0.1M	N/A	0.3%

(1) Budget of the measure / GDP

(2) No. beneficiaries / No. households

2.4.3.2 Energy efficiency policies in France

In France, a wide range of energy efficiency policies have been implemented for vulnerable households. Multiple programmes, involving various actors, aim to improve household energy efficiency. A significant number of these financing programmes targeting energy-poor households are implemented through national, regional and local governments, such as the social funds for energy renovation and the Living Better (*Habiteur Mieux*) programme. However, private financing is also present through the white certificates scheme which includes a specific obligation for energy suppliers to promote energy efficiency improvement actions in vulnerable households. Complementary programmes have been implemented in the last years and are summarised in Table 2. 9.

Another type of action in the fight against energy poverty in France from an efficiency perspective are the energy audit programmes (*Audit energetique*), developed in collaboration between the three sectors (NGOs, private actors and governments), in order to provide vulnerable households with energy saving advice. There are also multiple points where households can obtain information on energy savings. In this respect, the Local Energy Intervention Service aims to coordinate actions against energy poverty at departmental level.

A summarised description of energy efficiency measures is included in the following Table 2. 9.

Table 2. 9. Summary of energy efficiency programs in France

Measures	Type	Requirements	Application	Funding	Benefit	Number of beneficiaries (households/consumers)	Non- recoverable funds ratio (1)	Additional percentage (2)
Habiter Mieux Programme (a), (b), (c)	Aid for enclosure renovation / Aid for equipment replacement	Residency requirements Socio- economic requirements Technical requirements	Agence nationale de l'habitat (ANAH)	Agence nationale de l'habitat (ANAH), €760 million (2019):	-Habiter Mieux Sérénité: energy rehabilitation works. - Habiter Mieux Agilité: single energy refurbishment work- Habiter Mieux copropriét: project management support.	In 2019, works were financed in 116,995 homes and in 2018 in 62,345 homes.	Habiter Mieux Sérénité: 35-58.3%. Habiter Mieux copropriét: 20.7% Tenant support: 25% + bonus	100%
MAPRIMERÉNO V (7) (d), (a)	Aid for enclosure renovation / Aid for equipment replacement	Residency requirements Socio- economic requirements Technical requirements	Agence nationale de l'habitat (ANAH)	National government 2020 (including CITE): 740 M€2021 : 1700 M€	Improvements in home insulation, changes in the ventilation or heating system, home energy audit.	150,000 applications were registered in the first 12 months of the programme.	66%	65%
Dispositif des certificats d'économies d'énergie	Aid for enclosure renovation / Aid for equipment replacement	Socio-economic requirements	Energy trading companies	2000 M€ (2018-2020)	White certificates: Renovation of the enclosure: Up to 20 €/m2 (30 €/m2 in vulnerable households) Replacement of equipment: Up to 2500 €/m2 (4000 €/m2 in vulnerable households)	N/A	N/A	55%

Measures	Type	Requirements	Application	Funding	Benefit	Number of beneficiaries (households/consumers)	Non-recoverable funds ratio (1)	Additional percentage (2)
Eco-pret a taus zero	Aid for enclosure renovation / Aid for equipment replacement	Residency requirements	National Government	National Government (Ministry of Ecological Transition and Solidarity)	15-year interest-free loans for insulation work or equipment installation.	18,755 (2018)	0	0
TVA RÉDUITE	Aid for enclosure renovation / Aid for equipment replacement	Technical requirements	Certificate. Article 278-0 bis A of the General Tax Code	National Government	VAT rate at 5.5%: energy efficiency of the dwelling VAT rate at 10%: other improvement work	N/A	N/A	N/A
Eco-pret Logement social	Aid for enclosure renovation / Aid for equipment replacement	Housing typology requirements Technical requirements Geographical requirements	Banque des Territoires	National government (National public funds)	Loan for the renovation of social housing up to a limit of €27,000 per dwelling.	N/A	N/A	100%
Energy audit	Energy Saving Grants	Residency requirements Technical requirements	Agence de la Transition écologique (ADEME)	Agence de la Transition écologique (ADEME)	Subsidies for energy audits in households (and businesses)	N/A	N/A	N/A

(1) Non-repayable financing / Total investment (in the case of vulnerable households or in the general case if there is no difference)

(2) (Vulnerable household's benefit - Non-vulnerable household's benefit) / Non-vulnerable household's benefit

2.4.4 Portugal

In Portugal, the attention paid to the phenomenon of energy poverty has increased in recent years. A good indicator of this fact can be found in the numerous research studies carried out in the country in the last decade, e.g. [219], [220], [221], [132], which have focused on different topics such as the geographical distribution of energy poverty, thermal comfort and energy consumption. There is also a growing interest in investigating the inability to keep dwellings comfortably cool in summer, particularly related to the so called 'energy performance gap' [221], [222]. Table 2. 10 summarises some national macroeconomic and demographic data and shows the EPOV indicators shares for Portugal. Looking at the main EPOV indicators, there is a high percentage of households reporting that they are unable to maintain an adequate temperature in winter: 19.4%. The rest of the indicators are very close to the average for the EU as a whole.

In April 2021, the Ministry of the Environment and Climate Action published the first draft of the Long-Term National Strategy against Energy Poverty 2021-2050 (*Estratégia Nacional de Longo Prazo para o Combate à Pobreza Energética 2021-2050*) [48]. This document is still under public consultation but, among other contributions, it proposes definition and metrics to identify and measure this social issue, and an integrated policy plan. The following Sections 2.4.4.1 and 2.4.4.2 describe, respectively, the mitigating and structural policies introduced in Portugal.

Table 2. 10. Context data of Portugal, 2019

Indicator	**Population**	**Households**	**GDP**	**GDP per capita**	**Average income**	**% unemployment**	**GINI (1)**	**AROPE (2)**	**% EP**
Data	10.3M	4.1M (1)	213,979M€	20,802 €	Equivalent median net income: 10,023€.	6.70%	33.5 (2018)	21.6%	- 2M: 15.1% (households, 2015) - M/2: 6.8% (households, 2015) - Winter inadequate temperature: 19.4% (population, 2018) - Arrears in bills: 4.5% (population, 2018)
Source	World Bank	Eurostat	World bank	World bank	Eurostat	OECD	World Bank	Eurostat	EPOV

(1) Inequality indicator

(2) Percentage of population at risk of poverty or exclusion

2.4.4.1 Subsidies and additional protection measures in Portugal

Energy poverty is mainly tackled at the national level in Portugal by means of financial support through the social tariffs (*Tarifas sociais*). The electricity social tariff was launched in 2008 and aimed to provide financial assistance to households to pay their energy bills. Since 2016, the social tariffs include the natural gas supply and are automatically granted to vulnerable consumers receiving certain social benefits and low-income households. They provide savings of 33.8% on electricity bills (before tax) and 31.2% on gas bills, and they are paid for entirely by the energy supply companies. Among the ‘technical requirements’ to benefit from the social electricity tariff, consumers must have an electricity supply contract for domestic use and contracted power at low voltage ≤6.9 kW. In addition, to benefit from the social tariff for natural gas, consumers must have a supply contract for domestic use and an annual consumption ≤500 m^3. As mentioned before, the previous version of the social tariff that started in 2008 was different in scope (electricity only) and had different target groups. In recent years, the automatization of the social tariffs’ allocation produced an increase in beneficiaries. In 2019, around 19.5% of Portuguese households (i.e. 763,000 households) received the social tariff for electricity, whereas around 0.7% of them received the natural gas one (i.e. 34,000 households).

In addition to the social tariffs, in Portugal, consumers with less than 6.9 kW of contracted power benefit from a reduced VAT rate (*Redução de IVA*) on their electricity (23% to 13%, in a certain amount of kWh), which is more substantial for consumers contracting less than 3.45 kW (23% to 6%). The latter reduction is applied also to domestic natural gas supplies with a consumption less than 10,000 m^3 per year. Schematic information on both measures can be found in Table 2. 11. On the other hand, there is no specific disconnection ban or extension for vulnerable consumers but the general disconnection process has some guarantees as follows [223]. In the event of interruption due to non-payment, the supplier must give the consumer 20 days' notice in writing before interrupting the supply. The notice must provide information on the causes of the interruption, how to avoid it, and the costs the consumer has to bear for the interruption and subsequent reconnection of supply. For general low-voltage electricity customers, and as long as they have access to the installation, the service can only be interrupted for non-payment after the contracted power reduction to 1.15 kW. The power reduction must be communicated in writing at least 5 days in advance. If the consumer still does not pay, the service can be interrupted, counting 20 days from the power reduction.

Table 2. 11. Summary of subsidies and protection measures in Portugal, 2019

Measures	**Type**	**Requirements**	**Application**	**Funding**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Benefit ratio (1)**	**Beneficiary ratio (2)**
Tarifas sociais	Explicit direct subsidy with administrative guidance	Technical and socio-economic	Automatic	Suppliers. Electricity: 110M€; Natural gas: 1.6M€.	Transfer in kind: Discount on the tariff for access to low voltage electricity networks (33.8%) and/or natural gas (31.2%).	Electricity: 0.8M Natural gas: 0.03M	Electricity: 0. 051% Natural Gas: 0.001%.	Electricity: 19.5% Natural Gas: 0.7%.
Redução de IVA	Implicit direct subsidy	Technical and socio-economic	Automatic	PGE: 19M€ + 150M€ (estimated)	Reduced VAT rate in electricity and natural gas bills (depending on contracted power and consumption)	1.4M + 5.2M (estimated contracts)	Measure 1: 0.009% Measure 2: 0.070% (estimated)	N/A

(1) Budget of the measure / GDP

(2) No. beneficiaries / No. households

2.4.4.2 Energy efficiency policies in Portugal

The Portuguese national government also implemented general programmes and policies to improve energy efficiency and HVAC systems in households, but they do not specifically target the energy poor. In 2007, the programme for the Promotion of Efficiency in Electricity Consumption (*Plano de Promoção da Eficiência no Consumo de Energia Elétrica, PPEC*) was launched. The objective of this policy was to promote measures to improve the efficiency of electricity consumption through actions carried out by third parties, such as energy suppliers and grid operators. In 2010, Portugal launched the measure called Energy Efficiency Fund (Fundo de Eficiência Energética, FEE). It aimed to provide financial support to improve energy efficiency in a wide range of sectors, including the residential sector. It was proposed as a publicly funded grant. In 2021, this fund was transformed into the Financial Instrument for Rehabilitation and Urban Renewal (*Instrumento Financeiro para a Reabilitação e Revitalização Urbanas, IFRRU*).

Complementary to the FEE and the IFRRU, Portugal has other measures aimed at improving energy efficiency such as: (1) the Efficiency Voucher (*Vale Eficiência*), (2) the Support Programme for More Sustainable Buildings (*Programa de Apoio Edifícios mais Sustentáveis*) and (3) the More Sustainable Buildings Support Programme (*Programa de Apoio 'Edifícios* mais Sustentáveis', PAE+S). A more detailed description of these measures is included in the following Table 2. 12.

Table 2. 12. Summary of energy efficiency programs in Portugal

Measures	**Type**	**Requirements**	**Application**	**Funding**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Non-recoverable funds ratio (1)**	**Additional percentage (2)**
Fundo de Eficiência Energética (FEE)	Aid for enclosure renovation / Aid for equipment replacement	Ownership requirements Geographical requirements	Application on the NEEAP online portal	National government	Refurbishment of the enclosure and replacement of equipment.	N/A	55%	0
Instrumento Financeiro para a Reabilitação e Revitalização Urbanas (IFRRU 2020)	Aid for enclosure renovation / Aid for equipment replacement	Socio-economic requirements Geographical requirements Temporary requirements	Request for financing from selected banks	Public (National-EU) and private funding	20-year loans with below-market interest rates	As of September 2021: 1750 Housing rehabilitated	0	0
Vale eficiência (2021)	Aid for enclosure renovation / Aid for equipment replacement	Socio-economic requirements Geographical requirements Temporary requirements	Through the Platform "Fundo Ambiental"	Fundo Ambiental (Plano de Recuperação e Resiliência, National Government)	Vouchers to carry out interventions on the thermal enclosure or to replace or purchase energy efficient equipment and solutions	Programme target: 100,000 vouchers by 2025	100%	100%

Measures	**Type**	**Requirements**	**Application**	**Funding**	**Benefit**	**Number of beneficiaries (households/consumers)**	**Non-recoverable funds ratio (1)**	**Additional percentage (2)**
Programa de Apoio "Edifícios mais Sustentáveis" (PAE+S)	Aid for enclosure renovation / Aid for equipment replacement	Ownership requirements Technical requirements Geographical requirements	Through the Platform "Fundo Ambiental".	Environmental fund: 4.5 M€ 2020: 1.75 M€ 2021: 2.75 M€	Financing of thermal enclosure retrofitting measures, replacement of equipment and other measures.	N/A	N/A	N/A
Plano de Promoção da Eficiência no Consumo de Energia Elétrica (PPEC)	Aid for replacement of equipment/improvement of information	Temporary requirements	Central management: Entidade Reguladora dos Serviços Energéticos (ERSE)	For the Global System Usage Charge	Installation of equipment and dissemination of information	N/A	N/A	N/A

(1) Non-repayable financing / Total investment (in the case of vulnerable households or in the general case if there is no difference)

(2) (Vulnerable household's benefit - Non-vulnerable household's benefit) / Non-vulnerable household's benefit

2.4.5 Spain

Table 2. 13 summarises some national macroeconomic and demographic data and shows the EPOV indicators shares for Spain, which are further analysed in Section 2.2.5. Although concern about energy poverty in this country dates back only a few years (the first social tariff was implemented in 2009 through the Royal Decree Law – RDL – 6/2009), regulatory activity has been intense in recent years. Indeed, the Spanish Government have proposed aids to support both electricity and thermal energy services, i.e. an electricity social tariff (*Bono social eléctrico*), which has been subjected to frequent reforms between 2017 and 2021, and a Thermal Social Allowance (*Bono social térmico*), which was introduced in 2018. In addition, from 2019, Spain has had an energy poverty roadmap for the coming years through the National Strategy against Energy Poverty 2019-2024 (SNSEP). Some of the most recent milestones in this regulatory process can be summarised as follows.

The first of these milestones is RDL 897/2017, which introduced the income criterion in the definition of vulnerable consumers, those who according to Law 13/2013 on the electricity sector in its article 45 indicated that they would be beneficiaries of the electricity social tariff. Just one year later, the RDL 15/2018 introduced three important changes with respect to the vulnerable consumers support scheme defined in RDL 897/2017: (1) the income and electricity consumption thresholds for the electricity social tariff were increased, (2) a Thermal Social Allowance (TSA) was introduced, and (3) the need to draw up the SNSEP was established, which is described in the next paragraph. The latest economic measures relating to the aids and the protection of consumers (in particular vulnerable consumers) to deal with the rise in energy prices are set out in RDL 17/2021 and RDL 23/2021. Also, previous decrees (RDLs 463/2020, 8/2020, etc.) introduced various measures (under the 'social shield') to mitigate the effects of the COVID-19 pandemic.

On the 5th of April 2019, the SNSEP for the period 2019-2024 [26] was approved by agreement in the Council of Ministers. It is a document that does not carry the weight of law, but nevertheless represents an important step in the fight against energy poverty in the country. Firstly, it addresses the issue in a comprehensive manner, from the definition of the problem to policies, including the measurement of the phenomenon. Secondly, it serves as a reference for other actors involved and provides a 'common language'. Finally, it carries out an exhaustive analysis of the situation from which several lines of action and mitigation objectives are proposed. Thus, as the document itself highlights, the main contributions of the SNSEP can be summarised as follows [224]:

- An official definition of energy poverty.
- Suggestion of a more in-depth measurement and knowledge of the problem.
- Proposal of indicators to monitor the problem and reduction targets for 2025.
- Critical analysis of the mitigating measures such as the evolution of the current social tariffs and a ban on cuts.

- Proposal of structural measures and awareness-raising measures.

The first point refers to the proposal for an official definition of energy poverty in our country, which is shown in Table 2. 1. It is noted that the definition has two parts. On the one hand, it describes the issue, and on the other hand it points to the causes of it. Although it is an indicative, not exhaustive, definition of the problem, it does provide what is expected of it, namely a framework for a common understanding of the problem. The next two points that stand out as contributions of the SNSEP have to do with the indicators and are further analysed in Sections 2.1.2 and 2.2.5. Moreover, the Strategy sets the following energy-poverty reduction targets for 2025: 25% and 50%, respectively, as minimum target and desired target.

This section describes the two main direct and explicit subsidies that are currently in force in Spain, i.e. the electricity social tariff and the TSA, as well as measures to prohibit cuts (Section 2.4.5.1), and provide a summary of the housing energy efficiency policies (Section 2.4.5.2). For a description of all legal details, the reader is referred to the chapter on energy poverty in the *Informe España 2019* [225].

Table 2. 13. Context data of Spain, 2019

Indicator	**Population**	**Households**	**GDP**	**GDP per capita**	**Average income**	**% unemployment**	**GINI (1)**	**AROPE (2)**	**% EP**
Data	47.1M	18.7M	1,244,772M€	26,430 €	Equivalent median net income: 15,015€.	14.4%	34.7 (2018)	25.3%	- 2M: 16.8% (households, 2020) - M/2: 10.3% (households, 2020) - Winter inadequate temperature: 10.9% (population, 2020) - Arrears in bills: 9.6% (population, 2020)
Source	World Bank	Eurostat	Macro data	Macro data	Eurostat	OECD	WB	Eurostat	(MITERD, 2020)

(1) Inequality indicator

(2) Percentage of population at risk of poverty or exclusion

2.4.5.1 Subsidies and additional protection measures in Spain

Currently, the *bono social eléctrico* is a social tariff that considers different discounts on the electricity regulated market price, i.e. the Voluntary Price for Small Customer (VPSC), for different categories of vulnerable consumers, identified by socio-economic features. Thus, the basic requirement to obtain the electricity social tariff is to be in the regulated market. All consumers who meet this basic criterion must also meet certain socio-economic requirements structured around an income criterion, according to the composition of the family unit. These income thresholds refer to the Public Indicator of Multiple Income (*IPREM*), and categorise the consumer as vulnerable, severely vulnerable or 'at risk of social exclusion'. The latter is defined as a beneficiary who meets the requirements to be considered a severely vulnerable consumer and, in addition, is attended by the social services of a regional or local administration that finances at least 50 per cent of the amount of their bill. Electricity supply to these consumers at risk of social exclusion who have accredited their condition is considered essential by the Electricity Sector Law. Regarding the form of access to the subsidy, the application to obtain it is made through the reference last resort retailers (*CORs*), which are responsible for processing it. In addition to the above, limits are defined on the amount of consumption that can receive the subsidy. Regarding the funding of this measure, the cost of the discount on the electricity bill is assumed by all electricity suppliers (RDL 7/2016). According to data from the Ministry of Ecological Transition, the beneficiaries of the electricity social tariff at the end of 2016 were around 2.4 million. This number was maintained in 2017, due to the extension of the aid allocations. At the end of 2018, there was no extension (RDL 897/2017) and the number of beneficiaries decreased significantly (1.1 million consumers). In 2019, 2020, and 2021, the beneficiaries have been, respectively, 1.3 in the first mentioned year and 1.2 million in the last two ones (approximate figures at year-end). With regard to the mode of delivery, this subsidy falls into the 'Transfer in kind' typology, applying a discount on the tariff according to the category of consumer. For the vulnerable consumer category, a 25% discount is applied to all the terms that make up the VPSC. In the case of severe vulnerable consumers, a 40% discount is applied[18]. For consumers at risk of social exclusion: social services should cover at least half of the amount of the electricity bill and the rest has to be covered by the electricity supplier, i.e. these consumers do not have to pay their electricity bill. The requirements for accessing the social tariff for electricity and the annual consumption limits with discount are summarised in Table 2. 14. Therefore, the electricity social tariff is an administratively oriented measure, privately financed ('cross-subsidising', fully financed by the electricity suppliers) and is a transfer in kind (discount).

[18] RDL 23/2021 has increased these percentages temporarily (until 31 March 2021) to 60% for vulnerable consumers and 70% for severe vulnerable consumers.

Table 2. 14. Income and consumption thresholds of the Spanish social tariff for electricity per vulnerability level and household category. IPREM – Public indicator of Multiple Income (€ 7520/year for 2018 [226] *, as well as for 2019)*

Vulnerability level	**Discount**	**Household category**							
		Minimum pension	**Without minors**		**1 minor**		**2 minors**		**Large family**
Vulnerable	25%	All members are pensioners with minimum pension	€11,279 (1.5xIPREM)	€15,039 (2xIPREM)*	€15,039 (2xIPREM)	€18,799 (2.5xIPREM)*	€18,799 (2.5xIPREM)	€22,559 (3xIPREM)*	Non-compulsory income requirements
Severely vulnerable	40%	€7,520 (1xIPREM)	€5,640 (0.75xIPREM)	€7,520 (1xIPREM)*	€7,520 (1xIPREM)	€9,399 (1.25xIPREM)*	€9,399 (1.25xIPREM)	€11,279 (1.5xIPREM)*	€15,039 (2xIPREM)
At risk of social exclusion	100%	If the beneficiaries fulfil the requirements to be considered a severe vulnerable consumer and, in addition, the social services pay at least half of the amount of the electricity bill, they will not have to pay the bill.							
Annual consumption with discount		1,932 kWh	1,380 kWh		1,932 kWh		2,346 kWh		4,140 kWh

** For the following special circumstances:*

- *Recognised disability ≥ 33%*
- *Victim of gender violence*
- *Degree of dependency, grade II or III*
- *Single-parent families*

Special mention should be made of the TSA, created by the aforementioned RDL 15/2018. The beneficiaries of this allowance are those households already benefiting from the electricity social tariff on 31 December of the previous year. The TSA is intended to 'alleviate households' energy bills for heating, domestic hot water or cooking fuels', and its amount is modulated according to the winter climate zone and the household's degree of vulnerability. The financing of the TSA is covered by the General State Budget, and the amount varies each year according to budget availability. The management and payment of the allowance corresponds to the autonomous communities (i.e. the Spanish regions – NUTS2) and cities. The budget allocated for 2019 was 75 million euros, while in 2020 the allocation was increased by 20 million euros. On the other hand, in 2021, 109 million euros were allocated to this budget item, which has been increased by another 100 million following the publication of RDL 23/2021. The TSA is a payment into the beneficiary's account (bank transfer) for supporting thermal supplies (heating, domestic hot water and, where applicable, cooking). This payment currently depends on the average value of the winter climate severity range for the climate zone of the locality of residence (called $\overline{\mathrm{WS}}_{\mathrm{locality}}$) and a coefficient that is calculated on the basis of the allocated budget (called 'a'), as shown in the payment formula, i.e. Eq. (2.6):

$$\mathrm{TSA}\ [€/\mathrm{year}] = 25 + \mathrm{a} \cdot \frac{\overline{\mathrm{WS}}_{\mathrm{locality}}}{0.115} \tag{2.6}$$

In the case of a severely vulnerable consumer or one at risk of social exclusion, the payment is 60% higher than that allocated to a vulnerable consumer in the same climate zone. $\overline{WS}_{locality}$ assumes values between 0 (warmest climate zone) and 1.51 (coldest climate zone). The amount of support that finally resulted in 2019 is shown in Table 2. 15. Therefore, the TSA is an instrument of administrative guidance, as the electricity social tariff, but in this case financed by the National Budget and conveyed as a money transfer ('transfer in cash').

Table 2. 15. Amount of aid received (TSA) according to winter climate zone and vulnerability category (year 2019) [227]

Winter climate zone	Vulnerability category	Aid [€/year]
α	Vulnerable	25
	Severely Vulnerable	40
A	Vulnerable	29
	Severely Vulnerable	46.40
B	Vulnerable	37.68
	Severely Vulnerable	60.29
C	Vulnerable	49.84
	Severely Vulnerable	79.74
D	Vulnerable	67.56
	Severely Vulnerable	108.10
E	Vulnerable	77.46
	Severely Vulnerable	123.94

To describe the measures related to the ban on cuts in Spain, it is important to distinguish between two concepts. On the one hand, there is a temporary suspension of the supply cut-off, something that was regulated in RD 897/2017. There, in the first transitory provision, it is indicated that electricity consumers who, being beneficiaries of the social tariffs and in a procedure to suspend electricity supply due to non-payment, have a period for the suspension of supply extended to 4 months from when they have been reliably requested to pay. In other words, the period during which the cut-off is prohibited is increased by 2 months with respect to general consumers. On the other hand, there is the protection of consumers identified as essential, for whom under no circumstances may the electricity supply be suspended according to Law 24/2013 on the Electricity Sector. The groups in the residential sector that fall into this category were updated by RDL 15/2018 and are as follows:

- Electro-dependent: those domestic supplies in which there is documentary proof formalised by medical personnel that the electricity supply is essential for the power supply of medical equipment that is essential to keep a person alive.
- Severely vulnerable at risk of social exclusion: those supplies to consumers who are severely vulnerable under last resort tariffs and who are being attended (with respect to these supplies) by the social services of the competent Public Administrations, due to their income. As indicated above, in order for these supplies to be recognised as essential, the condition of risk of social exclusion must be accredited by the Social Services through the payment of 50% or more of their bill.

- Minors, dependents and people with disability: those supplies that incur in non-payment of the electricity bill whose holder is a beneficiary of the social tariffs and for its application has accredited to be part of a family unit in which there is at least one minor under sixteen years of age, or the holder, or any of the members of the family unit is in a situation of recognised dependency of degree II or III, or has a recognised disability equal to or greater than 33%.

Furthermore, the publication of the RDL 17/2021 introduced a third element to consider: the so-called Minimum Vital Supply (MVS). In practice, the MVS extends the term of the ban on cutting off electricity supply to consumers covered by the social tariffs for six months in addition to the four months stipulated in RD 897/2017 for vulnerable customers (ten in total), during which time a 'minimum comfort supply' will be guaranteed. In these cases, the limit power associated with the MVS is set at 3.5 kW, which will be applicable only when the contracted power is higher than this limit power. In this regard, the RDL also establishes that the climatological, social or economic circumstances of the beneficiary groups of the MVS must be taken into account with a view to possible future modifications of this power limit.

Moreover, it is worth mentioning that during the exceptional period of the COVID-19 pandemic, additional temporary measures have been put in place to protect consumers against power outages and extend the social tariffs to other vulnerable categories, such self-employed people who significantly decrease their income because of the lockdown. For further details, the reader is invited to consult the following references: [195], [196], [197]. Finally, several temporary measures have been implemented by the Spanish Government to mitigate the impact of the energy prices crisis on residential consumers (RDL 12/2021; RDL 17/2021; RDL 23/2021). These measures can be summarised as follows [198]:

- Social Tariffs:
  - Electricity social tariff: the discount on the electricity bill granted by the social tariff to vulnerable consumers was increased from the current 25% to 60% and from 40% to 70% for the severely vulnerable - until 31 March 2022.
  - TSA: the budget for the TSA was doubled in 2021 (the starting budget earmarked for 2021 was €100m), reaching 202.5 million euros. Considering the number of TSA beneficiaries in 2021 (1.22 million households), the average allowance has been €166 per household.
- Electricity price:

  - Reduction of VAT from 21% to 10%[19] (Royal Decree-Law 12/2021 of 24 June 2021, effective from the end of June).
  - Reduction of electricity tax from 5.11% to 0.5% (Royal Decree-Law 17/2021 of 14 September 2021, effective from mid-September).
  - Reduction of demand charges (96% reduction, Royal Decree-Law 17/2021 of 14 September 2021, effective from mid-September)
- Natural gas price:
  - Cap on the regulated price of natural gas (TUR) for winter 2021/2022 (Royal Decree-Law 17/2021 of 14 September 2021, Resolution of 26 September 2021, effective from the end of September).

Schematic information on the permanent mitigating measures can be found in Table 2. 16.

[19] VAT is reduced from 21% to 10% for consumers with contracted power up to 10 kW if the average market price exceeds 45 euros per MWh. The government reinforces the degree of protection for severely vulnerable consumers, applying 10% VAT regardless of the market price and the contracted power.

Table 2. 16. Summary of subsidies and additional protection measures in Spain, 2019

Measures	Type	Requirements	Application	Funding	Benefit	Number of beneficiaries	Budget/GDP ratio (1)	Beneficiary ratio (2)
Bono social eléctrico	Explicit direct subsidy with administrative guidance	- Regulated market- Socio-economic	Through the COR	All marketers: €139M	- Transfer in kind: Discount on electricity bill according to category (25%, 40%, 100% (6)))	1.3M	0.011%	6.99%
Bono social térmico	Explicit direct subsidy with administrative guidance	Beneficiary of the electricity social tariff as at 31 December of the previous year	'Automatic' allocation with electricity social tariff	General State Budge: 75M€	- Transfer in cash: Bank transfer, amount depending on climate zone and category (25€-124€)	1.3M	0.006%	6.99%
Prohibición de cortes de suministro (3) / SMV (4)	Consumer protection against disconnection	- Power supply to a medical team (3, only benefit 1) - Beneficiary of electricity social tariff (4)	Same as electricity social tariff	N/A	(1) 2/4 months of supply from the notification of non-payment + (2) 6 months of supply with Pmax=3.5 kW (SMV)	~1.3M (5)	N/A	~6.99% (5)
Información a la ciudadanía	Improving information	N/A	N/A	N/A	- Social tariffs websites - Telephone and email contact details	18.6M	N/A	100%

(1) Budget of the measure / GDP
(2) No. beneficiaries / No. households
(3) Budget of the measure / GDP
(4) No. beneficiaries / No. households
(5) Law 24/2013, of 26 December, on the Electricity Sector
(6) Royal Decree-Law 17/2021 of 14 September on urgent measures to mitigate the impact of soaring natural gas prices on the retail gas and electricity markets.
(7) This is somewhat higher as it includes households with a member dependent on medical equipment.
(8) For consumers at risk of social exclusion: If the beneficiary qualifies as a severely vulnerable consumer and, in addition, social services cover at least half of the electricity bill, they will not have to pay the bill. It is therefore not a discount on the bill.
COR: Reference marketers

2.4.5.2 Energy efficiency policies in Spain

The regulatory framework that guides the implementation and promotion of energy efficiency in Spain is set out in the RDL 390/2021. This RDL transposed the Directive 2018/844 into Spanish law, mainly regarding the modification of the registration of energy performance certificates, 'which will allow the collection of data on measured or calculated energy consumption of buildings, as well as the linking of financial incentives for the improvement of energy efficiency to the expected or achieved energy savings'. With regard to financial incentives for energy efficiency improvements in the renovation of buildings, Article 14 links such subsidies to energy savings through the comparison of energy performance certificates issued before and after the renovation or, alternatively, through one or more alternative criteria including, for example, the results of an energy audit.

With regard to the aid programmes for energy retrofitting of dwellings, it can be highlighted, among others, the Programme of aids for Energy Retrofitting actions in Existing buildings (*Programa de ayudas para actuaciones de Rehabilitación Energética en Edificios existentes, PREE*), which supplanted the PAREER-CRECE and PAREER II programmes, carried out between 2013 and 2018 and which had a combined budget of €404 million. These programmes enabled the energy-efficient refurbishment of around 80,000 Spanish dwellings. The budget allocation for the new programme, which comes from the National Energy Efficiency Fund (*Fondo Nacional de Eficiencia Energética*, created by Law 18/2014 of 15 October), was 300 million euros and has been distributed among the autonomous communities according to the number of primary dwellings. This programme is coordinated by the IDAE, but the application for the granting of the aid must be submitted to the Autonomous Community where the property is located. Table 2. 17 shows the percentage of the aid (with respect to the investment), which varies according to the type of action and the type of building. It should be noted that in four of the seven types of action aimed at the residential sector, an additional percentage is foreseen for residential buildings whose owners benefit from the electricity social tariff. Regarding the aforementioned National Energy Efficiency Fund, it is important to note that, at the end of May 2021, the public consultation period for the Royal Decree that will regulate energy saving certificates was opened. The specific objectives of this fund have not yet been defined, but one of the criteria that the Ministry is considering for these incentives is that these actions collaborate in the fight against energy poverty. Another public consultation [228] have been carried out between December 2021 and January 2022 to discuss the proposal for an Order establishing the obligations to contribute to the national energy efficiency fund in the year 2022 .

The measures implemented to date are detailed in Table 2. 17, following the classification of measures established in the introduction of Section 2.4. These measures are mostly framed within the 2020 update of the Long-Term Strategy for Energy Renovation in The Building Sector (LTRS) in Spain (*Estrategia a largo plazo para la Rehabilitación Energética en el Sector de la Edificación en España, ERESEE*), which is the national roadmap for advancing towards the objective of decarbonisation and improving the efficiency of buildings. Moreover, this strategy aims to contribute to the National Energy and Climate Plan 2021-2030 (*Plan Nacional Integrado de Energía y Clima, PNIEC*), which, among many other strategic objectives, is committed to the energy retrofitting of the existing building stock. Both roadmaps include a special mention of households in energy poverty which, in the case of the LTRS, translates into a specific action plan for them. Along the same lines, in October 2021, the RDL 19/2021 was approved. This RDL implements some of the measures proposed in the LTRS 2020 in the context of the Recovery, Transformation and Resilience Plan, development of the European instrument Next Generation EU, among others:

- It introduces three new temporary deductions in the annual tax returns process for investments in energy retrofitting works of the primary (own or rented) dwelling for its use as a dwelling (amendment of Law 35/2006, of 28 November).
- It includes amendments to the system for homeowners' associations: (1) it establishes a simple majority system for carrying out energy refurbishment work, as well as for applying for aid and financing for its development; (2) it constitutes the ‘consideration of general expenses’ for the purposes of applying the rules of preference established in Law 49/1960.
- It confers full legal capacity on homeowners' associations for credit operations related to the conservation, retrofitting and improvement of buildings.
- It creates a line of guarantees to partially cover the financing of the energy refurbishment of residential buildings.

In the same month (October 2021), the RDL 853/2021 [229] regulated the aid programmes for residential refurbishment and social housing under the Recovery, Transformation and Resilience Plan. In particular, this Royal Decree Law articulates the plan in six programmes: one to five, linked to building retrofitting actions, and six, to the promotion of the construction of social rental housing. The first and third programmes, i.e. the Support programme for retrofitting actions at the neighbourhood level (*Programa de ayuda a las actuaciones de rehabilitación a nivel de barrio*) and the Support programme for retrofitting actions at the building level (*Programa de ayuda a las actuaciones de rehabilitación a nivel de edificio*), include a specific criterion for vulnerable households: in case the owners or beneficiaries meet the criterion of economic or social vulnerability, up to 100% of the cost of the action will be financed by European funds.

Table 2. 17. Summary of energy efficiency programs implemented in Spain

Measures	**Type**	**Requirements**	**Application**	**Funding**	**Benefit (5)**	**Number of beneficiaries (households/consumers)**	**Non-recoverable funds ratio**	**Additional percentage (2)**
Programa PREE (Tipología 1, Subtipologías 2.3 y 2.4, y tipología 3)	Aid for enclosure renovation / Aid for equipment replacement	Ownership requirements: (A) and (B) Technical requirements Specific call requirements (Autonomous Communities, CCAA)	Through the CCAA	National Energy Efficiency Fund: 300 M€.	According to typology: 1. A: 35%-85%; B: 25%-75%. (includes an additional 15% for social criteria) 2.3. A: 35%-55%; B: 25%-45% (includes an additional 10% for social criteria). 2.4. A: 35%-45%; B: 25%-35%. 3. A-B: 15%-25%.	N/A	1. 55% 2.3. 40%	1. 23% 2.3. 40%
Programa (nº5) de fomento de la mejora de la eficiencia energética y sostenibilidad en viviendas	Aid for enclosure renovation / Aid for equipment replacement	Ownership requirements Ownership requirements (various categories) Technical requirements	Through the CCAA	GGE+CC AA (14): 2018-2021: 131.9 M€.	Max. amount: 12.000€ and 40% of the eligible investment. Exceptions: - Income < 3 IPREM (75%) - Disabled person (18.000€) - Severely disabled person (24.000€)	N/A	40% (max.)	88%
Apoyo del FEDER a la eficiencia energética en viviendas	Aid for enclosure renovation / Aid for equipment replacement	N/A	N/A	European Regional Development Fund (FEDER): 74M€.	N/A	N/A	N/A	N/A

Measures	**Type**	**Requirements**	**Application**	**Funding**	**Benefit (5)**	**Number of beneficiaries (households/consumers)**	**Non-recoverable funds ratio (1)**	**Additional percentage (2)**
Programa PREE 5000	Aid for enclosure renovation / Aid for equipment replacement	Ownership requirements: (A) and (B) Technical requirements Geographical requirements	Through the CCAA	European Recovery and Resilience Mechanism: €50 million	According to typology: 1. A: 50%-105%; B: 40%-95% 2. A: 40%-95%; B: 30%-85% 3. A-B: 20%-75% (including an additional 15% for social criteria)	N/A	1. 73% 2. 63% 3. 48%	1. 18% 2. 20% 3. 25%
Guía práctica para la gestión de ayudas a la rehabilitación energética de edificios	Improving information	N/A	N/A	Higher Council of the Spanish Architects' Associations (CSCAE)	Guide to facilitate the technical-administrative management of EPRSPs	18.6M	N/A	N/A
Guía de la energía	Improving information	N/A	N/A	IDAE	Guide to household energy consumption and energy savings	18.6M	N/A	N/A
Guía para la elaboración del Libro del Edificio Existente	Improving information	Technicians drafting the Existing Building Books for refurbishment	N/A	General Secretariat for the Urban Agenda and Housing of the Ministry of Transport, Mobility and the Urban Agenda	Instructions, recommendations, tips and examples for the preparation of the Existing Building Book for retrofitting.	N/A	N/A	N/A

(1) Non-repayable financing / Total investment (in the case of vulnerable households or in the general case if there is no difference)

(2) (Vulnerable household’s benefit - Non-vulnerable household’s benefit) / Non-vulnerable household’s benefit

2.4.6 Discussion, policy monitoring and pending issues

Given the multidimensionality of energy poverty [22], it is necessary to design an integrated strategy that includes both mitigating and structural measures [8]. The first type of measures tackles energy poverty in the short term by helping vulnerable households to pay their bills through financial aids and avoiding cuts and/or maintaining a 'minimum energy supply'. Structural measures, e.g. housing retrofitting interventions, usually take a longer time to be implemented, but they are more effective to avoid 'chronifying' energy poverty in the medium-long term [23].

Moreover, a recurring issue when it comes to the financing of investments in housing for vulnerable groups is who should be the beneficiary of that aid. If the tenancy regime is rent, the paradox arises from financing the landlord, who could even raise the rent by having more efficient housing (cfr. landlord/tenant dilemma). Considering the abovementioned problem, the best scenario for financing energy efficiency measures is social housing[20]. Nevertheless, the governments should implement policies to finance and carry out renovations in all types of houses, especially those inhabited by energy-poor people. The other fundamental task of governments should be the design of the appropriate regulation that establishes incentives for the contribution of private initiative.

This chapter have reviewed the main mitigating and structural policies that have been implemented in the UK and three reference Member States (i.e. France, Portugal and Spain), which are framed in the EU regulation. Some common insights can be pointed out from this analysis:

- *Mitigating policies*: The main energy consumption subsidies implemented in the four analysed countries are explicit direct subsidies with administrative guidance. However, the requirements and application process vary depending on the country. Concerning the latter, two of the countries have 'automatic' allocation of their energy consumption subsidies, i.e. France and Portugal, while the UK assigns automatically only two of the three allowances for vulnerable households. On the other hand, Spain requires an application trough the suppliers to receive the current two energy consumption subsidies. Regarding the benefit, these countries apply different types of transfers/payments, being Spain a special case where both the two identified strategies are implemented, i.e. transfer in kind for the electricity social tariff and transfer in cash for the TSA. On the other hand, in the Iberian countries, the energy suppliers fund the social tariffs (with exception of the Spanish TSA that is funded by the State), while the remaining countries mainly opt for public funding. Regarding consumer safeguards against disconnection, only Portugal (among the studied countries) does not have a specific protection for vulnerable consumers.

[20] A social house can be defined as an 'accommodation which is provided at affordable rates, on a secure basis to people on low incomes or with particular needs' [332]

- *Structural policies*: While the UK and France have been introducing specific energy efficiency programs for low-income households in the past decade, e.g. *Green Homes Grant* and *Habiter Mieux Programme*, Portugal introduced only recently a programme for 'vulnerable consumers', i.e. *Vale Eficiencia.* On the other hand, Spain lacks of these specific mechanisms but it introduced, in some cases (e.g. *Programa PREE)*, additional financial coverage when social criteria are verified. Moreover, most of the schemes implemented in the four countries include aids for both thermal enclosure's retrofitting and equipment replacement. It has to be highlighted that the UK and France started to implement these kinds of programmes well before than the Iberian countries, and this fact partially explain the much higher number of beneficiaries of such aids. Another good practice that has increased the coverage of these measures is the inclusion of the private sector in funding, e.g. in the French *Dispositif des certificats d'économies d'énergie.*

Overall, the four analysed countries have been introducing both mitigating and structural policies and enhancements for these measures have been proposed in the national strategies against energy poverty. The former are short-term measures necessary to temporarily reduce the energy burden of vulnerable households while the latter are medium- or long-term measures that aim to tackle structural causes of energy poverty, such as energy efficiency and people energy misinformation. However, measuring the concrete effect of each policy on this issue is a very complex task. The multiplicity of factors that converge in energy vulnerability means that it is not easy to isolate causes and consequences in the impact analysis of the different mitigating measures. In this regard, in the Spanish case study, only a few studies assessed the impact of mitigating measures, e.g. [230] and [231] analysed the electricity social tariff effectiveness in reducing energy poverty, and national level analyses of structural measures impact on vulnerable households are rare, e.g. the LTRS planned the energy retrofitting interventions in households affected by energy poverty. Among these studies, a working paper [230] showed that the social tariff for electricity has not significantly improved the comfort conditions of Spanish vulnerable households. A more recent study [231] confirmed the modest impact of this aid in Spain. Specifically, it estimated that this mitigating measure only reduced energy poverty by 2%, i.e. 59,000 households were no longer in energy poverty because of the implementation of the electricity social tariff, 'out of 2.8 million households still in energy poverty'. Regarding the measures introduced to address COVID-19 socio-economic consequences, [232] analysed the impact of unemployment benefits and the electricity social tariff extension on the energy poverty situation during lockdown, and suggested that the Spanish government should establish policies and targets that consider the constraints associated with future pandemics. Moreover, another study [196] presented a critical review of the COVID energy consumer protection measures, based on the regulatory theory and international experiences, and suggests that 'emergency measures should rely on a robust but flexible targeting strategy and be supported by appropriate financing'. Concerning structural measures and strategies, the LTRS included an energy poverty analysis by relating this social issue with economic vulnerability, expressed through the income level. This assessment offers an alternative official characterisation of this social issue to that proposed in the SNSEP. Based on this alternative analysis, the LTRS proposed two retrofitting scenarios for households in energy poverty, namely a scenario for active measures in household installations (mainly thermal systems) and another one that includes both passive measures for energy retrofitting of the thermal enclosure and active measures in installations.

The analysed studies and strategies proposed different methodologies to measure the impact of mitigating policies or including the energy poverty perspective in policy planning. Nevertheless, on the one hand, the Thermal Social Allowance effectiveness has not been assessed in previous studies, being this aid a key short-term measure to mitigate energy poverty in Spain, especially during winter (winter energy poverty, WEP). On the other hand, the reviewed analyses of energy efficiency policies to tackle energy poverty do not include an assessment of the impact on this social issue. Therefore, a systematic methodology to monitor the impacts of these mitigating and structural measures on energy services affordability and WEP is missing in the literature from Spain.

3. BOTTOM-UP MODEL OF SPANISH HOUSEHOLDS' ENERGY EXPENDITURE

As mentioned in Section 2.1, one crucial challenge of energy poverty investigation is the definition of households' required energy needs in order to have a reference for the design of both policies and metrics. However, to the best of the author's knowledge (see Section 2.1.1), there is no reference model for domestic theoretical energy expenditure in Spain.

Therefore, this chapter[21] proposes a bottom-up model to estimate the Spanish households' theoretical energy expenditure according to their characteristics. Namely, this model was developed to assess the Required ENergy Expenditure (RENE) of each Spanish household, i.e. the theoretical energy expenditure that a household would have to pay to meet their required energy needs, including both thermal (Required Thermal Energy Expenditure, RTEE) and electrical (Required ELectricity Expenditure, RELE) uses. Moreover, this chapter introduces some of the model's direct applications[22] carried out for this thesis.

The structure of the chapter is the following one. Section 3.1 introduces the household characteristics identified in the literature as crucial for the modelling of domestic energy costs and specifies the statistical key features in the Spanish case. Section 3.2 presents the methodology proposed to estimate a Spanish household's RTEE and RELE, then describing some direct applications of these two submodels. Subsequently, Section 3.3 analyses the results of RENE model's implementation and 'evaluation'. Finally, Section 3.4 points out some research insights and further work.

3.1 Introduction

The literature on modelling residential energy demand and expenditure, summarised in Section 2.1.1, shows that building characteristics (age, building type and energy efficiency), location, household consumption customs [66] and socio-demographic parameters, such as number of members and their occupation, are key features to define a required energy consumption.

Concerning these characteristics, is worth considering that the case of Spain is quite complex, as it covers a very broad framework of climatic conditions, housing types (in terms of construction age and characteristics) and multiple socio-demographic dimensions. Taking a statistical approximation of the structure of domestic energy

[21] This chapter partially uses the work carried out for the papers: 'Does cash money solve energy poverty? Assessing the impact of household heating allowances in Spain' and 'The dark side of energy poverty: who is underconsuming in Spain and why?', written by the author and other scholars. Both articles were published in Energy Research & Social Science [236], [136]. It also includes quotations from the mentioned articles.

[22] Its application to energy poverty indicators, alternative technological solutions and policies impact assessment are presented, respectively, in Chapters 4, 5 and 6.

consumption [55], heating accounts for the largest share of total consumption in Spanish households (42% in 2018), followed by consumption in household appliances and lighting (32%) and DHW consumption (17%). During the period 2016-2018, the Spanish Institute for Energy Diversification and Saving (IDAE) carried out a statistical analysis of the natural gas consumption in Spanish households with individual heating systems (SPAHOUSEC II [57]), which continued the research previously performed for the Spanish residential sector (SECH-SPAHOUSEC [54]). The most significant result was that the climatology and the typology of the dwelling are the main factors influencing natural gas consumption.

3.2 Methodology

This section presents the methodology used to model a Spanish household's Required ENergy Expenditure (RENE), i.e. the theoretical energy expenditure that a household would have to pay to meet their required energy needs. Both thermal (heating, cooling, DHW) and electrical (lighting, electrical appliances and cooking) uses are included. The former uses are studied in the 'Required Thermal-Energy Expenditure' (RTEE) model (presented in Section 3.2.1), while the latter are included in the 'Required Electricity Expenditure' (RELE) model (presented in Section 3.2.2). It is important to notice that the required energy consumption model proposed in this chapter is primarily intended for applications to domestic energy poverty ('affordability issue') in developed countries such as Spain, which may differ from the modelling of basic energy needs used in studies on the 'accessibility issue' in developing countries [67]. Moreover, the required energy expenditure does not represent a minimum subsistence value but a theoretical reference value to satisfy all the energy needs necessary [for a household] to live in comfort and be part and parcel of society.

3.2.1 Thermal energy services' model

This section presents the model implemented to assess the Spanish household's 'Required Thermal-Energy Expenditure' (RTEE), i.e. the theoretical expenditure required to ensure the indoor environment comfort during winter (heating) and summer (cooling) and to provide an adequate level of domestic hot water (DHW), considering the following primary parameters: climate zone, basic dwelling's characteristics (typology, size, energy efficiency rate and thermal installations' type) and household size (intended as number of members, only for DHW). Cooking has been considered among the electrical uses (see Section 3.2.2) according to statistics on the Spanish residential sector and literature on electricity consumption modelling [23].

[23] Cooking was not considered in thermal uses because, in 2018, more than 60% of Spanish households owned electric cooking appliances compared to 36% who owned gas appliances [92]. Moreover, according to the SPAHOUSEC II study, natural gas consumption during cooking is only 9.5% of the average natural gas consumption of Spanish households (with individual natural gas heating), so it does not have a notable effect on the gas bill [57]. Therefore, this energy consumption was considered in the electricity expenditure model and not in the thermal energy model, in line with the literature [94].

Spain is characterised by a varied climate with an evident difference between the inland and the coast, and cases, such as the Canary Islands, for which ad hoc climate classifications were created. The current official climate-classification, which determines the demand for Heating, Ventilation and Air Conditioning (HVAC), was set in the most recent version of the Spanish Technical Code for Building Construction (CTE 2019) [84]. Concerning space heating demand, the winter climate zone is identified by a letter, from A to E, in order of increasing winter severity. The additional letter α is used in the Canary Islands to identify the mildest zone (null heating demand). On the other hand, the summer climate zone, which determines the cooling demand, is identified by a number from 1 to 4, in order of increasing summer severity (from the coolest to the hottest one, 1 is used for no cooling demand). Furthermore, the CTE sets the base temperature for the calculation of the Heating Degree Days (HDD) and the Cooling Degree Days (CDD) at 20°C[24]. After processing this basic information (following the methodology established by IDAE [81] and CTE 2019), it is possible to obtain the reference heating demand (referred to 'winter' months from October to May, both inclusive) and cooling demand (referred to 'summer' months from June to September, both inclusive) to maintain the required comfort conditions in the house (see Section 3.2.1.1). In addition to the HVAC demand, an official report [82] and the CTE 2019 analyse the thermal demand for the preparation of domestic hot water (DHW) throughout the year. The sum of the energy demands for HVAC and DHW gives the 'Required Thermal-Energy Demand', which is the theoretical demand required to ensure the indoor environment comfort both in winter and summer (HVAC demand), and to provide an adequate level of DHW. Briefly, the HVAC required demand depends on the winter and summer climate zones of the locality and dwelling's characteristics, such as construction-period, typology (block dwelling or single-family house) and size. On the other hand, the demand for the DHW production varies with network water temperature, household size and dwelling typology. The detailed methodology is presented in the following Section 3.2.1.1.

3.2.1.1 Household's required demand and expenditure for HVAC and DHW

The HVAC demand has been calculated using the methodology described in the report carried out by the IDAE [81] and applying the CTE 2019. The values of annual specific reference-demand for heating (SD_h, in $\mathrm{kWh/(m^2\text{-}\,year)}$) were calculated by the IDAE by applying Eq. (3.1).

$$SD_h = (a_h + b_h \cdot WS\,) \tag{3.1}$$

[24] This temperature is critical in establishing HVAC needs and, for example, in the case of heating, is higher than the 18ºC set as a WHO comfort level. This issue is further discussed in Sections 4.2.2.2 and 4.3.2.

The same institute also calculated the reference-demand for cooling (SD_c, in $\text{kWh}/(\text{m}^2$ - year)) by applying Eq. (3.2).

$$SD_c = (a_c + b_c \cdot SS) \tag{3.2}$$

In Eq. (3.1), *WS* is the winter severity index, which is estimated for each winter climate zone from the Heating Degree Days (*HDD*) and the ratio of the number of sunshine hours to the number of maximum sunshine hours; a_h and b_h are the heating correlation coefficients. In Eq. (3.2), *SS* is the summer severity index, which is estimated for each summer climate zone from the Cooling Degree Days (*CDD*) and the ratio of the number of sunshine hours to the number of maximum sunshine hours; a_c and b_c are the cooling correlation coefficients. The heating and cooling correlation coefficients are the result of modelling thirteen types of building geometry [81] and vary according to the dwelling typology (block dwelling or single-family house). Therefore, the HVAC reference demand values vary according to the climate zone and the dwelling typology.

The values of SD_h for each winter climate zone are shown in Table 3. 1 [233]. Whereas Table 3. 2 shows the SD_c values for each summer climate zone.

Table 3. 1. Annual reference-demand for heating [kWh/(m² year)] per each Spanish winter climate zone and dwelling typology (new buildings in [233]*)*

Winter climate zone	Block dwelling	Single-family house
α	0.0	0.0
A	13.8	23.6
B	20.9	33.5
C	35.2	53.3
D	53.0	78.0
E	71.2	103.3

Table 3. 2. Annual reference-demand for cooling [kWh/(m² year)] per each Spanish summer climate zone and dwelling typology (new buildings in [233]*)*

Summer climate	Block dwelling	Single-family house
1	0.0	0.0
2	7.1	10.7
3	14.9	21.7
4	21.0	30.3

Based on the HVAC reference demand values (Table 3. 1 and Table 3. 2), the values of the specific required demand for heating and cooling, i.e.

SRD_h and SRD_c (kWh/(m^2 - year), of a Spanish household can be calculated using Eq. (3.3a).

$$SRD_j = \left(CF_j \cdot SD_j\right) \tag{3.3a}$$

$$CF_j = \frac{1 + (EEP \quad - 0{,}6) \cdot 2 \cdot \left(R_j - 1\right)}{R_j} \tag{3.3b}$$

$$RD_j = SRD_j \cdot DS \tag{3.3c}$$

Where CF_j is a correction factor that depends on the energy efficiency parameter (EEP) of the dwelling and on the dwelling dispersion factor R_j (Eq. (3.3b)); j can be heating (h) or cooling (c). Then, SRD_h and SRD_c (kWh/(m^2 - year) have to be multiplied by the dwelling size (DS, m^2) to obtain, respectively, the household's annual required demand for heating (RD_h, in kWh/year) and cooling (RD_c, in kWh/year), as shown in Eq. (3.3c).

Regarding the EEP values to be selected for Eq. (3.3b), the IDAE [233] presents two different energy efficiency parameters depending on the building age. In order to generalise the calculation, the model presented in this work sets a unique EEP, as shown in Table 3. 3.

Table 3. 3. Energy efficiency parameter (EEP) ranges according to the dwelling's energy class

Energy class	**EEP range**
A	EEP< 0.15
B	0.15 ≤ EEP< 0.50
C	0.50 ≤ EEP< 1.00
D	1.00 ≤ EEP< 1.75
E	(depends on the winter climate zone and the dwelling type)
F	(depends on the winter climate zone and the dwelling type)
G	(depends on the winter climate zone and the dwelling type)

Table 3. 4 and Table 3. 5 show the EEP ranges of the last three energy classes (i.e. the less efficient ones) according to the winter climate zone and dwelling typology. On the other hand, Table 3. 6 displays the R_j values used for the calculation of heating's and cooling's correction factors.

Table 3. 4. EEP ranges of the last three energy classes according to the winter climate zone in block dwelling

Winter Climate zone / Energy class	**α/A**	**B**	**C**	**D**	**E**
E	1.75 ≤ EEP< 3.98	1.75 ≤ EEP< 3.62	1.75 ≤ EEP< 3.33	1.75 ≤ EEP< 3.18	1.75 ≤ EEP< 3.12
F	3.98≤ EEP< 4.35	3.62≤ EEP< 3.96	3.33≤ EEP< 3.64	3.18≤ EEP< 3.49	3.12≤ EEP< 3.41
G	EEP≥4.35	EEP≥3.96	EEP≥3.64	EEP≥3.49	EEP≥3.41

Table 3. 5. EEP ranges of the last three energy classes according to the winter climate zone in single-family houses

Winter Climate zone / Energy class	**α/A**	**B**	**C**	**D**	**E**
E	1.75 ≤ EEP< 3.10	1.75 ≤ EEP< 3.09	1.75 ≤ EEP< 3.14	1.75 ≤ EEP< 3.03	1.75 ≤ EEP< 3.28
F	3.10≤ EEP< 4.02	3.09≤ EEP< 3.86	3.14≤ EEP< 3.73	3.03≤ EEP< 3.60	3.28≤ EEP< 3.94
G	EEP≥4.02	EEP≥3.86	EEP≥3.73	EEP≥3.60	EEP≥3.94

Table 3. 6. Heating's and Cooling's dispersion factors (R_j) according to the climate zone and dwelling typology

	Climate zone	Block dwelling	Single-family house
Winter (Heating)	α	-	-
	A	1.7	1.7
	B	1.7	1.6
	C	1.7	1.5
	D	1.7	1.5
	E	1.7	1.4
Summer (Cooling)	1	-	-
	2	1.6	1.5
	3	1.5	1.4
	4	1.5	1.4

Subsequently, the annual specific required demand for DHW (SRD_{DHW}, in kWh/(person - year)) in every Spanish locality can be calculated applying Eq. (3.4a) [82] to the average monthly network-water-temperature (ºC) of the Spanish provincial capitals (CTE 2019). For localities other than the provincial capitals, the network-water-temperature is estimated by subtracting a factor, defined in CTE 2019, which depends on the difference between the altitude of the locality and that of its provincial capital.

$$SRD_{DHW} = \sum_{i=1}^{12} \frac{SD_T \cdot (T - T_i) \cdot 4{,}176 \cdot n_i}{3600} \quad (3.4a)$$

$$RD_{DHW} = SRD_{DHW} \cdot HS \quad (3.4b)$$

In Eq. (3.4a), SD_T is the daily specific hot water consumption (l/(person - day)) at a given temperature T = 60 °C, which depends on the dwelling type; T_i is the average monthly network water temperature (°C), which depends on the locality considered; n_i is the number of days of the i-th month. Then, the household's annual required demand for DHW (RD_{DHW}, in kWh/year) can be computed by multiplying SRD_{DHW} (kWh/(person - year)) by the household size (HS, number of household members), as shown in Eq. (3.4b).

Thereafter, the required thermal energy consumption for heating, DHW or cooling is determined from the required thermal energy demand and the seasonal performance factor (SPF) of the installation, considering the type of system (e.g. individual or central systems), the type of energy carrier (e.g. natural gas, electricity, etc.) and, for electricity, differentiating according to the type of final installation (electric radiators or Electric Storage Heater[25]) as shown in Eq. (3.5).

$$RC_k = \frac{RD_k}{SPF_k} \tag{3.5}$$

Particularly, the required consumption for heating, DHW or cooling (RC_h, RC_{DHW} or RC_c) is obtained by calculating the ratio between the required demands (RD_h, RD_{DHW} or RD_c) and, respectively, the seasonal performance factor for heating (HSPF) or DHW, or the Seasonal Energy Efficiency Ratio for cooling (SEER). Reference values for these parameters were published by IDAE in 2011 [81] (for further details and elaboration, see Section 3.2.1.2).

Finally, the value of the annual required expenditure for heating (RE_h), cooling (RE_c) or DHW (RE_{DHW}) is estimated by applying the energy-carriers' prices and taxes (detailed in Section 3.2.1.2) to, respectively, RC_h, RC_c or RC_{DHW}. The sum of RE_h, RE_c and RE_{DHW} gives the household's RTEE.

3.2.1.2 Provincial level analysis of the winter energy needs

The provincial analysis (NUTS3) carried out in this section[26] focuses only on 'winter energy needs' (space heating during winter and domestic hot water preparation throughout the year), in accordance with the analysis presented in the SNSEP (which uses as reference the public consultancy's contribution of the author and other scholars of the Chair of Energy and Poverty [234]) and the residential thermal uses considered in the Thermal Social Allowance (TSA) policy. Moreover, according to the IDAE report on Spanish residential consumption [55], in 2018, the final energy consumption for heating and DHW was 59.4% of the total final domestic energy consumption.

Firstly, the winter climate zone of each Spanish locality was identified following the abovementioned regulation (CTE 2019), i.e. the climate zone of a locality is set according to the province it belongs to and its altitude with respect to the sea level [235]. Thereafter, the characterisation of the provincial household's Required 'Winter' Thermal Energy Expenditure (RWTEE)[27], has been carried out according to the following parameters: (a) winter climate zone; (b) network water temperature; (c) household size; (d) dwelling typology (block dwelling or single-family house); (e) dwelling size; (f) dwelling energy-

[25] Heat pumps were not included in the model due to their low penetration in vulnerable households, as in [333].

[26] The description of the methodology presented in this section and its results (shown in Section 3.3.1) is based on the paper: 'Does cash money solve energy poverty? Assessing the impact of household heating allowances in Spain', written by the author, José Ignacio Linares, José Carlos Romero, Eva Arenas and Efraim Centeno, and published in Energy Research & Social Science [236]. It also includes quotations from the mentioned article.

[27] The calculation of the provincial average expenditure for heating and DHW according, respectively, to the different climatic zones and network water temperature of the localities in the same province is explained thereafter (Eq. (3.6)).

efficiency rate (according to the 'aggregated-construction-period', explained thereafter); (g) type of thermal installations and (h) energy carrier type (shown in Fig. 3. 2 and Fig. 3. 3); (i) energy prices and taxes. Fig. 3. 1 shows the overall methodology with the different calculations carried out to estimate the Spanish provincial average values of RWTEE.

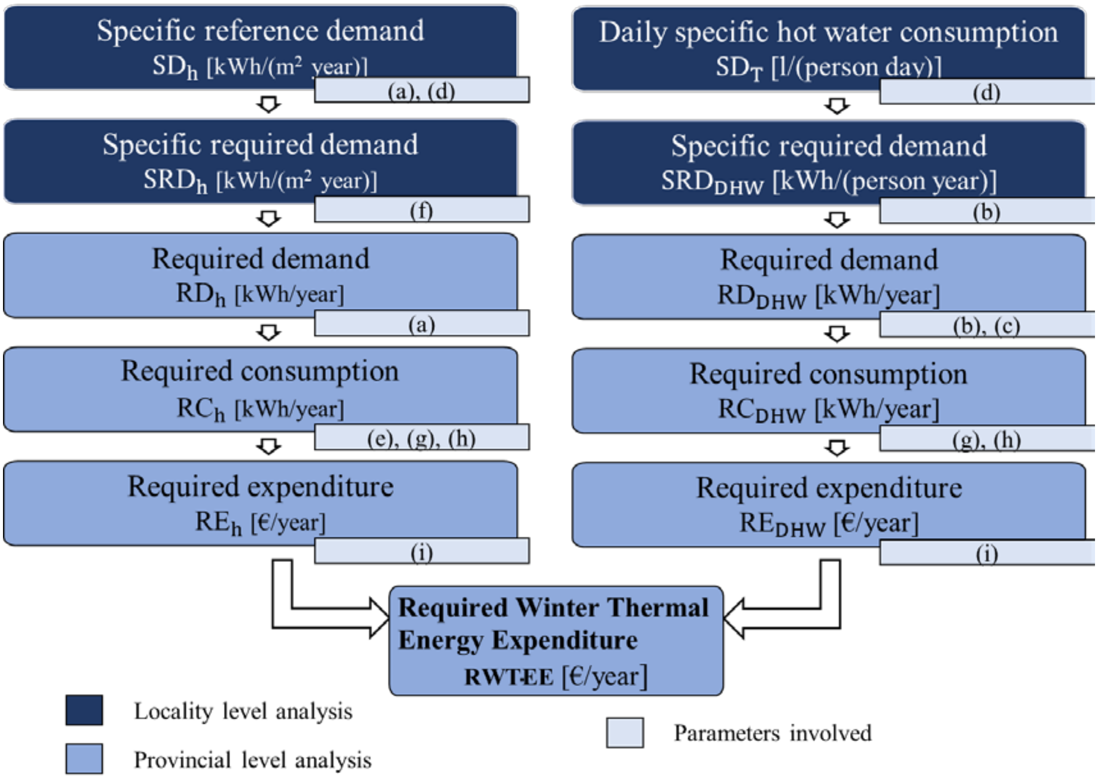

Fig. 3. 1. Flowchart of the provincial analysis of the Spanish households' Required 'Winter' Thermal Energy Expenditure (the parameters involved in the calculation are listed in the text) (reprinted from [236]*)*

The values of the annual specific required demand for heating (SRD_h, in kWh/(m^2 - year)) and the annual specific required demand for DHW (SRD_{DHW}, in kWh/(person - year)) for each one of the 8,131 Spanish localities have been assessed following the procedure explained in Section 3.2.1.1. Subsequently, a provincial-level analysis has been carried out to aggregate the results and point out some trends. A segmentation approach has been applied to the Spanish population to calculate a household's weighted average RWTEE for each province. The heating-expenditure clustering has been carried out according to the following parameters: (1a) Aggregated-construction-period; (2a) Dwelling typology; (3a) Type of heating installation; (4a) Heating energy carrier type. On the other hand, the DHW-expenditure segmentation has been performed depending on the following parameters: (1b) Dwelling typology; (2b)

Type of DHW installation; (3b) DHW energy carrier type. The derived household-segmentations are shown in Fig. 3. 2 and Fig. 3. 3.

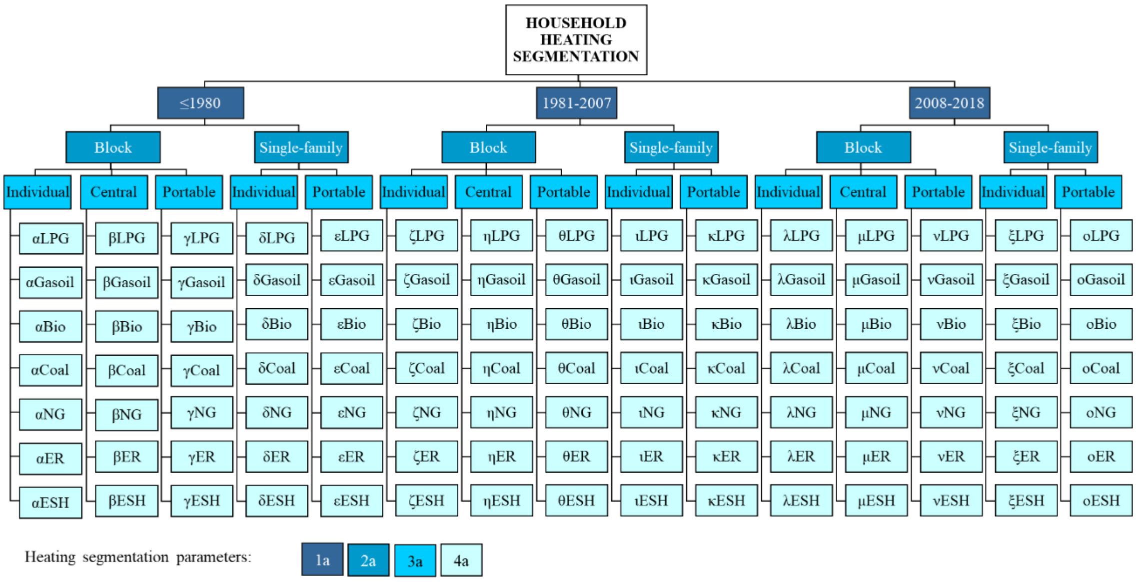

Fig. 3. 2. Household segmentation according to dwelling's heating parameters (Block: block dwelling; Single-family: single-family house; Individual: individual heating system; Central: central heating system; Portable: portable heater; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; Coal: anthracite coal; NG: natural gas; ER: Electric Radiator; ESH: Electric Storage Heater); (reprinted from [236]*)*

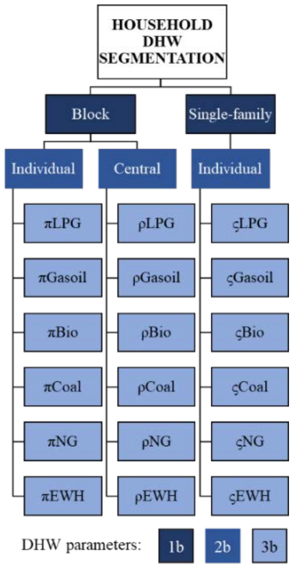

Fig. 3. 3. Household segmentation according to dwelling's DHW parameters (Block: block dwelling; Single-family: single-family house; Individual: individual DHW system; Central: central DHW system; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; Coal: anthracite coal; NG: natural gas; EWH: electric water heater); (reprinted from [236]*)*

The datasets used for the segmentation of the Spanish population are the following ones:

1. [88], the Spanish Census 2011 [237] and the Spanish Household Budget Survey 2018 [238] were consulted to carry out the clustering related to heating and the parameters (2b) and (3b) of DHW.
2. [239] and [88] were used for the parameter (1b) of the DHW clustering.

The SRD_j provincial values (where j can be heating or DHW) have been computed by a weighted average of the localities' specific required-demand-values (Eq. (3.6)[28]), with the population as the weighting parameter.

$$SRD_{j\,k} = \frac{\sum_{i=1}^{n} SRD_{j\,i} \cdot NI_i}{\sum_{i=1}^{n} NI_i} \tag{3.6}$$

Where i is the i-locality of the k-province and NI_i is the number of inhabitants of the i-locality [240]. This calculation has been repeated for each combination of aggregated-construction-period (only for heating) and dwelling typology for all the provinces. Regarding the first parameter, three aggregated-construction-period have been defined. The *EEP* of the dwellings of each period were assessed by cross-referencing the buildings age data of the CENSUS 2011 [237] with the report on the status of energy certification of buildings of December 2018 [241]. As a result of this cross-correlation, an energy efficiency class was assigned to each aggregated-construction-period as follows. An energy class between F and G (very low energy performance) was assigned to buildings constructed before 1981, i.e. before the application of the first Basic Building Standard NBE-CT 79 [242]. The abovementioned legislation sets out minimum energy efficiency requirements for the building sector, so the average energy class for residences built between 1981 and 2007 reached a level of E, close to D. Finally, an energy class C was assigned to new buildings (2008-2018), i.e. the ones built after the approval of the Basic Document of Saving of energy (DBHE) within the CTE in 2006 [243] . It has to be highlighted that the 2018 report on the status of energy certification of buildings made it possible to consider also the energy certificates of residences built between 2011 and 2018, although the number and type of houses refer to the stock built before the CENSUS 2011 (which was the last official dataset available on this topic when the study was performed). Table 3. 7 and Table 3. 8 show the values of the EEP resulting from the above described cross-correlation.

[28] Note that the weighting of the specific demand by number of inhabitants in each locality of the province is intended to 'weight' the winter climate zone (in the case of heating) and the network-water-temperature (in the case of DHW) in each province.

Table 3. 7. Values of EEP per each Spanish winter climate zone and aggregated-construction-period for block dwellings

Winter climate zone	≤1980	1981-2007	2008-2018
A	4.41	2.46	0.86
B	4.01	2.32	0.83
C	3.69	2.21	0.81
D	3.53	2.16	0.80
E	3.45	2.13	0.79

Table 3. 8. Values of EEP per each Spanish winter climate zone and aggregated-construction-period for single-family houses

Winter climate zone	≤1980	1981-2007	2008-2018
A	4.15	2.13	0.80
B	3.97	2.12	0.80
C	3.81	2.14	0.80
D	3.68	2.10	0.79
E	4.03	2.20	0.81

The energy efficiency parameter for block dwellings increases with the winter climate zone, i.e. residences in cold climates have higher energy performance than the ones in warm zones. This tendency is not so clear for single-family houses.

Then, the calculated SRD_h ($\text{kWh}/(\text{m}^2$ - year)) was multiplied by the provincial average dwelling size (m^2) of each combination of the parameters (1a) and (2a) [88] to obtain the household's annual required demand for heating (RD_h, in kWh/year) of each province. Furthermore, an average household size, based on official statistics [240], was assigned to each province, which made it possible to calculate the provincial household's required demand for DHW (RD_{DHW}, in kWh/year). Both demand values are referred to a provincial average household, i.e. a family unit with an average number of persons (used to calculate its DHW demand) that lives in a dwelling with an average size (used to calculate its heating demand). Subsequently, the values of annual required consumption for heating (RC_h) and DHW (RC_{DHW}) per Spanish province have been calculated dividing RD_h and RD_{DHW} by the seasonal performance factor (SPF) of the dwelling-thermal-installations defined by the IDAE [81]. Table 3. 9 and Table 3. 10 show the seasonal average performance factors used in the determination of heating and DHW consumption. The values of HSPF and SPF depend on the energy carrier and the type of installation).

Table 3. 9. Seasonal performance factor for heating systems (HSPF) [81] *- Individual: individual heating system; Central: central heating system; Portable: portable heater; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; Coal: anthracite coal; NG: natural gas; Electricity - Electric Radiator or Electric Storage Heater).*

Energy carrier	Individual	Central	Portable
NG	0.75	0.70	0.70
LPG	0.75	0.70	0.65
Gasoil	0.70	0.65	0.65
Bio	0.35	0.40	0.30
Coal	0.40	0.45	0.45
Electricity	0.99	0.99	0.95

Table 3. 10. Seasonal performance factor for DHW systems (SPF) - Individual: individual DHW system; Central: central DHW system; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; Coal: anthracite coal; NG: natural gas; EWH: electric water heater).

Energy carrier	Individual	Central
NG	0.78	0.82
LPG	0.78	0.82
Gasoil	0.78	0.82
Bio	0.35	0.40
Coal	0.40	0.45
Electricity	0.99	0.99

Thereafter, the provincial values of the annual required expenditure for heating (RE_h) and DHW (RE_{DHW}) were estimated by applying the 2019 energy-carriers' prices and taxes to, respectively, RC_h and RC_{DHW}. For electric and natural gas heating systems, the energy prices were set out as the regulated market tariffs in 2019: Voluntary Price for the Small Consumer (VPSC) for electricity [244] and the Tariff of Last Resort (TLR) for natural gas (weighted average price from [245] and [246]). The IDAE reports and the 2019 legislation were used as reference for the other energy carriers' price: LPG (weighted average price from [247] and [248]), heating gas oil and biomass (both in [249]). The fossil-fuel and electricity taxes and the VAT have been applied to the energy cost according to the Spanish regulation [250], [251] , considering the different VAT policy in Canary Islands (Las Palmas and Santa Cruz de Tenerife), Ceuta and Melilla. In these provinces, the VAT values applied to energy supplies are lower than 8%, whereas it is 21% in the rest of the country. Finally, the sum of $\mathrm{RE_h}$ and $\mathrm{RE_{DHW}}$ gives the provincial weighted average RWTEE.

With respect to potential changes in energy taxation [252], it is interesting to consider a tax-free scenario for vulnerable consumers and point out the differences with the current outline. Furthermore, a 'before tax' scenario makes it possible to analyse the proposed model across the Spanish winter climate zones because it eliminates the distortion introduced by the different VAT applied in certain Spanish provinces. Therefore, two different scenarios of RWTEE have been assessed: RWTEE after tax (AT) and RWTEE before tax (BT).

3.2.1.3 Application to the ECODES households' database

The NGO Fundación Ecología y Desarrollo (ECODES) promotes the program 'Not a single household without energy' ('Ni un hogar sin energía' in Spanish [253]) for the fight against energy poverty and improvement of the energy efficiency of Spanish households. Since 2013 this project has helped more than 10,000 families in all the Spanish provinces to reduce their energy bills and improve the comfort of their homes through energy audits and personalised advices. The energy diagnosis has been carried out by collecting data on the following households' characteristics: (1) socio-economic situation, (2) housing's energy efficiency condition and equipment, (3) households' habits and (4) information on energy consumption and supply contracts. The collection of data on families assisted in the framework of the 'Not a single household without energy' programme has been carried out in two stages. From the first stage (2015-17), the data provided represent 2029 records, corresponding to as many households. These data are the particularised response in each household to the questions included in the programme's questionnaire in this first stage. The questions are summarised in Table A 1 of Appendix A. From the second stage of the programme (data has been analysed from 2017 to 2019, but this stage is still ongoing), 2060 records have been obtained, corresponding to different questions, so the information available is not homogeneous in the two stages of the programme. The questions asked in this 2017-19 phase are summarised in Table A 2 of Appendix A. The data collected in this program have been used to evaluate the RWTEE model and point out some insights for households and energy-poverty and energy-efficiency stakeholders[29].

In order to determine the level of thermal insulation, characterised by the EEP, it is at least necessary to know the time of construction of the dwelling. In this regard, the 2015-17 survey collected more detailed information by establishing three aggregated construction periods[30]:

- Building built before or in 1980 (≤1980). As it was built prior to the Basic Building Standard (NBE) of 1977, it has been assigned an average EEP value of 3.8, which would be between the energy classes F and G.

[29] The full version of this analysis was described in a report published in 2019 by the author, E. Arenas, J.I. Linares, J.C. Romero, C. Foronda Díez, C. Pesque Castillo and L. Díez Alzueta [333].

[30] The '1981-2007' and '>2007' insulation levels are assumed to be less efficient than the general model's ones (shown in Table 3. 7 and Table 3. 8), being the sample of ECODES composed mostly by vulnerable households, which usually live in less efficient dwellings (see Chapter 4). Moreover, in this case the value of EEP that is assigned does not take into account the climate zone.

- Building constructed between 1981 and 2007 (1981-2007). This corresponds to the period when the NBE was in force, which means an improvement in the insulation requirement. It has been assigned an average EEP value of 3.3, corresponding to a certification between E and F.
- Building constructed after 2007 (>2007). In this period, the CTE is already in force, but given that the spectrum of the study focuses on vulnerable households, an EEP value of 1.75 has been assigned, in accordance with a certification between D and E.

In contrast, the 2017-19 survey did not indicate any construction period, so the lowest rating (average EEP value of 3.8) has been applied on the understanding that the survey was mostly focused on vulnerable households.

Moreover, in the data provided for 2017-19, multi-selection of thermal installations is allowed, which has led in some cases to mistakes or implausible combinations; in contrast, in the 2015-17 data, such multi-selection is not allowed, but some of the options available in the survey are confusing, such as the term 'city gas'. It has therefore been decided to calculate the RWTEE defined in the SNSEP[31] as a reference value, but also several alternative combinations that allow the comparison of operating costs of different solutions to achieve the same level of comfort in a given dwelling. It has to be noted that that the SNESP RWTEE does not refer to the actual characteristics of the dwelling (except for the location, i.e. the climate zone and network water temperature), while the other combinations have been calculated with the actual characteristics declared in the survey, thus obtaining the household RWTEE. Both calculations applied the methodology explained in Section 3.2.1.1. The values used for the average seasonal performance factors are the same as in Section 3.2.1.2. The energy prices are detailed in Table 3. 11. Commercial tariffs have been taken for the different energy carriers, also considering fossil fuel tax (0.00234 €/kWh) and fixed meter rental costs 4.6 €/month in the case of natural gas. On the other hand, VAT has been taken as 7% in the Canary Islands (IGIC), 4% in Ceuta and Melilla (IPSI) and 21% in the rest of Spain.

[31] - Type of dwelling: block dwelling
- Dwelling size: 100 m^2 (Average national dwelling size according to SECH-SPAHOUSEC)
- Household size: 3 persons (Average national household size according to SECH-SPAHOUSEC)
- Aggregated construction period: ≤1980 (55% of main dwelling in Spain, CENSUS 2011).
- Type of installation: old individual boiler (only 10% of Spanish households have a centralised boiler [269])
- Energy carrier: natural gas in mainland Spain, Balearic Islands, Ceuta and Melilla (most used energy carrier in the mainland according to HBS 2019); LPG in the Canary Islands (most used fossil fuel according to HBS 2019).

Table 3. 11. Energy prices (before tax) considered in the ECODES database's analysis.

Energy carrier	Fixed term [€/month]	Variable term [€/kWh]
Natural gas (C < 5 MWh/year)	4.36	0.059
Natural gas (5 MWh/year < C < 50 MWh/year)	8.84	0.050
LPG	0.00	0.092
Gasoil	0.00	0.075
Electricity (Radiator)	3.50[a]	0.136
Electricity (Storage Heater)	3.50[a]	0.084

[a]The fixed electricity term is expressed in [€/kW month]

Table 3. 12 shows the different combinations considered in the latter calculation, and Fig. 3. 4 shows an example of one of the 2017-19 cases. The figure shows that the thermal systems configuration used to define the SNESP RWTEE, i.e. individual natural gas boiler, is one of the most economical. On the other hand, it can be seen that, except for installations using electric heating (radiators or storage heaters), the RWTEE is similar in all the considered combinations of energy carriers and installations.

Table 3. 12. Thermal systems' combinations analysed for the calculation of the vulnerable household's RWTEE

Code	Heating		DHW	
	Installation	**Energy carrier**	**Installation**	**Energy carrier**
IGNIGN[a]	individual	Natural gas	individual	Natural gas
IGNITE	individual	Natural gas	individual	Electricity
IGLIGL[b]	individual	LPG	individual	LPG
IGLITE	individual	LPG	individual	Electricity
IERITE	individual	Electricity (Radiator)	individual	Electricity
IERIGL	individual	Electricity (Radiator)	individual	LPG
IEAITE	individual	Electricity (Storage Heater)	individual	Electricity
IEAIGL	individual	Electricity (Storage Heater)	individual	LPG
IGOIGO	individual	Gasoil	individual	Gasoil
IGOIGL	individual	Gasoil	individual	LPG
IGOITE	individual	Gasoil	individual	Electricity
CGNCGN	central	Natural gas	central	Natural gas
CGNITE	central	Natural gas	individual	Electricity
CGNIGN	central	Natural gas	individual	Natural gas
CGNIGL	central	Natural gas	individual	LPG
CGOCGN	central	Gasoil	central	Natural gas
CGOCGO	central	Gasoil	central	Gasoil
CGOITE	central	Gasoil	individual	Electricity
CGOIGN	central	Gasoil	individual	Natural gas
CGOIGL	central	Gasoil	individual	LPG

[a] Configuration to define the SNESP RWTEE in the mainland, Balearic Islands, Ceuta and Melilla.

[b] Configuration to define the SNESP RWTEE in the Canary Islands.

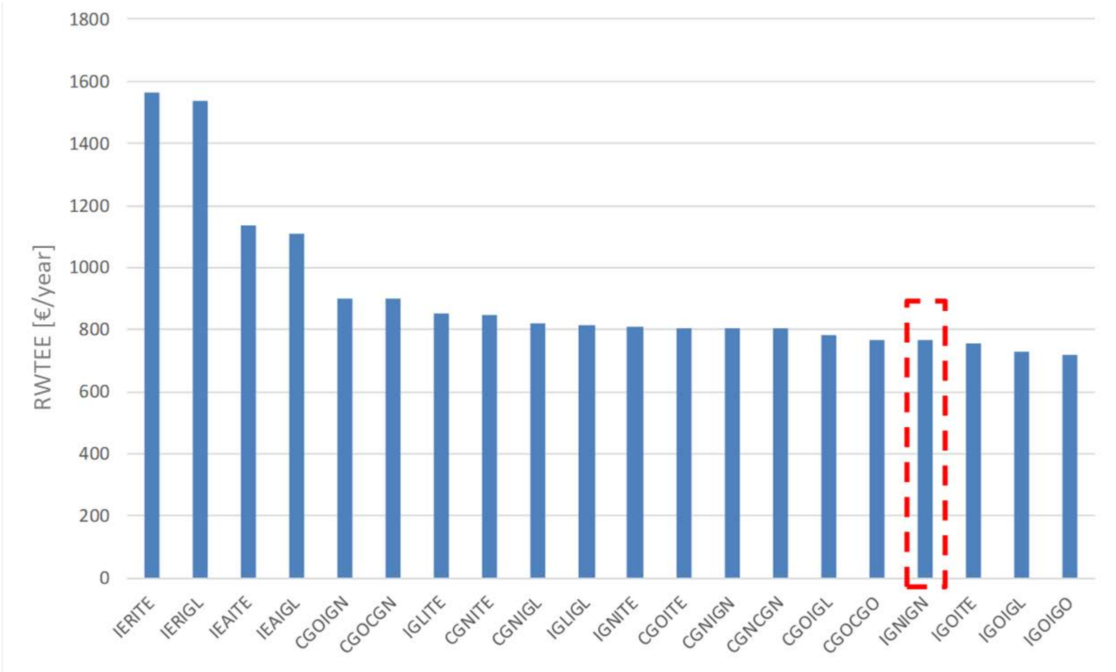

Fig. 3. 4. RWTEE for different thermal systems' combination in one of the households surveyed between 2017 and 2019: Zaragoza (D zone); 50 m^2; 1 person, block dwelling, construction period: ≤1980

3.2.2 Electricity services' model

The Required Electricity Expenditure (RELE) is understood to be the electricity expenditure required to satisfy the needs of a household connected to all 'typical' household appliances that operate with electrical energy (lighting, electrical appliances and cooking). Those systems for HVAC or DHW production are excluded from the study, even if they are electrical, because they were already studied in the thermal model (see Section 3.2.1). Sections 3.2.2.1 and 3.2.2.2 present two versatile bottom-up models for the Spanish households' required electricity consumption, carried out by involving three primary parameters: the household size (HS, number of household members), the household composition (activity, professional situation or occupation of the household members) and the dwelling size (DS, m^2). The first of these models, i.e. the Required ELectricity Consumption (RELC) Simplified-model, was developed starting from the assumptions of national statistics, such as SPAHOUSEC II, and considers all households' typical electrical appliances in Spanish homes. This simplified model uses the household size and the dwelling size (only for lighting) as input parameters. From this, a second model has been developed, i.e. the Required ELectricity Consumption (RELC) Advanced-model, which uses the Spanish Time Use Survey (TUS) [254] to define the frequency of use of some of the electrical appliances and distinguishing not only the household size, but also their composition. Cooking is considered in these 'electricity consumption' models (and not as a thermal use, as mentioned in Section 3.2.1), in line with [94], because, according to statistical data [92], more than 60% of the Spanish households own electric stoves. Both models were developed starting from an estimation of the power of each of the domestic electrical appliances considered. From this, a series of hypotheses were made about the frequency of use of each appliance, and usage factors were used to consider the household size and composition (the latter only for the advanced model). In the study of lighting consumption, both models take into account the DS. Moreover, for the electrical appliances' consumption calculated with the Simplified model, the months of the year have been separated into summer and winter months, to reflect the differences in temperature and sunlight, as well as the change in routines or use of appliances: summer months, from June to September (N_{summer} = 4 months), and winter months, from October to May (N_{winter} = 8 months), as established in the Spanish Technical Code for Building Construction [83]. On the other hand, in the appliances' consumption calculated in the Advanced model, the different routines in summer or winter are considered implicitly by using the Time Use Survey (TUS) data.

Then, Section 3.2.2.3 presents an 'evaluation' procedure of the proposed models[32] with the following steps. The two models were compared between each other and the Advanced model was checked against the following references: [54] and [55], [94], and [255]. Thereafter, the Advanced model was evaluated by comparing the results with the ECODES households' database, which is described in [256]. Finally, Section 3.2.2.4 presents the calculation of the RELE starting from the RELC Advanced-model.

3.2.2.1 Simplified model of the Required ELectricity Consumption

The Required ELectricity Consumption (RELC) Simplified-model[33] is based on the Minimum ELectricity Consumption model described in [257]. Nevertheless, while the latter sets a minimum vital supply, the RELC model has a different goal, i.e. estimating the theoretical consumption needed to cover all typical domestic electricity-needs. Indeed, most of the parameters have been adjusted according to information extracted from different sources (mainly national statistics) and other common appliances have been included.

Particularly, Eq. (3.7) was used to calculate the annual electricity consumption of the i-th appliance ($C_{i,annual}$ [kWh]).

$$C_{i,annual} = C_{i,winter} \cdot N_{winter} + C_{i,summer} \cdot N_{summer} \quad (3.7)$$

[32] Unlike HVAC (heating/cooling) and DHW demand/consumption, whose calculation is regulated in the Spanish Technical Code for Building Construction (CTE) and detailed in IDAE reports, the computation of the required consumption for cooking, lighting and household appliances is not regulated. Therefore, it was considered potentially insightful to compare the RELE model's results with statistics and a vulnerable households' database. However, this should not be considered as a validation of the submodel, because the general objective of the RENE model is not to reproduce behaviours, but to represent required needs.

[33] This section partially uses the work carried out for the conference paper "Modeling and analysis of electricity consumption in Spanish vulnerable households" [257], presented by the author, Á. Cosín, E. Arenas, J.I. Linares, J.C. Romero and E. Centeno at the 14th PowerTech Conference - PowerTech 2021.

The average winter and summer monthly consumption ($C_{i,winter}$ [kWh/month] and $C_{i,summer}$ [kWh/month]) were calculated by applying Eq. (3.8).

$$C_{i,j} = P_i \cdot f_{i,j} \cdot UF_i \quad (3.8)$$

Where: j can be winter or summer; P_i [kW] is the rated power of the appliance i; $f_{i,winter}$ [h/month] and $f_{i,summer}$ [h/month] represent the average monthly frequency of use of the appliance i, respectively, in winter and summer. Besides, UF_i [-] denotes the usage factor of the appliance i, which depends on the household size (HS). Both f_i and UF_i were set according to statistics on Spanish households' behaviour [57], [94]. The annual lighting consumption was computed by multiplying the specific lighting annual consumption ($C_{l,annual}$ [kWh/m^2]), which vary with HS, by the DS.

Regarding the primary variables, there are five different HS and the variable UF_i changes depending on the appliance considered, as shown in Table 3. 13. Most of these factors were set according to the statistics in [57].

Table 3. 13. Usage Factor according to the household size in the RELC model. W - Washing machine; D – Dishwasher; DR – Tumble Dryer; S – Stoves; O – Oven; TV – Televisions; PC – Computers; L - Lights

HS	UF_W	UF_D	UF_{DR}	UF_S	UF_O	UF_{TV}	UF_{PC}	UF_L
1	1.20	1.10	1.20	1.00	1.00	0.85	0.40	0.40
2	1.50	1.30	1.50	1.10	1.10	0.95	0.80	0.80
3	1.90	1.50	1.90	1.20	1.20	1.05	1.20	1.20
4	2.20	1.80	2.20	1.30	1.30	1.15	1.60	1.60
> 4	2.50	1.90	2.50	1.45	1.45	1.30	2.00	2.00

Moreover, Table 3. 14 shows the assumptions on P_i and f_i made for each of the electrical appliances considered and the references that support these assumptions. The P_i values were set according to [258]. The stand-by consumption was calculated as the 7% of the appliances' consumption, according to [54].

Table 3. 14. Assumptions made for the electrical appliances considered in the RELC model

Appliance	P_i [kW]	$f_{i,winter}$ [h/month]	$f_{i,summer}$ [h/month]
Refrigerator[a]	0.080/0.100	720.0	720.0
Freezer[a]	0.064/0.080	720.0	720.0
Washing machine	1.700	8.0	8.0
Tumble dryer	2.200	6.0	6.0
Stoves[b]	0.750/0.900	6.0/30.0	3.0/21.0
Oven	0.850	8.0	4.0
Dishwasher	1.900	8.0	8.0
TVs	0.255	95.4	95.4
Computers	0.280	68.7	68.7
Lights[c]	0.463	84.0	63.0
Others[d]	0.005/0.020/0.900	60.0/16.0/5.1	60.0/16.0/5.1

a. Pi is displayed for winter and summer and it is considered constant throughout the day, according to [94].

b. A small stove and a big one. Weighted average power according to the technologies in [57].

c. The light power is the weighted average unit power of national bulbs mix multiplied by the national average number of light bulbs [57]. To calculate the parameter f_i, the average daily use (which depends on the season) is multiplied by the average number of days per month.

d. It considers mobile phones, tablets and microwaves.

The required electricity consumption in an average Spanish household is calculated according to the household size, i.e. taking into account the percentage of households that exist with each household size, according to information extracted from the 'Continuous Household Survey' of the INE [259].

Table 3. 15 summarises the information corresponding to the survey. On the left-hand side are the survey categories and on the right-hand side the grouping made for this study. The average household had 2.5 members in 2019.

Table 3. 15. Summary of data from the Continuous Household Survey 2019 [259] *(left). Grouping done for this study (right)*

Household size	Household numbers (miles)	Share [%]
1	4771.4	25.68%
2	5651.5	30.42%
3	3848.7	20.71%
4	3241.3	17.45%
5	735.8	3.96%
6	216.7	1.17%
7	69.1	0.37%
8 or more	45.6	0.25%
Total	18580.1	100%

Household size	Household numbers (miles)	Share [%]
1	4771.4	25.68%
2	5651.5	30.42%
3	3848.7	20.71%
4	3241.3	17.45%
> 4	1067.2	5.74%
Total	18580.1	100%

In addition, for the estimation of the average consumption of a household, it has been taken into account that there are appliances that are not own by all households; in these cases, their average consumption has been multiplied by the appliance's ownership rate OR_i obtained according to various sources. OR_i generally takes a value equal to 1 except for those defined in Table 3. 16, where the value used is shown. For the remaining equipment, where the ownership rate is above 95%, it has been assumed that they are owned by all households.

