Unitat d'Història Econòmica
Departament d'Economia i d'Història Econòmica
Facultat d'Economia i Empresa
Universitat Autònoma de Barcelona

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Jesús Ramos-Martín[1, 2] and Shigeru Matsumoto[3]

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(1) Unitat d'Història Econòmica
Departament d'Economia i d'Història Econòmica
Universitat Autònoma de Barcelona
08193 Bellaterra, Spain
E-mail: jesus.ramos@uab.cat

(2) Institut de Ciència i Tecnologia Ambientals
Universitat Autònoma de Barcelona
08193 Bellaterra, Spain

(3) Department of Economics
Aoyama Gakuin University
Tokyo, 150-8366, Japan
E-mail: shmatsumoto@aoyamagakuin.jp

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Edifici B – Campus de Bellaterra
08193 Cerdanyola del Vallès, Barcelona, Spain
Tel.:(+34) 935811203; Fax: (+34) 935812012
http://www.h-economica.uab.cat

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Unitat d'Història Econòmica
Departament d'Economia i d'Història Econòmica
Edifici B, Campus UAB
08193 Cerdanyola del Vallès, Spain
Tel: (+34) 935811203
http://www.h-economica.uab.cat/

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Jesús Ramos-Martín[1, 2] and Shigeru Matsumoto[3]

(1) Departament d'Economia i d'Història Econòmica, Universitat Autònoma de Barcelona, Spain.

(2) Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Spain.

(3) Department of Economics, Aoyama Gakuin University, Japan.

Abstract

Residential energy consumption remains challenging to analyze due to its heterogeneity and evolving demographic trends. Population aging and declining household sizes alter energy demand, potentially offsetting efficiency gains. However, most studies fail to disaggregate energy use by household type over time, creating a research gap in understanding how demographic changes impact residential energy demand.

This study integrates demographic data from the Population and Housing Census with micro-level household energy consumption data from the Household Budget Survey (2006–2023). Using the Integrated Analysis of Demographic and Consumption Profile (IADCP) method, we quantify the impact of changes in household composition on energy demand. This approach allows us to isolate the effects of technological advancements, population growth, and shifts in household structure on energy consumption trends.

Findings reveal that while technological advancements and behavioral changes have led to notable energy efficiency gains, demographic changes have largely offset these benefits, leading to an energy efficiency loss due to household composition change of 3.31%. The increase in the number of households has a more profound effect in the Mediterranean region, whereas changes in household composition, with smaller and older households, exert a greater influence in the North Atlantic region.

This research contributes to energy policy by demonstrating the necessity of integrating demographic factors into efficiency strategies. Policies should prioritize energy-efficient housing, co-housing models, and behavioral interventions to mitigate the adverse effects of demographic shifts on residential energy demand.

Keywords: Households, residential energy consumption, household types, household budget survey, ageing

JEL codes: D10, I31, J11, Q41, Q57

1.Introduction

Like many other countries, Spain is undergoing an energy transition aimed at decarbonizing its economy through increased electrification and the extensive use of renewable energy sources (MITECO 2024a). While changes in energy consumption are relatively straightforward to analyze in the energy and industrial sectors, the residential and transport sectors exhibit diffuse energy consumption patterns due to the involvement of numerous actors. Demographic changes, particularly population aging and declining household sizes, are inherently linked to the energy transition, influencing household energy consumption dynamics. Despite a growing body of literature on this topic, several aspects remain understudied.

As populations age and average household sizes decrease, the resulting loss of economies of scale may offset efficiency gains (Schröder et al. 2015; Wu et al. 2021). Analyzing data from Spain's energy balances, we observe that the country's total final energy consumption declined by 15% between 2006 and 2023. In the residential sector, total final energy consumption fell by 11.22%, a smaller decline than in the overall economy. Consequently, the residential sector accounted for 17.85% of total final energy consumption in 2023, down from a peak of 19.91% in 2020 during the COVID-19 lockdown but up from 17.09% in 2006 (MITECO 2024b).

This increasing share of the residential sector in final energy consumption, particularly in electricity consumption, warrants further analysis. The residential sector is highly heterogeneous and plays a fundamental societal role, as it ensures the reproduction of human life and, by extension, economic activity and labor supply. Although it is not the main energy-consuming sector, understanding its energy metabolism is crucial for comprehending the broader energy dynamics of society. From a societal metabolic perspective, households engage in activities that support both their own reproduction and the functioning of other economic sectors, including industry and services, through the consumption of final goods (Pérez-Sánchez et al. 2022). However, due to the sector's diffuseness and the diversity of its actors, most studies analyze it in an aggregated manner without disaggregating consumption patterns by household size or type. This presents a challenge for policy recommendations since, as noted by Wang and Matsumoto (2021) in the case of Japan, progress in energy conservation measures in the household sector is much slower compared to industry and other sectors. This is why we present in this study an application of a new methodology that allows us to analyze how different household types have different energy consumption patterns, and how changes in the distribution of household types explain an important part of the evolution of residential energy consumption.

Some studies in the field of societal metabolism primarily focus on analyzing consumption patterns to characterize energy flows and establish benchmark values for various sectors without disaggregating them into their lower-level compartments (Giampietro et al. 2012; Ginard-Bosch and Ramos-Martín 2016; Ramos-Martín et al. 2009; Recalde and Ramos-Martin 2012; Sorman and Giampietro 2013). This is also the case for some modeling exercises, such as De Blas et al. (de Blas et al. 2019), who employ the MEDEAS integrated assessment framework to model sectoral energy demand using energy intensities, integrating input-output analysis with system dynamics. Another example is the official Integrated National Energy and Climate Plan of Spain (MITECO 2024a), which sets policy targets for the energy transition in Spain and incorporates an economic impact assessment of these targets using the DENIO model—a Dynamic Econometric Neo-Keynesian Input-Output model of the Spanish economy that combines elements of input-output econometrics with computable general equilibrium (CGE) modeling (Arto et al. 2021). More recent examples include Salim et al. (Salim et al. 2025), who utilize the newly developed TIMES-Europe energy system model to examine the role of the residential sector in meeting the EU's ambitious energy savings targets within the broader Fit-for-55 policy framework. Even recent advancements in energy systems modeling that incorporate traditionally underrepresented nexus elements of social-ecological systems, such as land use, water consumption, and human time allocation (Di Felice et al. 2024), tend to analyze the household sector in aggregate terms without disaggregating it into its lower-level compartments, such as household types. This limitation restricts a more nuanced understanding of how different household structures contribute to overall energy consumption patterns. Conversely, other studies disaggregate household energy consumption based on household size, income, and other socio-economic variables but often do not analyze changes in household composition over time (Aldás and Solaz 2019; Labandeira et al. 2006).

