Consequences of energy demand reduction interventions to the Chilean housing stock on Energy Poverty

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Abstract

The consequences of energy demand reduction interventions on energy poverty within the Chilean housing stock were investigated. Energy poverty, defined as the inability to afford adequate warmth due to inefficient housing, was examined in the context of Chile's diverse climates and economic challenges. The study used a mixed methods approach, integrating quantitative data from the Family Budget Survey and qualitative insights from the Uses of Energy in the Chilean Housing Survey. The key factors contributing to energy poverty, including low income, educational attainment, property tenure, energy prices, household size, and housing energy inefficiency, were analyzed.

Households in Thermal Zones 5 and 7, characterized by severe climates and high energy demands, were identified as particularly vulnerable to energy poverty. Energy modeling using EnergyPlus demonstrated that interventions such as roof, wall, and floor insulation, along with double glazing, could significantly reduce heating energy demand. The analysis revealed that roof insulation had the most substantial impact, followed by wall insulation, while floor insulation and double glazing contributed marginally. The concurrent application of all interventions led to substantial reductions in heating demand, highlighting the importance of targeted energy efficiency measures.

The findings underscore the need to implement customized energy efficiency measures to alleviate energy poverty and improve the quality of life of affected households. Policymakers are advised to prioritize interventions that offer the most significant impact on reducing energy demand, particularly roof and wall insulation. Future research should focus on improving the accuracy of data on parameters such as infiltration rates, building orientation, and heating usage patterns, as well as exploring the long-term benefits of energy efficiency measures on health and well-being.

Introduction

Energy poverty can be defined as the inability to afford adequate warmth due to the inefficiency of the home. The energy required to have adequate lighting, cooking, and typical domestic appliances in a dwelling is also considered within the concept of energy poverty. In 2015, the United Nations, through the international initiative Sustainable Energy for All, introduced the Sustainable Development Goals to be achieved by 2030. These goals encompass the provision of universal access to modern energy services that cater to fundamental human needs, emphasizing cost affordability and advances in electricity, as well as improvements in cooking appliances such as stoves.

Energy poverty represents one of the foremost challenges currently confronting the European Union. Whereas a decade ago, this issue was primarily addressed by the United Kingdom, it has now gained attention in several other countries, including Austria, Belgium, Bulgaria, France, Germany, Greece, Ireland, Italy, Poland, Portugal, and Spain, among others. Beyond Europe, energy poverty has also garnered interest in South America, exemplified by Chile's growing concern regarding its impacts. A significant consequence is the adverse effect on the health of individuals residing in affected dwellings. Those with preexisting health conditions experience exacerbation of their symptoms, resulting in increased pressure on national resources, particularly healthcare systems. Consequently, nation-states are increasingly interested in implementing measures to promote an active, healthy population.

The nation states have implemented policies and measures to alleviate energy poverty. However, the most significant challenge lies in developing policies that encompass the majority of the affected population. The majority of the policies devised so far have concentrated on specific demographics, such as families with children or pensioners, based primarily on political rather than technical considerations. Consequently, this approach excludes other segments of the population that may also be experiencing energy poverty but do not meet the eligibility criteria for assistance.

The implementation of retrofitting has been identified as a potential solution to address inefficiencies in housing energy consumption. Retrofitting enhances housing quality and strengthens efficiency standards, thereby reducing energy expenses and improving affordability. In the context of Chile, measures such as thermal enhancements of residences, the substitution of wood stoves with more efficient models or those utilizing alternative fuel sources, and wood certification are among the proposed strategies. Nevertheless, despite the adoption of these measures, pollution levels remain hazardous, and emergency events continue to prevail. The underlying causes may be attributed to the firewood market, which is characterized by its highly informal nature, complicating the regulation and control of wood quality. Moreover, wood remains the most economical source of energy for heating, with significant cost disparities when compared to other energy sources like electricity and gas. As a result, households facing financial constraints have limited motivation to transition to cleaner energy sources due to their higher costs, which would lead to an increase in energy expenditure. Furthermore, there is a noted lack of confidence in the reliability of alternative fuel sources, coupled with the financial barriers associated with transitioning from one fuel source to another, such as the cost involved in replacing furnaces.