Table 3. 16. Ownership rate of different electrical appliances in the Spanish households and sources used

Appliance	OR	Source
Tumble Dryer	28.30%	SECH-SPAHOUSEC 2011
Freezer	24.80%	SPAHOUSEC II 2019
Oven	77.10%	SECH-SPAHOUSEC 2011
Dishwasher	54.80%	SPAHOUSEC II 2019
Computer	80.90%	España en cifras 2020
Tablet	54.50%	España en cifras 2020

Using the model developed, the sum of the contributions of each of the appliances considered and of the lighting is calculated, obtaining the RELC [kWh/year], according to Eq. (3.9).

$$RELC = \sum_{i=1}^{n} C_{i,annual} \cdot OR_i \quad (3.9)$$

3.2.2.2 Advanced model of the Required ELectricity Consumption

In order to carry out the Advanced Theoretical Expenditure Model, the Spanish Time Use Survey [254] (TUS, carried out by the INE in 2010) has been used, from which it is possible to extract the living habits of households according to their composition. Table 3. 17 shows the composition of the households surveyed according to the number of people living in them.

Table 3. 17. Breakdown of households by number of members (household size) in the 2010 TUS [254]

Household size	Number of households	Share [%]
1	1714	18%
2	2931	31%
3	2259	24%
4	1964	21%
>4	673	7%
Total	9541	100%

The survey collects the information referring to each of the 9541 households surveyed, with data such as the Autonomous Community to which they belong, size of the municipality, type of household (single-person household, couple alone, couple with children under 25, etc.), total number of household members, etc. It also contains information on each of the household members, i.e. data on a total of 25,895 persons, with data such as their sex, month and year of birth or occupation. Appendix A analyses in detail the survey's queries used in this work. Regarding the topic of this thesis, the survey collects the primary and secondary activities carried out by each of the members of the household over 10 years of age in ten-minute intervals during a day. Moreover, it collects information about the place where the activity is carried out, whether they are alone or accompanied by a member of the household, and other aspects.

Information on the following factors was used to develop the model:

- Number of people in each household.
- Main and secondary activity being carried out in each ten-minute interval.
- Whether the person is doing the activity alone or accompanied, and whether they are accompanied by another member of the household.

The purpose of the Advanced model is to estimate the electrical energy consumed in households by those electrical appliances that have a variable consumption throughout the day, such as the stoves, washing machine, tumble dryer, dishwasher, television and computer. Both the fridge and the freezer are assumed to have a constant consumption throughout the day as in the Simplified model and in Escobar et al. [94].

Certain activities (collected by the survey) can be associated with the use of one of the appliances studied in this model. In this sense, the consumption of six appliances can be analysed using the TUS, i.e. stoves/oven (cooking), washing machine, tumble dryer, dishwasher, television and computer. For each of these appliances, an average power assumption has been made and the ownership rates described in Table 3. 16 have been taken into account.

To calculate the consumption of each appliance, the average power (P_{jkl}) [kW] of each appliance j in each of the time intervals k (intervals of 10 minutes throughout a day, therefore, k=1...144) has been calculated for each type of household with l number of members (1, 2, 3, 4 and more than 4), according to Eq. (3.10). The combination of these time intervals will result in average power curves over the day due to the use of appliance j.

$$P_{jkl} = \frac{\left(\sum_{i=1}^{N_l} FAP_{ij} + \sum_{i=1}^{N_l} FAS_{ij}\right)}{N_l} \cdot P_j \tag{3.10}$$

Where FAP_{ij} and FAS_{ij} are factors representing, respectively, primary and secondary activities and taking value *1* if respondent i is using appliance j or 0 if they are not using it, P_j is the rated power of appliance j [kW] and N_l is the number of households of l number of members.

For each type of household according to the number of members (l), the average appliance consumption (C_{jl} [kWh]) is calculated by multiplying the average power obtained according to Eq. (3.10) in each interval k by the duration of that time interval (10 minutes). Then, it is converted to kWh and multiplied by 360 days[34], as shown in Eq. (3.11).

$$C_{jl} = \left(\sum_{k=1}^{144} P_{jkl}\right) \cdot \left(\frac{10}{60}\right) \cdot 360 \tag{3.11}$$

Table 3. 18 shows the power assumptions (Pj) that have been taken into account in the forward model and explained in the previous sections. The average time per cycle (t_{cycle} [h]) of the washing machine, tumble dryer and dishwasher, and the average daily usage time of the other household appliances are also shown in the table. The detailed explanation of the assumptions made for each electrical appliance is described in Appendix B.

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[34] 360 days are used as a 'days per year' hypothesis instead of 365 days to consider that, generally, there are certain days during the year when no one may be at home, e.g. the average duration of trips by residents in Spain in 2019 was almost 4 days [334].

Table 3. 18. Power and cycle time assumptions of the Advanced RELE model

Appliance	Pj [kW]	t_{cycle} [h]
Cooking appliances (stoves+oven)	0.967	1.36
Washing machine	1.500	2.00
Tumble dryer	2.000	1.50
Dishwasher	1.500	1.50
TV	0.221	4.5
Computer	0.840	2.59

Combining the estimated consumption for the above appliances with the consumption of those that cannot be modelled through the TUS (and for which the estimates of the Simplified Model are maintained), the initial results of the Advanced Model (i.e. according to the household size) are obtained. Table 3. 19 shows the average electricity consumption of each electrical appliance according to the household size.

Table 3. 19. Required electricity consumption of household appliances (kWh/year), by household size and for the average household (Avg), following the Advanced Model; W - Washing machine; D – Dishwasher; DR – Tumble Dryer; S – Stoves; O – Oven; TV – Televisions; PC – Computers; L – Lights; RF – Refrigerator; FR – Freezer; OT – Others (mobile phones, tablets and microwaves); Standby – ST.

HS	**S+**	**W**	**DR**	**RF**	**FR**	**L**	**TV**	**PC**	**D**	**OT**	**ST**	**Total**
1	267	210	58	749	149	167	197	60	118	60	142	2175
2	459	262	72	749	149	334	342	132	139	70	190	2897
3	485	332	91	749	149	501	297	253	161	80	217	3314
4	552	385	106	749	149	668	314	344	193	90	248	3797
> 4	651	437	120	749	149	835	360	322	203	103	275	4203
Avg	442	295	81	749	149	413	292	186	151	75	198	3030

Thereafter, an additional parameter was added to the Advanced model, i.e. the household composition. For the calculation of the required consumption of households according to their composition, sufficient statistical evidence is needed because the new clusters are subclusters of the groups showed in Table 3. 17, so adding further disaggregation to the analysis. Thus, the number of the minimum sample of households in the Time Use Survey needed to calculate the consumption of appliances has been calculated. Eq. (3.12) was used for calculating the sample size (n), knowing the population size N (9541 households)[35].

[35] This is the procedure of sample size calculation for percentages or dichotomous variables in the case of finite populations, explained in [335].

$$n = \frac{N \cdot Z_a^2 \cdot p \cdot (1-p)}{d^2 \cdot (N-1) + Z_a^2 \cdot p \cdot (1-p)} \quad (3.12)$$

Where N is the population size, Z_a the confidence level[36], p the probability of success, $(1-p)$ the probability of failure and d the precision (maximum permissible error in terms of proportion). For the calculation of the minimum number of households according to their composition, a confidence level of 95% has been taken with Z = 1.96, p is the proportion of households with some member engaged in that occupation, $(1-p)$ the proportion of households with no member engaged in that occupation and a precision of 5%. Table 3. 20 shows the values of the parameters of Eq. (3.12) and the resulting minimum number of households to calculate the household cluster consumption according to their composition. Among the analysed household occupations, only households with volunteers have insufficient statistical evidence. Therefore, Table 3. 21 shows the different composition subclusters considered in the model (r stands for occupation type and s distinguishes the number of persons with such an occupation).

Table 3. 20. Calculation of the minimum number of households to calculate their consumption according to the occupations of their members.

Occupation	N	Z	p	q	e	n
Employed	9541.00	1.96	0.65	0.35	0.05	338.19
Unemployed	9541.00	1.96	0.21	0.79	0.05	250.21
Student	9541.00	1.96	0.36	0.64	0.05	339.41
Retired	9541.00	1.96	0.30	0.70	0.05	311.91
Pensioner 1	9541.00	1.96	0.05	0.95	0.05	76.42
Pensioner 2	9541.00	1.96	0.09	0.91	0.05	128.75
Volunteers	9541.00	1.96	0.00	1.00	0.05	0.80
Household chores	9541.00	1.96	0.26	0.74	0.05	286.89
Others	9541.00	1.96	0.09	0.91	0.05	121.81

[36] It expresses the certainty that the data sought is actually within the margin of error.

Table 3. 21.Composition subclusters considered in the Advanced model

Occupation (r)	Number of people with this occupation (s)	Household type (rs)
Employed (A)	1 Employed (1)	A1
	2 Employed (2)	A2
	3 or more Employed (3)	A3
Unemployed (B)	1 Unemployed (1)	B1
	2 Unemployed or more (2)	B2
Student (C)	1 Student (1)	C1
	2 Students or more (2)	C2
Retired (D)	1 Retired (1)	D1
	2 Retired or more (2)	D2
Pensioner 1 (E)	1 Pensioner-1 or more (1)	E1
Pensioner 2 (F)	1 Pensioner-2 or more (1)	F1
Household chores (G)	1 'Household chores' or more (1)	G1
Others (H)	1 Others or more (1)	H1

The electricity consumption of each appliance according to the household composition was calculated with the same methodology as the one applied for the calculation of the consumption by household size, but adding a new disaggregation level. The average power (P_{jklrs}) [kW] of each appliance j in each of the time intervals k has been calculated for each type of household according to their size *l* and their occupation *rs*. The combination of these time intervals will result in average power curves over the day due to the use of appliance *j*, according to Eq. (3.13).

$$P_{jklrs} = \frac{\left(\sum_{i=1}^{N_{lrs}} FAP_{ij} + \sum_{i=1}^{N_{lrs}} FAS_{ij}\right)}{N_{lrs}} \cdot P_j \; [kW] \tag{3.13}$$

Where FAP_{ijrs} and FAS_{ijrs} are factors representing primary and secondary activities respectively and taking value *1* if respondent *irs* is using appliance *j* or 0 if not using it; P_j is the power of appliance *j* [kW]; N_{lrs} is the number of households of *l* number of members and occupation *rs*.

For each type of household according to the number of members l and type of occupation rs, the calculation of the average consumption of the j appliances (C_{jlrs}) is performed by multiplying the average power obtained according to Eq. (3.13) in each interval *k* by the duration of that time interval (10 minutes). Then, it is converted to kWh and multiplied by 360 days per year, as shown in Eq. (3.14).

$$C_{jlrs} = \left(\sum_{k=1}^{n=144} P_{jkl}\right) \cdot \left(\frac{10}{60}\right) \cdot 360\ [kWh] \tag{3.14}$$

Thereafter, the total consumption of the six appliances considered in the TUS exploitation ($C_{6-appliances,lrs}$), according to the types of households *rs* and their occupation l, is calculated by summing up the six estimated consumption values C_{jlrs}. Thus, adjustment factors for the consumption of these appliances (f_{lrs}) are defined by applying Eq. (3.15), i.e. these factors are determined as the difference between the total consumption of the six appliances of each type of household according to their size *l* and occupation *rs* ($C_{6-appliances,lrs}$) and the total consumption of the six appliances of the average household with l number of members ($C_{6-appliances,l}$). The latter variable was easily obtained by summing up the consumption values of the considered six electrical appliances in the household size clusters shown in Table 3. 17.

$$f_{lrs} = C_{6-appliances,lrs} - C_{6-appliances,l} \tag{3.15}$$

Finally, the total RELC of a household according to their size and composition can be calculated by applying Eq. (3.16), thus also considering the rest of household appliances analysed in the Simplified model presented in Section 3.2.2.1, such as lighting, refrigerator, freezer, etc.

$$C_{Total,lrs} = \sum_{j=1}^{11} C_{jl} \cdot \beta_j + \sum_{i=1}^{l} f_{lrs_i} + Standby \tag{3.16}$$

Where β_j is a factor that takes a value of 1 if the household has appliance j[37] and 0 if the household does not have this appliance;α_{lrs}. In this way, the consumption of households with different compositions can be calculated, e.g. a five-people household with two students, one unemployed person and two employed people that owns all the considered electrical appliances has an RELC of 4,008 kWh/year.

3.2.2.3 Comparison with statistics and with the ECODES households' database

Firstly, the two models presented were compared with each other to point out the differences in assumptions and results. The consumption per appliance and the total one have been calculated for the average household in 2019, i.e. considering the average HS according to the Continuous Household Survey (ECH) [259], and the average DS of [57]. In addition, the ownership rate of those devices that are not present in all homes have been taken into account [57].

Secondly, the Advanced RELC model has been compared with the following bottom-up models' results and statistical data[38]:

- SECH-SPAHOUSEC project [54], using the corresponding HS, DS and ownership rate, referred to 2010.
- Escobar et al. [94], with same parameters as [54].

[37] The consumption values of the eleven 'appliances' are shown in Table 3. 38.
[38] This comparison was carried out because RELE is not based on standards (unlike the RTEE model).

- 'Synthetic report on energy efficiency indicators in Spain, Year 2018' (IEE 2018) [255], with the 2019 parameters.

Finally, the Advanced model was applied to the ECODES households' database, which has two different sources of information:

- Source1: Data collected during visits to vulnerable households (face-to-face interviews).
- Source2: Data collected by a web tool ('online self-diagnoses'). These data do not necessary come from vulnerable households [253].

Although the ECODES programme has data from before, it was in 2017 when the energy diagnosis questionnaire started to include the average monthly electricity consumption, which is the key parameter for carrying out the comparison with the RELE model's results. Therefore, for the 'evaluation' of the Advanced Model, the database from October 2017 until June 2021 was used, corresponding to 6748 households.

In order to carry out the analysis of the database and its comparison with the Advanced Model, a filtering of the database has been carried out to best fit the model. Firstly, those records considered to have some error in the data collection process were discarded, such as, for example, those with zero annual electricity consumption or those without household composition data. Subsequently, in order to eliminate outliers, the 5% and 95% percentile of the real annual consumption of the surveyed households, which are 672.6 kWh and 7920 kWh respectively, were calculated and filtered out of the sample. Finally, all households using electricity for heating and DHW, as well as those with air conditioning, have been excluded from the study, as these consumptions are excluded from the proposed electricity consumption model. With the filtering carried out, the data of 1650 households were obtained, which were finally used to 'evaluate' the model and obtain energy vulnerability indicators for the sample. The fields considered for this analysis are the following: dwelling size (DS, m^2), household size (HS, measured by the number of members), average monthly electricity consumption (kWh/month), electrical appliances included in the database (stoves, oven, dishwasher, tumble dryer and freezer) and occupation of the household members. For this last characteristic, only four types of occupations of those included in the TUS could be differentiated within the ECODES database: employed, unemployed, student and retired.

Thereafter, the ratio between the actual electricity consumption (AELC) and the RELC was calculated for each household in the whole sample (1650 households), considering the basic household characteristics, i.e. HS, DS and household composition. Based on the results obtained, the RELC model has been evaluated through the analysis of the following indicators: (1) the database's median AELC/RELC ratio and (2) the share of households whose AELC is lower than the corresponding RELC. The former estimates the adjustment of the model to the real consumption of the households (the use of the median value eliminates the extreme cases that could distort the result of the estimation). Whereas, the latter computes the percentage of households that have a lower consumption than the required one calculated with the model, or in other words an insufficient consumption to cover their electricity needs.

3.2.2.4 Calculation of the Required Electricity Expenditure

This section shows how to obtain the RELE from the RELC by applying the regulated market tariff (i.e. the VPSC) and the corresponding taxes.

Eq. (3.17) is applied to the monthly required electricity consumption ($RELC_{month}$) to determine the monthly required electricity expenditure ($RELE_{month}$).

$$RELE_{month} = \{[CP \cdot Tariff_{fixed-term} + Tariff_{variable-term} \cdot RELC_{month}] \cdot (1 + ET) + RE\} \cdot (1 + VAT) \qquad (3.17)$$

Where *CP* is the contracted power (kW); $Tariff_{fixed-term}$ is the fixed-term tariff or contracted power cost (€/kW-month); $Tariff_{variable-term}$ is the variable-term tariff, which is composed by the regulated system access fees (*AF*, €/kWh) and the cost of energy (*CE*, €/kWh); *ET* is the electricity tax and *RE* is the rental of metering and control equipment (€/month); *VAT* is the Value Added Tax [%], which, as mentioned in Section 3.2.1.2, depends on the region or autonomous city where the household lives.

All the values necessary to perform this calculation for the two possible VPSC tariffs (before the change in the bill in June 2021), i.e. 2.0A (no time metering or 'flat tariff') and 2.0DHA (time-of-use or 'hourly discrimination' tariff), are summarised in Table 3. 22. For the tariff with hourly discrimination, the assumption of a consumption distribution of 42% in the peak period and 58% in the off-peak period has been made (as shown in the LUMIOS tool [244]). For the two components of the cost of energy billed (*CE = energy market price + charges*), the average value in 2019 has been taken.

Table 3. 22. Values of the invoice items for calculating the RELE based on the RELC and the contracted power (reference year: 2019)

Invoice item	Value	Unit	Reference
RE	0.810	€/month	Orden ITC/3860/2007
ET	5.113	%	Ley 28/2014
AF	2.0A = 0.044 2.0DHA = 0.027	€/kWh	Orden IET/107/2014
CE	2.0A = 0.067 2.0DHA = 0.064	€/kWh	LUMIOS tool
$Tariff_{fixed-term}$	3.429	€/(kW -month)	Orden IET/107/2014 RDL 216/2014
VAT	21.000	%	Ley 37/1992

The hypothesis that has been formulated to estimate the contracted power is the following one. For one occupant (HS=1) it has been assumed that there could be the following simultaneous appliances' use: cooking (big stove), laundry (washing machine), refrigerating food (fridge) and 1/5 of the lighting. The contracted power of the rest of the household sizes is increased proportionally to the increase in RELC with respect to the case of 1 occupant (this is a 'global usage factor').

3.2.3 Web tool for energy expenditures' assessment in Spanish households

The energy cost models presented in the Sections 3.2.1 and 3.2.2 have been implemented in two different local tools detailed in the following sections 3.2.3.1 and 3.2.3.2. Thereafter, these two tools were migrated to a web platform[39], so that it can be used remotely, in particular by vulnerable households, volunteers and energy audit technicians. Specifically, it was integrated into the ECODES freely accessible tool in the website[40] of the 'Not a single household without energy' project. Moreover, the models were migrated also in a premium version of the ECODES tool, i.e. ENERSOC, which works as a household monitoring tool for energy poverty stakeholders (NGOs workers and volunteers, Social services, etc.).

[39] The programming of this web tool is out of the scope of the thesis.
[40] https://niunhogarsinenergia.org/cuestionarios/autodiagnostico.php#

3.2.3.1 Thermal energy expenditure's software tool

This section presents the software application DIAGNÓSTICO implemented using a local high-level language, i.e. programmed in Engineering Equation Solver (EES) [260], to determine the so-called Required Winter Thermal Energy Expenditure (RWTEE). In order to enable the handling and understanding of the information, DIAGNÓSTICO gives the results separated into three concepts: heating, DHW preparation and electricity expenditure, although electricity consumption for uses other than HVAC and DHW (cooking, lighting and electrical appliances) has been estimated constant based on a national average of 3,363 kWh/year per household. Subsequently, the latter expenditure was further programmed in a different software tool described in Section 3.2.3.2.

The methodology used by the tool to estimate the demand and consumption is the one presented in Section 3.2.1.1. On the other hand, the expenditure calculation was updated in line with the regulation and prices in 2021. In particular, commercial tariffs have been taken for the different energy carriers (Table A 17) except electricity (Table A 18), also considering taxes and fixed meter rental costs in the case of natural gas. The electricity tariff considered is the one in force in the regulated market (2.0 TD), which is a time-change tariff valid from the 1st of June 2021 in Spain [261], [262]. The amount of two of the 'charges' of the electricity bill[41] depends on in which of the regulated three day-bands the electricity is being consumed: peak hours (from 10 a.m. to 2 p.m. and 6 p.m. to 10 p.m.), flat or standard hours (from 8 a.m. to 10 a.m., from 2 p.m. to 6 p.m. and in the evening from 10 p.m. to midnight) and off-peak hours (from midnight to 8 a.m. on weekdays and the twenty-four hours of weekends and public holidays). Average values have been assumed for each period, as shown in Table A 18. The fixed (power) term is calculated from these average values according to Eq. (3.18a). To calculate the variable (energy) term, Eqs. (3.18b), (3.18c) or (3.18d) are applied, according to the following cases:

- Electric heating. Weights (*CW*, Table A 19) have been determined for each band according to the climate zone by using the heating demand discretisation presented in Section 5.2.1. This is reflected in Eq. (3.18b), applicable to electric radiators and heat pumps. On the other hand, if storage heaters are used, it is assumed that they are charged during the off-peak period, so the price is set according to Eq. (3.18c).
- Electric DHW. It is assumed that DHW is prepared by means of an electric boiler, equipped with a storage tank. In order to average that it will be charged mainly during the off-peak period, but that it may have other charging times depending on usage, the tariff corresponding to the flat period has been assumed (Eq. (3.18d)).
- Electricity consumption for purposes other than heating and DHW. The tariff corresponding to the flat period has been applied (Eq. (3.18d)).

[41] The invoices that are time-changing according to the [261], [262] are the following ones: regulated system access fees and the demand charges.

$$Tariff_{fixed-term} = \frac{Tariff_{fixed-term,peak} \cdot CP_{peak} + Tariff_{fixed-term,off-peak} \cdot CP_{off-peak}}{CP_{peak}} \quad (3.18a)$$

$$Tariff_{variable-term} = Tariff_{variable-term,peak} \cdot CW_{peak} + Tariff_{variable-term,off-peak} \cdot CW_{off-peak} + Tariff_{variable-term,flat} \cdot CW_{flat} \quad (3.18b)$$

$$Tariff_{variable-term} = Tariff_{variable-term,off-peak} \quad (3.18c)$$

$$Tariff_{variable-term} = Tariff_{variable-term,flat} \quad (3.18d)$$

Therefore, the electricity expenditure is calculated by applying Eq. (3.17). The prices and taxes are shown in Table A 15-Table A 18 of Appendix C. Moreover, the same Appendix C presents the input/output data, the source code and the other lookup tables of the tool.

3.2.3.1.1 RWTEE web tool checking

The migration of the DIAGNÓSTICO RWTEE local tool to the web tool, carried out by a computer scientist contracted by ECODES, has been checked through 386 cases, comparing the results of the tool in its original format with the migrated web version. The six winter climate zones have been tested where possible (in the Canary Islands there is no natural gas grid), block dwellings and single-family houses (in both cases with 100 m^2 and 3 people, reference household of the RTEE mentioned in the NSEP) and the three global types of insulation (energy certification). The coding to describe the different technologies (installation and energy carrier) is given in Table 3. 24, and was constructed as explained by Table 3. 23.

Table 3. 23. Explanation of the test studies' codification for the DIAGNÓSTICO RWTEE local - ECODES web tool checking

Installation	Energy carrier	.	Installation	Energy carrier
Heating			DHW	

Thus, for example, 'IGL.IE' would mean an Individual heating installation with LPG and an Individual DHW installation with an Electric boiler. The different combinations analysed are shown in Table 3. 25.

Table 3. 24. Test studies' codification for the DIAGNÓSTICO RWTEE local – ECODES web tool checking

Installation	Service	Energy carrier / system
I = Individual C = Central	Heating and DHW	GN= Natural Gas
		GL= LPG
		GO= Heating gasoil
		BM= Biomass
	Only Heating	EA = Electric storage heater
		ER = Electric radiator
		BC = Electrically driven heat pump
	Only DHW	E = Electricity

Table 3. 25. Test studies for the DIAGNÓSTICO RWTEE local – ECODES web tool checking

Winter climate zone	Construction period	Block dwelling	Single-family house	Number of cases
A ÷ E	Before 1980, between 1981 and 2007, after 2007	IGN.IGN	IGN.IGN	30
A ÷ E	Before 1980, between 1981 and 2007, after 2007	CGN.CGN		15
α ÷ E	Before 1980, between 1981 and 2007, after 2007	CGO.CGO	IGO.IGO	36
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IGL.IGL	IGL.IGL	36
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IGL.IE	IGL.IGE	36
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IEA.IGL	IEA.IGL	36
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IER.IE	IER.IE	36
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IEA.IE		18
α ÷ E	Before 1980, between 1981 and 2007, after 2007	CBM.CBM	IBM.IBM	36
A ÷ E	Before 1980, between 1981 and 2007, after 2007	IBC.IGN	IBC.IGN	30
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IBC.IE	IBC.IE	36
α ÷ E	Before 1980, between 1981 and 2007, after 2007	IBC.IGL	IBC.IGL	36
A ÷ E	Before 1980, between 1981 and 2007, after 2007	IBC.CGN		15

3.2.3.2 Electricity expenditure's software tool

The general objective of this section is to present the applied research for the development of a web tool that implement the Advanced RELE model described in Section 3.2.2.

Specifically, this section describes the local tool developed in Excel. Moreover, after programming both the local and web tools, being the latter out of the scope of this thesis, a series of tests have been carried out to compare the results obtained with the web tool with those of the original model in Excel to verify that it has been migrated correctly. The following is a description of the specific steps that have been carried out to programme the RELE model that has been developed in Section 3.2.2, based on the results obtained from the modelling (see Section 3.3.2).

The input data for calculating the average consumption per appliance use (excluding lighting) are:

- Household size (HS): 1, 2, 3, 4, more than 4.
- Presence or not of the household appliances shown in Table 3. 26 (possible answers: yes, no, don't know). Although the Advanced model includes the consumption of stoves and oven together, these appliances' consumption has been separated in the tool by using the proportions obtained from the Simplified RELE model. Moreover, the Others' consumption has been divided among the three appliances composing this specific model item, i.e. mobile phones, tablets and microwaves.

Table 3. 26 shows the corresponding consumption values for the electrical appliances available to the household (if available, the value is taken, otherwise zero).

Table 3. 26. Average annual electricity consumption of each appliance (kWh/year) in the RELE local tool when the user's answer is 'yes'

HS / Appliance	1	2	3	4	> 4
Stoves	227.86	394.95	417.74	474.70	558.25
Oven	48.96	84.86	89.76	102.00	119.95
Washing machine	209.83	262.29	332.23	384.69	437.17
Tumble dryer	203.38	254.55	322.34	373.08	424.17
Refrigerator	748.80	748.80	748.80	748.80	748.80
Freezer	599.04	599.04	599.04	599.04	599.04
TV	197.27	341.69	296.73	314.38	359.95
Computer	73.64	163.00	313.10	424.68	397.79
Dishwasher	214.97	254.06	293.14	351.77	371.31
Mobile phone	3.60	7.20	10.80	14.40	18.00
Tablet	4.11	6.17	8.23	10.29	12.34
Microwave	54.00	59.40	64.80	70.20	78.30

If it is not known whether any of the appliances are present ('don't know' answer), Table 3. 38 and Table 3. 27 are used, showing the latter the values applied for the split cooking's and Others' consumptions. It was assumed that all households have stoves, washing machine, refrigerator, TV, mobile phone and microwave and for the rest the average ownership rates in Spain have been applied (Table 3. 16)).

Table 3. 27. Average annual electricity consumption (kWh/year) for the split cooking's and Others' appliances in the RELE local tool when the user's answer is 'Don't know'

HS / Appliance	1	2	3	4	> 4
Stoves	227.86	394.95	417.74	474.70	558.25
Oven	37.75	65.43	69.20	78.64	92.48
Mobile phone	3.60	7.20	10.80	14.40	18.00
Tablet	2.24	3.36	4.48	5.61	6.73
Microwave	54.00	59.40	64.80	70.20	78.30

In order to calculate the electricity consumption for lighting in a household, the floor area of the dwelling is needed. Table 3. 28 shows the dwelling size's ranges set as alternative inputs of the electricity expenditure's local tool.

Table 3. 28. Dwelling size's ranges (m^2) in the RELE local tool

Dwelling size (m2)	40-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200	201-250	251-300	301-350	351-400	> 400	I don't know

The value that corresponds to the category 'I don't know' is the surface of the average Spanish household (103.7 m^2, according to SECH-SPAHOUSEC). For each of the household sizes (HS), the lighting consumption for a household whose dwelling has a floor area (DS) equal to the average (103.7 m^2) can be seen in Table 3. 29.

Table 3. 29. Annual electricity consumption per lighting (kWh/year) for the average dwelling size (103.7 m^2) according to household size in the RELE local tool

HS	1	2	3	4	> 4
Lighting	167.02	334.05	501.07	668.09	835.12

To obtain the estimated lighting consumption for a specific household with a floor area of DS (m^2, set as the range's average), Eq. (3.19) is applied:

$$Lighting\ consumption\ (kWh/year) = \frac{Average\ dwelling's\ lighting\ consumption}{103.7} \cdot DS \quad (3.19)$$

Subsequently, to obtain the total consumption in the household due to appliances and lighting, the values obtained in the previous tables are summed up. This gives a base value for consumption of a household with a certain HS, which is then corrected according to their composition (Table 3. 21) by applying the factors shown in Table 3. 39. After obtaining the total average consumption value for the particular household, the stand-by value of all appliances, estimated at 7% of this total value (see Section 3.2.2), is added. This would give the average annual electricity consumption of the household in question, measured in kWh/year, which is summarised in the following Eq. (3.20).

$$RELC\ \left(\frac{kWh}{year}\right) = \sum_{j=1}^{12} C_{jl} \cdot \beta_j + C_{lighting,l} \cdot DS + \sum_{i=1}^{l} f_{lrs_i} + Standby \quad (3.20)$$

The variables of Eq. (3.20) stand for the same as in Eq. (3.16). The expenditure calculation, i.e. RELE, was programmed as explained in Section 3.2.2.4. Screenshots of the local tool are shown in Appendix C (Fig. A 30).

3.2.3.2.1 RELE web tool checking

The following cases have been simulated both in the local and the web tool to verify that the electricity consumption calculation has been correctly transferred from the former to the latter:

1. Electrical appliances' and lighting consumption tests.
   The number of members should be combined with the presence or absence (or not known) of household appliances. Therefore, the electricity consumption has been simulated for each household size and response on the presence of each appliance (these inputs are defined in Section 3.2.3.2). On the other hand, lighting consumption depends on the household size and the dwelling size. In the local simulator several dwelling size's ranges were set as inputs, but in the web tool the dwelling size is asked directly to the user, i.e. the exact floor area is inserted by the user. Therefore, the lighting consumption outputs with the central values of the dwelling size range in Table 3. 28 have been tested in the web tool to check them with the local tool's results. Being the lighting consumption proportional to the floor area, each household size has been combined with five common dwelling sizes: 70, 90, 103.7 (average household size in Spain), 110 and 130 [m^2].

2. Occupation correction factor tests.
   For each household size, the different occupational possibilities (see Table 3. 21) should give the same result in the two tools. For simplicity' sake, for all household sizes (from 1 to more than 4) each of the occupation factors have been tested, as shown in Table 3. 30.

Table 3. 30. Occupation combinations tested

1	2	3	4	> 4
1 employed	1 employed and 1 unemployed	1 employed and 2 unemployed	1 employed, 2 students and 1 Household chores	1 employed, 2 unemployed, 2 students
1 unemployed	2 employed	2 employed and 1 unemployed	2 employed and 2 students	2 employed, 2 retired and 1 student
1 student	2 unemployed	3 employed	3 employed and 1 unemployed	4 employed and 1 pensioner type 1
1 retired	1 unemployed and 1 student	2 employed and 1 student	3 unemployed and 1 student	1 employed, 1 unemployed, 1 retired and 1 Household chores + 1 unemployed
1 pensioner type1	2 students	1 employed and 2 students	1 employed, 1 retired, 1 student, 1 pensioner type1	1 pensioner type2, 3 employed and 1 student
1 pensioner type2	1 student and 1 retired	1 retired, 1 unemployed and 1 employed	2 retired and 2 employed	2 employed, 1 retired and 2 students
1 Household chores	2 retired	1 unemployed and 2 retired	2 employed, 1 student and 1 pensioner type 2	3 employed and 2 students
	1 retired and 1 pensioner type1	2 employed and 1 pensioner type1		
	1 employed and 1 pensioner type2	2 employed and 1 pensioner type2		
	1 employed and 1 Household chores	1 employed, 1 student and 1 Household chores		

These occupation combinations (point 2) can be tested at the same time as the appliances' consumptions (point 1), as they are independent.

3.3 Results and discussion

3.3.1 Required Thermal Energy Expenditure

This section presents the results of the RTEE model and its applications whose methodology was described in Section 3.2.1. Firstly, the general results per climate zone are introduced. Secondly, some insights of the provincial RWTEE analysis are pointed out. Finally, the outputs of the application of the model to the ECODES vulnerable-households' database are discussed.

Table 3. 31 and Table 3. 32 show the values of the annual specific required demand for heating (SRD_h) per winter climate zone and aggregated-construction-period.

Table 3. 31. Values of the annual specific required demand for heating [kWh/(m² year)] per winter climate zone and aggregated-construction-period for block dwellings

Winter climate zone	≤1980	1981-2007	2008-2018
α	0.00	0.00	0.00
A	51.39	29.26	11.08
B	70.97	41.96	16.30
C	110.14	67.45	26.79
D	159.08	99.24	39.87
E	209.17	131.76	53.25

Table 3. 32. Values of the annual specific required demand for heating [kWh/(m² year)] per winter climate zone and aggregated-construction-period for single-family houses

Winter climate zone	≤1980	1981-2007	2008-2018
α	0.00	0.00	0.00
A	82.89	43.55	17.86
B	105.58	59.21	25.99
C	149.59	90.26	42.67
D	212.26	129.97	62.01
E	276.32	167.96	86.37

Table 3. 33 and Table 3. 34 show the values of the annual specific required demand for cooling (SRD_c) per climate zone and aggregated-construction-period. In this case, both climate zones (winter and summer one) have to be considered because the calculated EEPs depend on the winter climate zone while the reference demand is set according to the summer climate zone.

Table 3. 33. Values of the annual specific required demand for cooling [kWh/(m² year)] per climate zone and aggregated-construction-period for block dwellings

Climate zone	**≤1980**	**1981-2007**	**2008-2018**
α3c	47.76	28.42	12.52
A2	24.71	14.35	5.82
A3	47.76	28.42	12.52
A4	67.31	40.05	17.65
B2	22.59	13.62	5.68
B3	43.80	27.06	12.24
B4	61.73	38.13	17.26
C1	0.00	0.00	0.00
C2	20.87	13.02	5.56
C3	40.58	25.95	12.02
C4	57.19	36.57	16.94
D1	0.00	0.00	0.00
D2	20.04	12.74	5.50
D3	39.04	25.42	11.91
E1	0.00	0.00	0.00

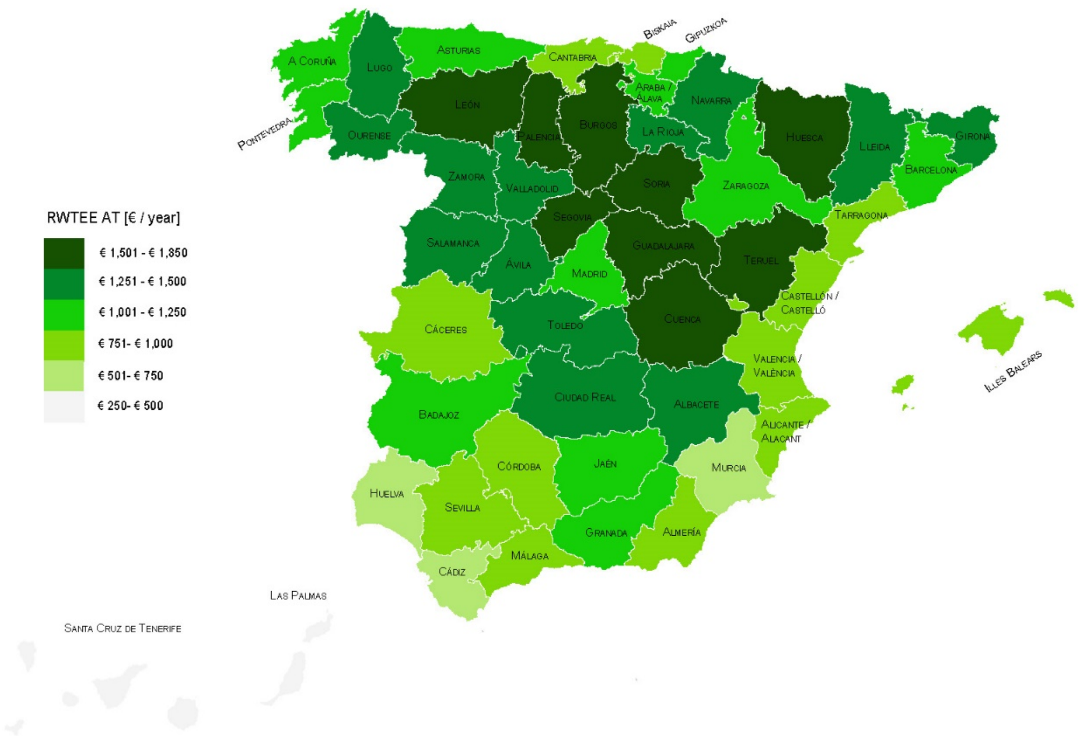
Table 3. 34. Values of the annual specific required demand for cooling [kWh/(m² year)] per climate zone and aggregated-construction-period for single-family house

Climate zone	**≤1980**	**1981-2007**	**2008-2018**
a3c	47.76	28.42	12.52
A2	24.71	14.35	5.82
A3	47.76	28.42	12.52
A4	67.31	40.05	17.65
B2	22.59	13.62	5.68
B3	43.80	27.06	12.24
B4	61.73	38.13	17.26
C1	0.00	0.00	0.00
C2	20.87	13.02	5.56
C3	40.58	25.95	12.02
C4	57.19	36.57	16.94
D1	0.00	0.00	0.00
D2	20.04	12.74	5.50
D3	39.04	25.42	11.91
E1	0.00	0.00	0.00

Apart from the climate zone, the values of SRD_h and SRD_c are considerably affected by the dwelling's construction-period and typology. For example, the average SRD_h of a block dwelling in a building constructed before 1981 is 4.1 times the one of a new built dwelling (2008-2018). On the other hand, the specific required demand for the DHW production (SRD_{DHW}) is significantly affected by the network water temperature throughout the year, which is usually proportional to the outdoor temperature that is one of the main determinants of the HVAC demand. The specific thermal demand values in each of the 8,131 Spanish localities are the first results of the RTEE bottom-up model.

Focusing on the 'winter energy needs', Fig. 3. 5 summarizes the results of the two scenarios of RWTEE analysis (before and after taxes) for the 'provincial weighted-average households' defined by the segmentation methodology described in Section 3.2.1.2. The RTEE values for Ceuta and Melilla, which are two small Spanish autonomous cities in the North African coast (not shown in Fig. 3. 5), are the following ones, respectively: €666 and €533 for RWTEE AT; €628 and €503 for RWTEE BT.

The RWTEE varies considerably depending on the province. Considering the scenario BT, the average RWTEE in the coldest province (*León*) is six times higher than the warmest-province's one (*Las Palmas*). Furthermore, Fig. 3. 5 points out that the difference between the RWTEE of the two scenarios is significantly smaller in Canary Islands (*Las Palmas* and *Santa Cruz de Tenerife*), *Ceuta* and *Melilla* because the VAT is much lower than in the rest of the provinces, where it is 21% for all energy supplies (see Section 3.2). That means also that fossil fuel taxes have a lower weight in the energy expenditure than the VAT. The weighted average values of RWTEE in Spain, respectively after and before taxes, are €1,055 and €812. From this, it can be inferred that the overall taxation is 23% of the average RWTEE AT, which confirms the abovementioned conclusion on energy taxation in Spain.



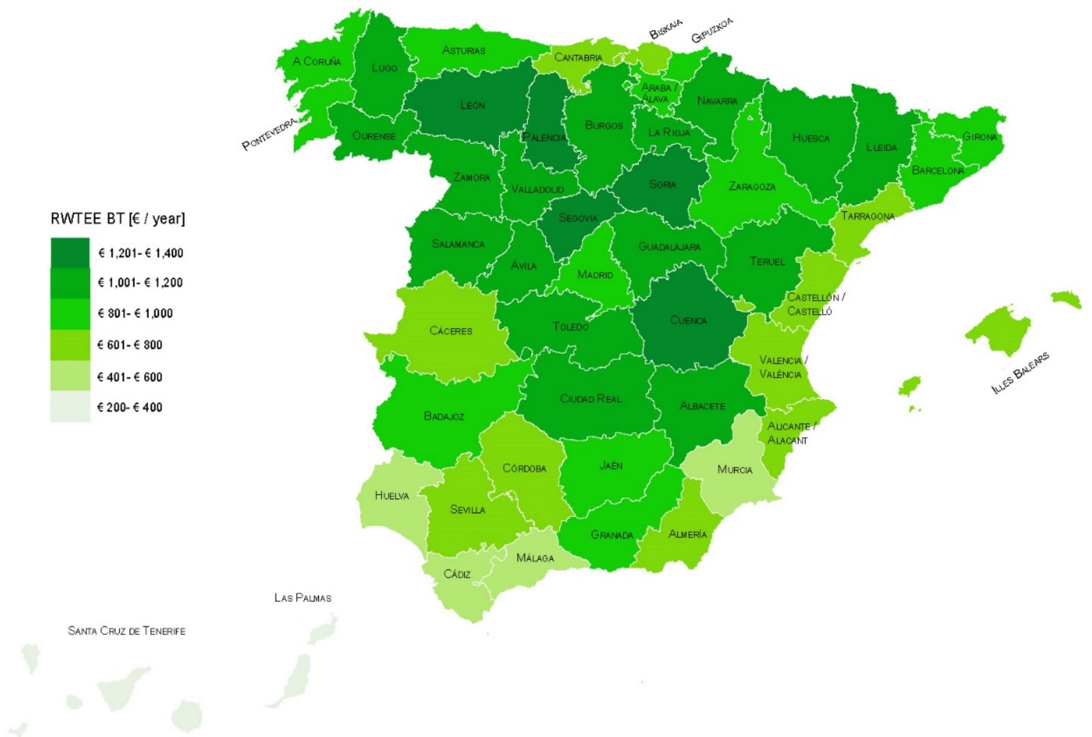


Fig. 3. 5. Provincial results for the two scenarios of the household RWTEE analysis [€/year]: RWTEE AT - RWTEE after tax (above); RWTEE BT- RWTEE before tax (below); (reprinted from [236] *)*

On the other hand, in the RWTEE application to the ECODES vulnerable-households' database, the solution requiring the lowest costs among the available solutions[42] has been identified for each household. The results of this calculation have been processed to highlight the trends of the most economical supplies by varying the following parameters: winter climate zone, dwelling size, household size (number of occupants), and aggregated construction period that affects the building thermal insulation (only for the 2015-17 survey, see Section 3.2.1.3). Fig. A 1 and Fig. A 2 of Appendix A show the minimum specific RWTEE among the analysed thermal-systems' configurations for each household, sorted by winter climate zone. In the 2015-17 survey, the inclusion of three different insulation levels outcomes in greater variability in Fig. A 1. Table 3. 35 summarises this minimum specific expenditure by climate zone for the two surveys as a whole. The RWTEE value strongly depends on the winter climate zone of the locality, the α zone value being almost seventeen times lower than the E zone value.

Table 3. 35. Minimum RWTEE by winter climate zone (combination of data from 2015-17 and 2017-19)

Winter climate zone	**Minimum RWTEE [€ / (m² year)]**
E	20.0
D	15.8
C	11.4
B	8.0
A	6.5
α	1.2

Fig. 3. 6 displays how the configuration that demands the lowest RWTEE is distributed according to the winter climate zone. It shows the dominance of centralised natural gas systems[43] for both heating and DHW, followed by individual natural gas systems for heating in the middle and cold areas (C, D and E). In areas with milder winters (A and B), the centralised natural gas system is still the most affordable solution, although the second option is the individual heating gasoil system and the third option (only in zone A) is heating by electric storage heater and individual LPG systems for DHW. It should be noted that the study carried out is purely economic and does not take into account environmental parameters, which explains why gasoil appears as the more economical option in some climate zones.

[42] For households in the Canary Islands, given the absence of natural gas supply, the following supply combinations have not been considered: IGNIGN; IGNITE; CGNCGN; CGNITE; CGNIGN; CGNIGL; CGOCGN; CGOIGN.

[43] It has to be noted that the study applied to the ECODES database did not include the heat pump among the heating and DHW systems because of its low ownership rate (and use) in vulnerable households. However, this promising technology was included in the tool described in Section 3.2.3, whose results are presented in Section 3.3.3.

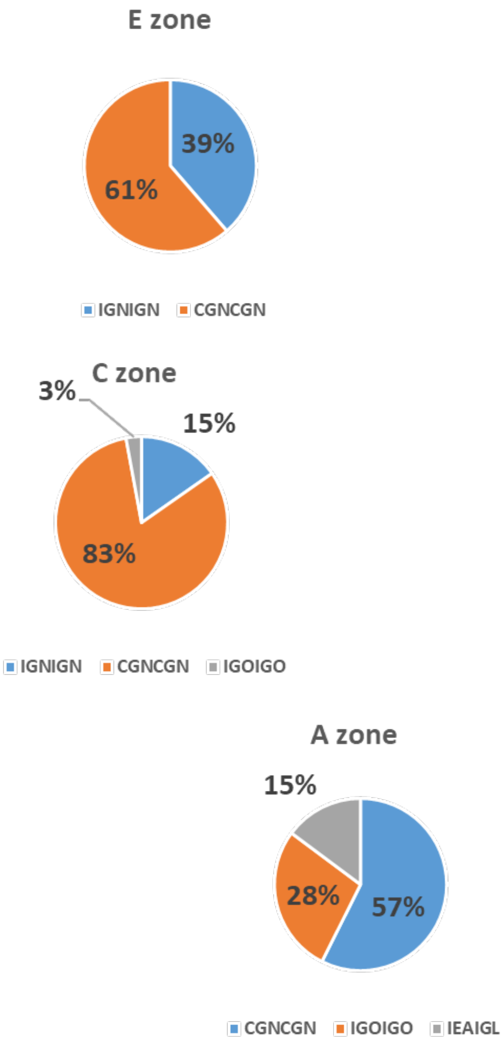


Fig. 3. 6. Configurations with lower RWTEE by winter climate zone (Surveys 2015-17 and 2017-19) (reprinted from [256]*)*

Considering the 2015-2017 survey, Fig. A 15-Fig. A 19 of Appendix A show the dependence of the annual minimum RWTEE [€/year] on the dwelling size and on the aggregated construction period (insulation level) in the different winter climate zones. Fig. 3. 7-Fig. 3. 9 summarise the above results by climate zones for each insulation level, with Table 3. 36 showing the slopes of the regression lines (required specific expenditure, €/(m^2-year)), i.e. the expenditure values have been obtained from the slopes of the regression lines in Fig. 3. 7-Fig. 3. 9. The α climate zone has been omitted, as it has null heating demand (which is the one influenced by the dwelling insulation level).

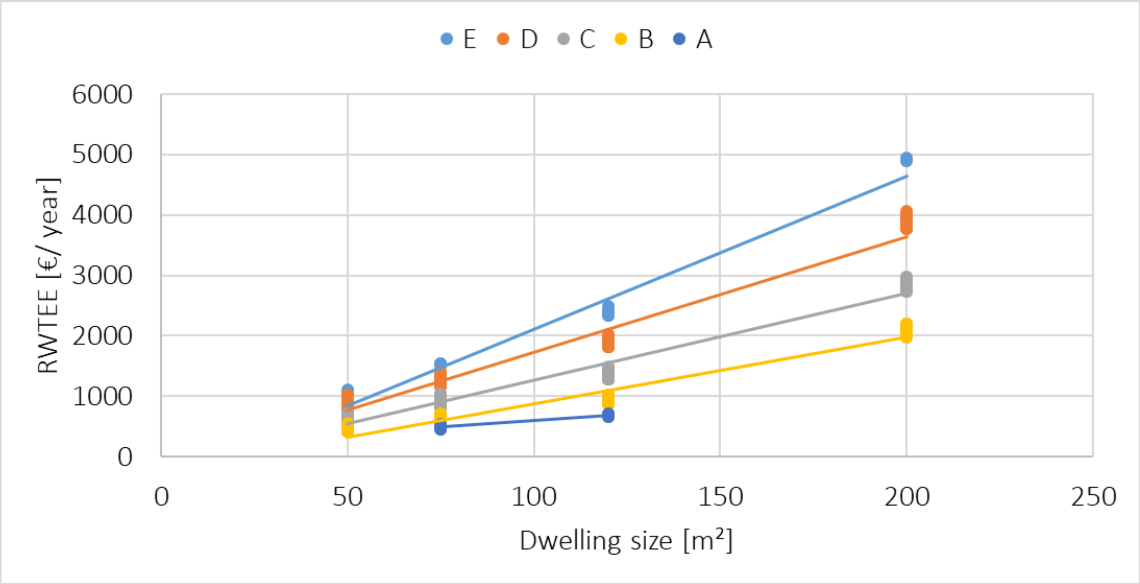


Fig. 3. 7. Minimum RWTEE trend for households in dwellings constructed before 1981 by dwelling size for each winter climate zone (data from 2015-17); (reprinted from [256])

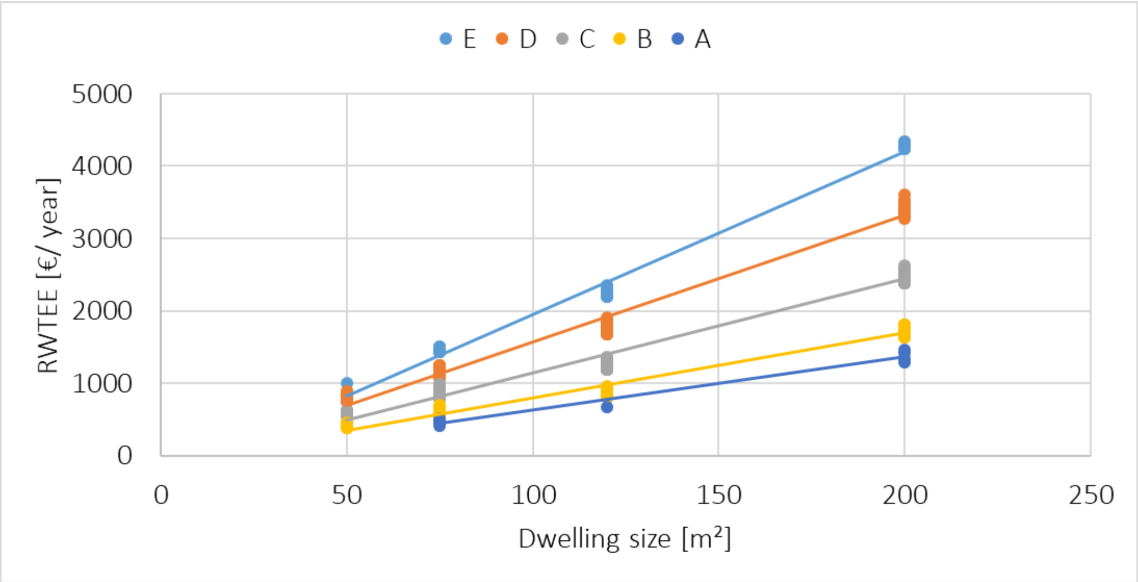


Fig. 3. 8. Minimum RWTEE trend for households in dwellings constructed between 1981 and 2007 by dwelling size for each winter climate zone (data from 2015-17); (reprinted from [256])

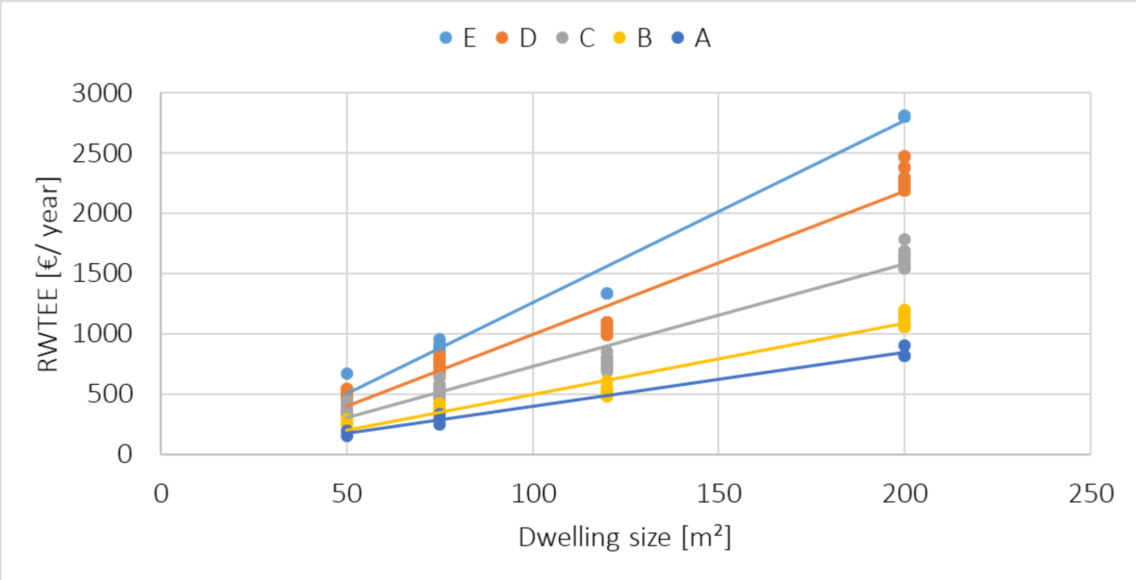


Fig. 3. 9. Minimum RWTEE trend for households in dwellings constructed after 2007 by dwelling size for each winter climate zone (data from 2015-17); (reprinted from [256]*)*

Table 3. 36. Minimum specific RWTEE [€/(m^2 year)] according to aggregated construction period and winter climate zone (data from 2015-17).

	Minimum RWTEE [€/(m^2 year)]		
Winter climate zone	**Aggregated construction period**		
	≤1980	**1981-2007**	**>2007**
E	25.26	22.52	15.12
D	19.17	17.54	11.92
C	14.40	13.06	8.55
B	11.08	9.00	5.97
A	4.44	7.37	4.44

The specific RWTEE highly depends on the winter climate zone. The second determinant is the insulation level, which depends on the construction period. The only exception is the case of the households in A winter climate zone living in dwellings constructed before 1980. They have the same value of average specific RWTEE as in the households living in dwellings constructed after 2007. This result is apparently counterintuitive but the explanation could be found by analysing the other input parameters in these households, i.e. the dwelling type and the household size. The former determines both the heating and DHW demand values, while the latter (analysed below in this section) influences the DHW demand, but not the heating one.

For the 2017-19 sample, Fig. A 8-Fig. A 13 of Appendix A show the dependence of the RWTEE [€/year] on the dwelling size (m^2). As these are data from the second survey, the same level of insulation (≤1980) has been assumed for all households. A worsening of the regression coefficient (R2) is observed as the climate zone becomes less severe. Specifically, in the zone α (Fig. A 13), no correlation can be seen as there is no heating demand so the expenditure value refers only to DHW.

To summarise, Fig. 3. 10 combines the 2017-19 data with the 2015-17 poor insulation data by winter climate zone. It clearly shows the independence of the area in the case of the no heating demand zone.

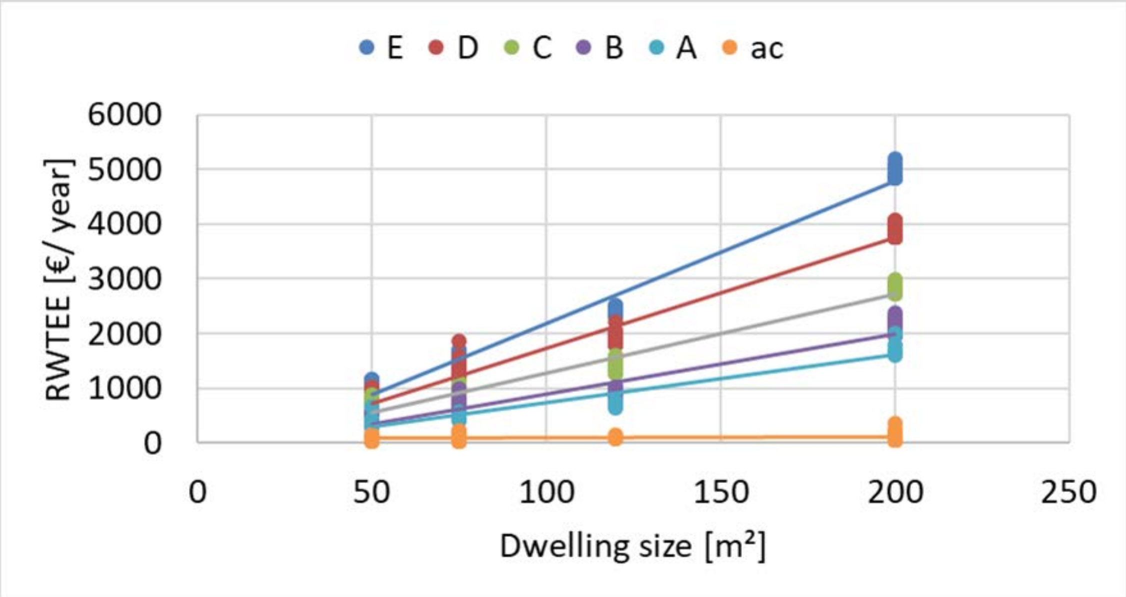


Fig. 3. 10. Minimum RWTEE trend by dwelling size for each winter climate zone (combined data from 2015-17 and 2017-2019); (reprinted from [256]*)*

Finally, Fig. 3. 11 compares the specific RWTEE obtained through various combinations of data. It can be seen how by maintaining the same level of insulation (second and third columns) the results are almost identical; on the other hand, by introducing the three insulations, with the poorest being the worst (fourth column), all the costs are reduced. These trends are not seen in zone A, given the greater relative importance of DHW.

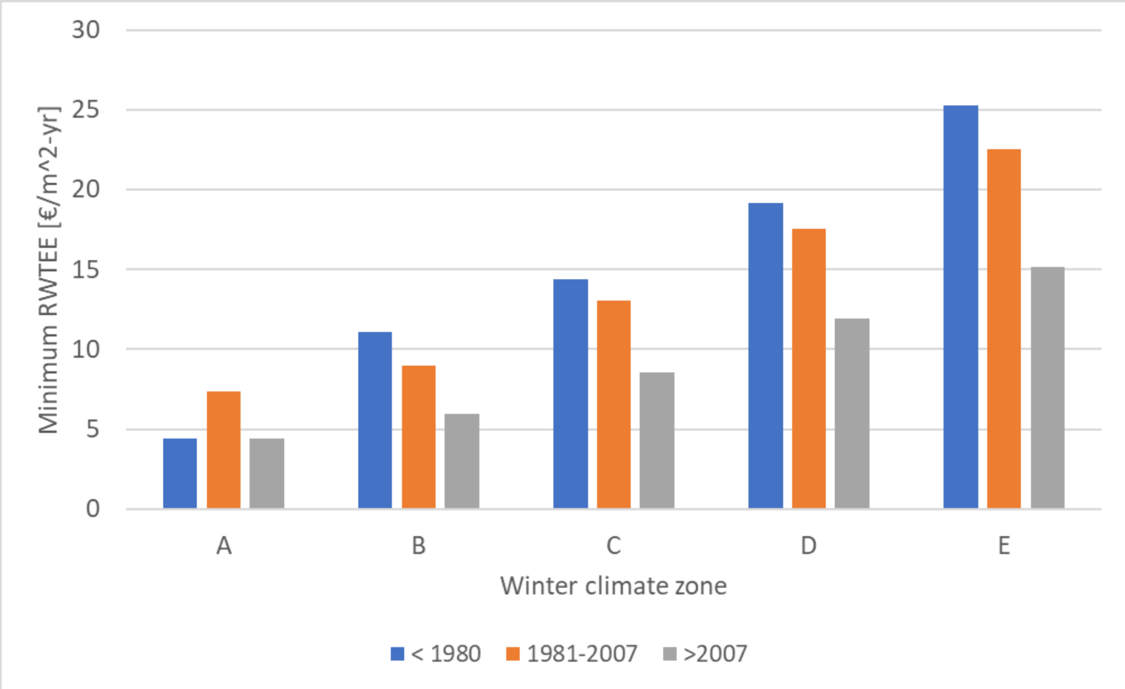


Fig. 3. 11.Minimum specific RWTEE [€/(m²year)] according to winter climate zone for different datasets (2015-2017 dataset for ≤1980 construction period and the combined datasets, i.e. data from 2015 to 2019, for the other two construction periods); (reprinted from [256]*)*

In order to explore the influence of the household size on the RWTEE, Fig. 3. 12 and Fig. 3. 13 show the average specific RWTEE depending on the number of occupants for 2015-17 data in the two extreme climate zones (A and E). The 2015-17 database was selected for this analysis because it makes it possible to consider more household sizes than the 2017-2019 one. From Fig. 3. 12 and Fig. 3. 13 it can be deduced that there is a dependence between the RWTEE and the number of occupants when the winter is milder, as the DHW component has a greater weight in the expenditure; on the contrary, in areas with harsh winters there is no clear dependence, as the heating component is much more important.

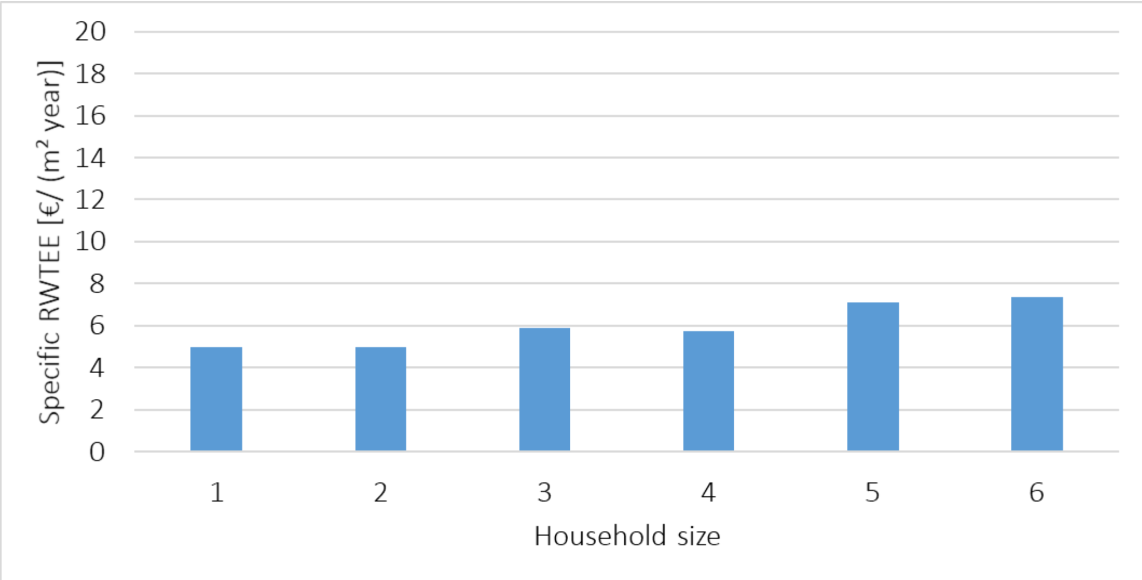


Fig. 3. 12. Average specific RWTEE [€/ (m² year)] by household size (A zone; 2015-17 data); (reprinted from [256]*)*

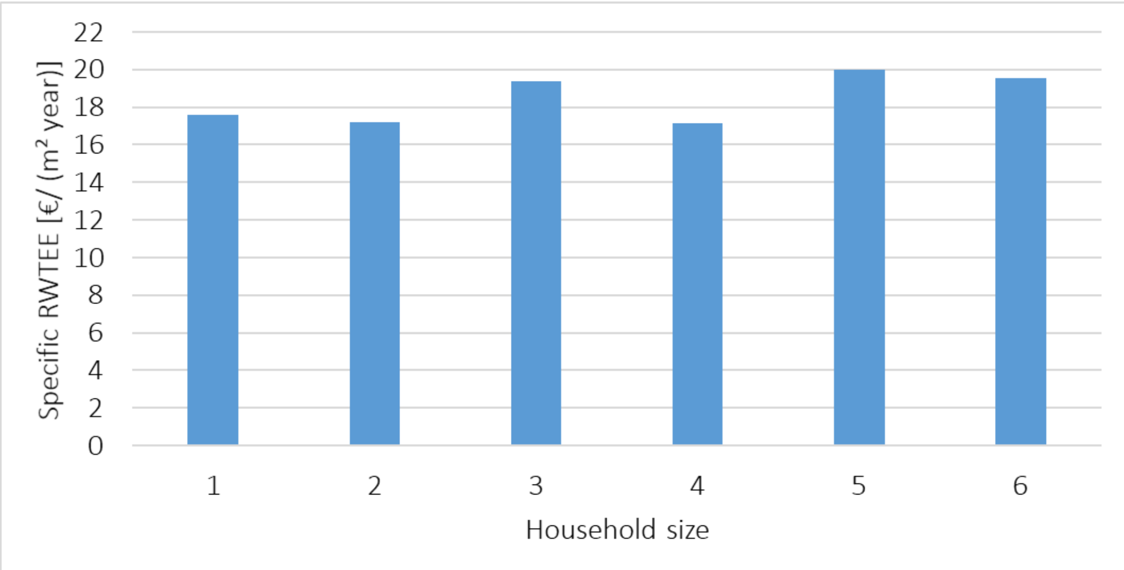


Fig. 3. 13. Average specific RWTEE [€/ (m² year)] by household size (E zone; 2015-17 data); (reprinted from [256]*)*

3.3.2 Required Electricity Expenditure

3.3.2.1 Annual electricity expenditure

Table 3. 37 shows the average consumption per appliance and the RELC estimated with the Simplified model according to the household size and for an average household in 2019. As this corresponds to the average consumption, the ownership rate of the different appliances (shown in Table 3. 16) have been taken into account. The RELC of an average household for the Simplified model has a value of 2,998 kWh per year. Regarding the influence of the household size, the RELC increase proportionally with the number of

occupants, i.e. each added person increases the annual consumption by around 440 kWh. The last case (>4 persons) contains different household sizes bigger than four members but the households with more than 5 members has a much lower weight than the 5-person household, i.e. the share of households with more than 5 members is not significant (see Table 3. 17). Therefore, the consumption increases by almost the same amount than the other cases.

On the other hand, Table 3. 38 shows the average consumption of Spanish households per appliance and the RELC estimated with the Advanced model according to the household size and for an average household in 2019. The RELC of an average household for the Advanced model has a value of 3,030 kWh per year, thus being slightly higher than the one estimated by using the Simplified model. Furthermore, the RELC does not increase proportionally to the household size. Particularly, the increase from the 1-person household to the 2-person one (722 kWh) is much higher than the other ones (around 436 kWh). On the other hand, the RELC of a >4-person household is 'only' 407 kWh higher than the one of a 4-person household. This difference in the household-size dependency with respect to the one of the Simplified model is due to the fact that the Advanced model is based on the TUS, thus considering the occupation and activities of Spanish households throughout the day (time discretisation in Section 3.3.2.2), while the first model utilises usage factors based on less sophisticated surveys[44] performed mostly with much smaller household samples (i.e. SECH-SPAHOUSEC and SPAHOUSEC II).

Table 3. 37. Annual domestic electricity consumption (kWh/year) per appliance, according to the household size and for the average household, following the Simplified model.

HS / Appliance	1	2	3	4	> 4	Avg. household
Stoves	338.02	371.83	405.63	439.43	490.14	388.74
Washing machine	195.84	244.80	310.08	359.04	408.00	275.05
Tumble dryer	53.79	67.24	85.17	98.62	112.07	75.55
Refrigerator	748.80	748.80	748.80	748.80	748.80	748.80
Freezer	148.56	148.56	148.56	148.56	148.56	148.56
Oven	52.43	57.67	62.91	68.16	76.02	60.29
Lighting	167.02	334.05	501.07	668.09	835.12	412.80
TV	247.86	277.02	306.18	335.34	379.08	291.61
Computer	74.56	149.11	223.67	298.23	372.79	184.27
Dishwasher	109.95	129.94	149.93	179.92	189.91	141.11
Other	59.78	69.87	79.96	90.05	102.84	74.78
Standby	153.76	181.92	211.54	240.40	270.43	196.11
Total	2350.38	2780.82	3233.51	3674.64	4133.76	2997.67

[44] The frequency of use of the appliances is given in number of times/week or number of hours/day without a time discretisation.

Table 3. 38. Annual domestic electricity consumption (kWh/year) per appliance, according to the household size and for the average household, following the Advanced Model

HS / Appliance	1	2	3	4	> 4	Avg. household
Stoves+Oven	266.58	458.97	485.03	552.08	650.55	442.21
Washing machine	209.83	262.29	332.23	384.69	437.17	294.7
Tumble dryer	57.56	72.04	91.22	105.58	120.04	80.90
Refrigerator	748.80	748.80	748.80	748.80	748.80	748.80
Freezer	148.56	148.56	148.56	148.56	148.56	148.56
Lighting	167.02	334.05	501.07	668.09	835.12	412.8
TV	197.27	341.69	296.73	314.38	359.95	291.57
Computer	59.57	131.87	253.29	343.57	321.81	186.29
Dishwasher	117.8	139.22	160.64	192.77	203.48	151.19
Other	59.78	69.87	79.96	90.05	102.84	74.78
Standby	142.29	189.52	216.83	248.4	274.98	198.23
Total	2175.07	2896.87	3314.37	3796.97	4203.31	3030.03

Table 3. 39 shows the RELC occupation factors calculated with the Advanced model according to household size and composition. These factors have to be added to the average consumption of each household size (The 'Total' line values shown in the above Table 3. 38) to calculate the household RELC according to the household composition. For example, a two-person household has an average consumption of 2,898 kWh/year. The presence of an employed person would subtract 100 kWh to the annual consumption while if an unemployed person is living there, the RELC would be reduced by 26 kWh.

Table 3. 39. Occupation factors in the Advanced RELE model, i.e. factors calculated according to household size and composition (type of occupation) [kWh/year].

HS / Occupation	1	2	3	4	> 4
With 1 employed person	-159.48	-100.12	101.47	31.20	134.25
With 2 employed persons	0.00	-242.16	-136.29	-125.21	-128.49
With 3 or more employed persons	0.00	0.00	-82.71	317.90	173.63
With 1 unemployed person	263.53	26.17	128.69	112.44	-69.98
With 2 or more unemployed persons	0.00	88.31	179.65	363.74	188.13
With 1 student	-266.71	-68.23	-2.39	41.97	-143.42
With 2 or more students	0.00	-438.96	-183.48	-95.06	2.12
With 1 retired person	-54.94	93.55	176.89	376.06	54.59
With 2 or more retired persons	0.00	123.12	116.36	204.04	165.43
With some pensioner-1	83.52	21.23	173.91	364.98	416.19
With some pensioner-2	9.29	95.24	104.52	206.31	273.04
With some homeworker (Household chores)	224.34	170.61	219.65	230.74	218.35
With some 'Others'	-138.47	-278.65	-370.61	-430.56	40.46

Fig. 3. 14 shows the appliances' annual consumption for the 'average 2019 household' (described in Section 3.2.2) calculated by using, respectively, the Simplified and Advanced RELC models, and compares them with the statistical values presented in the IEE 2018 [255].

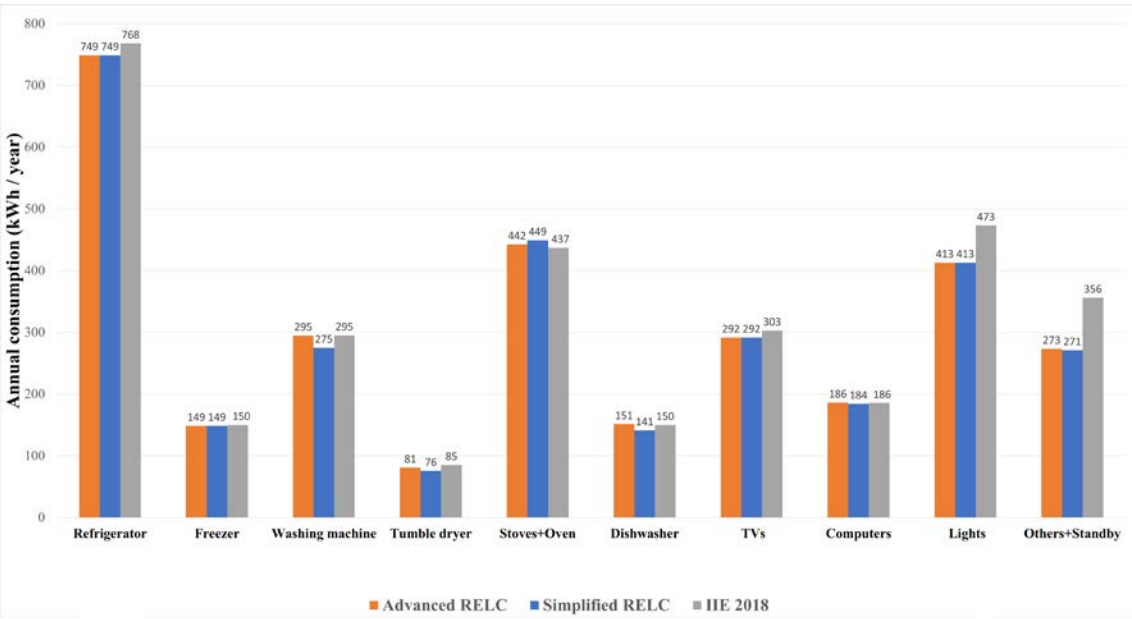


Fig. 3. 14. Comparison between the appliances' annual consumption for the 'average 2019 household' in the Simplified and Advanced RELC models, and the statistical values in IEE 2018 [255]

The main differences between the two models are due to the hypotheses made for the frequency of use of some of the electrical appliances considered, which reflect the different statistic sources, as mentioned before. Thus, in the Advanced model, the consumption of six of the appliances (considering stoves and oven as a unique appliance) is modelled by considering a much bigger household sample (statistically representing all the Spanish households) and discretising their activities throughout the day, which makes it a more accurate model. Nevertheless, summing up all the appliances' consumption values for the average 2019 household, the Advanced RELC (3030 kWh) is very similar to the Simplified RELC (2998 kWh), being the former only 1% higher than the latter. On the other hand, the results of both models are very much comparable with the statistical values of IEE 2018, which presents an average annual household electricity-consumption equal to 3203 kWh. However, the consumption values of lights and 'others+standby' in the models are significantly lower than in statistics. Both values were obtained by applying simplified assumptions to a static model. Nevertheless, the lighting consumption could change considerably depending, for example, from the geographical area, and the time discretisation of this service is also an important topic that should be taken into account in further work.

Table 3. 40 shows the differences in percentage between the Advanced RELC and the different references considered in the comparison analysis. It can be noticed that the RELC-model's results are very similar to the references' ones, with only a ±10% deviation in the total consumption calculation. Particularly, when comparing the Advanced RELC with a similar model, i.e. (Escobar et al., 2020 [94]), the difference in the estimated total consumption is only 1%. Moreover, the two new comparisons (Escobar et al., 2020 and SECH-SPAHOUSEC) confirm the need of better modelling lighting and 'others+standy'.

Table 3. 40. Comparison between Advanced RELC and electricity consumption in reference studies

Appliance	% (RELC - SECH-SPAHOUSEC)	% (RELC - (Escobar at al., 2020))	% (RELC – IEE 2018)
Refrigerators	14%	14%	-2%
Freezers	7%	7%	-1%
Washing machines	21%	12%	0%
Tumble dryers	17%	6%	-5%
Stoves+Ovens	-12%	-7%	1%
Dishwashers	16%	8%	1%
TV	13%	11%	-4%
Computers	44%	-2%	0%
Lights	24%	24%	-13%
Others	-4%	-8%	-16%
Stand-by	-12%	-12%	-27%
Total	10%	-1%	-5%

The results for the indicators calculated for the comparison of the Advanced model with the ECODES households' database are the following ones. The value of the first indicator (AELC/RELC) shows that the model fits to actual consumption of 0.83, or in other words that ECODES households have an actual consumption that is on average 83% of the modelled required consumption. On the other hand, the second indicator (AELC<RELC) shows that 64% of households have lower actual than required consumption and are potentially underconsuming. These values are mainly due to the fact that the database contains the values of vulnerable households, which usually have a lower energy consumption (see Chapter 4), although it may also be due to an overestimation of household electricity consumption.

On the other hand, the application of the Advanced RELC model to the ECODES household database shows different results depending on the household size and composition. Fig. 3. 15 shows a breakdown of the median electricity consumption by household size. The median actual consumption in one-person households is slightly higher than the theoretical consumption, but as the number of household members increases, while the actual consumption increases marginally, the increase in theoretical consumption is much more significant. This fact can also be seen in Fig. 3. 16, where the median AELC/RELC and AELC<RELC indicators for the first household-size group are 1 and 50% respectively, reflecting the good fit of the model for single-person households. However, as the number of household members increases, the first indicator (AELC/RELC) decreases and the second indicator increases (AELC<RELC), which shows a lower fit of the model to actual consumption, as well as a higher share of households with lower actual than theoretical consumption. As for the average value, this can be interpreted as household vulnerability increasing with the number of household members, but it may also indicate an overestimation of the Advanced RELE model.

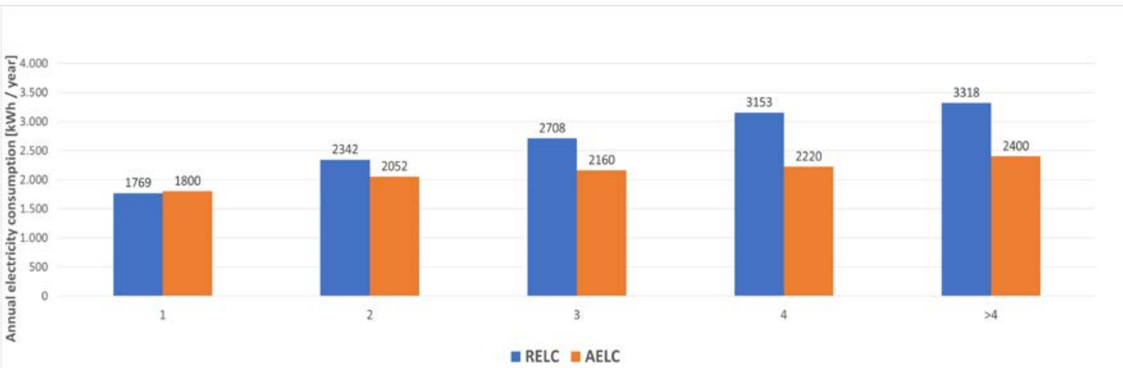


Fig. 3. 15. Median values of the ECODES households' actual and required electricity consumption for the Advanced RELC model [kWh/year] according to household size (average household composition); (reprinted from [263]*)*

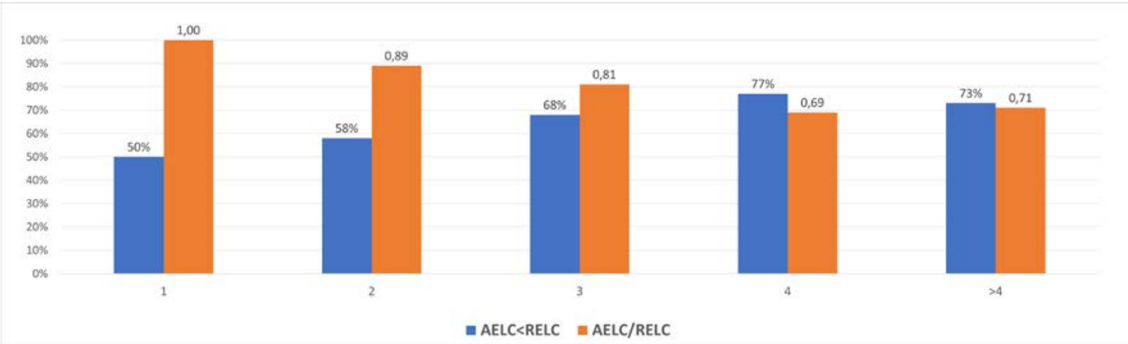


Fig. 3. 16. Values of the indicators of the Advanced RELC model comparison with the ECODES households' sample according to household size (average household composition); (reprinted from [263]*)*

A comparison has also been made by household composition. As there are numerous combinations, only the results of one of the most typical household types, namely households with an unemployed person, are presented below. This is also important to study as it may be a potential vulnerable household. Following the trend of the previous analysis, the median RELC is higher than the actual consumption, 2494 kWh versus 2124 kWh, respectively. The first indicator (AELC/RELC) indicates that the model fits to actual consumption by 0.81 and the second indicator (AELC<RELC) indicating that 65% of households with an unemployed person have lower actual than theoretical consumption and are potentially underconsuming. Fig. 3. 17 shows a breakdown of the ALEC and RELC results for the household with an unemployed person by number of members. It can be noticed that there is a small difference in consumption between actual and theoretical consumption in one-person households. But as the size of the household increases, the difference between theoretical and actual consumption increases, as was the case in the average composition household presented Fig. 3. 15. The same potential explanations could be pointed out: the underconsumption gap of households with an unemployed person increases with household size or that there is an overestimation of the theoretical model. Fig. 3. 18 shows the indicators' results for the household with an unemployed person. The AELC/RELC indicator decrease with the household size, which is related to the results in Fig. 3. 17. On the other hand, the share of household consuming less than their RELC increases with the household size. It has to be highlighted that, in both indicators, there is a slight trend reversal between households with 4 members and those with more than 4 members. When comparing the results for the household with an unemployed person (Fig. 3. 18) with the one for the average composition household (Fig. 3. 16), 1-person and 3-person households show significant worse indicators in the former than in the latter. On the other hand, the results of AELC/RELC indicator are the same in the rest of the household sizes. However, the share of households undeconsuming with respect to their RELC is always higher in households with an unemployed person. This could be a symptom of a particular underconsumption vulnerability of this kind of households.

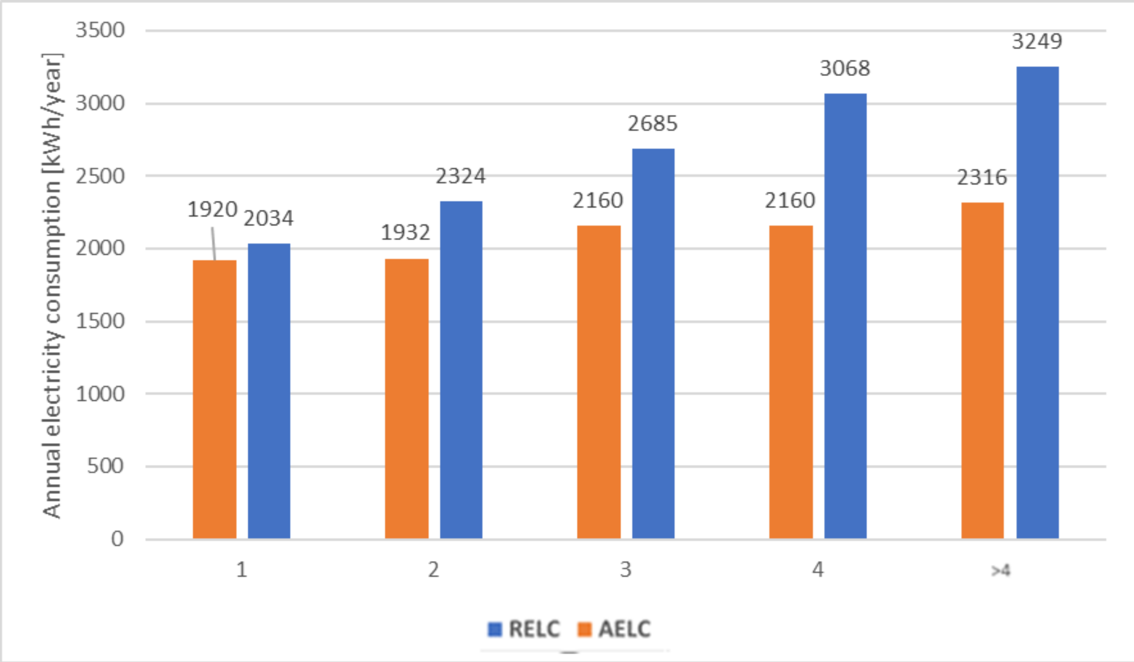


Fig. 3. 17. Median values of the ECODES households' actual and required electricity consumption for the Advanced RELC model [kWh/year] according to household size (household with 1 unemployed person); (reprinted from [263]*)*

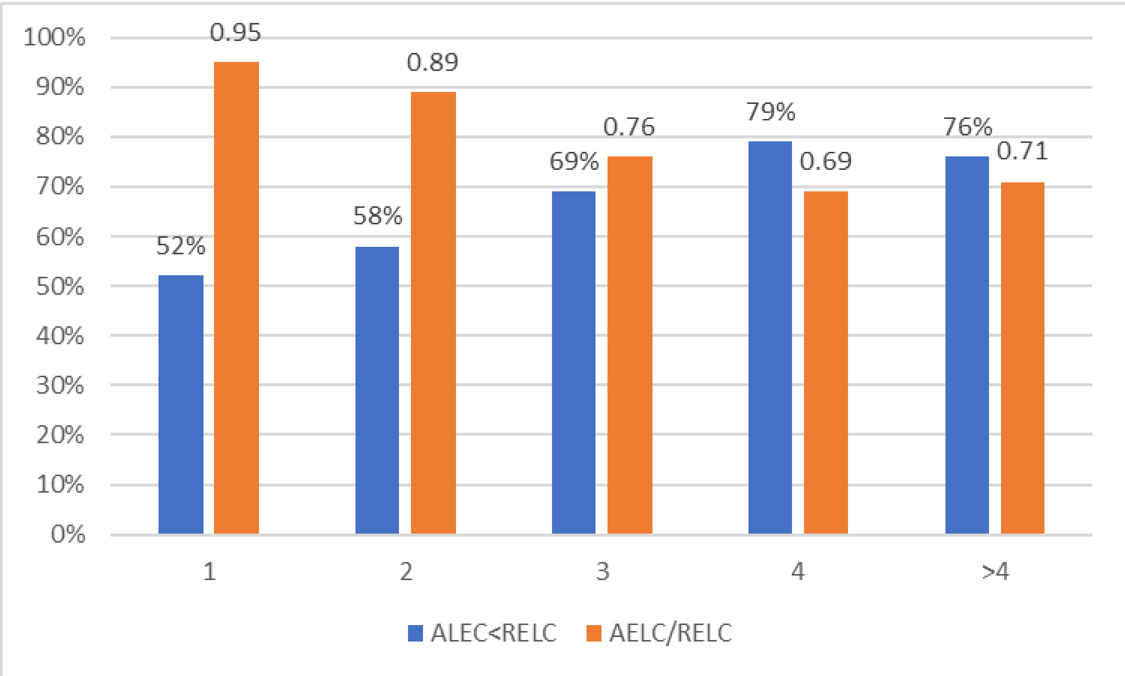


Fig. 3. 18. Values of the indicators of the Advanced RELC model comparison with the ECODES households' sample according to household size (household with 1 unemployed person); (reprinted from [263]*)*

Finally, the required expenditure was estimated by applying the assumptions on the contracted power and energy billing presented in Section 3.2.2.4. Thus, the costs associated with the consumption estimated by the Simplified model have been calculated and are shown in Table 3. 41. It should be emphasised that this estimate of contracted power is merely a hypothesis for calculating electricity expenditure and in no case does it represent a recommendation of contracted power for households.

Table 3. 41. Average RELE [€/year] according to the Simplified model as a function of household size and for the average household

Household size	RELC [kWh/year]	Contracted power [kW]	RELE VPSC 2.0A [€/year]	RELE VPSC 2.0DHA [€/year]
1	2350.38	2.79	491.50	430.12
2	2780.82	3.31	579.36	506.74
3	3233.51	3.84	671.76	587.32
4	3674.64	4.37	761.80	665.84
> 4	4133.76	4.92	855.51	747.56
Average	2997.67	3.56	623.62	545.34

The costs associated with the consumption estimated by the Advanced model have been calculated with the same contracted power (*CP*) assumption used in the simplified model for one occupant (2.79 kW) and adapting the rest of the *CP* to the advanced model (i.e. the *CP* rises proportionally to the consumption increase with the household size in the Advanced Model). Table 3. 42 shows the results of the abovementioned calculation.

Table 3. 42. Average RELE [€/year] according to the Advanced model as a function of household size and for the average household

Household size	RELC [kWh/year]	Contracted power [kW]	RELE VPSC 2.0A [€/year]	RELE VPSC 2.0DHA [€/year]
1	2175.24	2.79	466.66	409.85
2	2897.12	3.72	617.62	541.96
3	3314.70	4.26	704.95	618.39
4	3797.39	4.88	805.89	706.72
> 4	4203.81	5.40	890.88	781.10
Average	3030.32	3.89	645.47	566.34

Focusing on the second model, the RELE for an average household (2.5 members) is about €645 per year with the 2.0A tariff (no time metering or 'flat tariff') and €566 with the 2.0DHA tariff (time-of-use or 'hourly discrimination' tariff). This value is between 467 and 891 euros per year, respectively, for 1 and more than 4 members under a tariff without time discrimination, and 410 and 781 euros per year, respectively, for 1 and more than 4 members with a tariff with time discrimination. Therefore, it is estimated that an average household could save €79 per year by contracting the time-of-use tariff[45].

3.3.2.2 Time discretisation of the electricity consumption

This section shows and discusses the results of the time discretisation of the consumption of the six appliances modelled (assuming the power and cycle time of Table 3. 18) by applying Eq. (3.20) to the TUS data and taking into account the ownership rate of each appliance (see Table 3. 16). The consumption profiles of stoves and oven were considered together because they were both related to the TUS action 'Meal preparation and food preservation'. Indeed, Fig. 3. 19 shows the profile of the average power consumed in a household in Spain due to the use of the stoves and oven throughout the day and according to the household size. It can be seen that the peak of demand is between 1:30 and 2:00 p.m., corresponding to the time of preparation of lunch, and with another smaller peak between 8:30 and 9:00 p.m., corresponding to the time of preparation of dinner.

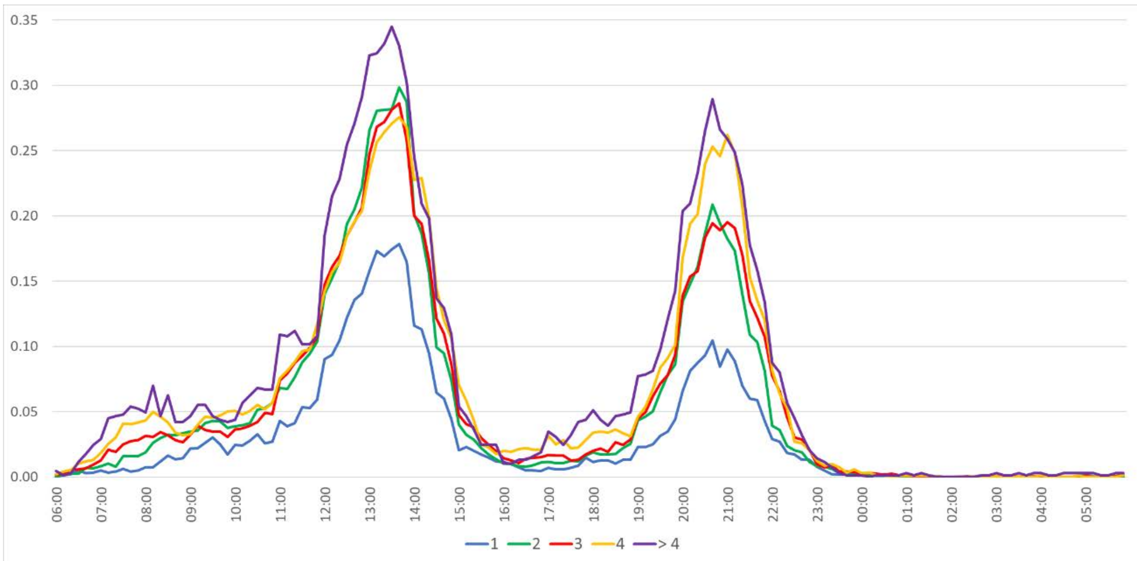


Fig. 3. 19. Average load curve (kW) over the day due to stoves and oven use, according to the household size; (reprinted from [263]*)*

Fig. 3. 20 shows the profile of the average power consumed due to dishwasher use throughout the day and as a function of the number of household members. The TUS action 'Dishwashing' has been considered. It can be seen that the peak demand is between 4:00 and 4:50 p.m., with a smaller peak between 11:00 and 11:30 p.m., corresponding to the times when households finish lunch and dinner respectively. In addition, it can be seen how the dishwasher consumption is staggered as the number of household members increases, with consumption being similar for households with 4 and more than 4 persons.