While these studies provide valuable insights and serve as a foundation for our research, our primary objective is to analyze the temporal evolution of household composition and its impact on residential energy consumption. In this study, we propose a bottom-up method we have called “Integrated Analysis of Demographic and Consumption Profile (IADCP)” to quantitatively analyze the impact of changes in household composition on the demand for goods. We then apply the method to analyze the particular case of energy consumption, to assess the impact of demographic changes on household energy consumption by integrating population data with micro-level data on household energy use. The method employs an approximation method based on the distribution function of energy consumption to analyze consumption patterns more effectively. We argue that this approach will enhance our understanding of household consumption, build more robust scenarios, and facilitate the development of more tailored policies to mitigate the environmental impact of household metabolism. Consequently, this study disaggregates residential energy consumption based on household composition and climatic zones from 2006 to 2023, utilizing microdata from the Household Budget Survey and the Population and Housing Census.

The findings enable a discussion on potential future trends in residential energy consumption based on the evolving distribution of household types. This study also proposes economic policy recommendations to enhance household energy efficiency. By distinguishing between households led by active versus non-active breadwinners, this research facilitates dialogue with other studies in the energy metabolism framework (Pérez-Sánchez et al. 2022), which employ the MuSIASEM approach to examine the nexus between energy, materials, space, and time in the residential sector.

The remainder of this article is structured as follows: Section 2 presents a brief review of related literature. Section 3 describes the data sources, scope, and methodology. Section 4 presents the results of our estimation of residential energy consumption patterns affected by changes in the distribution of household types, followed by a discussion in Section 5 that relates our findings to existing literature, and that also offers conclusions and policy recommendations.

2. Related literature

In this section, we present a selection of literature related to some of the topics investigated in this article. Readers can find elsewhere more extensive literature reviews on household metabolism (Di Donato et al. 2015), residential energy consumption (Han and Wei 2021; Inoue et al. 2024; Ma et al. 2019; Salami et al. 2023), modeling approaches used to analyze residential energy consumption (Nacht et al. 2023), the influence of urban design and density on residential energy consumption (Narimani Abar et al. 2023), and policy measures aimed at reducing residential energy consumption (Quintana and Cansino 2023).

The increase in population drives the formation of new households. While the share of residential energy consumption has increased globally over time (Matsumoto et al. 2022), per-household energy consumption has declined in certain regions, including China (Chen et al.

2021, 2025) and Spain (MITECO 2022). In Spain, this decline has been evident since 2005, particularly in thermal energy use. The trend was further exacerbated after 2008 due to the economic crisis, which constrained household income and spending capacity, leading to shifts in consumption behavior.

When analyzing the evolution of households, there is a trend towards smaller household size around the world (United Nations. Department of Economic and Social Affairs. Population Division 2017). This reflects lower fertility rates, higher life expectancy but also socio-economic variables such as housing affordability. This is found for Spain (Aldás and Solaz 2019; Inoue and Velasco-Fernández 2025), China (Chen et al. 2021, 2025), the EU-27 (Deuster et al. 2023), and worldwide (Esteve et al. 2024). This latter study finds that the decrease in household size is primarily related to the decline in the number of children in the household, explaining two thirds of the decline in recent decades, and having the implication of reducing the so-called family economies, which are important to explain residential energy consumption. For instance, Wu et al., (Wu et al. 2021), using nationally representative household survey panels from 2010 to 2016 for China, identified substantial household scale economies in electricity consumption. Specifically, reducing household size by one would incur in a 17.0-23.6% increase in electricity consumption per capita. In the same line, Schröder et al. (Schröder et al. 2015) used data from Japanese households to estimate that a 5% reduction in average household size between 2005 and 2010 led to a loss of household economies of scale, which was comparable to a 3.5% rise in household energy demand. The decrease in household size and the increase in the number of households not only affects consumption patterns of households but may affect the types of dwellings being constructed too (Mulder 2006).

This decrease in household size is also explained by an increase in the trend of living alone, starting toward the end of the twentieth century. This is more evident in areas with higher development levels, and actually, the more developed a country is, the higher the levels of solo living (Esteve et al. 2020; Esteve and Reher 2024; Reher and Requena 2018). The incidence, however, is different by age groups. Among young adults (25–29), the incidence of living alone is invariably higher among men, especially among men living in the developed world. Among mature adults (50–54), the incidence of living alone is mostly higher among men. Among the elderly (75–79), the incidence of living alone is often two to three times higher than among mature adults, and it is far higher among women than among men, due for the most part to differential mortality at those ages (Esteve et al. 2020).

Empirical studies consistently demonstrate a positive correlation between aging and energy consumption. In the case of the United States, O'Neill and Chen (O'Neill and Chen 2002) identify a clear pattern of increasing per capita energy consumption with age. Their findings distinguish between residential energy use, which rises steadily with age, and transportation energy use, which peaks at ages 51–55 before declining sharply in older age groups. Similarly, Estiri and Zagheni (Estiri and Zagheni 2019) confirm this upward trend in energy consumption among older adults, even after controlling for factors such as income, local climate, and housing characteristics (including age, type, and square footage). Notably, their study highlights a significant increase in energy consumption after age 70, particularly in warmer climates where energy demand intensifies. A similar result is found for the EU-27 (Deuster et al. 2023), which shows that when controlling for income, household size and place of residence, emissions from energy consumption tend to increase with age.

Evidence from China aligns with these findings (Yuan et al. 2024; Zeng et al. 2021). Similar trends are observed in other countries, like Italy (Bardazzi and Pazienza 2017), or Japan (Inoue et al. 2022). The latter study also shows that while younger cohorts tend to consume less energy, the aging and family structure effects—particularly the increasing number of dwellings—more than offset this decline. Additionally, Labandeira et al. (Labandeira et al. 2006) find a positive relationship between retirement and household energy expenditures in Spain, which they attribute to older individuals spending more time at home, thereby increasing their energy use.

Urbanization influences energy consumption patterns by promoting a shift toward more efficient and less polluting energy carriers, such as electricity and natural gas, in line with the energy ladder concept (Grubler and Hogan 2013). This transition has been observed in China (Chen et al. 2021) and Spain, where liquefied petroleum gas (LPG) played a crucial role during the rapid and unregulated urbanization of the 1960s and 1970s, driven by high inward migration (Bartolomé Rodríguez and Gutiérrez-González 2024). Between 1960 and 1979, LPG use in Spain increased from a marginal 0.08 percent to a substantial 4.1 percent of the final energy consumption at a time when the latter had tripled (Muñoz-Delgado and Rubio-Varas 2024). Urbanization also impacts overall household energy consumption. In China, the transition from rural to urban living has led to a net reduction in average household energy consumption, as rural households historically consumed more energy, and their decline in demand outweighed increases in urban areas due to higher living standards (Chen et al. 2021). However, other studies have found that urban household electricity consumption is growing at a faster rate than in rural areas (Nie et al. 2024).