The literature review has revealed that the Chilean government has recently integrated the concept of energy poverty into official policies. The 2050 Energy Policy articulates the necessity to define and quantify energy poverty within the country, to formulate policies aimed at its mitigation. Moreover, there has been no comprehensive analysis conducted to ascertain which interventions within the Chilean housing sector may result in a reduced energy demand and consequently alleviate energy poverty. For instance, the Ministry of Housing has concentrated its efforts on mitigating heat losses in social housing by implementing subsidies for thermal envelopes; however, the efficacy of these initiatives has yet to be evaluated. This research addresses this gap and initiates the process of understanding, from a modeling perspective, the potential benefits thereof. This forms the scope of the research to be developed.

The study has contributed to understanding of energy poverty in Chile by identifying key factors such as economic status, educational attainment, property tenure, energy prices, and sociodemographic characteristics. The effectiveness of various energy demand reduction interventions, including roof and wall insulation, double glazing, and heating system improvements, has been demonstrated. However, limitations include potential biases from self-reported data, assumptions in the modeling process, regional focus that restricts generalization, and the exclusion of long-term health and well-being impacts. Furthermore, the reliance on existing data sources and the applicability of findings to other nations with different socio-economic and climatic conditions have been acknowledged.

Research question, aim and objectives

0.1 Research question

- What are the consequences of energy demand reduction interventions in the Chilean housing stock on energy poverty?

0.2 Aims and objectives

The purpose of this research is to investigate the consequences of introducing energy demand reduction interventions in Chile's housing stock to reduce energy poverty.

The objectives of this research are derived from its primary aim. These objectives represent the specific actions the researcher plans to undertake to fulfill the overarching aim of the study. The objectives are outlined as follows:

- Identify the consequences of EP.
- Identify the main factors that contribute to energy poverty in the Chilean housing stock.
- Determine the number of households affected by energy poverty in Chile by assessing the EP metrics that are possible to apply according to the existing data sources in Chile.
- Characterize the Chilean housing stock and present a set of archetypal buildings to represent it.

- Gather information on building physics models and inputs used to feed the model to determine the energy demand in the Chilean housing stock most vulnerable to energy poverty.
- Determine the impact of introducing energy demand reduction interventions on the Chilean housing stock most vulnerable to energy poverty.

Thesis outline

The outline of this thesis delineates the stages that were strategically devised to achieve the research aim and objectives previously articulated.

Chapter 1: Review of the literature. This chapter provides a comprehensive introduction to the concept of energy poverty and its ramifications, delineates the main factors that contribute to energy poverty, and examines existing metrics. In addition, it explores the Chilean context, encompassing climate, economy, national energy consumption, energy market dynamics, energy policy, and existing data sources within the country.

Chapter 2: Methodology This chapter elucidates the methodology used to determine the main factors that contribute to energy poverty in Chile, along with an analysis of the current state of energy poverty within the country. Furthermore, it provides a comprehensive overview of the utilization of archetypes, followed by a detailed explanation of the methods used to develop the Chilean archetypes and their description both at the national level and across various thermal zones.Finally, an elucidation is provided regarding the methodology for modeling energy demand, accompanied by an exploration of building physics models. In addition, the criteria for selecting the appropriate model to calculate the heating energy demand in Chile are discussed, with particular attention to the inputs and settings used in the modeling process.

Chapter 3: Results. This chapter delineates the main factors that contribute to energy poverty, with a particular focus on those that increase the vulnerability of Chilean households to such conditions. The quantification of households affected by energy poverty is determined. In addition, the chapter presents the findings related to the implementation of energy demand reduction interventions within the housing sector that is most susceptible to energy poverty.

Chapter 4: Discussion and Conclusion. This chapter presents a detailed analysis of the findings of the previous chapter on the determinants of energy poverty in Chile, the prevalence of households experiencing energy poverty and the thermal zones most affected. In addition, it examines the results of policy interventions aimed at modifying energy demand for heating purposes. Particular attention is paid to the constraints imposed by the available data sources and the scarcity of key inputs necessary for comprehensive modeling.