[45] It has to be noted that this amount refers to the electricity tariffs in force before June 2021.

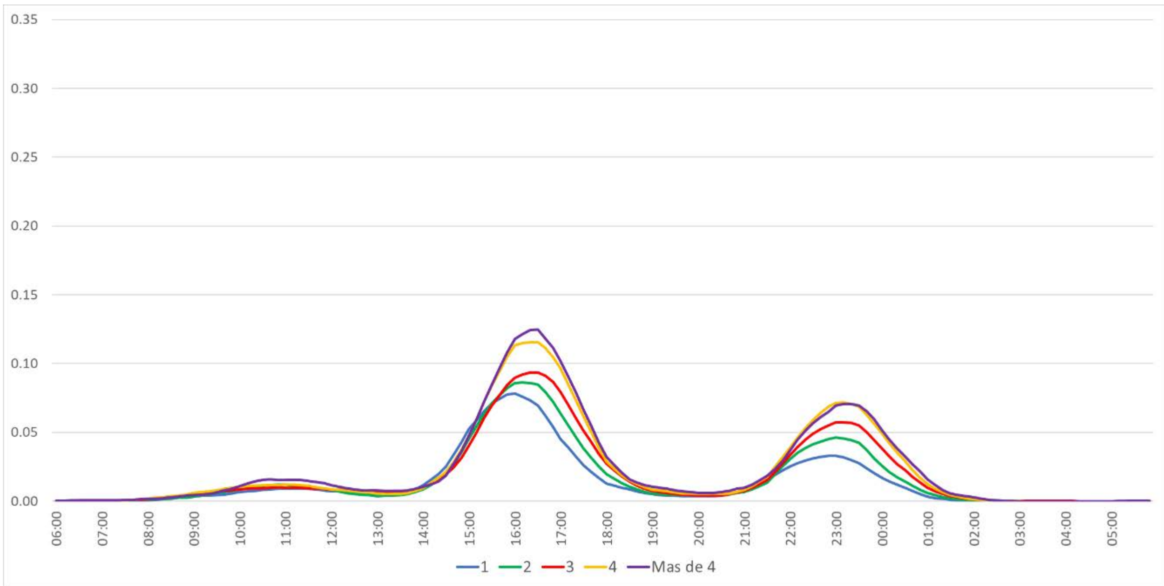


Fig. 3. 20. Average load curve (kW) over the day due to dishwasher use, according to the household size; (reprinted from [263]*)*

Fig. 3. 21 shows the profile of the average power consumed due to washing machine use throughout the day and as a function of the household size. It can be seen that the peak demand is between 12:00 and 1:00 p.m., with a smaller peak between 7:00 and 8:00 p.m.. In addition, it can be seen how washing machine consumption rises as the number of household members increases, with more difference during peak demand.

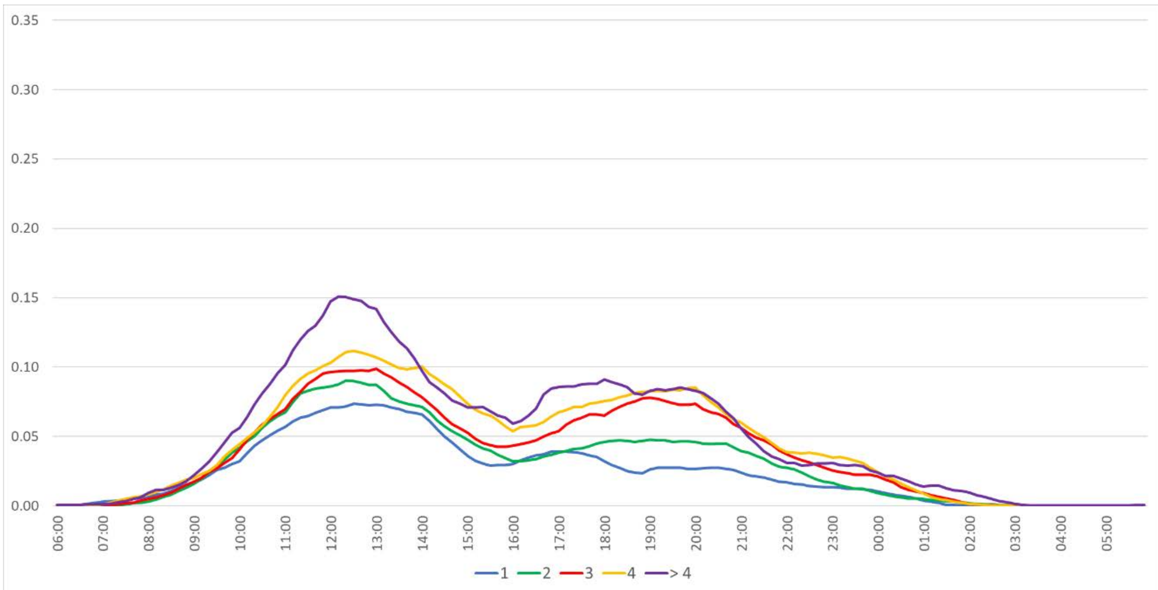


Fig. 3. 21. Average load curve (kW) over the day due to washing machine use, according to the household size (reprinted from [263]*)*

Fig. 3. 22 shows the profile of the average power consumed in Spain due to tumble dryer use throughout the day and as a function of the number of household members. These curves are very similar to those of the washing machine, as their calculation is based on the same survey activity, i.e. 'Laundry'. The only difference is that the peaks are shifted

two hours further apart in the day, with the peak demand being between 2:00 and 3:00 p.m., with another smaller peak between 9:00 and 10:00 p.m..

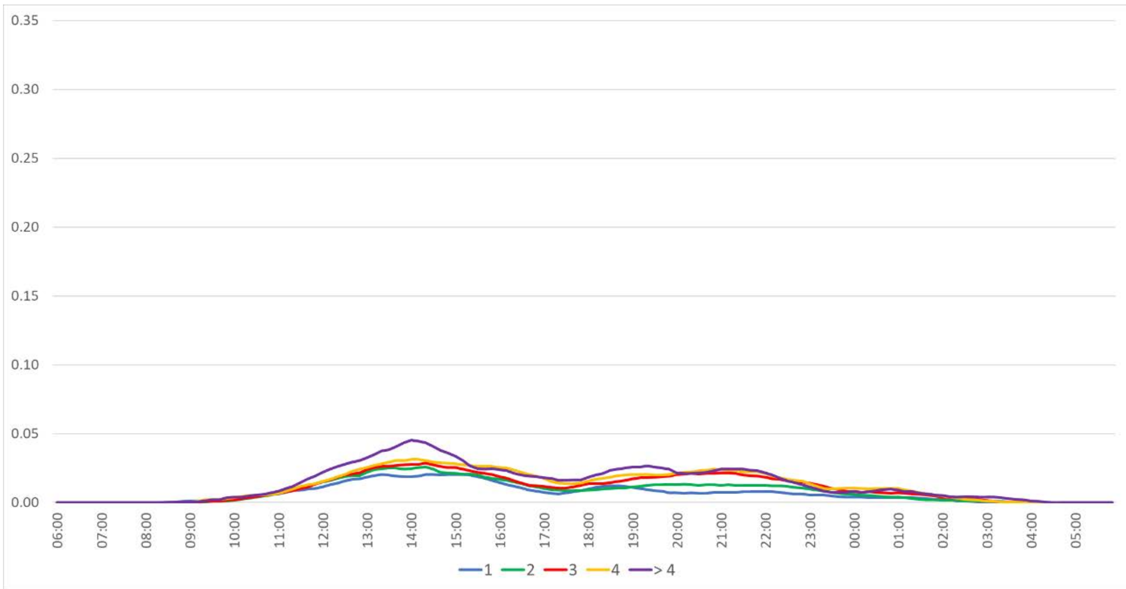


Fig. 3. 22. Average load curve (kW) over the day due to tumble dryer use, according to the household size (reprinted from [263]*)*

To model television consumption, the following TUS activities have been considered: 'Watching television', 'Watching DVDs or videos' and 'Watching television, DVDs or videos, specified or unspecified'. Fig. 3. 23 shows the profile of the average power consumed in Spain due to television use throughout the day and according to the number of household members. It can be seen that the peak demand is around 23:00 hours and a smaller peak between 15:00 and 17:00 hours. It is worth highlighting the consumption of households with two members, which is higher than that of households with three or four members.

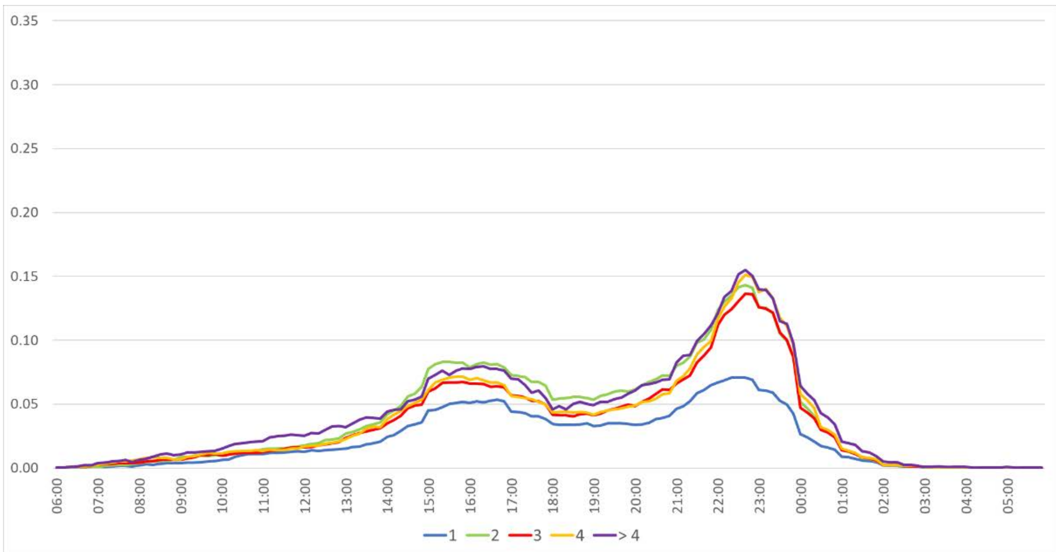


Fig. 3. 23. Average load curve (kW) over the day due to TV use, according to the household size (reprinted from [263]*)*

In the case of computers, data have been collected for four TUS actions, i.e. 'Computer programming', 'Computer-based information retrieval', 'Computer-based communication' and 'Other computer activities, specified and unspecified'. Fig. 3. 24 shows the profile of the average power consumed in Spanish households due to computer use throughout the day and according to the household size. It can be seen that the peak demand is around 11:00 p.m., with smaller peaks between 4:00 and 4:30 p.m., and between 8:00 and 8:30 p.m.. This is the appliance that most varies the shape of the curves according to the number of members. It is worth noting that the consumption of households with 4 members is higher than that of households with more than 4 members.

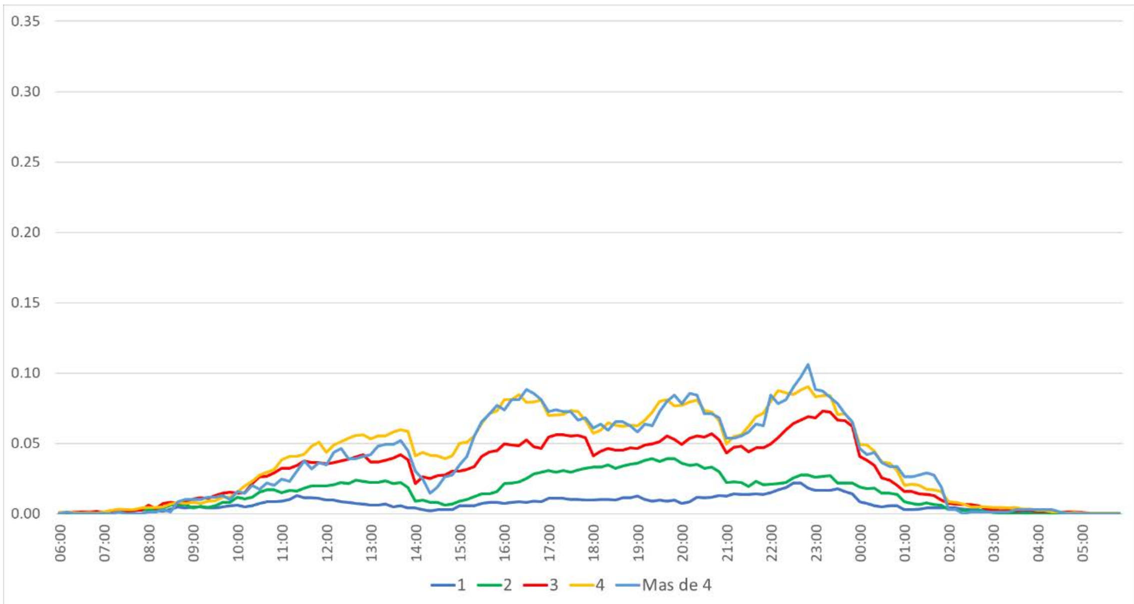


Fig. 3. 24.Average load curve (kW) over the day due to computer use, according to the household size (reprinted from [263]*)*

3.3.3 Software tool for the RENE-estimation

The following sections present the results of the case studies simulated to check the results of the ECODES web tool with the two local tools programmed and introduced in this thesis. These results make it possible to check the correct migration of the tools from the local to web environment and show some interesting insights from the energy efficiency and household behaviour perspective.

3.3.3.1 RWTEE software tool

For each of the combinations shown in Table 3. 25, the resulting values of demand, consumption and expenditure have been analysed. The results of this comparison are shown in Fig. A 17 - Fig. A 29 of Appendix C.

In order to point out some insights from the abovementioned figures, the cases corresponding to buildings prior to 1980 have been selected, and therefore with worse energy certification (between F and G), and as extreme values the A and E winter climate zones. Thus, Fig. 3. 25 shows the RWTEE in these hypotheses for block dwellings. It can be concluded that:

- There is little difference in the cost obtained with the different energy carriers in a mild climate.
- In areas of high climatic severity, two groups of technologies can be distinguished. On the one hand, heat pumps (irrespective of the DHW preparation technology) and central natural gas have the lowest costs, closely followed by central heating gasoil and individual natural gas. LPG, electric radiators and biomass, on the other hand, emerge as the highest energy cost options.
- As for biomass, it should be borne in mind that the focus is being placed on older dwellings (pre-1980), which are associated with low installation efficiency (HSPF=35%). If the biomass boiler were replaced, even with the same insulation, the efficiency would be 70%, which would bring the expenditure into the low-cost group, with a total value of 2,160 € in zone E (4% lower than the average expenditure with a heat pump), as shown in Fig. 3. 26.

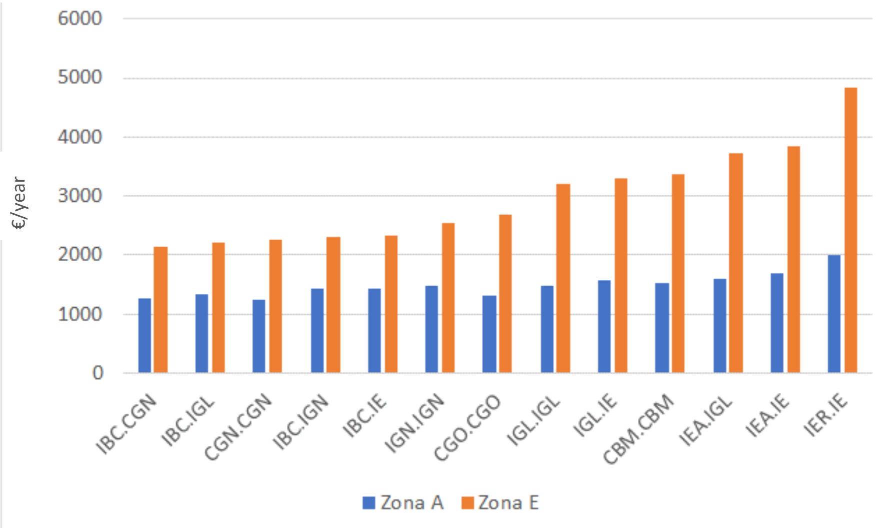


Fig. 3. 25. RWTEE in different configurations in a block dwelling (100 m^2 and 3 persons) in extreme climate zones (A and E) in pre-1980 dwellings – Zona: Winter Climate Zone

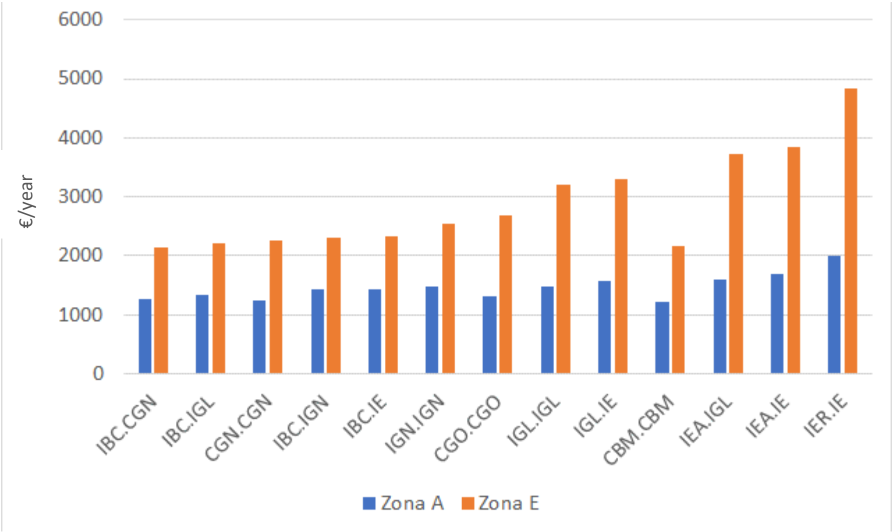


Fig. 3. 26. RWTEE in different configurations in a block dwelling (100 m² and 3 persons) in extreme climate zones (A and E) in pre-1980 dwellings, where the biomass installation (CBM.CBM) is considered refurbished – Zona: Winter Climate Zone.

For single-family dwellings, the trend is similar. The corresponding results are shown in Fig. 3. 27 and Fig. 3. 28.

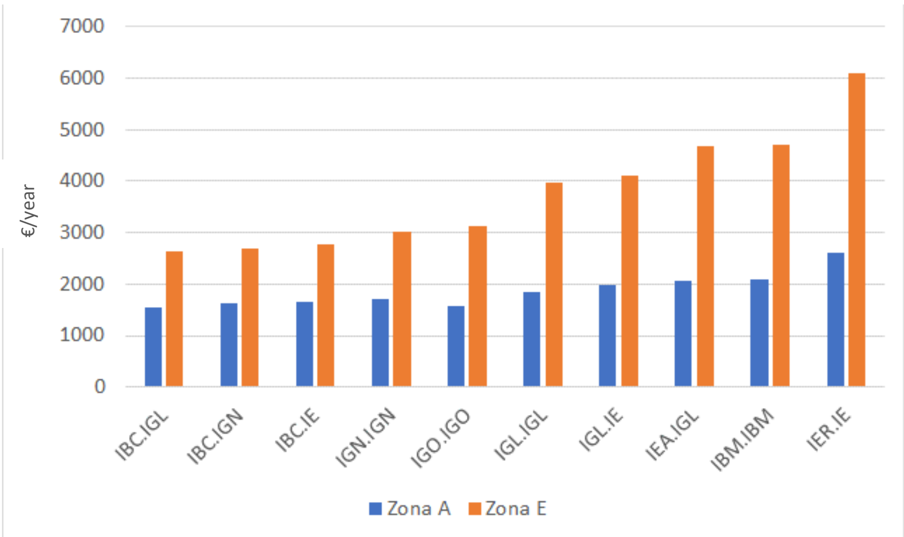


Fig. 3. 27. RWTEE in different configurations in a single-family house (100 m² and 3 persons) in extreme climate zones (A and E) in pre-1980 dwellings – Zona: Winter Climate Zone.

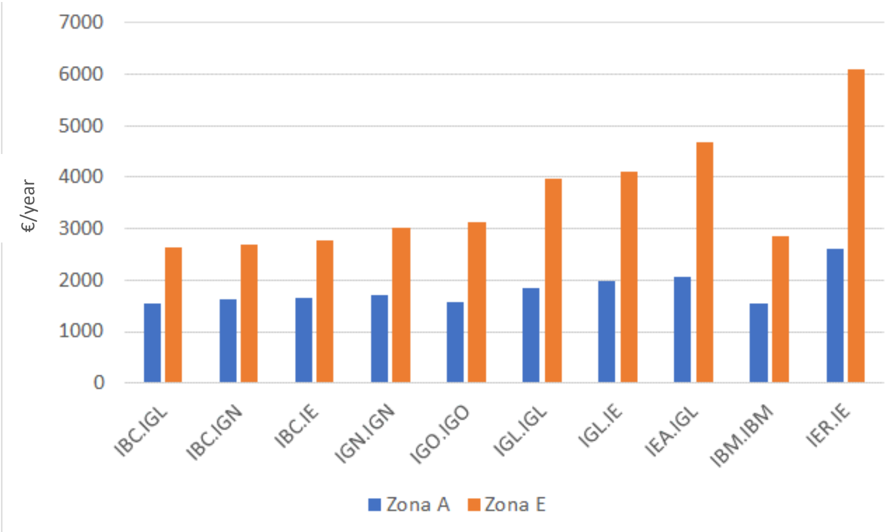


Fig. 3. 28. RWTEE in different configurations in a single-family house (100 m^2 and 3 persons) in extreme climate zones (A and E) in pre-1980 dwellings, where the biomass installation (IBM.IBM) is considered refurbished – Zona: Winter Climate Zone

3.3.3.2 RELE software tool

For each of the cases presented in Section 3.2.3.2.1, the resulting values of RELC have been analysed. For simplicity sake, only the results of the following two checking tests categories are shown in Fig. A 31 and Fig. A 32 of Appendix C:

1. Electrical appliances' ownership comparison: For each appliance, the consumption derived from the three possible inputs (yes, no, don't know) have been compared among each other while selecting 'don't know' for the rest of the appliances. An example of the inputs and corresponding results (outputs) for the stoves' testing are shown, respectively, in Table 3. 43 and Fig. 3. 29.

Table 3. 43. Inputs to check the influence of the stoves' ownership and use on the RELC

Appliance	Input
Stove	Yes/ No/ Don't know
Oven	Don't know
Washing machine	Don't know
Tumble Dryer	Don't know
Refrigerator	Don't know
Freezer	Don't know
TV	Don't know
Computer	Don't know
Dishwasher	Don't know
Mobile phone	Don't know
Tablet	Don't know
Microwave	Don't know

Fig. 3. 29. Influence of the stoves' ownership and use on the RELC

2. Household compositions' comparison: the consumptions of different household compositions (occupation) for each household size have been compared among each other to test the occupation factors. The nomenclature used to identify the household composition and example of the corresponding results (outputs) for the 3-person household are shown, respectively, in Table 3. 44 and Table 3. 45, and Fig. 3. 30.

Table 3. 44. Nomenclature used to identify the household composition in the RELE tool checking

Occupation	Nomenclature
Employed	O
Unemployed	P
Student	E
Retired	J
Pensioner 1	I
Pensioner 2	V
Household chores	H

Table 3. 45. Combinations' legend for the household composition in the RELE tool checking

Xn.Yn.Zn	Combination with:
	n persons of type X
	n persons of type Y
	n persons of type Z

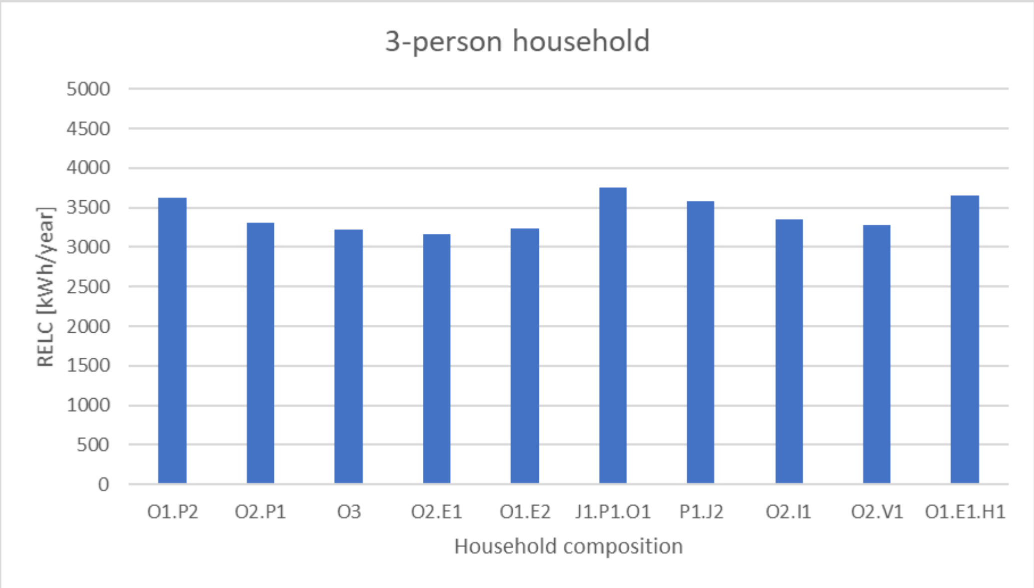


Fig. 3. 30. RELC results for the 3-person household with different household compositions

The former comparison makes it possible to check the impact of the presence (and use) of a certain electrical appliance on the RELC. On the other hand, the latter comparison makes it possible to assess the influence of the household composition on the RELC.

Some insights can be pointed out from the analysis of Fig. A 31 and Fig. A 32 of Appendix C:

- The refrigerator is the electrical machine that most influence a household's RELC (averagely, +32%), followed by the freezer (averagely, +20.5%) and stoves (averagely, +16.6%). Even if the washing machine, the tumble dryer and the dishwasher have a higher power rate, their frequency of use is much lower than the abovementioned appliances' one, thus resulting in a lower impact on the RELC (averagely, +12%, 10.6% and 10.2%, respectively).
- On the other hand, it is difficult to highlight a common trend in the household compositions' comparison. The single-person households composed by an unemployed person or one doing household chores have the higher RELC. In the 2-person and 3-person households, members who are retired, unemployed or doing household chores have the greatest influence on a household RELC. Therefore, it can be deducted that, in these three kinds of households, there are certain occupancies that clearly determine a higher RELC. This trend could be justified by the longer time these categories of people spend at home. On the other hand, it is not possible to point out a clear trend for the 4-person and 5-person households because the higher number of members determines a greater number of composition combinations, which makes the household energy behaviour more complex to analyse.

3.4 Conclusions

3.4.1 Research insights

According to the IDAE report on 2018 Spanish residential demand [55], the final energy consumption for heating and DHW was more than 59% of the total final domestic energy consumption. Therefore, the provincial analysis presented in Section 3.2.1.2 has been focused on the quantification of the cost to attain the domestic 'winter thermal energy needs', i.e. the Required Winter Thermal-Energy Expenditure (RWTEE). This model, which was selected as reference in the SNSEP, assesses the household theoretical expenditure required to ensure the indoor environment comfort during winter (heating) and to provide an adequate level of domestic hot water (DHW), considering climate zone, dwelling characteristics, and household size. The RTEE analysis has been carried out at the provincial level, starting from the calculation of the annual required demand for heating and DHW for each of the 8,131 Spanish localities. This calculation shows that Spanish families' heating-and-DHW needs require an average annual cost of €1,055. However, this amount varies considerably depending on the climate zone and the overall dwelling energy efficiency (i.e. considering both the building thermal insulation and the performance of thermal systems). Indeed, the average before tax RWTEE in the coldest province (León, E zone) is 2.7 times higher than the second warmest-province's one (Cadiz, A zone) and six times higher than the warmest ((almost) null heating demand) province (Las Palmas, α zone). On the other hand, the difference between the RWTEE values in the two scenarios (after tax and before tax) is significantly smaller in the Canary Islands, Ceuta and Melilla, because in these locations, the VAT values are much lower than the rest of the country. This result also highlights that, in the Spanish mainland, fossil fuel taxes have a lower weight in the energy expenditure than the VAT.

In the first application to the ECODES households' database, the theoretical thermal cost to maintain comfort conditions in winter and provide DHW to these households has been evaluated, i.e. the RWTEE. Up to twenty configurations have been studied to cover this cost, combining central and individual installations with different types of energy carrier (natural gas, LPG, heating gasoil and electricity). By applying each of these to the almost 3500 households for which valid data is available, the configurations that minimise the theoretical heat cost have been determined. Centralised natural gas most frequently achieves the minimum RWTEE in all climate zones, with the next option being individual natural gas in areas with medium (C) to severe (E) winters or individual heating gasoil in areas with milder winters (A and B). In zone A, with low heating demand, electric storage heaters and individual LPG boilers for DHW also stand out. With regard to the factors influencing the minimum required thermal-energy costs, the following insights can be pointed out:

- The specific RWTEE [€/(m^2- year)] depends on the insulation level of the dwelling and this dependency is more significant in the coldest winter climate zones (between B and E). Moreover, this expenditure is 60% lower in dwellings built according to the new Building Technical Code regulation (i.e. after 2007, with energy rating between D and E) than in dwellings built before 1981 (≤1980), when there was no clear regulation (rating between F and G). In areas with very mild winters (α and A) this trend is not verified due to the predominance of DHW in thermal consumption.

- The 'absolute' RWTEE [€/year] depends linearly on the surface area of the dwelling in climate zones B to E. With poor insulation and for a dwelling of 100 m^2 the minimum theoretical thermal expenditure varies between 873 (zone B) and 2110 (zone E) euros per year.
- The number of occupants only has a significant influence in zones with very mild winters (α and A), due to the predominance of DHW preparation over heating coverage.

Some insights and recommendations on how to apply the RTEE model for policy design and impact assessment are presented in Chapter 6.

On the other hand, the objective of the section 3.2.2 and 3.3.2 is to quantify the electricity needs of Spanish households and to enhance the characterization of the electricity consumption in vulnerable households. In order to do this, two models are presented: the Simplified model and the Advanced model. Both models estimate the Required ELectricity Consumption (RELC) to meet domestic electricity needs (lighting, cooking and electrical appliances), according to the most representative household characteristics. In the former, the dwelling size and the number of members (household size) are the variables used to characterise the consumption, while in the latter an additional variable is included to consider the household composition. A bottom-up approach is used to simulate the electricity consumption in both models. Three key parameters of common electrical appliances determine the consumption, i.e. power, frequency of use and usage factor, which vary with season (winter/summer) and household size. Additionally, the dwelling size is also considered for estimating the lighting consumption in both models and adjustment factors have been included in the Advanced model to take into account the change in consumption due to the household composition. Moreover, in the latter model, the consumption of the most 'time-dependent' appliances have been modelled by using data from the TUS, thus discretising its consumption throughout the day.

Then, the RELC model is compared with reference studies and applied to the households' database of the Spanish NGO ECODES. The main conclusions that can be drawn from the work carried out can be summarised as follows:

- The average consumption estimated by the advanced model does not deviate more than 10% above or below the different references used.
- Although the methodology used to find the electricity consumption of The Simplified and Advanced models is different, a quite similar annual consumption value is obtained due to the fact that they use the same appliances' power assumptions.
- The analysis of the Advanced Model shows that households with employed people, students and those in 'other inactive situations' in general consume less electricity. Households with unemployed people, retired people, pensioners on permanent incapacity or disability, widows' or orphans' pensioners and those who carry out household chores in general consume more energy.
- The Advanced model has been applied to the database of the 'Not a Household Without Energy' programme of ECODES, with the aim of comparing the

theoretical consumption of the model with the actual consumption declared by each household. This 'evaluation' shows that the model reproduces the actual consumption of households relatively well, especially in single-person households; however, as the number of members increases, this adjustment decreases, mainly in households with four members. This may be mainly due to the fact that this database consists mostly of vulnerable households, but it could also be a symptom of the model slightly overestimating the electricity consumption. On the one hand, as pointed out in a previous study on this sample, the families in the ECODES database are mostly vulnerable households, thus they tend to use appliances less than 'average income families' for concern about the bill. On the other hand, the difference in consumption is not very high because they usually own inefficient appliances with higher consumption. Moreover, the above comparison shows how the model can detect a higher vulnerability of households as the number of members increases.

- The electricity expenditure for an average household (2.5 members) is estimated at around €624 per year with a tariff without time discrimination, while those who opt for a tariff with time discrimination will spend approximately €79 less, i.e. €545, following the tariff scheme in force until June 2021[46].
- Eventually, the model presented might help energy-poverty stakeholders to better understand vulnerable households' electricity needs and to enhance the current social tariff for electricity.

These conclusions suggest two potential actions to combat energy poverty:

- The first one is to reform mitigating measures such as the social tariff schemes so that they depend on the characteristics of the dwelling, and the occupation of the members. In this way, the aid provided to households will be more personalised and will be more effective in the fight against the energy vulnerability of these households.
- Measures to improve the energy efficiency of households through the replacement of electrical appliances that are over-consuming, either because they are old or because they are damaged.

Furthermore, a RWTEE local tool has been developed in EES so that households, volunteers or workers from NGOs can check whether the household consumption is above or below the theoretical expenditure and identify people living in discomfort. The results of this tool show that there is little difference in expenditure among the different energy carriers in a mild climate. On the other hand, in areas of high winter climate severity, heat pumps and centralised natural gas boilers have the lowest RWTEE. Moreover, an Advanced RELE local tool has been developed in Excel so that households can check whether their real expenditure is above or below the theoretical one and third parties' users can help vulnerable households to understand which electrical appliance are more energy intensive. The tool testing's results show that refrigerator, freezer and stoves are the electrical appliances that most contribute to a household's RELC.

[46] This result takes into account prices until September 2021. In the particular situation at the end of 2021 with very high energy prices, these results would clearly be different (see, for example, [198].

Moreover, members with occupations that involve more time spent at home, i.e. unemployed, retired and 'household chores' people, are the ones who consume the most. Both tools make it possible to compare the household required expenditure with the real one, thus potentially identifying households in underconsumption (see Chapter 4 for a deep analysis on this issue).

These two local tools were then migrated in a web tool host in the Not a single household without energy web page (ECODES' program) to provide an open-access energy audit instrument to Spanish households (specially the most vulnerable ones). Moreover, the models were migrated also in a premium version of the ECODES tool, i.e. ENERSOC, which works as a households' monitoring tool for energy poverty stakeholders (NGOs workers and volunteers, Social services, etc.).

3.4.2 Limitations and further work

The RTEE model shows some methodological limitations stemming from the simplifying assumptions. The Required Thermal-Energy Demand (HVAC and DHW) was assessed using a stationary method established in the official regulation. This method does not consider the change of the involved parameters, such as HVAC installations' operation, i.e. consumption patterns, which might vary because of the personal and changing nature of these needs [264]. However, the influence of basic parameters such as dwelling size and household size on HVAC and DHW needs was reflected in the calculation of the RTEE. On the other hand, both the provincial analysis and the application to vulnerable households presented in this chapter have not considered the cooling demand, given that in 2018 the final consumption of the space cooling service in Spain was only 1%[47] of the final energy consumption of the residential sector [55]. Nevertheless, it is included in the regional analysis presented in Chapter 4, given the growing importance of air conditioning in summer, especially in the hot areas of Spain. Moreover, the assessment of the cooling demand was further investigated in an international collaboration paper published by the author and several European scholars within COST Action 'European Energy Poverty: Agenda Co-Creation and Knowledge Innovation' (ENGAGER 2017–2021, CA16232) [265]. This paper analyses the effects of change in temperatures in the residential sector cooling demand in 2050 for a case study of nineteen cities across seven countries: Cyprus, Finland, Greece, Israel, Portugal, Slovakia, and Spain, by estimating cooling degree days and hours (CDDs and CDHs) and using both fixed and adaptive thermal comfort temperature thresholds.

Regarding the analysis of the RWTEE in vulnerable households, the emergence of gasoil as the cheapest option in some climate zones is due to the fact that the study is based exclusively on current market tariffs, which do not include environmental externalities. Therefore, this and other externalities (such as impact on health and wellbeing) may be

[47] This low percentage is also due to the reduced ownership of cooling systems in Spain (according to the most recent official statistics, only 35.5% of households own air-conditioning units [265]) and the fact that cooling is still considered a luxury.

analysed in further work to consider citizens' wellness and the society's just transition to carbon neutrality.

Regarding the RWTEE local and web tools implementation, the reference framework for the developed model is energy poverty. This means that when determining the thermal installations and seasonal efficiencies, constraints have been introduced in line with this framework. In this sense, the tool is considered valid for assessing the theoretical energy consumption of a household, but care must be taken if it is used to assess the reduction of energy consumption if improvements are made. For example, an energy renovation of the thermal enclosure that would improve the dwelling energy rating is reproducible, as it is a parameter introduced in the model, but an improvement in heating and DHW systems (e.g. replacing gas radiators with underfloor heating) cannot be evaluated.

The chosen installations respond to what is considered usual in vulnerable dwellings, in order to obtain the theoretical expenditure that should be incurred in order to maintain the comfort conditions established by the regulations with the current means. In this sense, the efficiencies of heat pumps are the average of conventional equipment, not state-of-the-art, centralised or with sophisticated terminal installations. In this sense, the feasibility of replacing the current system with a centralised air-water heat pump is studied in Chapter 5. Moreover, it has already been seen that the efficiency of biomass has been made dependent on the age of the dwelling, which makes it necessary to update the energy rating for the tool to consider a boiler upgrade. Ultimately, the tool is intended to facilitate the use of the assessment of a current situation, not to assess the effect of thermal systems' improvements. Moreover, the thermal modelling excludes the demand for air-conditioning in summer. This limitation will be resolved in future projects.

Regarding the RELE model, further work is ongoing [23] to take into account the prospect of behavioural changes (throughout the day or between weekdays and weekend), in relation to flexible (time-of-use) tariffs (e.g. the new Spanish electricity tariff structure in force from 1 June 2021), thus estimating the potential savings in household energy bills. Moreover, further work could assess the impact of subsidized energy appliances exchange programs (i.e. replacement of the old appliances with energy efficient appliances with lower electricity consumption) on the vulnerable households' electricity expenditure. In this line, the EU energy efficiency labelling scheme (both the old and the new one) is being introduced in the Advanced model to study the difference in consumption depending on the energy class of the appliances. On the other hand, improvements are being planned for the modelling of some of the household appliances, such as the fridge, which has been modelled with constant consumption that does not correspond to the reality, or the lighting, which can vary according to geographical position. Finally, the analysis of RELE tool checking's results point out the need of further research on the influence of energy behaviour and economics in household's RELC, especially in larger families that are more complex to model.

4. A NOVEL METHODOLOGY TO MEASURE HIDDEN ENERGY POVERTY

Section 2.2.6 points out that the ‘traditional’ metrics are usually focused on the *disproportionate expenditure* dimension of energy poverty. On the other hand, the circumstances of (self-)imposed energy *underspending* have not been sufficiently addressed in the reviewed indicators. This explains the term assigned to this energy vulnerability dimension, i.e. ‘hidden energy poverty’. Thus, this chapter[48] presents an absolute approach to measure hidden energy poverty by introducing two conditions to be verified for identifying a household as energy poor. The first condition makes it possible to estimate the share of households with low absolute energy expenditure (underconsumption) by applying a threshold based on the RENE model presented in Chapter 3. The second condition, based on an income threshold, filters (from the first sample) the households who are underconsuming because of an affordability issue, i.e. it identifies the share of families or individuals in hidden energy poverty. The above methodology is applied to the Spanish Household Budget Surveys (HBS) of four consecutive years (2016-2019) to estimate the extent and depth of this energy poverty dimension in the case study country.

The structure of the chapter is as follows. Section 4.1 introduces the topic and the main research questions addressed in this chapter. Section 4.2 presents the methodology proposed to identify underconsumption and hidden energy poverty and shows some initial findings. Subsequently, Section 4.3 analyses the results of the two indexes, with a special focus on the HEP indicator, and shows the main insights of the sensitivity analysis. Finally, Section 4.4 brings up some conclusions and policy recommendations in light of the chapter’s findings.

4.1 Introduction

Among the income-expenditure (objective) indicators, the ‘traditional’ metrics, summarised in Section 2.2.1, have been usually based on a disproportionate expenditure approach, which quantifies the so-called ‘measured energy poverty’ [124]. This term refers to households whose energy expenditure is considered too high compared to their income, i.e. households that spend too much of their disposable income on energy. On the other hand, low-income households often apply coping strategies to reduce their consumption [125–128], such as 'switching on heating only in one room, wearing more clothes or slipping under the duvet even during daytime' [125]. Energy spending reduction was identified in [126] as the primary strategy adopted by poor people to cope with the lack of financial resources. The term 'hidden energy poverty', introduced by

[48] This chapter is based on the paper ‘The dark side of energy poverty: who is underconsuming in Spain and why?’, written by the author, José Carlos Romero, José Ignacio Linares, Eva Arenas, María Asín, Efraim Centeno and published in Energy Research & Social Science [136]. It also includes quotations from the mentioned article.

Meyer et al. [124], refers to the circumstance of '(self-)imposed restriction' of energy consumption, which is the most difficult to identify and tackle through existing energy poverty indicators and assistance programs. Indeed, this 'hidden face' of energy poverty has not been sufficiently addressed neither in measurement nor in policies [124], [18].

The underconsumption approach makes it possible to detect the systematic ‘false negative’ cases of the ‘disproportionate expenditure’ indicators, i.e. households with low energy expenditure. Nonetheless, among these ‘underconsuming households’, it is crucial to identify the ones that reduce their energy expenditure because they cannot afford basic energy services, thus suffering from hidden energy poverty. Considering the state of the art presented in Section 2.2.1.1, using absolute thresholds makes it possible to assess energy poverty rather than energy inequality, the latter being the most common outcome of metrics based on relative thresholds. However, modelling energy costs is a complex task because of the diversity of influence factors to consider and, therefore, the numerous simplifying assumptions that have to be introduced. According to Sovacool et al. [266], simplified theoretical models ‘abstract from real-world complexities and focus on key mechanisms, either conceptually or by combining theoretical assumptions with empirical data’. In this regard, the absolute approach studies described in Section 2.2.1.1 either used mixed relative-absolute thresholds, e.g.[132], [133], [134], or focused only on a single energy service [135]. Therefore, to the best of the author’s knowledge, the literature lacks a full absolute hidden energy poverty approach, which could identify the extent and the depth of this social issue by comparing households’ actual energy expenditures with their required ones. In this regard, this chapter proposes using a theoretical model for estimating energy consumption and expenditure as a transparent and versatile tool to serve the policy-maker or other relevant stakeholders (who hold ultimate responsibility for fixing its key parameters). In any case, this is not intended to be used as a ‘substitute’ for the invariably-complex reality.

Regarding the Spanish case study, presented in Section 2.2.5, researchers from the Association of Environmental Sciences [39] and the research centre Economics for Energy [20,21] characterized the energy poverty phenomenon in an integrated way using different metrics. Nevertheless, in the abovementioned research works and, in general, in all studies concerning Spain, the HEP indicator is not considered or does not include a characterisation of the domestic theoretical energy expenditures. From the policy perspective, the SNSEP (summarised in Section 2.4.5) attempts to monitor hidden energy poverty by using the EPOV’s M/2 indicator, which, as mentioned in Section 2.2.1.1, focuses only on ‘relative’ underconsumption that could be related to circumstances other than lack of affordability.

Therefore, this chapter aims to fill the abovementioned gaps (i.e. the lack of a whole absolute HEP methodology and the characterisation of this phenomenon in Spain and generally in the EU) by presenting an absolute approach to measure hidden energy poverty. This work might help stakeholders to answer two critical outstanding questions (being the former the necessary first step to answer the latter):

1. *Who is underconsuming?* The first objective is defining an absolute energy expenditure threshold below which a household’s actual energy expenditures are ‘objectively’ too low to achieve a ‘necessitated level of energy services’ [267].

Thus, a household is underconsuming if their actual energy expenditures are lower than their theoretical threshold.

2. *How to assess the share of households in hidden energy poverty?* The second objective of this chapter is selecting a criterion to eliminate false positives, i.e. households that have low actual energy expenditures for reasons other than lack of affordability, such as high energy efficiency of the housing[49]. This could make it possible to classify as 'in hidden energy poverty' only the households that cannot afford to satisfy their required energy needs.

Therefore, this chapter presents a new methodology to characterise the extent (share of households in hidden energy poverty) and the depth (energy poverty gap) of this social issue. The first query (*Who is underconsuming?*) is addressed by defining an absolute energy-costs' threshold based on the Required ENergy Expenditure (RENE) model and estimating the share of households whose actual energy expenditures are too low compared with their threshold ('Low absolute energy-expenditure' indicator). Thereafter, an income threshold is introduced as a proxy to eliminate false positives, thus identifying households in hidden energy poverty (HEP indicator). Moreover, a sensitivity analysis was carried out to determine the impact of changing several primary parameters of the absolute energy expenditure threshold on the HEP results. Based on this, an alternative 'adjusted to household's comfort strategy' scenario is presented to address the potential overestimation of households' required energy expenditure in the base case scenario. Finally, the HEP indicator is calculated by using an alternative income threshold. The above methodology is applied to the Spanish Household Budget Surveys (HBS) of four consecutive years (2016-2019). However, the reference year of all post-analyses is the latest in the series. This macro-level analysis characterises hidden energy poverty in Spain and could be replicated in other developed countries. Moreover, the results and conclusions might advise policymakers in targeting policies and prevention programmes.

4.2 Methodology and preliminary results

4.2.1 An absolute energy expenditure threshold for energy poverty studies

Sections 2.1.1 and Chapter 3 point out that accurate knowledge on the connection between household characteristics and energy consumption is crucial. This could be used not only for designing appropriate policies and programmes to optimise domestic energy consumption, but also for a better characterisation of energy poverty (as mentioned in the SNSEP). Indeed, the latter is the main objective of this section, i.e. defining an absolute energy expenditure threshold that can be used for hidden energy poverty studies. In order to do that, the energy costs of households in the Spanish HBS[50] was modelled.

[49] The Spanish HBS does not give the energy rating of the dwelling but only a proxy of the construction year (see Appendix D). Therefore, basing the calculation only on the construction age's proxy does not make it possible to consider the dwelling's energy class and/or capturing possible retrofitting.

[50] The structure of the Spanish HBS is similar to the one of equivalent surveys in other Member States, which makes this model 'adaptable' to other countries. However, before adapting the model, the following

Nevertheless, this survey lacks of some household features needed for the model, thus this work substitutes them with 'proxies', e.g. the residence's region instead of the locality (for more details, see Appendix D). Thus, the methodology presented in this chapter applies an 'HBS-adaptation' of the RTEE model presented in Sections 3.2.1 and the Simplified RELE model described in Section 3.2.2. These two models make it possible to assess the Required Energy Expenditure (RENE) of each HBS household, i.e. the theoretical energy costs that a household would have to pay for to meet its required energy needs, including both thermal energy (heating, cooling and DHW) and electricity (lighting, electrical appliances and cooking [92]) uses. The RENE is estimated according to eight input variables: (a) region[51]; (b) household size (number of members); (c) dwelling typology (block dwelling or single-family house); (d) dwelling size; (e) dwelling energy-efficiency rate (according to its 'aggregated-construction-period'); (f) type of thermal energy carrier; (g) national ownership rate of each electrical appliance in households; (h) energy prices and taxes. The HBS variables used for the calculation and the corresponding inputs of the model are shown in Table A 24 of Appendix D.

4.2.1.1 Adaptation of the RTEE model to the Spanish Household Budget Survey

The RTEE model presented in Section 3.2.1 considers the theoretical costs in heating/cooling (HVAC) and domestic hot water (DHW). That methodology was used (as a novelty of this chapter, the cooling demand was integrated in the household and regional level analysis) to estimate the annual specific thermal demand for the three services. Therefore, the RTEE model presented in this chapter is an adaptation of the model presented in Section 3.2.1 and is based on the requirements of the Spanish regulation (Spanish Technical Code for Building Construction, CTE 2019). The three most significant assumptions made in HVAC demand calculation according to the CTE 2019 are the following ones: (1) it sets a baseline comfort temperature of 20ºC; (2) it assumes that 100% of the dwelling's floor area is conditioned, (3) it supposes a 24h/7d occupancy. Moreover, the required HVAC demand is based on climate data of a standard year, which are provided by the Spanish building regulator as complementary files of the CTE. Appendix E presents the details of the methodology used to estimate the annual specific thermal demand.

Firstly, it is necessary to determine which winter and summer climate zones (described in Section 3.2.1) each household belongs to (HVAC demand), as well as the network water temperature (DHW demand), both set according to their province of residence and the altitude of the locality (CTE 2019). As mentioned before, due to the lack of information on the household's locality in the HBS, the specific thermal energy demand was calculated as a regionally weighted parameter (see Appendix E). The provincial specific-demand values for heating [kWh⁄(m² year)] and DHW [kWh⁄(person year)],

country features should be analysed: socio-demographic characteristics, building's stock and regulation, energy prices and climatic characteristics.

[51] This input is used as a proxy of the Spanish climatic features, i.e. winter climate zone, summer climate zone, and network water temperature. See Appendix E for further explanations.

estimated using the methodology presented in Section 3.2.1.2, were weighted by number of inhabitants to calculate the regional specific demand values. On the other hand, the specific cooling demand [kWh/(m² year)] (which was not considered in 3.2.1.2) was estimated for the 8,131 Spanish localities and then, regionally weighted. Secondly, households were classified according to the dwelling type (block dwellings or single-family houses, see Table A 24 in Appendix D). Thirdly, the energy efficiency parameter (EEP in Section 3.2.1.2), which mainly depends on the insulation level of the dwelling's thermal enclosure, was set for each household according to the HBS aggregated construction period. In this regard, the HBS indicates whether the building was constructed 'less than 25 years ago', or '25 or more years ago'. However, this classification differs from the construction periods defined in Section 3.2.1.2. Therefore, in order to fix the value of the EEP of each HBS household, it was necessary to adjust the calculation presented in Section 3.2.1.2 to the HBS variable. In addition, the EEP values (see Appendix E) were updated based on the 2019 IDAE report on energy performance certificates [268].

Subsequently, the specific required HVAC demand [kWh/(m^2 year)] for each household was assessed according to the region of residence, the dwelling type and its year of construction (see Appendix E). A similar procedure was applied to obtain the specific DHW demand [kWh/(person year)] of each household according to their region and dwelling type. Thereafter, the values of required demand for HVAC and DHW [kWh/year] of each HBS household were calculated by multiplying the specific demand values, respectively, by the dwelling size or the household size (obtained from the HBS variables shown in Table A 24).

The required consumption for heating, DHW and cooling was then calculated as the ratio between the required demand and, respectively, the seasonal performance factor for heating (HSPF) and DHW (SPF), and the Seasonal Energy Efficiency Ratio for cooling (SEER). The values of HSPF and SPF are set according to the energy carrier and the type of installation (individual or central). However, as a proxy, all households were considered to have individual systems (both for heating and DHW) because of three main reasons: (1) there is no information available in the HBS to know whether a household has central or individual systems; (2) the values of HSPF and SPF are similar (see [269]) so using this assumption does not change the results to a large extent; (3) [269] estimates that only 10% of Spanish households have a centralised installation serving a group of dwellings. Moreover, five types of energy carriers for heating and DHW are distinguished (natural gas, LPG, heating gasoil, biomass[52] and electricity) whose seasonal average efficiency is given according to the values shown in Table A 33-Table A 34 and Table A 37. Secondly, for the SEER calculation, air-to-air units were considered, as this is the most common air conditioning system in the Spanish residential sector (according to the IDAE [57], they are 92% of the installed air conditioning systems). Table A 35 and Table

[52] In the HBS biomass and coal are included in a unique energy carrier option, i.e. 'solid fuels'. Since the use of coal for reason other than cooking in Spanish households is limited (in 2019 only 4.2% of households declared expenses on this fossil fuel compared to 10.2% declaring expenses on biomass), the 'solid fuels' option was considered as biomass (see Table A 24).

A 36 show the SEER values used for the different summer climate zones. Starting from that, a weighted average of the SEERs of all localities in each region (according to the number of inhabitants of each locality) was calculated to assign a weighted regional-average SEER.

Finally, to assess the costs allocated to the required thermal energy consumption, the energy-price's terms were set according to the type of energy carrier and the year in question. Particularly, the yearly average regulated-market-prices and the regional tax rates (see Appendix F) were applied to the required consumption of each service. Therefore, the sum of the required expenditure for heating, cooling and DHW determines the household's RTEE.

4.2.1.2 Analysing the preliminary results of the adapted RENE model

The RENE of each HBS household was finally assessed by summing up their RTEE and RELE. Fig. 4. 1 condenses the components and parameters involved in the calculation of the RENE.

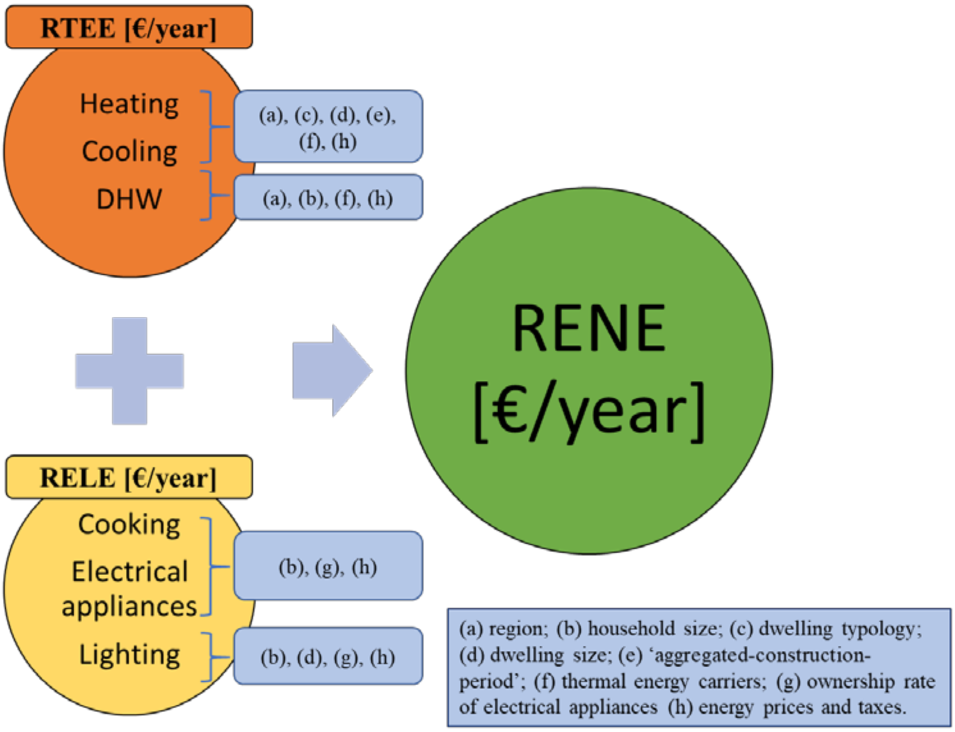


Fig. 4. 1. Components and parameters involved in the calculation of a household's RENE (reprinted from [136]*)*

Therefore, as a reference for the national results, Fig. 4. 2 shows the 2019 average required expenditure for each energy use considered in the model. The RELE is displayed in an aggregated form because it was calculated from the required electricity consumption as a whole.

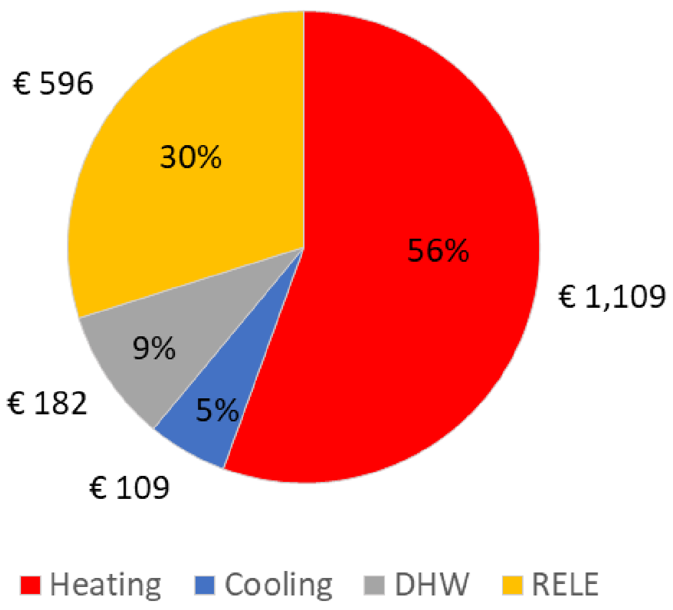


Fig. 4. 2. Average required annual expenditure [€/year] and costs' share [%] for each energy use in the 2019 HBS (reprinted from [136]*)*

The weighted national average RENE for 2019 were €1,997 and the energy use that most impact the household's expenditures was heating (56%), followed by the appliances included in the RELE (30%). Fig. 4. 3 shows the average RENE results for the four years of the series.

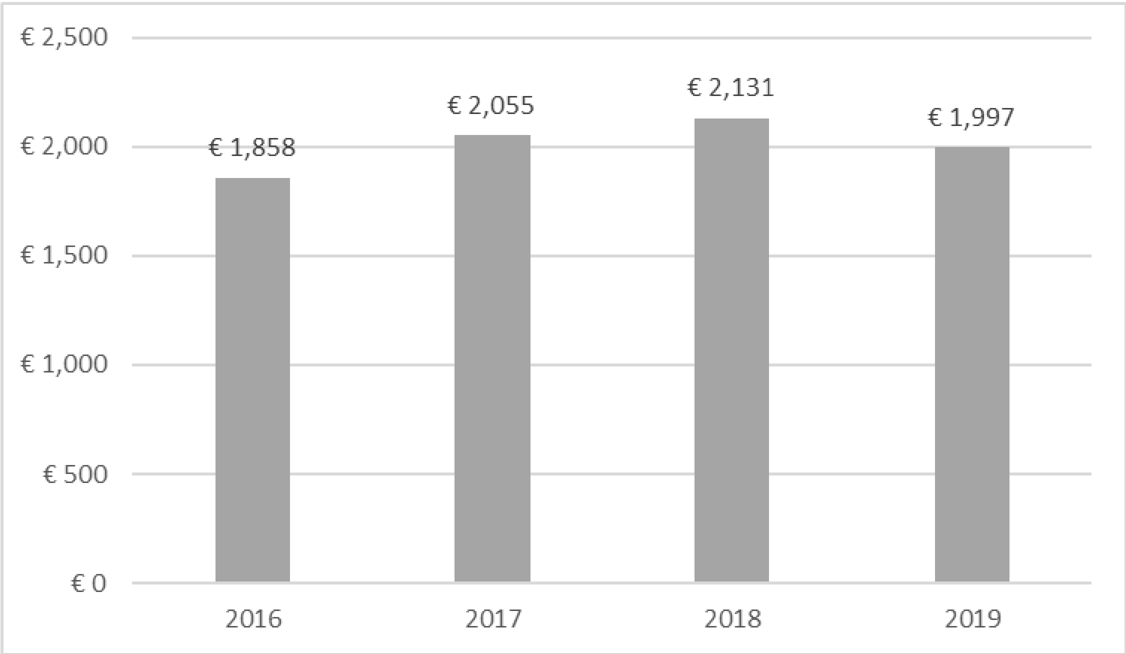


Fig. 4. 3. National average RENE values in the 2016-2019 series (reprinted from [136]*)*

The prevalence of the heating share is consistent with the distribution of the total actual domestic consumption analysed in statistics by IDAE [55]. However, the share of required heating expenditure in the 2019 RENE is 32% higher than the actual heating-consumption share in IDAE statistics. Moreover, there is a significant difference in the cooling share, which is five times higher in model than in statistics. This inconsistency may be explained by the fact that only 35.5% of Spanish households own air-conditioning units [265] compared with 84.7% of population that would require to cool their home for some period during the year (own calculation from the RENE analysis), i.e. space cooling is still considered 'a luxury' in Spain. These findings were crucial to set up most of the sensitivity analyses presented in Section 4.2.2.2. Moreover, it has to be highlighted that the allocation method of the fixed terms of the electricity and natural gas tariffs in the RENE model (see Appendix F) has also an impact on the cost's distribution. Specifically, it slightly increases the RELE share in all households and, depending on the household's heating energy carrier, it could produce an increase of the share of heating expenditure. On the other hand, the RENE 2016-2019 values shown in Fig. 4. 3 are strongly influenced by the corresponding average energy prices shown in Fig. A 33.

Finally, Table 4. 1 shows some examples of 2019 RENE value for several household types. These values referred to actual HBS households that were selected to show the RENE variation according to key parameters, i.e. region, household size, dwelling's typology and construction period. The dwelling size was not incorporated in the selection process (even if it is a major parameter) because its value is difficult to categorize (its range of values is much broader in comparison to other key parameters).

Table 4. 1. Examples of the value of the RENE for different HBS household types in 2019

Region	Household size	Dwelling typology	Dwelling size [m^2]	Construction period	Heating energy carrier	DHW energy carrier	RENE [€/year]
Canarias	1	Block dwelling	100	≥ 25 years ago	Electricity	LPG	480
Canarias	4	Single-family house	100	< 25 years ago	Biomass	Electricity	871
Andalucía	1	Block dwelling	70	< 25 years ago	Natural gas	Electricity	890
Andalucía	2	Single-family house	140	≥ 25 years ago	Electricity	Electricity	1684
Madrid	1	Block dwelling	72	≥ 25 years ago	Natural gas	Natural gas	1175
Madrid	5	Block dwelling	90	< 25 years ago	Natural gas	Natural gas	2136
Castilla - La Mancha	2	Block dwelling	99	≥ 25 years ago	Electricity	Electricity	1762
Castilla - La Mancha	1	Single-family house	132	< 25 years ago	LPG	LPG	1327

4.2.2 Exploring underconsumption and hidden energy poverty

This section proposes two indexes that aim to differentiate households affected by hidden energy poverty from the ones that are underconsuming for other reasons, e.g. high energy efficiency standards. Particularly, the 'Low absolute energy expenditure' indicator estimates the extent of domestic energy underconsumption in the country by using an absolute energy expenditure threshold (see Section 4.2.2.1). On the other hand, the hidden energy poverty indicator (HEP) introduces a further threshold (based on the results of the former index) as a proxy to evaluate the share of households that cannot attain an adequate level of energy services due to financial restraints (see Section 4.2.2.2). Both indicators are applied to the Spanish HBS samples of four consecutive years (2016-2019), thus estimating the extent (share of households in hidden energy poverty) and the depth (energy poverty gap) of this social issue in Spain. The goal of the latter calculation is to assess the difference between the actual energy expenditure of households identified as energy poor and their absolute threshold, thus quantifying the additional budget that these families or individuals would have to spend on energy to meet their required energy needs. Furthermore, elevating this amount to the whole households in the country would allow policymakers to have a reference of the national budget needed for a hidden energy poverty mitigation policy.

4.2.2.1 Low absolute energy expenditure indicator

The absolute difference [€/year] between the actual energy expenditure of a household and their RENE is called 'energy-expenditure gap'. Fig. 4. 4 shows the 2019 boxplot of this gap among the income deciles. The distance between the first and third quartiles (lower and upper parts of the box) shows the degree of dispersion (spread) in the gap data, and the lines indicate the variability outside the quartiles. The outliers are excluded from the plot.

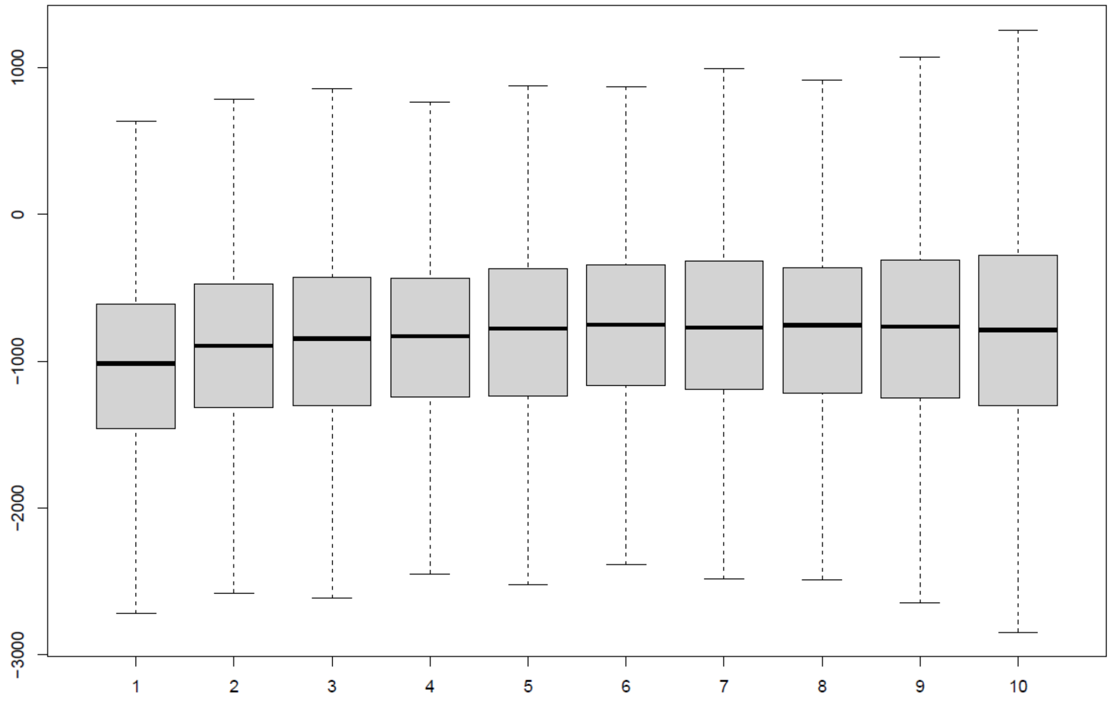


Fig. 4. 4. 2019 distribution and median Spanish households' energy-expenditure gap [€/year] with respect to the RENE disaggregated by equivalised income decile (reprinted from [136]*)*

The median value of the gap is practically the same in the five highest income deciles, while it decreases (in absolute terms) with revenue in the five lowest income ones.

Regarding the distribution, the number of positive gap cases and the value of the Maximum (100th percentile) increase with income, i.e. in the highest income deciles there is greater probability of finding households that overconsume ('energy obesity'[221], [270]). On the other hand, the negative gap (underconsumption) cases have not a clear trend. Indeed, the lowest Minimum of all the sample (lowest 0th percentile value) belongs to the highest income decile, whereas the lowest income decile has the smallest first quartile value. Overall, the highest two income deciles show the greatest degrees of data dispersion, i.e. the casuistry of richest households may be very diverse. The median value (black horizontal line in the chart) is negative in all the income deciles, i.e. averagely, the Spanish household actual expenditure is lower than their RENE. Therefore, given the weaknesses of the HBS, e.g. lack of exact geographical information (see Appendices Appendix D and Appendix E), and considering the model assumptions (see Section 4.2.1.1), it can be inferred that the 'adapted RENE model' may overestimate the Spanish domestic theoretical energy expenditure. In order to clarify this issue, this procedure was iterated to find the proportion of RENE that determines a median gap of the five highest income deciles equal to €0. These income deciles were selected because it was assumed that these households, in principle, do not have financial restraints that 'force' them to underconsume. This calculation was carried out to align the modelled absolute energy expenditure threshold with the Spanish situation. The null value for 2019 is achieved by setting the threshold at RENE/1.73. Using the latter value as threshold for the 'low absolute energy expenditure' indicator would enhance the accuracy of the results. Nonetheless, when applying this methodology to a specific case study, the proportion of RENE that 'fits' with each year would have to be calculated, thus adding complexity to its adaptation. This would make the indicator difficult to integrate, for instance, in the annual energy poverty monitoring of the Member States' Climate Action Social Plans (defined in the 'Fit for 55' EU proposal [216]), e.g. in the SNSEP that is already carrying out this analysis for Spain. Indeed, the other main goal of this chapter is to introduce a hidden energy poverty indicator potentially replicable for other geographical contexts, e.g. other EU member states, both at national and regional level. The ambition of finding the exact share of RENE to 'zero the gap' would make the methodology difficult to understand and replicate. Moreover, in the other years analysed for the Spanish case study, the denominator of 'RENE/X' would be: 1.83 (2018), 1.87 (2017), 1.75 (2016). These values are between 1.4% and 8.4% higher than the 2019 one and the corresponding thresholds in the four years, i.e. RENE/1.73, RENE/1.83, RENE/1.87 and RENE/1.75, could be assimilated to RENE/2 for the sake of clarity and replicability. Thus, following the literature on hidden energy poverty, e.g. [124], the boxplot was redrawn considering half the RENE as reference value for the energy-expenditure gap and proposed absolute energy expenditure threshold of the indicator. Fig. 4. 5 shows the 2019 energy-expenditure-gap's boxplot with respect to the RENE/2 disaggregated by income deciles.

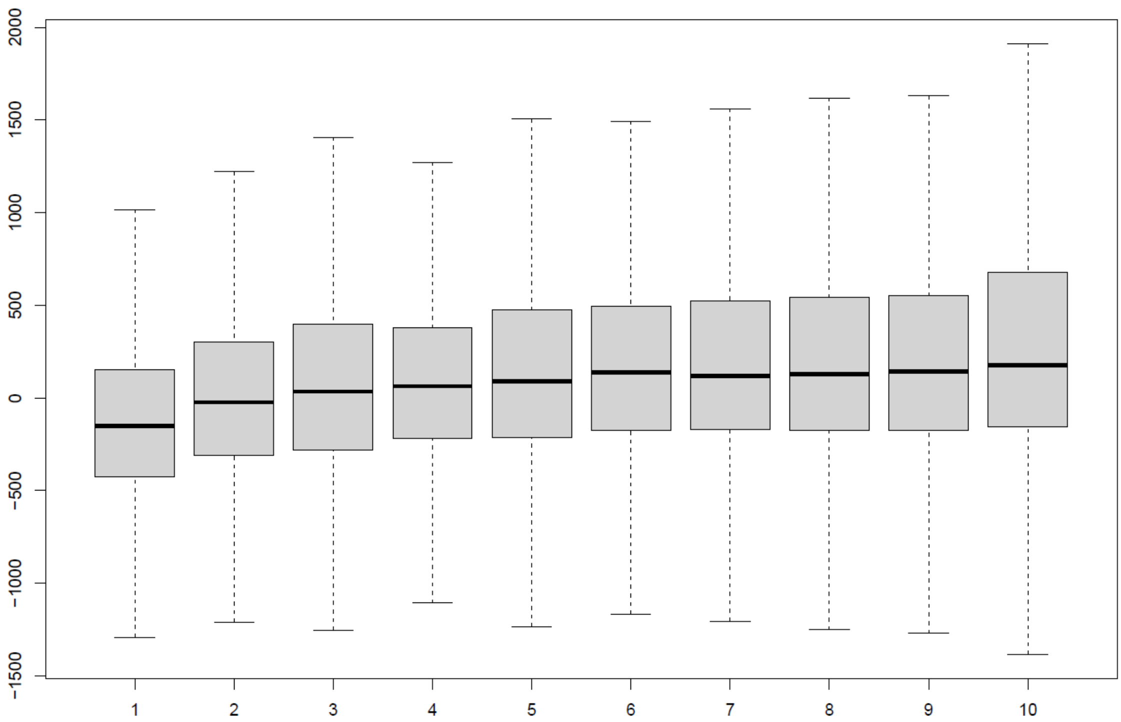


Fig. 4. 5. 2019 distribution and median Spanish households' energy-expenditure gap [€/year] with respect to the RENE/2 disaggregated by equivalised income decile (reprinted from [136]*)*

In this case, the median energy-expenditure gap is negative (potential[53] underconsumption) only in the first two income deciles (lowest income). In the rest of deciles, it is positive (potential overconsumption). For reference purposes, the median energy-expenditure gap of the five highest income deciles was calculated. The results show that this value ranges between €65[54] (in 2017) and €139 (in 2019). This means that, averagely, the Spanish households belonging to the five highest income deciles spend on energy more than their RENE/2. However, given the above explanations and the low median gap with respect to the RENE/2, setting half the RENE as absolute energy expenditure threshold for the chapter's proposed indicators seems accurate enough to identify households that are underconsuming.

'In the light of this finding, to calculate the 'Low absolute energy expenditure' indicator, the actual energy expenditure of each household of the HBS[55] was compared with half their Required ENergy Expenditure (RENE/2), considering as 'underconsuming households' the ones whose actual energy expenditure is below their absolute energy

[53] Energy prices and household behaviour could influence the results, so it is not possible to clearly identify underconsuming and overconsuming households at this stage.

[54] 66€ in January 2019, i.e. updated with the General CPI (CPI system base 2021) between January 2017 and January 2019 (1.6% variation). Source: INE CPI tool

[55]The HBS assigns an expansion factor to each household, therefore the HBS households represent a statistically significant sample of the Spanish population.

expenditure threshold. Afterwards, the indicator was disaggregated by income deciles[56], with the aim of ruling out those households whose low energy expenditure might be due to factors not related to a social vulnerability situation, such as high energy efficiency in housing. Indeed, the energy retrofit of a household's dwelling reduces its required energy consumption, something that the RENE/2 indicator is not able to detect (due to the lack of specific data in the HBS), which could lead to false positives. It is therefore necessary to introduce an income criterion to identify who is underconsuming due to lack of financial resources (affordability problem), i.e. who is truly in a situation of hidden energy poverty'. Fig. 4. 6 shows the 2019 share of underconsuming households in each income decile with respect to the decile's total households.

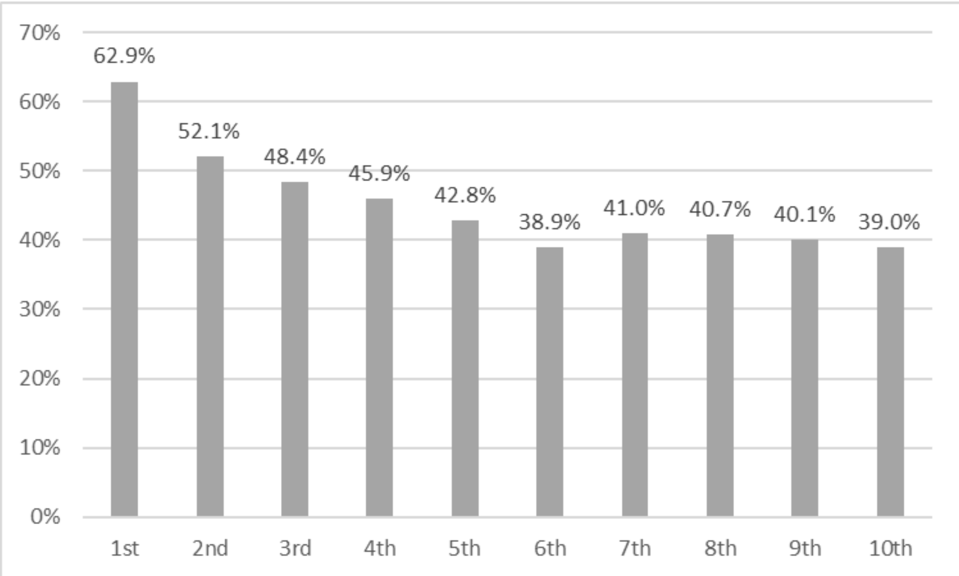


Fig. 4. 6. 2019 share of underconsuming households according to the RENE/2 indicator in each equivalised income decile with respect to the decile's total households (reprinted from [136]*)*

The share of underconsuming households in the lowest income deciles is greater than in the highest income deciles. Indeed, there is a clear income-driven 'upward trend' (from 42.8% in the fifth decile to 62.9% in the first decile, a difference of 20%) only in the lowest five income deciles; in the five highest income deciles there is no clear trend and the indicator hovers between 38.9% and 41%. Fig. 4. 7 illustrates that a similar RENE/2 trend can be observed in the other years of the series, i.e. the share of underconsuming households in the first five deciles drops with income, while it remains quite stable in the last five deciles.

[56] To classify the sample by equivalised income deciles, the household's equivalised total expenditure (see Table A 24) was used as reference value following the same methodology as in [108]. Hereafter, this variable will be called 'equivalised income' or just 'income' for simplicity's sake.

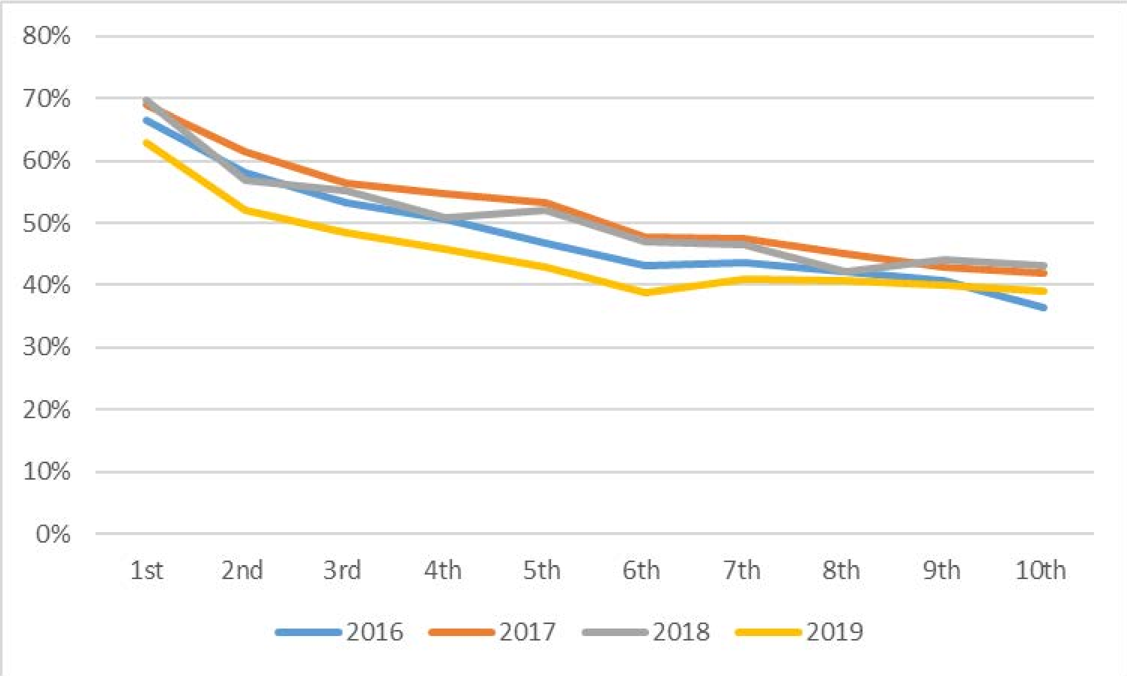


Fig. 4. 7. 'Low absolute energy expenditure' indicator disaggregated by equivalised income deciles in each analysed year

Thus, looking at Fig. 4. 6 and Fig. 4. 7, it can be noticed that there is a fixed percentage of households in the higher income deciles that underconsume for reasons that are apparently unrelated to lack of affordability. This assumption is supported by numerous studies in the literature. For example, [271] suggested that 'voluntary underconsumption' could be related to high energy efficiency standards, ecologist behaviour, conscious consuming or other drivers related to a higher education level, which are more common features of high-income households. Indeed, according to the 2019 HBS, 37% of Spanish households belonging to the five highest income deciles live in recent constructed dwellings (i.e. constructed less than 25 years ago), whereas this share is 25% lower for the five lowest income deciles (i.e. 28%). On the other hand, the financial constraints of low-income households 'force' them to underconsume [272] and it is also a major barrier for the retrofitting of their dwellings or the purchasing of more efficient equipment [273]. Moreover, several studies, e.g. [274], indicated that low-income households are more often tenants than owners of their dwelling and that rented dwellings have a lowest energy efficiency than owner-occupied dwellings. In these cases, tenants have no decision-making power to renovate appliances (in some cases) and retrofit the dwelling, and landlords 'do not gain any direct advantage from improvements in energy efficiency in the property' [274] (cf. tenant-landlord dilemma). In this regard, in the thesis case study (i.e. Spain), 23% of the lowest income households (belonging to the five lowest income deciles) live in rented dwellings compared with 13% of the highest income ones (HBS, 2019). Furthermore, as mentioned before, low-income households usually live in older dwellings: the 72% of them live in buildings built more than 25 years ago (HBS, 2019). Therefore, the 'underconsumption condition' identified in the latter can more likely be related to an issue of forced self-restriction. Thus, the income threshold chosen for the calculation of the HEP indicator was to exclude the five highest income deciles, i.e. the households belonging to these deciles and being in underconsumption are considered as false positives.

4.2.2.2 Proposed new Hidden Energy Poverty indicator (HEP)

According to the proposed HEP indicator, a household is in hidden energy poverty if: (1) their actual energy expenditure is below half their required energy expenditure (RENE/2), and (2) the family unit belongs to one of the five lowest equivalised income deciles. Accordingly, this metric was applied to the 2016-2019 Spanish HBS samples as follows.

Firstly, the national share of households in hidden energy poverty (extent of hidden energy poverty in Spain) is estimated for the four years analysed. Then, for these households in hidden energy poverty, the ‘energy poverty gap’ (depth) is calculated as the difference between their RENE/2 and their actual energy expenditure. Furthermore, the national budget needed to fill this gap is calculated by multiplying each ‘energy poverty gap’ value by the household’s ‘spatial expansion factor’[57], i.e. scaling the result over the entire population. This calculation is partially inspired by the one proposed by the World Bank for the ‘poverty gap’ [275] and it has already been applied to energy poverty in other countries (using different methodologies), such as Belgium [124], France [218] and the UK [205].

Secondly, this chapter introduces five disaggregated analyses on the HEP extent. In the first one, the HBS households are clustered by region to analyse the geographical and socio-economical differences. The second disaggregated analysis estimates the HEP extent according to the household size, thus analysing the influence of the number of household members on this social issue. The third one analyses the influence of the building age (as a proxy of its thermal enclosure’s energy efficiency) on hidden energy poverty. The fourth and fifth disaggregated analyses dive into two characteristics that have been suggested in literature as influencing energy poverty, i.e. the dwelling’s tenure status (own or rented) [274] and the locality’s degree of urbanisation (living in urban or rural areas) [276].

Finally, three types of sensitivity analysis were conducted by studying the influence of primary parameters of the absolute threshold on the HEP indicator’s results:

- HDD_18 and HDD_16 - Given the high share of the HVAC expenditure in the total RENE (see Fig. 4. 2), it is relevant to analyse the impact of changing key baseline parameters of its calculation. Regarding heating expenditure (which represents 56% of the households’ RENE), in the base case scenario, it was calculated by using IDAE reference demand [233] that applies 20 °C as baseline temperature. Nevertheless, according to the World Health Organization (WHO), the comfort temperature required to avoid health problems during the cold season is 18 °C [277]. Therefore, the required heating demand calculation was repeated

[57] The spatial expansion factors are used to raise the sample data to the population, so that the spatial expansion factor of a sampled household is the number of households in the population that it represents.

using 18 °C as baseline temperature. Table A 38 of Appendix G shows the reference demand values to ensure comfort assuming the WHO lower threshold temperature. Setting the base temperature at 18°C instead of 20°C in the Heating Degree Days (HDDs) calculation reduces the heating demand by averagely 38% (in line with studies that use adaptive comfort thresholds [90]; see Table A 39). Moreover, some studies (e.g. [278]) pointed out an even lower indoor temperature threshold to avoid respiratory diseases, i.e. 16ºC. Therefore, the heating demand was calculated again by assuming a baseline comfort temperature of 16ºC. In this case, the heating demand decreases by averagely 63% (see Table A 40 and Table A 41). The results of these two calculations were applied to estimate two HEP scenarios with lower heating requirements: HDD_18 and HDD_16.

- A_0.9/0.8/0.7 - The second sensitivity analysis was carried out assuming a decrease in the floor area conditioned (HVAC) by households. This scenario is considered because it is common that households do not have (or do not use) HVAC appliances in all dwelling's rooms. For example, storage rooms and kitchens are spaces that frequently do not need to be climate-controlled. Given the variability of this parameter, different percentages of air-conditioned floor area (90%, 80% and 70%) were assumed for the calculation. Therefore, these new demand values were integrated in the HEP estimation, thus introducing three new HEP scenarios (A_0.9/0.8/0.7).
- RENE/4 and 3/4 RENE - The third kind of sensitivity analysis focused on the percentage of RENE set as absolute threshold. On the one hand, some severely vulnerable households tend to compress their energy consumption to an extreme point. Therefore, to detect this extreme hidden energy poverty, the calculation of the indicator was repeated by setting the threshold to RENE/4 as a proxy of the household's minimum energy expenditure. On the other hand, some households are either placed outside but close to the energy poverty area defined by the threshold RENE/2 or are approaching that area. Thus, a higher threshold, i.e. 3/4 RENE, was considered as a proxy to identify households that could be vulnerable to hidden energy poverty.

The initial results of the 'Low absolute energy expenditure' indicator (see Fig. 4. 6 and Fig. 4. 7) and the sensitivity analysis' findings (see Section 4.3.2) pointed out that the required HVAC expenditure assessed according to the Spanish regulation might not be reflecting the actual consumption patterns of a considerable share of Spanish households. This could cause an overestimation of the households in hidden energy poverty. In this line, the results of [279] indicate that German households consume, on average, 30% less energy on heating than the modelled one. A similar energy performance gap is found in other German studies [280]. However, when considering countries more similar to Spain, i.e. Portugal, [78] shows that all the locations analysed have an energy performance gap in nominal conditions (based on regulation) higher than 60%, with average gaps for heating and cooling of 92.5% and 97.1%, respectively, i.e. the actual consumption is approximately half of the required one. These findings are in line with the presented results for the Spanish case (see sections 4.2.2.1, in particular Fig. 4. 5). Thus, this work proposes an alternative scenario 'adjusted to household's comfort strategy' (in line with the literature from other countries, e.g. Portugal [78]) as an additional sensitivity analysis: the HEP indicator was estimated again after adjusting the HVAC demand's primary parameters to the Spanish residential sector's characteristics and the WHO recommendations, i.e. 18 ºC as baseline comfort temperature (WHO), 75% of heated floor area [281] and 60% of cooled floor area [282].

Finally, the HEP indicator was assessed by using the base-case energy threshold and, as income threshold, the EU 'at risk of poverty' criterion (AROP) [283], i.e. 60 % of the national median equivalised income, which was already applied in several studies on energy poverty (e.g. [131]). It should be noticed that the equivalised income proxy used to compose this threshold is the same as the one used in the base case scenario (see Section 4.2.2.1).

4.3 Results and discussion

4.3.1 Analysing the extent and depth of hidden energy poverty in Spain

To understand the results of the HEP index presented in this chapter, it is crucial to analyse the absolute energy expenditure threshold proposed for the two indicators. Fig. 4. 8 shows the regional weighted-average RENE computed *a posteriori* from the required energy expenditure values of each 2019 HBS household. The RENE values for the two autonomous cities not shown in the map, i.e. *Ceuta* and *Melilla*, are, respectively, €1,262 and €1,055.

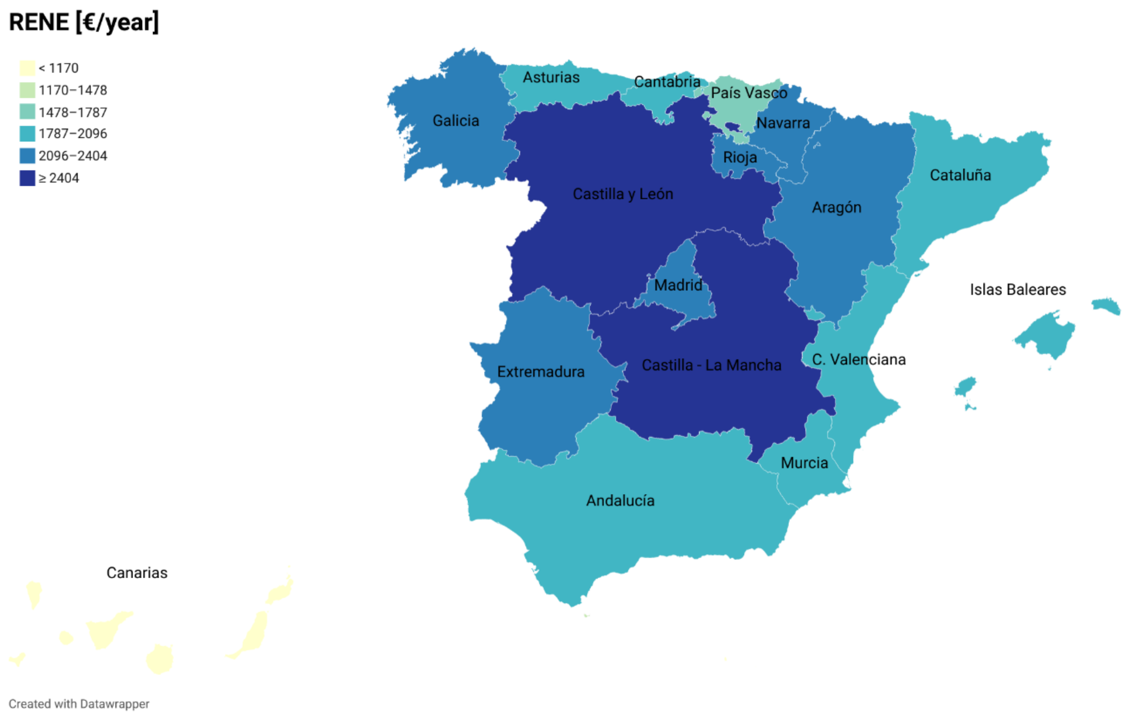


Fig. 4. 8. Regional weighted-average RENE per household in 2019 [€/year] (reprinted from [136])

Fig. 4. 8 points out that the required energy expenditure varies considerably depending on the household's region of residence, with a marked difference between the inland and the coastal regions. The main driver that explains this difference is climatology, which influences the thermal energy demand. Particularly, the winter climate severity is the parameter that largely impacts the RENE values, being the average required heating expenditure 56% of the total energy one (see Fig. 4. 2). Indeed, this share is much greater in the two regions with the highest RENE (65% and 68%, respectively, in *Castilla - La Mancha* and *Castilla y León*) than the ones with the lowest required expenditure on energy (23% and 28%, respectively in *Melilla* and *Canarias*). Two exceptional cases are *Extremadura* and *Canarias*. The former has high required energy expenditure both on heating and cooling, having actually the highest air-conditioning expenditure value within the country. On the contrary, *Canarias* is a region with a mild climate, thus having the lowest required expenditure for heating and among the lowest required cooling costs in the country. On the other hand, the RELE mostly depends on the household size (it increases with the number of members), and it does not vary with climatology. Therefore, it has a lower geographical variability than the RTEE.

Fig. 4. 9 displays the trends of the 'Low absolute energy expenditure' (RENE/2) and HEP indicators for the analysed years. It shows that the shares of households identified by both metrics decrease after 2017. Nonetheless, it has to be noted that they are measuring two related phenomena, i.e. underconsumption and hidden energy poverty, thus it is critical to deeply analyse the results to understand the multiple causes and effects of these phenomena.

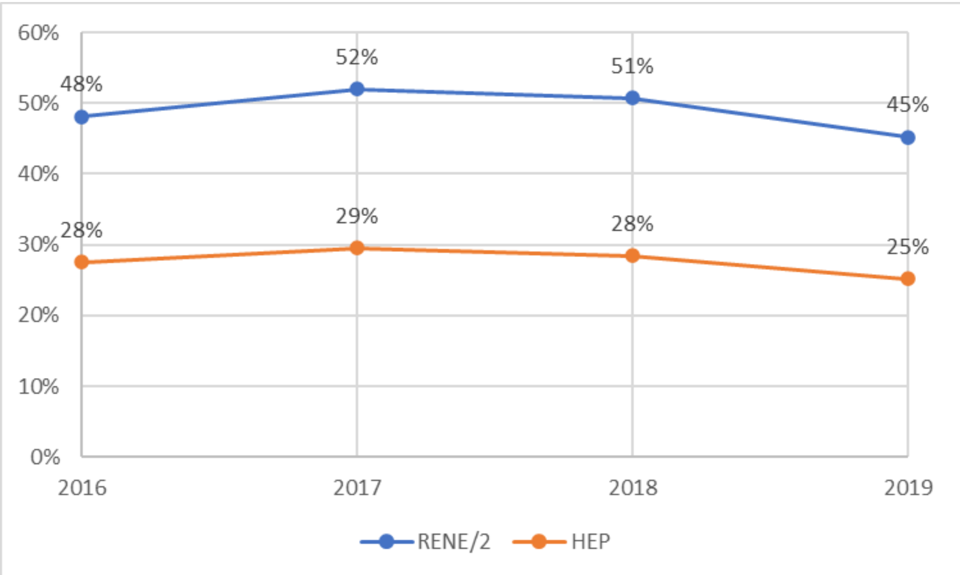


Fig. 4. 9. Values of the RENE/2 and HEP indicators from 2016 to 2019 (reprinted from [136]*)*

The higher values of both indicators were reached in 2017, followed by the 2018 ones. A potential partial explanation of this result is that the energy prices in these two years were higher than the other two analysed years (see Appendix F) and this fact may have induced households to reduce their energy consumption. On the other hand, it is not possible to clearly assess the impact of the climatology across the years because the RTEE model uses climate data of a typical year, following the Spanish regulation (CTE, 2019). Nevertheless, the years in question (2016-2019), according to the Meteorological State Agency of Spain (AEMET), registered similar average temperature values: 15.8ºC (2016); 16.2ºC (2017); 15.5ºC (2018); 15.9ºC (2019). The average temperature of the typical year (15.1ºC) differs significantly only from the 2017 one, which was a particular warm year. This could also have contributed to determine higher values of the indicators in that year[58]. However, according to [284], the temperature sensitivity of the Spanish actual daily electricity consumption is very low, especially around 15ºC. Therefore, the actual consumption variation due to temperature changes might have been small over the four years.