In Spain, electricity consumption patterns also vary by urbanization level. Households in small cities and rural areas tend to consume more electricity than those in large cities, with detached and semi-detached houses using significantly more than apartments or other attached housing (Lasarte Navamuel et al. 2018). Moreover, urban sprawl has a notable effect, particularly among high-income households. This finding was later reinforced by a study incorporating a sprawl index, which demonstrated that in Spain's largest cities and along the Mediterranean coast, greater sprawl is associated with higher electricity consumption (Cartone et al. 2021).

Spain's demographic and spatial distribution presents a unique context at the intersection of aging and the rural-urban divide, significantly shaping residential household energy consumption. Nearly 90% of Spain's territory is uninhabited, with population highly concentrated along the Mediterranean coast and in Madrid (Gutiérrez et al. 2023). This uneven distribution is reflected in municipal demographics: 61.5% of municipalities have fewer than 1,000 residents, and nearly half (48.4%) have a population density below 15.5 inhabitants per square kilometer—the threshold set by the European Union for identifying areas at risk of depopulation—while collectively housing only 2.3% of the population. Furthermore, in 25% of municipalities, the retired population outnumbers the working population, and in 9% of municipalities, more than 30% of residents are over the age of 75 (FUHEM 2023). These demographic trends underscore the necessity of incorporating a regional perspective – particularly the rural-urban divide – into analyses of household energy consumption.

The literature reviewed highlights the multifaceted factors influencing residential energy consumption in general, and in Spain, including demographic shifts, urbanization trends, and household size dynamics. These insights provide a critical foundation for our study, which aims to empirically examine these relationships using robust data sources and analytical techniques. In the following section, we outline the methodology and the data employed in our analysis of the impact of demographic changes on residential energy consumption.

3. Methods and Data

3.1. Integrated Analysis of Demographic and Consumption Profile

Consumption and population surveys are conducted in many countries. The former involves collecting data from sampled households regarding their expenditure and consumption volume over a specified period, while the latter focuses on gathering information about household composition. By integrating these two types of survey data, we propose a bottom-up method called "Integrated Analysis of Demographic and Consumption Profile (IADCP)" to quantitatively analyze the impact of changes in household composition on the demand for goods.

In conventional demand analysis based on expenditure data, researchers assess the influence of household income and the prices of goods on consumption patterns, followed by examining the effects of household characteristics on demand. This analysis frequently involves parameterizing the household demand function (Baker et al. 1989; Deaton and Muellbauer 1980). While such a parametric approach effectively estimates key economic indicators such as income and price elasticities, household demand for goods remains highly complex. Indeed, even when a comprehensive set of household characteristics is considered, only a limited portion of the variation in demand can typically be explained. This is one reason why recent research has increasingly employed quantile regression analysis (Huang 2015; Kaza 2010; Kim 2020). Furthermore, substantial heterogeneity exists even among households with identical characteristics.

Given these challenges, this study proposes an alternative methodology to examine the effects of household composition changes on demand for goods using the following procedure:

1) Classify households into distinct groups.

2) Analyze the distribution of goods consumption across household groups.

3) Approximate the distribution of goods consumption using a probability density function to extract relevant information.

4) Integrate the approximated distribution with census data to quantify the effects of household composition changes on demand for goods.

The total consumption for household group g in each region r during sampling period t is determined using the following equation:

$$E[TC^{g,r,t}] = \left[\sum_k \pi^{g,r,t}\left(c_{k,k+1}\right) \cdot \bar{c}_{k,k+1}\right] \cdot s^{g,r,t} \cdot N^{r,t} = E[C^{g,r,t}] \cdot s^{g,r,t} \cdot N^{r,t}. \qquad (1)$$

$\pi^{g,r,t}\left(c_{k,k+1}\right)$ represents the probability that the goods consumption of a household of group g in region r during sampling period t falls within the interval $[c_k, c_{k+1}]$. The term $\bar{c}_{k,k+1} = (c_k + c_{k+1})/2$ represents the midpoint of the interval, and thus, the expression within square brackets, $E[C^{g,r,t}]$, denotes the expected goods consumption for households of group g in region r during sampling period t. The total consumption of group g, $E[TC^{g,r,t}]$, was obtained by multiplying the expected goods consumption, $E[C^{g,r,t}]$, by the number of households, $s^{g,r,t} \cdot N^{r,t}$, where $s^{g,r,t}$ and $N^{r,t}$ are the share of group g and the total number of households in region r during sampling period t.

The total goods consumption in region r can be determined by aggregating the goods consumption across all household groups,

$$E[C^{r,t}] = \sum_g E[C^{g,r,t}] \cdot s^{g,r,t} \cdot N^{r,t}. \qquad (2)$$

The IADCP model, utilizing Equations (1) and (2), assumes that the distribution of goods consumption is independent of the demographic profile and does not consider potential consumption-related externalities or supply-side responses to changes in the number of households. Under this independence assumption, the impact of demographic shifts on consumption patterns can be assessed by modifying $s^{g,r,t} \cdot N^{r,t}$.

3.2. Description of data and summary statistics

In the following sections, we apply the analytical framework outlined above to assess the impact of changes in Spain's demographic structure on energy consumption patterns. We utilize data from the Population and Housing Censuses (2001, 2011, 2021) and the Household Budget Survey (2006–2023), both provided by Spain's National Statistics Institute. The census is conducted every 10 years, while the Household Budget Survey has been conducted annually since 2006.

According to the census data, Spain's population increased by approximately 16%, from 40.84 million in 2001 to 47.4 million in 2021. Over the same period, households grew by about 30.1%, from 14.19 million to 18.54 million. As a result, the average household size declined from 2.88 to 2.56, reflecting a trend towards smaller households. The demographic composition also shifted, with the proportion of children under 16 decreasing slightly from 15.6% to 15.2%, the working-age population declining from 67.3% to 65.1%, and the elderly population (65+) increasing from 17.0% to 19.6%, highlighting ongoing trends of low birth rates and an aging society, which is only mitigated by immigration. Between 2001 and 2011 residents with foreign nationality grew from 1.54 million to 5.24 million, that is from representing 3.79% of population to 11.20%. Moreover, while residents with Spanish nationality in working age represented 65% of total population in 2011, 79.8% of foreign residents were in working age, contributing more to the labor force in relative terms than nationals. These values barely changed in 2021, with 5.4 million foreign residents, representing 11.4% of the population, 75.7% of them in working age. So, without this large inflow of immigrants, which explains a large part of the increase in the number of households, Spain's demographic structure would have shifted more acutely towards even more households with senior people, in relative terms.