Focusing on the reference year (2019), 45% of Spanish households had a low absolute energy expenditure, but only 56% of the latter (25% of the total family units, i.e. 4.7 million of households) were in hidden energy poverty. Comparing the HEP number of households with the ones that benefitted from the social tariffs in 2019, i.e. 1.3 million households [285], it could be inferred that at least 3.3 million of households in hidden energy poverty did not benefitted from the national mitigating measures. As explained above, the HEP metric considers the underconsuming households belonging to the five highest income deciles as false positives because, among other possible reasons (e.g. physiological and generational habits [278] or long-term absence due to business trips; see Fig. 4. 4[59]), they have more purchasing power. Thus, in spite of the fact that for the HBS they live in old buildings[60], they could have retrofitted their homes thus reducing their required energy consumption. On the contrary, according to a Red Cross report [38], 81% of vulnerable households surveyed by the NGO in Spain (low-income deciles) do not own energy-saving systems, either because they are unaware of them or cannot afford them. Moreover, the appliances' quality in rented apartments depends sometimes on the owner's concern (i.e. there could be different appliances provided by the owner who could prefer a low-cost appliance to an energy efficient one). However, most of the people surveyed by the Spanish Red Cross declared to be very cautious in their expenditure on electricity and gas services. Consequently, given the above facts and considering the constancy of the richest households' underconsumption share shown in Fig. 4. 6 (confidently not income-driven), the income threshold set for the HEP indicator can be considered an acceptable assumption.

Fig. 4. 10 shows the 2019 results of the HEP indicator and the equivalised net disposable income disaggregated by region.

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[58] The modelling of the required heating demand for the 2017 HBS (based on the typical year climate) considerably overestimated the required heating needs of that year (being the 2017 significantly warmer than the typical year).

[59] Fig. 4. 4 shows that the lowest 0^{th} percentile value belongs to the highest income decile, i.e. there is a considerable number of very high-income households that have an extremely low actual energy consumption, which is certainly not due to energy poverty.

[60] The limited information on the building construction age and the absence of data on the energy performance certificate prevents a detailed analysis of the influence of energy efficiency on hidden energy poverty.

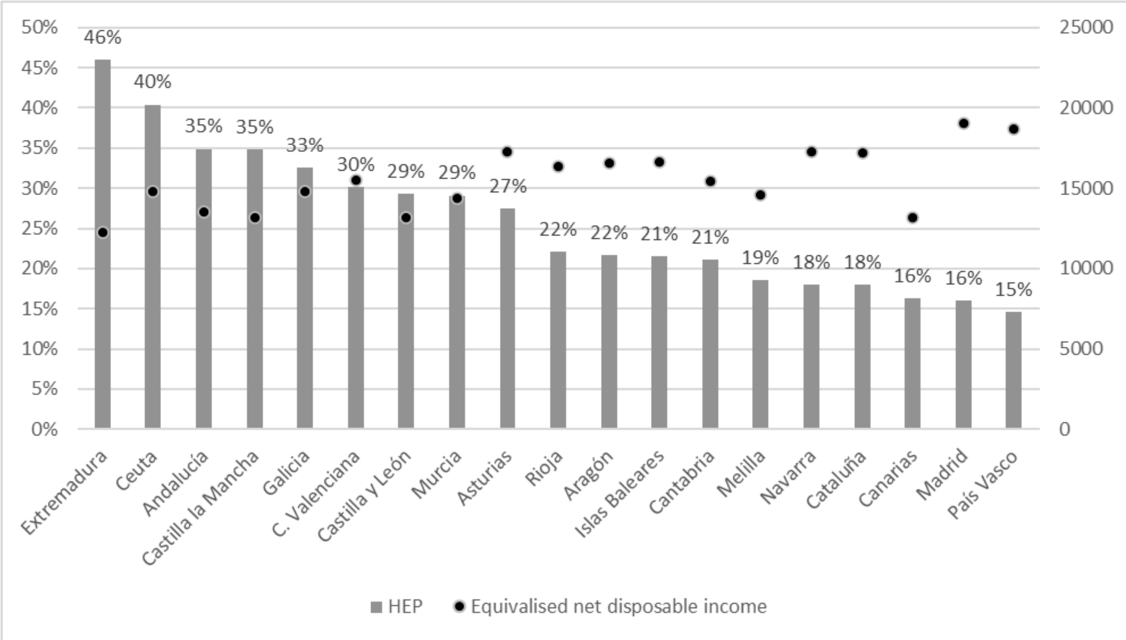

Fig. 4. 10. 2019 HEP indicator [%] and equivalised net disposable income [€/year] (OECD modified equivalisation of the IMPEXAC variable of the HBS 2019) disaggregated by region (reprinted from [136]*)*

From Fig. 4. 10, it can be concluded that there is a wide disparity in the HEP results across Spanish regions. While a priori the high shares of energy poverty in *Ceuta* and *Andalucía* might be apparently counterintuitive (their RENE values are definitely not among the highest ones in the country), this result may be explained by two issues: they are low-income regions (their equivalised net disposable income, respectively, €14,788 and €13,556, are lower than the national average one, i.e. €15,786) and the majority of households living there do not own heating devices (respectively, 98% and 78%, according to the HBS) even if they would require them to achieve comfort (as shown in Table A 27). On the other hand, giving the explanation of Fig. 4. 8, the drivers that make *Extremadura* the region with the highest HEP share are more evident. As mentioned before, households living in this region have high required HVAC expenditure. Moreover, they have on average the lowest net disposable income within the country. On the contrary, the richest regions, i.e. *Madrid* and *País Vasco*, have the lowest HEP shares.

Additionally, Fig. 4. 11 shows that the HEP proportion varies quite significantly with the household size. Indeed, households with more than four members are the most affected by this social issue, followed by single-member households. On the one hand, Spanish large families have lower equivalised net disposable income and need more energy than the rest of the households. On the other hand, a possible explanation of the high HEP share of single-member households lies in the fact that people living alone might spend less time at home and use HVAC devices only in one or two rooms.

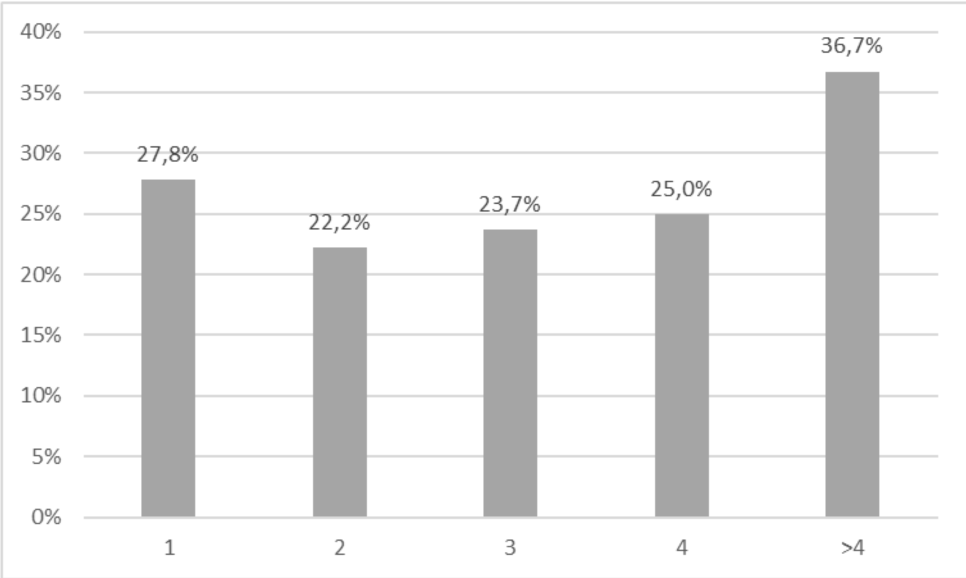

Fig. 4. 11. HEP indicator in 2019 disaggregated by household size (reprinted from [136]*)*

Regarding the influence of the housing age on energy poverty, the HEP disaggregated value for buildings constructed 'less than 25 years ago' is 13.8%, while 30.7% of households living in buildings constructed '25 or more years ago' are in hidden energy poverty. Therefore, considering that the HVAC expenditure represents the major share of RENE (see Fig. 4. 2), the results can be interpreted as follows: the building construction period is a major factor influencing the household's ability to pay the required costs for maintaining an adequate indoor temperature. This finding clearly alludes to the relevance (at least concerning their ability to impact on energy poverty) of designing and implementing policies and strategies that support residential building retrofitting, such as the 2020 Spanish Strategy for Energy Renovation in the Building Sector [286]. In this regard, it is also significant to analyse the HEP results disaggregated according to the dwelling's tenure type: 31% of tenants are affected by hidden energy poverty compared to 23% of owners. Thus, the status of tenant increases the probability of being energy poor. Particular mention should be made of households living in semi-free or rent-free houses whose HEP share reaches 36%. This phenomenon might be due to the fact that households living in social housing are included in this subgroup. On the other hand, considering the urbanisation degree of the locality, households living in rural areas experience higher HEP levels than households living in urban areas. Indeed, the HEP share in the former is 35% compared to the 24% of the latter. This might be partially determined by the characteristics of the Spanish building stock and the households' consumption patterns[61]. On the one hand, in rural areas there are more single-family houses (Census 2011 and HBS) with higher thermal energy requirements than block dwellings (which are more common in urban localities). Thus, the RENE is averagely higher in households living in villages than the ones of households living in cities. On the

[61] The difference in altitude (so in climate severity) between urban and rural areas is also a key factor but it could not be included in the chapter's analysis because of the lack of information on the locality in the HBS.

other hand, energy behaviour is a key parameter that could influence results. Consequently, further studies should be carried out to characterise Spanish households' consumption patterns in urban and rural contexts, thus pointing out the intrinsic reasons of the difference in HEP level.

Finally, the 'energy poverty gap' analysis makes it possible to estimate the depth of hidden energy poverty in the country. In 2019, this gap was averagely 374 euros per household and the budget to address it and potentially eradicate this issue in Spain was €1,692m (0.14% of the Spanish GDP[62]; see Table 4. 2 for the results in each year). Comparing this value with the actual budget earmarked for social tariffs in 2019 (€214m[63]), the one calculated in this chapter is almost eight times higher than the actual 2019 one. Moreover, the average household energy poverty gap calculated for Spain is comparable with the one estimated for the UK (€381), but it is considerably lower than the French one (between €526 and €735, depending on the metric used). However, it should be highlighted that an accurate comparison would require to apply the same methodology for the three cases and adjust it to consider socio-demographic, building stock, energy prices and climatic differences.

Table 4. 2. Average annual energy poverty gap and national annual budget needed for a hypothetical hidden energy poverty mitigation policy

	2016	**2017**	**2018**	**2019**
Average energy poverty gap	€349	€399	€408	€374
National annual budget	€1,701m	€2,086m	€2,079m	€1,692m

4.3.2 Sensitivity Analysis

Fig. 4. 12 shows the results of the three kinds of HEP indicator's sensitivity analysis (described in Section 2.2.2) that study the impact of changing primary parameters of the absolute energy-expenditure threshold.

[62] https://datosmacro.expansion.com/pib/espana?anio=2019
[63] Summing up the budget for the social tariff for electricity and the thermal social allowance, which, in 2019, were granted to 1.3 million of households.

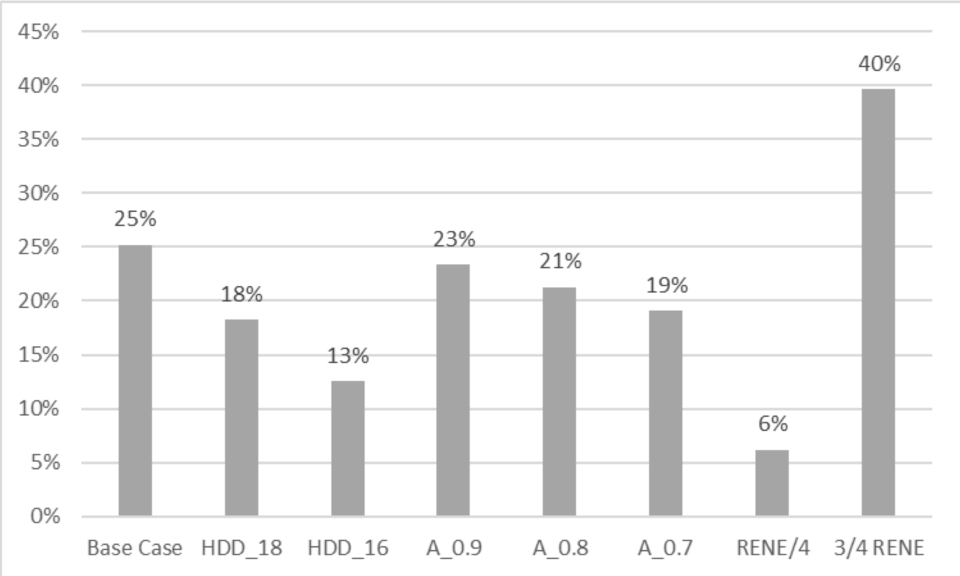

Fig. 4. 12. Sensitivity analysis of the HEP indicator in 2019 (HDD_18 – comfort temperature at 18ºC; HDD_16 – comfort temperature at 16ºC; A_0.9/0.8/0.7 – reduced percentage of conditioned floor area at 90%, 80% and 70%; RENE/4 – extreme hidden energy poverty; 3/4 RENE - vulnerable to hidden energy poverty) (reprinted from [136]*)*

The first two kinds of sensitivity analysis (from HDD_18 to A_0.7 in Fig. 4. 12) were obtained by changing primary parameters of the RTEE model. From the results shown in Fig. 4. 12, it can be observed that the variation of the winter comfort temperature has the largest impact on the value of the energy poverty indicator. Indeed, when supposing lower comfort temperatures, i.e. 18ºC and 16ºC, the HEP share decrease, respectively, by 28% and 50% compared with the base-case scenario. Since 18°C is considered by the WHO as the minimum temperature value to ensure comfort, the related indicator's result could be considered as the 'minimum comfort-temperature scenario. On the other hand, 16ºC was pointed out as the minimum indoor temperature threshold to avoid respiratory diseases. Thus, this extreme scenario could be considered as the 'minimum healthy-temperature scenario''. Fig. 4. 13 and Fig. 4. 14 show the 2019 'Low absolute energy expenditure' indicator's results in these two scenarios disaggregated by income deciles.

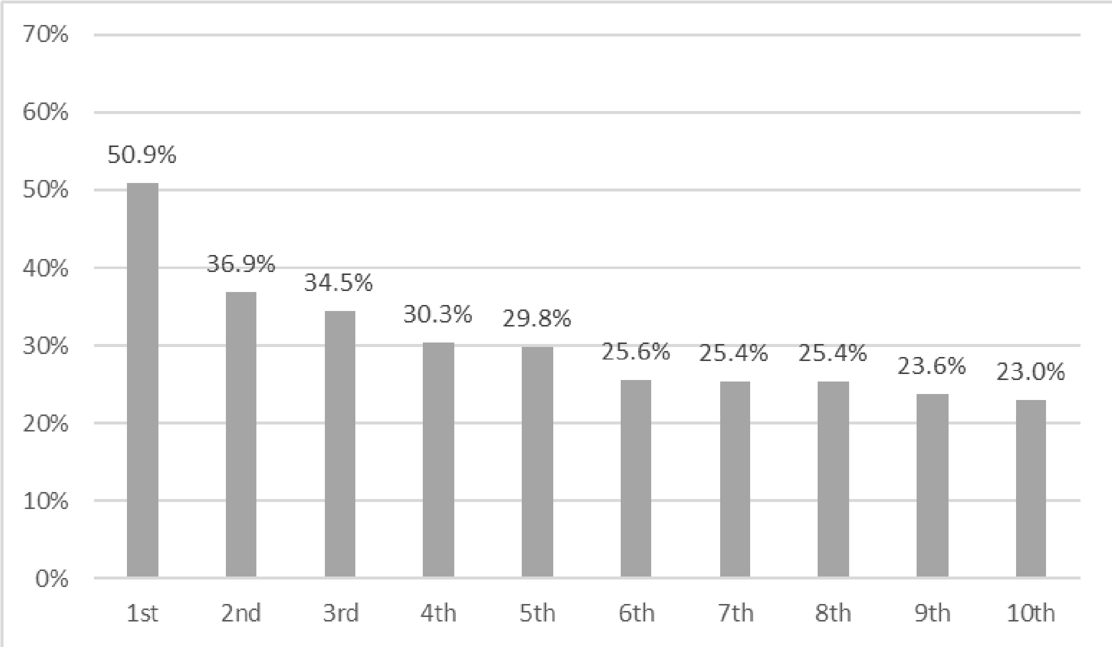

Fig. 4. 13. RENE/2 indicator's values in 2019 for each equivalised income decile in the HDD_18 scenario (reprinted from [136]*)*

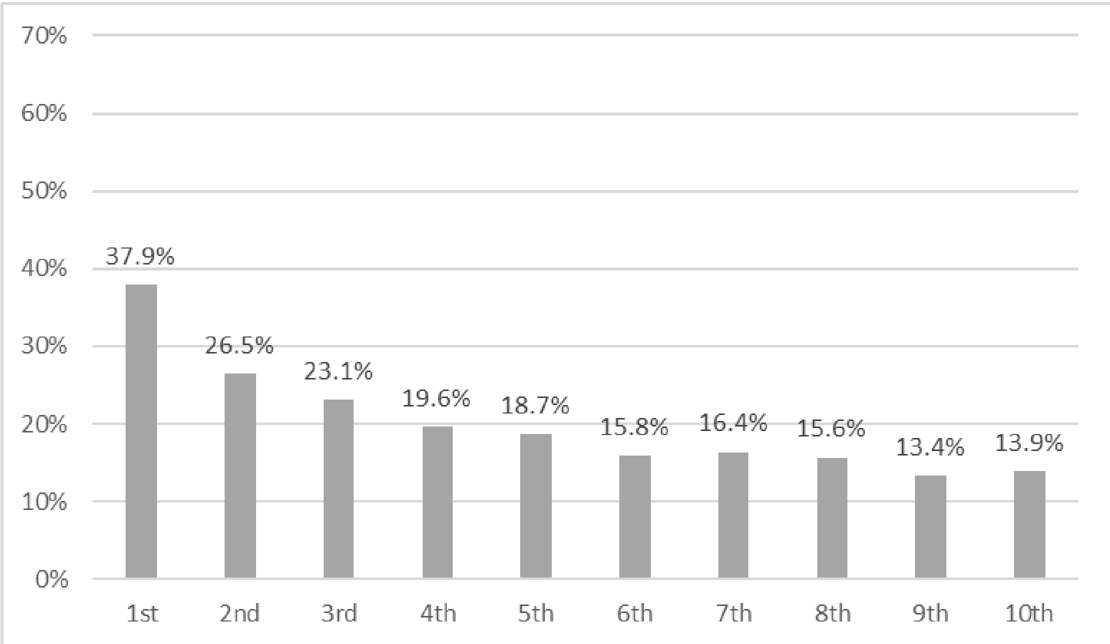

Fig. 4. 14. RENE/2 indicator's values in 2019 for each equivalised income decile in the HDD_16 scenario (reprinted from [136]*)*

In both scenarios, the reduction in the indicator value with respect to the base case (shown in Fig. 4. 6) is less substantial in the low-income deciles. This finding highlights the lower sensitivity of the indicator to the winter comfort temperature in these deciles or, in other words, it might point out that the poorest households are more likely to live in dwellings with an extremely low indoor temperature during winter. Moreover, as shown in Fig. 4.

12, the variation in climate-controlled floor area has also a significant influence on the indicators' results. The HEP values show a reduction of more than 24% by moving from the baseline scenario to the 70% floor area scenario. Furthermore, the decrease of the indicator value from A_90 to A_70 is somewhat linear. This result suggests that it could be beneficial to obtain more information on the proportion of floor space that is air-conditioned in households in order to obtain a more accurate picture of the household's HVAC consumption restrictions. On the other hand, low-income households often live in dwellings with a small floor area (HBS, 2019)[64], thus they would therefore need to air-condition most of their homes to achieve comfort (also given the inefficiency of their dwellings). The third kind of sensitivity analysis to the energy-expenditure threshold (the last two scenarios in Fig. 4. 12) focuses on the percentage of RENE set as absolute threshold. Fig. 4. 12 shows that 6% of households constrict their energy expenditure below a quarter of the RENE, thus experiencing 'extreme hidden energy poverty'. Moreover, 40% of Spanish households have actual energy expenditures below three-quarters of their RENE, thus they could be 'vulnerable to hidden energy poverty'.

Finally, only 10% of Spanish households could be considered in hidden energy poverty according to the 'adjusted to household's comfort strategy' scenario. This result implies that the 'adjusted to household's comfort strategy' HEP value decreases by 58% with respect to the base case scenario. Nevertheless, the reduction of the 'low absolute energy expenditure' indicator (RENE/2) is even bigger: the underconsuming households in the alternative scenario are 16%, i.e. the indicator's share decreases by 64% compared with the base case scenario. In this regard, Fig. 4. 15 shows the RENE/2 indicator's values in the 'adjusted to household's comfort strategy' scenario disaggregated by equivalised income decile. The share of underconsuming households has a similar distribution as in the base case scenario (see Fig. 4. 6), i.e. it is lower and quite stable in the five highest income deciles and it decreases with revenue in the five lowest income deciles. However, the indicator reduction with respect to the base case is more significant in the former (as already noticed in the HDD_18 and HDD_16 scenarios), where the RENE/2 share ranges between 9.5% and 12.5% (Fig. 4. 15).

In all analysed scenarios, the households belonging to the first income decile stands out as the ones with a much greater probability of being in hidden energy poverty.

[64] Exception cases exist, such as the single older people who are still living in their big family-dwellings.

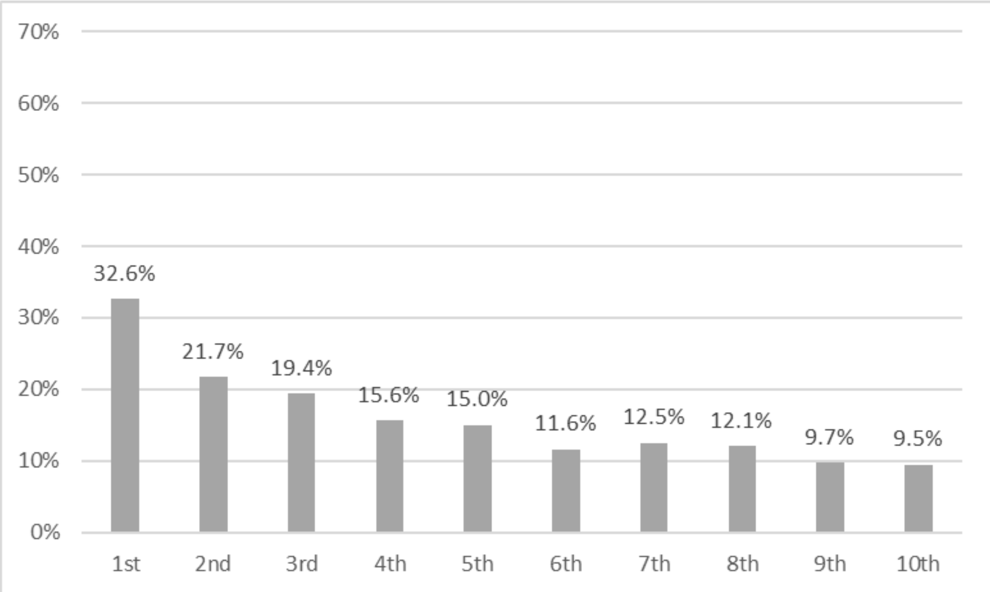

Fig. 4. 15. RENE/2 indicator's values in 2019 for each equivalised income decile in the 'adjusted to household's comfort strategy' scenario (reprinted from [136]*)*

Regarding the income threshold's sensitivity analysis, the value of HEP indicator calculated by using the AROP threshold as income criterion (16%) is much lower than the one obtained in the base case (25%). This significant difference can be corroborated by comparing the thresholds used in the two cases, i.e. €9,809 in the former and €11,716 in the latter. In other words, the AROP threshold is almost equal to the maximum income value considered in the third income decile. This implies that the sensitivity analysis' case considers only the households belonging to the first three income deciles.

All the above findings point out the sensitivity of the HEP indicator proposed in this chapter to both the absolute energy expenditure threshold and the income threshold considered. Nevertheless, giving the model's versatility, this methodology and its current and further applications might advise decision-makers to: (1) enhance the knowledge about households' required energy needs, (2) design absolute energy poverty indicators, and (3) implement more effective policies.

4.4 Conclusions and policy implications

The 'traditional' energy-poverty objective indicators have been usually based on a disproportionate expenditure approach, thus assessing the share of households whose energy expenditure is too high compared to their income. Nonetheless, vulnerable families often cope with their consumption, but this 'hidden face' of energy poverty has not been sufficiently addressed in the EU member states.

In this regard, the SNSEP included, among its energy poverty indicators, the EPOV's M/2 (as a proxy of the HEP indicator). Nevertheless, this metric uses a relative energy expenditure threshold (national median energy-expenditure), thus not considering households' required energy expenditures. Therefore, the EPOV's approach may have induced a misestimation of underconsumption in the country. Moreover, the M/2 indicator does not include any criterion to exclude false positives, i.e. those households that are 'voluntary' underconsuming (or, in other words, those that are not forced to reduce their energy consumption because of lack of affordability). The methodology presented in this chapter aims to fill these two gaps and is based on the same survey as the SNSEP (i.e. the HBS), so it could be integrated into the official monitoring of energy poverty in Spain and compared with other objective indicators.

Specifically, the analysis presented in this chapter shows that hidden energy poverty is a dimension of the overall phenomenon (i.e. energy poverty) that cannot be overlooked. Indeed, the high values of the proposed HEP indicator in Spain imply that there are households affected by energy poverty that are not benefitting from any national support scheme. In particular, the five lowest income deciles are the most affected by the underconsumption issue. In that regard, this work presents a criterion to distinguish the 'voluntary energy underconsumption', i.e. self-restriction driven by reasons other than an energy affordability issue (e.g. high energy efficiency standards, conscious consuming and physiological habits), from hidden energy poverty.

Therefore, the first objective of the methodology presented in this chapter is to determine an absolute threshold below which households' actual energy expenditures are 'objectively' too low to attain an adequate level of energy services (underconsumption). Thus, Section 4.2.1.1 introduces an adapted version of the Required ENergy Expenditure (RENE) model, which is used to assess the theoretical energy costs of the households included in the Spanish HBS, including both thermal energy (heating, cooling and DHW) and electricity (lighting, electrical appliances and cooking) uses. In this regard, the analysis carried out using the data from the Spanish HBS makes it possible to 'validate' the RENE/2 as absolute energy expenditure threshold and to introduce an income threshold as a proxy to estimate the share of households in hidden energy poverty. Finally, the 'energy poverty gap', calculated (only for households identified as energy poor) as the difference between half the household's RENE and their actual energy expenditures, makes it possible to estimate the depth of hidden energy poverty in Spain. Moreover, it might enable policymakers to calculate the annual budget needed to eradicate this social issue from the country.

According to the chapter's results, in 2019, 45% of Spanish households had low absolute energy expenditure, but only 56% of them (25% of the total households) were affected by hidden energy poverty. In the same year, the average 'energy poverty gap' per household was €374 and the national budget needed for a potential HEP-eradicating policy was €1,692m. This amount is eight times higher than the actual budget earmarked for the social tariffs in 2019. This finding could be justified also by comparing the HEP results with the number of households benefitted from the social tariffs in that year: at least 3.3 million of households in hidden energy poverty did not benefitted from the national mitigating measures. Another result obtained is the significant diversity of the HEP share across the different regions. The absence of HVAC systems or their sparing use (especially in households living in apparently mild winter climate regions), together with a low-income level, determine a higher HEP rate and raise the energy poverty gap in these households. Indeed, analysing the pattern of the regional average RENE, the heterogeneity of the climate among the Spanish regions has a major influence on the result. When considering the household size and income characteristics, large families with low-income are the most affected by hidden energy poverty, followed by single-member households. Moreover, the building age significantly influences this issue, i.e. households living in old dwellings have a higher HEP share than the ones living in recently constructed dwellings. The last two key factors included in the disaggregated analysis carried out in this work are the housing tenure and the urbanisation degree of the locality of residence. According to the chapter's results, tenants are more affected by hidden energy poverty than owners, as well as households living in rural areas compared to the ones living in more urbanised localities.

Furthermore, this chapter presents a sensitivity analysis of the HEP indicator to the primary parameters assumed for the absolute energy expenditure threshold. In this regard, varying the baseline heating temperature from 20ºC (comfort temperature in the Spanish regulation) to lower values, i.e. 18ºC (WHO comfort temperature) and 16ºC (minimum 'healthy-temperature' according to [278]), has a significant impact on the results obtained (the HEP value decreases, respectively, by 28% and 50%). Moreover, changing the share of RENE considered in the threshold makes it possible to identify both households in 'extreme hidden energy poverty' (using RENE/4) and households 'vulnerable to hidden energy poverty' (using 3/4 RENE). Alternatively, the chapter introduces an 'adjusted to household's comfort strategy' scenario that goes beyond the HVAC requirements of the Spanish regulation by adopting the WHO winter comfort temperature and the typical share of conditioned dwelling floor area of Spanish households. On the one hand, the alternative scenario's results show the same underconsumption pattern across the income deciles as the base case scenario, thus confirming that the five-highest-income-deciles' households with a low absolute energy expenditure should not be identified as energy poor. On the other hand, the HEP indicator in the 'adjusted to household's comfort strategy' scenario detects a significantly lower share of households in hidden energy poverty, thus pointing out the advisability (for the society) of engaging in a socio-political debate on what should be considered basic and required energy needs. Finally, an income sensitivity scenario based on the EU 'at risk of poverty' threshold shows that the income criterion selected to eliminate the false positives is also a key determinant of the share of households identified as affected by hidden energy poverty.

A general conclusion of all analysed scenarios is that the households belonging to the first income decile stands out as the ones with a much greater probability of being in hidden energy poverty. This suggests the urgent need to help these families whose economic situation pushes them to systematically and drastically reduce their energy consumption, and who therefore probably live in unhealthy conditions.

4.4.1 Policy recommendations and further work

The results presented in this chapter show that having low incomes is the main cause of hidden energy poverty in Spain, being the consumption's forced-self-restriction highly related to the household's financial resources. In addition, climatology and dwelling's energy efficiency are also key factors influencing the ability of families or individuals to meet their required energy needs.

In the light of these findings, the following policy implications are pointed out:

1. *Mitigating measures should consider the multifaceted nature of energy poverty.*
   The current national mitigating policies in Spain are not reaching all the households affected by energy poverty, and their impact is limited (as shown in [236] and [230]). The lack of knowledge partially explains the former problem, i.e. vulnerable households often do not know the support programs or are uninformed about how to apply for them. Thus, the SNSEP proposals to tackle this issue should be implemented in the short-term ‘to raise people awareness on energy poverty and improve households' information in respect of energy use and support programs available to consumers’ [287].
   On the other hand, the insufficient characterisation of energy poverty in the country has caused an inaccurate design of these measures. Indeed, according to the results of this chapter for 2019, at least 3.3 million households in hidden energy poverty did not benefit from the social tariffs. Therefore, energy poverty mitigation programs need to be adapted to incorporate this widespread casuistry. Nonetheless, social tariffs would hardly eradicate hidden energy poverty because a (small) discount does not remove the 'fear of the bill'. One key to alleviating this hidden face of energy poverty could be to complement or replace social tariffs with the implementation of a minimum vital supply (MVS, which was already included in the SNSEP as future regulatory proposal), or apply social tariffs to more household categories by targeting those more vulnerable to hidden energy poverty.
2. *The energy efficiency programs should prioritise vulnerable households.*
   The EU Renovation Wave and the long-term national strategies for energy renovation in the building sector need to adopt the perspective of vulnerable households, also acknowledging externalities caused by housing market mechanisms. Energy renovation measures, such as retrofitting the building envelope or replacing the thermal systems and household appliances, can help households (of all income levels) to achieve better comfort conditions in their home while reducing their bills. Given the chapter’s results (30.7% of the households living in older dwellings are in hidden energy poverty), the renovation should prioritise vulnerable households living in inefficient houses, which frequently cannot attain a required level of energy services. Moreover, given the higher share of tenants in hidden energy poverty compared to the HEP share in households that own their home, it is important to design effective schemes to solve the tenant-landlord dilemma, thus supporting the energy retrofitting of rented dwellings. Furthermore, the HBS should contain more specific information on the energy efficiency and age of dwellings. These data could help stakeholders and scholars to monitor the implementation of the energy renovation strategies and assess their impact on energy poverty.
3. *Local actions are crucial to tackle energy poverty.*
   The local differences in climatology (especially in a changing climate scenario [265]) and socio-demographic features should be taken into account when designing policies. In this sense, the chapter’s results point out that the geographical area and urbanisation degree of the municipalities where households live are crucial factors to consider when analysing and tackling hidden energy

poverty. Thus, national and local administrations, together with other stakeholders, should enhance their collaboration to target mitigating and structural energy poverty measures appropriately. In this line, the new EU Energy Poverty Advisory Hub aims to provide direct support, training, and information to local authorities and civil society organisations and identify and promote local actions to tackle energy poverty.

These policy recommendations could be integrated within the European framework of the New Green Deal to develop and implement policies that support a 'right to (modern and clean) energy' [288], [289] as well as a 'right to energy efficiency' [290].

Further work could analyse the significance of other household characteristics, such as their composition and employment[65] [291], or the impact of temperature and climate changes on the HVAC demand (by using the HDD and CDD). Moreover, the methodology presented in this chapter may be adapted to other countries by considering the dissimilarities in socio-demographic features, building stock and regulation, energy prices, and climatic characteristics, as shown in previous studies [292].

Eventually, this chapter provides a flexible methodology to assess the share of households that are underconsuming because of a lack of affordability and purchasing power. However, considering the weaknesses of official national statistics such as the HBS (e.g. lack of information on: household's locality of residence, the financial supports the households benefit from and their contracted energy tariffs, etc.), the macro-level analysis carried out in this chapter provides a general picture of hidden energy poverty in Spain, but does not make it possible to identify individual cases. Notably, there are some social groups not included in the HBS (households living in informal dwellings, Roma communities, etc., [13] presented an example from Spain) that are usually ruled out from energy poverty analyses ('invisible energy poverty'). Moreover, several assumptions and simplifications were made to adapt the RENE model to the Spanish HBS, which, in some instances, could have led to a less accurate evaluation of the theoretical energy costs. Indeed, the first reason of the detected high under-consumption is the strict HVAC standard set by the CTE, which does not correspond to the actual patterns of all Spanish households (even the richest one), neither in the comfort temperature, nor in the heated or cooled floor area, nor in the hours of use. Some of these limitations have been addressed by introducing an 'adjusted to household's comfort strategy' scenario that 'enhances' the RTEE hypotheses, but further work is still needed to integrate the HVAC consumption patterns in the model (e.g. considering the dwelling's occupancy and setting different baseline temperatures for daytime and night-time). Eventually, giving the model's versatility, this methodology and its current and further applications might help policymakers implement policies and prevention measures that tackle hidden energy poverty properly at both national and regional levels.

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[65] Both household characteristics contribute to determine the consumption patterns [66]; these could be studied using the time use surveys, which are carried out both at national and European level, or specific surveys on the households' energy lifestyle [291].

Finally, it should be emphasised that the HEP indicator presented in this chapter is not proposed as an alternative to subjective metrics such as the ‘inadequate temperature at home’ (both in winter and summer), which could also detect hidden energy poverty circumstances (i.e. self-imposed restriction of heating or cooling consumption), but as a complementary indicator. Therefore, further work is required to, on the one hand, carry out and analyse primary energy poverty surveys (which could provide micro-level information on this issue). On the other hand, ongoing and published works [119], [293] are complementing the HEP indicator with other metrics to consider the multidimensionality of energy poverty.

5. FEASIBILITY STUDY OF AIR-WATER HEAT PUMPS TO FACE ENERGY POVERTY IN SPAIN

Regarding energy needs that remain totally or partially unmet in energy poor households, heating needs are particularly remarkable, as pointed out in Chapter 4. A potential enhancement in this respect could be the installation of clean and efficient heating systems, such as centralised heat pumps. Therefore, this chapter[66] studies the tecno-economic feasibility of two typologies of centralised air-water devices, namely electrically driven and natural gas engine driven heat pumps, as potential structural measures to decrease the energy burden of vulnerable households and achieve thermal comfort at home.

The structure of the chapter is as follows. Section 5.1 introduces the regulatory and technical framework of heat pumps in the EU and Spain, and presents the chapter's contribution. Section 5.2 describes the methodology proposed to calculate the hourly required heating demand and the heat pumps modelling. Subsequently, Section 5.3 analyses the results of the heating demand assessment and the coupling and application of the heat pumps' modelling. Finally, Section 5.4 points out some conclusions and further work.

5.1 Introduction

The European Heat Pump Association, within the EU consultation 'Energy efficiency in buildings – consultation on 'renovation wave' initiative' [294], stated that 'heat pumps offer already today a variety of solutions for heating, cooling, and domestic hot water production, which are ready-to-use for the large majority of the residential and commercial building stock in Europe, as well as for industrial processes'. In this regard, the air-water heat pumps are a promising alternative to replace the old heating boilers of households living in block dwellings, and it could contribute to tackle energy poverty in the EU Member States. These dwellings usually have oversized radiators, which enables them to be fed with low temperature water, then having a temperature range that is suitable for air source heat pumps water heaters (ASHPWH) [295]. The EU considers that the energy taken from the air in the evaporator can be accounted as renewable energy if the HSPF exceeds certain values [296]. Due to this, the replacement of centralised gas boilers by heat pumps would make it possible to introduce renewable energies in heating, so achieving an efficient and clean heating system. Such renovation should take into account the impact of the electricity taken from the grid in terms of CO_2 emissions, which depends on the electricity generation mix of the country. Moreover, heat pumps must face two further environmental issues, i.e. the ozone depletion potential (ODP, already solved

[66] This chapter is partially based on the paper: 'Feasibility Study of a Centralised Electrically Driven Air Source Heat Pump Water Heater to Face Energy Poverty in Block Dwellings in Madrid (Spain)', written by the author, Irene Priego, José Ignacio Linares, Eva Arenas, José Carlos Romero and Efraim Centeno and published in Energies [308]. It also includes quotations from the mentioned article.

with the use of hydrofluorocarbons, HFCs) and the global warming potential (GWP). Indeed, the GWP of the HFCs used as refrigerants is frequently too high. In this regard, the EU has regulated the use of fluorinated greenhouse gases (F-gases) [297] by establishing a roadmap to move from HFC to natural refrigerants[67] (propane, butane, ammonia, CO_2, etc.), passing through hydrofluoroolefins (HFO) as intermediate fluids. Regarding the case study of this chapter, in December 2019, the Spanish regulation [84] included heat pumps as a renewable option to supply thermal services to buildings, especially for domestic hot water (DHW) production. Nevertheless, the use of heat pumps for heating purposes is still not common in Spain. Particularly, space heating from these systems is usually a by-product of cooling services, using the so-called air-to-air reversible heat pumps, which are the most common heat pumps on the Spanish residential sector [298]. This situation is considered by the EU [296], but they penalise this type of heat pumps when counting renewable energy due to the fact that they are usually designed to operate in cooling mode.

In this context, the current chapter analyses the efficiency of both electrically and gas engine driven heat pumps as realistic alternative technologies to achieve winter thermal comfort in vulnerable households and enhance heating's energy efficiency in the residential sector. Particularly, this work investigates the feasibility of air source heat pumps water heaters (ASHPWH) as a structural measure to tackle energy poverty and reduce CO_2 emissions. This study was firstly performed for electrically driven heat pumps (EHPs), due to its higher commercial deployment in Spain. Subsequently, the analysis was replicated for gas engine driven heat pumps (GHPs), which are thermally driven by an internal combustion engine. For both heat pumps, the baseline case is defined for a block of dwellings with a middle-level of energy efficiency (constructed between 1981 and 2007, see Section 3.2.1.2 for further explanation) in Madrid (D winter climate zone). Additionally, several parametric analyses were performed to assess the heat pumps' behaviour in different winter climate zones and building energy efficiency levels. Therefore, retrofitting alternatives are considered to analyse the combine effect of heating system replacement and thermal enclosure retrofit. The performance of both types of heat pumps is compared with other alternatives (centralised and decentralised natural gas boilers). Moreover, the cost breakdown of the EHP is detailed, which makes it possible to evaluate potential subsidy schemes in order to fund this kind of devices.

The novelty of this chapter lies on the evaluation of the use of centralised heat pumps to meet the heating demand in the Spanish residential sector. These solutions are usually

[67] This change faces to some challenges. Summarising:
- Many HFOs are flammable, to varying degrees, which requires training and qualification for refrigeration technicians. In fact, their flammability had to be reclassified so that they could retain the right to intervene.
- On the other hand, some natural refrigerants are also flammable and toxic (ammonia: R717) or directly combustible (butane: R600 and R600a; propane: R290, etc.).
- CO_2 (R744) is very promising, but requires special control regulation systems because of its transcritical cycle: it does not condense, so there is no relationship between pressure and temperature in the condenser (now called gas cooler), which means there are optimal working pressures.
- Finally, oil compatibility problems should be taken into account, which always exist when changing refrigerants.

employed in northern European countries, especially using ground source heat pumps. However, as mentioned before, the use of air-water heat pumps is not common in Spain, but it is already regulated in the last release of the Spanish Technical Building Code (CTE) [84] . In this regard, the presented heat pump model is not sophisticated, although it is accurate enough, as can be derived from the comparison with commercial machines. Regarding the required hourly heating demand model, a simpler version has been proposed in previous studies[86], but, as a novelty, the version that is used in this work is able to consider the thermal insulation level of the building. This information makes it possible to evaluate the effect of energy building retrofitting. Therefore, the objective of this chapter is to analyse the feasibility of ASHPWHs as active measure to fight energy poverty in Spanish dwelling blocks. Specifically, the performed environmental and economic assessment may eventually provide insightful information to policy makers for implementing clean and efficient measures to tackle energy poverty.

5.2 Methodology and initial results

5.2.1 Hourly Required Heating Demand

The Spanish Building Technical Code (CTE) regulates the calculation of energy demand in both winter and summer as a function of the climate severity index [81]. In this chapter, only heating demand is considered, so focusing on winter energy needs, because of two main reasons: (1) both statistics and theoretical models referred to this demand as the predominant one in the Spanish residential sector (see Chapter 3 and 4); (2) energy poverty studies have been mainly focused on winter being it a crucial season for vulnerable households [299]. The base case scenario refers to block dwellings in the city of Madrid (tier D of winter severity in Spain). Subsequently, a parametric analysis was performed to extend the results to other Spanish winter climate zones.

The reference specific demand (*RD*[68], kWh/m^2) in winter is given by Eq. (5.1), where *WS* stands for the winter severity index and Table 5. 1 provides the coefficients α and β. The winter severity index is defined in Eq. (5.2), where *RAD* is the average accumulated global radiation over horizontal surface during January, February, and December (Eq. (5.3)), and HDD is the average heating degree-days value (at base temperature T_b = 20 °C) for the same months (Eq. (5.4a)) [300]. Table 5. 2provides the coefficients for Eq. (5.2). The calculation of *RAD* requires the global hourly radiation over horizontal surface (r_k), whereas the calculation of *HDD* requires the hourly temperature difference (ΔT_k), as defined by Eq. (5.4b). Hourly values of T_k are available for each climatic zone in the web site of the CTE [301].

[68] The nomenclature for the reference specific demand used in this chapter is different from the one used in Chapter 3 because the aim of Chapter 5 is to obtain the hourly heating demand, and it is in line with the published paper [308].

$$RD = \alpha + \beta \cdot WS \tag{5.1}$$

$$WS = a \cdot RAD + b \cdot HDD + c \cdot RAD \cdot HDD + d \cdot RAD^2 + e \cdot HDD^2 + f \tag{5.2}$$

$$RAD = \frac{\sum_{k=1}^{24\times 90} r_k}{3} \tag{5.3}$$

$$HDD = \frac{\sum_{k=1}^{24\times 90} \Delta T_k}{24 \times 3} \tag{5.4a}$$

$$\Delta T_k = \begin{cases} T_b - T_k & if\ T_b > T_k \\ 0 & otherwise \end{cases} \tag{5.4b}$$

Table 5. 1. Coefficients required to obtain the reference specific demand in winter [302].

	α	β
Single-family house	9.29	54.98
Block dwellings	3.51	39.57

Table 5. 2. Coefficients required to obtain the winter severity index (WS) [300].

a	b	c	d	e	f
-8.35×10^{-3}	3.72×10^{-3}	-8.62×10^{-6}	4.88×10^{-5}	7.15×10^{-7}	-6.81×10^{-2}

RD and WS are overall values, that is, they are calculated for the complete winter season, as it is observed in Eqs. (5.1) and (5.2). Based on these equations, a Taylor series expansion of first order around (RAD, HDD) has been carried out over WS. This procedure leads to an hourly expression of the specific reference demand (Eq. (5.5a)), where: (1) the index j is extended from 1 to 4368 (number of hours from January to March and from October to December), (2) N_d is equal to 182 days (number of days in the same period), (3) N_m is equal to 6 (number of months), and (4) the star denotes that this specific reference demand needs to be corrected. This correction has to be done to take into account two different issues. Firstly, the effect of the radiation and second, the fact that three additional months have been included with respect to the original correlation.

The correction of the radiation is performed because, sometimes, its value is high enough to result in a cooling demand (negative heating demand). In this case, the heating demand is set to zero. On the other hand, to consider the inclusion of additional months in the formulation, a reduction coefficient (C_r) is defined as the ratio of the actual specific seasonal demand (RD^a, given in regulations [303] and equal to 53 kWh/m^2 for Madrid) to the sum of RD_j^* over the 4,368 h. Accordingly, the corrected hourly specific reference demand $\left(RD_j\right)$ is given in Eq. (5.5d).

$$RD_j^* = \frac{\alpha + \beta \cdot (WS - \rho \cdot RAD - \delta \cdot HDD)}{24 \cdot N_d} + \left(\frac{\beta \cdot \rho}{N_m}\right) \cdot r_j + \left(\frac{\beta \cdot \delta}{24 \cdot N_m}\right) \cdot \Delta T_j \qquad (5.5a)$$

$$\rho = a + 2 \cdot d \cdot RAD + c \cdot HDD \qquad (5.5b)$$

$$\delta = b + c \cdot RAD + 2 \cdot e \cdot HDD \qquad (5.5c)$$

$$RD_j = (RD_j^* \cdot \gamma) \cdot \underbrace{\left(\frac{RD^a}{\sum_{j=1}^{4368}(RD_j^* \cdot \gamma)}\right)}_{C_r} \qquad (5.5d)$$

$$\gamma = \begin{cases} 1 & if\ RD_j^* > 0 \\ 0 & otherwise \end{cases} \qquad (5.5e)$$

Once the hourly specific reference demand is obtained, it should be corrected according to the energy performance index (*EEP*) and the ratio of the reference demand of the whole stock of reference buildings to the 10-th percentile of this stock (*R*) [81]. This correction leads to the calculation of the hourly absolute demand (D_j, Eq. (5.6)), where the heated floor area (*A*) has been included. In Eq. (5.6), the *EEP* is obtained from the energy performance certificate of the building and *R* is given at Table 5. 3, where the climatic zone ranges from mild winter (A) to severe winter (E). For the current research, the *EEP* values have been calculated by cross-correlating the CENSUS 2011 data and the buildings-energy-certification data [304]. The average *EEP* values for D zone (Madrid) are found to be 3.53 for block dwellings built before 1980, 2.18 if they were built between 1981 and 2007 and 0.92 for the ones built after 2007. Vulnerable households typically live in old buildings and use inefficient heating installations, typically electric radiators, as shown in the literature [305], [306], [307]. For this reason, the first two building age categories are those in which this collective of households is commonly located. In this study, as explained in Section 5.1, the block dwellings built between 1981 and 2007 are chosen as the baseline case.

$$D_j = A \cdot RD_j \cdot \left(\frac{1 + (EPI - 0.6) \cdot 2 \cdot (R - 1)}{R}\right) \qquad (5.6)$$

Table 5. 3. Values for R in Eq. (5.6) [81].

Winter Climatic Zone	Single-Family House	Block Dwellings
A	1.7	1.7
B	1.6	1.7
C	1.5	1.7
D	1.5	1.7
E	1.4	1.7

Fig. 5. 1 displays the hourly demand for each ambient wet bulb temperature (Wet bulb temperature is used as a measurement of the enthalpy of humid air). It shows a cloud of points following a linear regression curve (enclosed in a red dashed line), along with a set of disperse data with lower heating demand. The data density increases with the temperature, in agreement with the radiation issue previously explained.

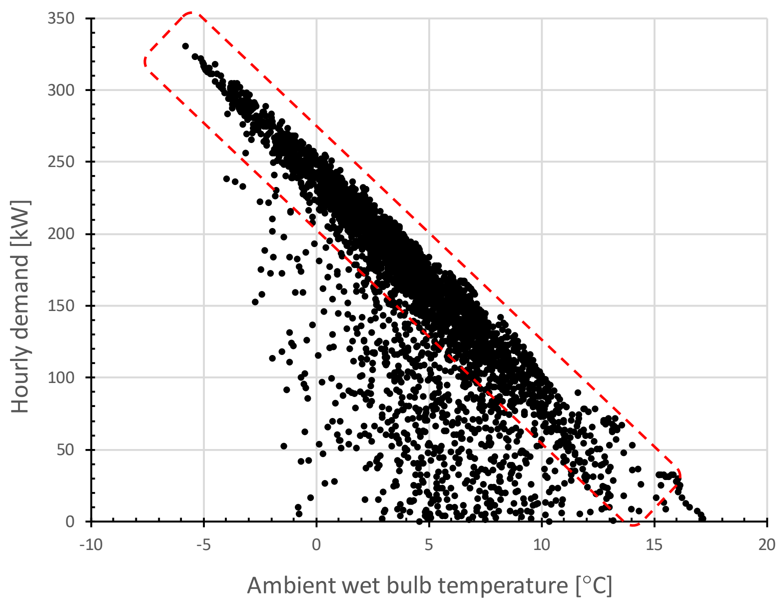

Fig. 5. 1. Hourly heating demand profile for each ambient wet bulb temperature for a set of block dwellings in Madrid built between 1981 to 2007 with 6000 m2 of total heated floor area (reprinted from [308]*)*

Finally, the hourly demand is sorted from maximum to minimum, obtaining the annual cumulative heating demand profile, as shown in Fig. 5. 2.

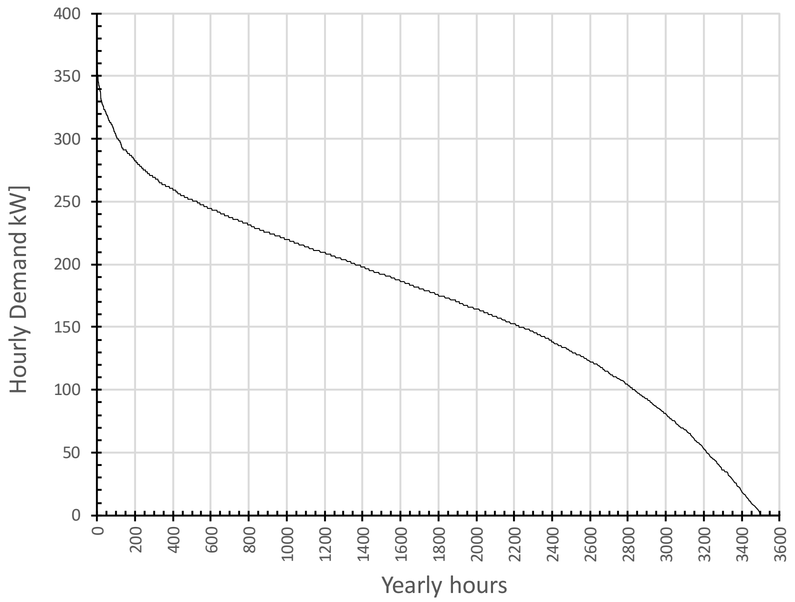

Fig. 5. 2. Annual cumulative heating demand profile for a set of block dwellings in Madrid built between 1981 to 2007 with 6000 m² of total heated floor area (reprinted from [308]*).*

5.2.2 Heat Pump Models

5.2.2.1 Electrically driven heat pump

Two models have been developed to obtain the performance of the heat pump: one for the best efficiency point (BEP) and another for the off-design operation. The former is used to size the main components and the latter to obtain the performance map. The heat pump uses the air as thermal source. Thus, a rotational speed control (inverter) driving the compressor motor is assumed in order to avoid the loss of heating capacity when the ambient temperature decreases. Nominal rotational speed is taken as 1,490 rpm, with a range of variation from 745 to 2,235 rpm (± 50 %). Out of these limits, a back-up system is necessary, assumed as a condensing boiler with modulation, fuelled by natural gas. The efficiency of this boiler has been taken as 95% (based on higher heating value, HHV), assumed constant considering the usual seasonal performance factor values reported by manufacturers [309]. In order to further improve the heat pump efficiency, the rotational speed of the evaporator fan is also controlled to keep constant the temperature drop in the air. The heat pump is an air/water system, so water of the existing radiators' heating loop is heated in the condenser. The heat pump takes advantage of the usual oversizing employed in the radiators heat transfer area to make them behave as low temperature radiators, so enabling the use of heat pump as heater. Domestic hot water demand is covered by solar thermal energy supported by natural gas, but this is out of the scope of this analysis. Cooling demand is not considered, according to the common trend in energy poverty studies [299].

Fig. 5. 3 shows a scheme of the heat pump. An adiabatic reciprocating compressor is chosen, in accordance with actual commercial trends [310]. The isentropic efficiency (Eq. (5.7)) is used to model the compressor and the polytropic exponent (*n)* can be obtained as shown in Eq. (5.8). Regarding the refrigerant mass flow rate ($\dot{m}$), the volumetric efficiency (η_v, Eq. (5.9)) is used. In Eqs. (5.7) to (5.9) *h* stands for enthalpy, *s* entropy, *p* pressure, *v* specific volume, V_s swept volume, *r* pressure ratio and α relative clearance volume.

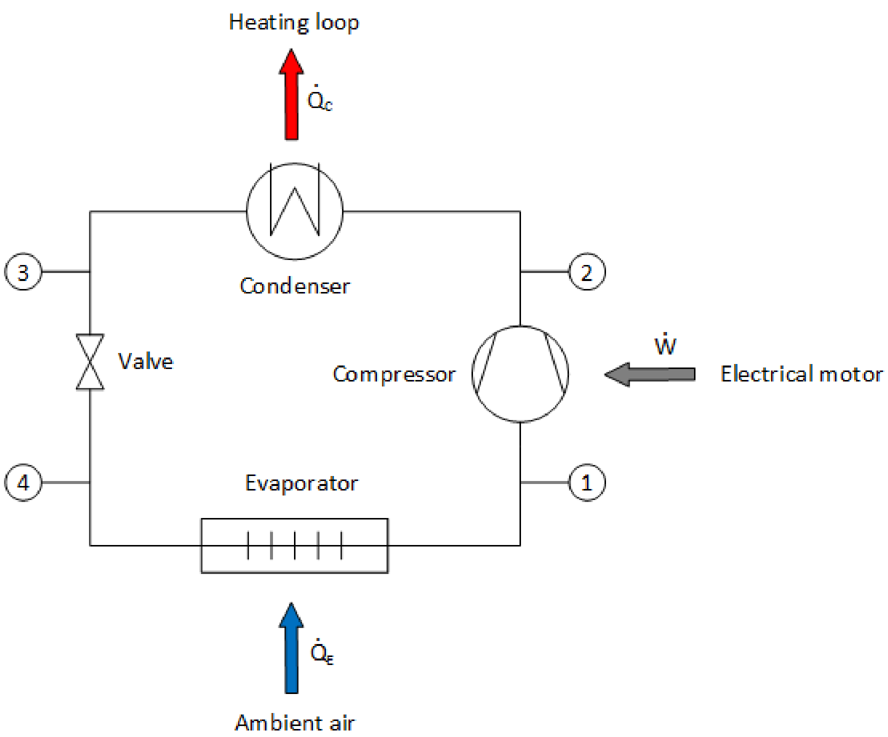

Fig. 5. 3 Layout of the heat pump (reprinted from [308]*).*

The nominal parameters to solve the best efficiency point are:

- Condenser:
  - Heating capacity $(\dot{Q}_c)$: 200 kWth
  - Water conditions: 45°C at condenser inlet (T_{wi}) and 55°C at condenser outlet (T_{wo}). A counterflow heat exchanger is assumed, feeding the water to an existing low temperature radiator system.
  - Outlet refrigerant conditions: saturated liquid and appropriate approach temperature (ΔT_c) to achieve 5°C of pinch point (at saturated vapour state). This approach temperature is 13°C for R290 (propane), which, as it will be explained below, has been chosen as the refrigerant of the heat pump.

- Evaporator:
    - Air conditions: 5°C as ambient wet bulb temperature (taken as evaporator inlet, T_{ai})) and -5°C as wet bulb temperature at evaporator outlet (T_{ao}). An ambient pressure of 95 kPa is assumed (Madrid exhibits an elevation over the sea level of 655 m).
    - Outlet working conditions: superheating (ΔT_v) of 5 °C
    - Inlet working conditions: approach temperature (ΔT_e) of 10 °C
- Compressor:
    - Speed (N): 1490 rpm
    - Isentropic efficiency (η_s): 75 % (includes motor and inverter efficiencies)
    - Relative clearance volume (α): 3 %.

$$\eta_s = \frac{h(s_1; p_2) - h_1}{h_2 - h_1} \tag{5.7}$$

$$r = \left(\frac{p_2}{p_1}\right) = \left(\frac{v_1}{v_2}\right)^n \tag{5.8}$$

$$\eta_v = \frac{\dot{m}}{\left(\frac{V_s}{v_1}\right) \cdot \left(\frac{N}{60}\right)} = 1 - \alpha \cdot \left(r^{1/n} - 1\right) \tag{5.9}$$

The condenser is a refrigerant/water counter-flow heat exchanger. The energy balance is given in Eq. (5.10), where $\dot{m}_w$ stands for mass flow rate of water. The approach temperature results in a relationship between both fluids (Eq. (5.11)), where refrigerant outlet temperature is the condensation temperature (refrigerant is saturated liquid at state 3), linked to the condensation pressure (Eq. (5.12)). Enthalpy for water is assessed as enthalpy of saturated liquid at the water temperature. No pressure drop is considered (Eq. (5.13)).

$$\dot{Q}_C = \dot{m} \cdot (h_2 - h_3) = \dot{m}_w \cdot (h_{wo} - h_{wi}) \tag{5.10}$$

$$\Delta T_c = T_3 - T_{wi} \tag{5.11}$$

$$T_3 = T_{sat}(p_3) \tag{5.12}$$

$$p_2 = p_3 \tag{5.13}$$

The valve is considered to be adiabatic, so as kinetic and potential energy are neglected, it is modelled as iso-enthalpic (Eq. (5.14)). Besides, the valve is assumed to be a thermostatic expansion valve, so it keeps the superheating at the compressor suction (Eq. (5.15)) constant by acting on the refrigerant mass flow rate.

$$h_3 = h_4 \tag{5.14}$$

$$\Delta T_v = T_1 - T_4 = constant \tag{5.15}$$

The evaporator is an air/refrigerant cross-flow heat exchanger. The energy balance is given in Eq. (5.16), where $\dot{m}_a$ stands for air mass flow rate and $\left(\dot{Q}_E\right)$ stands for the rate of heat transfer. As in the condenser, the approach temperature establishes a relationship between the fluids (Eq. (5.17)), where refrigerant inlet temperature is the evaporation temperature (refrigerant is a liquid-vapor mixture at state 4), linked to the evaporation pressure (Eq. (5.18)). No pressure drop is considered (Eq. (5.19)).

$$\dot{Q}_E = \dot{m} \cdot (h_1 - h_4) = \dot{m}_a \cdot (h_{ai} - h_{ao}) \tag{5.16}$$

$$\Delta T_e = T_{ao} - T_4 \tag{5.17}$$

$$T_4 = T_{sat}(p_4) \tag{5.18}$$

$$p_4 = p_1 \tag{5.19}$$

The main performance parameters of the heat pump in its nominal point (BEP) are the heating capacity (useful heat released in the condenser), previously defined, the compressor consumption ($\dot{W}$, Eq. (5.20)) and the *COP* (Eq. (5.21)). In the design point, all of them are instantaneous values; later on, in the off-design operation, they will be redefined in a seasonal sense, and the power rates ($\dot{Q}_C$ and $\dot{W}$) and the instantaneous *COP* will be time-integrated.

$$\dot{W} = \dot{m} \cdot (h_2 - h_1) \tag{5.20}$$

$$COP = \frac{\dot{Q}_C}{\dot{W}} \tag{5.21}$$

The refrigerant has to comply with regulations about the global warming potential (GWP) and ozone depletion potential (ODP) [297] of the European Union. So, in order to select a fluid valid for long term, R-290 (propane) is chosen, due to the fact that it is a natural refrigerant with null ODP and a GWP value of 3. On the other hand, it is included in the A3 class of the flammability safety classification (ASHRAE), thus considered highly flammable. Fig. 5. 4 shows the pressure-enthalpy diagram for R-290, where the assumptions previously stated for the best efficiency point are represented. It can be seen that the compressor discharge temperature is not too high and the de-superheating interval is small (around 20% of the overall heating capacity). Both values are in accordance with the fact that domestic hot water is heated by using other procedures.

Once the design point has been solved, the main parameters of the heat pump are fixed. They are summarised in Table 5. 4. At this point (inlet air temperature of 5°C and outlet water temperature of 55°C, usually known as A5/W55) the heating capacity is set as 200 kWth, the compressor consumption is found to be 76.15 kWe, and then the COP results in 2.626.

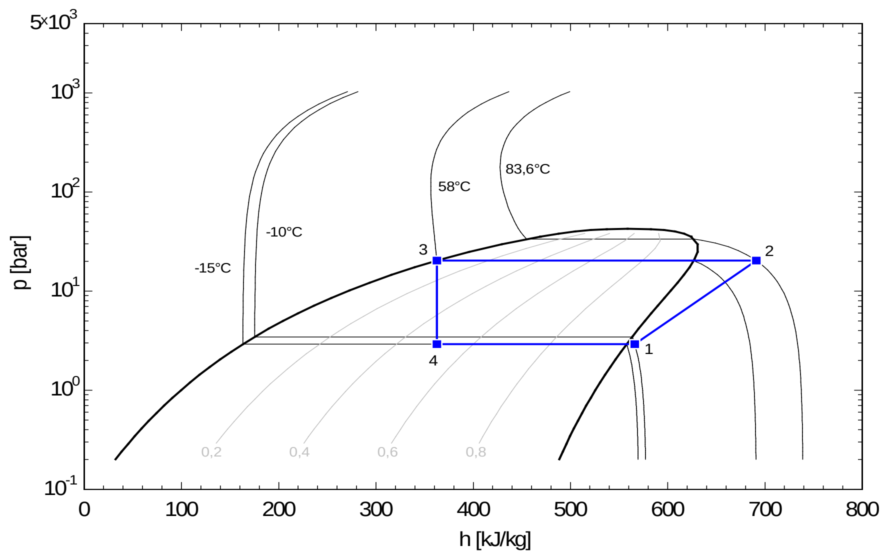

Fig. 5. 4. P-h diagram for the design point (reprinted from [308]*).*

Table 5. 4. Main parameters of the heat pump calculated in the design point and set as constant in off-design operation.

Heat pump parameter	
Swept volume, V_s [cm^3/rev]	4,558
Polytropic exponent, n [-]	1.075
Condenser approach, ΔT_c [°C]	13
Evaporator approach, ΔT_e [°C]	10
Temperature drop at air, $T_{ai} - T_{ao}$ [°C]	10
Superheating at compressor suction, ΔT_v [°C]	5
Water inlet temperature, T_{wi} [°C]	45
Water outlet temperature, T_{wo} [°C]	55

The modelling of the BEP and the off-design operation have been carried out for different purposes. On one hand, the model of the BEP is developed to define the heat pump parameters that determine its size (listed in Table 5. 4). On the other hand, the off-design model aims to obtain the performance of the heat pump as a function of both the ambient temperature and the heating load, in order to work out the seasonal performance of the device. The input variables are the ambient wet bulb temperature and the rotational speed of the compressor. Eqs. 5.8 to 5.21 are now solved using the parameters given in Table 5. 4. Note that isentropic efficiency of the compressor is replaced by the polytropic relationship (Eq. 5.8) and that the mass flow rates of refrigerant, air and water are now unknown. Approach temperatures in the heat exchangers have been fixed, assuming that the number of transfer units are high enough to work in the asymptotic range of effectiveness. The main functions of the off-design model are listed in Eqs. (5.22) and (5.23), which lead to Eq. (5.24). Another limit should be imposed: the maximum driving power of the motor, assumed as 1.5 times the power consumed at BEP.

$$\dot{Q}_C = \dot{Q}_C(T_{ai}, N) \tag{5.22}$$

$$\mathrm{COP} = COP(T_{ai}, N) \tag{5.23}$$

$$\dot{W} = \frac{\dot{Q}_C(T_{ai}, N)}{COP(T_{ai}, N)} = \dot{W}(T_{ai}, N) \tag{5.24}$$

5.2.2.2 Gas engine driven heat pump

Two different GHPs have been used for this study: the former with a design heating capacity of 75 kWth and the latter with a design heating capacity of 25 kWth. These two models were used as they are provided by the manufacturer (see [311]). Combining these two models will allow the higher rated heat pumps to be used to cover the bulk of the demand as they have better efficiencies and the 25 kWth pump will be used to cover the peak of the demand as it allows optimising the load degree of the pumps in operation.

In order to characterise the operation of these devices, Table A 42 and Table A 43 were used, which define the operation of the machines under different operating conditions. Using these tables, a linear regression was conducted to understand how the different variables affect the heat pump performance. To determine whether the linear regression model is good enough, a value of 95% was used as the lower limit of R2; if this minimum value was not achieved, the complexity of the models was increased to take into account the interaction between the variables and to include higher degree polynomial terms.

5.2.2.3 Coupling of the Demand and Heat Pump Models

Once the hourly heating demand (Eq. (5.6)) and the EHP performance (Eqs. (5.22) and (5.24)) are determined, the map of the device coupled to the demand can be obtained, producing a diagram similar to the one shown in Fig. 5. 5, where the heating demand only considers the linear regression curve for the sake of clarity. At the nominal rotational speed, a positive slope line determines the heating capacity of the heat pump for each temperature. This line cuts to the heating load line in one point. In order to modulate the response of the heat pump, the rotational speed is varied, so sweeping the operation zone and cutting to the load curve in a large range. For temperatures out of that range, the back-up system acts (if the load is higher than the heat pump capacity) or the machine is operated in on/off mode, to adapt the excess of capacity to the low demand.

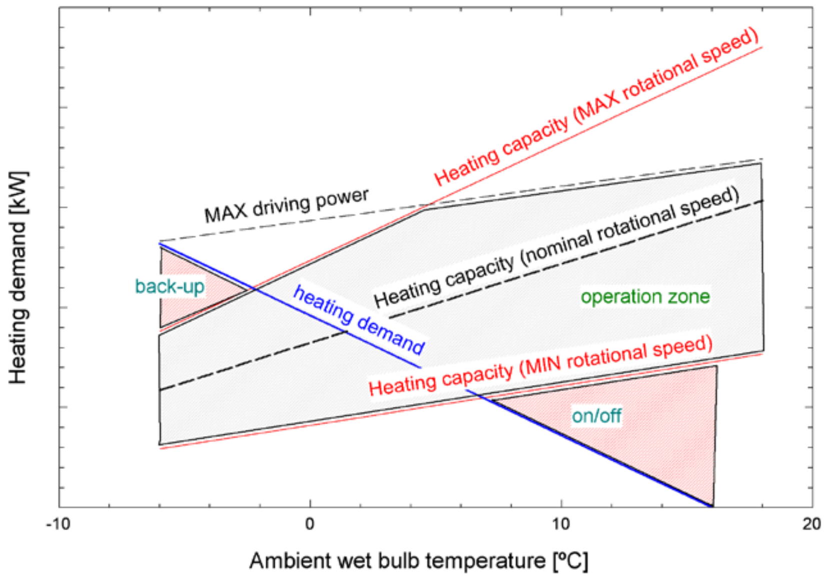

Fig. 5. 5 Coupling between demand and performance of the heat pump (reprinted from [308]*)*

Thus, the consumption of the heat pump ($\dot{W}_j$) and the back-up system ($\dot{F}_j^{bkp}$) (if any) to meet the demand are calculated, for each operation hour, using the functions given in Eqs. 5.25.a, b, c and d. In Eq. (5.25.c), *bkp* stands for the back-up system, assumed as a natural gas condensing boiler with a constant efficiency (η_{bkp}) value of 95 % on higher heating value basis. In the same equation, $\dot{F}$ stands for the (again based on HHV) of the back-up system. Eq. (5.25.d) determines the power of the back-up boiler ($\dot{Q}_{bkp}$). As it is derived from the algorithm described in Eqs. (5.25), in the on/off operation range the demand is covered by the heat pump working at the minimum rotational speed. Defrosting cycles are neglected, due to the usually low air moisture content in Madrid [312].

$$\dot{Q}_{C,j}^{max} = max\{\dot{Q}_C(T_{ai,j}, N_{max}), COP(T_{ai,j}, N_{max}) \cdot 1.5 \cdot \dot{W}(T_{ai,j}^{design}, N_{design})\} \quad (5.25.a)$$

$$\dot{W}_j = \begin{cases} \dot{Q}_{c,j}/COP\left(T_{ai,j}, N_j\right) & if\ D_j \le \dot{Q}_{C,j}^{max} \\ \dot{Q}_{C,j}^{max}/COP\left(T_{ai,j}, N_j\right) & otherwise \end{cases} \tag{5.25.b}$$

$$\dot{F}_j^{bkp} = \begin{cases} 0 & if\ D_j \le \dot{Q}_{C,j}^{max} \\ \left(D_j - \dot{Q}_{C,j}^{max}\right)/\eta_{bkp} & otherwise \end{cases} \tag{5.25.c}$$

$$\dot{Q}_{bkp} = max\left\{\dot{F}_j^{bkp}\right\} \tag{5.25.d}$$

Some seasonal performance indexes have been defined: heating seasonal performance factor (*HSPF*, Eq. (5.26)), CO_2 avoided ratio (*AVCO2*, Eq. (5.27)) and renewable input to heating demand ratio (*R2H*, Eq. (5.28)). Numerical coefficients employed in Eqs. (5.27) and (5.28.a) make it possible to consider the environmental impact of the electricity coming from the grid to drive the heat pump. They have been taken from [313],according to the Spanish energy sector. In Eq. (5.27), 0.331 and 0.252 are the CO_2 emission factors for, respectively, electricity (considering the Spanish electricity mix) and natural gas. In Eq. (5.28.a), the factor 0.414 represents the ratio of renewable primary energy to final electrical energy in Spain. Eq. (5.28.b) comes from the current EU regulation about the support to heat pumps [296].

$$HSPF = \frac{\sum_{j=1}^{4,368} \dot{W}_j \cdot COP\left(T_{ai,j}, N_j\right)}{\sum_{j=1}^{4,368} \dot{W}_j} \tag{5.26}$$

$$AVCO2 = \frac{\left(\frac{\sum_{j=1}^{4,368} D_j}{\eta_{bkp}}\right) \cdot 0.252 - \left[0.331 \cdot \sum_{j=1}^{4,368} \dot{W}_j + 0.252 \cdot \sum_{j=1}^{4,368} \dot{F}_j^{bkp}\right]}{\sum_{j=1}^{4,368} D_j} \tag{5.27}$$

$$R2H = \frac{\sum_{j=1}^{4,368} RES_j + 0.414 \cdot \sum_{j=1}^{4,368} \dot{W}_j}{\sum_{j=1}^{4,368} D_j} \tag{5.28.a}$$

$$RES_j = \begin{cases} \dot{Q}_{C,j} \cdot \left(1 - \frac{1}{HSPF}\right) & if\ HSPF \ge 2.5275 \\ 0 & otherwise \end{cases} \tag{5.28.b}$$

On the other hand, the algorithm followed to allocate the GHPs to be switched on and the load rating at which they work was as follows:

1. Knowing the thermal demand for one hour, if a single pump is capable of meeting the demand, only one pump is switched on.
2. If the demand is greater than the maximum power that can be delivered by one pump, the power must be distributed between two or more machines. If the demand is greater than the power that 1.9 pumps can deliver, the first pump operates at nominal power and the next one supplies the rest. If the power required is less than that provided by 1.9 pumps, the two pumps share the demand, so that at least one pump will work at 50% of its capacity.
3. In the case of the 25 kWth heat pumps, they serve as back-up for the peak hours. These pumps only come into operation when all 75 kWth pumps are at nominal load and the demand cannot be met.

Fig. 5. 6 shows a more visual representation of the behaviour described in the previous paragraph. As can be seen in this figure, it will always be a priority to have as many 75 kWth pumps at the highest possible load as possible, even if the efficiency of the 25 kWth pump is penalised. This is because the 75 kWth pumps have a higher efficiency than the 25 kWth one.

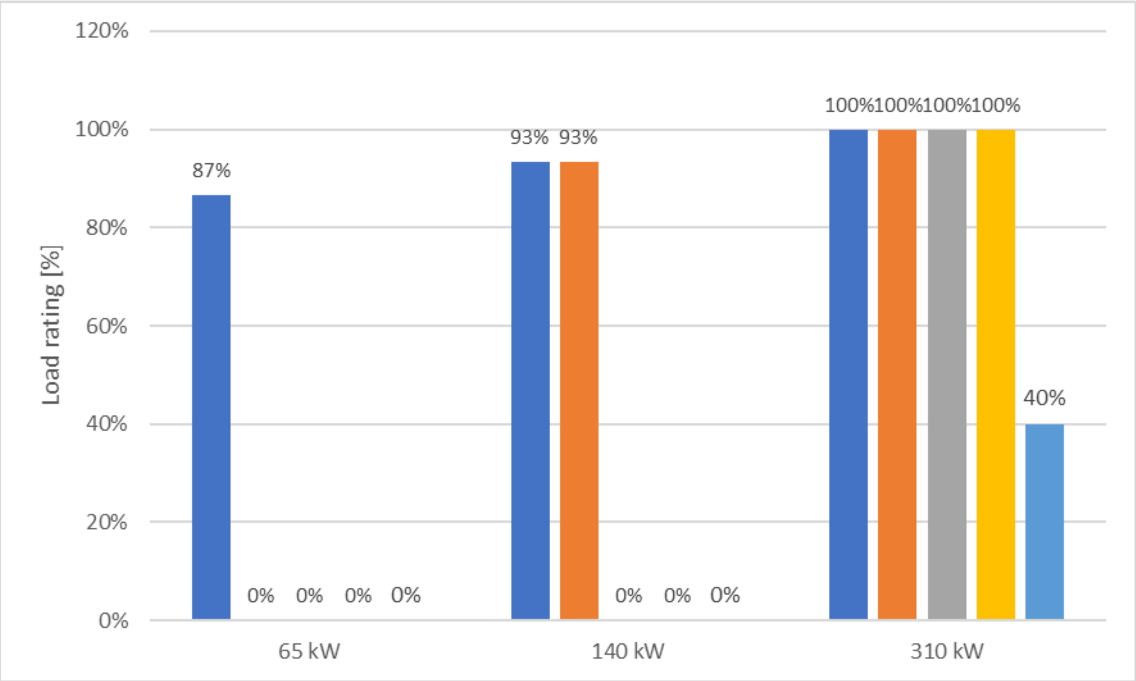

Fig. 5. 6. Explanatory graphic of the GHPs switching-on system – Dark blue: 1st 75kWth GHP; Orange: 2nd 75kWth GHP; Grey: 3rd 75kWth GHP; Yellow: 4th 75kWth GHP; Light blue: 25kWth GHP. (Reprinted from [311]*)*

Once the operation of the GHPs and the criteria to be used to switch on the pumps to meet the demand are set, the baseline case described in Section 5.1 is studied. For this case the required installation is four 75 kWth heat pumps and one 25 kWth heat pump. Fig. 5. 7 shows at what load rating each of the devices have been working in order to meet the demand. From this figure it can be seen that this heating system is designed so that the demand on the pumps falls mainly on the large pumps, which have a higher efficiency, and that the 25 kWth pump is used as a back-up for peak demand.

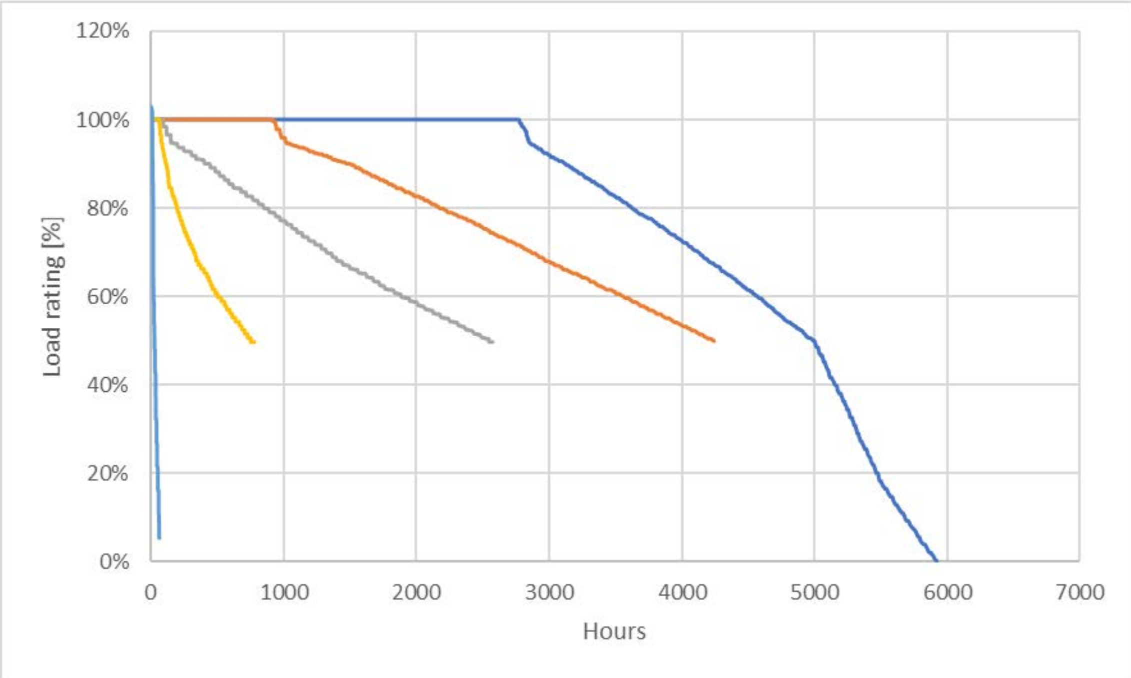

Fig. 5. 7. Monotonous load curve of the GHPs – Dark blue: 1st 75kWth GHP; Orange: 2nd 75kWth GHP; Grey: 3rd 75kWth GHP; Yellow: 4th 75kWth GHP; Light blue: 25kWth GHP

5.2.2.4 Economic Model

The reference indicator to assess the economic feasibility of this kind of devices is usually the levelised cost of heating (LCOH), which integrates both the investment and the operating costs [314]. LCOH is a method for analysing and comparing different heating technologies, as it is a technique that considers the initial investment and the different production costs over the lifetime of the project, assuming a certain constancy in these production costs, i.e. in the absence of market or technology risks.

For the EHP solution, two LCOH have been calculated: one referred to the whole heating demand ($LCOH_{DB}[€/MWh]$, Eq. (5.29.a1)) and another referred to the whole heated floor area ($LCOH_{AB}[€/m^2]$, Eq. (5.29.a2)). In Eq. (5.29.a1) *INV* stands for investment, *C* for annual cost, superscript *M* refers to maintenance, *W* to power consumption, *F* to fuel consumption, subscript *0* to costs in year zero, *CRF* to the capital recovery factor (Eq. (5.29.b)), *CELF* stands for the constant escalation levelisation factor (Eq. (5.29.c)). In Eqs. (5.29.b) to (5.29.d) r_x represents the nominal escalation rate of the item *x*, *wacc* the weighted average capital cost and *Ny* is the life span of the project.

$$LCOH_{DB} = \frac{\left(INV_{HP} + INV_{bkp}\right) \cdot CRF + C_0^W \cdot CELF^W + C_0^F \cdot CELF^F + C_0^M \cdot CELF^M}{\sum_{j=1}^{4,368} D_j} \quad (5.29.a1)$$

$$LCOH_{AB} = LCOH_{DB} \cdot \left[\frac{\sum_{j=1}^{4,368} D_j}{A}\right] \quad (5.29.a2)$$

$$CRF = \frac{wacc \cdot (1 + wacc)^{Ny}}{(1 + wacc)^{Ny} - 1} \quad (5.29.b)$$

$$CELF_x = \left[\frac{k_x \cdot \left(1 - k_x^{Ny}\right)}{1 - k_x}\right] \cdot CRF \quad (5.29.c)$$

$$k_x = \frac{1 + r_x}{1 + wacc} \quad (5.29.d)$$

The investment for the heat pump (inverter model with 200 kWth of heating capacity) has been taken as 24,753 € [310], and a scale law has been fit for the investment of the back-up boiler (Eq. (5.30)).

$$INV_{bkp}[€] = 1087.6 \cdot \dot{Q}_{bkp}^{0.506}[kW_{th}] \quad (5.30)$$

For consumptions with installed power higher than 15 kWe, the cost of electricity includes a term for maximum consumed power in a year and a term for annual consumed energy. Moreover, this consumption exhibits hourly discrimination in three periods (P1, P2 and P3), according to Table 5. 5.

Table 5. 5. Electricity free market tariff with hourly discrimination [315].

Period	Power term [€/kW][a]	Energy term [€/MWh]
P3: 0.00 a.m. to 8.00 a.m.	16.7803	85.3
P2: 8.00 a.m. to 6.00 p.m.; 10.00 p.m. to 0.00 a.m.	25.1704	114.1
P1: 6.00 p.m. to 10.00 p.m.	41.9507	127.1

[a]The cost associated to the power term is derived from multiplying the tariff by the maximum power consumed along the year at each period.

Table 5. 6 shows the economic parameters assumed to calculate the levelised costs[69].

[69] For both EHP and GHP economic models, a *wacc* of zero is assumed as the studied solutions have a social objective and do not seek an economic return on investment.

Table 5. 6. Assumed economic parameters for the EHP

Parameter	Value
Weighted average capital cost, *wacc* [%]	0
Nominal rate of power, r_W [%]	5
Nominal rate of gas, r_F [%]	5
Nominal rate of maintenance, r_M [%]	2.5
Life span, *Ny* [years]	15

For the gas engine heat pumps solution, the information on the required investment was obtained from the manufacturer's catalogue (Panasonic). In the case of the 25 kWth heat pump, the U-10ME2E8 pump was used as a reference, with a price of 10,940 €. In the case of the 75 kWth pumps, as the manufacturer does not have a model with the same design heating capacity as the pump used in this work, it was decided to interpolate the price of two of its models to obtain an estimate of the price. The Panasonic U-20GE3E5 model with a rated power (capacity) of 63 kWth and the U-30GE3E5 model with a rated power (capacity) of 80 kWth were used for the interpolation, obtained by applying Eq. (5.31).

$$Prize_{GHP,75kWth} = Prize_{20G} + \frac{Prize_{30G} - Prize_{20G}}{Capacity_{30G} - Capacity_{20G}}(75 - Capacity_{20G}) \quad (5.31)$$

Applying the formula yields a price for the 75 kWth pump modelled of €43,941. Additionally, the effect of economies of scale has been taken into account when calculating the value of the investment. To take these effects into account, Eq. (5. 32)has been used in cases where more than one unit of the same model had to be purchased.

$$Prize_{scaling} = Prize_{unit} * {N_{units}}^{0,6} \quad (5.32)$$

These factors were confirmed as reasonable by the Spanish Gas Association (SEDIGAS) when purchasing this type of equipment, so using this factor will allow more realistic LCOH values to be given. Moreover, these devices must be serviced regularly in order to guarantee the condition of the machines and their correct operation. The annual cost of maintenance and servicing of heat pumps is about 475 € per pump. Regarding the energy cost, i.e. natural gas cost, the tariff used is a free market tariff [316]. Due to the thermal needs of the installations, tariff 3.4 is used, as gas consumption always exceeds 100,000 kWh. The information provided by the energy supplier for this tariff is given in Table 5. 7 and Table 5. 8. Some taxes have to be applied to the above values: the fossil fuel tax (set at €0.002341/kWh by Law 15/2012) is applied to the variable term; on the other hand, the VAT (21%) is applied to both fixed and variable term. In this way the values given in Table 24 are obtained [316].

Table 5. 7. Natural gas tariff 3.4 [316]

Fixed term	80.97 €/month
Variable term	0.04385 €/kWh

Table 5. 8. Natural gas tariff 3.4 after taxes [316]

Fixed term	97.97 €/month
Variable term	0.05589 €/kWh

Eq. (5.33) shows the calculation of the GHPs' levelised cost of heating referred to the whole heating demand ($LCOH_{GHP}[€/MWh]$).

$$LCOH_{GHP}[€/MWh] = \frac{(INV_{GHP}) \cdot CRF + C_0^F \cdot CELF^F + C_0^M \cdot CELF^M}{\sum_{j=1}^{4,368} D_j} \tag{5.33}$$

INV_{GHP} is the total investment for the gas engine heat pumps. *CRF* and *CELF* are defined as for the EHP, i.e. applying Eqs. (5.29.b), (5.29.c) and (5.29.d). *C* stands for annual cost, superscript *M* refers to maintenance, *F* to fuel consumption (i.e. natural gas), subscript 0 to costs in year zero. Table 5. 9 shows the economic parameters assumed to calculate the levelised costs of this solution.

Table 5. 9. Assumed economic parameters for the GHPs' solution.

Parameter	Value
Weighted average capital cost, *wacc* [%]	0
Nominal rate of gas, r_F [%]	5
Nominal rate of maintenance, r_M [%]	5
Life span, *Ny* [years]	20

For comparison purposes, two additional scenarios have been considered, one decentralised and one centralised, both using only condensing natural gas boilers with the same efficiency as the EHP's back-up boiler (95% based on HHV). In the de-centralised boiler case, 60 block dwellings of 100 m^2 are considered, each employing a natural gas boiler with an investment of 800 € and maintenance costs of 150 €/year. In the centralised boiler scenario, a larger boiler is used to meet the overall demand, being given its investment by Eq. (5.30) and a maintenance cost assumed of 2,000 €/year.

All the costs include taxes (VAT, fossil fuel tax) and fixed meter rental costs. Regarding the natural gas costs, two tariffs have been selected, depending on the annual consumption. So, for large consumptions (centralised cases in both heat pump with back-up and boiler alone) the tariff is 971.64 €/year (fixed term) plus 40.66 €/MWh (variable term, based on HHV), whereas for small consumptions (decentralised boilers) the tariff is 115.98 €/year (fixed term) plus 42.4 €/MWh (variable term, again based on HHV)[70]. Maintenance cost was set to 2,000 €/year for the proposed heating system (heat pump supported by a backup boiler).

5.2.3 Parametric analyses

The baseline case has been selected to be representative of the middle energy efficiency level of the Spanish residential sector, with an energy performance class of E, close to D. Nevertheless, vulnerable households commonly live in older dwellings, which were grouped in the built 'before 1980' aggregate construction period with worse insulation condition than this middle energy-efficiency-level. Furthermore, as mentioned before, according to the 2011 CENSUS, 55% of primary dwelling are in this group.

To extend the EHP model application, several parametric analyses have been carried out according to: (1) the energy performance level of the building (EEP), which depends on the year of construction of the building - three tiers have been distinguished ('before 1980', '1981-2007' and 'after 2007', see Section 3.2.1.2), and (2) the floor area to be

[70] https://tarifasgasluz.com/comercializadoras/naturgy/tarifas (Accessed on 12 December 2019)

heated. Both analyses have been carried out for five winter climatic zones in Spain[71]. A representative city is chosen for each climate zone, as listed in Table 5. 10.

Table 5. 10. City chosen for each of the winter climate zones assessed

Winter climate zone	Reference city
A	Almería (A4)
B	Sevilla (B4)
C	Barcelona (C2)
D	Madrid (D3)
E	Burgos (E1)

Considering the different values of EEP corresponding to the '1981-2007' building energy performance level (see Table 5. 11) and a reference heated floor area of 6,000 m^2 for all climate zones, the annual cumulative heating demand profiles and the power delivered by the heat pump are shown, respectively, in Fig. 5. 8 and Fig. 5. 9.

Table 5. 11. EEP for block dwellings according to winter climate zone and age of dwelling

Winter climate zone	Before 1980	1981-2007	After 2007
A	4.41	2.48	0.99
B	4.01	2.34	0.96
C	3.69	2.23	0.93
D	3.53	2.18	0.92
E	3.46	2.15	0.91

[71] The α zone has null heating demand.