Table 1 Near Here

Given the limitations of census data, we classify households into 9 types and compare their energy consumption patterns. The types we have selected reflect on the one hand our interest in single-member households, and on the other hand the interest in analyzing households conformed basically by working-age population versus those with dependent population (seniors and minors). Table 1 presents the national-level distribution of these household types, highlighting key demographic shifts: First, an increase in single-person households that go from representing 20.3% of total households in 2001 to 27% in 2021. Within this type, both single working age and single senior have increased in total number of households and as a share of the total, although single working-age has risen faster, indicating an increasing trend of living solo, as we mentioned in Section 2. Second, there is a decline in larger households. Third, there is a rise in households with seniors.[1] Conversely, the number of households with children has decreased.

The Household Budget Survey collects annual expenditure and purchase volume data from approximately 20,000 households, including energy consumption details. This study examines household energy use, specifically electricity, city and natural gas, liquid gas, and liquid fuel. Using conversion factors detailed in Appendix A1, we convert these energy sources into primary energy equivalent measured in megajoules (MJ). Energy consumption includes that of secondary residences where it applies, while households with missing data on energy consumption are excluded. To improve data accuracy, we also have removed the top and bottom 5% of households in terms of energy consumption.

We use the pooled data from Sampling Period 1 (2006–2008) and Sampling Period 2 (2021–2023) for two main reasons. First, the global financial crisis of 2007-08 and the COVID-19 pandemic significantly impacted household energy consumption. During these periods, increased unemployment and time spent at home due to lockdowns affected household energy use (Romero-Jordán et al. 2016; Zapata-Webborn et al. 2023). To minimize these distortions and better capture

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[1] In Table 1, the term 'minor' refers to individuals under the age of 16, 'working age' includes those aged 16 to 64, and 'senior' refers to individuals aged 65 and over. The term 'adults' encompasses both 'working age' and 'senior' groups, meaning it includes all individuals aged 16 and over.

the effects of demographic changes, we have excluded years when these events had a strong influence. Second, household energy consumption is susceptible to weather conditions. We reduce the risk of data selection bias due to extreme weather conditions by analyzing three-year periods rather than single years.

Figure 1 Near Here

Figure 1 illustrates the distributions of total annual energy consumption (MJ) at the national level by household type during Sampling Period 1.[2] The horizontal axis is presented in a logarithmic scale to enhance visualization. The solid curve represents an approximation using a normal distribution, which closely aligns with the shape of the histogram. This suggests that total annual household energy consumption itself follows a log-normal distribution.

Figure 2 Near Here

Following a study by Spain's Institute for Energy Diversification and Savings (IDAE 2011), the country was divided into three climate zones (North Atlantic, Continental, and Mediterranean), see Appendix A2. In the above data, the provinces of Lérida, Orense, and Álava are classified as part of the Continental region. However, since the household budget survey only identifies respondents' residence at the Autonomous Community level, Lérida is classified under the Mediterranean region while Orense and Álava are classified under the North Atlantic region. See Figure 2.

Table 2 Near Here

Table 2 presents the changes in average energy consumption (measured in MJ) by household type from Sampling Period 1 to Sampling Period 2, both at the national level and across meteorological regions. Several key observations can be drawn from the table.

First, according to our estimates, there has been a reduction in the average consumption by households of 26% in the period. The average annual energy consumption of Spanish households in Sampling Period 2 was 39,814 MJ. According to IDAE (2024), in 2021, a typical household would consume 3,695 kWh for heating, 92 kWh for cooling, 2,439 kWh for home appliances, 1,829 kWh for hot water, 731 kWh for cooking, and 463 kWh for lighting. This results in total

[2] Total energy consumption is defined as the sum of all electricity consumed in both the main and secondary houses, along with the total consumption of city gas, natural gas, liquefied gas, and liquid fuel.

annual energy consumption of 33,308 MJ. The differences may be due to second-dwelling consumption not estimated.

Second, energy consumption increases with household size; however, due to the shared use of energy services among household members and the presence of economies of scale, the increase in energy consumption is lower than the increase in household size. Households with elderly members consume more energy than those composed solely of the working-age population. In contrast, the rise in energy consumption associated with the presence of children is lower than that observed for adults.

Third, energy consumption varies significantly across meteorological regions. The highest levels are observed in the Continental region, characterized by sharp contrasts between winter and summer and which shows values 25% higher than the other two regions, the North Atlantic and the Mediterranean, which benefit from milder weather thanks to their proximity to the sea. Substantial regional disparities in energy consumption are evident across all household types.

Finally, during the survey period, energy consumption decreased overall for most household types. However, energy consumption did not decrease much for households with elderly people, and it increased for North Atlantic households.

4. An Application of IADCP to Energy Consumption in Spanish Households

4.1. Estimating residential energy use: a bottom-up approach

Following the methodology outlined in the previous section, we analyzed the changes in household energy consumption between Sampling Periods 1 and 2. The baseline cases, summarized in Table 3, reveal several key insights.

Table 3 Near Here

At the gross consumption level, energy consumption has declined across all regions. The reduction rates are 6.7% nationwide, 8.6% in the Continental region, 3.2% in the Mediterranean region, and 10.4% in the North Atlantic region. However, in all cases, the annual rate of decline remains below 1%, suggesting that energy conservation within the household sector in Spain has been relatively limited. Further details can be found in the bottom three rows of Table 3.

The table also reveals significant variations across household types. While energy consumption has decreased for large households, it has increased for small households. As shown in Table 1, the proportion of these household types has grown over time, contributing to a net increase in energy consumption.

Moreover, energy consumption has risen considerably in households with elderly members, particularly in single-person elderly households and in households with two adults, including at least one elderly person. This trend is driven by both an increase in per-household energy consumption among elderly households (as shown in Table 2) and a rise in the overall number of such households (as indicated in Table 1).

The bottom two rows of Table 3 also present changes in energy consumption per household and per person. Compared to these declines, the reduction in gross energy consumption is relatively modest. This can be attributed to an increase in the number of households and a decrease in average household size over the period under consideration. Furthermore, the decline in energy consumption per person is less pronounced than the decline in energy consumption per household, primarily due to the reduction in household size.

In the following section, we will conduct a simple simulation analysis to further examine this issue in greater depth.