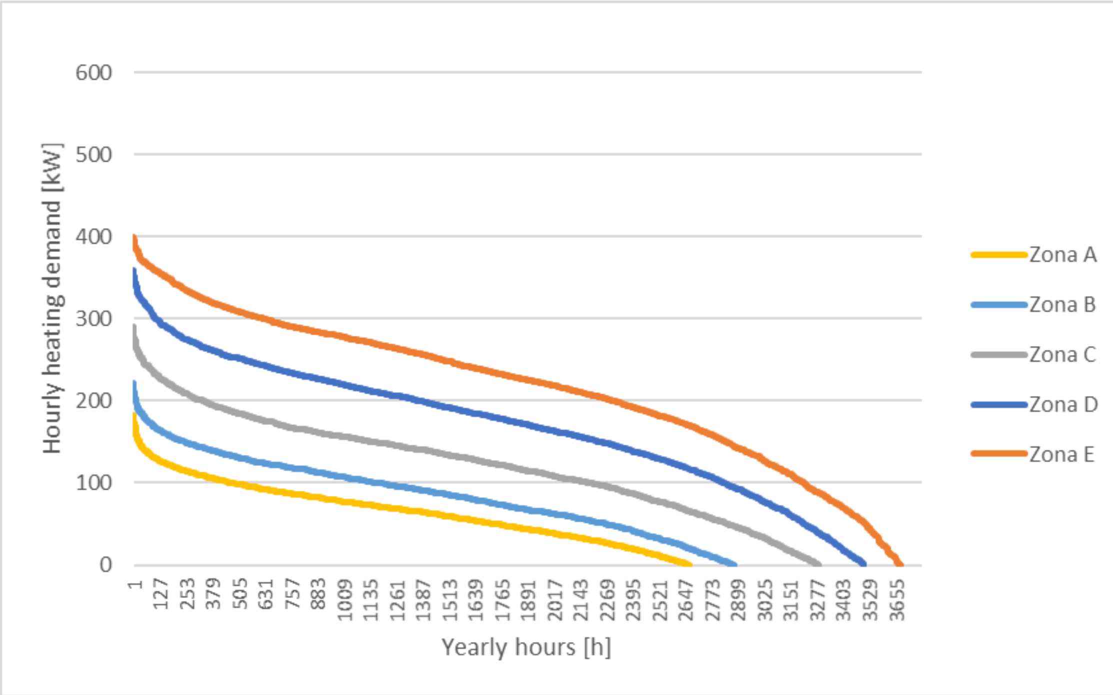

Fig. 5. 8. Annual cumulative heating demand profile considering '1981-2007' thermal insulation according to the winter climate zone (Zona). (Reprinted from [317]*)*

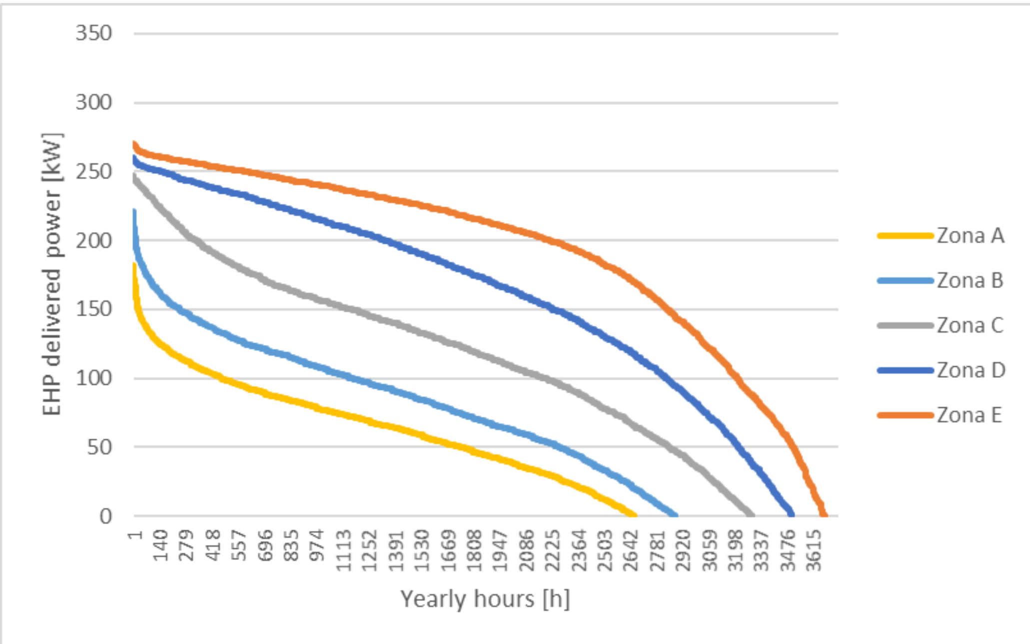

Fig. 5. 9. Annual cumulative EHP delivered power profile considering '1981-2007' thermal insulation according to the winter climate zone (Zona) (Reprinted from [317]*)*

Thereafter, these curves were drawn for the other two building energy performance levels (considering the same reference heated floor area).

The criteria used according to the type of thermal insulation to select the case studies in the parametric analysis are detailed below. The results are shown in Section 5.3.3.

For a '1981-2007' building energy performance level, the parametric analysis' heated floor area chosen are those:

- That do not require more than 5% of the backup hours, as in the baseline case study.
- Requiring approximately 30% of the backup hours.
- Floor area 1.5 times less than that of the case study.

For a 'before 1980' thermal insulation type, the areas considered are the following ones:

- Case study floor area
- Floor area requiring backup of not more than 5% of hours
- Floor area 1.5 times the previous one

For an 'After 2007' building energy performance level, the floor areas chosen are the following ones:

- Case study floor area
- Floor area requiring backup for 30% of the hours
- Floor area requiring backup for no more than 5% of the hours.

On the other hand, an adjustment of the heated floor area and the standardised cost is determined for each climate zone, based on the EEP values for each zone listed in Table 5. 11, also adding three new values of EEP (0.5; 1.5; 3), in order to obtain greater accuracy in the potential adjustment for the first case and linear for the second, requiring for both that the hours of operation of the backup system do not exceed 5%. In addition, Eq. (5.34) has been used for the calculation of LCOH on a floor area basis.

$$LCOH[€/m^2] = \frac{LCOH[€/MWh] \cdot \sum_{\mathrm{j=1}}^{4.368} D_j \ \ [\mathrm{MWh}]}{A_{heated}[m^2]} \tag{5.34}$$

Regarding the GHP, the LCOH [€/MWh] has been assessed for two alternative climate zones only, i.e. A and E, being the ones with, respectively, lower and higher required heating demand. On the other hand, the calculation of the LCOH [€/MWh] have been repeated for three alternative floor area configurations representing the maximum area that could be heated by alternative GHP solutions (1 x 75 kWth and 1 x 25 kWth; 2 x 75 kWth and 1 x 25 kW5h; 3 x 75 kWth and 1 x 25 kWth), i.e. 1708 m^2, 2976 m^2 and 4243 m^2.

Starting from the above results, the impact of a thermal enclosure retrofitting in the baseline case (i.e. Madrid, D zone) was assessed in order to analyse the double energy efficiency intervention, i.e. building and heating system retrofitting.

5.3 Results and discussion

5.3.1 Heat pump models

5.3.1.1 Results of the electrically driven heat pump model

Regarding the EHP, Eqs. (5.22)-(5.24) were solved, obtaining Eqs. (5.35)-(5.37), respectively. As it can be seen in Eq. (5.35), for a given rotational speed, the relation between heat capacity and air temperature is linear, and the slope increases with the speed. Regarding the COP, Eq. (5.36) is obtained, but it does not depend on rotational speed. This result is foreseeable, because the COP is the ratio between heat capacity and compressor consumption, both proportional to the mass flow rate, which is directly dependent on the rotational speed. Combining both equations, the expression for the compressor consumption is obtained (Eq. (5.37)).

$$\dot{Q}_C = (0.1106 \cdot N + 0.0002) + (0.0053 \cdot N + 0.0003) \cdot T_{ai} \tag{5.35}$$

$$\mathrm{COP} = 2.49499 + 0.02981 \cdot T_{ai} \tag{5.36}$$

$$\dot{W} = \frac{(0.1106 \cdot N + 0.0002) + (0.0053 \cdot N + 0.0003) \cdot T_{ai}}{2.49499 + 0.02981 \cdot T_{ai}} \tag{5.37}$$

Fig. 5. 10 shows the iso-lines of heating capacity as a function of the rotational speed and the ambient wet bulb temperature. Limitation of maximum electrical power (Eq. (5.25.a)) has been taken into account.

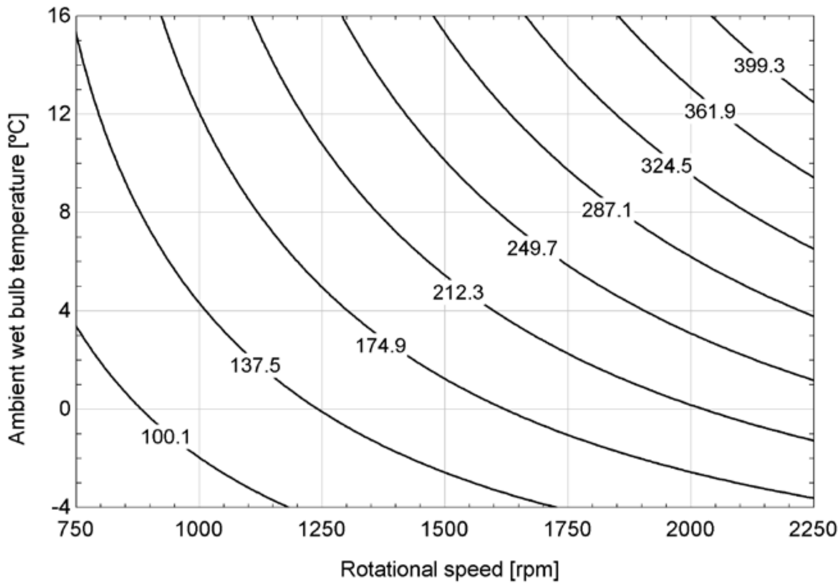

Fig. 5. 10. Iso-lines of heating capacity of the ASHPWH (reprinted from [308]*).*

A comparison with an actual machine has been performed to validate the results of the EHP model. A literature search has been performed to find an existing device that fit with the characteristics of the modelled heat pump. The selected equipment is HERA 190-2-2 [318], an electrically driven air to water heat pump from EUROKLIMAT. It is driven by a reciprocating compressor using an inverter and has a design heating capacity of 190 kWth. The refrigerant is R290 as the one selected in this chapter. The water outlet temperature of the existing heat pump is 55 °C, as in the model. Fig. 5. 11 plots the comparison of the COP, showing a good match, especially at low temperatures. This behaviour is due to the fact that the HERA 190-2-2 data are based on dry bulb air temperature, whereas the data from the model are based on the wet bulb temperature and both temperatures are very similar at low dry bulb temperature.

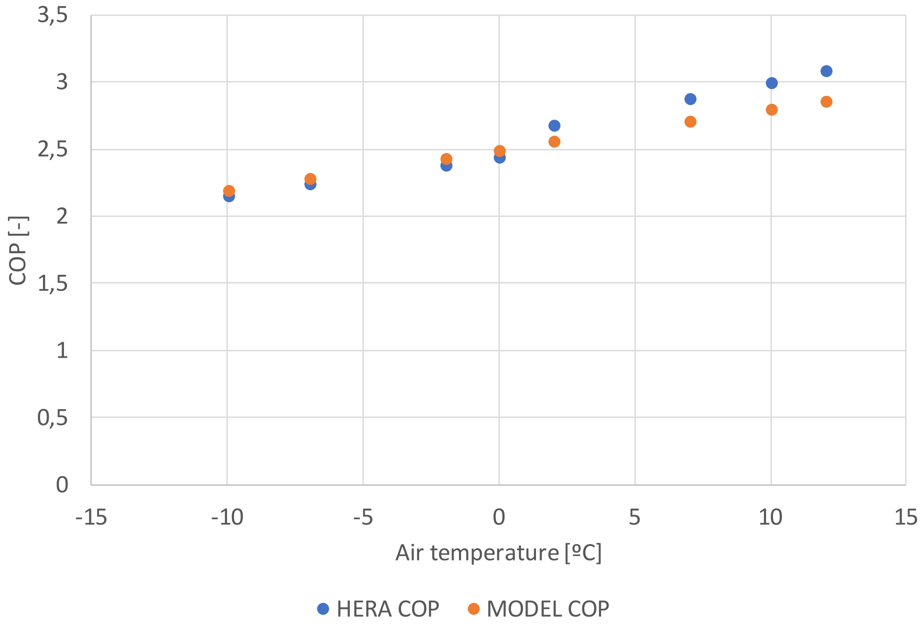

Fig. 5. 11. Comparison between the COP obtained with the model and the COP of HERA 190-2-2 from EUROKLIMAT (reprinted from [308]*).*

5.3.1.2 Results of the gas engine driven heat pump model

Eq. (5.38) was used to find out how the load rating (LR [%]) and the outside temperature (which corresponds to the air inlet temperature, T_{ai}) affect the heating capacity ($\dot{Q}_C$) of the first analysed GHP (75 kWth). The values of the parameters used for the linear regression (a_0, a_1, a_2) and the corresponding standard error are shown in Table 5. 12. Thus, Table 5. 13 shows the statistical values of the regression for the heat provided by the 75 kWth heat pump and Fig. 5. 12 shows the trend of the delivered power as a function of the outdoor temperature. The almost constant value of the power output can be noticed when varying the outside temperature, due to the use of the engine heat (both cooling water and flue gases) to support the condenser.

$$\dot{Q}_C = a_0 + a_1 * LR + a_2 * T_{ai} \tag{5.38}$$

Table 5. 12. Regression values for power provided (heating capacity) by the 75 kWth GHP

	Value	Standard error
a_0	0.714900972	1.327179
a_1	71.9167935	1.762664
a_2	0.03718169	3.140005

Table 5. 13. Statistical values of the regression for power provided (heating capacity) by the 75 kWth GHP

Metric	Value
RMS	3.1678
Bias	$4.7636 \cdot 10^{-18}$
R^2	96.37%

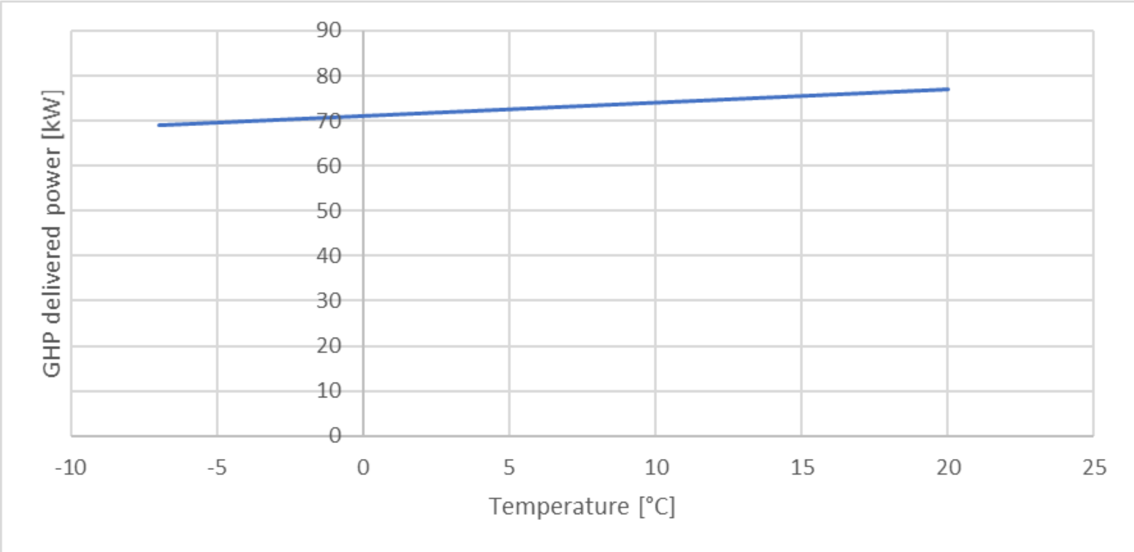

Fig. 5. 12. Power delivered by the 75 kWth GHP (heating capacity) as a function of the outdoor temperature. (Reprinted from [311]*)*

Moreover, Eq. (5.39) was applied to calculate the natural gas consumption ($\dot{F}_{GHP}$) to bring the heat pump to the desired working conditions. The values of the parameters of Eq. (5.39) used for the linear regression (a_0, a_1, a_2, a_3, a_4) and the corresponding standard error are shown in Table 5. 14. Thus, Table 5. 15 shows the statistical values of the regression and Fig. 5. 13 shows the natural gas consumption's trend as a function of the outdoor temperature.

$$\dot{F}_{GHP} = a_0 + a_1 * T_{ai} + a_2 * T_{ai}^2 + a_3 * \dot{Q}_C + a_4 * \dot{Q}_C^{\ 2} \qquad (5.39)$$

Table 5. 14. Regression values for natural gas consumption by the 75 kWth GHP

	Value	Standard error
a0	2.24808	2.788006
a1	-1.239446	0.06134589
a2	0.03489427	0.0001995928
a3	0.6903814	0.1227968
a4	0.001526826	0.001270924

Table 5. 15. Statistical values of the regression for natural gas consumption by the 75 kWth GHP

Metric	Value
RMS	2.553
Bias	$-1.0904*10^{-17}$
R^2	97.13%

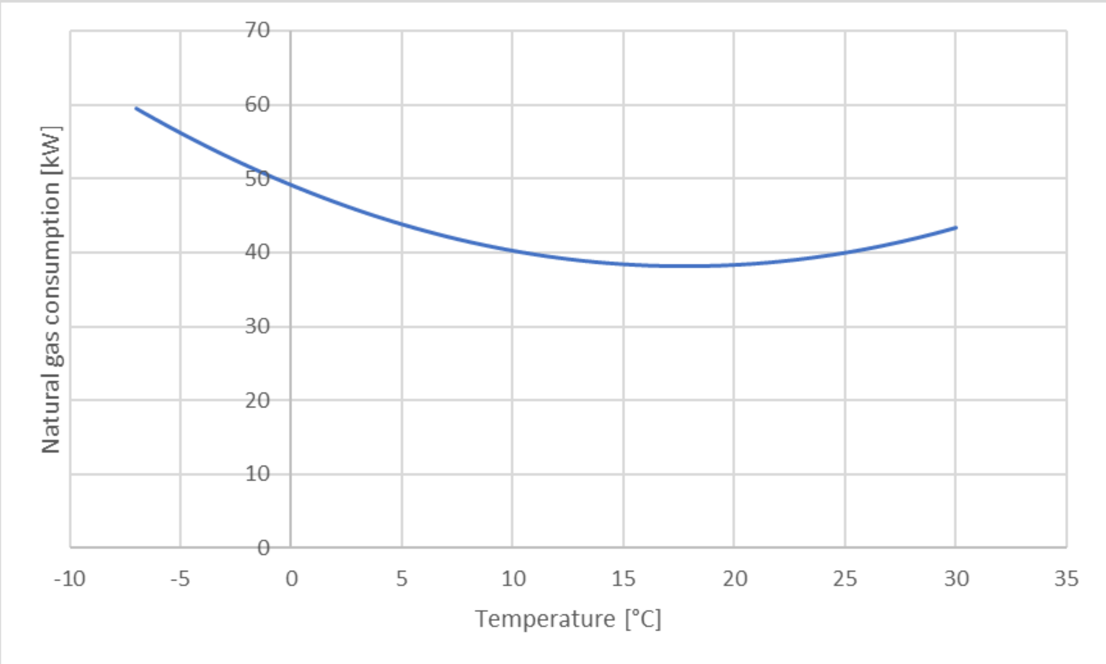

Fig. 5. 13. Natural gas consumption of the 75 kWth GHP as a function of the outdoor temperature (Reprinted from [311]).

On the other hand, Eq. (5.40) is used to find out how the Load rating (%) and the outside temperature affect the heating capacity ($\dot{Q}_C$) of the 25 kWth heat pump. The values of the parameters used for the linear regression (a_0, a_1, a_2) and the corresponding standard error are shown in Table 5. 16. Thus, Table 5. 17 shows the statistical values of the regression for the thermal power delivered by the 25 kWth heat pump and Fig. 5. 14 shows its trend as a function of the outdoor temperature.

$$\dot{Q}_C = a_0 + a_1 * LR + a_2 * T_{ai} \tag{5.40}$$

Table 5. 16. Regression values for power provided (heating capacity) by the 25 kWth GHP

	Value	**Standard error**
a_0	-0.937131059	0.3383719
a_1	24.7482857	0.4296231
a_2	-0.074427187	0.004722005

Table 5. 17. Statistical values of the regression for power provided (heating capacity) by the 25 kWth GHP

Metric	Value
RMS	0.56834
Bias	$-2.3274*10^{-18}$
R^2	98.35%

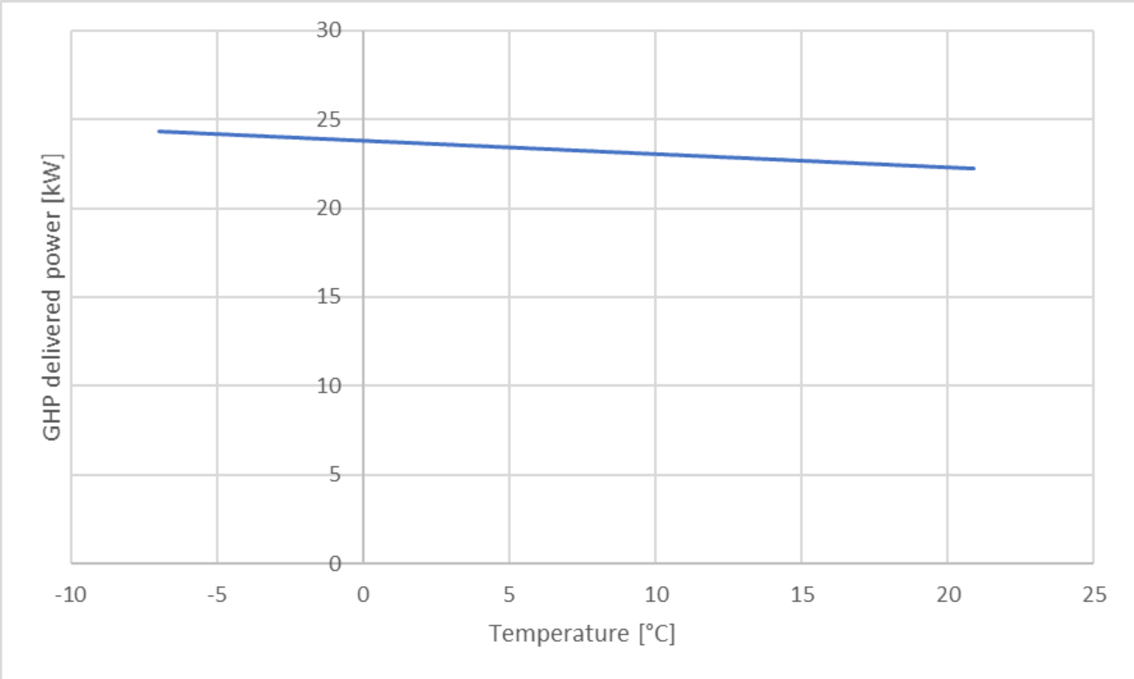

Fig. 5. 14. Power delivered by the 25 kWth GHP (heating capacity) as a function of the outdoor temperature (Reprinted from [311]*).*

In the 25 kWth heat pump model, in order not to overly penalise the efficiency of the machine, it is appreciated that the heat from the motor is used from higher ambient temperatures, thus causing the pump to provide more heat when temperatures decrease.

On the other hand, Eq. (5.41) was applied to calculate the natural gas consumption ($\dot{F}_{GHP}$) to bring the 25 kWth heat pump to the desired working conditions. The values of the parameters of Eq. (5.41) used for the linear regression ($a_0, a_1, a_2, a_3, a_4, a_5$) and the corresponding standard error are shown in Table 5. 18. Thus, Table 5. 19 shows the statistical values of the regression and Fig. 5. 15 shows the natural gas consumption's trend of the 25 kWth heat pump as a function of the outdoor temperature.

$$\dot{F}_{GHP} = a_0 + a_1 * T_{ai} + a_2 * T_{ai}^2 + a_3 * \dot{Q}_C + a_4 * \dot{Q}_C{}^2 + a_5 * T_{ai} * \dot{Q}_C \quad (5.41)$$

Table 5. 18. Regression values for natural gas consumption by the 25 kWth GHP

	Value	**Standard Error**
a_0	13.47885	3.10473
a_1	-0.610211	0.05496532
a_2	0.01364459	0.0007251772
a_3	-0.3136262	0.3264011
a_4	0.02386973	0.008291255
a_5	-0.00006729405	0.002388825

Table 5. 19. Statistical values of the regression for natural gas consumption by the 25 kWth GHP

Metric	Value
RMS	1.0283
Bias	$6.1438*10^{-19}$
R^2	95.51%

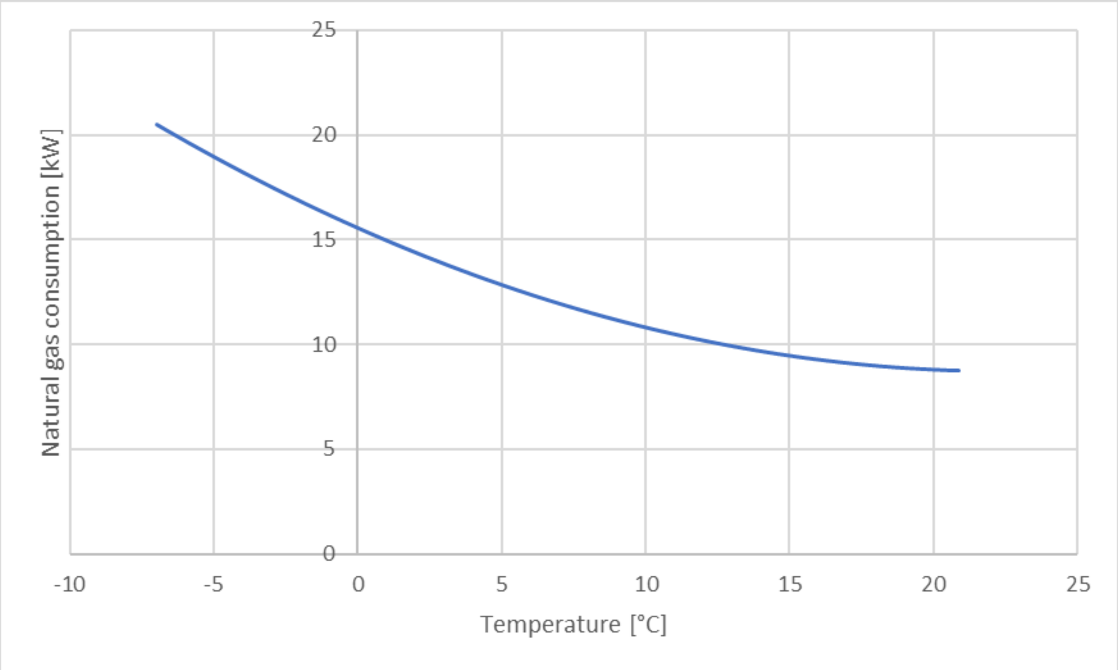

Fig. 5. 15. Natural gas consumption of the 25 kWth GHP as a function of the outdoor temperature (Reprinted from [311]*).*

5.3.2 Baseline Case

A block of dwellings with an overall heated floor area of 6,000 m^2 and EEP of 2.18, i.e. built between 1981 and 2007, located in Madrid (D zone), has been simulated. The selected baseline-building-age represents a considerable percentage of vulnerable households in Spain and the 41% of the overall main dwellings with heating (Census

2011). Fig. 5. 16 shows its annual cumulative heating demand profile, while Table 5. 20 summarises the results obtained for the EHP by applying the algorithm given by Eq. (5.25) to each winter hour[72]. Thus, the performance indexes are calculated by applying Eqs. (5.26)–(5.28), whose results are shown in Table 5. 21. Moreover, Fig. 5. 16 displays the contribution to the heating demand of both the heat pump (96%) and the back-up boiler (4%).

Table 5. 20. Energy results in the baseline case of the EHP

Parameter	Value
Seasonal heating demand, $\sum_{j=1}^{4,368} D_j$ [MWh]	600.833
Heating demand met by heat pump, $\sum_{j=1}^{4,368} \dot{W}_j \cdot COP_j$ [MWh]	576.675
Seasonal consumption of heat pump, $\sum_{j=1}^{4,368} \dot{W}_j$ [MWh]	223.080
Back-up boiler consumption, $\sum_{j=1}^{4,368} \dot{F}_j^{bkp}$ [MWh]	25.430
Size of back-up boiler, $\dot{Q}_{bkp}$ [kW]	180
Renewable energy taken from the ambient air, $\sum_{j=1}^{4,368} RES_j$ [MWh]	445.949

Table 5. 21.Performance indexes in the baseline case of the EHP

Parameter	Value
Heating seasonal performance factor, HSPF [-]	2.585
Avoided CO_2 emissions, AVCO2 [g CO_2/kWhth]	131.7
Renewable to heating demand ratio, R2H [%]	74.22

[72] The seasonal heating demand value considered is the same for both types of heat pump.

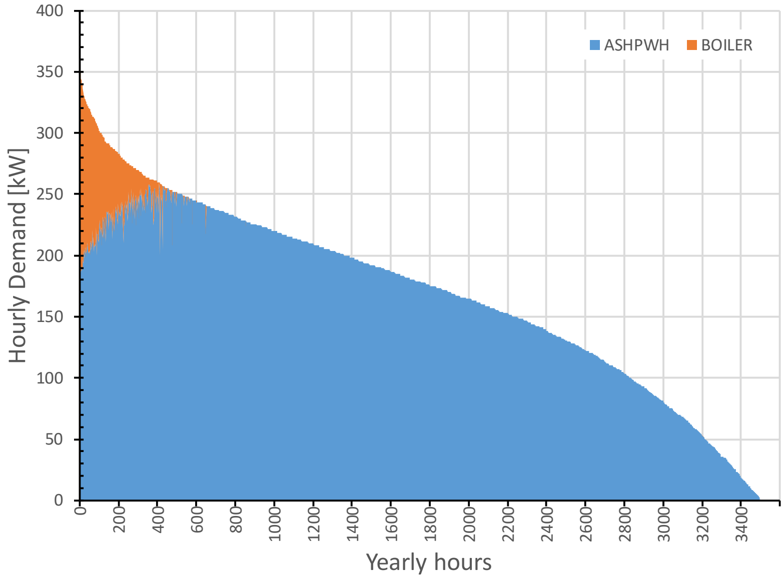

Fig. 5. 16. Contribution of the electrically driven heat pump (ASHPWH) and back-up boiler (BOILER) to meet the annual cumulative heating demand profile in the baseline case (block dwellings in Madrid built between 1981 to 2007 with 6,000 m^2 of total heated floor area) (reprinted from [308]*).*

A temperature of 7.9ºC is obtained as minimum temperature in the on/off operation mode, corresponding to a thermal power of 114.2 kWth, by applying Eq. (5.31) to the lowest rotational speed and the thermal demand points cloud in Fig. 5. 1. From Fig. 5. 16, the energy demand for lower heating power values results 51.7 MWh, which is lower than 9% of the seasonal heating demand. Furthermore, as the rotational speed is the lowest one, the expected electrical peak is moderate. Considering the above facts, the eventual energy losses in the on/off operation mode have been neglected.

Regarding the costs, the results for the EHP are summarised in Table 5. 22.

Table 5. 22. Levelised costs in the baseline case for the EHP, de-centralised and centralised boilers

Levelised costs	EHP	De-centralised boiler	Centralised boiler
Levelised cost of heating (demand based), LCOHDB [€/MWh]	92.22	108.55	73.54
Levelised cost of heating (floor area based), LCOHAB [€/m2]	9.23	10.87	7.36

Fig. 5. 17 shows the breakdown of the LCOH of the EHP compared with the ones of the analysed conventional systems[73]. As the heating demand and the heated floor area are

[73] This analysis has been carried out only for electrically driven heat pumps because they are considered the most promising clean technology for the decarbonisation of heating in the residential sector.

established, the breakdown is the same for both levelised costs (see Eq. (5.29.a)). It is evident the key importance of the operating costs (especially the energy term, being the maintenance less significant) over the investment (heat pump and boiler).

Giving the cost breakdown and the LCOH, the proposed active measure (to be competitive with the centralised natural gas boilers) should be supplemented by the application of a social electricity tariff. This would make it possible to take advantage of the environmental benefits of the proposed system at the same LCOH of the most economical system, i.e., the centralised boiler. In this case, a discount of 23.75% in the electricity cost (overall cost, including fixed and variable terms) would reduce the levelised cost to 73.54 €/MWh, thus matching the cost of the centralised boiler. This discount is in accordance with the current Spanish social electricity tariff, which (in its 'normal times' application [319]) ranges from 25% for vulnerable consumers, 40% for severely vulnerable consumers and 'up to 100%' for consumers at risk of social exclusion (see Section 2.4.5.1). Considering the distribution of each cluster in 2019 (respectively, 648,826 and 630,086 households in the first two categories, and 4,545 in the third one [285]), the average discount was 32%. Therefore, the required discount to make the proposed system economically competitive with centralised gas boilers would be even lower than the one currently applied to vulnerable-households´ electricity bill.

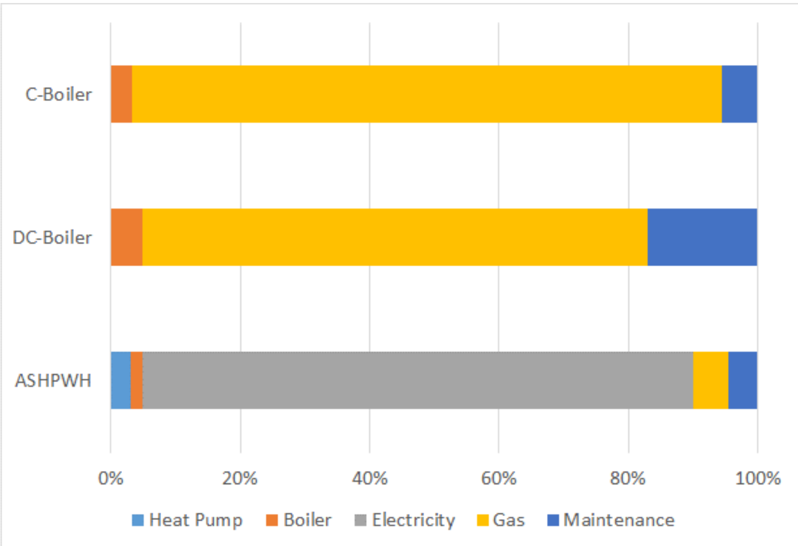

Fig. 5. 17. Percentage breakdown of the levelised costs in the EHP (reprinted from [308]*).*

From the optimisation process explained in Section 5.2.2.3 and the results shown in 5.3.1.2, the GHPs' configuration that is capable to meet the heating demand in the baseline case is the one with four devices of 75 kWth and one of 25 kWth. The LCOH [€/MWh] of this heat pump solution in the baseline case was calculated by applying Eq (5.34) and taking into account the assumption made in Section 5.2.2.4. The resultant value, i.e. 107.78 €/MWh, is higher than the ones of both the centralised solutions shown in Table 5. 22, but it is slightly lower than the de-centralised boiler's one.

5.3.3 Parametric analyses

Giving the EHP model presented and considering the ‘before 1980’ thermal insulation and a reference floor area of 6000 m^2 for all climate zones, the cumulative curves of heating demand and thermal power delivered by the heat pump are shown, respectively, in Fig. 5. 18 and Fig. 5. 19.

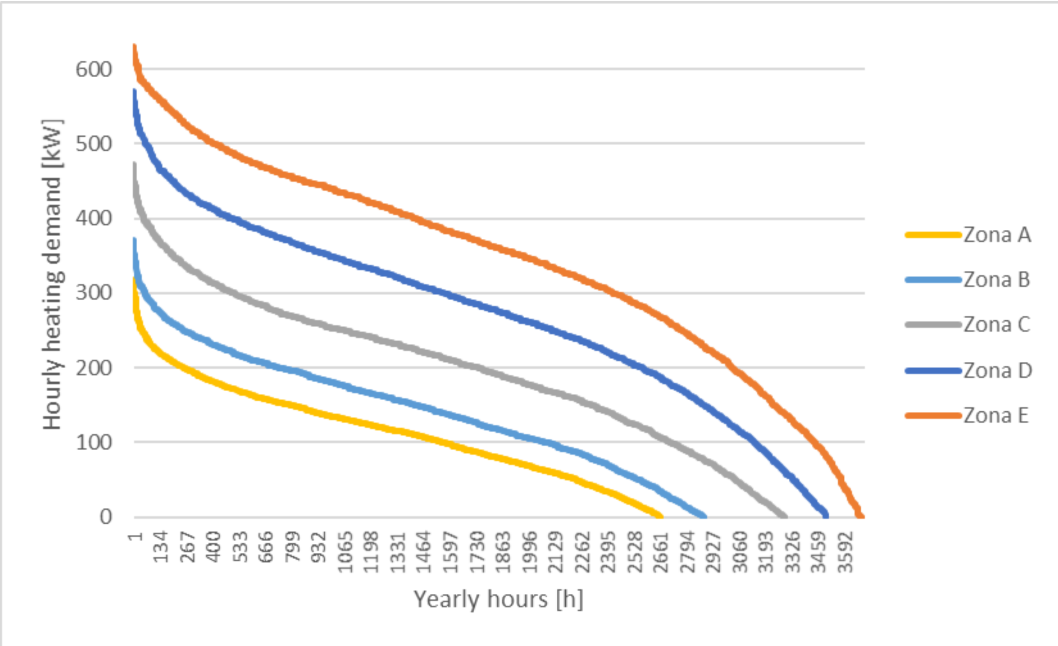

Fig. 5. 18. Annual cumulative heating demand profile considering ‘Before 1980’ thermal insulation according to the winter climate zone (Zona) (Reprinted from [317]*).*

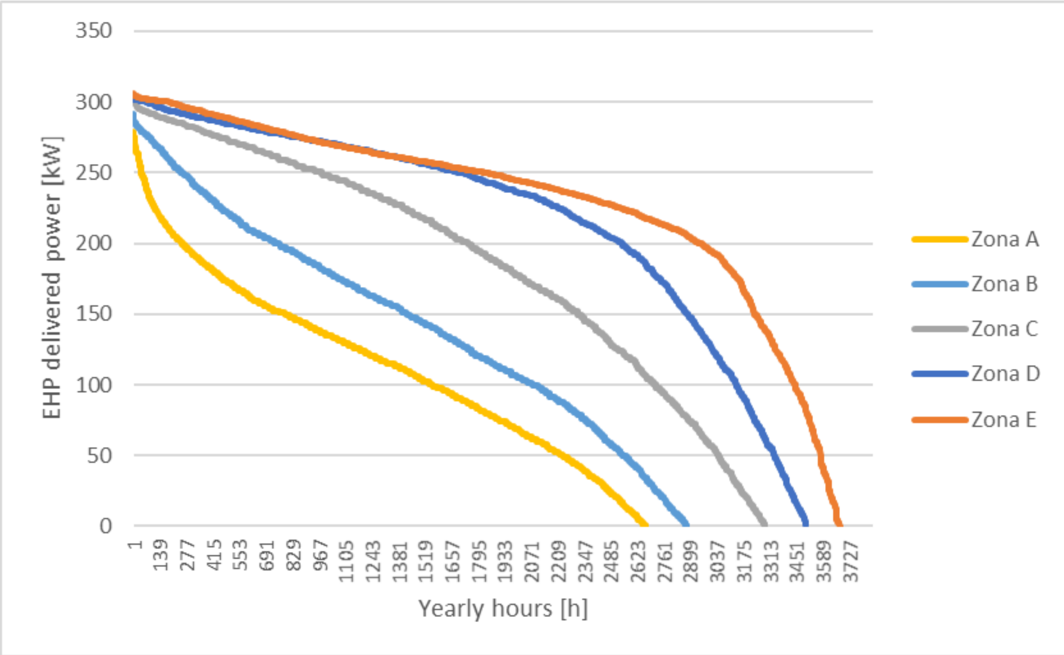

Fig. 5. 19. Annual cumulative EHP delivered power profile considering 'Before 1980' thermal insulation according to the winter climate zone (Zona) (Reprinted from [317]*).*

On the other hand, Fig. 5. 20 and Fig. 5. 21 show the cumulative curves of, respectively, heating demand and thermal power delivered by the EHP if we consider a newly constructed building ('After 2007') with a reference floor area of 6000m2.

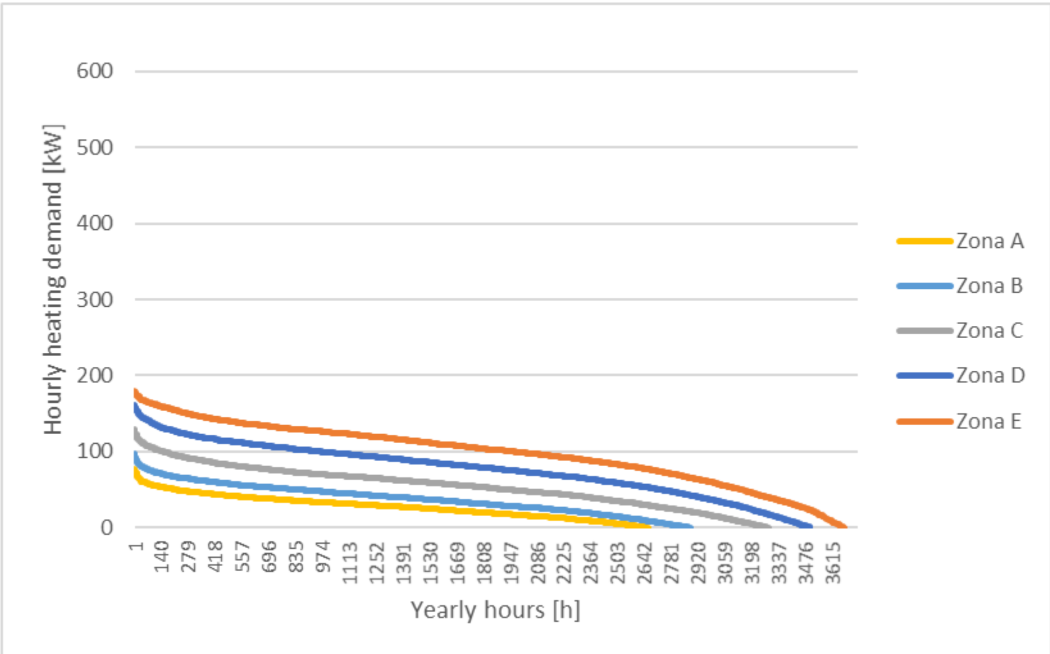

Fig. 5. 20. Annual cumulative heating demand profile considering 'After 2007' thermal insulation according to the winter climate zone (Zona) (Reprinted from [317]*).*

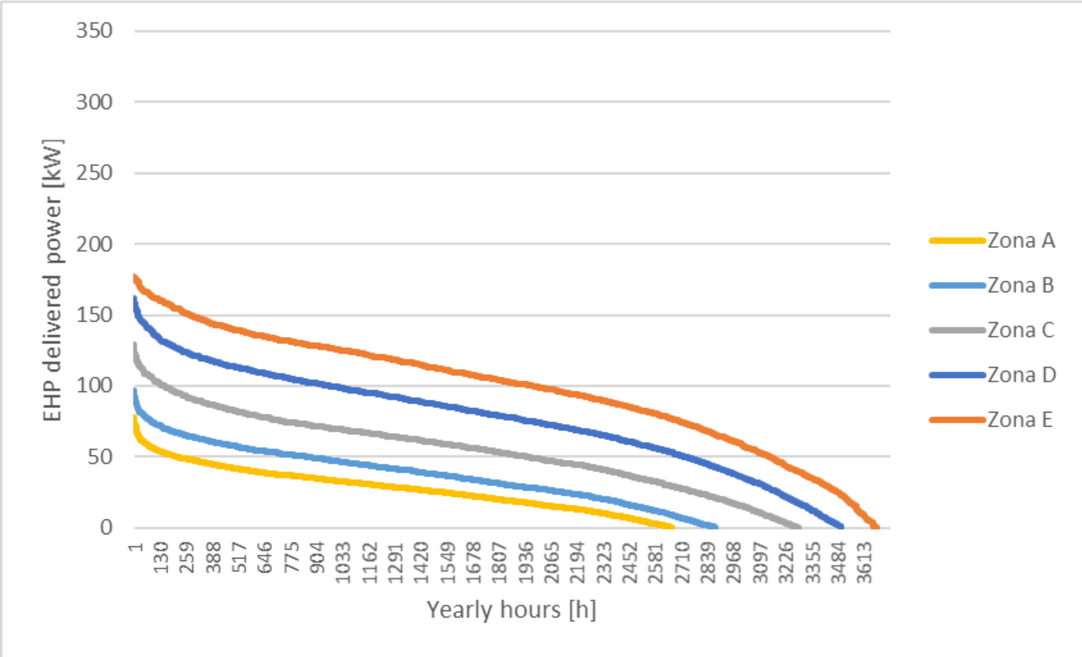

Fig. 5. 21. Annual cumulative EHP delivered power profile considering 'After 2007' thermal insulation according to the winter climate zone (Zona) (Reprinted from [317]*).*

In view of the results obtained (Fig. 5. 8-Fig. 5. 9 and Fig. 5. 18-Fig. 5. 21), it can be seen that as the thermal enclosure becomes more efficient, the heating demand cumulative curve is lower, which is the expected result. In addition, it can be seen that at certain times the power demand values are not able to be satisfied with the heat pump production, so that in these cases, the support system is coupled to meet the demand (as explained in Section 5.2.2.3). Moreover, analysing the different climatic zones presented, it can be seen that the city with the highest heating demand is in zone E (Burgos), which is considered to be the coldest, while zone A (Almeria) is the warmest and requires the least heating demand.

The multiple results obtained for the different analysed climate zones (detailed in Table 5. 10) according to the type of thermal insulation are shown in Table 5. 23-Table 5. 27, which reflect the cases described in Section 5.2.3. From these tables it can be seen that:

- As the thermal power delivered by the heat pump grows:
  - The normalised cost of the heat pump grows.
  - The input of renewable primary energy to meet the demand grows.
  - Avoided CO_2 emissions grow.
- As the heating demand grows (heated floor area for the same insulation):
  - The standardised cost of the central boiler is reduced.
  - The standardised cost of the heat pump is reduced (the demand covered by the heat pump is reduced).

The obtained settings to adjust, respectively, the heated floor area and the standardised cost for each climate zone are given in Eqs. (5.42)-(5.51) and in Fig. 5. 22 and Fig. 5. 23. From Fig. 5. 22 it can be seen that the EEP (insulation) does not affect the floor area covered by the heat pump in zones C, D and E, unless it is really low ('After 2007' rating). On the contrary, the floor area is more dependent on the insulation in zones A and B. Fig. 5. 23 shows the advantage of the energy renovation, which allows reducing the certification rate and thus the LCOH of the proposed system, especially in zones C, D and E.

Zone A $$A_{heated}[m^2] = 33{,}145 \cdot EEP^{-0.925} \quad (5.42)$$

Zone B $$A_{heated}[m^2] = 23{,}483 \cdot EEP^{-0.924} \quad (5.43)$$

Zone C $$A_{heated}[m^2] = 14{,}701 \cdot EEP^{-0.923} \quad (5.44)$$

Zone D $$A_{heated}[m^2] = 9{,}801.5 \cdot EEP^{-0.923} \quad (5.45)$$

Zone E $$A_{heated}[m^2] = 7{,}341.8 \cdot EEP^{-0.922} \quad (5.46)$$

Zone A $$LCOH\ [€/m^2] = 1.2848 \cdot EEP^{-0.9248} \quad (5.47)$$

Zone B $$LCOH\ [€/m^2] = 1.8959 \cdot EEP^{-0.9238} \quad (5.48)$$

Zone C $$LCOH\ [€/m^2] = 3.1481 \cdot EEP^{-0.9229} \quad (5.49)$$

Zone D $$LCOH\ [€/m^2] = 4.7654 \cdot EEP^{-0.9226} \quad (5.50)$$

$$\text{Zone E} \qquad LCOH\ [€/m^2] = 6.3733 \cdot EEP^{-0.9226} \tag{5.51}$$

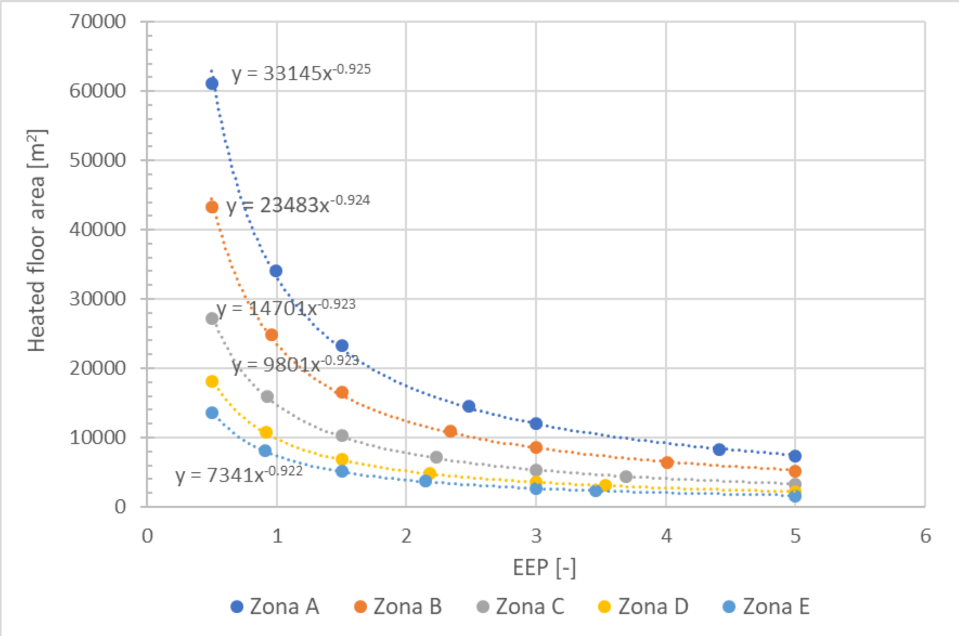

Fig. 5. 22. Adjustment of the heated floor area according to EEP and winter climate zone (Zona) (Reprinted from [317]*).*

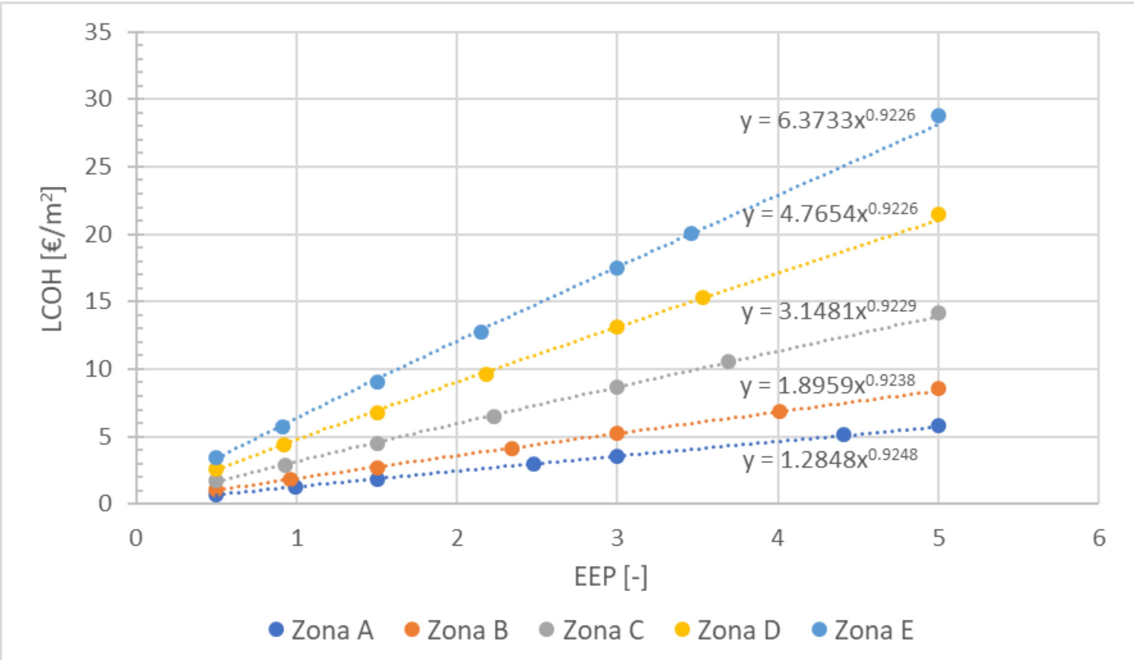

Fig. 5. 23. Adjustment of LCOH according to EEP and winter climate zone (Zona) (Reprinted from [317]*).*

The trend observed indicates that the cost of the boiler-supported heat pump always exceeds that of the centralised boiler. In order to define an aid policy that facilitates the penetration of this technology given its environmental advantages, an analysis has been carried out on what the average energy price should be so that the LCOH of the central boiler case is identical to that of the technology analysed in this study (heat pump with boiler back-up). The discount required has been determined in the case of discounting only on the energy term or on the sum of the energy term (or variable term) and the power term (or fixed term). The case has been chosen in which the hours requiring backup do not exceed 5% of the total, with '1981-2007' thermal insulation. The results are shown in Table 5. 28.

From Table 5. 28 it can be deduced that a decrease on the sum of the fixed and variable electricity bill of between 26% and 30% (higher in climatic zones with milder winters) would equalise the costs of the proposed system with the central condensing boiler. Such percentage decrease is comparable, for example, with the current social electricity tariff, although the latter limits the amount of subsidised energy. Thus, in the base scenario (Madrid) the annual electricity consumption of the system is 38.3 kWh/m^2, which for a 100 m^2 house is 3,830 kWh/year, while for a 60 m^2 house it is 2,300 kWh/year. The eligible energy limitation of the social tariff, depending on the characteristics of the household, ranges from 1,380 kWh/year (family unit without minors) to 4,140 kWh/year (large family). In a scenario where only the social electricity tariff is applied as assistance program, these consumption limits would not be enough in most of the cases.

Table 5. 23. Results obtained in the case studies of the parametric analysis for the winter climate zone A according to the year of construction (insulation)

Construction age	**1981-2007**			**Before 1980**			**After 2007**		
Value of EEP [-]	**2.48**			**4.41**			**0.99**		
Floor area [m^2]	**14,488**	**22,167**	**9,659**	**14,488**	**8,307**	**12,461**	**14,488**	**52,077**	**34,037**
Support needed hours [%]	4.99	30.00	0.38	39.98	4.99	28.30	0.00	29.99	4.99
HSPF [-]	2.75	2.76	2.75	2.76	2.75	2.76	2.75	2.76	2.75
Avoided emission $[gCO_2/kWhth]$	143.05	128.00	144.90	121.25	143.05	130.05	144.95	129.00	143.05
R2H [%]	77.63	69.88	78.67	65.64	77.63	70.46	78.70	69.88	77.63
Demand covered by the pump [%]	98.62	88.70	99.96	83.30	98.62	89.44	100.00	88.69	98.62
$LCOH_{EHP+boiler}$ [€/MWh]	103.17	88.19	117.80	85.04	103.18	88.72	128.24	88.19	103.17
$LCOH_{centralised-boiler}$ [€/MWh]	77.52	73.64	82.92	72.72	77.52	73.79	91.83	73.64	77.52
$LCOH_{individual-boiler}$ [€/MWh]	203.39	203.39	203.39	155.15	155.15	155.15	353.39	353.39	353.39

Table 5. 24. Results obtained in the case studies of the parametric analysis for the winter climate zone B according to the year of construction (insulation)

Construction age	**1981-2007**			**Before 1980**			**After 2007**		
Value of EEP [-]	**2.34**			**4.01**			**0.96**		
Floor area [m^2]	**10,860**	**16,337**	**7,240**	**10,860**	**6,457**	**9,686**	**10,860**	**37,323**	**24,783**
Support needed hours [%]	5.00	29.97	0.17	38.37	5.00	29.79	0.00	29.97	5.00
HSPF [-]	2.72	2.73	2.71	2.73	2.72	2.72	2.71	2.73	2.72
Avoided emission [$gCO_2/kWhth$]	141.41	129.04	143.25	122.68	141.42	129.23	143.28	129.04	141.42
R2H [%]	77.34	70.44	78.39	69.92	77.34	70.55	78.40	70.44	77.35
Demand covered by the pump [%]	98.62	89.73	99.98	85.23	98.63	89.87	100.00	89.73	98.63
$LCOH_{EHP+boiler}$ [€/MWh]	100.52	87.43	112.26	84.84	100.55	87.52	121.18	87.43	100.56
$LCOH_{centralised-boiler}$ [€/MWh]	76.46	73.00	81.46	72.27	76.47	73.03	89.09	73.00	76.48
$LCOH_{individual-boiler}$ [€/MWh]	169.81	169.81	169.81	133.07	133.07	133.07	269.48	269.48	269.48

Table 5. 25. Results obtained in the case studies of the parametric analysis for the winter climate zone C according to the year of construction (insulation)

Construction age	**1981-2007**			**Before 1980**			**After 2007**		
Value of EEP [-]	**2.23**			**3.69**			**0.93**		
Floor area [m^2]	**7,109**	**11,589**	**4,739**	**7,109**	**4,381**	**6,572**	**7,109**	**26,015**	**15,960**
Support needed hours [%]	4.96	30.00	0.03	29.54	4.96	22.70	0	30.00	4.96
HSPF [-]	2.66	2.67	2.66	2.67	2.66	2.67	2.66	2.67	2.66
Avoided emission [$gCO_2/kWhth$]	138.91	125.82	140.63	126.04	138.91	129.44	140.64	125.82	138.91
R2H [%]	76.93	69.50	77.93	69.62	76.93	71.54	77.94	69.50	76.93
Demand covered by the pump [%]	98.68	89.03	99.99	89.19	98.68	91.68	100.00	89.03	98.68
$LCOH_{EHP + boiler}$ [€/MWh]	97.83	85.46	107.99	85.56	97.83	87.44	116.01	85.46	97.83
$LCOH_{centralised\ boiler}$ [€/MWh]	75.64	71.89	80.34	71.92	75.64	72.41	87.16	71.89	75.64
$LCOH_{individual\ boiler}$ [€/MWh]	135.66	135.66	135.66	112.40	112.40	112.40	200.49	200.49	200.49

Table 5. 26. Results obtained in the case studies of the parametric analysis for the winter climate zone D according to the year of construction (insulation)

Construction age	**1981-2007**			**Before 1980**			**After 2007**		
Value of EEP [-]	**2.18**			**3.53**			**0.92**		
Floor area [m^2]	**4,843**	**7,655**	**3,228**	**4,843**	**3,049**	**4,573**	**4,843**	**16,980**	**10,743**
Support needed hours [%]	4.97	30.00	0.11	30.43	4.97	25.91	0	30.00	4.97
HSPF [-]	2.58	2.59	2.58	2.59	2.58	2.59	2.57	2.59	2.58
Avoided emission [$gCO_2/kWhth$]	135.20	123.29	136.86	123.06	135.20	125.56	136.87	123.29	135.20
R2H [%]	76.27	69.36	77.26	69.23	76.27	70.66	77.27	69.36	76.27
Demand covered by the pump [%]	98.68	89.62	99.99	89.44	98.68	91.32	100.00	89.62	98.68
$LCOH_{EHP + boiler}$ [€/MWh]	97.60	87.35	106.84	87.24	97.60	88.21	114.79	87.35	97.60
$LCOH_{centralised\ boiler}$ [€/MWh]	75.36	71.86	79.99	71.83	75.36	72.19	86.47	87.35	75.36
$LCOH_{individual\ boiler}$ [€/MWh]	116.18	116.18	116.18	100.94	100.94	100.94	164.83	164.83	164.83

Table 5. 27. Results obtained in the case studies of the parametric analysis for the winter climate zone A according to the year of construction (insulation)

Construction age	**1981-2007**			**Before 1980**			**After 2007**		
Value of EEP [-]	**2.15**			**3.46**			**0.91**		
Floor area [m^2]	**3,676**	**5,625**	**2,451**	**3,676**	**2,329**	**3,494**	**3,676**	**12,433**	**8,125**
Support needed hours [%]	5.01	30.03	0.00	32.37	5.01	27.99	0	30.03	5.01
HSPF [-]	2.53	2.54	2.53	2.54	2.53	2.54	2.53	2.54	2.53
Avoided emission [$gCO_2/kWhth$]	133.48	123.18	134.50	121.74	133.47	124.03	134.50	123.18	133.48
R2H [%]	76.23	70.17	76.85	69.34	76.23	70.67	76.85	70.18	76.24
Demand covered by the pump [%]	99.18	91.19	100.00	90.09	99.18	91.85	100.00	91.20	99.18
$LCOH_{EHP + boiler}$ [€/MWh]	96.75	87.97	105.11	87.30	96.75	88.33	113.12	87.97	96.75
$LCOH_{centralised\ boiler}$ [€/MWh]	75.08	71.84	79.62	71.65	75.08	71.96	85.95	71.84	75.08
$LCOH_{individual\ boiler}$ [€/MWh]	106.07	106.07	106.07	94.70	94.70	94.70	143.63	143.63	143.63

Table 5. 28. Results in different winter climate zones for equal LCOH in the case of centralised boiler and EHP with back-up boiler

Winter climate zone	A	B	C	D	E
Floor area [m^2]	14,488	10,860	7,109	4,843	3,676
Value of EEP [-]	2.48	2.34	2.23	2.18	2.15
Support needed hours [%]	4.99	5.00	4.96	4.97	5.01
Current electricity cost					
Variable term [€/year]	14,985.66	16,512.49	18,053.67	18,851.85	19,558.44
Average variable price [€/MWh]	97.96	99.13	100.68	101.67	102.34
Fixed term [€/year]	9,583.64	9,427.08	8,703.25	8,002.49	7,421.65
Average fixed price [€/kW-year]	125.85	123.80	114.29	105.09	97.59
Reduced electricity costs					
Variable term [€/year]	7,729.74	9,207.62	10,957.39	11,711.81	12,556.03
Average variable price [€/MWh]	50.53	55.27	61.11	63.16	65.70
Fixed term [€/year]	9,583.64	9,427.08	8,703.25	8,002.49	7,421.65
Average fixed price [€/kW-year]	125.85	123.80	114.29	105.09	97.59
Discount on the fixed+variable term [%]	48.42	44.24	39.31	37.87	35.80
Discount on the bill [%]	29.53	28.16	26.52	26.59	25.94
$LCOH_{EHP + boiler}$ [€/MWh]	77.52	76.46	75.64	75.36	75.08
$LCOH_{centralised\ boiler}$ [€/MWh]	77.52	76.46	75.64	75.36	75.08

In the lower energy performance buildings (e.g. built 'before 1980'), a dwelling's energy retrofit is recommended, which would make it possible to reduce the heating cost. In order to assess the impact of this additional structural measure, Fig. 5. 24 has been obtained for the EHP, varying EEP and maintaining the levelised cost of heating in demand base with the same value as the baseline case, i.e. Madrid (D zone). This new condition requires varying the heated floor area obtaining a potential fitting curve (Eq. (5.52)). Fig. 5. 24 represents in the x-axis the EEP values for dwelling blocks in Spain, and in the left y-axis their heated floor area to maintain the same levelised cost as in the baseline case (fitting curve). In the right y-axis, it shows also the LCOH in €/m^2 as a function of the EEP. This figure highlights both the energy performance classes' bands and the three aggregated construction periods, which makes it possible to evaluate different baseline cases and the impact of the thermal enclosure retrofitting.

$$A = 11139 \cdot EPI^{-0.789} \quad (5.52)$$

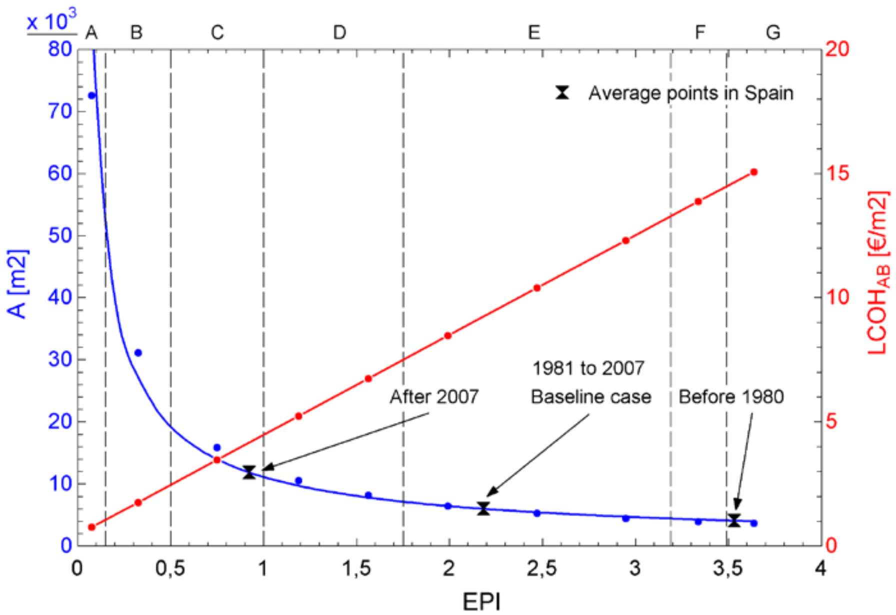

Fig. 5. 24.Required heated floor area (A) for each energy performance index (EEP) to maintain the same LCOHDB than in the baseline case (92.22 €/MWh) and LCOHAB obtained. Energy performance assessment (A to G) limits are indicated in dashed lines (reprinted from [308]*).*

Fig. 5. 25 - Fig. 5. 27 represent the LCOH values obtained in climate zones D, A and E, for the maximum floor area that could be covered by the tested GHP configurations (1 X 75 kWth and 1 X 25 kWth; 2 X 75 kWth and 1 X 25 kWth; 3 X 75 kWth and 1 X 25 kWth and 4 X 75 kWth and 1 X 25 kWth). From the above figures it can be seen that the LCOH values vary significantly among the climate zones considered, reaching lower values in floor areas where there is higher heating demand. This is due to the fact that as the demand covered increases, the denominator in the LCOH formula increases (see Eq. (5.52)). There is also a general tendency for the LCOH to decrease as the relative share of 75 kWth machines increases, mainly due to the fact that the 75 kWth pump has a higher efficiency than the 25 kWth pump. Nevertheless, in none of the cases studied is achieved

the same LCOH as that obtained when using an EHP (e.g. the LCOH of the latter in the baseline case is 92.2 €/MWh), being higher in the case of the GHP.

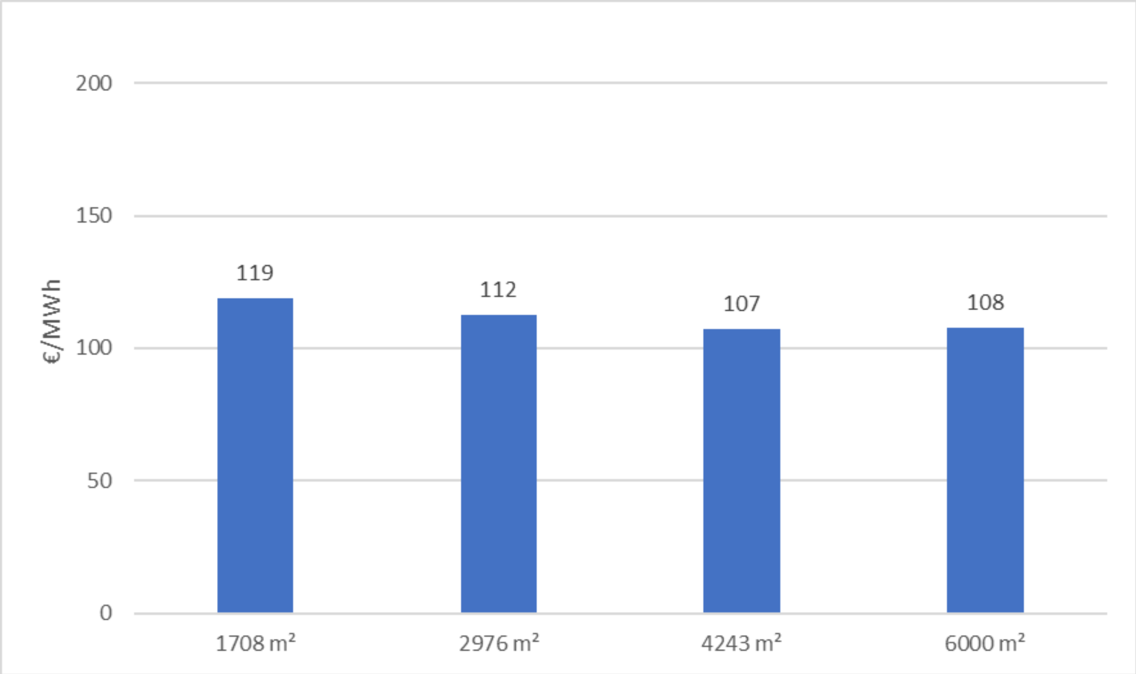

Fig. 5. 25. LCOH [€/MWh]of the GHP according to the heated surface (D winter climate zone) (Reprinted from [311]*).*

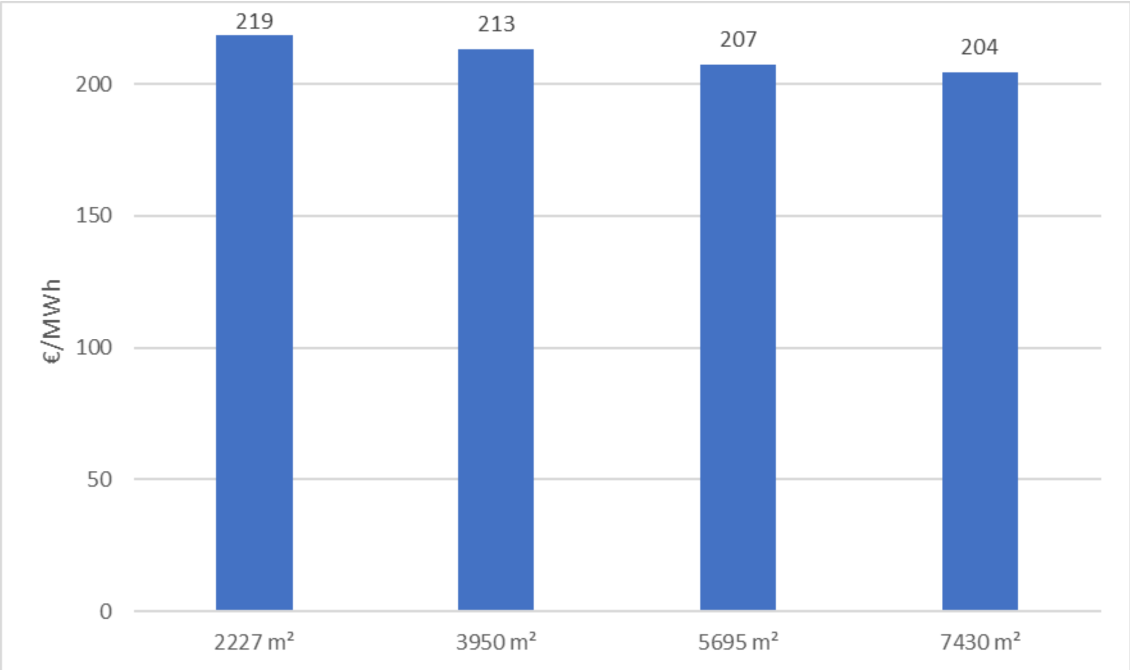

Fig. 5. 26. LCOH [€/MWh] of the GHP according to the heated surface (A winter climate zone) (Reprinted from [311]*).*

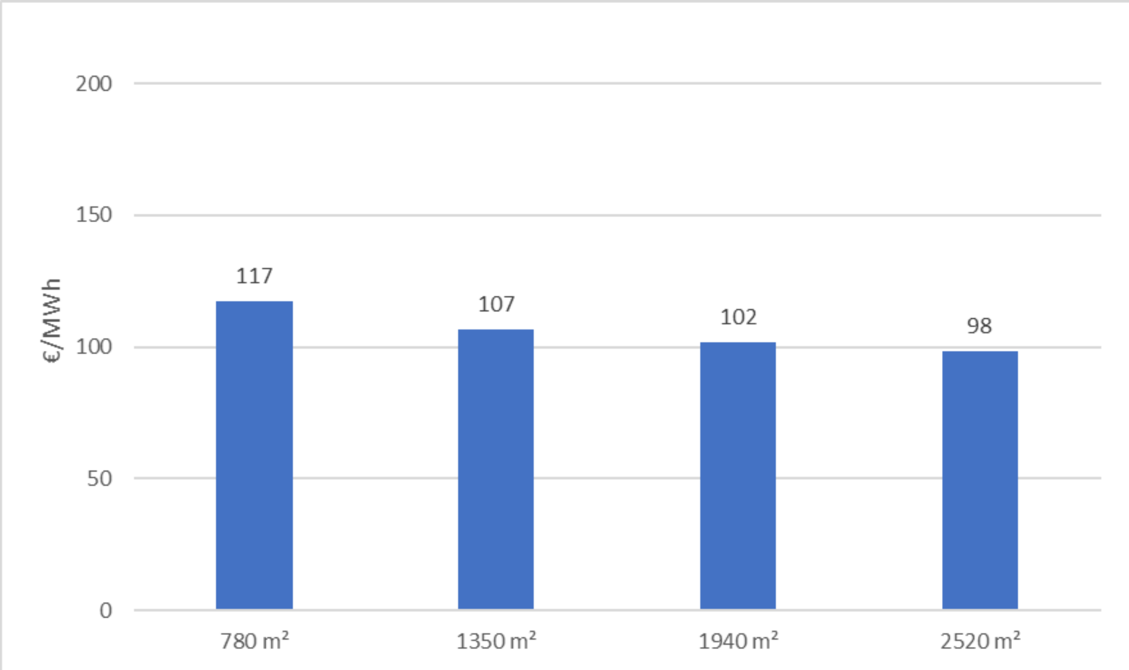

Fig. 5. 27. LCOH [€/MWh] of the GHP according to the heated surface (E winter climate zone) (Reprinted from [311]*).*

5.3.4 Discussion

The proposed demand model makes it possible to obtain the hourly heating demand profile of a building, which is crucial to work out the instantaneous consumption values of the heating system. The shape of the annual cumulative heating demand profile is consistent with the values for these type of curves obtained by other simulation tools [86]. This model only requires the location of the building, its useful floor area and the energy performance certificate (EPC). A detailed simulation of the building thermal behaviour is necessary to assess the EPC, which leads to the EEP that is integrated in the proposed model. The fact that no specific additional information about the building is required by the model makes it very easy-to-use and helpful for planning purposes. The flexibility of the model has been used in order to solve a case study representative of vulnerable dwellings.

Regarding the EHP, R290 (propane) has revealed as a suitable refrigerant for this application, selection that is supported by many manufacturers[74]. It is a natural fluid, with zero ODP and very low GWP. The low compressor discharge temperature and the low de-superheating zone in the condenser advise to take this fluid into consideration for the future. Its high flammability is not relevant in the current case, due to the fact that it is a centralised unit, with roof-top allocation and maintenance performed by professional workers. On the other hand, the speed control in the compressor allows the heat pump to meet nearly all the heating demand (96% in the baseline case) with a good efficiency.

[74] The GHP models uses the refrigerants set by the manufacturer (see [311])

Specifically, in the baseline case, the heating seasonal performance factor (SCOP) achieved is 2.585, exceeding the minimum required to consider the thermal energy taken from the air as renewable energy. The overall renewable energy to meet the heating demand using this system is obtained by considering both the energy supplied by the air and the renewable share in the Spanish electricity mix applied to the electricity consumption of the heat pump. Thus, each kWhth met with the proposed system avoids the emission of 131.7 g CO_2, whereas if a natural gas boiler is used 265.3 g CO_2 are emitted.

Regarding the cost analysis of the EHP in the baseline case, the proposed technology (heat pump plus boiler back-up) reduces the levelised cost of heating 15 % with respect to the de-centralised natural gas boiler. However, the proposed system has a LCOH 25 % higher than a centralised natural gas boiler. On the other hand, with the latter technology neither renewables are employed nor carbon dioxide emissions are avoided. The cost breakdown shows that the most important contribution to the overall cost is the energy cost, which suggests the need of measures to lower electricity bills. One short-term solution could be the implementation of subsidies policies to cover the operation, together with the possibility of the investment cost being covered by non-profit organisations, energy companies, Administration, etc. Regarding the former measure, a discount of 23.75% in electricity bill (comparable with the current social-tariff average-discount) would be enough to equalise the LCOH of the proposed system with the centralised boiler (the most economical scenario). Both programs to finance the proposed system (respectively, its variable and fixed costs) would be endorsed due to its excellent environmental performance, so balancing de-carbonisation with energy affordability. On the other hand, four devices of 75 kWth and one of 25 kWth were selected for the GHPs' configuration in order to meet the heating demand in the baseline case. The LCOH [€/MWh] of this heat pump solution in this case is 107.78 €/MWh, which is higher than the ones of EHP and centralised natural gas boiler, but it is slightly lower than the de-centralised boiler's one, i.e. it would be economically competitive with the latter technology but not with the studied centralised solutions.

In light of the EHP parametric analysis' results, comparing the case in which 5% backup hours are required (equal heated floor area), it can be seen that, as the thermal enclosure is more efficient, i.e. EEP is smaller (better insulation level):

- The covered floor area is larger, as shown graphically in Fig. 5. 22.
- Both HSPF and R2H, and avoided CO2 emissions remain constant and are therefore independent of thermal insulation.
- The LCOH per unit floor area decreases and this result can be seen graphically in Fig. 5. 23.

On the other hand, for the same level of insulation, as the floor area increases:

- The hours in which the coupling of the backup system is required increase.
- The HSPF increases because the heat pump works longer near its nominal point.
- Avoided CO2 emissions [gCO2/kWh_{th}] decrease so the relative environmental impact is higher.

- The ratio of renewable input to heating demand (R2H) decreases, as the heat pump covers less demand.
- The LCOH per unit demand decreases.

Furthermore, analysing the different climate zones chosen, it can be seen that:

- For the given system (constant heat pump power) more floor area can be heated the better the energy rating index (better the insulation), being this floor area smaller when the climate is more severe.
- The LCOH per unit area heated increases as the energy rating decreases (the rating index increases), being this increase higher when the climate is more severe.

Starting from the parametric analysis' results, the effect of energy retrofitting in the baseline case has been analysed. Results show that, if the energy performance assessment is improved from E to C due to a retrofit, the same heat pump would be able to meet the demand of 160 dwellings of 100 m^2 instead of 60 dwellings of the baseline case. Regarding the heating cost per square meter, the cost drops 4 €/m^2 for every EEP unit reduction. So, in the same example, the levelised cost of heating decreases €500 for a dwelling of 100 m^2 (with a baseline cost of €848).

Regarding the GHP solution, it could be seen that as the number of devices increases, the heating demand covered also increase and the LCOH decreases. Moreover, the levelised cost decrease with the winter climate severity, i.e. it is more economically feasible to install a GHP in a colder climate. On the other hand, the economic results are comparable with the one of individual natural gas boiler but are less competitive when compared with two alternative centralised solutions, i.e. the EHPs (also studied in this chapter) and the centralised natural gas boiler. However, it should be noted that the thesis results do not consider neither the potential heat recovery from the engine for DHW production nor the GHP cooling reverse mode, which could increase the GHP efficiency, thus reducing the operational costs.

5.4 Conclusions

This chapter analyses the techno-economic feasibility of two alternative heating technologies, i.e. centralised air-water electrically driven and gas engine driven heat pumps, as active measures against energy poverty in Spain. Moreover, an environmental analysis is also performed for the former device to frame this study also in the heating's decarbonisation process.

Firstly, the feasibility of heating a middle-energy-efficiency block dwelling in Madrid (baseline case) by, alternatively, the two studied technologies have been investigated as a retrofit of the current heating system. Thus, an existing system based on radiators is assumed, and the operation temperatures of the heat pump are adapted to this configuration. An expansion methodology based on the Spanish regulation has been used to forecast the hourly required heating demand. The performance map for the electrically driven heat pump (EHP) has been drawn once an eco-friendly refrigerant has been selected (R290), and a speed variation control over the compressor has been considered.

This control makes it possible to meet nearly the whole demand with high efficiency. On the other hand, two different gas engine driven heat pumps (GHPs) have been selected and characterised to meet both the base and peak heating demands. Finally, the heating demand has been coupled to the performance of both heat pumps.

Regarding the environmental and efficiency indicators, the results show an excellent performance of the EHP compared with the classical solution of the centralised condensing boiler system. On the other hand, the GHPs solution has worse seasonal performance[75] but offers a better response to low temperatures. Regarding the economic analysis, the levelised cost of heating (LCOH) of the EHP system is 25 % higher than the centralised boiler, due to the low prices of natural gas (2020 free market reference) for high consumption volumes. In this sense, if this kind of heat pump was selected to replace the existing heating system, a reduction of the electricity cost for vulnerable households (or for households in general) might have to be considered to make it competitive with the most economical technology analysed (i.e. centralised natural gas condensing boiler), thus considering both social aspects and environmental benefits. The situation is reversed in case of comparing the EHP with the de-centralised boiler solution, being the LCOH of the heat pump 15 % lower than the boiler’s one. In all the scenarios, the main share to the overall cost is the operation, particularly the energy cost. On the other hand, the economic results of the GHP are comparable with the one of individual natural gas boiler but are less competitive when compared with the two alternative centralised solutions, i.e. the EHPs and the centralised natural gas boiler. However, for an overall comparison, the cases of HVAC (heating+cooling) and HVAC+DHW would need to be considered in further work in order to consider their benefits in terms of cost savings.

Therefore, according to this work, the EHPs and GHPs can be considered as efficient systems to tackle energy poverty in a typical case of vulnerable households living in block dwellings in Madrid, particularly when compared with a de-centralised boiler heating system. On the other hand, modifications such as proposing a new electricity tariff frame (e.g. creating an actual ‘social tariff for electricity’[76]), increasing renewable energy generation (that would reduce the regulated market price) or extending the current social tariff to the EHPs case could be alternative or complementary solutions to reduce the operation costs of heat pumps with respect to the centralised boiler technology. Moreover, future studies would have to consider the ‘explicit carbon pricing’ due to the (potential) implementation of the Emission Trading System (ETS) in the residential sector. This mechanism is expected to make EHP more competitive when compared to fossil fuels’ driven technologies. On the other hand, less technological maturity has been detected in GHPs, both in terms of available sizes and refrigerants, which, for example, affects the optimisation of the load degree of the thermal system.

[75] Taking into account that the efficiency in a GHP is measured against primary energy (natural gas), whereas in an EHP is measured against final energy (electricity).

[76] This would be intended as a new ‘protected tariff’ for vulnerable households. Proposals on this topic have been presented by both civil society organizations [336], [337] and energy companies [338].

Furthermore, it should be noted that these technologies were modelled in a 2019 energy price reference scenario. In the current scenario (2021-2022), the prices of both the considered energy carriers (i.e. natural gas and electricity) have increased, mainly due to the natural gas price increase. Given the medium and long-term prospects for gas and electricity prices in a context of energy transition, where fossil fuels will be increasingly penalised, it seems that EHP will become more and more competitive compared to GHP.

Additionally, a parametric analysis of the EHPs has been carried out in five large cities in Spain belonging to different climate zones. The results show that performance of this technology vary broadly depending on the climate zone considered. Moreover, as the building energy efficiency is better, the heated floor area is larger, the technical performance and environmental parameters remain constant (thus, they are independent of thermal insulation), but the LCOH per unit floor area decreases, i.e. the system is more economically feasible. If an energy refurbishment is carried out that improves the rating from E (average of dwellings built between 1981 and 2007) to C (average of dwellings built after 2007), the cost of the system is reduced by 60%. Finally, for the same building energy efficiency, as the floor area increases: the hours in which the coupling of the backup system is required increase, the seasonal performance factor increases, the environmental parameter worsen, and the LCOH per unit demand decreases, i.e. the system is more techno-economical feasible but it shows worse environmental performance. Regarding the parametric analysis on the GHPs, it shows that as the number of devices increases, the heating demand covered also increase and the LCOH decreases. Moreover, a second parametric analysis shows that it is more economically feasible to install a GHP in a colder climate.

Eventually, the performed environmental and economic assessment may provide insightful evidence to policy makers for implementing clean and efficient measures to tackle energy poverty. In future works, the model could be expanded to summer season (cooling demand), taking advantage of the reversible ability of heat pumps. In the context of energy poverty, this is a relatively new trend, especially in countries in Southern Europe (as studied by the author and other scholars in [265]). Moreover, in the case of the gas driven heat pump, the full utilisation of the heat from the gas engine should be considered when designing the installation, for example, to provide DHW[77]. Other disadvantages of the EHP remain to be analysed, such as the high installed electrical power required (100 kW), which could make its deployment difficult in older neighbourhoods of towns. Finally, the impact of a parallel energy retrofitting of the thermal enclosure (additional to installation of a gas engine heat pump system) could be analysed in further work.

[77] Although this use is limited in the current CTE due to the fact that natural gases, even biomethane, are not considered in-situ renewable energy.

6. EFFECTIVENESS OF THE MAIN POLICIES AGAINST WINTER ENERGY POVERTY IN SPAIN

This chapter analyses and compares the impact of mitigating and structural policies on thermal energy services' affordability and winter energy poverty (WEP). The latter issue is intended as the energy poverty dimension related to households' heating and DHW expenditures. This analysis was carried out by using the RTEE model described in Chapter 3 and considering both the social (overall cost including both investment subsidies and household energy expenditures) and financial (energy-consumption subsidies' budget) costs of these two kinds of energy poverty policies.

The structure of the chapter is as follows. Section 6.1 highlights the main aspects of the current heating allowances and the structural measures proposed in Spain and presents the contribution of this chapter for their impact assessment. Section 6.2 explains the methodology used to apply the RTEE model to this effectiveness analysis and estimate the impact of both kinds of measures on thermal energy services' affordability and WEP. Section 6.3 presents and discusses the results obtained by applying the analysed policies to the Spanish vulnerable consumers. Finally, Section 6.4 points out the conclusions and policy implications of this chapter.

6.1 Introduction

As pointed out in Section 2.4, several energy-poverty mitigating and structural policies have been implemented in the EU Member States during the last decades. However, their actual impact on energy affordability has not been analysed sufficiently, which involves not having a reference to correctly target and improve them in the future.

In the European context, as described in Section 2.4, financial mitigating measures, e.g. the French Energy Voucher, are typically allocated only according to the household's income level and composition. In this regard, the Spanish Thermal Social Allowance (TSA) policy introduced a novelty by considering differences in energy needs depending on the climate zone. However, it does not include a calculation of the expenditure required to adequately cover these needs. To fill this gap, Section 6.2.1 analyses the current TSA and proposes an enhancement to this policy, i.e. it suggests the implementation of a Thermal Energy Cheque (TEC), which is a cheque for vulnerable consumers that depends on the household's 'Required Winter Thermal-Energy Expenditure' (RWTEE) defined and characterised at Spanish provincial level in 3.2.1.2. Namely, 6.2.1.1 assesses the potential impact of the TSA and TEC policies on vulnerable-households' thermal energy expenditure, according to the RWTEE analysis and the Spanish-vulnerable-consumers' classification. Thereafter, the same section presents a comparative analysis of the effectiveness of the current policy (TSA) and the proposed one (TEC) in reducing 'winter energy poverty' (i.e. considering only households' heating and DHW expenses) in Spanish vulnerable households. Briefly, as a novelty of the methodology presented in Section 6.2.1 and its results (Section 6.3.1), the TEC proposal integrates the RWTEE analysis in the calculation of an energy cheque that would enhance the current Spanish

TSA policy, thus meeting a more significant share of vulnerable households' winter energy needs. The importance of this work lays on the essential task of designing effective measures to support households' thermal energy costs such as the ones related to heating and DHW. On the one hand, as pointed out in Section 3.2.1.2, these services account for the majority of the Spanish residential final energy consumption. On the other hand, as pointed out in Chapter 4, low-income households tend to use heating installations sparingly to reduce their energy bills, thus suffering from 'hidden energy poverty' that could imply several (e.g. health) negative effects. Therefore, it is essential to accurately design and implement these kinds of policies to improve vulnerable households' health and wellbeing in the short term. It has to be highlighted that the TEC is proposed as a policy that mitigates the financial issues related to energy bills of vulnerable households in the short-term. Nevertheless, it is a costly measure and does not tackle other constituent causes of energy poverty, such as low energy efficiency of housing, which excludes it as a medium-long term measure.

Regarding the abovementioned cause of energy poverty, Chapter 4 shows that energy poor households typically live in energy inefficient houses with old or no heating systems, which makes it difficult to achieve indoor environmental comfort. This is both a social and environmental issue because, on one hand, vulnerable households cannot afford to pay high energy bills but, on the other hand, (only) subsiding their consumption could lead to an increase of the residential-sector carbon footprint or the total primary energy. As mentioned in Section 2.4.5.2, the 2020 Spanish Long-Term Strategy for Energy Renovation in the Building Sector (LTRS) sets out a specific plan to combat energy poverty but does not evaluate its impact on households' energy bills. In this regard, Section 6.2.2 of this chapter applies the RTEE bottom-up methodology to assess the effect of structural measures on reducing Spanish vulnerable households' thermal energy expenditure, and combating winter energy poverty. This high-geographical-resolution analysis makes it possible to evaluate the differences between the current outline and different 2030 scenarios, thus assessing the impact of various retrofitting measures, such as improvement of thermal enclosure and HVAC systems. Particularly, the effectiveness of these measures was assessed expanding the methodology proposed in Section 3.2.1.2 to all thermal energy services, i.e. adding cooling needs to the winter ones. Therefore, the provincial and national average RTEE (heating, cooling and DHW) values were calculated under different housing retrofitting scenarios to compare their impact on vulnerable household thermal energy expenses and winter energy poverty. Particularly, the considered strategies include the implementation of thermal enclosure's retrofitting and thermal systems' replacement measures.

Finally, this chapter compares the socio-economic effectiveness and the national financial burden of different implementation scenarios of the studied policies, thus pointing out some policy implications and future research work.

6.2 Methodology

6.2.1 Alternative heating allowances

This section[78] analyses the impact of the TSA on thermal-energy services' affordability and on winter energy poverty in Spain, thus proposing an alternative allowance called Thermal Energy Cheque (TEC).

Currently, as mentioned in Section 2.4.5.1, the calculation of the TSA amount in Spain is carried out according to Eq. (2.6). An enhancement to the current policy, based on the TEC, i.e. a cheque for thermal uses (heating and DHW), is proposed. This alternative allowance would be calculated for each household according to Eq. (6.1).

$$\mathrm{TEC}_i\ [€/\mathrm{year}] = \mathrm{f_v}\ \cdot \mathrm{RWTEE}_i \tag{6.1}$$

Where i is the i-th household; $\mathrm{f_v}$ is the Vulnerability Level Factor that takes the following values: 25% for vulnerable consumers, 40% for severely vulnerable consumers and 100% for the ones at risk of social exclusion (inspired by the Spanish social-electricity-tariff legislation[79]); RWTEE_i is the Required Winter Thermal-Energy Expenditure of i-th household calculated according to the methodology defined in Section 3.2.1.2. A proper use of the TEC might be ensured by establishing a cheque processing system similar to the French Energy-Voucher's one (see Section 2.4.3).

Ultimately, the implementation of the proposed TEC policy would need to collect some additional data for each vulnerable household. The family unit sheet, which is already part of the social tariff's application form, could also ask for basic dwelling's characteristics, such as its construction age and floor area[80]. This would make it possible to improve the calculation of required TEC to each beneficiary. To ensure the accuracy of the data, social services and NGOs could help vulnerable families to fill out the form correctly.

In this work, the 'annual budget required to implement the proposed TEC policy' has been calculated (see Appendix I) by applying the results of the 2019 provincial RWTEE analysis (see Section 3.3.1) to the number of households who benefited from the subsidy

[78] The alternative heating allowances analysis presented in this chapter is based on the paper 'Does cash money solve energy poverty? Assessing the impact of household heating allowances in Spain' written by the author, José Ignacio Linares, José Carlos Romero, Eva Arenas, Efraim Centeno, and published by Energy Research & Social Science [236]. It also includes quotations from the mentioned article.

[79] As mentioned in Section 2.4.5.1, for the purpose of mitigating the impacts of the 2021 energy prices crisis, the social electricity tariff discounts for vulnerable and severely vulnerable consumers have been temporarily raised to respectively, 60% and 70%. However, this chapter considered 25% and 40% because they are the permanent discounts of the Spanish social tariff.

[80] The other RTEE's key input parameters (identified in Chapter 3 and 4), i.e. family unit's size, a proxy of its composition and the residence locality, are already collected in the current form.

in 2019 (identified vulnerable consumers). This data, categorised per province, vulnerability level and household category, was provided by the Spanish Ministry for the Ecological Transition and the National Commission on Markets and Competition in response to two different inquiries [285], [320].

To consider potential future changes in energy taxation [252], such as the one that have been temporarily introduced to mitigate the impact of the 2021 energy prices crisis (see Section 2.4.5.1), it is interesting to consider a tax-free scenario for vulnerable consumers and point out the differences with the current outline. Furthermore, a 'before tax' scenario makes it possible to analyse the proposed TEC policy across the Spanish winter climate zones because it eliminates the distortion introduced by the different VAT applied in certain Spanish provinces (see Appendix F). Therefore, two different scenarios of RWTEE, and thus of TEC implementation, have been assessed: RWTEE after tax (AT) and RWTEE before tax (BT).

On the other hand, as mentioned before, the 2021 energy crisis has affected Spanish households' energy expenditure (particularly the electricity and natural gas bills) in different ways depending on if the consumer is on the regulated or free market and the kind of tariff contracted. When focusing on the 2021 winter months[81] (which are the focus of this analysis) and on the 'regulated' prices[82] (as explained in 2.4.5.1, in Spain, consumers must be on the electricity regulated market as primary condition to benefit from social tariffs), the energy prices changes with respect to 2019, have been the ones shown Table 6. 1. These values take into account the Government's price-mitigation measures described in Section 2.4.5.1 [198].

[81] According to the Spanish building regulation, the winter months (heating season) are from January to May and from October to December. However, the presented data assume that the average price in November and December will be the same as in October.

[82] Regulated prices for electricity, natural gas and LPG. The prices used for gasoil and biomass are based on average price statistics "at delivery point".