4.2. Energy efficiency loss resulting from shifts in population dynamics

Household energy consumption is believed to have changed over the period under consideration due to three key factors: (1) improvements in energy conservation, (2) changes in the number of households, and (3) shifts in household composition. In the following analysis, we will evaluate these influences by examining three distinct scenarios. The results will then be compared with the baseline case presented earlier to estimate the impact of each factor on household energy consumption.

Scenario 1: In this scenario, we assume that no technological advancements occurred and that household energy-saving efforts did not progress. Essentially, time passes without any improvements in energy efficiency. Consequently, the distribution of energy consumption remains unchanged. However, the number of households and household compositions are assumed to have evolved as they did during the period under consideration.

Scenario 2: In this analysis, we assume that the distribution of energy consumption evolves in accordance with real-world trends, while the number of households and household composition remain constant. This approach enables us to isolate and examine the impact of changes in energy consumption patterns.

Scenario 3: In this scenario, the energy consumption distribution evolves as observed in reality, and the number of households changes in response to population growth. However, household composition remains unchanged, enabling an assessment of how demographic growth, independent of shifts in household structure, influences energy consumption.

Table 4 Near Here

Using Equations 1 and 2, we perform the three types of simulation analyses described above to calculate hypothetical energy consumption. The assumptions underlying these simulations are summarized in Table 4. By comparing the estimated energy consumption derived from the three scenarios with the original energy consumption observed during Sampling Period 1, we can assess energy efficiency gains through technological and behavior improvements and energy efficiency losses resulting from shifts in population dynamics.

Table 5 Near Here

In the analysis of Scenario 1, which assumes no improvements in energy efficiency through technological advancements or the adoption of energy-saving behaviors while accounting for demographic changes, national energy consumption is estimated to have increased by 11.24% between Sampling Period 1 and Sampling Period 2. However, actual energy consumption decreased by 6.75% over this period. Consequently, the total energy efficiency gain attributed to technological and behavior improvements is calculated to be 17.99% (i.e., 11.24% (a) − 6.75% (b)), with higher values for the Continental region.

Conversely, in Scenario 2, which assumes that energy conservation was achieved without any changes in the number of households or population structure, energy consumption is estimated to have decreased by 16.83% between Sampling Period 1 and Sampling Period 2. However, as the actual decrease in energy consumption was only 6.75%, then the total energy efficiency loss resulting from shifts in population dynamics is calculated to be 10.07% (i.e., 16.83% (d) – 6.75% (b)), with significant differences between regions, with the Mediterranean showing a 17% increase in the number of households, and the North Atlantic an 11%.

Furthermore, in the analysis of Scenario 3, which assumes that the number of households increased in proportion to population growth while household composition remained constant, energy consumption is estimated to have decreased by 10.06% between Sampling Period 1 and Sampling Period 2. However, given that the actual decrease in energy consumption was 6.75%, the energy efficiency loss due to household composition change is calculated to be 3.31% (i.e., 10.06% (c) – 6.75% (b)).

Finally, by subtracting the energy efficiency loss due to household composition change from the total energy efficiency loss resulting from shifts in population dynamics, the energy efficiency loss resulting from household growth is estimated to be 6.76% (i.e., 10.07% (d) − 3.31% (c)).

Using a similar methodology, the gains in energy efficiency resulting from technological advancements and behavioral changes, as well as the losses due to demographic changes, can be assessed for the Continental, Mediterranean, and North Atlantic regions. The results are summarized in Table 5. This table demonstrates that, across all regions, demographic changes largely counteract the benefits of energy savings. However, the extent of the impact varies by region. Specifically, the increase in the number of households has a more pronounced effect in the Mediterranean region, whereas changes in household composition exert a greater influence in the North Atlantic region. In the North Atlantic Region, the number of households increased despite the population remaining nearly constant. Therefore, this increase in households can be attributed to changes in household composition. Consequently, the associated energy loss during this period can also be attributed to shifts in household composition. Meanwhile, the population and number of households increased in the Mediterranean region. As a result, the energy efficiency loss in this region reflects not only the increase in the number of households due to population growth but also the impact of changes in household composition.

5. Discussion and conclusions

This study has examined the evolving patterns of residential energy consumption in Spain, revealing that while technological advancements and behavioral changes have led to notable energy efficiency gains, demographic changes have largely offset these benefits. The increase in the number of households and the growing prevalence of small and elderly households have driven up per capita energy consumption, despite a general decline in gross residential energy use.

This study finds that demographic changes –particularly shifts in household composition over time –have a significant impact on residential energy consumption. The increasing prevalence of smaller and elderly households between 2006 and 2023 has led to a loss of potential energy savings of 3.31%. While most household types have reduced their average energy consumption over the analyzed period, the two household types that grew in prevalence –smaller and elderly households –have simultaneously increased their average consumption. As a result, despite an 11.22% decline in final energy consumption in the residential sector over the study period (compared to a 15% reduction across the overall economy), the residential sector has increased its relative share of total final energy consumption, reaching 17.85% in 2023.

This result was obtained through a methodological innovation that integrates demographic evolution data from the census with micro-level household energy consumption data from the Household Budget Survey. We argue that this bottom-up method allows us to quantitatively analyze the impact of changes in household composition on the demand for goods, and it may prove useful for analyzing other consumption goods, part of the metabolism of households. In the application carried put in this study, the methodology provides valuable insights into how energy consumption patterns evolve as the population ages – one of the major challenges for many developed countries, particularly Spain.

This trend is closely linked to the decline in household size, which has decreased from 2.88 to 2.56 members, alongside a 30.1% increase in the number of households, reaching 18.54 million in 2023. The rise in single-person households – from 20.3% in 2001 to 27% in 2021 – is particularly notable and is associated with higher average energy consumption, especially among elderly individuals living alone. The factors driving this shift include both social and economic considerations, such as changing lifestyle preferences, financial constraints affecting cohabitation patterns, and evolving household structures among immigrant populations, the majority of whom are of working age (75%). At the same time, the effects of population aging in Spain have been partially mitigated by mass immigration (Inoue and Velasco-Fernández 2025), with census data revealing a sharp increase in the share of foreign residents from 3.79% in 2001 to 11.20% in 2011. While preliminary evidence suggests that immigrant-headed households tend to consume less energy on average, further research is needed to understand these differences in greater detail.