Table 6. 1. 2021-2019 'regulated' energy prices' difference during winter [236], [321]

Energy carrier	**2021-2019 difference**
LPG	11%
Gasoil	-3%
Biomass	-2%
Natural Gas	-14%
Electricity ('flat tariff')[83]	48%
Electricity ('time-change tariff')	113%

It can be noticed that the highest price increase was the one related to the electricity time-change tariff, which was much cheaper in 2019. On the other hand, the regulated natural-gas price cap set by the Government in October 2021 has resulted in a decrease of the regulated natural gas tariff in 2021 compared to 2019. Besides, as mentioned in Section 2.4.5.1, the Royal Decree Law 23/2021 increased the assistance programs' coverage, both for the electricity social tariff and the TSA.

It should be highlighted that the policy proposed in this document aims to improve the current TSA, but not with the intention of converting it into a medium-long term policy, but as a short-term policy until the implementation of structural measures, such as building retrofit. Indeed, Section 6.2.2 use the RTEE model to evaluate the impact of energy efficiency measures on thermal-energy service affordability.

6.2.1.1 Impact of heating allowances on thermal energy services' affordability and winter energy poverty

This section presents a comparative analysis of the impact of the two alternative heating allowances considered (i.e. the TSA and the TEC) on thermal energy services affordability and on the proportion of 'winter energy poor households'[84] in the 2019 and 2021 vulnerable-consumers samples, which include every household who benefited from the TSA policy in those two years [285]. It should be highlighted that this analysis does not consider the implementation of other types of energy poverty measures, such as

[83] Before June 2021, there were two main regulated market tariffs, i.e. 2.0A (no time metering or 'flat tariff') and 2.0DHA (time-of-use or 'hourly discrimination' tariff). The electricity tariff considered for the months after June 2021 is a new time-change tariff (2.0 D) valid for all consumer on the regulated market.
[84] i.e. considering only their heating and DHW expenses.

energy retrofit interventions in buildings, which are analysed separately in Section 6.2.2. The used metric is based on the 2M indicator's approach[85], mentioned in Section 2.2.1.

Thus, this analysis was carried out by calculating the proportion of households whose share of equivalised RWTEE in equivalised income is more than twice the M_t, which is the national median share of thermal energy expenditure (heating and DHW) in income. M_t was calculated by applying the methodology presented in [39] to the Spanish Household Budget Survey 2018 (using the data on households' income and actual energy expenditures[86]). On the other hand, the consumers' equivalised RWTEE-in-income share was estimated as follows. The RWTEE of each consumer cluster corresponds to the provincial average shown in Fig. 3. 5 (RWTEE AT) equivalised by using indexes that consider the influence of dwelling's and household's size on heating and DHW needs, and a proxy of the energy-needs' increase due to age. Particularly, these indexes have been set by following Moore's approach ([30], [322]), adjusted to the case study of this thesis. Firstly, the average household size of each vulnerable consumers' cluster was estimated according to the Spanish 2018 Household Budget Survey, starting from assumptions on the number of adults and minors composing the household. Table 6. 2 shows the values assigned to each cluster.

Table 6. 2. Average household size assigned to each vulnerable consumers' cluster

	Minimum pension	**Without minors**	**1 minor**	**2 minors**	**Large family**
No. of adults	1.6	1.9	2	2	3.6
No. of minors	0	0	1	2	1.8
Household size	1.6	1.9	3	4	5.4

Moreover, the average dwelling size of each cluster was also set according to the Spanish 2018 Household Budget Survey. The reference values are shown in Table 6. 3.

Table 6. 3. Average dwelling size assigned to each vulnerable consumers' cluster

	Minimum pension	**Without minors**	**1 minor**	**2 minors**	**Large family**
Dwelling size [m^2]	101	102	97	106	104

Finally, Table 6. 4 shows the indexes comparing heating and DHW required expenditures by consumer cluster. As mentioned before, these values were set by applying Moore's methodology to the Spanish case, i.e. taking into account the household characteristics shown in Table 6. 2 and Table 6. 3.

[85] In the case of the vulnerable consumers' database, it is not possible to estimate the impact of these measures on hidden energy poverty (HEP), e.g. by using the methodology presented in Chapter 4, because the actual consumption of the sampled households is not known.

[86] Households' income was equivalised by considering the number of adults and minors composing the household (OECD modified equivalence scale). In contrast, households' actual expenditures were equivalised according to the household size [39].

Table 6. 4. Equivalisation indexes for heating and DHW expenditures (own elaboration following [30,322]*)*

	Minimum pension	**Without minors**	**1 minor**	**2 minors**	**Large family**
Heating	1.00	0.94	0.90	1.03	1.17
DHW	1.00	0.86	1.13	1.30	1.56

The unit value index was assigned to the 'national average household' (2.5 persons living in a dwelling of 103 m^2). The heating indexes are ultimately set according to the assumptions on the dwelling size of the different household clusters (Table 6. 3). For example, the households with one minor have a smaller index value because they have an average dwelling size lower than the rest of the clusters. On the other hand, the DHW indexes mainly depend on the average household size assumed (Table 6. 2). Moreover, the heating and DHW indexes for the minimum pension cluster are calculated considering an increase in energy needs due to age. The same assumption partially explains the higher values of the indexes for large families than those of households with two minors, i.e. there is a higher presence of aged people in large families than in two-minor ones.

On the other hand, the consumer-cluster's income was set as the corresponding equivalised income threshold of the social tariff (best-case scenario), which depends on the vulnerability level and the household category (see Table 2. 14). For example, in the first vulnerability level, i.e. 'Vulnerable', the annual income threshold for a household without minors (€11,279) is lower than the threshold set for a household with one minor (€15,039). On the other hand, both thresholds are higher than the ones set for the same household categories in the second vulnerability level ('Severely vulnerable').

Firstly, this $2M_t$ indicator has been estimated for the initial vulnerable consumers' sample, i.e. before the application of the heating allowances. Secondly, the impact of the TSA and the proposed TEC (in the scenario 'After Tax') are compared as follows. The aid amount corresponding to each vulnerable-consumer cluster, identified by the Province of residency and the vulnerability level, was subtracted from the cluster's RWTEE. Therefore, the indicator was calculated for the two alternative scenarios, considering the reduction in expenditure produced by, respectively, the TSA or TEC application.

Thirdly, an additional analysis was carried out for the 2019 case study. The calculation of the TEC impact was iterated to identify the share of RWTEE that should be covered by the aid, depending on the vulnerability level, in order to fulfil the energy poverty reduction targets set by the SNSEP (25% and 50%). Moreover, an ideal scenario of eradication of WEP was assessed and the national annual budget values corresponding to each scenario were compared. In this last analysis, the TEC amount for consumers at risk of social exclusion has not been modified because the cheque's first proposal already reduces their share of WEP by 100%. Table 6. 5 shows an example of the WEP estimation for the province of Madrid in the six analysed scenarios. The consumer clusters whose share of RWTEE in income is more than twice the M_t ($2M_t$=5.1% for 2018) are highlighted in blue and counted as winter energy poor.

Table 6. 5. Example of the WEP estimation: share of RTEE in income of the consumer clusters in the six analysed scenarios for the province of Madrid. The consumer clusters in WEP are highlighted in blue (P - Minimum Pension; MN - Minor(s); L - Large family).

	Vulnerable consumers								**Severely vulnerable consumers**								**Consumers at risk of social exclusion**							
Scenario	**P**	**0 MN**	**0 MN***	**1 MN**	**1 MN***	**2 MN**	**2 MN***	**L**	**P**	**0 MN**	**0 MN***	**1 MN**	**1 MN***	**2 MN**	**2 MN***	**L**	**P**	**0 MN**	**0 MN***	**1 MN**	**1 MN***	**2 MN**	**2 MN***	**L**
Before aid	-	10.1%	7.6%	7.5%	6.0%	6.8%	5.7%	-	16.2%	20.1%	15.1%	14.9%	11.9%	13.7%	11.4%	9.8%	16.2%	20.1%	15.1%	14.9%	11.9%	13.7%	11.4%	9.8%
After TSA	-	9.5%	7.1%	7.0%	5.6%	6.5%	5.4%	-	14.8%	18.2%	13.7%	13.5%	10.8%	12.5%	10.4%	9.1%	14.8%	18.2%	13.7%	13.5%	10.8%	12.5%	10.4%	9.1%
After TEC	-	7.6%	5.7%	5.6%	4.5%	5.4%	4.5%	-	10.3%	12.3%	9.2%	9.0%	7.2%	9.0%	7.5%	6.9%	1.5%	0.5%	0.4%	0.2%	0.2%	1.9%	1.6%	2.4%
25% WEP reduction	-	6.1%	4.6%	4.5%	3.6%	4.5%	3.7%	-	7.7%	8.8%	6.6%	6.4%	5.1%	6.8%	5.7%	5.5%	1.5%	0.5%	0.4%	0.2%	0.2%	1.9%	1.6%	2.4%
50% WEP reduction	-	5.2%	3.9%	3.8%	3.0%	3.9%	3.2%	-	6.0%	6.6%	4.9%	4.8%	3.8%	5.5%	4.6%	4.7%	1.5%	0.5%	0.4%	0.2%	0.2%	1.9%	1.6%	2.4%
WEP eradication	-	3.0%	2.3%	2.2%	1.7%	2.6%	2.2%	-	3.4%	3.1%	2.3%	2.1%	1.7%	3.4%	2.8%	3.4%	1.5%	0.5%	0.4%	0.2%	0.2%	1.9%	1.6%	2.4%

* For the following special circumstances:

- Recognised disability ≥ 33%
- Victim of gender violence
- Degree of dependency, grade II or III
- Single-parent families

Table 6. 5 highlights the different impact of the two measures analysed (TSA and TEC) on the reduction of the household share of RWTEE in income and, therefore, on WEP. The last three scenarios constitute a complementary analysis on the calculation of the national budget to achieve the SNSEP targets and the ideal eradication of WEP.

Finally, the joint impact of energy prices crises and government mitigating measures (including the TSA budget enhancement) on thermal energy services affordability and winter energy poverty in 2021 was estimated following the above methodology. The same assessment was repeated in the case of implementation of the proposed TEC in that year.

6.2.2 Building energy retrofitting strategies

This section presents an application of the RTEE model to the effectiveness assessment of the implementation of alternative energy retrofitting strategies in vulnerable households. In order to do that, the provincial RWTEE analysis carried out in 3.2.1.2 has been completed by calculating the required cooling expenditure at provincial and national level by using the methodology presented in 4.2.1. The resulting 'complete' characterisation of the RTEE (heating, cooling and DHW) in Spain made it possible to analyses the impact of different energy retrofitting strategies on energy services affordability and winter energy poverty[87] in the medium-term, i.e. 2030.

Several 2030 scenarios of energy retrofitting in vulnerable households have been analysed, and a reference scenario was set as follows. 2020 energy prices have been considered as starting point to make it possible to apply the 2030 price projections presented in the LTRS. Particularly, the LTRS forecasted an average fossil fuel price increase of 43.3% in 2030 (compared to 2020). The rest of the reference scenario's parameters are the same as for the 2019 TSA and TEC assessment (see Section 6.2.1). On the other hand, for the 2030 scenarios, the medium-term (2020-2030) effect of temperature changes on the theoretical HVAC demand was considered 'negligible' according to the LTRS[88]. The winter energy poverty analysis was carried out by using the 2019 vulnerable consumers data, which make it possible to compare the effectiveness of mitigating and structural measures (see Section 6.3.3). All the studied scenarios can be summarized as follows:

- Reference Scenario
- Projected Future Scenarios (2030):

[87] This analysis excluded cooling needs to make the results comparable with the ones obtained for heating allowances.

[88] The LTRS forecasts an increase of the domestic space cooling demand in Spain from 2020 to 2030 of between 10% and 21% (according to the climate zone). On the other hand, the space heating demand is expected to decrease by 3-4% in the same period. This tendency is also confirmed by a report analysing the adaptation to climate change in the Spanish Energy Sector [339]. Therefore, giving the much higher heating share in the RTEE (see Fig. 6. 4) and the LTRS forecasting, these two changes would balance each other resulting in a negligible HVAC demand change between 2020 and 2030. Nevertheless, a revision of the calculations in the future is desirable in view of new predictions, such as the most recent IPCC report [340].

- Scenario 0 – 'Business as usual': Neither building thermal-enclosure retrofitting nor thermal systems replacement's measures are implemented.
- Scenario I –'Low-cost building retrofit': a set of low-cost thermal-enclosure's retrofitting measures (own elaboration from [91]) are performed in vulnerable consumers living in dwelling built before 1981.
- Scenario II – 'Thermal systems replacement': The existing thermal systems are replaced with the most efficient equivalent (same energy carrier[89] and type) systems in 2030 (own elaboration from [269])
    a. Heating systems
    b. Cooling systems
    c. HVAC + DHW systems
- Scenario III – 'Multiple energy retrofit measures' (I+IIc): All the measures mentioned in Scenario I and IIc are implemented in vulnerable consumers' dwellings.

6.2.2.1 Impact of energy retrofitting on thermal energy services affordability and winter energy poverty

In order to assess the effectiveness of the structural measures proposed in the different scenario presented above, it is crucial to understand how they contribute to reduce the energy burden of vulnerable households. The low-cost building retrofitting measures included in Scenario I and III focus on improving the insultation of the dwelling's thermal enclosure. This improvement reduces the required demands for heating and cooling. In this regard, the 'reduction rates' were calculated by extrapolating the results of a previous study [91] to all Spanish climate zones. That work analysed in depth the category of measures included in Scenarios I and III. Particularly, that study proposed an express housing energy retrofitting comprising a series of low-cost measures that can be applied to Spanish low-income households. They calculated the energy saving resulting from the application of the low-cost energy retrofitting in a modelled building. The calculation, based on the adaptive comfort criterion (see Section 2.1.1), was carried out for four Spanish cities (*Barcelona, A Coruña*, *Madrid* and *Seville*). An own elaboration of the report results shows that the reduction in thermal energy demand was inversely proportional to the winter climate zone. Table 6.6 and Table 6. 7 shows the results obtained for, respectively, heating and cooling needs.

[89] Previous work [341] projected fuel use in Western Europe to remain quite stable until 2030, i.e. no significant changes in energy carriers.

Table 6.6. Required heating demand after a 'Low-cost building retrofit' with respect to the 'Business as usual' required heating demand [%] according to the climate zone

Winter climate zone	$\frac{RD_{h,retrofit}}{RD_h}$ [%]
A	29%
B	31%
C	38%
D	46%
E	53%

Table 6. 7. Required cooling demand after a 'Low-cost building retrofit' with respect to the 'Business as usual' required cooling demand [%] according to the climate zone

Climate zone	$\frac{RD_{c,retrofit}}{RD_c}$ [%]
a3c	44%
A2	37%
A3	44%
A4	53%
B2	37%
B3	44%
B4	53%
C1	30%
C2	37%
C3	44%
C4	53%
D1	30%
D2	37%
D3	44%
E1	30%

On the other hand, the replacement of thermal systems with ones with a higher performance factor[90] reduces the household's required thermal energy consumption. The seasonal performance factors assumed for 2030 were obtained by elaborating the results presented in [269]. Table 6. 8, Table 6. 9 and Table 6. 10 summarise, respectively, the

[90] The replacement of existing boilers with heat pumps is not included in this chapter's 2030 scenarios, in line with the LTRS. In this regard, the Strategy states that 'heat pumps have technical operating characteristics that in the short term (2021-2030) make their integration in all climate zones difficult'. Thus, in the 2030 LTRS horizon, the installation of aerothermal heat pumps is recommended only in areas with milder winters (up to climate zone C).

HSPF, SPF[91] and SEER values assumed for the new 2030 thermal systems in the Scenarios II and III.

Table 6. 8. Seasonal performance factor for new heating systems (HSPF) assumed in the 2030 scenarios (own elaboration from [81]*) - Individual: individual heating system; Central: central heating system; Portable: portable heater; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; NG: natural gas; Electricity - Electric Radiator or Electric Storage Heater).*

Energy carrier	**Individual**	**Central**	**Portable**
NG	1.00	0.94	1.00
LPG	0.99	0.99	0.99
Gasoil	0.93	0.86	0.93
Bio[a]	0.70	0.69	0.70
Electricity	1.00	1.00	1.00

[a] Biomass was assumed to replace all the coal-fuelled heating systems

Table 6. 9. Seasonal energy efficiency rating for cooling (SEER) per summer climate assumed for new cooling systems in the 2030 scenarios (own calculation using the methodology described in [311]*)*

Summer climate zone	**SEER[a]**
1	6.14
2	5.92
3	5.60
4	5.45

[a] Reversible air-to-air aerothermal heat pumps (76% of cooling equipment in dwellings according to SPAHOUSEC II)

Table 6. 10. Seasonal performance factor for new DHW systems (SPF) assumed in the 2030 scenarios (own elaboration from [81]*) - Individual: individual DHW system; Central: central DHW system; LPG: liquefied petroleum gas (butane/propane); Gasoil: heating gasoil; Bio: biomass; NG: natural gas; EWH: electric water heater).*

Energy carrier	**Individual**	**Central**
NG	0.95	0.92
LPG	0.94	0.92
Gasoil	0.94	0.92
Bio[a]	0.72	0.72
Electricity	0.99	0.99

[a] Biomass was assumed to replace all the coal-fuelled DHW systems

[91] The considered DHW energy carriers (except for biomass) would likely not respect the regulation of the CTE [84], which requires on-site renewables or solid biomass for DHW, between 60 and 70% of primary energy. In the case of HVAC systems, the CTE states that if no more than 25% of the building thermal enclosure is refurbished (which is the case of the considered low-cost building retrofit), it is not necessary to respect the primary energy requirements. Therefore, giving the tecno-economic nature of this analysis and the higher share of HVAC consumption than DHW one, the CTE primary energy requirements are not considered relevant to this chapter's purpose.

Firstly, the provincial and national average RTEE in Scenario 0 were calculated by applying the projected 2030 energy prices to the Reference Scenario, which was characterised by using the methodology described in Section 3.2.1.2 (for the heating and DHW expenditures) and Section 4.2.1 (for the cooling expenditures). Secondly, the 'reduction rates' due to low-cost building retrofit (Table 6.6 and Table 6. 7) were applied to the heating and cooling demands of dwellings constructed before 1981 to estimate the provincial and national average RTEE in Scenario I. Thirdly, starting from Scenario 0, the 2030 seasonal performance factors (Table 6. 8 and Table 6. 9) were applied to the required consumption for heating and cooling to assess, respectively, the average RTEE in Scenario IIa and IIb; besides, Scenario IIc was characterised by applying the 2030 performance factors to the required consumption of the three analysed thermal services, i.e. heating, cooling and DHW (Table 6. 10 shows the new SPF for DHW systems). Finally, Scenario III was assessed by complementing the impacts of low-cost building retrofit (Scenario I) and thermal systems replacement (Scenario IIc), thus reducing, respectively (and simultaneously), the HVAC demand and the required thermal energy consumption.

Starting from the above results, the impact of different retrofitting strategies on thermal services' affordability was calculated by comparing the RTEE of the 2030 retrofitting scenarios with the 'Business as usual' one (Scenario 0). On the other hand, the WEP share in all scenarios was estimated by using the methodology described in Section 6.2.1.1, thus measuring the impact of the abovementioned structural measures on winter energy poverty in Spain. Besides, the budgets needed to implement such measures in Scenario I, IIc and III was calculated by assuming the following unit investment costs: around €4500 per household for the low-cost building retrofit [91][92], €1500 approx. per household for the heating/DHW systems' replacement and €1200 for air conditioner replacement[93]. The third scenario includes the two kind of measures analysed, which are applied to different numbers of vulnerable consumers. Therefore, its budget is the sum of the two measures budget, as shown in Table 6. 16. Regarding the useful life of the thermal systems' replacement, the Spanish LTRS estimates it between 15 years for individual boilers and 25 years for centralised boilers, being the useful time of electric radiators or storage heaters around 20 years. Thus, applying the Census distribution assumptions to the number of centralised and individual installations existing at national level, the LTRS calculates an average useful life time of each kind of heating/DHW systems, i.e. heat pumps, natural boilers, etc. Giving the systems considered in this chapter, the average useful life would be 18.5 years for block dwellings (individual/centralised installations) and 16.7 years for single-family dwellings (individual installations). Therefore, giving the shares of these two types of dwellings in Spain (Census 2011), the average useful life of heating/DHW systems was set at 18 years. Moreover, the average air conditioner's useful life was set at 10 years [323]. On the other hand, the low-cost retrofit useful time

[92] This study showed that even a modest investment in the energy efficiency of homes (approx. 4,500 €) can lead to considerable energy savings.

[93] The latter two amounts were estimated applying a previous techno-economical study [342] (market prices in case of electric radiators[343]) to the characteristics of the Spanish residential buildings' stock and existing thermal systems ([344], [269] and Census 2011).

(interval between each retrofitting intervention) was set at 30 years. This is in line with the literature and the timespan fixed in the city of Madrid to carry out a new Technical Building Inspection (ITE in Spanish) from the date of completion of the new building or renovation works (applying the national regulation [324]).

Therefore, the levelised investment cost per household was calculated for each 2030 retrofitting scenario starting from the information described in the above paragraph. Considering the vulnerability of the beneficiaries, it is assumed that the investment would be fully covered by the State (or with a mix of public-private financing), i.e. with a non-repayable grant. Considering a reasonable discount rate (*wacc*=5% [325]), this parameter was calculated as the product of the investment cost and the capital recovery factor (*CRF*), the latter being calculated by applying Eq. (6.2.e). Moreover, in the low-cost building retrofit scenario, the levelised investment cost per average household takes into account that this measure would be applied only to the 55% of dwellings, i.e. the ones built before 1981.

Regarding the 'operating costs', the levelised cost of the j-th energy carrier $LC_{ec,j}$ was calculated by applying Eq. (6.2a)-(6.2e).

$$LC_{ec_j}\ [€/\mathrm{MWh}] = \mathrm{C}_{ec,10_j} \cdot f_{\Sigma_j} \cdot CRF \tag{6.2a}$$

$$\mathrm{C}_{ec,10_j}\ [€/\mathrm{MWh}] = C_{ec,0_j} \cdot (1 + r_{ec_j})^{10} \tag{6.2b}$$

$$f_{\Sigma_j}[-] = \left(\frac{k_{ec_j} \cdot (1 - k_{ec_j}^{\ N})}{1 - k_{ec_j}}\right) \tag{6.2c}$$

$$k_{ec_j}\ [-] = \frac{1 + r_{ec,j}}{1 + wacc} \tag{6.2d}$$

$$CRF = \frac{wacc \cdot (1+wacc)^N}{(1+wacc)^N - 1} \tag{6.2e}$$

Where $C_{ec,10_j}$ is the j-th energy carrier cost at the base year (2030); $C_{ec,0_j}$ is the j-th energy carrier cost at the reference price year (2020); $r_{ec,j}$ is the nominal escalation rate of the j-th energy carrier, assumed according to the 2030 projections of the LTRS; f_{Σ_j} is the accumulation factor of the j-th energy carrier; N is the thermal system useful life (according to the LTRS). When $r_{ec,j}$ is zero, f_{Σ_j} is the inverse of the CRF, so $LC_{ec_j} = C_{ec,0_j}$. On the other hand, in all the analysed scenarios, the maintenance cost is assumed equal to zero.

This calculation made it possible to compare the retrofitting scenarios among each other by considering the 'social cost' of each set of measures, i.e. the sum of the average levelised RTEE in that scenario and the levelised investment cost of the implemented measures. Finally, the financial comparison among the variuos mitigating and structural policies analysed in this chapter was performed by considering the annual budget of the heating allowances and the national levelised investment needed in each retrofitting scenario.

6.3 Results and discussion

6.3.1 Effectiveness of heating allowances

Fig. 3. 5 maps the 2019 RWTEE values for the 'provincial weighted-average households', which (together with the 2021 RWTEE values) were used to assess the impact of the two considered heating allowances. In 2021, despite of the price-mitigation measures implemented by the government, the average-household's RWTEE AT increased by 10% compared with its value in 2019 (2019: €1,055; 2021: €1,159).

For reference purposes, the cost to cover 100% of the RWTEE for all vulnerable consumers in the alternative tax scenarios for the two analysed years would be, respectively, AT €1,156m and BT €886m approx. in 2019, and AT €1,409m and BT €1,092m approx. in 2021. It has to be highlighted that two different phenomena contributed to determine these values. The number of allowances' beneficiaries in 2021 (1.22m) were 13% higher than the 2019's one (1.08m). On the other hand, as shown in Table 6. 1, the average regulated electricity prices in 2021's winter were considerably greater than the 2019's one, while (considering the Government price mitigating measures) other fuel prices didn't change significantly when comparing the two analysed years.

However, the objective of the proposal presented in this section is not to cover 100% of this cost, but to support (in the short term, pending the implementation of structural measures) a share of household's RWTEE that varies according to the consumer's vulnerability level. Different values of TEC-annual-budget were obtained by applying Eq. (6.1) to the two abovementioned RWTEE-scenarios in the two analysed (see Appendix I for the provincial results for 2019): AT €374m and BT €286m approx. in 2019, and AT €458m and BT €355m approx. in 2021. The BT scenario in 2019 is selected for the comparison among the winter climate zones because it eliminates the distortion introduced by the different taxation applied in some locations, whereas the AT scenario represents the actual policy proposal.

Fig. 6. 1 compares the values of the proposed 2019 TEC in scenario BT with the 2019 TSA (presented in Section 2.4.5.1), for each consumer category, in six provinces representative of the six Spanish winter climate zones. In the proposed TEC, the smaller amount corresponding to the mildest climate zone (α) is related to DHW expenditures. Meanwhile, the cheque of the coldest zone is significantly greater than the other zones' one because of the considerable higher heating expenditures. Moreover, the proposed TEC allocates a much higher aid to consumers at risk of social exclusion than to the other two categories. However, this does not produce a significant rise of the cheque-annual-

budget because in 2019 this category of consumers was only 0.3% of total beneficiaries [285]. Comparing the proposed cheque with the current allowance (Fig. 6. 1), it is noticeable that, in 2019, the TSA covered only a small percentage of the RWTEE of Spanish vulnerable households (6.7% on average). Whereas, the proposed TEC, if applied, would cover on average 33.4% of households' theoretical heating-and-DHW expenditures. This is even more evident for consumers at risk of social exclusion, i.e. the most vulnerable ones, who currently receive the same aid as the severely vulnerable ones (whereas, applying the proposed energy cheque, they would receive 100% of their RWTEE). The value differences pointed out in Fig. 6. 1 are mostly explained by the fact that the TSA-annual-budget in 2019 (€75m, see Section 2.4.5.1) was, respectively, 20.1% and 26.7% of the proposed TEC budget in the two scenarios. This produced a much slighter increase in the TSA amount with the winter severity compared to the TEC one. The vulnerable consumers living in the coldest zone were clearly the most affected by this fact since they received a cash transfer that was between 7% and 17% of the TEC AT. This meant also that the TSA amount of zone E in 2019 was only three times the one of zone α. So, the subsidy-rise with the winter severity was only half the increase of the RWTEE-value. Fig. 6. 2 shows the comparison between the TSA[94] and the proposed TEC in 2021. It can be noticed from the figure that, in 2021, the TSA covered a higher percentage of the RWTEE of Spanish vulnerable consumers (14.3% on average) than in 2019, with an average aid of €166 per household. This is almost half the average amount of the proposed TEC AT in that year (€376 per household), which, compared to the 20.1% reached in 2019, denotes the Spanish Government will to enhance mitigating measures during the 2021 energy crises. It has to be highlighted that this estimation considers also the higher number of TSA beneficiaries in 2021 compared to 2019 (+13%), which is an additional symptom of the improvement in coverage of this measure.

[94] The 2021 TSA amounts for the different climate zone were estimated by using Eq. (2.6) and comparing the budget and number of beneficiaries with the 2019 ones.

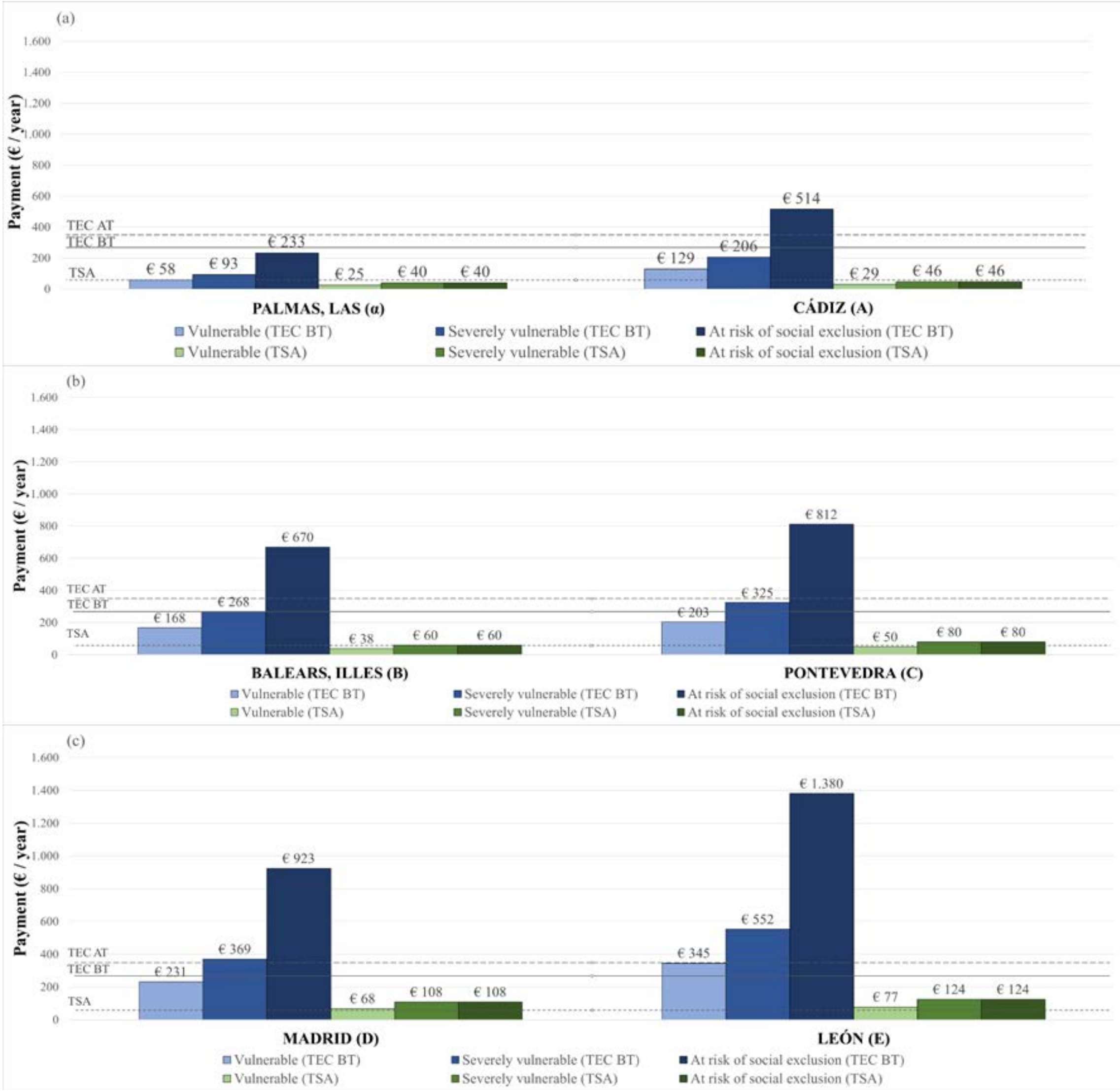

Fig. 6. 1. Comparison between the proposed TEC in Scenario BT and the TSA (both in 2019), per winter climate zone and consumer category: (a) Warm climate zones, (b) Temperate climate zones, (c) Cold climate zones. The national average payment values are shown as lines in the chart (reprinted from [236]*).*

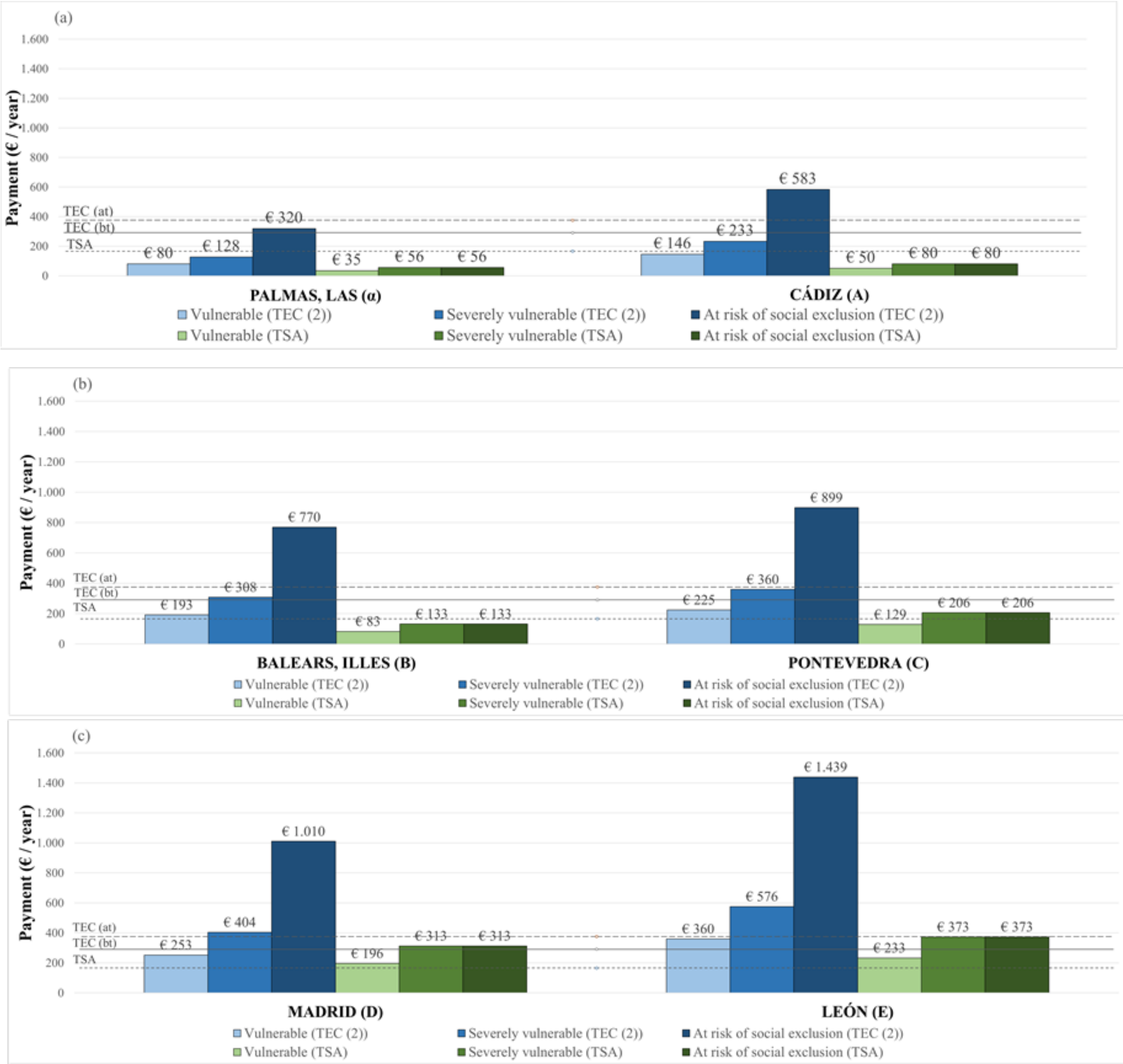

Fig. 6. 2. Comparison between the proposed TEC in Scenario BT and the TSA (both in 2021), per winter climate zone and consumer category: (a) Warm climate zones, (b) Temperate climate zones, (c) Cold climate zones. The national average payment values are shown as lines in the chart.

The energy cheque proposed in this section (TEC AT) for 2019 is, on average, €347 per vulnerable consumer. Table 6. 11 shows the comparison among the proposed cheque for Spain and the mitigating measures implemented in the UK and France in 2019.

Table 6. 11. Comparison among the proposed TEC (Spain) and the mitigating measures implemented in the UK and France in 2019

Measure	**Energy services**	**Energy carriers**	**Average payment [€/year]**
TEC (ES)	Heating and DHW	All	€347
Winter Payments (UK)	Heating	Electricity / Gas (one allowance) and Unspecified (two allowances)	€388
Energy Voucher (FR)	All	All	€200

Bearing in mind the differences and similarities of these measures (Table 6. 11), the TEC average payment would be in between the average Energy Voucher in France (€200) and the sum of winter payments assigned to vulnerable households in the UK (€388). However, for a rigorous comparison, the values would have to be adjusted to take into account the differences in socio-demographic characteristics and climate. Furthermore, it should be noticed that the French Energy Voucher was designed to support all domestic energy costs.

Table 6. 12 and Table 6. 13 show the results of the analysis of the TSA's and TEC's impact on the proportion of winter energy poor households, respectively, in the 2019 and 2021 vulnerable-consumers sample [285], estimated using the $2M_t$ indicator explained in Section 6.2.1.1 ($2M_t$=5.1% for 2018 HBS).

Table 6. 12. Proportion of winter energy poor households in the 2019 vulnerable-consumers sample before and after the application of the analysed policies

Scenario	**Vulnerable consumers**	**Severely vulnerable consumers**	**Consumers at risk of social exclusion**	**Total**	**WEP variation**
Before aid	92%	98%	100%	96%	0%
After TSA	90%	98%	100%	95%	-1%
After TEC	73%	93%	0%	86%	-11%

Table 6. 13. Proportion of winter energy poor households in the 2021 vulnerable-consumers sample before and after the application of the analysed policies

Scenario	**Vulnerable consumers**	**Severely vulnerable consumers**	**Consumers at risk of social exclusion**	**Total**	**WEP variation**
Before aid	93%	99%	100%	97%	0%
After TSA	90%	98%	100%	96%	-2%
After TEC	82%	98%	0%	92%	-6%

Table 6. 12 shows that the implementation of the TSA in 2019 reduced the proportion of energy poor by only 1%. Replacing the current allowance with the energy cheque proposed in this paper would lead to more significant WEP reduction (11%)[95]. Nevertheless, this reduction is still below the SNSEP targets. Thus, Fig. 6. 3 shows the TEC amount (as percentage of RWTEE, i.e. the parameter f_v in Eq. (6.1)) needed to achieve the abovementioned targets and the ideal eradication of WEP. It should be noticed that this analysis does not include the potential implementation of other types of energy poverty measures, e.g. building energy retrofitting (analysed in Section 6.2.2), which could reduce the households' RWTEE, thus reducing WEP.

[95] It should be highlighted that this is a theoretical assessment sensitive to the indexes used for the equivalisation of energy expenditures (see Section 6.2.1.1).

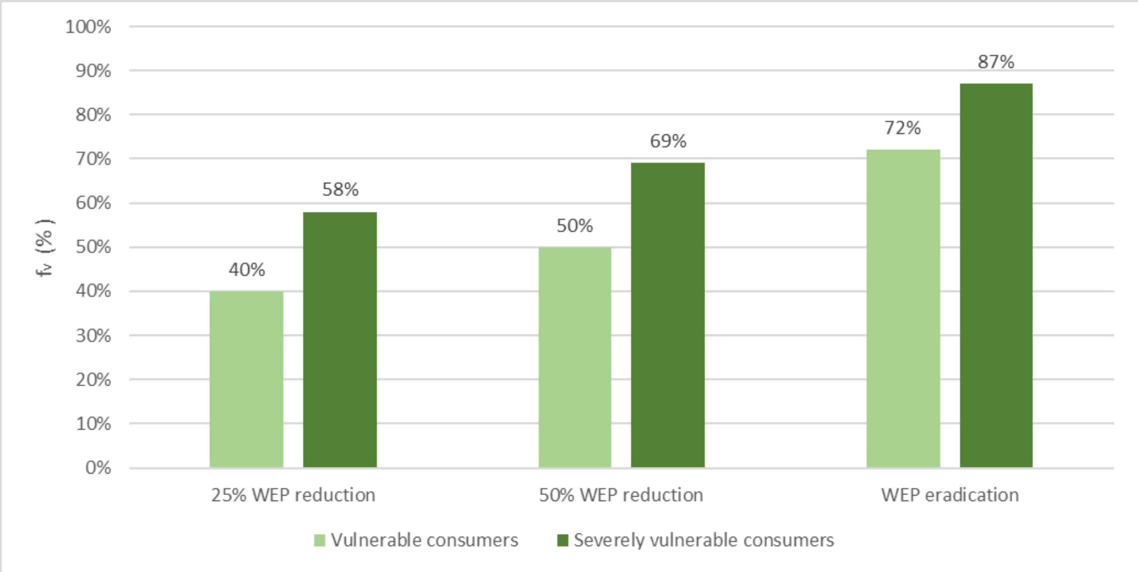

Fig. 6. 3. Values of the parameter fv (percentage of RWTEE covered by the TEC) needed to achieve the SNSEP reduction targets (25% and 50%) and the ideal eradication of winter energy poverty (reprinted from [236]*).*

The corresponding annual national budgets for these three complementary scenarios are €493m, €598m, and €801m, which are, respectively, seven, eight and eleven times the 2019 TSA budget.

On the other hand, in 2021 (see Table 6. 13), despite the price mitigation policies implemented by the government, the WEP share in the vulnerable consumers sample increased with respect to the 2019 (1.2% increase in vulnerable consumers affected by energy poverty during winter, thus reaching 97% in the Before aid scenario). The good news is that the increase in the TSA budget allowed the Government to enhance the mitigation impact on WEP (-2% compared to -1% achieved in 2019). Regarding the TEC effectiveness in 2021, maintaining the same f_v values as in 2019 would produce a much lower impact on WEP, i.e. 6% reduction compared to 11% in 2019.

Briefly, according to the results presented in this section, the TSA had a limited impact on WEP in both analysed years. On the other hand, the proposed TEC would significantly improve the ability of vulnerable consumers to pay their 'winter's energy bills', thus achieving a higher reduction of WEP.

Nevertheless, it should also be noted that allocating a higher amount of the cheque to less efficient housing might seem to be a disincentive for households to make energy-efficiency improvements. However, the TEC is proposed as a short-term measure to alleviate the effects of energy poverty on vulnerable households (who cannot afford to retrofit their houses or pay higher rent to live in more efficient housing). Nonetheless, this energy cheque, with the current residential building stock, is a costly measure, as shown in the complementary analysis on the calculation of the national budget to achieve the SNSEP targets. Therefore, in the medium to long term, it should be combined with a comprehensive building renovation plan, such as the 2020 Spanish LTRS [286], which will progressively improve the energy efficiency of housing, thus reducing households' energy expenditures. In this regard, Section 6.3.2 evaluate the effect of alternative retrofitting strategies on the RTEE, and its impact on WEP.

Furthermore, this approach might be extended to other European countries, thus promoting an enhancement of the current measures to help vulnerable households to address their energy needs in the short term. This analysis could be carried out by considering the differences in climate classification, building stock and household characteristics, according to the national regulation and statistical data (usually provided by Eurostat and national statistical institutes).

The methodology used to characterize the RWTEE of Spanish households is based on the Spanish building regulation, official surveys and the report on building certification, which are periodically updated. This makes it possible to keep the results updated considering the most recent data available. Moreover, the flexibility of the model makes it also a useful tool for policy planning. Eventually, the model could allow households and stakeholders to easily assess theoretical thermal-energy expenditures and the TEC amount assigned. The TEC proposal is especially oriented to cover the energy needs of households who are too poor to afford any heating (zero heating expenditures) or have very low heating consumption, i.e. the ones in hidden energy poverty [135]. Indeed, the TEC is an energy cheque that depends on the required thermal-energy expenditure of each household. This is a novel concept that differs it from the TSA and goes beyond the mechanism of the social tariff for electricity, which is a discount on actual household expenditure. In the TEC proposal, a household that spends too little (or zero) on heating would receive a cheque to increase its consumption and achieve (or be closer to) an acceptable level of comfort in home. On the other hand, it has already been proven [230] that the discount on actual expenditure of the social tariff for electricity has not improved significantly the comfort condition of Spanish vulnerable households.

In this context, it has to be noted that the current mitigating measures do not reach all those who need it because of their vulnerable situation (see Chapter 4 and [230]). For example, there are people in situations of substandard housing or who do not have a VPSC contract who, with the current allocation criteria, cannot access the discounts of the social tariff and, thus, do not receive the TSA. Furthermore, the lack of information is also a problem for some vulnerable households that do not know about the support or do not know how to apply. Indeed, in 2019, 1.07 million households benefitted from the TSA, whereas, in the same year, the Government estimated between 1.2 and 3.1 million households as energy poor (depending on metric used). Therefore, in economic terms, the annual budget should increase by 290% to extend the proposal of this paper (TEC AT) to the high value in the range of energy poor households (ceteris paribus).

6.3.2 Effectiveness of energy retrofitting policies

Fig. 6. 4 shows the results for the national average required expenditures for heating, cooling and DHW in the Reference Scenario. In particular, it shows both the absolute average expenditure values and their shares in the RTEE. Summing up the three energy services' expenditures gives the average national RTEE, which is €993 per household.

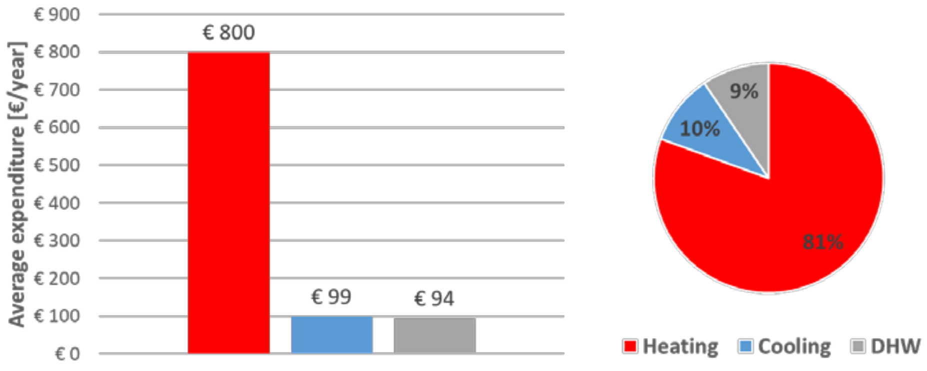

Fig. 6. 4. Thermal services' average required expenditures (left) and their shares in the RTEE (right) for the Reference Scenario

Fig. 6. 4 confirms most of the results presented in Section 3.3 and 4.3, even if the latter mentioned results were obtained with an adapted HBS model. The most evident insight of the three calculations is that heating expenditure has the highest share in RTEE by far.

Fig. 6. 5 compares the thermal services' average required expenditures in the 2030's Scenario 0 ('Business as usual') with the Reference Scenario's ones. The Scenario 0 considers energy prices changes but characterises the thermal energy needs of the original building stock, i.e. it does not take into consideration later renovation measures. Indeed, Fig. 6. 5 shows that heating and DHW expenditure increase, respectively, by 24% and 26%, whereas cooling expenditure does not change. This can be explained, on the one hand, by the projected fossil fuel prices' increase and electricity price's stability and, on the other hand, by the assumption on the 'negligibility' of temperature changes in 2030.

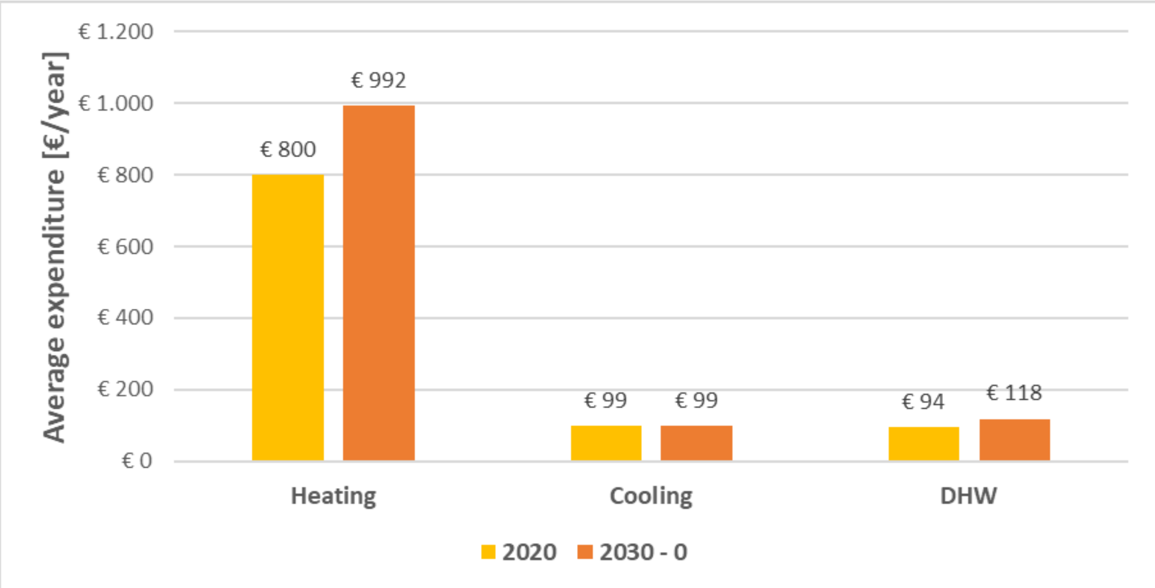

Fig. 6. 5. Thermal services' average required expenditures in the Scenario 0 compared to the Reference Scenario

Fig. 6. 6 and Fig. 6. 7 show the impact on the RTEE of, respectively, low-cost building retrofitting (Scenario I) or thermal systems replacement (Scenario II), having the latter several subscenarios.

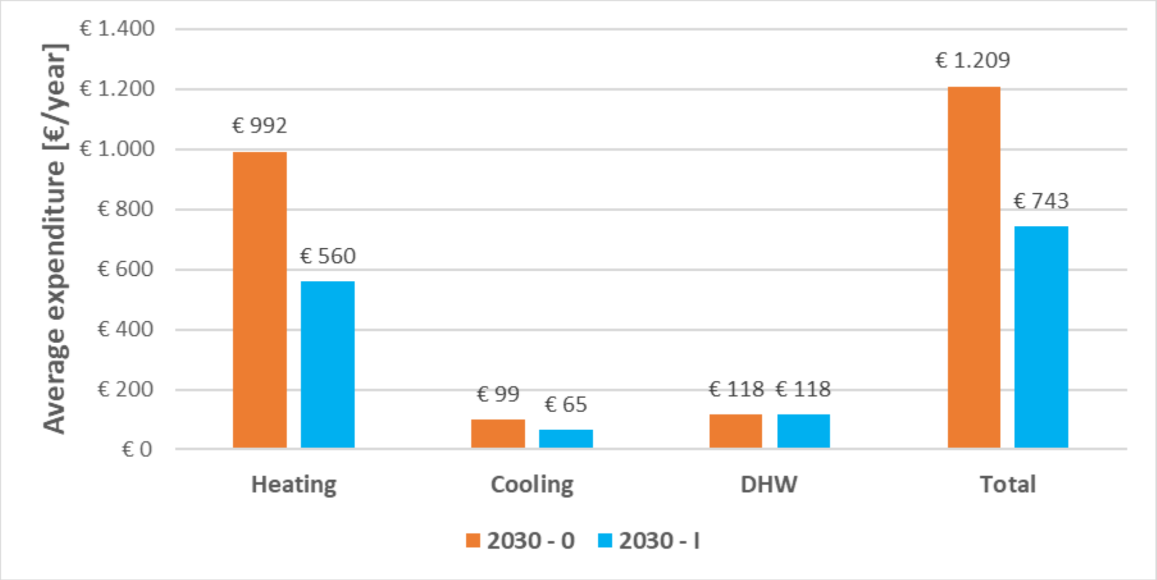

Fig. 6. 6. Thermal services' average required expenditures in the Scenario I compared to Scenario 0

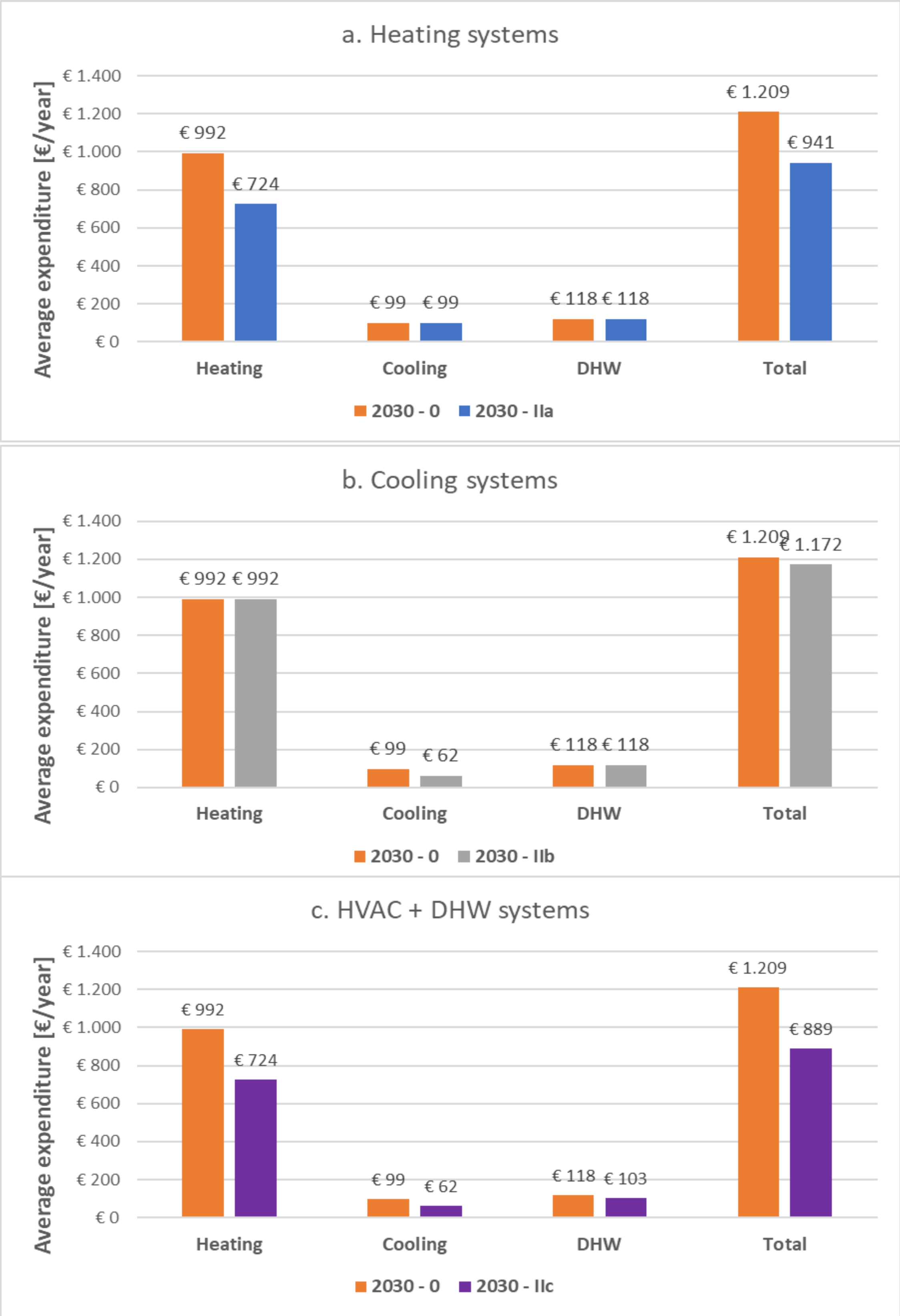

Fig. 6. 7. Thermal services' average required expenditures in the different subscenarios of Scenario II compared to Scenario 0

The low-cost building retrofit (Fig. 6. 6) achieves the greatest RTEE reduction, i.e. it reduces the average household thermal energy burden by 25%, being heating and cooling expenditures the ones affected by this measure. On the other hand, Fig. 6. 7 shows that, to have a significant impact on the RTEE, it is recommended to replace all the thermal systems with new ones (Scenario IIc), thus achieving a 10% reduction in expenditure. Finally, Fig. 6. 8 shows the joint impact of low-cost building retrofitting and thermal systems replacement, i.e. the Scenario III compared to the Reference Scenario. It is evident that combining both kinds of retrofitting measures could have the higher effectiveness, i.e. it could reduce heating and cooling required expenditures by, respectively, 49% and 59%. On the other hand, one common insight from all analysed scenarios is that the rise in fossil-fuel prices projected for 2030 is expected to increase the RWTEE if no measure is taken (Scenario 2030-0). Moreover, it could affect the impact of the energy retrofitting strategies included in the analysis. Particularly it might significantly reduce or outset the positive effect of, respectively, heating or DHW systems replacement.

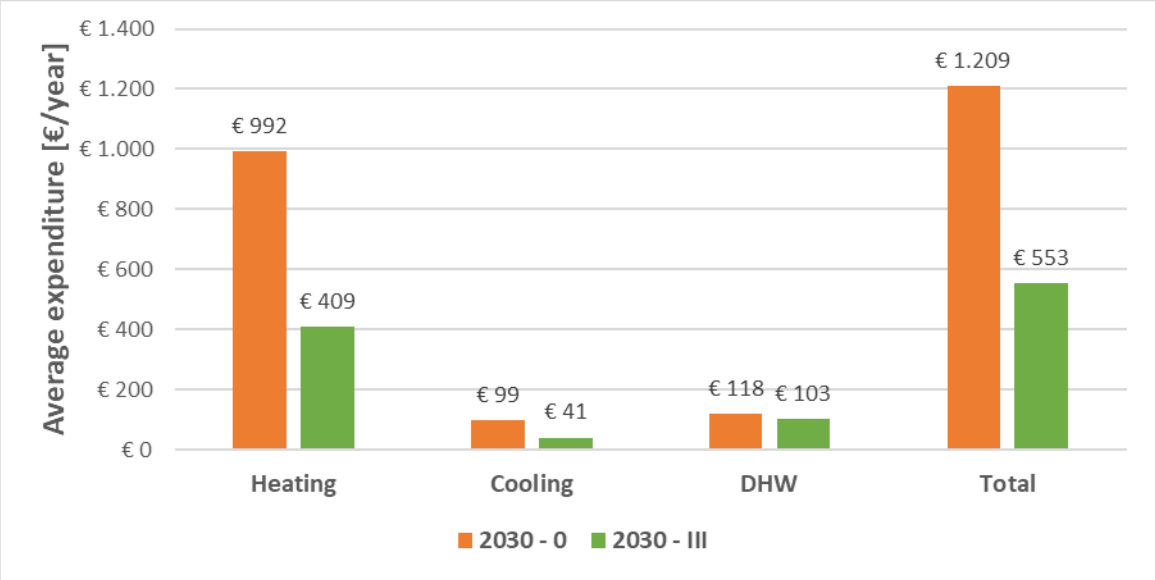

Fig. 6. 8. Thermal services' average required expenditures in the Scenario III compared to the Scenario 0

Table 6. 14 summarises the RTEE variation in the 2030 retrofitting scenarios with respect to the Scenario 2030-0. As expected, the most effective structural measure (among the analysed scenarios) is the combined solution of retrofitting the thermal enclosure and replacing the thermal systems with more efficient ones, i.e. Scenario III.

Table 6. 14. RTEE variation in the 2030 retrofitting scenarios with respect to Scenario 2030-0

Service	2030 - I	2030 - IIa	2030 - IIb	2030 - IIc	2030 - III
Heating	-44%	-27%	0%	-27%	-59%
Cooling	-34%	0%	-37%	-37%	-59%
DHW	0%	0%	0%	-13%	-13%
Total	-39%	-22%	-3%	-26%	-54%

Finally, Fig. 6. 9 shows the 'social cost' (levelised RTEE + levelised investment cost) per household of the main 2030 retrofitting scenarios. This economical comparison shows that the 'low-cost building retrofit' scenario (2030-I) is the most social-cost effective among the analysed ones, followed closely by the 'multiple energy retrofit measures' scenario (2030-III). This result can be partially explained by the higher reduction of RTEE produced by the low-cost building retrofit compared to the thermal systems' replacement. Combining the two kind of measures (2030-III) would have an even higher impact on the RTEE (see Fig. 6. 9). However, the thermal systems replacement's levelised investment cost per average household (€284) is significantly greater than the one for low-cost building retrofit (€161[96]), which determines a higher 'social cost' in the Scenario III (€1,012) than in the Scenario I (€921).

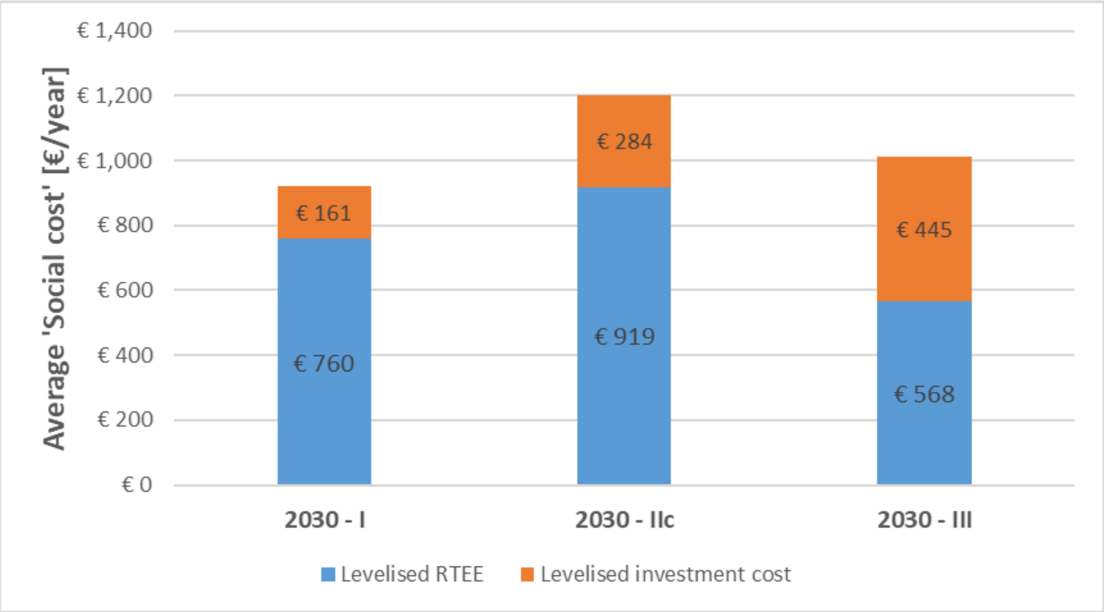

Fig. 6. 9. 'Social cost' (levelised RTEE + levelised investment cost) per average household of the main 2030 scenarios

[96] It should be reminded that this value takes into account that the low-cost building retrofit would only be implemented in 55% of vulnerable households and has a much higher useful time than the thermal systems.

Regarding the effectiveness of the analysed structural measures in mitigating energy poverty during winter, Table 6. 15 shows their impact on the WEP share among vulnerable consumers and its variation with respect to the Reference Scenario.

Table 6. 15. WEP shares in the analysed 2030 scenarios and their variation with respect to the Reference Scenario (2020)

Scenario	**Vulnerable consumers**	**Severely vulnerable consumers**	**Consumers at risk of social exclusion**	**Total**	**WEP variation**
Reference Scenario	84%	97%	100%	93%	0%
2030 - 0	92%	98%	100%	96%	+4%
2030 - I	50%	90%	99%	77%	-17%
2030 - IIa	72%	96%	99%	88%	-5%
2030 - IIc	67%	94%	99%	85%	-8%
2030 - III	23%	80%	87%	61%	-35%

If no action against energy poverty is taken (Scenario 0), the calculation shows that WEP would increase by 4% in 2030 due to the fossil fuel prices' rise. On the other hand, implementing both kinds of analysed structural measures (Scenario III), i.e. building retrofitting in the oldest dwellings and thermal systems' replacement in all vulnerable households, would reduce WEP by 35%.

Table 6. 16 shows the calculation of the budgets that would have to be earmarked to implement the three most effective 2030 scenarios.

Table 6. 16. Numbers of beneficiaries and budgets of the three most effective 2030 energy retrofitting scenarios.

Scenario	**Vulnerable consumers involved (1st measure)**	**Vulnerable consumers involved (2nd measure)**	**Investment per measure (1st measure) [M€]**	**Investment per measure (2nd measure) [M€]**	**Budget [M€]**
2030 I	588,882	0	4,500	0	2,650
2030 IIc	1,077,593	0	2,697	0	2,906
2030 III	588,882	1,077,593	4,500	2,697	5,556

6.3.3 Comparing the impact of mitigating and structural measures on winter energy poverty

Table 6. 17 compares the results obtained in Section 6.3.1 and Section 6.3.2 regarding the WEP reduction (with respect to the 2019 level) that would be achieved by implementing the analysed heating allowances or the proposed energy retrofitting interventions.

Table 6. 17. WEP reduction achieved by the analysed heating allowances or the energy retrofitting interventions in the different scenarios with respect to the 2019 level

Scenario	Vulnerable consumers	Severely vulnerable consumers	Consumers at risk of social exclusion	Total	WEP variation
2019	92%	98%	100%	96%	0%
2019 TSA	90%	98%	100%	95%	-1%
2019 TEC	73%	93%	0%	86%	-11%
2030 I	50%	90%	99%	77%	-20%
2030 IIc	67%	94%	99%	85%	-12%
2030 III	23%	80%	87%	61%	-37%

In Table 6. 17, the structural measures implementation is condensed in three main 2030 scenarios, which would achieve a WEP reduction between 12% and 37% compared to the 2019 level. The WEP reduction produced by mitigating measures such as the TSA and TEC is lower than the one that could be achieved by implementing the abovementioned measures. On the other hand, the national levelised investment costs to implement the 2030 Scenarios I, IIc and III retrofitting measures, are respectively, €172.4m, €287.5m and €459.9m. The latter amount, which refers to the most WEP-reduction effective scenario, is only 23% higher than the annual budget that would have to be earmarked to implement the TEC.

The higher WEP-reduction effectiveness of the analysed structural measures (shown in Table 6. 17) does not detract from the fact that energy poverty mitigating measures such as the analysed heating allowances are necessary in the short term. However, as highlighted in this chapter, they must be complemented by structural measures in the medium to long term from both economic and social perspectives.

6.4 Conclusions and policy implications

This chapter presents an effectiveness assessment of heating allowances and energy retrofitting measures in reducing thermal energy services' burden and winter energy poverty (WEP). This analysis was carried out by using the RTEE model and estimating both their impact on energy affordability and the 'social cost' of such measures.

Section 4.2.1.2 shows that the major part of the Spanish households RENE is related to the 'winter energy needs', mostly space heating. In this regard, it is striking that the mitigating measures proposed to tackle energy poverty in Spain between 2011 and 2018 have been exclusively focused on electricity consumption. In the same years, other European countries, such as the UK, have been mainly supporting the heating costs of vulnerable households rather than the electrical ones, in accordance with the literature on energy poverty. The inclusion for the first time in RDL 15/2018 of a 'Thermal Social

Allowance' (TSA) marked a change in the Spanish trend. The TSA was designed as a transfer-in-cash for vulnerable consumers to support heating, DHW, and cooking costs. It mainly depends on the budget earmarked by the State and the climate zone of the household's location. The latter parameter is not considered in similar assistance programs of other European countries, e.g. the French Energy Voucher and the British winter-payments' scheme. Nevertheless, the TSA policy would benefit from a change in the formula that determines the aid amount. In this line, Section 6.2.1 of this chapter proposes the Thermal Energy Cheque (TEC) as an alternative allowance. The TEC policy would be based on a more accurate quantification of domestic winter thermal energy needs (heating and DHW), i.e. the Required Winter Thermal-Energy Expenditure (RWTEE) calculation presented in Section 3.2.1.2.

To evaluate the effectiveness of this alternative aid, two different scenarios have been analysed for 2019 to consider the possible tax changes that could be implemented in the future. Scenario AT (RWTEE after tax) is a 'business as usual' status representing the implementation of the TEC in the current Spanish situation. Scenario BT (RWTEE before tax) is an alternative setting where no taxation is applied to vulnerable-households' energy-bills. The financial difference between the two scenarios (€87.5m approx.) corresponds to the amount of money related to energy taxation, which might change in case of a new VAT policy for vulnerable consumers or changes in fuel taxation. Indeed, a temporarily VAT decrease in electricity bills have been implemented by the Government in 2021 (together with other price-mitigation measures, see Section 2.4.5.1) to alleviate the negative impact of the energy price crisis. Therefore, a comparative analysis of the impact of TSA and TEC on energy services affordability and winter energy poverty was carried out by using the vulnerable consumers' data of the two selected years, i.e. 2019 and 2021. The analysis carried out in this chapter points out that the 2019 average-TSA-value (€70) was 20% of the average TEC in Scenario AT (€347) and covered only 6.6% of the average household's RWTEE. In contrast, the proposed TEC would cover, on average, 33% of households' theoretical heating-and-DHW expenditures. Furthermore, this cheque would be comparable to the energy-subsidy amounts assigned to vulnerable households in the UK (€388) and France (€200). Scenario BT makes it possible to analyse the proposed TEC policy across the Spanish winter climate zones because it eliminates the distortion introduced by the different taxation applied in certain provinces. This analysis points out that the TEC in the coldest climate zone (E) would be six times higher than in the mildest climate zone (α). According to the results presented in Section 6.3.1, the 2019 TSA mitigated winter energy poverty (WEP) in Spain by only 1%. On the other hand, the proposed alternative cheque would achieve a reduction of winter energy poor households of 11%. Furthermore, this chapter presents an additional analysis on the estimation of the 2019 TEC national annual budget that would be needed to accomplish the SNSEP targets and the ideal eradication of WEP. On the other hand, the WEP assessment carried out for 2021 shows that, despite the price-mitigation measures implemented by the government, energy poverty increased ('Before aid' scenario). The good news is that the scenario that consider also the increase in the budget for the TSA ('After TSA' scenario) shows that the government policies at least alleviated the effects of the energy price crisis.

In summary, the TEC policy proposed, based on the theoretical domestic thermal-energy expenditures, makes it possible to consider the differences in climate, dwelling characteristics, and household size. This is a ground-breaking concept that goes beyond the mechanism of the social tariff for electricity, which is a discount on actual household expenditure. In the TEC case, a household that spends too little (or zero) on heating because of low-income (hidden energy poverty) would receive a cheque to increase its consumption, thus achieving (or getting closer to) an acceptable level of comfort at home. Moreover, its implementation would improve the aid amount criteria currently used for the allocation of the TSA, which, both in 2019 and 2021, had minimal impact on WEP. However, in the chapter case study, i.e. the Spanish vulnerable consumers sample, it is not possible to estimate the effect of these allowances on hidden energy poverty (HEP), e.g. using the methodology presented in Chapter 4, because the actual consumption of the sampled households is not known. In this sense, the $2M_t$ methodology used for the WEP assessment is not based on household actual expenditure but on their required energy expenditure, thus applying a theoretical costs approach. Eventually, the proposed TEC formula might allow policymakers to assess the effect of changes in energy prices and taxation, as shown in this chapter for the 2021 case study. Nevertheless, future work should reflect one of the conclusions of Chapter 4, i.e. that the current mitigating measures do not reach all those who need it because of their vulnerable situation. Indeed, the social tariffs' allocation criteria are being revised by the Spanish Government to consider both social and regulatory issues. Moreover, it is essential to highlight that the results presented in Section 6.3.1 do not consider the possible implementation of structural measures, such as housing energy retrofits, which are analysed in Sections 6.2.2 and 6.3.2.

Indeed, the latter mentioned sections use the proposed methodology to evaluate the impact of these measures on the RTEE and on WEP. Several insights and policy recommendations can be pointed out by analysing the results of the retrofitting strategies' scenarios presented in this chapter:

- The Spanish residential sector urgently needs an energy refurbishment. The elevated value of the average required thermal energy expenditure is a symptom of both a disproportionate high required energy burden in vulnerable households and a potential unsustainable high emission of 'theoretical'[97] greenhouse gases (see Chapter 5 for an example of environmental parameters' calculation).
- Low-cost building's thermal-enclosure retrofitting is a very 'WEP-reduction effective' measure. Moreover, 2030's Scenario I shows that the most 'social-cost' efficient strategy (among the analysed ones) could be implementing such kind of measure in vulnerable households living in building constructed before 1981 (the most energy inefficient ones).
- Combining both kinds of analysed retrofitting measures (2030's Scenario III), i.e. low-cost building retrofitting and thermal systems' replacement, could produce the highest RTEE and WEP reduction (among the analysed scenarios) with the second best 'social-cost' effectiveness. Namely, it could reduce heating and

[97] This refers to the theoretical greenhouse gases that would be emitted by vulnerable households if they meet their required energy needs.

cooling required expenditures by, respectively, 49% and 59%, and decrease the WEP share by 37% (with respect to 2019 level) or 35% (with respect to 2020 level), at an average 'social cost' of €1,012 per household.

- However, the increase in fossil-fuel prices projected for 2030 could reduce or outset the positive effect of some retrofitting measures (e.g. heating or DHW systems replacement). One feasible alternative solution to both avoid high energy burdens in vulnerable households using fossil fuels and 'green' the residential sector could be the electrification of heating and DHW services (grounded on an already strong political will), as shown in Chapter 5. In this regard, the replacement of existing boilers with heat pumps is included in the LTRS proposals. Nevertheless, the LTRS states that 'heat pumps have technical operating characteristics that in the short term (2021-2030) make their integration in all climate zones difficult'. Therefore, an analysis of the impact of their integration in a 2050 scenario is more aligned with the Spanish government plans and could be an interesting further work.

Additional future work could analyse the following unexplored topics:

- The variables included in the 2030 analysis may change in many different ways. A sensitivity analysis could be performed to include these changes, e.g. different energy prices scenarios or the implementation of an ETS for the residential sector.
- A 2050 scenarios' analysis could be carried out by analysing some parameters' long-term variation, e.g. the impact of temperature changes on energy affordability and summer energy poverty.
- Moreover, occupant behaviour and socio-economical parameters also affect energy consumption and saving habits. Therefore, further work could include different household consumption patterns in the RTEE and energy poverty scenarios.
- On the other hand, the improvement of electrical appliances could be considered by including the RELE analysis both in the 2030 and 2050 scenarios.
- Finally, comprehensive thermal-enclosure retrofit scenarios could be included to analyse their social-cost effectiveness.

The proposed structural measures' implementation would achieve a WEP reduction between 12% and 37% compared to the 2019 level, which is a higher impact compared to the one produced by mitigating measures such as the TSA and TEC (respectively, 1% and 11%). Moreover, the levelised investment cost to implement the most WEP-effective structural measures' scenario (i.e. 'multiple energy retrofit measures') is only 23% higher than the budget needed to apply the TEC in a single year. However, it has to be highlighted that the analysed retrofitting measures are medium-long term policies while heating allowances can be implemented in the short period. In this sense, the results of the chapter's comparative analysis point out two main conclusions. On the one hand, energy poverty mitigating measures such as the TSA and TEC are necessary to reduce the energy burden of vulnerable households in the short term. On the other hand, they produce a limited impact on energy poverty, especially in the long run perspective. Therefore, they must be complemented by structural measures in the medium to long term to avoid cronifying this social issue and being economically feasible.

7. CONCLUSIONS

Energy poverty is a major issue both in developing and developed countries. Nowadays, in the latter countries (which are the focus of this thesis), having access to energy services at an affordable price is a crucial prerequisite for allowing people to live decently from a material, personal and social point of view. The first mentioned perspective of decent life concerns the ‘physical benefit’ from the use of modern energy services, such as space heating/cooling, cooking, lighting, the use of mobile phones and other electronic devices, etc., which allows people to keep their indoor environment comfortably warm/cool, to cook their meals, to light their home, to communicate with other people and access the Internet, among others. The second mentioned point of view is directly connected with the personal perception of a decent life, which could depend, for example, on the culture, the country standard of living or on subjective preferences. On the other hand, using modern energy services makes it possible to participate to social life in many ways, e.g. being confident with inviting friends or family at home, allowing children to do their homework, being connected with the people close to you and being able to navigate the Internet or taking a warm shower before going to a job interview.

Being deprived of these energy services, therefore, affects the everyday life of a person and may cause, among other consequences, both physical and mental health problems. This should not be considered just a personal issue but as a society duty’s of ensuring ‘access to affordable, reliable and modern energy services’, as stated in SDG 7.1. Based on this premise, this thesis reflects a personal and scientific will to contribute to the identification and tackling of energy poverty in Spain, i.e. as an energy affordability issue, also framing this issue in a broader European context.

This journey started from the very beginning, that is, exploring when and how this social issue was recognised in Spain and identifying the studies and policies that have attempt to define, measure and tackle energy poverty in the country and their relation with the EU policy framework and neighbour countries’ response. Starting from this review process, the literature and policy gaps were identified, thus raising some outstanding and unaddressed queries that led to the definition of the general scope and the specific objectives of the thesis, presented in Section 1.3. The former can be expressed as the aim to enhance the knowledge on the measurement and fight against energy poverty in Spain within the European context.

This concluding chapter is organised as follows. Section 7.1 summarises the main contributions of this thesis and points out the relevant conclusions and lessons learnt from the pursuit of its academic and social objectives. Then, Section 7.2 presents the ongoing research that aims to continue and enhance the thesis’ work, thus proposing and motivating some future work that could inspire new collaborations and further improvements. Finally, Section 7.3 lists the main publications and working papers carried out as a part or in close relation to this piece of writing.

7.1 Main contributions and conclusions

This thesis unpacks the domestic-energy-poverty issue in Spain from the modelling of households' energy needs to the assessment of the impact of both mitigating and structural policies. Moreover, this work applies the results of the former analysis to a proposal of an absolute hidden energy poverty indicator and to a technical-economic feasibility assessment of alternative centralised heat pumps solutions to fight energy poverty in block dwellings.

The reviewing process and the pursuit of the four sub-objectives presented in Section 1.3 led to five main contributions of this thesis that can be summarised as follows.

1. *A critical review of the background of the assessment and tackling of domestic energy poverty in Spain and the EU*
   Chapter 2 analyses the recognition of domestic energy poverty as an issue in Europe and presents the state of art of the main topics related to the four sub-objectives of the thesis. After analysing the identified methodologies and studies proposed to model households' energy needs, a critical review of the main literature's and official energy-poverty indicators is carried out. Moreover, Chapter 2 reviews the most relevant studies on housing's active/passive energy-efficiency measures and analyses the energy poverty policies implemented in different European countries (UK, France, Portugal and Spain). In the light of the abovementioned review, the literature gaps are pointed out to frame the contributions of the thesis.
2. *A bottom-up model of Spanish households' required energy expenditures and its direct application to energy poverty studies*
   Chapter 3 proposes a bottom-up model to estimate the Spanish households' theoretical energy expenditures according to their characteristics, which was selected as reference in the SNSEP. Specifically, this model was developed to assess the Required ENergy Expenditure (RENE) of each Spanish household, i.e. the theoretical energy expenditure that a household would have to pay to meet their required energy needs, including both thermal and electrical uses. The former uses are estimated by using the Required Thermal Energy Expenditure (RTEE) sub-model, which relies on the Spanish building regulation and calculates the required costs for HVAC and DHW by considering basic household features, such as the climate zone of the residence locality, the dwelling's construction age and size, and the household size. The last two parameters are also included as inputs of the Required ELectricity Expenditure (RELE) sub-model, which estimates the annual domestic energy costs for electrical uses, i.e. lighting, electrical appliances and cooking. Besides, the advanced version of this model considers the household composition (specifically, the members' occupation) that have been pointed out in the literature as a key factor determining the energy behaviour of a family or individual. Moreover, Chapter 3 presents some RENE model's direct applications such as the estimation of the provincial average required expenditure for heating and DHW ('Required Winter Thermal-Energy Expenditure', RWTEE) and the energy characterisation of the ECODES NGO vulnerable households' sample. Finally, this chapter describes the implementation

of the RTEE and RELE models into two different local tools, which were later migrated to a web platform, so creating an energy audit tool accessible by vulnerable (and non-vulnerable) households, social services, volunteers and energy technicians.

3. *A novel indicator to measure hidden energy poverty*

   Chapter 4 presents a methodology to estimate the extent and depth of hidden energy poverty in a country by applying two criteria. The first one makes it possible to estimate the share of households with low absolute energy expenditure (energy *underspending*) by applying a threshold based on the RENE model presented in Chapter 3. The second criterion, based on an income threshold, filters (from the first sample) the households who are underconsuming because of an affordability issue, i.e. it identifies the share of families or individuals in hidden energy poverty (HEP extent). Moreover, Chapter 4 introduces a method to quantify the energy poverty gap (HEP depth) as the average difference between the absolute energy expenditure threshold and the actual energy expenditure of the households identified as in hidden energy poverty. The above methodologies are applied to the Spanish Household Budget Surveys (HBS) of four consecutive years (2016-2019). On the one hand, this makes it possible to propose an absolute energy expenditure threshold that matches with the Spanish case study. On the other hand, this calculation might allow the relevant stakeholders to understand the trends of this energy poverty dimension across the years and take actions to fight hidden energy poverty.

4. *Techno-economic feasibility study of centralised air-water heat pumps to face energy poverty in Spain*

   Chapter 5 studies the tecno-economic feasibility of two typologies of centralised air-water thermal systems, i.e. electrically driven (EHP) and natural gas engine driven (GHP) heat pumps, as potential structural interventions to decrease the energy burden and achieve thermal comfort in Spanish vulnerable households living in block dwellings. The novelty of this chapter lies both on the study of the use of centralised air-water heat pumps to meet the heating demand in a sector and a country where they are not commonly installed, i.e. the Spanish residential sector, and their evaluation as measures to fight energy poverty. Regarding the required hourly heating demand, this chapter proposes an advanced version of the model presented in previous studies [40], which also considers the thermal insulation level of the building. Thereafter, two mathematical models are proposed to obtain the performance of the EHP: one for the best efficiency point and another for the off-design operation. The former is used to size the main components and the latter to obtain the performance map. On the other hand, two different devices are considered for the GHP study, having a design heating capacity of, respectively, 75 kWth and 25 kWth. The latter device is introduced to cover the peak of the demand, which makes it possible to optimise the load degree of the pumps in operation. Moreover, an economic analysis is performed by using the levelised cost of heating method, which allows the author to compare the studied heat pumps between each other and with conventional technologies such as individual and centralised natural gas boilers.

5. *Assessment of the effectiveness of the main policies against winter energy poverty in Spain*
   Chapter 6 assesses the impact of heating allowances (mitigating policies) and housing energy retrofitting strategies (structural policies) on thermal energy services' affordability and winter energy poverty (WEP) in Spain. This analysis is performed by applying the RTEE model described in Chapter 3 to a socio-economic assessment of these two kinds of energy poverty policies. Firstly, this chapter presents a WEP impact analysis of the current Spanish Thermal Social Allowance and proposes an enhancement to this policy, i.e. the Thermal Energy Cheque, which is a cheque for vulnerable consumers whose amount depends on the household's RWTEE. Secondly, the national average RTEE is calculated under different housing retrofitting strategies implemented in 2030 (including thermal enclosure's low-cost retrofitting and thermal systems' replacement measures) to compare their impact on vulnerable households' thermal energy expenditures and WEP. Finally, this chapter compares the effectiveness and the national financial burden of different implementation scenarios of the analysed measures (mitigating or structural ones) and estimates the 'social cost' of the retrofitting measures, thus providing some policy recommendations.

All this work pointed out several insights and conclusions that are wrapped up in the following paragraph. For the sake of clarity, they have been separated into different bullet points, each one related to one of the abovementioned thesis' main contributions.

1. The literature review process offers the following insights:
   1.1. The analysis of the existing domestic-energy-demand's studies suggests that the modelling of household energy expenditures should consider climate, structural characteristics of the dwelling, household composition and other socio-demographic variables that could influence their energy burden. In this regard, to the best of the author's knowledge, no comprehensive model of the domestic required thermal energy and electricity expenditure was proposed and applied to Spanish vulnerable households (prior to this work).
   1.2. Regarding the objective energy poverty indicators, the 'traditional' metrics are usually focused on the *Disproportionate expenditure* dimension, thus estimating the so-called 'measured energy poverty'. On the other hand, the circumstances of '(self-)imposed restriction' of energy expenditure (*Underspending*) have not been adequately addressed both in official indicators and policies. Particularly, in the analysed studies and, in general, in all works concerning Spain, this 'hidden face' of energy poverty is not considered or the proposed metric does not include a characterisation of the households' required energy expenditure.
   1.3. The techno-economic feasibility of alternative technologies such as centralised heat pumps applied to Spanish vulnerable households have not been sufficiently studied in the previous literature. In this sense, an unexplored research topic is the assessment of the performance of aerothermal air source heat pumps water

heaters, electrically or gas driven, and their economic feasibility as structural measure against energy poverty.

1.4. The policy review points out that, in order to efficiently tackle energy poverty, it is necessary to design an integrated strategy that includes both mitigating and structural measures. On the other hand, measuring the impact of each policy on energy poverty is a very complex endeavour that have not been frequently approached by scholars. In particular, in the Spanish case study, the TSA effectiveness has not been assessed and the structural policies' analyses carried out in previous studies do not include an energy poverty impact assessment.

2. The RENE model and its explored and potential applications might contribute to better understand the Spanish households' energy burden and enhance the future energy saving strategies. In this regard, several conclusions can be pointed out from the results of Chapter 3:
   - 2.1. The specific required expenditures on HVAC [€/(m^2 year)] and DHW [€/(person year)] mainly depend on the climate zone of the residence locality, the dwelling's insulation level and typology, and the thermal systems' performance. On the other hand, when looking into the overall energy burden of a household, the dwelling and family size are key parameters that determine their RTEE [€/year].
   - 2.2. A household's RELE (lighting, electrical appliances and cooking) is mainly influenced by the its size and composition. Regarding the latter, families with unemployed or retired people, pensioners for other reasons and homemakers in general consume more energy. The comparison of the model's results with the actual electricity expenditures of the ECODES households' sample shows that, as the number of members increases, the adjustment between the two values decreases. This phenomenon could be mostly justified by the vulnerability condition of the majority of these households, which potentially increases with the household size.
   - 2.3. The implementation of the two sub-models in local tools, lately migrated to a web one, and the corresponding results' checking provided further insights:
     a. In cold climates, the thermal energy-carrier and system election has a high impact on the energy burden. Specifically, among the analysed 'conventional technologies', electrically driven air-to-air heat pumps and centralised natural gas boilers are the most cost-saving ones;
     b. Three electrical appliances stand out as those associated with the highest electricity consumption, namely refrigerator, freezer and stoves.
   - 2.4. 'External factors' that could significantly affect both thermal energy and electricity expenditures are the energy prices and taxation.

3. The analysis presented in Chapter 4 shows that hidden energy poverty is a dimension of the overall phenomenon (i.e. energy poverty) that cannot be overlooked. Indeed, the high values of the proposed HEP indicator in Spain imply that there is a large number of households affected by energy poverty that are not benefitting from any national support scheme. Further specific conclusions can be pointed out from this analysis:
   - 3.1. In 2019, 25% of the Spanish households were affected by hidden energy poverty. In the same year, the average 'energy poverty gap' per household was €374 and the national budget needed for a potential HEP-eradicating policy was €1,692m.

This amount is eight times higher than the actual budget earmarked for the social tariffs in that year.

3.2. The residence region, household size and income level are key determinants of the possibility of being energy poor. Respectively, households living in *Extremadura,* with more than 4 members and belonging to the first income decile are the most vulnerable to this social issue. This points out the urgent need to design effective assistance programs for these families (and in general for the identified energy poor households), which should consider the multifaceted nature of energy poverty.

3.3. Moreover, the building age significantly influences this issue, i.e. households living in old dwellings have a higher HEP share than the ones living in recently constructed dwellings. On the other hand, families or individuals who are tenants of their homes and live in rural areas are also particularly vulnerable to hidden energy poverty. These results suggest the designing of financial mechanisms for the implementation of energy efficiency measures that prioritise vulnerable households living in rented dwellings, with ad-hoc programs for villages. In this sense, the Spanish LTRS and the *PREE 5000* package (described in Chapter 1) are good examples of plans and programs specifically designed for, respectively, energy poor households and rural areas.

3.4. Finally, the HEP indicator in the 'adjusted to household's comfort strategy' scenario detects a significantly lower share of households in hidden energy poverty, thus pointing out the advisability (for the society) of engaging in a socio-political debate on what should be considered basic and required energy needs.

4. According to the environmental and techno-economic assessment presented in Chapter 5, the centralised air-water EHPs and GHPs can be considered as promising systems to tackle energy poverty in Spanish vulnerable households living in block dwellings. Eventually, this study may provide insightful evidence to stakeholders for implementing these clean and efficient technologies. Nevertheless, several caveats should be pointed out:

4.1. Regarding the environmental and technical indicators, the results show an excellent performance of the EHPs compared with classical solutions such as decentralised and centralised condensing boilers fuelled by natural gas. On the other hand, the GHPs solution has worse seasonal performance but offers a better response to low temperatures.

4.2. Both technologies are very much economically competitive with a de-centralised natural gas boiler. However, measures to reduce the electricity bill in the centralised EHPs case would be highly recommended to lower their operation costs and make them competitive also with centralised natural gas boiler solutions. On the other hand, less technological maturity has been detected in GHPs, both in terms of available sizes and refrigerants, which affects the techno-economic feasibility of this thermal system.

4.3. The parametric analysis shows that the performance indicators of EHPs vary broadly depending on the climate zone considered. Moreover, the heated floor area and the LCOH per unit floor area depends on the building energy efficiency. On the other hand, for the same building insulation level, as the floor area increases: the hours in which the coupling of a backup system is required increase, the seasonal performance factor increases, the environmental parameters worsen, and the LCOH per unit demand decreases, i.e. the system is more techno-economical feasible but it shows worse environmental performance.

4.4. Regarding the GHPs' parametric analysis, it shows that as the number of devices increases, the heating demand covered also increase and the LCOH decreases. Moreover, a second parametric analysis shows that it is more economically feasible to install a GHP in a colder climate.

5. The implementation of the structural measures analysed in Chapter 6 would achieve a winter energy poverty (WEP) reduction in 2030 between 12% and 37% compared to the 2019 share, which is a higher impact compared to the one produced by heating allowances such as the current Thermal Social Allowance (TSA) and the proposed Thermal Energy Cheque (TEC). Indeed, the latter policies were estimated to reduce WEP by 1% and 11%, respectively, in 2019. However, these results should be analysed by considering the following subtle points:
   5.1. It has to be highlighted that the analysed retrofitting measures are medium-long term policies while heating allowances are necessary to reduce the thermal energy burden of vulnerable households in the short term, even more during an energy prices' crisis such as the 2021's one. However, the latter should be temporary solutions complemented by structural measures in the medium to long term. This 'rolling' policy strategy could avoid cronifying energy poverty by improving energy efficiency of vulnerable households. Moreover, it would reduce the national annual financial burden in the long run.
   5.2. Regarding the last aspect, i.e. the national financial 'feasibility', the levelised investment cost to implement the most WEP-reduction structural measures' scenario (among the analysed ones, i.e. 'multiple energy retrofit measures') is only 23% higher than the budget needed to apply the TEC in a single year.
   5.3. However, the increase in fossil-fuel prices projected for 2030 could reduce or outset the positive effect of some retrofitting measures (e.g. the replacement of heating or DHW systems with more efficient ones, maintaining the same energy carrier). One feasible alternative solution to both avoid high energy burden in vulnerable households and 'green' the residential sector could be the electrification of heating and DHW services by the implementation of heat pumps, as shown in Chapter 5.

Overall, this thesis might contribute to enhance the knowledge and tackling of energy poverty in Spain within the European framework. Moreover, the highlighted conclusions and policy recommendations could be helpful insights for the EU New Green Deal to design and implement policies and strategies that support a 'right to modern and clean energy' as well as a 'right to energy efficiency'.

The scientific journey that has been condensed in this piece of work has allowed me to grow both from a personal and professional point of view and to do my bit for the fight against this energy-related face of poverty. Indeed, addressing energy and poverty issues has been one of my main concerns during the last fourteen years and I believe that this thesis is both the conclusion of a process and the beginning of a work line that still has much to contribute to society.