The implications of these demographic shifts are further compounded by climate change. Rising temperatures, particularly an increase in the number of warmer days and nights, are likely to raise energy demand among the elderly, as has been documented in the United States (Estiri and Zagheni 2019). Given that this population group is highly vulnerable, policies must ensure affordable energy access to mitigate potential negative impacts. Similar findings have been reported in China, where warmer weather has been found to increase energy consumption due to higher electricity use during hot days (Su and Ullah 2024). In Spain, this trend may lead to a more pronounced increase in household energy consumption in the Mediterranean region and the North Atlantic compared to the Continental, potentially closing the current gap in average energy consumption observed in this study.

From a policy perspective, the increasing prevalence of single-person and two-person households, which, as our findings and previous literature indicate, tend to consume more energy, have implications for the housing market. Household composition influences housing demand, and policies should encourage the development of smaller housing units, as suggested by Mulder (2006). This could impact energy demand since housing size is a key determinant of residential energy consumption (O'Neill and Chen 2002). In Spain, where heating is the primary household energy service – accounting for 41.2% of total household energy use in 2022 (IDAE 2024) – smaller housing units would likely result in lower heating needs, particularly in mainland Spain, and more specifically in the Continental region where heating demand is higher than in the rest of the country. Additionally, such measures could contribute to reducing energy poverty, given that a majority of Spanish households rely on individual and inefficient heating systems (82% in 2011 compared to 8% with central heating) (IDAE 2011).

To address these challenges, differentiated energy policies should be designed to promote the adoption of high-efficiency modern heating systems, particularly for lower-income populations. Previous research has shown that electricity consumption among medium-to-high-income households is responsive to price increases, whereas medium-to-low-income households are more sensitive to changes in income (Romero-Jordán et al. 2016). Ensuring access to energy-efficient appliances and equipment for lower-income households is therefore crucial. In Spain, the promotion of smaller housing units should be accompanied by an accelerated implementation of the *Long-Term Strategy for Energy Rehabilitation in the Building Sector*, which aims to achieve a zero-emission housing stock by 2050 (MITMA 2020). Combining energy-efficient housing rehabilitation with the development of smaller housing units or co-housing arrangements that share certain facilities, such as kitchens, could lead to significant reductions in residential energy consumption.

Our results indicate that the annual rate of decline of residential energy consumption has remained below 1%, suggesting a limited success of energy conservation in the household sector. Beyond housing policies, behavioral changes will be essential in complementing energy efficiency improvements. As highlighted in the case of Japan, efficiency gains alone will not be sufficient to meet national targets for energy efficiency, renewable energy adoption, and electrification (Inoue et al. 2024). However, previous research in Spain suggests that behavioral responses vary significantly by socioeconomic group: higher-income and more educated households are more likely to invest in energy efficiency but are less inclined to adopt energy-saving habits, while older households are less likely to invest in energy efficiency and also display fewer eco-friendly behaviors (Ramos et al. 2016). Encouraging behavioral change through targeted interventions – such as informational campaigns emphasizing health benefits, which have been shown to be more effective than purely economic or environmental messages – could help reduce energy consumption (Kirchler et al. 2024). Moreover, technological solutions such as real-time residential energy management systems based on smart meters and the Internet of Energy with scheduling strategies (Zhao et al. 2025), as well as forecasting tools based on neural network models in adaptive federative learning (Abdulla et al. 2024), may further optimize energy consumption patterns.

Looking ahead, population aging and the declining average household size result in a loss of economies of scale in energy consumption, potentially leading to higher per capita energy use than anticipated in both academic and policy-oriented modeling exercises. Future research should incorporate these demographic trends into energy demand forecasting and planning. Additionally, some scholars have proposed promoting extended-family households as a potential policy measure (Zeng et al. 2021). Such arrangements could restore economies of scale, reduce unwanted loneliness among the elderly, and facilitate work-life balance for families.

These findings underscore the need for targeted policy interventions that integrate both technological efficiency improvements and demographic realities. Policies promoting shared living arrangements, improved insulation in homes occupied by older individuals, and incentives for energy-efficient housing design could help mitigate the negative effects of demographic shifts.

Future research should further explore the interplay between aging, urbanization, and household structure to inform more effective energy conservation strategies. For instance, applying this methodology to estimate differential energy consumption by household type would allow for an analysis of the potential impacts of various future demographic scenarios on energy use, which could then be compared with official energy consumption projections. Future research could also examine with more detail the Household Budget Survey to provide insights into key variations in energy consumption patterns, such as differences between immigrant and non-immigrant households, variations between working-age and dependent households, the influence of housing tenure on energy use, and differences in energy source utilization across household types and climatic zones.

Appendix A1.

In the Household Budget Survey, energy consumption is reported in different units: electricity in kWh, city gas in m^3, natural gas in kg, liquefied gas in kg, and liquid fuel in liters. To ensure comparability, we convert these values into megajoules (MJ) using standard conversion factors from the OECD and International Energy Agency (IEA 2004). The conversion factors are as follows: City gas: 33.9 MJ/m^3, Natural gas: 46.2 MJ/kg, Liquid gas: 46.2 MJ/kg, Liquid fuel: 34.8 MJ/L.

For electricity, after converting kWh into MJ, we apply the partial substitution method to get a primary energy equivalent value. Instead of using a flat 2.6:1 conversion factor – aligned with the IEA's standard for thermal electricity generation – we use official data from Spain's energy balances (MITECO 2024b) to account for changes in the power mix. The specific conversion factor for electricity is provided in Table A1.

Table A1 Near Here

Appendix A2.

Following the procedure outlined in Figure 1, we analyzed the histogram of the logarithm of the annual total energy consumption (MJ) from the Household Budget Survey by household type and approximated it using normal distributions. The means and standard deviations of those approximate normal distributions obtained are shown in Table A2. These values are used in the simulations conducted in this study.

Table A2 Near Here

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Figure 1. Normal Distribution Approximation of Energy Use in Spanish Households
Sampling year 2006 – 2008