7.2 Ongoing and future work

Regarding the RENE model itself and its direct applications, several improvements have been planned and could be explored in further work:

- Environmental externalities and other external factors (such as impact on health and wellbeing) may be included in the RTEE model to do not limit the simulation to a purely economic perspective. The same variables could be analysed in a more comprehensive assessment of the impact of housing retrofitting measures.
- The RENE web tool could be enhanced by introducing some retrofitting options such as the replacement of heating and DHW systems or electrical appliances with more efficient ones. This could allow the user to evaluate both the economic and environmental improvements produced by these measures. On the other hand, the cooling expenditure is expected to be included in tool's future updates.
- Regarding the RELE sub-model, work is ongoing to introduce the EU energy efficiency labelling scheme in the Advanced model to study the difference in consumption depending on the energy class of the appliances. Moreover, improvements are being planned for the modelling of some of the household electrical uses, such as the fridge or lighting. Finally, further work is ongoing to consider potential behavioural changes in relation to flexible (time-of-use) tariffs (e.g. the new Spanish electricity tariff structure in force from 1 June 2021).
- Furthermore, occupant behaviour and socio-economical parameters also affect energy consumption and saving habits. Therefore, further work could include different household consumption patterns both in the RTEE and RELE models.

Additional future work could analyse the unexplored issue of the indirect applications of the RENE model and the other thesis' contributions as follows:

- Regarding the indicator's proposal, further work could analyse the influence of other household characteristics on the probability of being in hidden energy poverty, such as their age, gender and occupation. Moreover, the methodology presented in Chapter 4 may be adapted to other countries by considering the dissimilarities in socio-demographic features, building stock and regulation, energy prices, and climatic characteristics. Finally, ongoing and published works [119], [293] are including the HEP in a multiple indicators' analysis to consider other dimensions of energy poverty in Spain.
- In ongoing and future works, the heat pumps' models presented in Chapter 5 are expected to be expanded to the summer season (cooling demand), taking advantage of the reversible ability of these devices. Moreover, in the case of the gas driven heat pump, the full utilisation of the heat from the gas engine should be considered when designing the installation, for example, to provide domestic hot water. Finally, the impact of a simultaneous thermal enclosure retrofitting (additional to installation of a gas engine heat pump system) could be analysed in further work.
- The variables included in the analysis of future households' energy expenditures may change in many different ways. A sensitivity analysis could be performed to include these changes, e.g. different energy prices scenarios. In this sense, a 2050

scenarios' analysis could be carried out by analysing some parameters' long-term variation, e.g. the impact of climate and regulatory changes on energy affordability and summer energy poverty. On the other hand, the improvement of electrical appliances or comprehensive thermal-enclosure retrofit scenarios could be considered both in the 2030 and 2050 scenarios.

Finally, additional work was started during the PhD exchange period at NOVA School of Science and Technology of Lisbon (Portugal). The literature review pointed out that several studies have analysed energy poverty in Portugal and Spain from a national and regional perspective. However, comprehensive research that frame the measurement and the fight against this social issue in the Iberian Peninsula is missing. Following the spirit of territorial cooperation promoted by the European Commission, this collaborative academic work, already drafted as a working paper (see Section 7.3), aims to address this gap by proposing a common and integrated framework to analyse and potentially enhance the various aspects of energy poverty research and policies in these two countries. Specifically, this study will explore proposals for innovative new energy poverty indicators, links between energy poverty and external factors, and policies and programs to tackle energy poverty.

7.3 Main publications and working papers

Journal papers

R. Barrella, J.C. Romero, J.I. Linares, E. Arenas, M. Asín, E. Centeno, The dark side of energy poverty: Who is underconsuming in Spain and why?, Energy Res. Soc. Sci. 86 (2022) 102428. https://doi.org/10.1016/J.ERSS.2021.102428

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R. Castaño-Rosa, R. Barrella, C. Sánchez-Guevara, R. Barbosa, I. Kyprianou, E. Paschalidou, N.S. Thomaidis, D. Dokupilova, J.P. Gouveia, J. Kádár, T.A. Hamed, P. Palma, Cooling Degree Models and Future Energy Demand in the Residential Sector. A Seven-Country Case Study, Sustainability. 13 (2021) 2987. https://doi.org/10.3390/su13052987

R. Barrella, I. Priego, J.I. Linares, E. Arenas, J.C. Romero, E. Centeno, Feasibility study of a centralised electrically driven air source heat pump water heater to face energy poverty in block dwellings in Madrid (Spain), Energies. 13 (2020). https://doi.org/10.3390/en13112723

Conference papers

R. Barrella, A. Cosin, E. Arenas, J.I. Linares, J.C. Romero, E. Centeno, Modeling and analysis of electricity consumption in Spanish vulnerable households, 2021 IEEE Madrid PowerTech, PowerTech 2021 - Conf. Proc. (2021). https://doi.org/10.1109/PowerTech46648.2021.9494785

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R. Barrella, P. Palma, J.P. Gouveia, J.I. Linares, J.C. Romero, E.M. Arenas, An integrated framework to address energy poverty in the Iberian Peninsula, 2022. https://www.iit.comillas.edu/publicacion/working_paper/es/450/An_integrated_framework_to_address_energy_poverty_in_the_Iberian_Peninsula

D. Dokupilová, P. Palma, A. Stojilovska, J.P. Gouveia, E.G. Paschalidou, R. Barrella, M. Feenstra, A. Horta, C. Sánchez-Guevara, J. Kádár, Majda Tesanovic, N.S. Thomaidis, T.A. Hamed, The urban/rural divide: exploring energy poverty determinants for eight countries in Europe and the Middle East, 2021. https://www.iit.comillas.edu/publicacion/working_paper/en/445/The_urban/rural_divide:_exploring_energy_poverty_determinants_for_eight_countries_in_Europe_and_the_Middle_East

Reports and other publications

J.C. Romero Mora, R. Barrella, E. Centeno Hernáez, L. Mariño Galindo, Informe de Indicadores de Pobreza Energética en España 2020, Descr. Inf. Cátedra Energía y Pobr. (2022). https://repositorio.comillas.edu/xmlui/handle/11531/65128

R. Barrella, R. Castaño-Rosa, M. Dereniowska, A. Dobbins, J.P. Gouveia, R. Guyet, K. Grossmann, A. Horta, M.J. Manjón, F. Martín-Consuegra, L. Papamikrouli, A. Stojilovska, L. Zivcic, A toolkit for a just transition with the people, Brussels, 2021. http://www.engager-energy.net/wp-content/uploads/2021/11/Engager-Toolkit-_-draft-2.pdf

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E.M. Arenas, R. Barrella, A. Cosín López-Medel, J.I. Linares, J.C. Romero, C. Foronda Díez, L. Díez Alzueta, Investigación aplicada para el desarrollo de una herramienta web de cálculo del gasto eléctrico teórico para hogares españoles, 2021. https://ecodes.org/images/que-hacemos/MITERD_2021/Informes/Investigacion_aplicada_para_el_desarrollo_de_una_herramienta_web_de_calculo_del_gasto_electrico_para_hogares_espanoles.pdf

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Appendix A. Questionnaire inputs and outputs of the analysis of the ECODES households' database

The collection of data on household assisted in the framework of the 'Not a single household without energy' programme has been carried out in two stages. From the first stage (2015-17), the data provided represent 2029 records, corresponding to as many households. These data are the particularised answers in each household to the questions included in the programme's questionnaire in this first stage, summarised in Table A 1.

Table A 1. Questionnaire of the 'Not a single household without energy' programme at the 2015-17 stage

Date of realization	What is the monthly household income? (in total)
Municipality	What is the average monthly amount of your electricity bills?
Province	What is the average monthly amount of the sum of all your energy supplies? (electricity, gas, butane, diesel, Etc.)
How old are you?	What is your contracted electricity power? (kW)
Gender	Do you benefit from the social tariff?
How many adults live in your household?	What system do you have to heat your house?
How many children live in your household?	Can you keep your home at an adequate temperature in winter?
Total persons in the household	What DHW system do you have at home?
What type of housing do you have?	What type of kitchen do you own?
When was it built?	Do you have a dishwasher at home?
Do you have damp in your home?	Do you have air conditioning?
Do you get outside air through doors and windows?	What type of lighting do you mostly use in your home?
How many members of your household are unemployed?	

From the second stage of the programme (this work used data from 2017 to 2019, but the program is still ongoing), 2060 records have been obtained, corresponding to different questions. The questions asked in this 2017-19 phase are summarised in Table A 2.

Table A 2. Questionnaire of the 'Not a single household without energy' programme at the 2017-19 stage

Date	Adequate winter temperature
Province	Adequate summer temperature
Locality	Window comfort
Postal code	Home heating
Adults	DHW
Minors (0 to 3)	Kitchen
Minors (4 to 8)	Oven
Minors (9 to 12)	Fridge frost
Minors (13 to 17)	Fridge closing
Household income	Other equipment
Large family	Lighting
Minimum pension	Regulated market tariff
Special Situation	Un-regulated market tariff
Dwelling size	Contracted power
House's floor	Social Tariff
House's property	Maintenance contract
It has damp	Hold the electricity supply contract
Air infiltration	Up to date with payments
Average energy consumption	

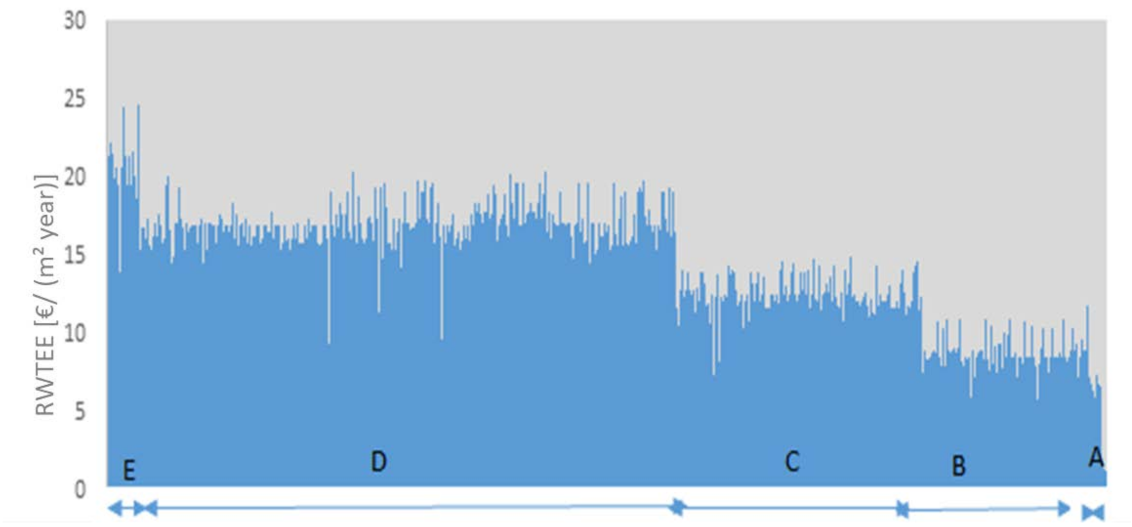


Fig. A 1. Minimum RWTEE for each ECODES household sorted by winter climate zone (Survey 2015-17)

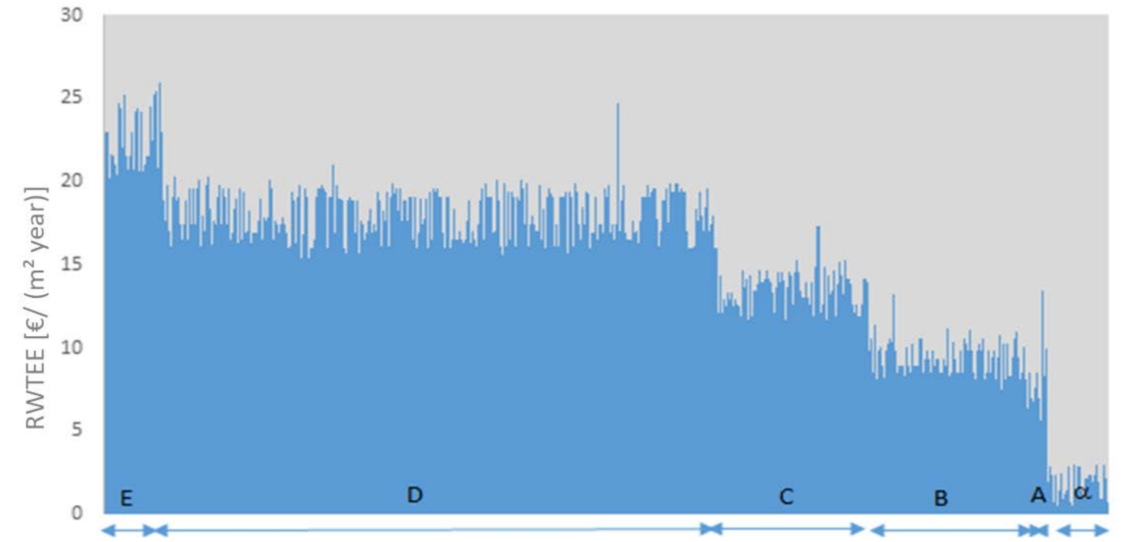


Fig. A 2. Minimum RWTEE for each ECODES household sorted by winter climate zone (Survey 2017-19)

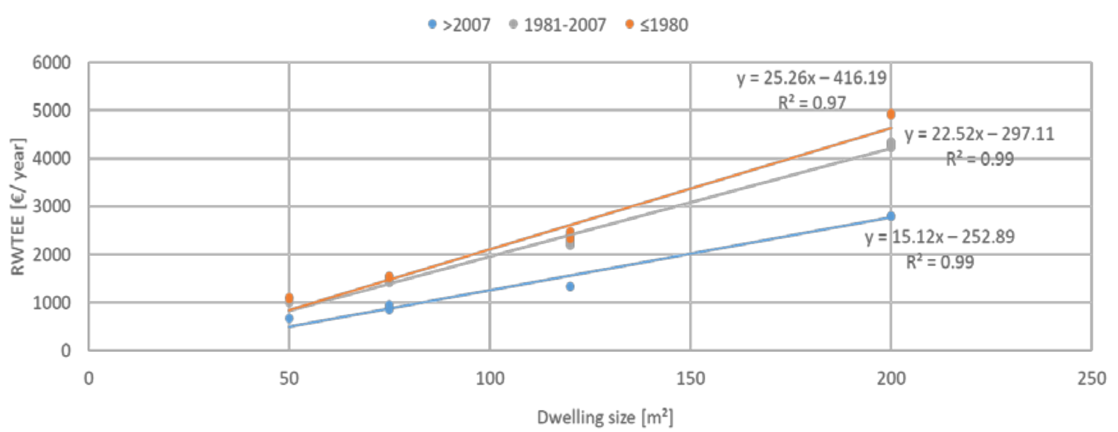


Fig. A 3. Minimum annual RWTEE by dwelling size for each aggregated construction period (E zone; 2015-17 data)

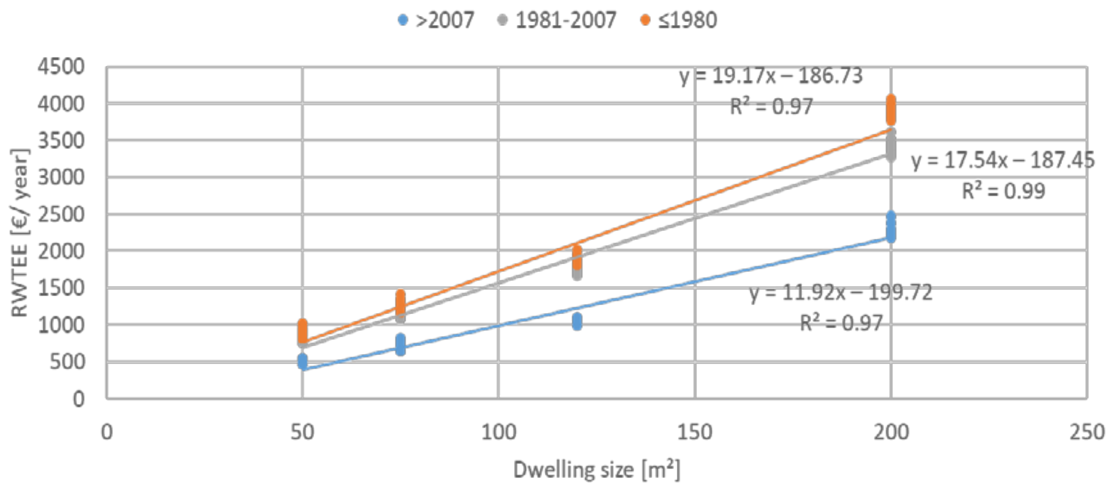


Fig. A 4. Minimum annual RWTEE by dwelling size for each aggregated construction period (D zone; 2015-17 data)

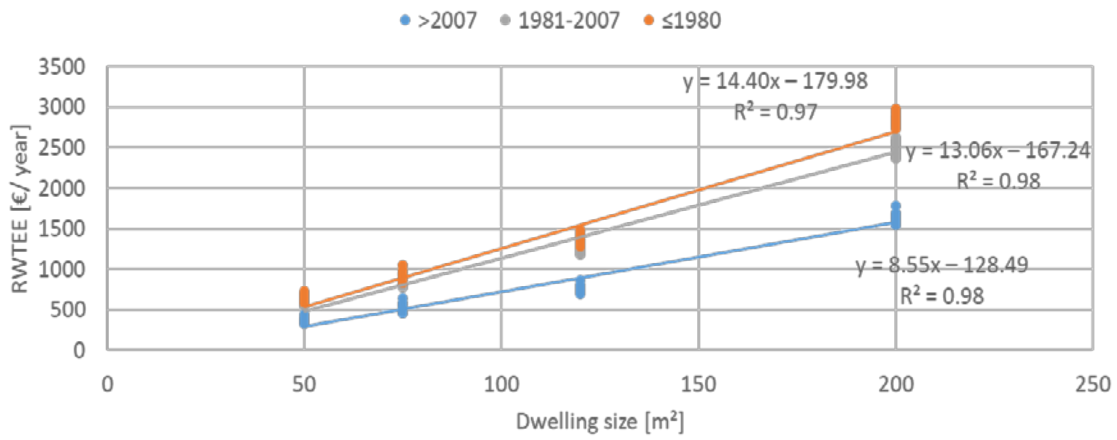


Fig. A 5. Minimum annual RWTEE by dwelling size for each aggregated construction period (C zone; 2015-17 data)

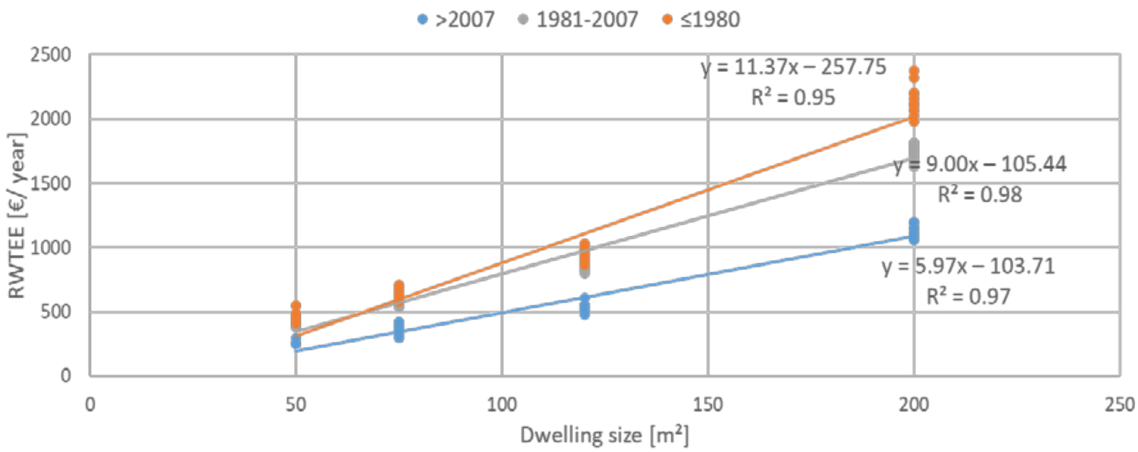


Fig. A 6. Minimum annual RWTEE by dwelling size for each aggregated construction period (B zone; 2015-17 data)

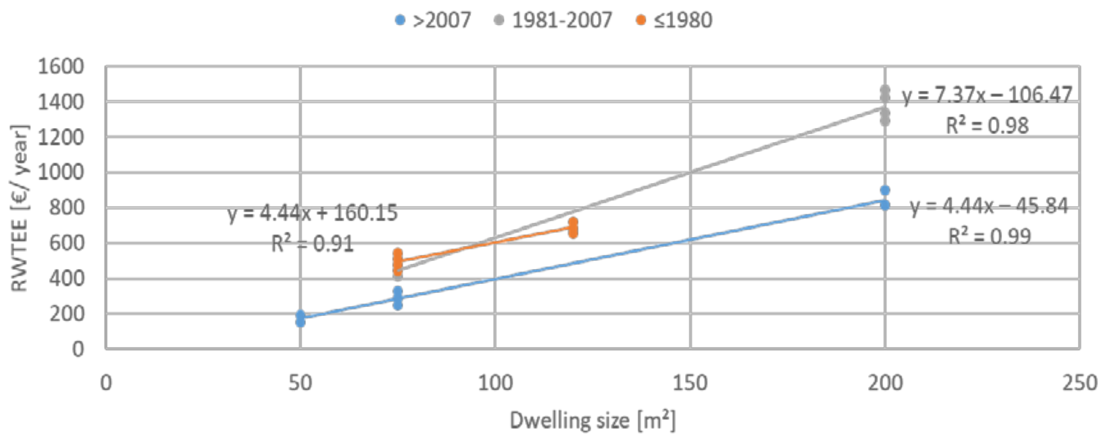


Fig. A 7. Minimum annual RWTEE by dwelling size for each aggregated construction period (A zone; 2015-17 data)

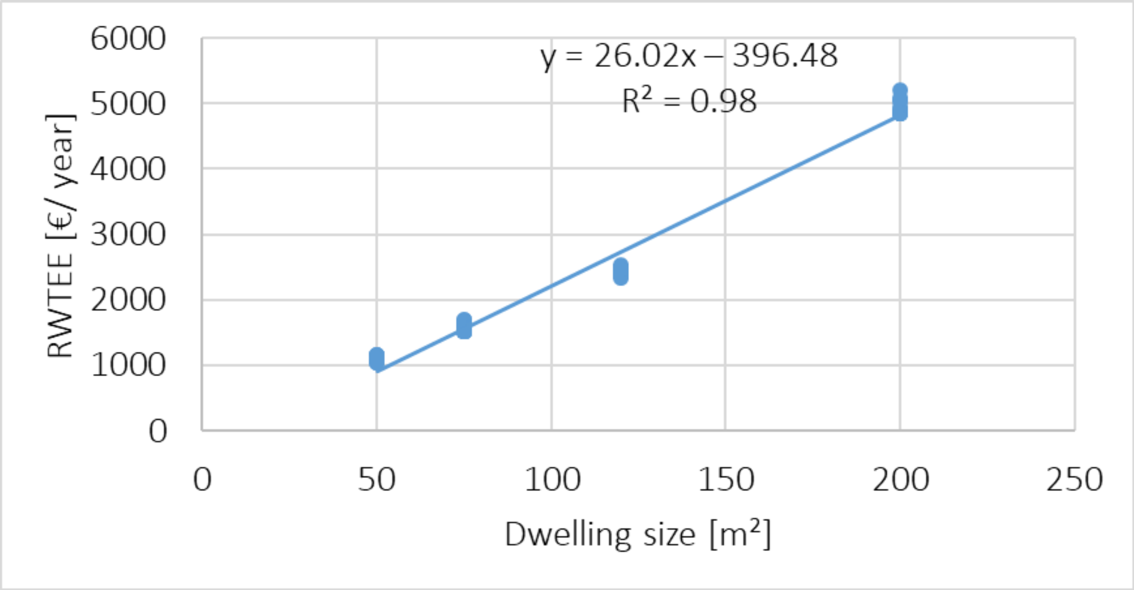


Fig. A 8. Minimum annual RWTEE by dwelling size (E zone; 2017-19 data)

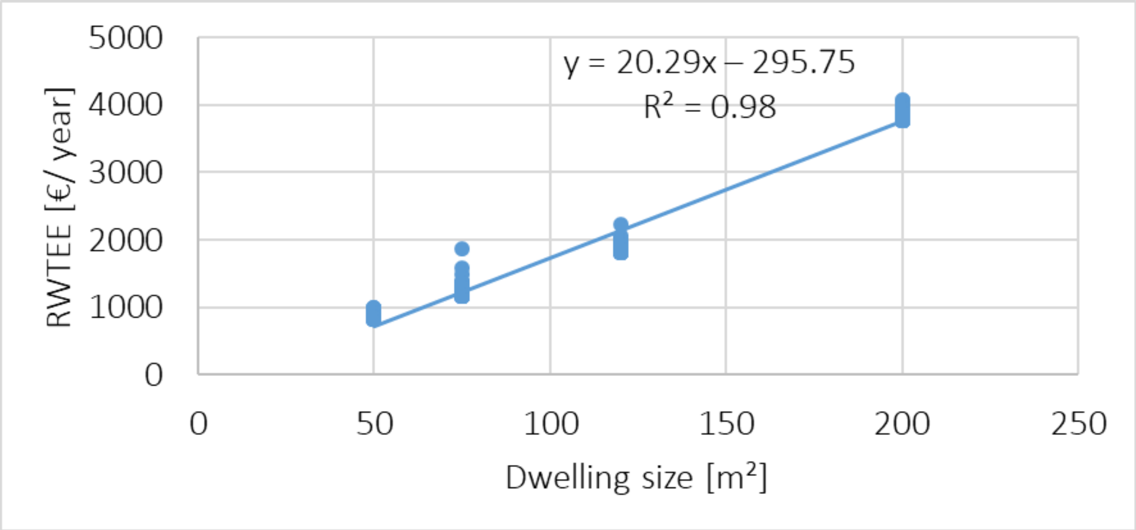


Fig. A 9. Minimum annual RWTEE by dwelling size (D zone; 2017-19 data)

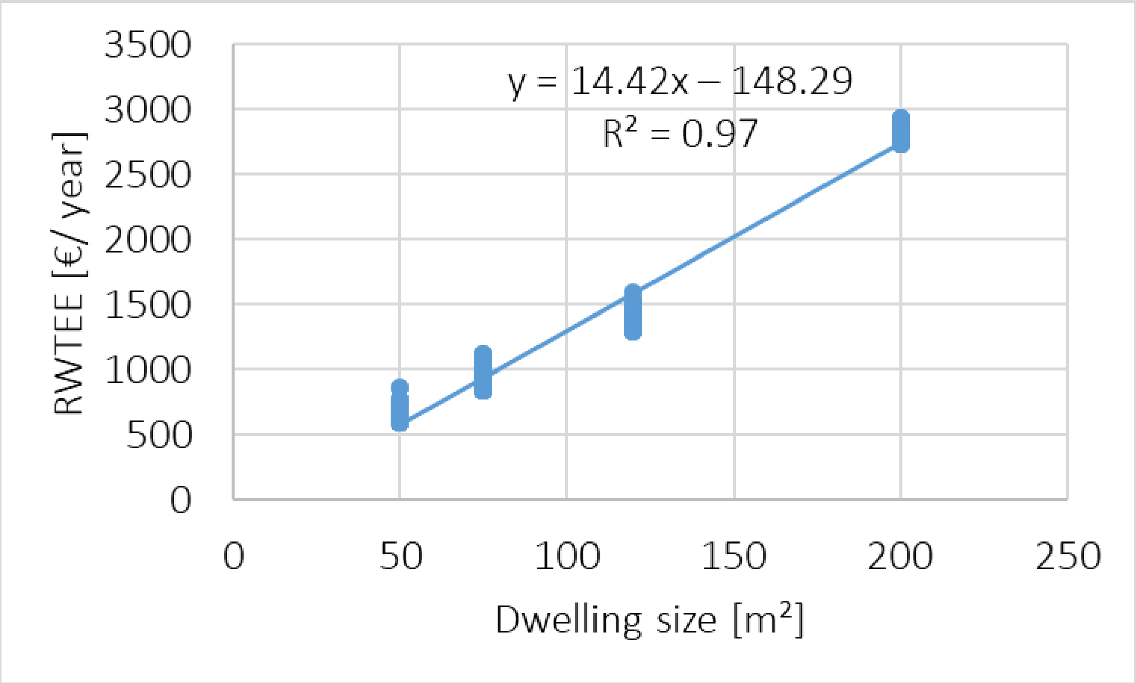


Fig. A 10. Minimum annual RWTEE by dwelling size (C zone; 2017-19 data)

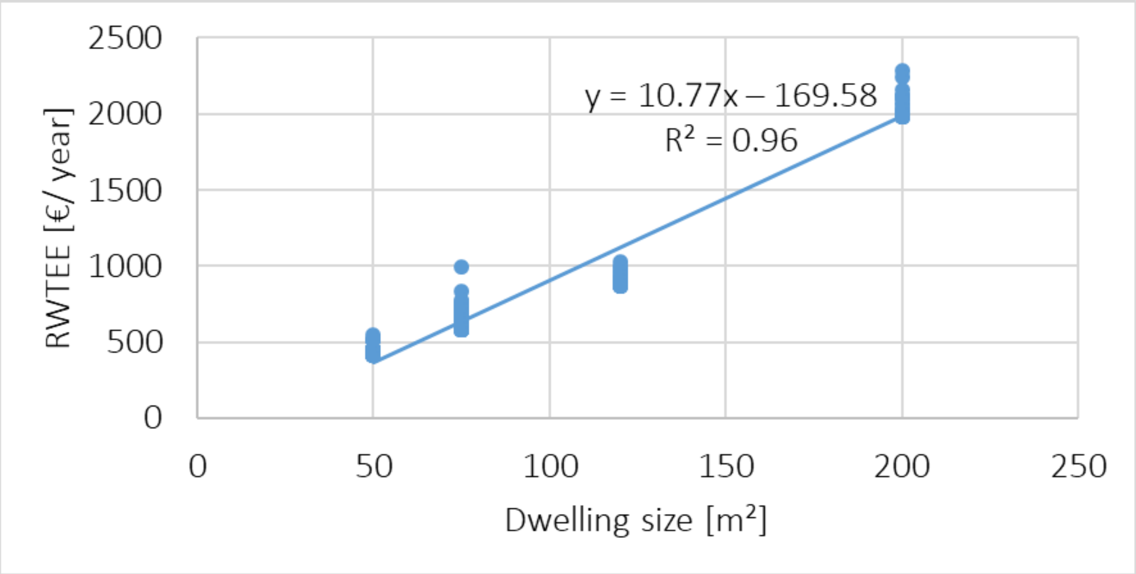


Fig. A 11. Minimum annual RWTEE by dwelling size (B zone; 2017-19 data)

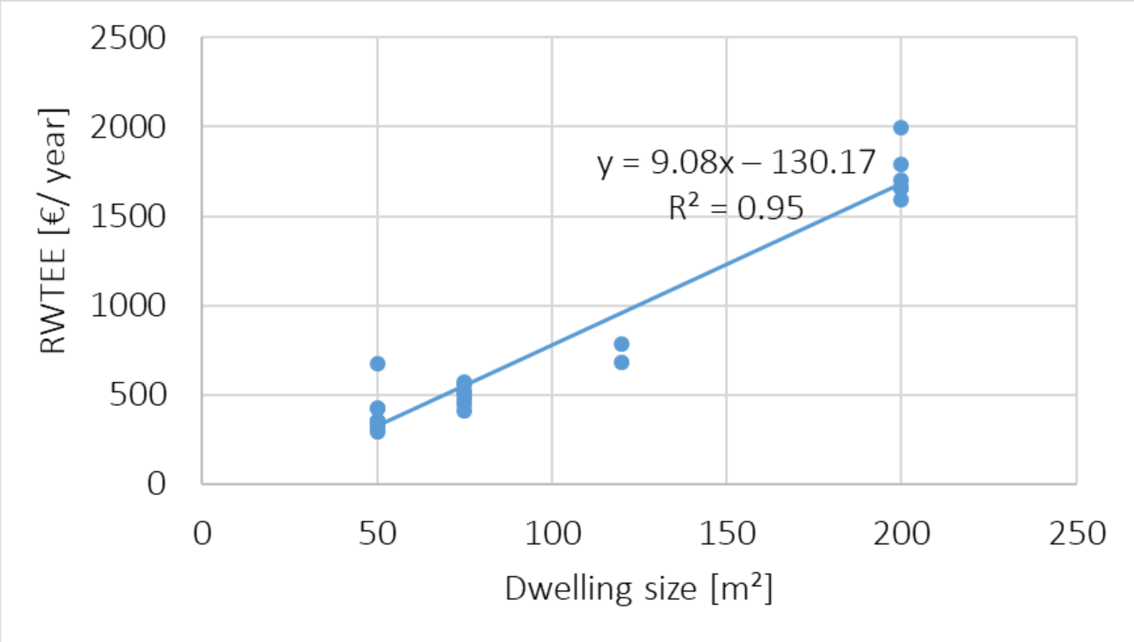


Fig. A 12. Minimum annual RWTEE by dwelling size (A zone; 2017-19 data)

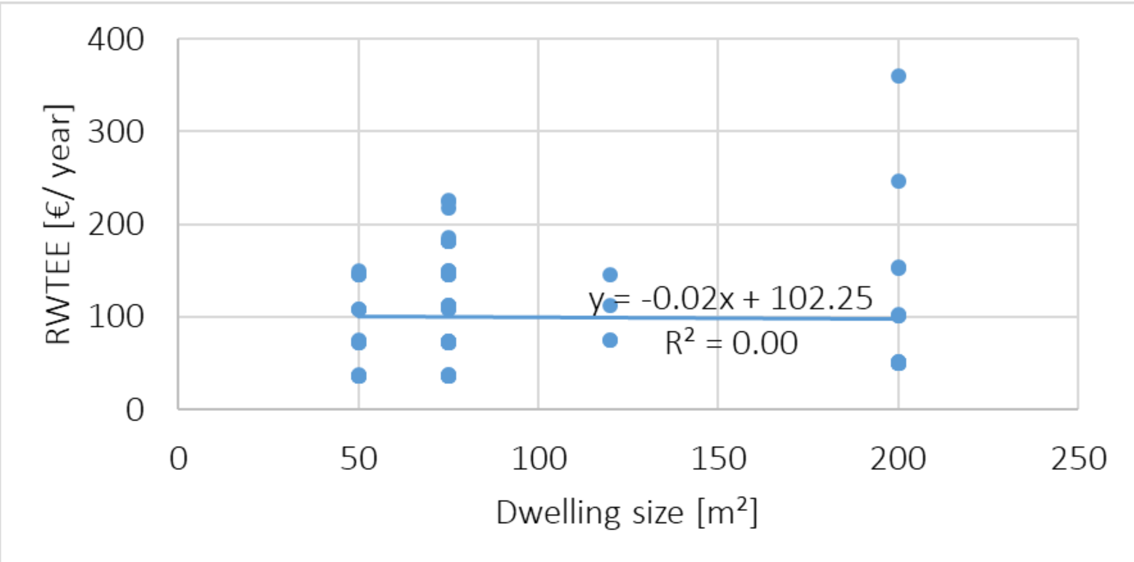


Fig. A 13. Minimum annual RWTEE by dwelling size (α zone; 2017-19 data)

Appendix B. Calculation of the electrical appliances' consumption in the Advanced Required-Electricity-Consumption model

The following paragraphs describes the TUS variables used and the assumptions made for the calculation of the electrical appliances' consumption in the Advanced model.

Cooking (stoves + oven)

The actions included in the TUS variable 311 (‘Preparation of meals and food preservation’) have been collected. The cooking model includes the consumption of electrical energy derived from both the stoves and the oven, taking into account that the latter appliance is found in 77.10% of households.

The following hypotheses are formulated:

- Power: 0.907 kW. Weighted average of stoves and oven power taken from the assumptions specified in Section 3.2.2.1.
- Stoves are electric or glass-ceramic hobs.
- 77.10% of the households have an oven.
- The average number of hours spent by households using the stoves and oven is 1.36 hours, corresponding to the weighted average of both appliances according to the hypotheses in section 3.2.2.1.

Dishwasher

The action number 312 listed in the TUS as ‘Dishwashing’ was considered.

The following assumptions are made to fit the model:

- Power of 1.5 kW (Minimum power of [258]).
- Average programme duration: 2 hours.
- The frequency of use (number of times/week) of the dishwasher in SPAHOUSEC II, as specified in Table A 3, has been taken as a reference.

Table A 3. Frequency of use of the dishwasher, according to the number of household members.

HS	1	2	3	4	>4	Average
$f_{i,j}$	1.1	1.3	1.5	1.8	1.9	1.4

Washing machine

This consumption was estimated by considering the action number 331 collected in the TUS as ‘laundry’.

The following hypotheses are formulated:

- Power of 1.5 kW (minimum power listed in [258].
- Average duration of the washing programme: 2 hours.
- The frequency of use (number of times/week) of the washing machine in SPAHOUSEC II, as specified in Table A 4, has been taken as a reference.

Table A 4. Frequency of use of the washing machine and tumble dryer, according to the number of household members.

HS	1	2	3	4	>4	Average
$f_{i,j}$	1.2	1.5	1.9	2.2	2.5	1.7

Tumble dryer

As for the washing machine, those actions included in the variable 331, i.e. 'laundry', have been collected, as drying cloths is part of it.

The following hypotheses are formulated:

- Power of 2 kW (estimated from [326]).
- Average duration of the drying programme: 1.5 hours.
- The ownership rate of 28.30% (SPAHOUSEC II) is applied.
- The dryer starts after two hours of the washing cycle.
- The frequency of use (number of times/week) of the washing machine of SPAHOUSEC II, as specified in Table A 4, has been taken as a reference, since it is considered that both appliances are used with the same frequency.

Television

Those actions with number 821, 822 and 829 listed in the TUS as, respectively, 'Watching television', 'Watching DVD or videos' and 'Watching television, DVD or videos, specified or not', have been considered. Implicit in these three actions is the use of a television.

The following assumptions are formulated:

- An average power of 0.15 kW per television is taken from the minimum power of [258].
- People who are carrying out any of these activities alone will consume this average power; on the other hand, when they do so in the company of a member of the household, they will be counted as consuming half the power, i.e. 0.075 kW. This assumption is made to minimise double counting of the activity.
- The frequency of use (number of hours/day) of the SPAHOUSEC II has been taken as a reference, which is 4.5 hours.

Computer

This consumption estimation considers those actions listed in the TUS variables 721, 722, 723 and 729 as, respectively, 'Computer programming', 'Computer-based information retrieval', 'Computer-based communication' and 'Other computer-based activities, specified or unspecified'. These four actions involve the use of a computer.

Fitting the model, the following hypothesis is formulated:

- An average computer power of 0.2 kW has been assumed [327].

- The frequency of use (number of hours/day) of television in SPAHOUSEC II has been taken as a reference, which is 3.2 hours. Considering an ownership rate of 80.9% [328], a frequency of use of 2.59 hours will be taken.

Appendix C. *Local RENE tools*

Input/output data, source code and lookup tables of the DIAGNÓSTICO RWTEE tool

Firstly, this section indicates the data to be selected or entered by the user of the tool and the output displayed at the end. For the former, input fields for numerical values and drop-down fields for selecting predefined values have been enabled. The LOCATION menu was thought to select in a drop-down menu the locality where the dwelling is located[98]. To do this, the following drop-down menus were created. When a province is selected, only the municipalities of that province will appear, to avoid having to search through all the municipalities in Spain.

- Province

- Municipality

In order to create the drop-down lists, a table with all the Spanish municipalities, indicating the province to which they belong and their altitude above sea level [235], was used. The HOUSING menu has two numerical input values: household size and dwelling size. There will also be two drop-down lists, with the values given in Table A 5.

Table A 5. HOUSING (VIVIENDA) drop-down submenus (in blue the name of the variables)

TIPO DE VIVIENDA	ANTIGÜEDAD / CALIFICACIÓN ENERGÉTICA
TIPO_VIVIENDA$	califE$
unifamiliar	Anterior a 1981
bloque	1981 a 2007
	Posterior a 2007
	A
	B
	C
	D alta
	D baja

[98] To simplifying the programming, in the local version of the tool this required input was replaced by answer on the province and the altitude of the locality. However, the LOCATION input in the online version of the tool was designed as prescribed, i.e. province and locality where the household lives, to be more user-friendly.

	E alta
	E media
	E baja
	F
	G

The INSTALLATIONS menu has two selection areas, each with two drop-down lists, with the values given in Table A 6 and Table A 7.

Table A 6. HEATING (CALEFACCIÓN) selection area (in blue the name of the variables)

TIPO	SUMINISTRO
inst_calefaccion$	tipo_calefaccion$
individual	glp
central	gasóleo
aparatos	biomasa
	carbón
	gas natural
	electricidad (radiadores)
	electricidad (acumuladores)
	bomba de calor

Table A 7. DHW (ACS) selection area (in blue the name of the variables)

TIPO	SUMINISTRO
inst_ACS$	tipo_ACS$
individual	glp
central	gasóleo
	biomasa
	carbón
	gas natural
	electricidad

Regarding the inputs, six variables are shown, which include the demand, consumption and expenditure of the three energy services considered. These outputs are shown in Table A 8.

Table A 8. RESULTS (RESULTADOS) display fields (in blue the name of the variables)

RESULTADOS
Demanda anual de calefacción [kWh]: demanda_CorregidaCal
Demanda anual de preparación ACS [kWh]: demanda_ACS
Consumo anual de calefacción [kWh]: consumo_calefaccion
Consumo anual de preparación ACS [kWh]: consumo_acs
Gasto anual en calefacción [€]: gasto_CAL
Gasto anual en preparación ACS [€]: gasto_ACS

Secondly, the source code of the local DIAGNÓSTICO tool and the Lookup Tables containing various coefficients for the operation of the application are shown below. Several of these coefficients have to be updated periodically, so they are set as editable variables (mostly in editable tables), not by the user, but by an administrator, in a simple way.

The source code of DIAGNÓSTICO is listed below. It is written in the high-level language EES. An executable version of the tool can be downloaded at this link.

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++

Function zonainv$(provincia$; altitud)

    row = lookup$row('zonas';31;provincia$)

    if(altitud<8000) Then

      indice_bruto = 1+(altitud-50)*26/1300

      if(indice_bruto >= 27) Then

          indice = 27

      Else

          indice = trunc(indice_bruto)+1

      Endif

      zona$ = lookup$('zonas'; row; indice+3)

    Else

      zona$ = lookup$('zonas'; row; 3)

    Endif

    zonainv$ = copy$(zona$;1;1)

End
```

```
Function zonainvlocalidad$(provincia$; altitud)
    row = lookup$row('zonas';31;provincia$)
    if(altitud<8000) Then
      indice_bruto = 1+(altitud-50)*25/1250
      if(indice_bruto >= 26) Then
         indice = 26
      Else
         indice = trunc(indice_bruto)+1
      Endif
    Else
      indice = 0
    Endif
    zonainvlocalidad$ = lookup$('zonas'; row; indice+3)
End

Function demanda_referenciacalefaccion(provincia$; altitud; tipo_vivienda$)
       zonainvlocalidad$ = zonainvlocalidad$(provincia$; altitud)
       row = lookup$row('sci_referencia';1;zonainvlocalidad$)
       SCI = lookup('sci_referencia'; row;2)

              if(tipo_vivienda$ = 'bloque') Then
                demanda_referenciacalefaccion =  lookup('sci_referencia'; row; 'DR nuevo bloque')
              Else
                demanda_referenciacalefaccion =  lookup('sci_referencia'; row; 'DR nuevo unif')
              Endif
End

Function elevacion(altitud; fila_capital)
    if(altitud >= 8000) Then
      elevacion = 0
```

```
    Else
      elevacion = altitud - lookup('Temp red ACS'; fila_capital; 2)
    Endif
End

Function referencia$(tipo_vivienda$)
    if(tipo_vivienda$ = 'unifamiliar') Then
      referencia$ = 'cal uni'
    Else
      referencia$ = 'cal bloq'
Endif
End

Function litros_acs(tipo_vivienda$)
    if(tipo_vivienda$ = 'unifamiliar') Then
      litros_acs = 28
    Else
      litros_acs = 28*(22/30)
Endif
End

Function hspf(tipo_calefaccion$;inst_calefaccion$;zona_invierno$;califE$)
If ( (califE$ = 'Posterior a 2007') OR (califE$ = 'A') OR (califE$ = 'B') OR (califE$ = 'C')) Then
    tabla_HSPF$ = 'HSPF_nuevo'
Else
    tabla_HSPF$ = 'HSPF_existente'
Endif
    fila_HSPF = lookup$row(tabla_HSPF$;'sistema';tipo_calefaccion$)
    hspf = lookup(tabla_HSPF$;fila_HSPF;inst_calefaccion$)
End
```

```
Function tabla_acsspf$(califE$)
If ( (califE$ = 'Posterior a 2007') OR (califE$ = 'A') OR (califE$ = 'B') OR (califE$ = 'C')) Then
    tabla_acsspf$ = 'ACS_SPFnuevo'
Else
    tabla_acsspf$ = 'ACS_SPFexistente'
Endif
End
Function alquiler_equipos(tipo_calefaccion$)
if(tipo_calefaccion$ = 'gas natural') Then
    alquiler_equipos = lookup('alquiler equipos';1;'coste')   "€/mes, incluye canon IRC"
Else
    alquiler_equipos = 0  "electricidad en luz"
Endif
End

Function alquiler_equiposacs(tipo_acs$; inst_acs$)
if(tipo_acs$ = 'gas natural') and (inst_acs$ = 'individual') Then
    alquiler_equiposacs =  lookup('alquiler equipos';1;'coste')  "€/mes, incluye canon IRC"
Else
    alquiler_equiposacs = 0  "electricidad en luz"
Endif
End

Function  impuesto_gas(suministro$)
if(suministro$ = 'gas natural') Then
    impuesto_gas =  lookup('impuestos';1;'impuesto')   "€/kWh de gas natural"
Else
    impuesto_gas = 0
Endif
End
```

Function impuesto_electricidad(tipo$)

if(tipo$ = 'electricidad (radiadores)') or (tipo$='electricidad (acumuladores)') or (tipo$='bomba de calor') ***Then***

impuesto_electricidad = **lookup**('impuestos';2;'impuesto')/100 "porcentaje sobre gasto variable; en gastos de luz se pondrá el porcentaje sobre gasto fijo"

Else

if(tipo$ = 'electricidad') ***Then***

impuesto_electricidad = **lookup**('impuestos';2;'impuesto')/100 "porcentaje sobre gasto variable; en gastos de luz se pondrá el porcentaje sobre gasto fijo"

Else

impuesto_electricidad = 0

Endif

Endif

End

Function coste_fijocalreparto(tipo_calefaccion$; inst_calefaccion$;coste_fijoCAL)

if(tipo_calefaccion$ = 'gas natural') ***Then***

if(inst_calefaccion$ = 'central') ***Then***

coste_fijocalreparto = 0

Else

coste_fijocalreparto = coste_fijoCAL

Endif

Else

coste_fijocalreparto = 0

Endif

End

Function coste_fijoacsreparto(inst_acs$;tipo_acs$;inst_calefaccion$;tipo_calefaccion$;coste_fijoACS)

if(tipo_acs$ = 'gas natural') and (inst_acs$ = 'individual') ***Then***

if(tipo_calefaccion$ = 'gas natural') and (inst_calefaccion$ <> 'central') ***Then***

coste_fijoacsreparto = 0

Else

```
        coste_fijoacsreparto = coste_fijoACS
    Endif
Else
    coste_fijoacsreparto = 0
Endif
End

Function factor_ivacal(tipo$; provincia$)
if(tipo$ = 'electricidad (radiadores)') or (tipo$='electricidad (acumuladores)') or (tipo$='bomba de calor')
Then
    if(provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') Then
        factor_ivacal = lookup('impuestos';4;2)
    Else
      if(provincia$ = 'Ceuta') or (provincia$ = 'Melilla') Then
          factor_ivacal =  lookup('impuestos';6;2)
      Else
          factor_ivacal = lookup('impuestos';3;2)
      Endif
    Endif
Else
    if(tipo$='gas natural') Then
    if(provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') Then
        factor_ivacal = lookup('impuestos';5;2)
    Else
      if(provincia$ = 'Ceuta') or (provincia$ = 'Melilla') Then
          factor_ivacal =  lookup('impuestos';7;2)
      Else
          factor_ivacal = lookup('impuestos';3;2)
      Endif
    Endif
    Else
```

```
        factor_ivacal = 0
    Endif
Endif
End

Function factor_ivaacs(tipo$; provincia$)
if(tipo$ = 'electricidad') Then
      if(provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') Then
        factor_ivaacs = lookup('impuestos';4;2)
      Else
        if(provincia$ = 'Ceuta') or (provincia$ = 'Melilla') Then
            factor_ivaacs =  lookup('impuestos';6;2)
        Else
            factor_ivaacs = lookup('impuestos';3;2)
        Endif
      Endif
Else
      if(tipo$='gas natural') Then
      if(provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') Then
        factor_ivaacs = lookup('impuestos';5;2)
      Else
        if(provincia$ = 'Ceuta') or (provincia$ = 'Melilla') Then
            factor_ivaacs =  lookup('impuestos';7;2)
        Else
            factor_ivaacs = lookup('impuestos';3;2)
        Endif
      Endif
      Else
        factor_ivaacs = 0
    Endif
Endif
```

```
End

Function factor_ivaelectricidad_conta(provincia$)
fila_IVAelectricidad = lookup$row('impuestos';'tipo';'IVA')
if(provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') Then
    factor_ivaelectricidad_conta = lookup('impuestos';4;2)
Else
    if(provincia$ = 'Ceuta') or (provincia$ = 'Melilla') Then
        factor_ivaelectricidad_conta =  lookup('impuestos';6;2)
    Else
        factor_ivaelectricidad_conta =  lookup('impuestos'; fila_IVAelectricidad; 'impuesto')
    Endif
Endif
End

Function factor_ivaelectricidad_noconta(provincia$)
fila_IVAelectricidad = lookup$row('impuestos';'tipo';'IVA')
if(provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') Then
    factor_ivaelectricidad_noconta = 0
Else
    if(provincia$ = 'Ceuta') or (provincia$ = 'Melilla') Then
        factor_ivaelectricidad_noconta =  lookup('impuestos';6;2)
    Else
        factor_ivaelectricidad_noconta =  lookup('impuestos'; fila_IVAelectricidad; 'impuesto')
    Endif
Endif
End

Function potencia_poromision(tipo_calefaccion$; tramo$)
if(tipo_calefaccion$ = 'electricidad (radiadores)') or (tipo_calefaccion$ = 'electricidad (acumuladores)') or
(tipo_calefaccion$ = 'bomba de calor') Then
```

```
    if(tipo_calefaccion$ = 'electricidad (acumuladores)') Then
        if(tramo$ = 'Punta') Then
            potencia_poromision = 3,45
        Else
            potencia_poromision = 6,9
        Endif
    Else
        potencia_poromision = 6,9  {el tramo valle es por la noche y findes, por lo que hay que poner la potencia máxima siempre}
    Endif
Else
    potencia_poromision = 3,45
Endif
End


Function tarifa_suministro(inst_termica$; tipo_instalacion$; consumo_gn; termino$; provincia$; zona_invierno$; potencia_punta; potencia_valle)
if(tipo_instalacion$ = 'gas natural') Then
    If (inst_termica$ = 'individual') Then
      if(consumo_gn > 5000) Then
         fila = lookup$row('tarifas'; 'sistema'; 'gas natural')
         tarifa_suministro = lookup('tarifas'; fila; termino$)
      Else
         fila = lookup$row('tarifas'; 'sistema'; 'gas natural (bajo consumo)')
         tarifa_suministro = lookup('tarifas'; fila; termino$)
      Endif
    Else
         fila = lookup$row('tarifas'; 'sistema'; 'gas natural central')
         tarifa_suministro = lookup('tarifas'; fila; termino$)
    Endif
Else
```

```
if(tipo_instalacion$ = 'glp') Then
    if(provincia$ = 'Ceuta') Then
        fila = lookup$row('tarifas'; 'sistema'; 'glp_ceuta')
    Else
        if(provincia$ = 'Melilla') Then
            fila = lookup$row('tarifas'; 'sistema'; 'glp_melilla')
        Else
            if( (provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') ) Then
                fila = lookup$row('tarifas'; 'sistema'; 'glp_canarias')
            Else
                fila = lookup$row('tarifas'; 'sistema'; tipo_instalacion$)
            Endif
        Endif
    Endif
    tarifa_suministro = lookup('tarifas'; fila; termino$)
Else
if(tipo_instalacion$ = 'gasóleo') Then
    if(provincia$ = 'Ceuta') Then
        fila = lookup$row('tarifas'; 'sistema'; 'gasóleo_ceuta')
    Else
        if(provincia$ = 'Melilla') Then
            fila = lookup$row('tarifas'; 'sistema'; 'gasóleo_melilla')
        Else
            if( (provincia$ = 'Palmas, Las') or (provincia$ = 'Santa Cruz de Tenerife') ) Then
                fila = lookup$row('tarifas'; 'sistema'; 'gasóleo_canarias')
            Else
                fila = lookup$row('tarifas'; 'sistema'; tipo_instalacion$)
            Endif
        Endif
    Endif
    tarifa_suministro = lookup('tarifas'; fila; termino$)
```

```
Else
    if( (tipo_instalacion$ = 'carbón') or (tipo_instalacion$ = 'biomasa')) Then
        fila = lookup$row('tarifas'; 'sistema'; tipo_instalacion$)
        tarifa_suministro = lookup('tarifas'; fila; termino$)
    Else  {caso eléctrico}
        if(termino$ = 'fijo') Then
            fijo_punta = lookup('pvpc'; 1; 'fijo')
            fijo_valle = lookup('pvpc'; 2; 'fijo')
            tarifa_suministro = (fijo_punta*potencia_punta +
fijo_valle*potencia_valle)/potencia_punta
        Else
            variable_punta = lookup('pvpc'; 1; 'variable')
            variable_valle = lookup('pvpc'; 2; 'variable')
            variable_llano = lookup('pvpc'; 3; 'variable')

            fila_pesos = lookup$row('pesos tarifa electrica';1;zona_invierno$)
            peso_punta = lookup('pesos tarifa electrica'; fila_pesos; 'peso_punta')
            peso_valle = lookup('pesos tarifa electrica'; fila_pesos; 'peso_valle')
            peso_llano = lookup('pesos tarifa electrica'; fila_pesos; 'peso_llano')

            if(tipo_instalacion$ = 'electricidad (acumuladores)') Then
                tarifa_suministro = variable_valle
            Else
                if(tipo_instalacion$ = 'electricidad') Then  {ACS por termo eléctrico}
                    tarifa_suministro = variable_llano
                Else   {radiadores o bomba de calor}
                    tarifa_suministro = variable_punta*peso_punta + variable_llano*peso_llano +
variable_valle*peso_valle
                Endif
            Endif
        Endif
```

```
        Endif
      Endif
   Endif
Endif
End

Function tarifa_electrica(termino$; potencia_punta; potencia_valle)
   if(termino$ = 'fijo') Then
      fijo_punta = lookup('pvpc'; 1; 'fijo')
      fijo_valle = lookup('pvpc'; 2; 'fijo')
      tarifa_electrica = (fijo_punta*potencia_punta + fijo_valle*potencia_valle)/potencia_punta
   Else
      variable_punta = lookup('pvpc'; 1; 'variable')
      variable_valle = lookup('pvpc'; 2; 'variable')
      variable_llano = lookup('pvpc'; 3; 'variable')
      tarifa_electrica = variable_llano
   Endif
End

Function consumo_gas(tipo_calefaccion$; tipo_acs$; consumo_calefaccion; consumo_acs;
inst_calefaccion$; inst_ACS$; llamada$)
If (tipo_calefaccion$ = 'gas natural') Then
   cal = 1
   If (llamada$ = 'calefaccion') Then
     peso_cal = 1
   Else
     If (inst_calefaccion$ = inst_ACS$) Then
        peso_cal = 1
     Else
        peso_cal = 0
     Endif
```

```
    Endif
Else
    cal = 0
    peso_cal = 0
Endif

if(tipo_acs$ = 'gas natural') Then
    acs = 1
    If (llamada$ = 'ACS') Then
      peso_acs = 1
    Else
      If (inst_calefaccion$ = inst_ACS$) Then
          peso_acs = 1
      Else
          peso_acs = 0
      Endif
    Endif
Else
    acs = 0
    peso_acs = 0
Endif

consumo_gas = consumo_calefaccion*cal*peso_cal + consumo_acs*acs*peso_acs
End

Function fdemanda_corregidacal(demanda_CorregidaSigno)
if(demanda_CorregidaSigno < 0) Then
    fdemanda_corregidacal = 0
Else
    fdemanda_corregidacal = demanda_CorregidaSigno
Endif
```

```
End

Function io\is(zona_invierno$;tipo_vivienda$;C1)
    row = lookup$row('Dispersion R'; 'Zona';zona_invierno$)
    R = lookup('Dispersion R'; row;tipo_vivienda$)
    io\is = (1+(C1-0,6)*2*(R-1))/R
End

Function calcula_c1(califE$;zona_invierno$; tipo_vivienda$)
    if(tipo_vivienda$ = 'bloque') Then
      row = lookup$row('C1_bloque';'zona';zona_invierno$)
      calcula_c1 = lookup('C1_bloque'; row; califE$)
    Else
      row = lookup$row('C1_unifamiliar';'zona';zona_invierno$)
     calcula_c1 = lookup('C1_unifamiliar'; row; califE$)
    Endif
End


{**********************************************************************************
*********}
{            PROGRAMA PRINCIPAL                                    }
{**********************************************************************************
*********}