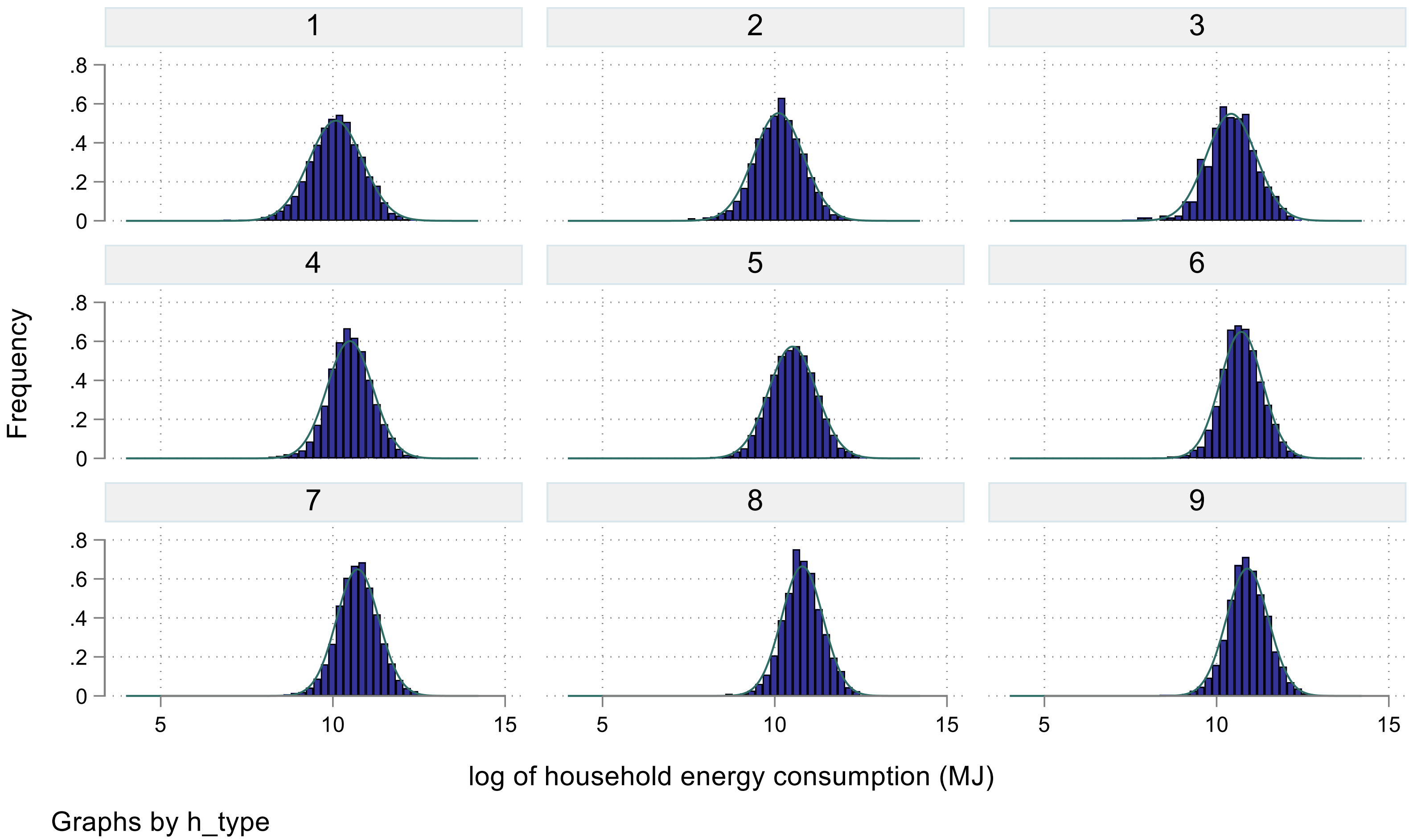

Figure 2. Climate Regions in Spain

Table 1. Number of households by type						
	2001		2011		2021	
Household type	Number	Share	Number	Share	Number	Share
One adult						
1. Single working-age	1,517,635	10.7%	2,484,135	13.7%	2,912,556	15.7%
2. Single senior	1,358,937	9.6%	1,709,185	9.5%	2,088,603	11.3%
One adult and minors						
3. One adult and minors	282,153	2.0%	462,475	2.6%	658,593	3.6%
Two adults						
4. Two working-age persons	1,627,401	11.5%	2,758,725	15.3%	2,280,318	12.3%
5. Two adults, including at least one senior	1,776,697	12.5%	2,389,575	13.2%	2,524,002	13.6%
Two adults and minors						
6. Two adults and minors	2,423,995	17.1%	3,226,430	17.8%	2,669,538	14.4%
Three adults						
7. Three adults only	1,893,251	13.3%	2,198,405	12.2%	2,420,565	13.1%
8. Three adults and minors	740,062	5.2%	915,365	5.1%	1,019,604	5.5%
Four or more adults						
9. Four or more adults with or without minors	2,567,038	18.1%	1,939,390	10.7%	1,957,200	10.6%
Total	14,187,169	100.0%	18,083,685	100.0%	18,530,979	100.0%

Source: Population and Housing Censuses (2001, 2011, 2021)

Table 2. Average annual energy consumption by climatic region (Megajoule)

	National		Continental		Mediterranean		North Atlantic	
	2006-2009	2021-2023	2006-2009	2021-2023	2006-2009	2021-2023	2006-2009	2021-2023
1. Single working-age	32,013	27,196	37,186	31,657	27,959	25,413	29,884	24,272
2. Single senior	31,755	31,396	39,033	36,367	27,799	27,443	28,209	29,900
3. One adult and minors	43,157	32,313	53,443	38,268	39,092	30,536	39,524	28,581
4. Two working-age persons	44,592	37,236	51,860	43,291	40,254	33,417	41,759	34,963
5. Two adults, including at least one senior	47,048	44,654	52,549	51,268	41,932	39,569	45,503	42,122
6. Two adults and minors	54,394	41,679	63,398	47,547	49,749	38,580	48,678	38,792
7. Three adults only	54,591	45,481	63,135	52,344	49,768	41,082	49,626	42,809
8. Three adults and minors	58,305	46,591	67,522	53,191	53,029	42,884	54,784	44,116
9. Four or more adults with or without minors	64,814	50,487	74,568	56,706	58,212	47,172	61,887	47,696
Total	50,300	39,814	58,105	45,815	45,703	36,466	46,291	36,861

Table 3. Change in energy consumption by household type: basis estimates (consumption unit = Petajoule)