"CALEFACCIÓN"
zona_invierno$ = zonainv$(provincia$; altitud)
C1 = calcula_c1(califE$;zona_invierno$; tipo_vivIenda$)
Io_Is = io\is(zona_invierno$;tipo_vivienda$;C1)
demanda_RefCal = demanda_referenciacalefaccion(provincia$; altitud; tipo_vivienda$)
demanda_CorregidaSigno = Io_Is * demanda_RefCal * superficie
demanda_CorregidaCal = fdemanda_corregidacal(demanda_CorregidaSigno)
```

HSPF = **hspf**(tipo_calefaccion$;inst_calefaccion$;zona_invierno$;califE$)

consumo_calefaccion = demanda_CorregidaCal / HSPF

consumo_gnCAL = **consumo_gas**(tipo_calefaccion$; tipo_acs$; consumo_calefaccion; consumo_acs; inst_calefaccion$; inst_ACS$; 'calefaccion')

coste_fijoCAL = **tarifa_suministro**(inst_calefaccion$; tipo_calefaccion$; consumo_gnCAL; 'fijo'; provincia$; zona_invierno$; potencia_contratada_punta; potencia_contratada_valle)

coste_fijoCALreparto = **coste_fijocalreparto**(tipo_calefaccion$;inst_calefaccion$; coste_fijoCAL)

coste_variableCAL = **tarifa_suministro**(inst_calefaccion$; tipo_calefaccion$; consumo_gnCAL; 'variable'; provincia$; zona_invierno$; potencia_contratada_punta; potencia_contratada_valle)

alquiler_equiposCAL = **alquiler_equipos**(tipo_calefaccion$)

impuesto_gas = **impuesto_gas**(tipo_calefaccion$)

impuesto_electricidad = **impuesto_electricidad**(tipo_calefaccion$)

gasto_CAL = (coste_fijoCALreparto*12 + coste_variableCAL*consumo_calefaccion + alquiler_equiposCAL*12 + impuesto_gas*consumo_calefaccion + impuesto_electricidad*coste_variableCAL*consumo_calefaccion)*(1+**factor_ivacal**(tipo_calefaccion$; provincia$)/100)

gasto_CALsinimp = coste_fijoCALreparto*12 + coste_variableCAL*consumo_calefaccion

"ACS"

B[4..9] = [0,0033; 0,0033; 0,0033; 0,0033; 0,0033; 0,0033]

B[1..3] = [0,0066; 0,0066; 0,0066]

B[10..12] = [0,0066; 0,0066; 0,0066]

fila_capital = **lookup$row**('Temp red ACS';15;provincia$)

elevacion = **elevacion**(altitud; fila_capital)

Duplicate i=1;12

temperatura_AguaRed[i] = **lookup**('Temp red ACS';fila_capital;i+2) - B[i]***if**(elevacion;0;0;0;elevacion)

End

litros_paxACS = **litros_acs**(tipo_vivienda$)

demanda_ACS = Npax*litros_paxACS*(365/12)*4,176*(12*60-**sum**(temperatura_AguaRed[1..12]))/(3600)

tabla_ACSspf$ = **tabla_acsspf$**(califE$)

fila_ACS_SPF = **lookup$row**(tabla_ACSspf$;'sistema';tipo_ACS$)

ACS_SPF = **lookup**(tabla_ACSspf$;fila_ACS_SPF;inst_ACS$)

consumo_ACS = demanda_ACS / ACS_SPF

consumo_gnACS = **consumo_gas**(tipo_calefaccion$; tipo_acs$; consumo_calefaccion; consumo_acs; inst_calefaccion$; inst_ACS$; 'ACS')

coste_fijoACS = **tarifa_suministro**(inst_acs$; tipo_acs$; consumo_gnACS; 'fijo'; provincia$; zona_invierno$; potencia_contratada_punta; potencia_contratada_valle)

coste_fijoACSreparto = **coste_fijoacsreparto**(inst_acs$;tipo_acs$;inst_calefaccion$;tipo_calefaccion$;coste_fijoACS)

coste_variableACS = **tarifa_suministro**(inst_acs$; tipo_acs$; consumo_gnACS; 'variable'; provincia$; zona_invierno$; potencia_contratada_punta; potencia_contratada_valle)

alquiler_equiposACS = **alquiler_equiposacs**(tipo_acs$; inst_acs$)

impuesto_gasACS = **impuesto_gas**(tipo_acs$)

impuesto_electricidadACS = **impuesto_electricidad**(tipo_acs$)

gasto_ACS = (coste_fijoACSreparto*12 + coste_variableACS*consumo_ACS + alquiler_equiposACS*12 + impuesto_gasACS*consumo_ACS + impuesto_electricidadACS*coste_variableACS*consumo_ACS)*(1+**factor_ivaacs**(tipo_acs$; provincia$)/100)

gasto_ACSsinimp = coste_fijoACSreparto*12 + coste_variableACS*consumo_ACS

"ELECTRICIDAD"

potencia_contratada_punta = **potencia_poromision**(tipo_calefaccion$; 'punta')

potencia_contratada_valle = **potencia_poromision**(tipo_calefaccion$; 'valle')

potencia_contratada = potencia_contratada_punta {potencia normalizada para obtener el coste}

energia_electrica = 3363

coste_fijoELECTRICIDAD = **tarifa_electrica**('fijo'; potencia_contratada_punta; potencia_contratada_valle)*potencia_contratada

coste_variableELECTRICIDAD = **tarifa_electrica**('variable'; potencia_contratada_punta; potencia_contratada_valle)

impuesto_electricidadELEC = **lookup**('impuestos';2;'impuesto')/100

alquiler_equiposELECTRICIDAD = **lookup**('alquiler equipos';2;'coste') "€/mes"

gasto_ELECTRICIDAD = ((coste_fijoELECTRICIDAD*12 + coste_variableELECTRICIDAD*energia_electrica)*(1+impuesto_electricidadELEC))*(1+**factor_ivaelectricidad_noconta**(provincia$)/100) + alquiler_equiposELECTRICIDAD*12*(1+**factor_ivaelectricidad_conta**(provincia$)/100)

++

Finally, the following tables (Table A 9-Table A 23, Lookup Tables) show the values of the parameters and variables needed for the operation of the application. Several of these coefficients have to be updated periodically, so they were set as easily editable by each tool administrator.

Table A 9. Dispersion factors in the DIAGNÓSTICO RWTEE local tool

Dispersion R		
Zona	unifamiliar	bloque
A	1.7	1.7
B	1.6	1.7
C	1.5	1.7
D	1.5	1.7
E	1.4	1.7

Table A 10. HSPF for existing buildings (before 2007) in the DIAGNÓSTICO RWTEE local tool

HSPF_existente			
sistema	individual	central	aparatos
glp	0.75	0.7	0.65
gasóleo	0.7	0.65	0.65
biomasa	0.35	0.4	0.3
carbón	0.4	0.45	0.45
gas natural	0.75	0.7	0.7
electricidad (radiadores)	0.99	0.99	0.95
electricidad (acumuladores)	0.99	0.99	0.96
bomba de calor	3.2	3.2	3.2

Table A 11. HSPF for new buildings (after 2007) in the DIAGNÓSTICO RWTEE local tool

HSPF_nuevo			
sistema	individual	central	aparatos
glp	0.89	0.83	0.77
gasóleo	0.83	0.77	0.77
biomasa	0.70	0.68	0.51
carbón	0.70	0.68	0.51
gas natural	0.91	0.85	0.85
electricidad (radiadores)	1.00	1.00	0.96
electricidad (acumuladores)	1.00	1.00	0.96
bomba de calor	3.9	3.9	3.9

Table A 12.Network water temperatures in the DIAGNÓSTICO RWTEE local tool

Temp red ACS														
capital	Altitud_capACS	enero	febrero	marzo	abril	mayo	junio	julio	agosto	septiembre	octubre	noviembre	diciembre	provincia
Albacete	686	7	8	9	11	14	17	19	19	17	13	9	7	Albacete
Alicante	8	11	12	13	14	16	18	20	20	19	16	13	12	Alicante/Alacant
Almeria	16	12	12	13	14	16	18	20	21	19	17	14	12	Almería
Avila	1131	6	6	7	9	11	14	17	16	14	11	8	6	Ávila
Badajoz	186	9	10	11	13	15	18	20	20	18	15	12	9	Badajoz
Barcelona	12	9	10	11	12	14	17	19	19	17	15	12	10	Barcelona
Bilbao	6	9	10	10	11	13	15	17	17	16	14	11	10	Bizkaia
Burgos	929	5	6	7	9	11	13	16	16	14	11	7	6	Burgos
Caceres	459	9	10	11	12	14	18	21	20	19	15	11	9	Cáceres
Cadiz	14	12	12	13	14	16	18	19	20	19	17	14	12	Cádiz
Castellon	27	10	11	12	13	15	18	19	20	18	16	12	11	Castellón/Castelló
Ceuta	40	11	11	12	13	14	16	18	18	17	15	13	12	Ceuta
Ciudad_Real	628	7	8	10	11	14	17	20	20	17	13	10	7	Ciudad Real
Cordoba	106	10	11	12	14	16	19	21	21	19	16	12	10	Córdoba
La_Coruna	26	10	10	11	12	13	14	16	16	15	14	12	11	Coruña, A
Cuenca	999	6	7	8	10	13	16	18	18	16	12	9	7	Cuenca

San_Sebastian	12	9	9	10	11	12	14	16	16	15	14	11	9	Gipuzkoa
Gerona	70	8	9	10	11	14	16	19	18	17	14	10	9	Girona
Granada	683	8	9	10	12	14	17	20	19	17	14	11	8	Granada
Guadalajara	685	7	8	9	11	14	17	19	19	16	13	9	7	Guadalajara
Huelva	30	12	12	13	14	16	18	20	20	19	17	14	12	Huelva
Huesca	488	7	8	10	11	14	16	19	18	17	13	9	7	Huesca
Jaen	568	9	10	11	13	16	19	21	21	19	15	12	9	Jaén
Leon	838	6	6	8	9	12	14	16	16	15	11	8	6	León
Lerida	182	7	9	10	12	15	17	20	19	17	14	10	7	Lleida
Logrono	385	7	8	10	11	13	16	18	18	16	13	10	8	Rioja, La
Lugo	454	7	8	9	10	11	13	15	15	14	12	9	8	Lugo
Madrid	655	8	8	10	12	14	17	20	19	17	13	10	8	Madrid
Malaga	11	12	12	13	14	16	18	20	20	19	16	14	12	Málaga
Melilla	15	12	13	13	14	16	18	20	20	19	17	14	13	Melilla
Murcia	39	11	11	12	13	15	17	19	20	18	16	13	11	Murcia
Orense	139	8	10	11	12	14	16	18	18	17	13	11	9	Ourense
Oviedo	232	9	9	10	10	12	14	15	16	15	13	10	9	Asturias
Palencia	734	6	7	8	10	12	15	17	17	15	12	9	6	Palencia
P._de_Mallorca	15	11	11	12	13	15	18	20	20	19	17	14	12	Baleares, Illes
Las_Palmas	13	15	15	16	16	17	18	19	19	19	18	17	16	Palmas, Las
Pamplona	490	7	8	9	10	12	15	17	17	16	13	9	7	Navarra

Pontevedra	27	10	11	11	13	14	16	17	17	16	14	12	10	Pontevedra
Salamanca	800	6	7	8	10	12	15	17	17	15	12	8	6	Salamanca
SC_de_Tenerife	5	15	15	16	16	17	18	20	20	20	18	17	16	Santa Cruz de Tenerife
Santander	11	10	10	11	11	13	15	16	16	16	14	12	10	Cantabria
Segovia	1002	6	7	8	10	12	15	18	18	15	12	8	6	Segovia
Sevilla	11	11	11	13	14	16	19	21	21	20	16	13	11	Sevilla
Soria	1063	5	6	7	9	11	14	17	16	14	11	8	6	Soria
Tarragona	69	10	11	12	14	16	18	20	20	19	16	12	11	Tarragona
Teruel	912	6	7	8	10	12	15	18	17	15	12	8	6	Teruel
Toledo	629	8	9	11	12	15	18	21	20	18	14	11	8	Toledo
Valencia	13	10	11	12	13	15	17	19	20	18	16	13	11	Valencia/València
Valladolid	698	6	8	9	10	12	15	18	18	16	12	9	7	Valladolid
Vitoria	540	7	7	8	10	12	14	16	16	14	12	8	7	Araba/Álava
Zamora	649	6	8	9	10	13	16	18	18	16	12	9	7	Zamora
Zaragoza	199	8	9	10	12	15	17	20	19	17	14	10	8	Zaragoza

Table A 13. SPF for existing buildings (before 2007) in the DIAGNÓSTICO RWTEE local tool

ACS_SPFexistente		
sistema	individual	central
glp	0.7679	0.8092
gasóleo	0.7679	0.8092
biomasa	0.35	0.4
carbón	0.4	0.45
gas natural	0.7679	0.8092
electricidad	0.99	0.99

Table A 14. SPF for new buildings (after 2007) in the DIAGNÓSTICO RWTEE local tool

ACS_SPFnuevo		
sistema	individual	central
glp	0.8453	0.8907
gasóleo	0.7679	0.8092
biomasa	0.714	0.714
carbón	0.714	0.714
gas natural	0.8453	0.8907
electricidad	0.99	0.99

Table A 15. Energy taxes in the DIAGNÓSTICO RWTEE local tool

impuestos		
tipo	impuesto	unidades
gas natural	0.0012	€/kWh
electricidad	5.5112	% sobre fijo + variable
IVA	21	% sobre todo
IVA_electricidadCANARIAS	7	
IVA_termicoCANARIAS	7	
IVA_electricidadCEUTAyMELILLA	1	
IVA_termicoCEUTAyMELILLA	1	

Table A 16. Rental of metering and control equipment in the DIAGNÓSTICO RWTEE local tool

alquiler equipos		
suministro	coste	unidades
gas natural	4.6	€/mes; incluye IRC
electricidad	0.7989	€/mes

Table A 17. Fuel prices in the DIAGNÓSTICO RWTEE local tool

tarifas			
sistema	fijo	variable	observaciones
	[€/mes]	[€/kWh]	
glp	0	0.08131	
gasóleo	0	0.0559	
biomasa	0	0.0466	
carbón	0	0.0308	
gas natural	8.2677	0.0406271	> 5 MWh/año y < 50 MWh/año
gas natural (bajo consumo)	4.26	0.0476888	< 5 MWh/año
glp_canarias	0	0.08151	
glp_ceuta	0	0.08145	
glp_melilla	0	0.08292	
gas natural cenrtal	0	0.0357	comunidades vecinos
gasóleo_canarias	0	0.0462	
gasóleo_ceuta	0	0.04666	
gasóleo_melilla	0	0.04666	

Table A 18. Electricity tariffs in the DIAGNÓSTICO RWTEE local tool

pvpc		
Tramo	fijo	variable
	[€/kW-mes]	[€/kWh]
Punta	2.81547	0.241429
Valle	0.1186966	0.103583
Llano		0.145333

Table A 19. Climate weights (CW) for the electricity tariffs in the DIAGNÓSTICO RWTEE local tool

Zona invierno	Peso_punta	Peso_valle	Peso_llano
A	0.13	0.73	0.14
B	0.14	0.71	0.15
C	0.15	0.67	0.17
D	0.16	0.65	0.19
E	0.17	0.63	0.20

Table A 20. Climate zones according to the province and the height of the locality in the DIAGNÓSTICO RWTEE local tool

Capital	altitud capital	ZC capital	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	provincia
Albacete	681	D3	C3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	E1	E1	E1	E1	E1	E1	E1	E1	Albacete
Alicante	5	B4	B4	B4	B4	B4	B4	C3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Alicante/Alacant
Almería	16	A4	A4	A4	B4	B4	B4	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Almería
Ávila	1131	E1	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Ávila
Badajoz	182	C4	C4	C4	C4	C4	C4	C4	C4	C4	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Badajoz
Barcelona	13	C2	C2	C2	C2	C2	C2	D2	D2	D2	D2	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Barcelona
Bilbao/Bilbo	6	C1	C1	C1	C1	C1	C1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	Bizkaia
Burgos	859	E1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Burgos
Cáceres	450	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	D3	D3	D3	D3	D3	D3	D3	D3	D3	E1	E1	E1	E1	E1	E1	Cáceres
Cádiz	13	A3	A3	A3	A3	B3	B3	B3	B3	B3	B3	C3	C3	C3	C2	C2	C2	C2	C2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	Cádiz
Castellón/Castelló	27	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	Castellón/Castelló
Ceuta	27	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	B3	Ceuta
Ciudad Real	625	D3	C4	C4	C4	C4	C4	C4	C4	C4	C4	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Ciudad Real
Córdoba	106	B4	B4	B4	B4	C4	C4	C4	C4	C4	C4	C4	C4	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Córdoba
Coruña. La/ A Coruña	7	C1	C1	C1	C1	C1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	Coruña, A
Cuenca	997	D2	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	Cuenca
Donostia/San Sebastián	7	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Gipuzkoa
Gerona/Girona	69	C2	C2	C2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Girona
Granada	684	C3	A4	B4	B4	B4	B4	B4	B4	C4	C4	C4	C4	C4	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	E1	Granada
Guadalajara	685	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D2	E1	E1	E1	E1	E1	E1	E1	Guadalajara
Huelva	24	A4	A4	B4	B4	B3	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Huelva

Huesca	483	D2	C3	C3	C3	C3	D3	D3	D3	D3	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Huesca
Jaén	570	C4	B4	B4	B4	B4	B4	B4	B4	C4	C4	C4	C4	C4	C4	C4	C4	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	E1	E1	Jaén
León	837	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	León
Lérida/Lleida	167	D3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Lleida
Logroño	384	D2	C2	C2	C2	C2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Rioja, La
Lugo	462	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Lugo
Madrid	657	D3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D2	E1	E1	E1	E1	E1	E1	E1	Madrid
Málaga	8	A3	A3	A3	B3	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Málaga
Melilla	30	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	Melilla
Murcia	42	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Murcia
Orense/Ourense	135	C3	C3	C3	C3	C2	C2	C2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Ourense
Oviedo	232	D1	C1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Asturias
Palencia	734	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Palencia
Palma de Mallorca	24	B3	B3	B3	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	Baleares, Illes
Palmas de Gran Canaria. Las	6	a3c	a3c	a3c	a3c	a3c	a3c	a3c	a3c	a2c	a2c	a2c	a2c	a2c	a2c	a2c	a2c	b2c	b2c	b2c	b2c	b2c	c2c	c2c	c2c	c2c	c2c	c2c	c2c	Palmas, Las
Pamplona/Iruña	450	D1	C2	C2	D2	D2	D2	D2	D2	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Navarra
Pontevedra	20	C1	C1	C1	C1	C1	C1	C1	C1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	Pontevedra
Salamanca	798	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Salamanca
Santa Cruz de Tenerife	1	a3c	a3c	a3c	a3c	a3c	a3c	a3c	a3c	a2c	a2c	a2c	a2c	a2c	a2c	a2c	a2c	b2c	b2c	b2c	b2c	b2c	c2c	c2c	c2c	c2c	c2c	c2c	c2c	Santa Cruz de Tenerife
Santander	6	C1	C1	C1	C1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Cantabria
Segovia	1002	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	Segovia
Sevilla	11	B4	B4	B4	B4	B4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	Sevilla
Soria	1061	E1	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Soria
Tarragona	69	B3	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Tarragona
Teruel	915	D2	C3	C3	C3	C3	C3	C3	C3	C3	C3	C2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	Teruel
Toledo	512	D3	C4	C4	C4	C4	C4	C4	C4	C4	C4	C4	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3	Toledo
Valencia/València	16	B3	B3	C3	C3	C3	C3	C3	C3	C3	C3	C3	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	Valencia/València

Valladolid	690	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Valladolid
Vitoria/Gasteiz	539	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	D1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Araba/Álava
Zamora	649	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	D2	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Zamora
Zaragoza	208	D3	C3	C3	C3	C3	D3	D3	D3	D3	D3	D3	D3	D3	D3	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	E1	Zaragoza

Table A 21. Winter severity index (WS) and reference demand for heating (SD_h) according to the winter climate zone and dwelling typology in the DIAGNÓSTICO RWTEE local tool

zona referencia	SCI	DR nuevo unif	DR nuevo bloque
a3	0.1865	23.6	13.8
A4	0.1779	23.6	13.8
B3	0.364	33.5	20.9
B4	0.3561	33.5	20.9
C1	0.8293	53.3	35.2
c2	0.765	53.3	35.2
C3	0.7816	53.3	35.2
C4	0.7374	53.3	35.2
D1	1.282	78	53
D2	1.232	78	53
D3	1.212	78	53
E1	1.697	103.3	71.2
a3c	-0.2154	0	0
a2c	0.1728	23.6	13.8
b2c	0.3149	33.5	20.9
c2c	0.6291	53.3	35.2

Table A 22. Energy efficiency parameter (EEP) for block dwellings according to the energy class or the construction period in the DIAGNÓSTICO RWTEE local tool

zona	A	B	C	D alta	D baja	E alta	E media	E baja	F	G	Anterior a 1981	1981 a 2007	Posterior a 2007
A	0.15	0.325	0.75	1.188	1.563	2.122	2.866	3.611	4.169	4.541	4.41	2.46	0.76
B	0.15	0.325	0.75	1.188	1.563	2.062	2.686	3.31	3.791	4.131	4.01	2.33	0.74
C	0.15	0.325	0.75	1.188	1.563	2.013	2.539	3.065	3.484	3.797	3.68	2.21	0.72
D	0.15	0.325	0.75	1.188	1.563	1.99	2.469	2.948	3.337	3.637	3.53	2.16	0.71
E	0.15	0.325	0.75	1.188	1.563	1.978	2.434	2.89	3.264	3.558	3.45	2.13	0.71

Table A 23. Energy efficiency parameter (EEP) for single-family houses according to the energy class or the construction period in the DIAGNÓSTICO RWTEE local tool

zona	A	B	C	D alta	D baja	E alta	E media	E baja	F	G	Anterior a 1981	1981 a 2007	Posterior a 2007
A	0.15	0.325	0.75	1.188	1.563	1.975	2.426	2.876	3.561	4.48	4.15	2.13	0.72
B	0.15	0.325	0.75	1.188	1.563	1.974	2.421	2.869	3.476	4.244	3.96	2.12	0.71
C	0.15	0.325	0.75	1.188	1.563	1.981	2.443	2.906	3.432	4.021	3.81	2.14	0.71
D	0.15	0.325	0.75	1.188	1.563	1.963	2.39	2.816	3.315	3.887	3.68	2.1	0.71
E	0.15	0.325	0.75	1.188	1.563	2.005	2.516	3.027	3.611	4.266	4.03	2.2	0.72

Fig. A 14-Fig. A 16 show the interface windows of the local DIAGNÓSTICO tool.

Fig. A 14. Main interface window of the DIAGNÓSTICO RWTEE local tool

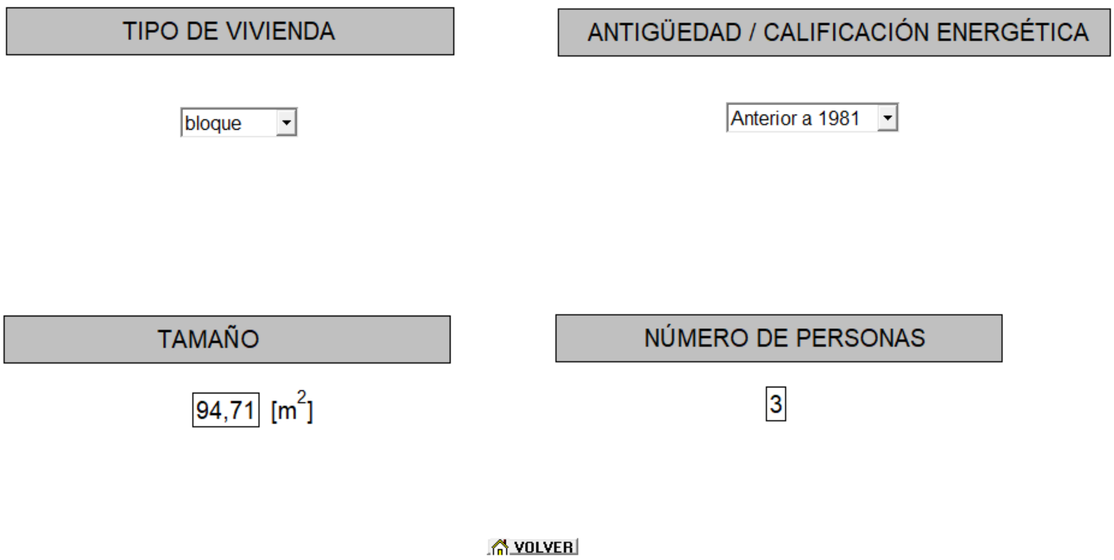


Fig. A 15. Household and dwelling characteristics' interface window of the DIAGNÓSTICO RWTEE local tool

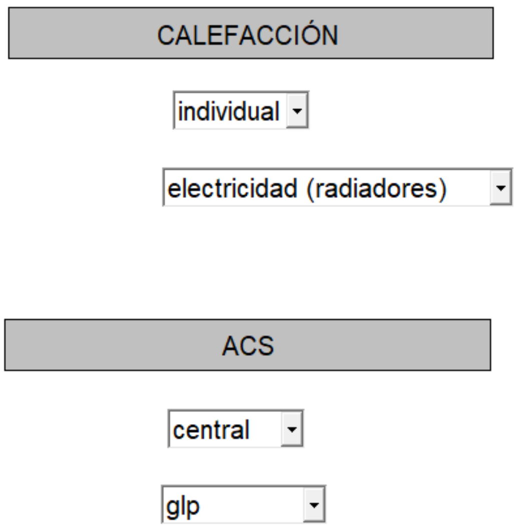
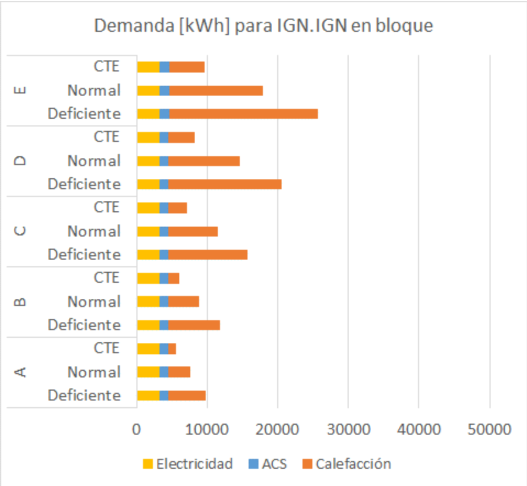
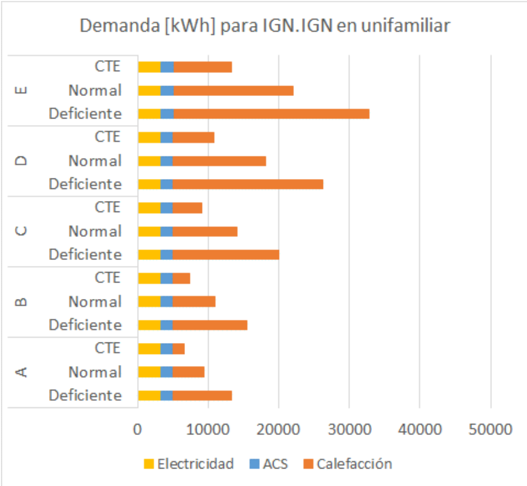


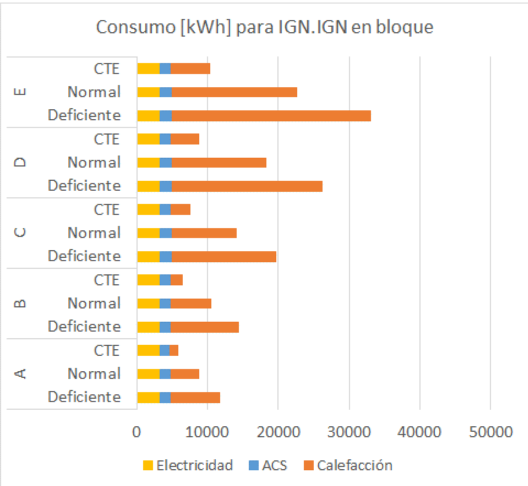
Fig. A 16. Heating and DHW systems characteristics' interface window of the DIAGNÓSTICO RWTEE local tool

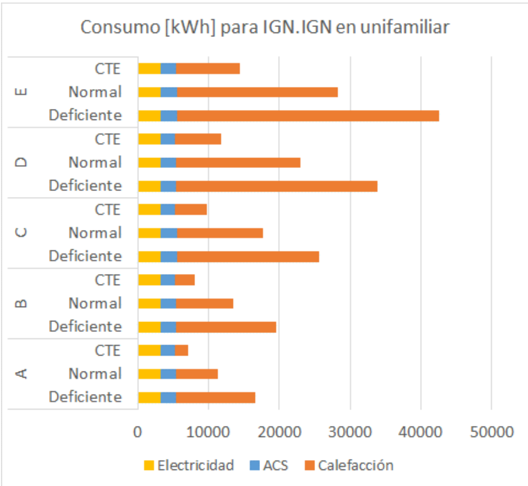
DIAGNÓSTICO local - ECODES web RWTEE tool testing

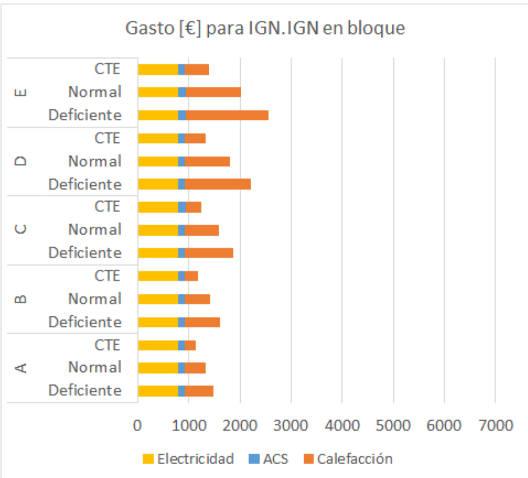
Fig. A 17-Fig. A 29 show the results of the local-web RWTEE tool testing.


Demanda [kWh] para IGN.IGN en bloque
E
D
C
B
A
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Demanda [kWh] para IGN.IGN en unifamiliar
E
D
C
B
A
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Consumo [kWh] para IGN.IGN en bloque
E
D
C
B
A
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Consumo [kWh] para IGN.IGN en unifamiliar
E
D
C
B
A
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Gasto [€] para IGN.IGN en bloque
E
D
C
B
A
CTE
Normal
Deficiente
0
1000
2000
3000
4000
5000
6000
7000
Electricidad
ACS
Calefacción

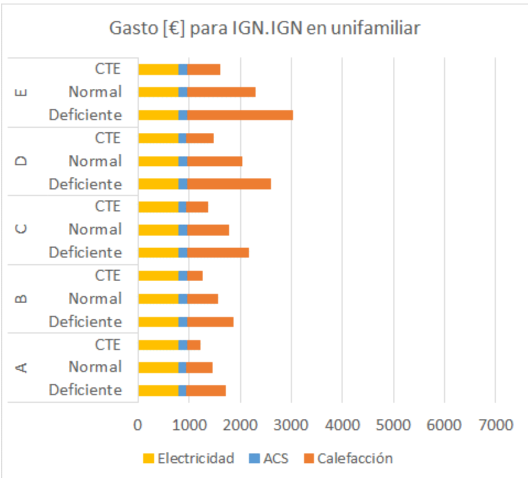
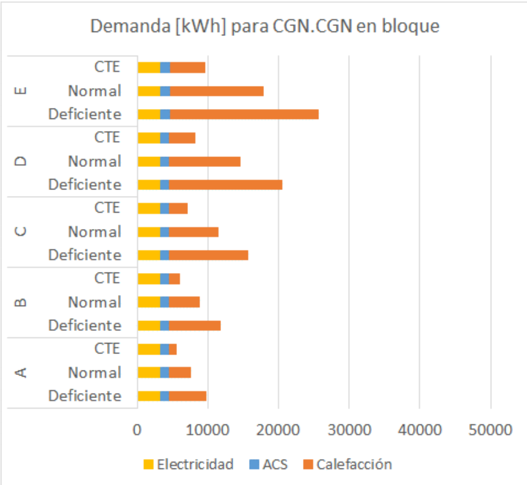
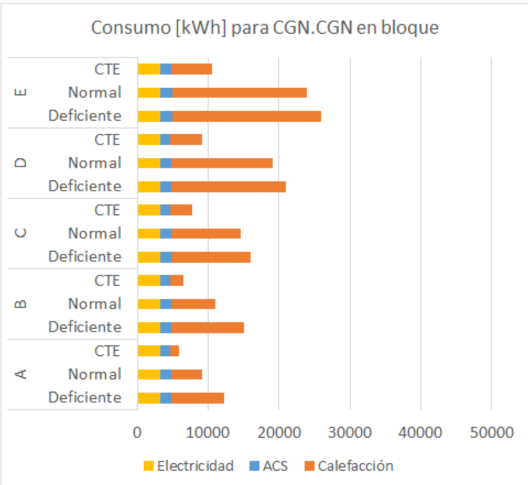

Gasto [€] para IGN.IGN en unifamiliar
E
D
C
B
A
CTE
Normal
Deficiente
0
1000
2000
3000
4000
5000
6000
7000
Electricidad
ACS
Calefacción

Fig. A 17. Demand, consumption and expenditure for individual natural gas installations in the DIAGNÓSTICO RWTEE local tool.





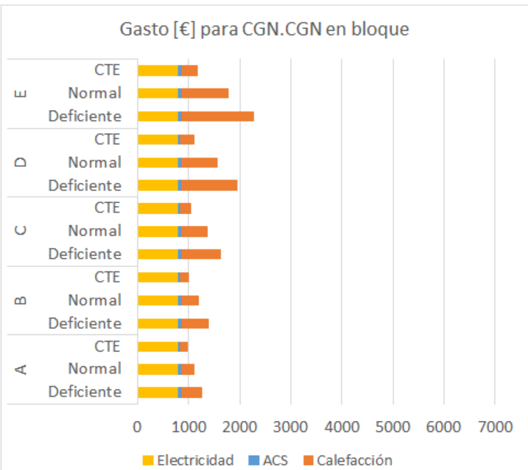


Fig. A 18. Demand, consumption and expenditure for centralised natural gas installations in the DIAGNÓSTICO RWTEE local tool

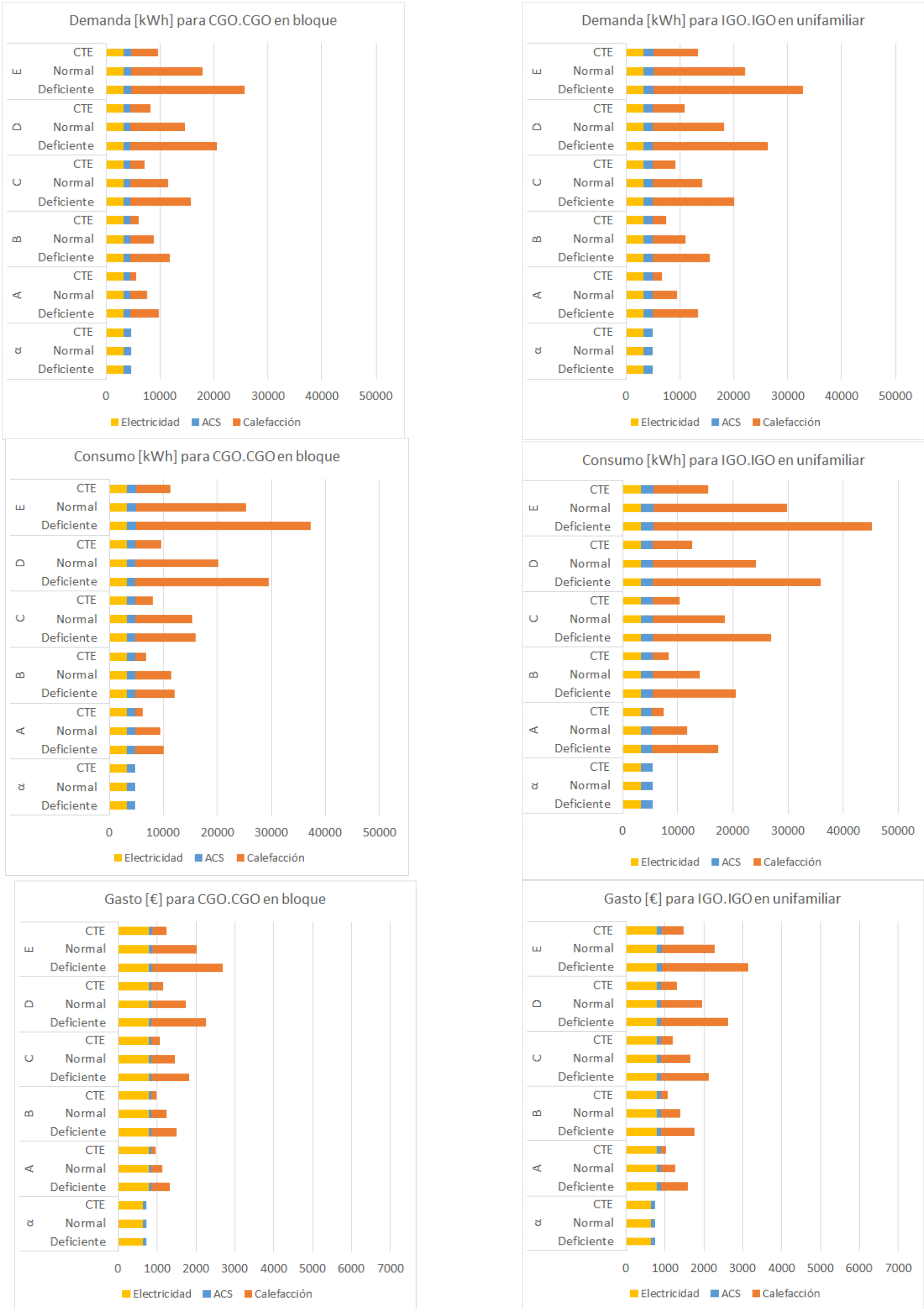
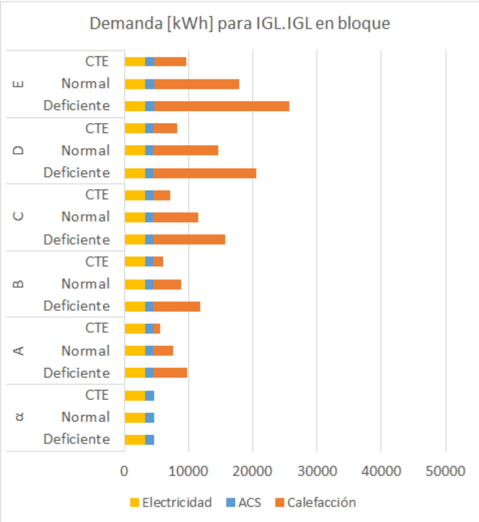
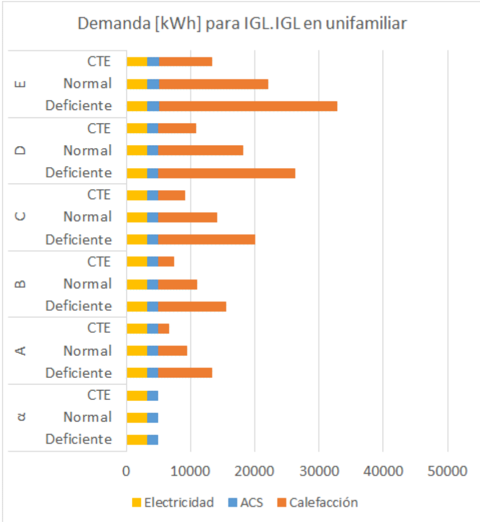
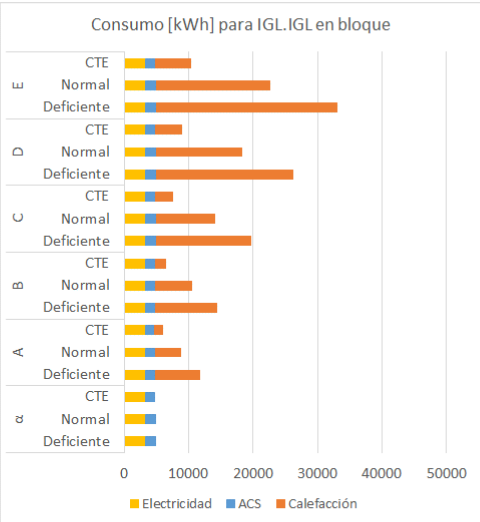
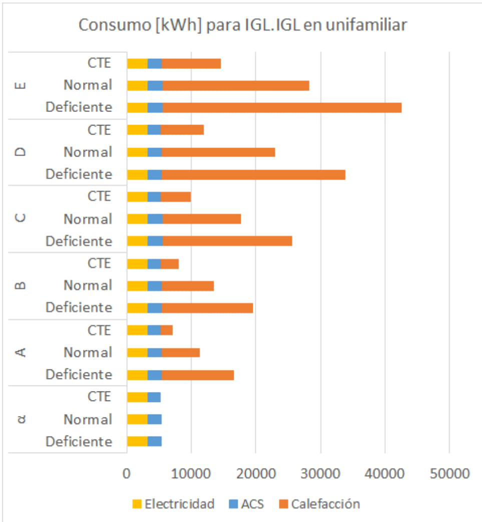


Fig. A 19. Demand, consumption and expenditure for heating gasoil installations in the DIAGNÓSTICO RWTEE local tool


Demanda [kWh] para IGL.IGL en bloque
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Demanda [kWh] para IGL.IGL en unifamiliar
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Consumo [kWh] para IGL.IGL en bloque
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Consumo [kWh] para IGL.IGL en unifamiliar
E
D
C
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CTE
Normal
Deficiente
0
10000
20000
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Electricidad
ACS
Calefacción

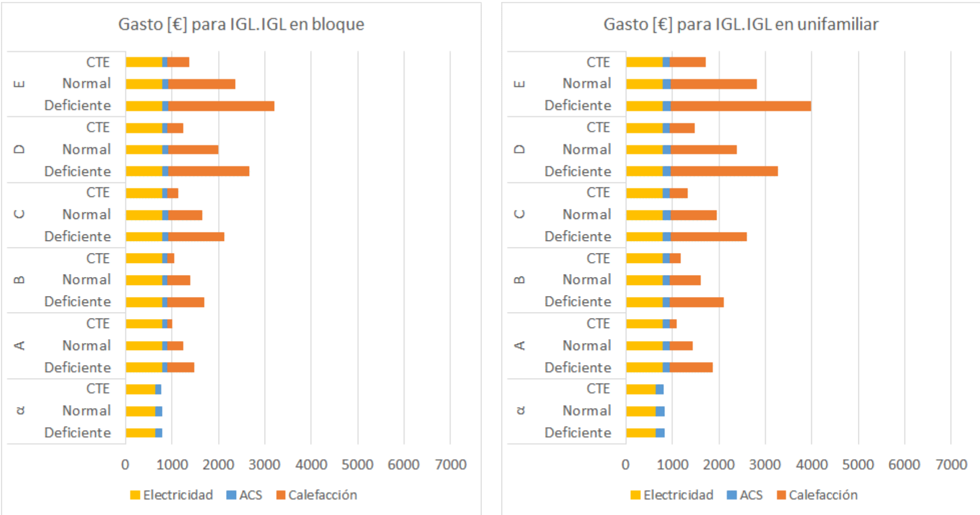


Fig. A 20.Demand, consumption and expenditure for individual LPG installations in the DIAGNÓSTICO RWTEE local tool

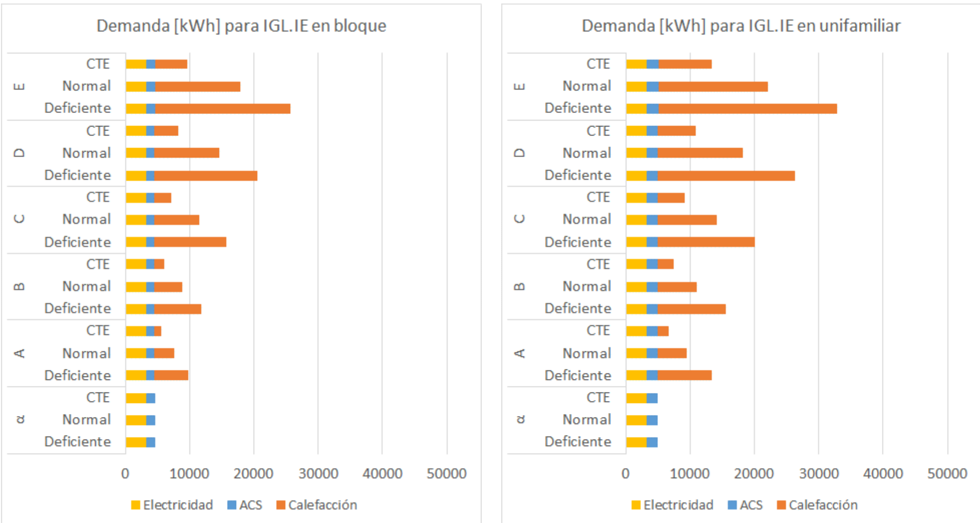
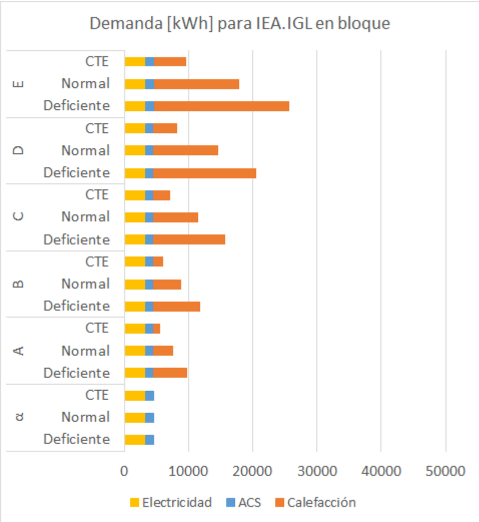
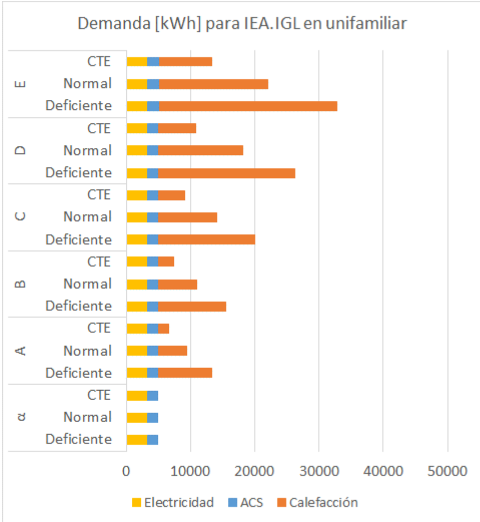


Fig. A 21. Demand, consumption and expenditure for individual LPG for heating and electricity for DHW in the DIAGNÓSTICO RWTEE local tool


Demanda [kWh] para IEA.IGL en bloque
E
D
C
B
A
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Demanda [kWh] para IEA.IGL en unifamiliar
E
D
C
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A
CTE
Normal
Deficiente
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10000
20000
30000
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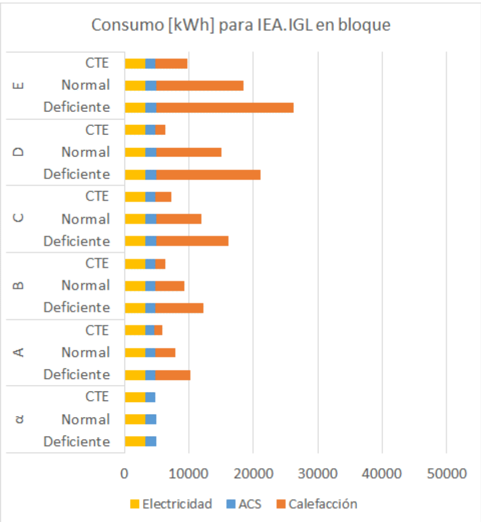
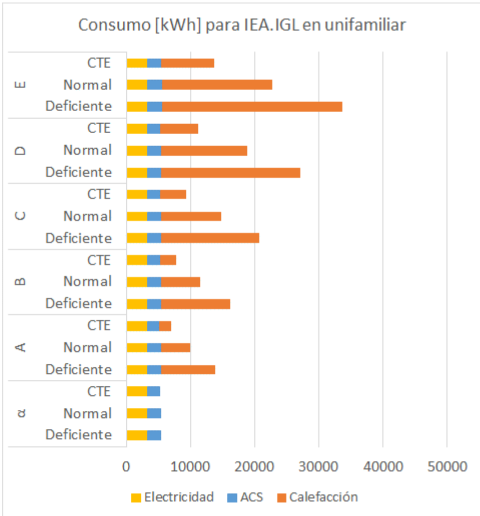
Electricidad
ACS
Calefacción


Consumo [kWh] para IEA.IGL en bloque
E
D
C
B
A
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Consumo [kWh] para IEA.IGL en unifamiliar
E
D
C
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CTE
Normal
Deficiente
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10000
20000
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50000
Electricidad
ACS
Calefacción

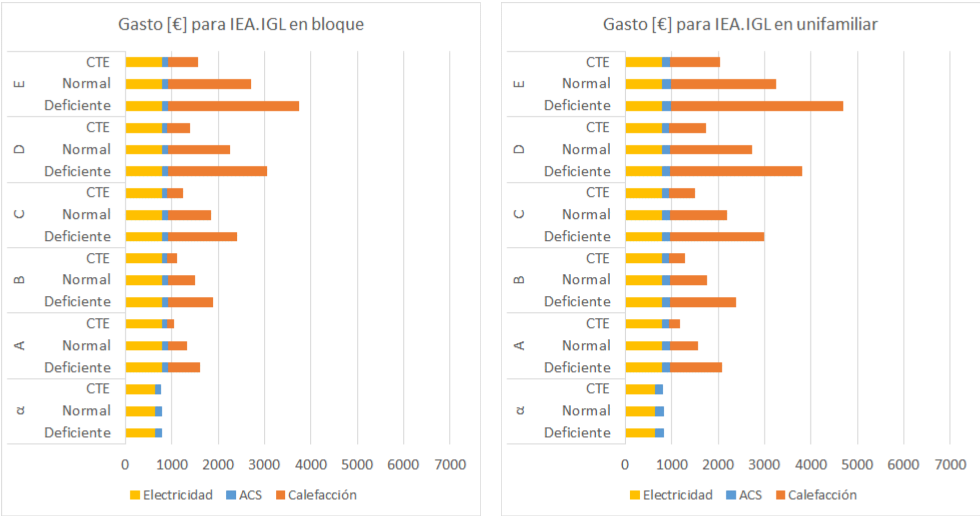
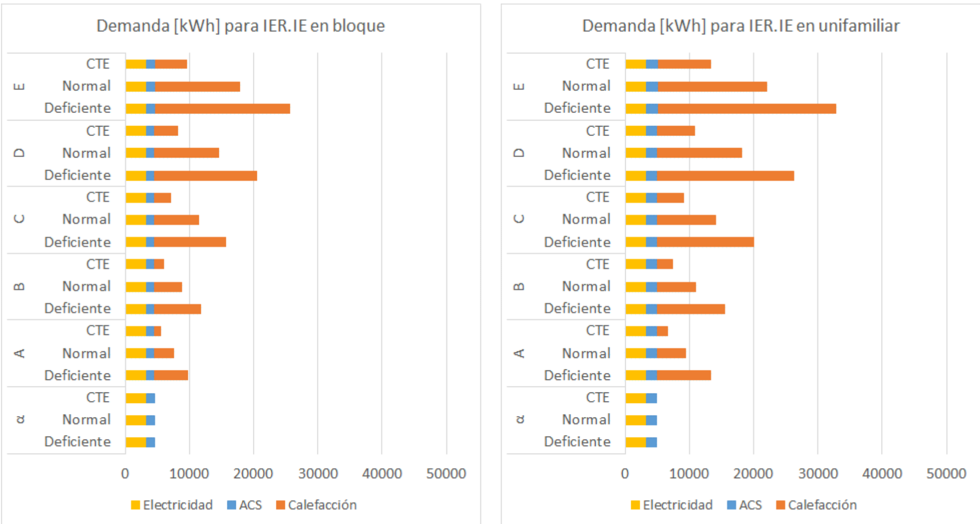


Fig. A 22. Demand, consumption and expenditure for electric storage heater for heating and individual LPG for DHW in the DIAGNÓSTICO RWTEE local tool



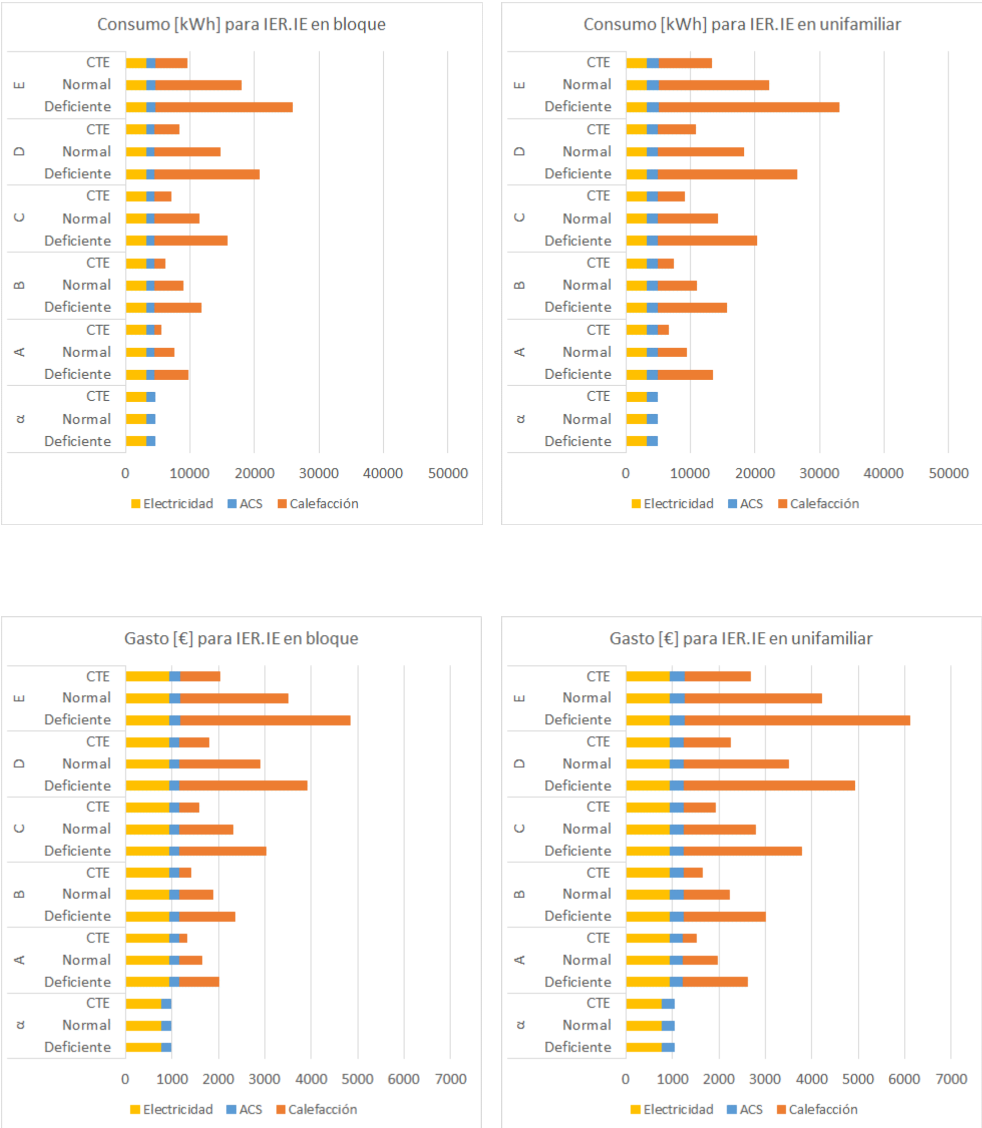
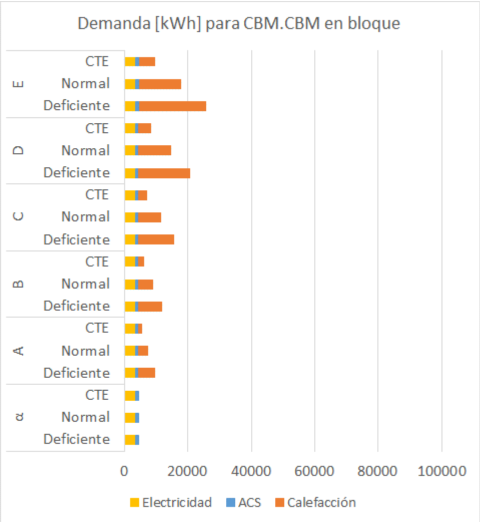
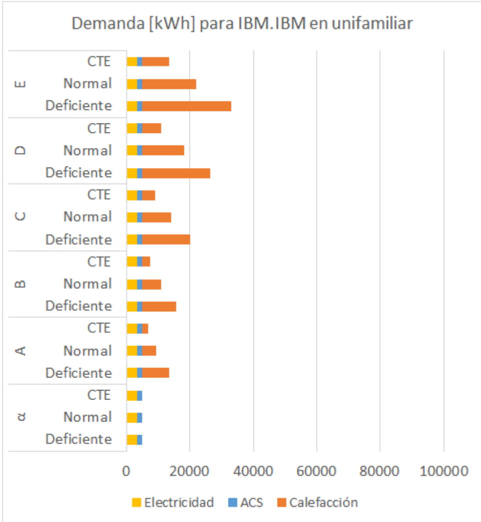


Fig. A 23. Demand, consumption and expenditure for individual electric radiators for heating and electricity for DHW in the DIAGNÓSTICO RWTEE local tool


Demanda [kWh] para CBM.CBM en bloque
E
D
C
B
A
α
CTE
Normal
Deficiente
0
20000
40000
60000
80000
100000
Electricidad
ACS
Calefacción


Demanda [kWh] para IBM.IBM en unifamiliar
E
D
C
B
A
α
CTE
Normal
Deficiente
0
20000
40000
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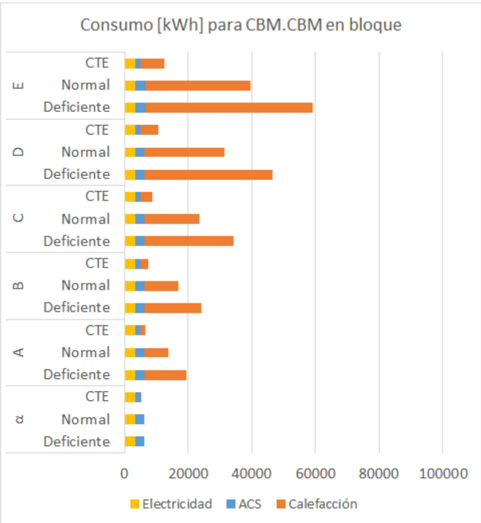
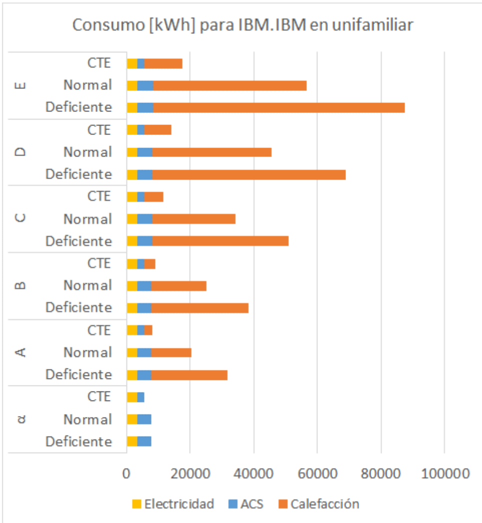
80000
100000
Electricidad
ACS
Calefacción


Consumo [kWh] para CBM.CBM en bloque
E
D
C
B
A
α
CTE
Normal
Deficiente
0
20000
40000
60000
80000
100000
Electricidad
ACS
Calefacción


Consumo [kWh] para IBM.IBM en unifamiliar
E
D
C
B
A
α
CTE
Normal
Deficiente
0
20000
40000
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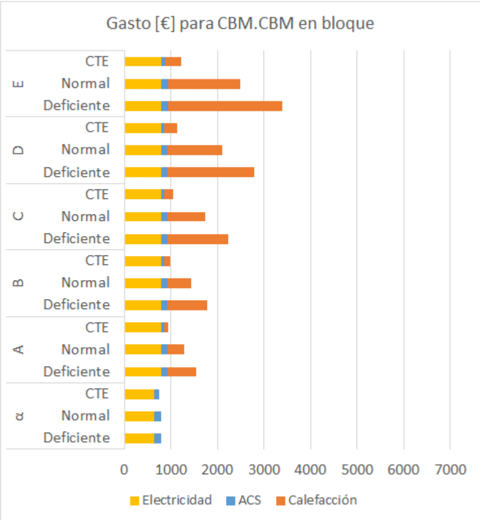
80000
100000
Electricidad
ACS
Calefacción



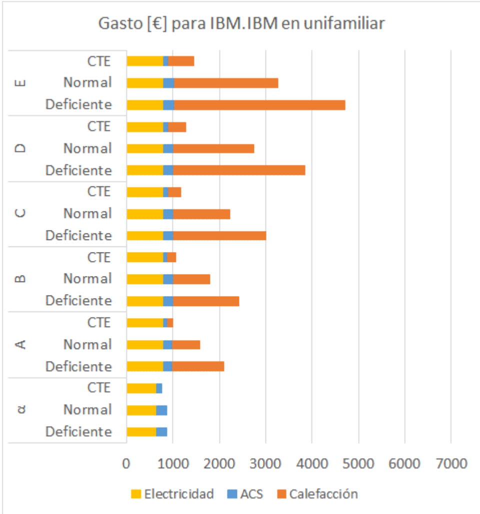
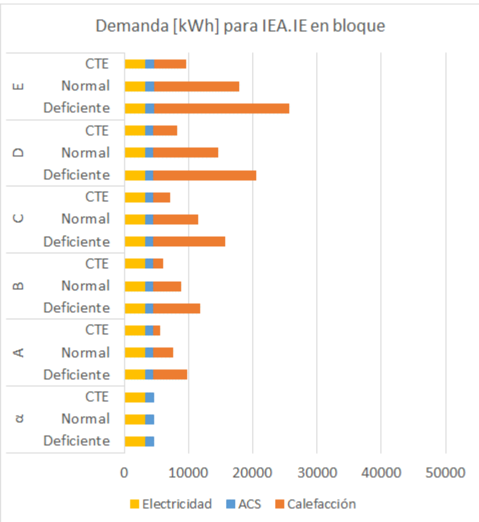
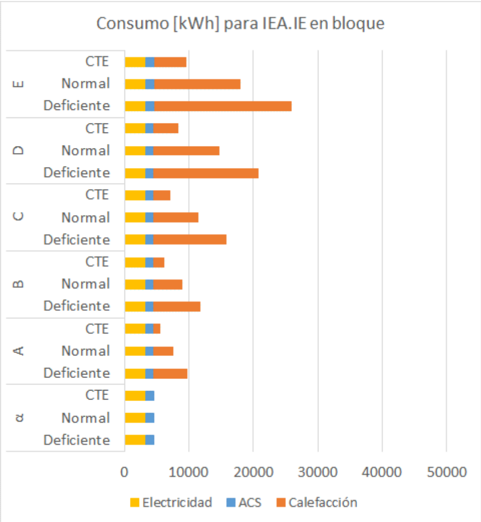


Fig. A 24. Demand, consumption and expenditure for biomass installations in the DIAGNÓSTICO RWTEE local tool





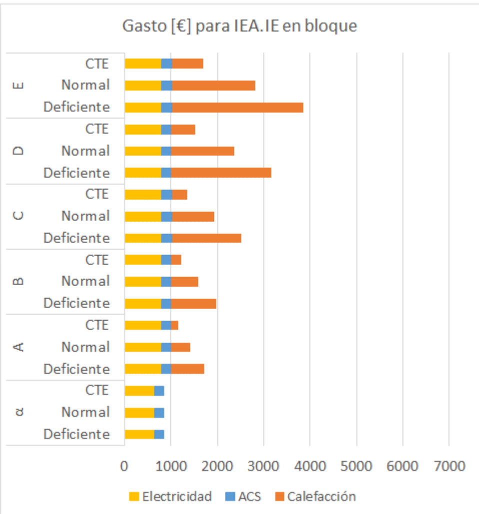
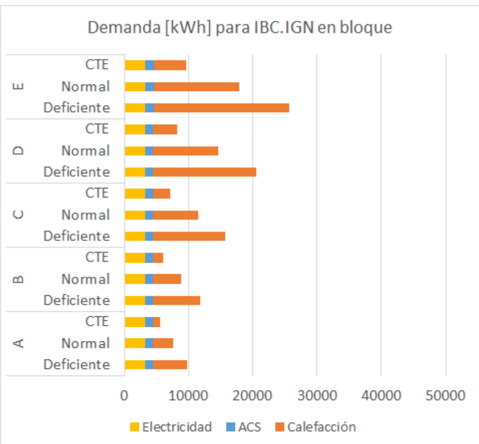
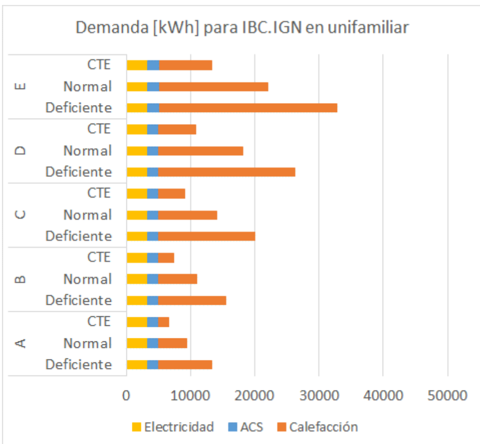


Fig. A 25. Demand, consumption and expenditure for individual electric storage heater for heating and electricity for DHW in the DIAGNÓSTICO RWTEE local tool





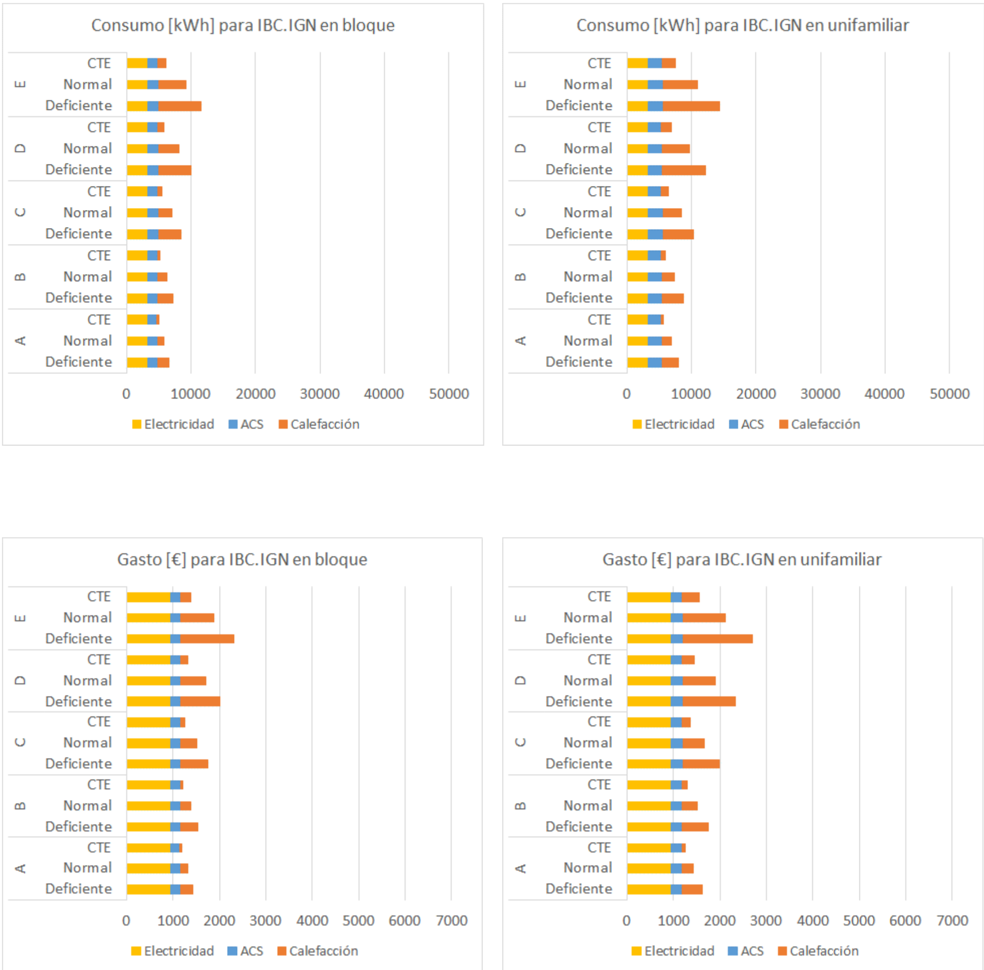
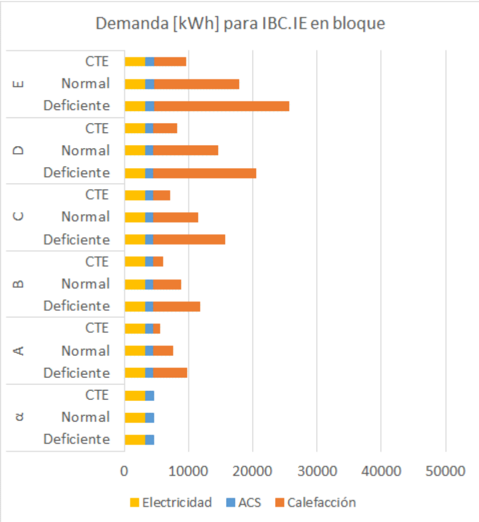


Fig. A 26. Demand, consumption and expenditure for heat pump for heating and individual natural gas for DHW in the DIAGNÓSTICO RWTEE local tool


Demanda [kWh] para IBC.IE en bloque
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
30000
40000
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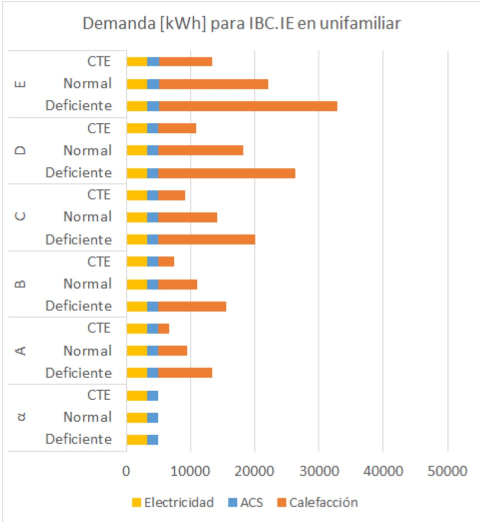
Electricidad
ACS
Calefacción


Demanda [kWh] para IBC.IE en unifamiliar
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
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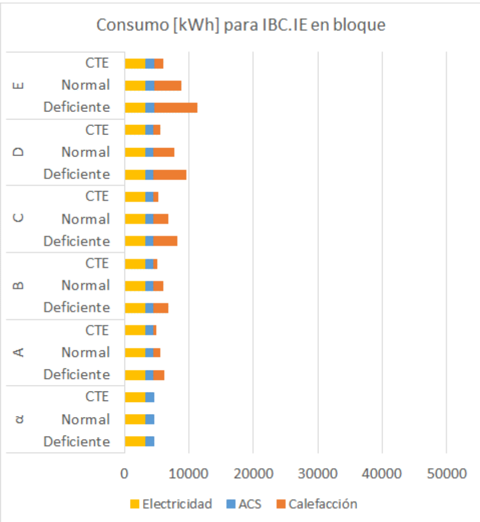
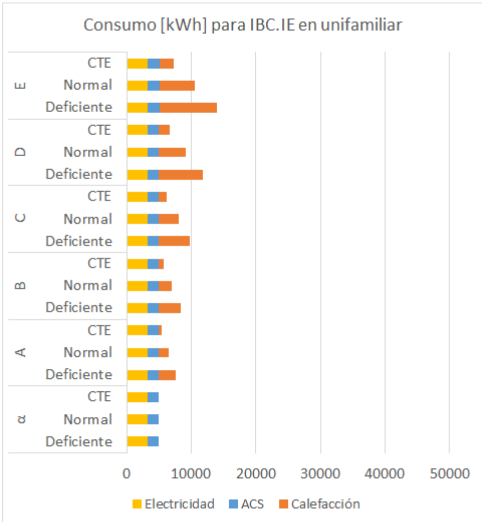
Electricidad
ACS
Calefacción


Consumo [kWh] para IBC.IE en bloque
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción


Consumo [kWh] para IBC.IE en unifamiliar
E
D
C
B
A
α
CTE
Normal
Deficiente
0
10000
20000
30000
40000
50000
Electricidad
ACS
Calefacción

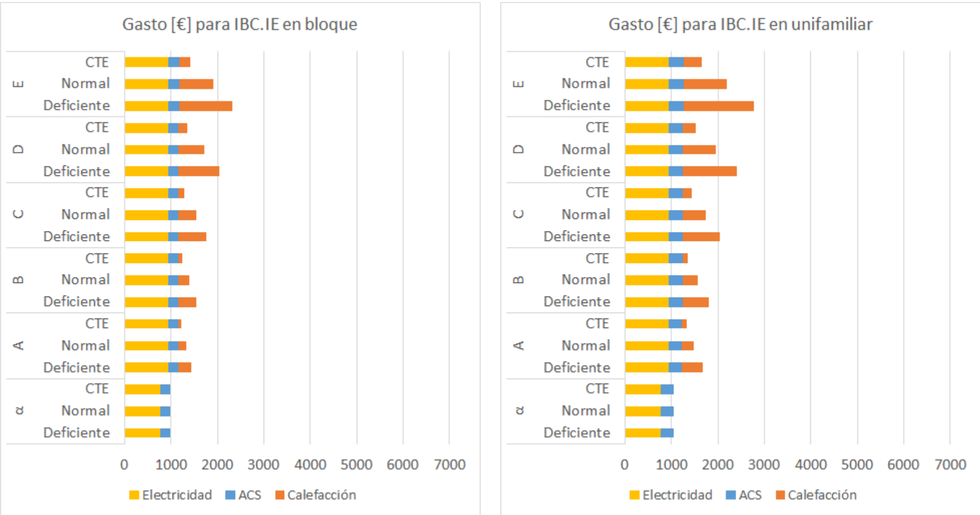


Fig. A 27. Demand, consumption and expenditure for heat pump for heating and electricity for DHW in the DIAGNÓSTICO RWTEE local tool

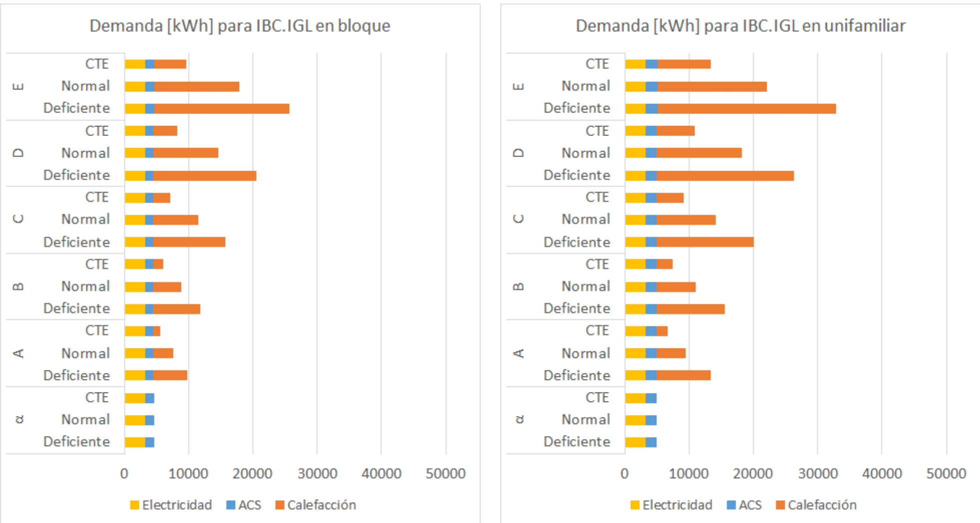
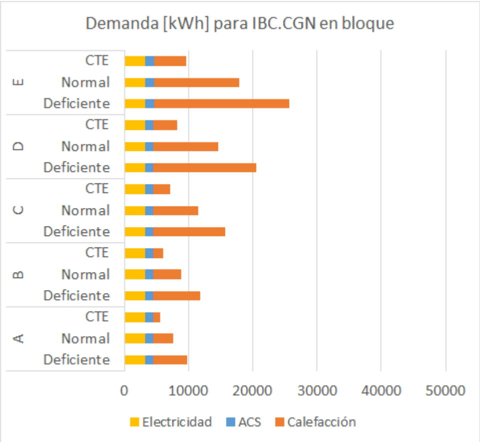
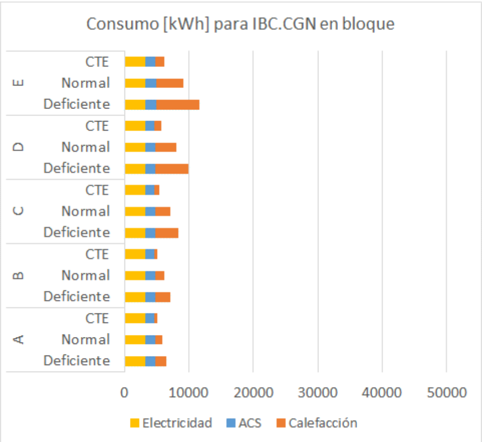


Fig. A 28. Demand, consumption and expenditure for heat pump for heating and individual LPG for DHW in the DIAGNÓSTICO RWTEE local tool





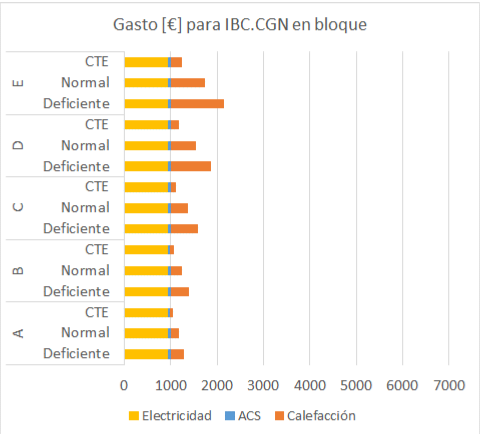


Fig. A 29. Demand, consumption and expenditure for heat pump for heating and central natural gas for DHW in the DIAGNÓSTICO RWTEE local tool

Local RELE tool interface

On the other hand, Fig. A 30 shows the interface of the local RELE tool that has been developed in Excel to calculate the annual consumption and the theoretical electricity cost:

As explained in Section 3.2.2.4, the calculation of the expenditure does not correspond to the current tariff system, but to the previous one, which was used in the first versions of the model. The current tariff system has been implemented in the web tool.

Número de miembros del hogar	3
Tamaño de la vivienda (m2)	101 a 120

Cosumo total al año [kW/h]	4221,69
Gasto anual PVPC 2.0A (€/año)	787,14
Gasto anual PVPC 2.0DHA (€/año)	674,39

Ocupaciones	
Ocupado/a	3 o mas
Parado/a	0
Estudiante	0
Jubilado/a, prejubilado/a	0
Cobrando una pensión de incapacidad permanente o invalidez	0
Cobrando una pensión de viudedad u orfandad	0
Realizando tareas del hogar	0
Otra situación de inactividad	0

Aparatos / Electrodomésticos	
Cocina electrica (Fogones)	Si
Horno eléctrico	Si
Lavadora	Si
Secadora	Si
Frigorifico	Si
Congelador	Si
TV	Si
Ordenador	Si
Lavavajillas	Si
Movil	Si
Tablet	Si
Microondas	Si

Fig. A 30. RELE local tool's interface

Local - ECODES web RELE tool testing

The results of the RELE tools checking are shown in Fig. A 31 and Fig. A 32, which shown, respectively, the outputs of the electrical appliances' ownership comparison and the household compositions' comparison, described in Section 3.2.3.2.1.

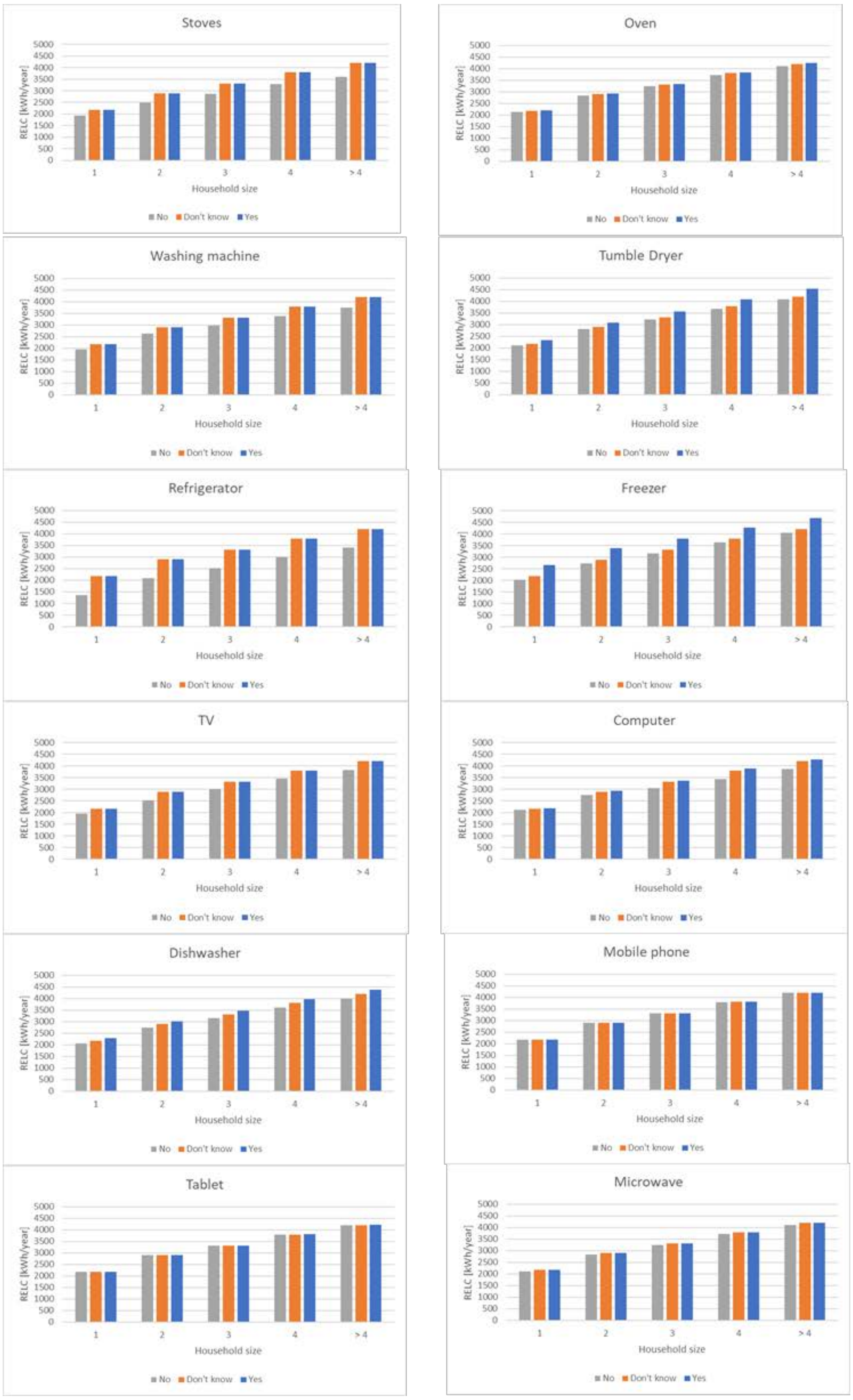


Fig. A 31. RELC values of the household compositions' comparison

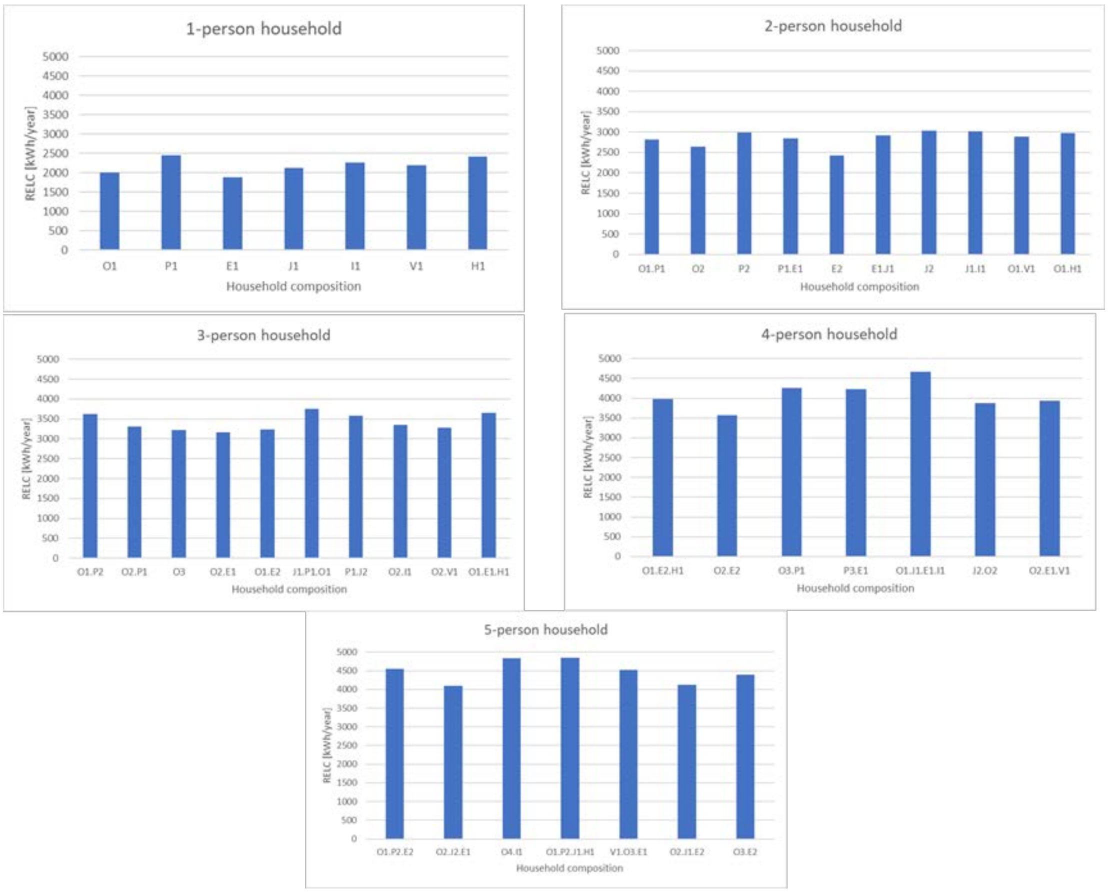


Fig. A 32. RELC values of the electrical appliances' ownership comparison

Appendix D. Spanish HBS variables and indicators' inputs

Table A 24 shows the Spanish HBS variables used for the assessment of the indicators and the corresponding inputs.

Table A 24. Spanish HBS variables used for the calculation of the indicators and corresponding inputs

HBS variable	Variable description	Possible values in the HBS	Indicators' inputs
CCAA	Region of residence	1 Andalucía 2 Aragón 3 Asturias, Principado de 4 Balears, Illes 5 Canarias 6 Cantabria 7 Castilla y León 8 Castilla – La Mancha 9 Cataluña 10 Comunitat Valenciana 11 Extremadura 12 Galicia 13 Madrid, Comunidad de 14 Murcia, Región de 15 Navarra, Comunidad Foral de 16 País Vasco 17 Rioja, La 18 Ceuta 19 Melilla	1 Andalucía 2 Aragón 3 Asturias 4 Islas Baleares 5 Canarias 6 Cantabria 7 Castilla y León 8 Castilla la Mancha 9 Cataluña 10 C. Valenciana 11 Extremadura 12 Galicia 13 Madrid 14 Murcia 15 Navarra 16 País Vasco 17 La Rioja 18 Ceuta 19 Melilla
FACTOR	Spatial expansion factor	Any value other than b and 0	FACTOR/1000000
NMIEMB	Number of household members	1-20	1-20
ANNOCON	Date of construction of the building	1 Less than 25 years ago 6 25 or more years ago -9 No record	1 Less than 25 years ago 6 25 or more years ago -9 25 or more years ago [329][99]

[99] According to the Spanish CENSUS 2011 and the 2019 data of [329] the great majority of dwellings were constructed 25 or more than 25 years ago.

HBS variable	**Variable description**	**Possible values in the HBS**	**Indicators' inputs**
TIPOEDIF	Type of building in which the dwelling is located	1 Detached single-family house 2 Semi-detached or semi-detached single-family dwelling 3 With less than 10 dwellings 4 With 10 or more dwellings 5 Other (used for other purposes or fixed accommodation) -9 No record	1, 2: Single-family house 3, 4, 5: Block dwelling -9: (Excluded)
SUPERF	Dwelling's floor area	35 35 metres or less 36-299 metres (actual value) 300 300 metres or more -9 No record	35 35 m^2 36-299 X m^2 (actual value) 300 300 m^2 -9 (Excluded)
AGUACALI	Presence of DHW system	1 Yes 6 No -9 No record	1 Yes 6 Yes -9 Yes
FUENAGUA	DHW energy carrier	1 Electricity 2 Natural gas 3 Liquefied gas 4 Other liquid fuels 5 Solid fuels 6 Other b Not applicable (if AGUACALI=6) -9 No record	1 Electricity 2 Natural gas 3 Liquefied petroleum gas (LPG) 4 Heating gasoil 5, 6 Biomass b Regional mode -9 Regional mode
CALEF	Presence of heating system	1 Yes 6 No -9 No record	1 Yes 6 Yes -9 Yes
FUENCALE	Heating energy carrier	1 Electricity 2 Natural gas 3 Liquefied gas 4 Other liquid fuels 5 Solid fuels 6 Other b Not applicable (if CALEF=6) -9 No record	1 Electricity 2 Natural gas 3 Liquefied petroleum gas (LPG) 4 Heating gasoil 5, 6 Biomass b Regional mode -9 Regional mode
CODIGO	Expenditure code [€]	4.5.1.1 Electricity 4.5.2.1 Natural gas 4.5.2.3 Liquefied gas 4.5.3.1 Liquid fuels 4.5.4.1 Coal 4.5.4.8 Other solid fuels (All values are for the main dwelling)	Actual Energy expenditure = Sum (Annual energy expenditures in the main dwelling)

HBS variable	Variable description	Possible values in the HBS	Indicators' inputs
REGTEN	Type of tenure	1 Property with no current loan or mortgage 2 Property with ongoing loan or mortgage 3 Rent 4 Reduced rent (old rent) 5 Provided semi-free 6 Provided free	1, 2 Owner-occupied dwelling 3, 4 Rented dwelling 5, 6 Semi-free or rent-free dwelling
ZONARES	Type of area of residence	1 Upmarket urban area 2 High-income urban area 3 Middle-income urban area 4 Low-income urban area 5 Industrial rural area 6 Fisheries rural area 7 Agricultural rural area -9 No record	1, 2, 3, 4 Urban area 5, 6, 7 Rural area -9 (Excluded from the disaggregated analysis)
UC2	Equivalent household size. Modified OECD scale	1-110 (actual value)	1-110 (actual value)
GASTOT	Total amount of monetary and non-monetary expenditure raised temporally and population-wise	1-999999999999999	Equivalised total expenditure = GASTOT/(FACTOR* UC2)
IMPEXAC	Exact amount of the total net monthly household income	0-99999	Equivalised net disposable income = (IMPEXAC*12)/UC2

Appendix E. Calculation of the household's required thermal energy consumption in the 'adapted HBS' RENE model

The annual specific required-demands for heating and cooling ($\mathrm{kWh/(m^2\ year)}$) have been calculated using the methodology described in [236] and [81], and applying the requirements set in CTE 2019. These variables depend on the annual specific reference-demand values (also in $\mathrm{kWh/(m^2\ year)}$), which are calculated by the IDAE for a baseline comfort temperature of 20ºC[100]. Particularly, these reference demands depend on the climate severity indexes (winter climate severity and summer climate severity) and the building correlation coefficients. The former ones are estimated for each winter and summer climate zone and depend on, respectively, the Heating Degree Days (HDD) and Cooling Degree Days (CDD), and the ratio of the number of sunshine hours to the number of maximum sunshine hours. The building correlation coefficients are the result of modelling thirteen types of building geometry [81] and vary according to the dwelling typology (block dwelling or single-family house). Subsequently, the values of the annual specific required demand for DHW ($\mathrm{kWh/(person\ year)}$) were calculated as a function of the average monthly network-water-temperature (ºC) of the Spanish provincial capitals and the daily specific hot water consumption (l/(person day)) at a given temperature T = 60 °C, which depends on the dwelling type (CTE 2019 and [82]). For localities other than the provincial capitals, the network-water-temperature is estimated by considering the difference between the locality's altitude and provincial capital's altitude.

The database of all the Spanish localities belonging to each region (and each province in the region) has been used as a starting point for the approximation of the thermal demand according to the CCAA variable of the HBS (see table A1). In this database, the number of inhabitants [240] and the altitude of each locality [235] is known. Using the latter parameter and the locality's province, it is possible to assign the winter and summer climate zone (which determines the heating and cooling specific demand), and the network-water-temperature (which determines the DHW specific demand) to each Spanish locality (CTE, 2019).

Therefore, for each locality, the specific required thermal demand is determined for single-family houses and block dwellings (from TIPOEDIF variable in Table A1) by distinguishing (for the HVAC demand) from buildings constructed 25 or more years ago and buildings constructed less than 25 years ago (from ANNOCON variable in Table A1). Table A 25 and Table A 26 show the energy efficiency parameter (EEP) assigned to each of these dwelling's type according to the winter climate zone. These values have been obtained using the methodology of [236] updated based on the 2019 IDAE report on energy performance certificates.

[100] In concrete terms, the baseline comfort temperature is the set point temperature of the thermal system.

Table A 25. EEP values in block dwellings according to the winter climate zone and the building construction period

Winter climate zone	**≥ 25 years ago**	**< 25 years ago**
α	3.55	1.77
A	3.55	1.77
B	3.27	1.71
C	3.05	1.65
D	2.94	1.63
E	2.89	1.61

Table A 26. EEP values in single-family houses according to the winter climate zone and the building construction period

Winter climate zone	**≥ 25 years ago**	**< 25 years ago**
α	3.11	1.61
A	3.11	1.61
B	3.05	1.62
C	2.96	1.60
D	3.19	1.64
E	3.19	1.61

Subsequently, a weighted average (according to the number of inhabitants) of the specific demand values by provinces has been carried out. These provincial weighted specific-required-demand values ($\overline{SRD}_{j,i}$) were calculated applying the procedure presented in [236] to each thermal energy use considered in this paper, i.e. heating, cooling and DHW. Finally, because of the regional disaggregation of the Spanish HBS, the weighted average was carried out by region (Eq. (A1)), considering the provincial demand values ($\overline{SRD}_{j,i}$) and the number of inhabitants in each province belonging to the region. Eq. (A1) shows the mathematical formulation used to calculate the regional weighted average of the specific-required-demand ($\overline{SRD}_{j,k}$)[101].

[101] Note that the regional weighting of the specific demands of heating, cooling and DHW by number of inhabitants in each province of the region aims to 'weight', respectively, the winter climate zone, the summer climate zone and the network-water-temperature.

$$\overline{\mathrm{SRD}}_{\mathrm{j,k}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} \overline{\mathrm{SRD}}_{\mathrm{j,i}} \cdot \mathrm{NI_i}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{NI_i}} \tag{A1}$$

Where *i* is the *i*-province of the k-region, NI_i is the number of inhabitants of the i-province [240], and *j* can be heating, cooling or DHW. This computation has been reiterated for each combination of aggregated-construction-period (only for heating and cooling) and dwelling typology for all the regions. Thus, Table A 27, Table A 28 and Table A 29shows the values of the regional weighted specific demand, respectively, for heating, cooling and DHW.

Table A 27. Regional weighted specific demand for heating [kWh/(m² year)] per aggregated construction period and dwelling type

Region	**≥ 25 years ago**		**< 25 years ago**	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	64.40	91.09	35.00	50.94
Aragón	133.02	174.20	75.82	103.56
Asturias	114.56	150.21	64.84	89.37
Baleares	58.36	84.25	31.39	46.35
Canarias	15.48	24.09	8.05	12.43
Cantabria	96.24	128.76	53.95	75.19
Castilla y León	153.40	199.25	87.94	118.76
Castilla - La Mancha	130.89	170.86	74.56	101.98
Cataluña	98.23	131.15	55.13	76.77
C. Valenciana	66.79	93.94	36.41	52.77
Extremadura	98.69	130.86	55.41	77.12
Galicia	104.62	139.03	58.93	81.68
Madrid	133.40	174.80	76.05	103.93
Murcia	70.68	98.95	38.73	55.76
Navarra	133.32	173.52	76.00	103.84

País Vasco	112.28	148.65	63.49	87.61
La Rioja	134.53	176.34	76.72	104.78
Melilla	41.65	64.22	21.46	33.53
Ceuta	58.30	83.93	31.35	46.30

Table A 28. Regional weighted specific demand for cooling [kWh/(m^2 year)] per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	44.27	55.93	25.29	33.59
Aragón	29.02	39.26	17.53	24.34
Asturias	0.00	0.00	0.00	0.00
Baleares	36.48	46.73	20.93	28.02
Canarias	32.49	39.85	17.77	23.25
Cantabria	0.00	0.00	0.00	0.00
Castilla y León	7.49	10.63	4.39	6.32
Castilla - La Mancha	32.76	43.95	19.82	27.43
Cataluña	19.29	26.70	11.19	15.82
C. Valenciana	40.25	51.74	23.25	31.19
Extremadura	45.12	59.76	26.93	36.86
Galicia	2.63	3.65	1.55	2.18
Madrid	32.72	44.15	19.85	27.48
Murcia	35.77	46.50	20.76	28.03
Navarra	3.78	5.32	2.21	3.18
País Vasco	0.00	0.00	0.00	0.00
La Rioja	16.41	23.29	9.62	13.84
Melilla	39.24	47.62	21.60	28.04
Ceuta	36.48	46.59	20.93	28.02

Table A 29. Regional weighted specific demand for DHW [kWh/(person year)] per dwelling type

Region	**Block dwelling**	**Single-family house**
Andalucía	488.96	536.05
Aragón	506.69	559.76
Asturias	508.72	565.24
Baleares	507.73	534.45
Canarias	496.76	522.91
Cantabria	506.29	562.55
Castilla y León	533.15	579.71
Castilla - La Mancha	528.07	557.75
Cataluña	502.67	553.47
C. Valenciana	487.62	540.03
Extremadura	520.85	548.26
Galicia	524.97	562.81
Madrid	502.15	557.94
Murcia	502.51	543.25
Navarra	526.44	569.12
País Vasco	511.02	567.80
La Rioja	511.19	567.99
Melilla	498.36	524.59
Ceuta	489.03	543.36

Then, the weighted standard deviation of each region ($\sigma_{j,k}$) was calculated to evaluate the grade of variation of the provincial values with respect to the regional weighted average value. Therefore, the weighted coefficient of variation ($CV_{j,k}$, defined as in [330]) of the specific required demand in each region was computed by applying Eq. (A2), i.e. computing the ratio of the region's weighted standard deviation to the regional weighted mean ($\overline{SRD}_{j,k}$).

$$CV_{j,k} = \frac{\sigma_{j,k}}{\overline{SRD}_{j,k}} \tag{A2}$$

Table A 30-Table A 32 show the results of the latter calculation.

Table A 30. Weighted coefficient of variation of the specific required heating demand in each region per aggregated construction period and dwelling type

Region	**≥ 25 years ago**		**< 25 years ago**	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	9.7%	8.1%	10.7%	9.4%
Aragón	0.8%	0.8%	0.8%	0.7%
Asturias	0.0%	0.0%	0.0%	0.0%
Baleares	0.0%	0.0%	0.0%	0.0%
Canarias	34.0%	37.1%	33.5%	34.2%
Cantabria	0.0%	0.0%	0.0%	0.0%
Castilla y León	3.7%	3.5%	3.8%	3.5%
Castilla - La Mancha	1.6%	1.8%	1.7%	1.6%
Cataluña	6.8%	6.2%	7.2%	6.7%
C. Valenciana	1.0%	0.8%	1.1%	1.0%
Extremadura	2.2%	2.5%	2.3%	2.2%
Galicia	6.9%	6.3%	7.3%	6.8%
Madrid	0.0%	0.0%	0.0%	0.0%
Murcia	0.0%	0.0%	0.0%	0.0%
Navarra	0.0%	0.0%	0.0%	0.0%
País Vasco	10.9%	10.1%	11.5%	10.8%
La Rioja	0.0%	0.0%	0.0%	0.0%
Melilla	0.0%	0.0%	0.0%	0.0%
Ceuta	0.0%	0.0%	0.0%	0.0%

Table A 31. Weighted coefficient of variation of the specific required cooling demand in each region per aggregated construction period and dwelling type

Region	**≥ 25 years ago**		**< 25 years ago**	
	Block dwelling	**Single-family house**	**Block dwelling**	**Single-family house**
Andalucía	3.2%	2.9%	3.5%	3.3%
Aragón	2.5%	2.5%	2.8%	2.7%
Asturias	0.0%	0.0%	0.0%	0.0%
Baleares	0.0%	0.0%	0.0%	0.0%
Canarias	16.1%	7.2%	17.8%	14.5%
Cantabria	0.0%	0.0%	0.0%	0.0%
Castilla y León	1.6%	1.8%	1.7%	1.8%
Castilla - La Mancha	1.3%	1.3%	1.4%	1.4%
Cataluña	3.2%	2.9%	3.4%	3.1%
C. Valenciana	5.3%	4.7%	5.6%	5.0%
Extremadura	1.1%	0.8%	1.1%	1.0%
Galicia	3.5%	3.7%	3.7%	3.7%
Madrid	0.0%	0.0%	0.0%	0.0%
Murcia	0.0%	0.0%	0.0%	0.0%
Navarra	0.0%	0.0%	0.0%	0.0%
País Vasco	0.0%	0.0%	0.0%	0.0%
La Rioja	0.0%	0.0%	0.0%	0.0%
Melilla	0.0%	0.0%	0.0%	0.0%
Ceuta	0.0%	0.0%	0.0%	0.0%

Table A 32. Weighted coefficient of variation of the specific required DHW demand in each region per dwelling type

Region	**Block dwelling**	**Single-family house**
Andalucía	0.9%	0.4%
Aragón	1.4%	0.5%
Asturias	0.0%	0.0%
Baleares	0.0%	0.0%
Canarias	0.4%	0.4%
Cantabria	0.0%	0.0%
Castilla y León	0.9%	0.3%
Castilla - La Mancha	0.7%	0.7%
Cataluña	1.5%	0.6%
C. Valenciana	0.7%	0.3%
Extremadura	0.6%	0.6%
Galicia	1.8%	0.6%
Madrid	0.0%	0.0%
Murcia	0.0%	0.0%
Navarra	0.0%	0.0%
País Vasco	0.6%	0.6%
La Rioja	0.0%	0.0%
Melilla	0.0%	0.0%
Ceuta	0.0%	0.0%

The single-province regions have 0% of demand variation for the three thermal energy uses (since their regional weighted demand is equal to the demand of the only province belonging to that region). In the rest of the regions, the coefficients of both heating and cooling demands are higher than the DHW ones, i.e. the HVAC demand has a higher variability. Particularly, the variation coefficients of the DHW demand are lower than 1.8% in all regions. Whereas, for the HVAC demand, the higher values are achieved in *Canarias*[102], where the weighted coefficient of variation reaches 37.1% for single-family houses constructed 25 or more years ago. Moreover, the heating coefficients are generally higher than the cooling ones. Eventually, giving the significant variability of the HVAC demand among the provinces in some of the Spanish regions, more disaggregated geographical information should be added to the HBS. Particularly, in the light of the analysis on the coefficient of variation, the household's province of residence is considered a crucial data to improve the accuracy of the 'HBS adapted' RENE model.

Afterwards, the values of required demand for HVAC and DHW [kWh/year] of each HBS household were calculated by multiplying the specific demand values, respectively, by their dwelling size (SUPERF) or the number of household members (NMIEMB). Finally, the household's required consumption values were calculated by dividing its required thermal energy demand by the seasonal performance factor of the corresponding thermal systems (following the official procedure established by the IDAE [81]). The seasonal performance factors of HVAC systems (i.e. HSPF and SEER) for buildings constructed less than 25 years ago have been calculated as a weighted average (depending on the HBS year) between the parameter for existing buildings and that for new buildings (since the boundary year in [236] is 2008, i.e. entry into force of the CTE, which falls within those 25 years). On the other hand, the factors of HVAC systems for buildings constructed 25 or more years ago was set as the ones of existing buildings. No differentiation was considered for the DHW systems. Table A 33-Table A 37 show the values set for the seasonal performance factors of each system considered.

Table A 33. Seasonal performance factor of heating systems (HSPF) for buildings constructed 25 or more years ago

Energy carrier	HSPF
Natural gas	0.75
LPG	0.75
Heating gasoil	0.70
Biomass	0.35
Electricity	0.99

[102] This is because the two provinces of *Canarias* have almost the same number of inhabitants but quite different HVAC demand values (especially the heating one).

Table A 34. Seasonal performance factor of heating systems (HSPF) for buildings constructed less than 25 years ago (depending on the HBS year)

Energy carrier	HSPF (2016)	HSPF (2017)	HSPF (2018)	HSPF (2019)
Natural gas	0.80	0.81	0.81	0.82
LPG	0.79	0.80	0.81	0.81
Heating gasoil	0.74	0.75	0.75	0.76
Biomass	0.46	0.48	0.49	0.50
Electricity	0.99	0.99	0.99	0.99

Table A 35. Seasonal energy efficiency rating for cooling (SEER) per summer climate zone for buildings constructed 25 or more years ago

Summer climate zone	SEER
1	3.82
2	3.69
3	3.49
4	3.39

Table A 36. Seasonal energy efficiency rating for cooling (SEER) per summer climate zone for buildings constructed less than 25 years ago (depending on the HBS year)

Summer climate zone	SEER (2016)	SEER (2017)	SEER (2018)	SEER (2019)
1	4.17	4.22	4.26	4.30
2	4.02	4.06	4.10	4.14
3	3.80	3.84	3.88	3.92
4	3.70	3.74	3.78	3.81

Table A 37. Seasonal performance factor of DHW systems (SPF)

Energy carrier	SPF
Natural gas	0.77
LPG	0.77
Heating gasoil	0.77
Biomass	0.37
Electricity	0.99

Appendix F. Energy prices and regional tax rates used in the RENE model and RENE results

The regulated-market-price, i.e. the Voluntary Price for the Small Consumer (VPSC), is applied to the consumption of electricity, both in the RTEE and RELE models, as it is the tariff selected by around 40% of the Spanish households [331] and by all vulnerable consumers benefitted from the social tariff for electricity (according to the data provided by the Ministry for the Ecological Transition and the Demographic Challenge). On the other hand, the contracted power term is not considered in the RTEE because it is assigned to the RELE. The regulated market tariff was also used for the natural gas, i.e. the Tariff of Last Resort (TLR), since, between 2017 and 2019, around 75% of households (within the ones that were aware of their natural gas tariff) declared to have the TLR [92]. In the paper's case study (Spanish HBS), if the household uses natural gas for both heating and DHW, the DHW system is considered the same as the heating system. Thus, the fixed term is only considered in the calculation of the heating expenditure. For heating gasoil and biomass, the IDAE's quarterly price reports have been taken as a reference, and these prices were weighted annually. Finally, the price of regulated bottled LPG has been taken as a reference, which includes a term for the cost of the raw material, a term for the marketing cost and a term for mismatch. In *Ceuta*, *Melilla* and *Canarias* a marketing surcharge/extra cost is applied due to logistical costs. Fig. A 33 shows the energy prices across the four years analysed.

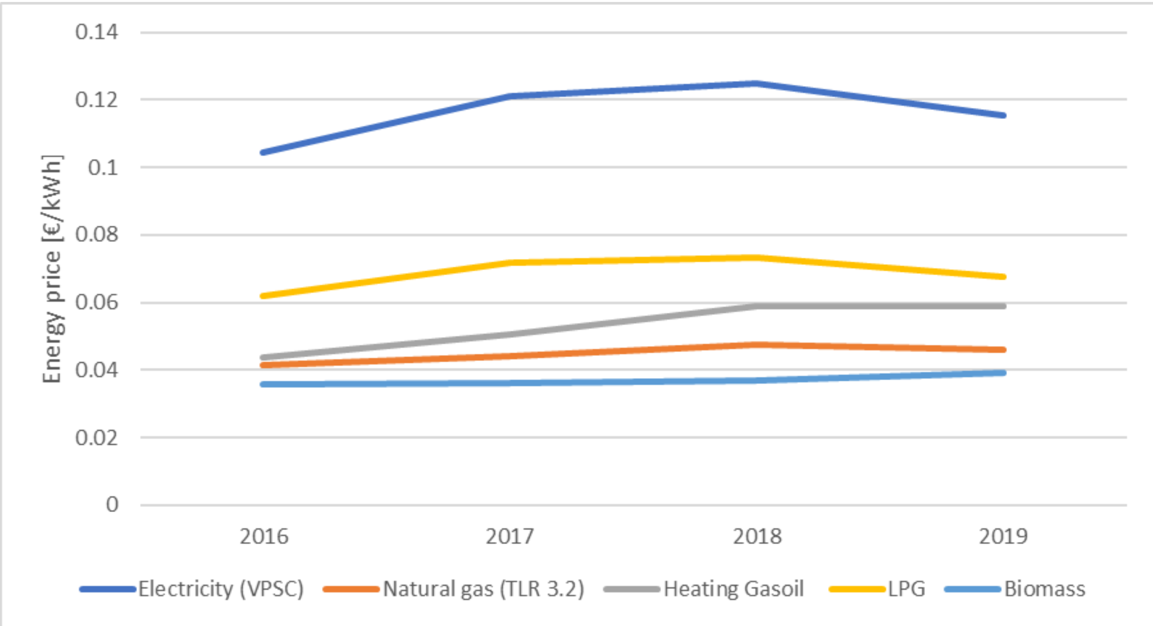


Fig. A 33. Energy prices across the four years analysed (2016-2019) (reprinted from [136]*)*

2017 and 2018 were the years with the highest energy prices for electricity, natural gas and LPG, which constitute the major share of final energy consumption in the Spanish residential sector [55]. On the other hand, the prices for heating gasoil and biomass reached their maximum in 2019. Regarding the tax rates, the fossil-fuel and electricity taxes and the VAT have been set according to the Spanish regulation [250], [251] considering the different VAT policy in *Canarias*, *Ceuta* and *Melilla*. These regions apply different VAT values depending on the energy carrier, whereas, in the rest of the country, the VAT is 21% for all fuels.

Appendix G. Minimum heating demands

Table A 38-Table A 41 show the minimum heating demand values used in the winter-baseline-temperature sensitivity analyses (HDD_18 and HDD_16) and the relative difference with the base case scenario.

Table A 38. Regional weighted specific demand for heating [kWh/(m^2 year)] using 18°C as baseline temperature (minimum comfort-temperature heating demand) per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	Single-family house	Block dwelling	Single-family house
Andalucía	31.02	49.49	17.08	28.03
Aragón	96.79	129.53	55.18	77.02
Asturias	79.91	107.87	45.26	64.20
Baleares	24.34	41.55	13.09	22.86
Canarias	4.00	9.34	2.10	4.85
Cantabria	63.05	87.91	35.36	51.35
Castilla y León	114.85	151.71	65.84	90.43
Castilla - La Mancha	94.91	126.69	54.07	75.63
Cataluña	64.65	89.83	36.33	52.64
C. Valenciana	32.95	51.74	18.05	29.20
Extremadura	65.35	90.12	36.71	53.12
Galicia	70.77	97.37	39.89	57.24
Madrid	97.23	130.16	55.43	77.39
Murcia	36.80	56.60	20.28	32.07
Navarra	97.12	129.15	55.36	77.29
País Vasco	77.82	106.17	44.03	62.61
La Rioja	98.24	131.52	56.02	78.15
Melilla	8.97	23.25	4.62	12.14
Ceuta	24.27	41.35	13.05	22.81

Table A 39. Relative difference [%] between the regional weighted values of the minimum comfort-temperature heating demand (18°C as baseline temperature) and the required heating demand (20°C as baseline temperature), per aggregated construction period

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	Single-family house	Block dwelling	Single-family house
Andalucía	-52%	-46%	-51%	-45%
Aragón	-27%	-26%	-27%	-26%
Asturias	-30%	-28%	-30%	-28%
Baleares	-58%	-51%	-58%	-51%
Canarias	-74%	-61%	-74%	-61%
Cantabria	-34%	-32%	-34%	-32%
Castilla y León	-25%	-24%	-25%	-24%
Castilla - La Mancha	-27%	-26%	-27%	-26%
Cataluña	-34%	-32%	-34%	-31%
C. Valenciana	-51%	-45%	-50%	-45%
Extremadura	-34%	-31%	-34%	-31%
Galicia	-32%	-30%	-32%	-30%
Madrid	-27%	-26%	-27%	-26%
Murcia	-48%	-43%	-48%	-42%
Navarra	-27%	-26%	-27%	-26%
País Vasco	-31%	-29%	-31%	-29%
La Rioja	-27%	-25%	-27%	-25%
Melilla	-78%	-64%	-78%	-64%
Ceuta	-58%	-51%	-58%	-51%

Table A 40. Regional weighted specific demand for heating [kWh/(m^2 year)] using 16°C as baseline temperature (minimum healthy-temperature heating demand) per aggregated construction period and dwelling type

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	Single-family house	Block dwelling	Single-family house
Andalucía	13.89	23.65	7.76	13.68
Aragón	66.45	92.03	37.89	54.72
Asturias	51.91	73.57	29.42	43.81
Baleares	4.63	16.88	2.49	9.29
Canarias	0.75	1.31	0.40	0.72
Cantabria	37.40	56.28	20.99	32.89
Castilla y León	82.12	111.26	47.09	66.32
Castilla - La Mancha	64.82	89.66	36.93	53.52
Cataluña	38.81	57.99	21.84	34.02
C. Valenciana	11.92	25.58	6.61	14.54
Extremadura	39.37	58.31	22.13	34.38
Galicia	44.04	64.41	24.85	37.89
Madrid	66.81	92.53	38.09	55.02
Murcia	15.19	29.66	8.47	16.94
Navarra	66.72	91.80	38.04	54.94
País Vasco	50.11	71.94	28.38	42.46
La Rioja	67.68	93.69	38.60	55.67
Melilla	1.39	1.25	0.72	0.65
Ceuta	4.57	16.76	2.46	9.25

Table A 41. Relative difference [%] between the regional weighted values of the minimum healthy-temperature heating demand (16°C as baseline temperature) and the required heating demand (20°C as baseline temperature), per aggregated construction period

Region	≥ 25 years ago		< 25 years ago	
	Block dwelling	Single-family house	Block dwelling	Single-family house
Andalucía	-78%	-74%	-78%	-73%
Aragón	-50%	-47%	-50%	-47%
Asturias	-55%	-51%	-55%	-51%
Baleares	-92%	-80%	-92%	-80%
Canarias	-95%	-95%	-95%	-94%
Cantabria	-61%	-56%	-61%	-56%
Castilla y León	-46%	-44%	-46%	-44%
Castilla - La Mancha	-50%	-48%	-50%	-48%
Cataluña	-60%	-56%	-60%	-56%
C. Valenciana	-82%	-73%	-82%	-72%
Extremadura	-60%	-55%	-60%	-55%
Galicia	-58%	-54%	-58%	-54%
Madrid	-50%	-47%	-50%	-47%
Murcia	-79%	-70%	-78%	-70%
Navarra	-50%	-47%	-50%	-47%
País Vasco	-55%	-52%	-55%	-52%
La Rioja	-50%	-47%	-50%	-47%
Melilla	-97%	-98%	-97%	-98%
Ceuta	-92%	-80%	-92%	-80%

Appendix H. Working conditions of the GHP

Table A 42. Working characteristics of the 75 kWth GHP [311]

Outdoor temperature (°C)	Charge rating (%)	HVAC capacity (kW)	Consumed power (kW)	DHW (kW)
35	100%	63.5	55	27.55
35	90%	57.1	47.5	23.75
35	80%	50.7	404.4	20.2
35	70%	44.3	34.8	17.4
35	60%	38	29.2	14.6
35	50%	31.6	23.9	11.95
35	40%	25.2	18.8	9.4
35	30%	18.9	13.6	6.8
27	100%	71	53.1	26.55
27	90%	63.9	46.4	23.2
27	80%	56.9	39.7	19.85
27	70%	49.8	33	16.5
27	60%	42.6	27.1	13.55
27	50%	35.4	21.4	10.7
27	40%	28.3	46.4	8.2
27	30%	21.2	11.5	5.75
22	100%	75.7	51.9	25.93
22	90%	68.13	45.12	22.56
22	80%	60.56	38.09	29.04
22	70%	53.2	31.9	15.94
22	60%	45.42	25.4	12.7
22	50%	37.8	19.8	9.92
22	40%	30.28	14.68	7.34
22	30%	22.6	10.2	5.09
19	100%	78.5	51.1	25.55
19	90%	70.65	43.8	21.94
19	80%	62.8	37.16	18.58
19	70%	53.2	30.02	15.6
19	60%	47.1	14.49	12.24
19	50%	37.8	18.23	9.45
19	40%	31.4	13.73	6.86

19	30%	22.6	9.04	4.7
12	100%	74.5	49	14.7
12	90%	66.9	43.1	12.93
12	80%	59.3	37.2	11.16
12	70%	52.1	32.1	9.63
12	60%	44.8	27	8.1
12	50%	37.6	21.9	6.57
12	40%	29.9	17.2	5.16
12	30%	22.1	12.6	3.78
7	100%	75	53.6	13.4
7	90%	67.4	47.5	11.88
7	80%	59.8	41.4	10.35
7	70%	52.4	35.4	8.85
7	60%	45	29.3	7.33
7	50%	37.6	23.7	5.93
7	40%	30.2	18.9	4.73
7	30%	22.8	14	3.5
2	100%	73	63.5	0
2	90%	65.8	56	0
2	80%	58.6	48.5	0
2	70%	51.2	41.4	0
2	60%	47.7	34	0
2	50%	36.4	27.4	0
2	40%	29.3	21.7	0
2	30%	23	16.6	0
-7	100%	66.5	72.5	0
-7	90%	59.9	63.6	0
-7	80%	53.3	54.7	0
-7	70%	46.6	46.5	0
-7	60%	39.9	38.9	0
-7	50%	33.3	31.3	0
-7	40%	26.6	23.7	0

Table A 43. Working characteristics of the 25 kWth GHP [311]

Outdoor temperature (°C)	Charge rating (%)	HVAC capacity (kW)	Consumed power (kW)	DHW (kW)
40	100%	21.1	15.98	8
40	90%	19	14.17	7.1
40	80%	16.9	12.51	6.25
40	70%	14.8	10.88	5.45
40	60%	12.7	9.477	4.75
40	50%	10.6	8.617	4.3
35	100%	22.4	15.03	7.5
35	90%	20.2	13.03	6.5
35	80%	17.9	11.47	5.75
35	70%	15.7	10	5
35	60%	13.4	8.701	4.35
35	50%	11.2	7.887	3.95
30	100%	23.7	13.62	6.8
30	90%	21.3	11.89	5.95
30	80%	18.9	10.5	5.25
30	70%	16.5	9.217	4.6
30	60%	14.2	7.888	3.95
30	50%	11.8	7.195	3.6
25	100%	24.9	12.38	6.2
25	90%	22.4	10.87	5.45
25	80%	19.9	9.521	4.75
25	70%	17.4	8.285	4.15
25	60%	14.9	7.303	3.65
25	50%	12.4	6.595	3.3
15	100%	24.3	11.79	4.01
15	90%	21.7	10.48	3.57
15	80%	19.3	9.698	3.3
15	70%	16.8	9.6	3.26
15	60%	14.3	9.597	3.26
15	50%	11.9	8.5	2.89
11	100%	24.6	13.59	4.08
11	90%	22.1	12.20	3.66
11	80%	19.6	10.82	3.24

11	70%	17.1	9.884	2.97
11	60%	14.6	9.798	2.94
11	50%	12.1	9.603	2.88
6	100%	25	15.92	3.98
6	90%	22.5	14.42	3.6
6	80%	19.9	12.92	3.23
6	70%	17.4	11.29	2.83
6	60%	14.9	10.06	2.53
6	50%	12.4	9.92	2.53
1	100%	26.5	21.72	2.48
1	90%	23.85	19.71	0
1	80%	21.09	17.57	0
1	70%	18.44	15.36	0
1	60%	15.79	13.73	0
1	50%	13.14	13.54	0
-2	100%	26.5	25.48	0
-2	90%	23.85	22.93	0
-2	80%	21.09	20.67	0
-2	70%	18.44	18.07	0
-2	60%	15.79	16.11	0
-2	50%	13.14	15.83	0
-7	100%	26.5	27.04	0
-7	90%	23.85	24.58	0
-7	80%	21.09	21.96	0
-7	70%	18.44	19.20	0
-7	60%	15.79	17.16	0
-7	50%	13.14	16.84	0

Appendix I. Thermal Energy Cheque annual budget

The TEC annual budget for each Spanish province has been assessed by applying the results shown in Fig. 3. 5 to Eq. (6.1). The 2019 budget estimation is described hereafter (the same methodology was applied also to 2021). The number of households who benefited from the subsidy in each province, provided by the Ministry for the Ecological Transition and the National Commission on Markets and Competition in response to two different inquiries [285], [320] was used to quantify the provincial budgets that would have been required for 2019. Finally, the national TEC budget was estimated summing up all the provincial ones.

Table A. 1 shows the distribution of the proposed TEC-annual-budget (Scenario AT) among the Spanish provinces, divided depending on the vulnerability level. In 2019, the subsidy's beneficiaries were 7% of the Spanish households but they were not equally spread among all provinces. The greater relative percentages of TSA-beneficiaries were accounted in three regions: *Castilla y León, Castilla–La Mancha and Extremadura*. The first two ones, i.e. the inland regions bordering the province of Madrid in Fig. 3. 5, are the coldest regions in Spain and the last one is the region with the higher percentage of consumers at risk of social exclusion.

In Scenario AT, 59% of TEC-annual-budget would be assigned to severely vulnerable consumers. This category consists of almost the same number of households as the vulnerable one, but it has a higher cheque assigned (as shown in Fig. 6. 1), which determines a greater annual budget.

Table A 44. Distribution of the proposed TEC-annual-budget (Scenario AT) among the Spanish provinces (grouped into regions) per consumer category (from [236]*)*

Region	**Province**	**Vulnerable consumers (fv = 25%)**	**Severely vulnerable consumers (fv = 40%)**	**Consumers at risk of social exclusion (fv = 100%)**
ANDALUCÍA	ALMERÍA	€ 1,885,490	€ 2,901,120	€ 0
	CÁDIZ	€ 3,103,657	€ 4,581,067	€ 9,149
	CÓRDOBA	€ 3,414,191	€ 5,131,644	€ 1,850
	GRANADA	€ 4,729,375	€ 7,546,989	€ 1,137
	HUELVA	€ 1,402,168	€ 1,978,118	€ 0
	JAÉN	€ 4,566,330	€ 7,379,520	€ 0
	MÁLAGA	€ 3,780,110	€ 6,120,121	€ 155,027
	SEVILLA	€ 6,784,343	€ 9,195,054	€ 5,905
ARAGÓN	HUESCA	€ 1,124,411	€ 1,678,694	€ 0
	TERUEL	€ 803,584	€ 1,433,823	€ 1,569
	ZARAGOZA	€ 3,492,031	€ 6,195,654	€ 1,103
ASTURIAS, PRINCIPADO DE	ASTURIAS	€ 3,614,776	€ 8,235,491	€ 8,564
BALEARS, ILLES	BALEARS, ILLES	€ 2,196,435	€ 2,405,437	€ 0
CANARIAS	PALMAS, LAS	€ 599,498	€ 901,642	€ 0
	SANTA CRUZ DE TENERIFE	€ 875,089	€ 1,306,996	€ 0
CANTABRIA	CANTABRIA	€ 1,476,093	€ 2,511,231	€ 0
CASTILLA Y LEÓN	ÁVILA	€ 1,553,536	€ 2,800,799	€ 0
	BURGOS	€ 2,373,385	€ 3,858,388	€ 0
	LEÓN	€ 3,269,558	€ 5,851,619	€ 0
	PALENCIA	€ 1,317,492	€ 2,111,927	€ 0
	SALAMANCA	€ 3,133,370	€ 5,140,541	€ 0
	SEGOVIA	€ 964,419	€ 1,624,832	€ 0
	SORIA	€ 639,880	€ 1,159,426	€ 0
	VALLADOLID	€ 3,140,763	€ 4,966,607	€ 0
	ZAMORA	€ 1,708,449	€ 3,030,704	€ 0
CASTILLA-LA MANCHA	ALBACETE	€ 3,593,881	€ 6,185,409	€ 0
	CIUDAD REAL	€ 4,045,005	€ 6,797,360	€ 0
	CUENCA	€ 2,577,308	€ 4,349,898	€ 0
	GUADALAJARA	€ 1,321,097	€ 1,851,734	€ 1,516
	TOLEDO	€ 4,943,045	€ 8,058,572	€ 0
CATALUÑA	BARCELONA	€ 13,939,201	€ 17,670,805	€ 68,913
	GIRONA	€ 1,866,602	€ 2,479,070	€ 7,752
	LLEIDA	€ 1,363,877	€ 1,975,628	€ 8,778
	TARRAGONA	€ 1,891,618	€ 2,895,783	€ 2,555
COMUNITAT VALENCIANA	ALICANTE/ALACANT	€ 6,245,388	€ 11,004,468	€ 50,466
	CASTELLÓN/CASTELLÓ	€ 1,766,085	€ 2,943,050	€ 0
	VALENCIA/VALÈNCIA	€ 9,368,735	€ 16,058,289	€ 15,752
EXTREMADURA	BADAJOZ	€ 5,922,808	€ 9,021,039	€ 2,217,456
	CÁCERES	€ 2,682,013	€ 4,292,338	€ 727,499
GALICIA	CORUÑA, A	€ 5,118,233	€ 7,849,609	€ 1,461,103
	LUGO	€ 1,708,642	€ 2,820,135	€ 598,270
	OURENSE	€ 2,129,735	€ 3,723,586	€ 516,771
	PONTEVEDRA	€ 3,587,011	€ 5,672,807	€ 1,332,510
MADRID, COMUNIDAD DE	MADRID	€ 23,996,373	€ 29,958,773	€ 12,186
MURCIA, REGIÓN DE	MURCIA	€ 5,301,986	€ 7,296,513	€ 11,729
NAVARRA, COMUNIDAD	NAVARRA	€ 4,308,318	€ 3,178,358	€ 0
PAÍS VASCO	ARABA/ÁLAVA	€ 1,338,389	€ 1,616,417	€ 0
	BIZKAIA	€ 3,418,282	€ 5,176,418	€ 0
	GIPUZKOA	€ 2,685,352	€ 2,263,287	€ 1,123
RIOJA, LA	RIOJA, LA	€ 1,667,601	€ 3,035,181	€ 2,691
CEUTA	MELILLA	€ 12,130	€ 4,266	€ 0
MELILLA	CEUTA	€ 131,449	€ 197,257	€ 0
TOTAL		€ 178,878,597	€ 268,423,493	€ 7,221,374