	National				Continental				Mediterranean				North Atlantic			
	2006-2008		2021-2023		2006-2008		2021-2023		2006-2008		2021-2023		2006-2008		2021-2023	
Household type	Cons.	Share	Cons.	Share	Cons.	Share	Cons.	Share	Cons.	Share	Cons.	Share	Cons.	Share	Cons.	Share
1. Single working-age	65.0	8.2%	79.9	10.9%	24.1	8.4%	29.2	11.1%	30.1	7.9%	34.9	9.5%	9.1	8.2%	10.8	10.9%
2. Single senior	49.1	6.2%	66.3	9.0%	20.4	7.1%	25.3	9.6%	21.6	5.7%	34.5	9.4%	7.1	6.4%	10.9	11.0%
3. One adult and minors	16.3	2.1%	21.4	2.9%	5.8	2.0%	7.7	2.9%	8.5	2.2%	11.5	3.1%	2.0	1.8%	2.2	2.2%
4. Two working-age persons	98.7	12.5%	85.1	11.6%	35.5	12.4%	30.3	11.6%	48.5	12.8%	37.9	10.3%	13.2	11.9%	11.1	11.2%
5. Two adults, including at least one senior	98.0	12.4%	112.9	15.4%	36.4	12.7%	40.7	15.5%	43.4	11.4%	57.5	15.7%	15.9	14.3%	18.0	18.1%
6. Two adults and minors	154.4	19.6%	111.5	15.2%	54.9	19.1%	38.4	14.7%	80.7	21.3%	58.8	16.0%	17.0	15.3%	12.9	13.0%
7. Three adults only	111.8	14.2%	110.7	15.1%	40.5	14.1%	39.9	15.2%	52.0	13.7%	53.8	14.7%	17.9	16.1%	15.9	16.0%
8. Three adults and minors	48.6	6.2%	47.7	6.5%	16.6	5.8%	15.8	6.0%	25.4	6.7%	25.9	7.1%	5.9	5.3%	5.1	5.2%
9. Four or more adults with or without minors	146.3	18.6%	99.4	13.5%	52.4	18.3%	34.8	13.3%	69.0	18.2%	52.3	14.2%	22.9	20.7%	12.4	12.5%
Total[1]	788.1	100.0%	734.9	100.0%	286.6	100.0%	262.1	100.0%	379.2	100.0%	367.2	100.0%	110.9	100.0%	99.3	100.0%
Rate of energy consumption reduction																
Gross consumption			-6.7%				-8.6%				-3.2%				-10.4%	
Per household consumption			-18.8%				-19.4%				-17.2%				-19.3%	
Per capita consumption			-13.8%				-14.5%				-12.9%				-10.1%	

Note 1. The total for the three regions does not precisely correspond to the national total because the national estimate is based on the overall distribution of energy consumption across the country, whereas the regional estimates are derived from the energy consumption distribution specific to each region.

Table 4. Summary of simulation studies

	Energy consumption	Demographic composition	Number of households
Baseline case: Observed	$E[C^{g,r,t=1}]$	$s^{g,r,t=1}$	$N^{g,r,t=1}$
Scenario 1: No technological progress	$E[C^{g,r,t=0}]$	$s^{g,r,t=1}$	$N^{g,r,t=1}$
Scenario 2: No demographic change	$E[C^{g,r,t=1}]$	$s^{g,r,t=0}$	$N^{g,r,t=0}$
Scenario 3: No demographic composition change	$E[C^{g,r,t=1}]$	$s^{g,r,t=0}$	$\varphi \cdot N^{g,r,t=0}$ where $\varphi = \frac{\sum_g s^{g,r,t=1} N^{g,r,t=1}}{\sum_g s^{g,r,t=0} N^{g,r,t=0}}$

Note. In this analysis, $t = 0$ corresponds to using energy consumption data from 2006 to 2008 or the 2006 census, while $t = 1$ represents the use of data from 2021 to 2023 or the 2021 census.

Table 5. Change in energy efficiency gains and losses from Sampling Period 1 (2006 – 2008) to Sampling Period 2 (2021 – 2023)	National	Continental	Mediterranean	North Atlantic
Scenario 1: No technological progress (a)	11.24%	10.11%	13.58%	5.62%
Baseline case (2006 - 2008)	**0.00%**	**0.00%**	**0.00%**	**0.00%**
Baseline case (2020 - 2023) (b)	-6.75%	-8.55%	-3.17%	-10.43%
Scenario 3: No demographic composition change (c)	-10.06%	-11.76%	-6.36%	-16.48%
Scenario 2: No demographic change (d)	-16.83%	-17.55%	-15.72%	-16.12%
Total energy efficiency gain through technological and behavior improvements (a − b)	17.99%	18.67%	16.75%	16.06%
Total energy efficiency loss resulting from shifts in population dynamics (d − b)	-10.07%	-9.00%	-12.55%	-5.68%
Energy efficiency loss due to household composition change (c − b)	-3.31%	-3.21%	-3.19%	-6.04%
Energy efficiency loss resulting from household growth (d − c)	-6.76%	-5.79%	-9.36%	0.36%

Table A1. Conversion factors from electricity to primary energy

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014
Factor	2.63	2.58	2.51	2.43	2.37	2.42	2.24	2.46	2.49
Year	2015	2016	2017	2018	2019	2020	2021	2022	2023
Factor	2.27	2.41	2.46	2.35	2.29	2.27	2.19	2.42	2.28

Source: MITECO (2025).

Table A2. Approximation by the normal distributions (log of household energy consumption)																
	National				Continental				Mediterranean				North Atlantic			
	2006-2008		2021-2023		2006-2008		2021-2023		2006-2008		2021-2023		2006-2008		2021-2023	
Variable	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
1. Single working-age	10.09	0.78	9.97	0.70	10.22	0.82	10.10	0.74	9.98	0.73	9.91	0.69	10.04	0.76	9.89	0.65
2. Single senior	10.11	0.72	10.10	0.73	10.31	0.75	10.23	0.76	10.00	0.69	9.96	0.73	10.03	0.68	10.09	0.67
3. One adult and minors	10.42	0.73	10.14	0.71	10.68	0.67	10.29	0.74	10.29	0.77	10.07	0.71	10.42	0.60	10.08	0.63
4. Two working-age persons	10.49	0.66	10.31	0.66	10.65	0.67	10.45	0.69	10.40	0.64	10.21	0.64	10.44	0.66	10.27	0.62
5. Two adults, including at least one senior	10.52	0.70	10.48	0.67	10.63	0.71	10.61	0.70	10.40	0.67	10.36	0.67	10.50	0.69	10.46	0.60
6. Two adults and minors	10.72	0.61	10.44	0.63	10.87	0.61	10.56	0.66	10.63	0.61	10.36	0.64	10.63	0.58	10.42	0.55
7. Three adults only	10.72	0.61	10.51	0.66	10.86	0.63	10.64	0.69	10.63	0.61	10.42	0.64	10.66	0.57	10.48	0.61
8. Three adults and minors	10.80	0.60	10.54	0.65	10.95	0.60	10.66	0.67	10.71	0.59	10.47	0.63	10.76	0.56	10.52	0.61
9. Four or more adults with or without minors	10.89	0.61	10.63	0.64	11.02	0.64	10.75	0.63	10.80	0.58	10.56	0.65	10.86	0.59	10.61	0.59
All	10.60	0.70	10.36	0.70	10.74	0.71	10.48	0.72	10.51	0.68	10.27	0.69	10.53	0.67	10.31	0.65

Source: The author's calculation based on the Household Budget Survey