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Nomenclature

BREDEM Building Research Establishment Domestic Energy Model

CASEN Encuesta de Caracterización Socio-Económica Nacional

CDT Corporation of Technological Development

CEV Calificación Energética de Viviendas

CNE Comisión Nacional de Energía

EHCS English Housing Condition Survey

EP Energy Poverty

EPF Encuesta de Presupuestos Familiares

EPOV Energy Poverty Observatory

EU European Union

EU SILC European Survey on Income and Living Conditions

EUROSTAT Statistical Office of the European Union

EWM Excess Winter Mortality

FNE Fiscalía Nacional Económica

FPEER Fuel Poverty Energy Efficiency Rating

GDP Gross Domestic Product

HEP Hidden Energy Poverty

HSM Housing stock models

ICV Cost of Living

INE Instituto Nacional de Estadísticas

IPC Consumer Price Index

LCA Life Cycle Assessment

LIHC Low Income High Cost

LILEE Low-Income Low Energy Efficiency

MINVU Ministerio de Vivienda y Urbanismo

MIS Minimum Income Standard

MR Metropolitan Region

OECD Organization for Economic Co-operation and Development

PADHI Poverty Adaptive Degree Hourly Index

RCP Residential, Commercial, and Public sectors

RENAM Red Nacional de Monitoreo de Viviendas

SA Sensitivity Analyzes

SAP Standard Asessment Procedure

TPR Ten Per cent Rule

WHD Warm Home Discount

CHAPTER 1

Literature review

1.1 Energy poverty concept

Energy poverty is a significant challenge worldwide, with several countries adopting different strategies to address it. In Europe, the issue has gained attention in countries like Austria, Belgium, Bulgaria, France, Germany, Greece, Ireland, Italy, Poland, Portugal, and Spain. Strategies to combat energy poverty include interventions in energy tariffs, energy efficiency measures, and targeted support for vulnerable households. For example, France has introduced social tariffs and debt reduction measures, while Australia offers payment arrangements and reduced tariffs, although these measures have faced criticism for being overly restrictive [178]. Spain provides targeted support, but lacks comprehensive interventions such as energy retrofitting [180]. The UK has invested in improving the thermal performance of social housing through measures such as exterior wall insulation and boiler replacements [87]. These varied approaches reflect the complexity of energy poverty.

The concept of fuel poverty was first conceptualized by Boardman in the United Kingdom in 1991. Boardman defined fuel poverty as the inability to afford adequate warmth due to the inefficiency of the home [22]. She stated that a household is energy poor when spends more than ten per cent of their income in energy services. However, Boardman [23] herself warned about uncritically transferring this threshold which is UK specific as it was derived from UK 1988 data. The survey results showed that the average energy cost of a house was 5% of monthly income and 30% of the households with the lowest income spent 10%. At that time, she also indicated that these people lived in cold homes due to a lack of insulation and the use of inefficient or expensive heating systems. Therefore, they had to spend large proportions of their income on energy. In addition, most people living in fuel poverty lived in rented accommodation, so they could not receive subsidies to improve their homes. Boardman stated that the only way to alleviate fuel poverty is to improve energy efficiency and thermal performance [22].

Therefore, energy poverty is a complex concept because it is multifaceted. An energy poverty framework includes physical, economic, and behavioral dimensions [28, 116]. The physical dimension includes poor quality housing, the structure of the home environment, and inefficient appliances. The economic dimension consists of the affordability of energy services as a function of income, the absence of savings, the type of housing tenure, and the relative price of energy. The behavioral dimension focused on coping strategies, social vulnerabilities, and resilience indicators.

It is difficult to define energy poverty, but it is important to do it for policy making. The definition of energy poverty is needed for two purposes: to establish which groups need the most financial help and to monitor what is happening to the number of energy poverty in general [23]. So, the definition of energy poverty will affect the groups that governments will prioritize. That is why the elaboration of the definition of energy poverty has not been exempted from discussion.

Some researchers and policy makers argue that low-income pensioners should be prioritized because, even though they often own their home, they do not have enough income to maintain it at an adequate temperature. For example, in Chile, 83% of adults 80 years or older (equivalent to 474,000 people) are owners or are in the process of owning their home. However, the average pension received by these people is $268.337 CLP, which is about the minimum wage proposed by law in 2017 ($270.000 CLP)[38]. This implies that while they may own their home, it is likely that they will struggle to maintain it to meet their comfort needs. This is because the Chilean minimum wage is a value established by law that does not have a formal criterion to calculate it [84], therefore it must not be considered a living wage.

In relation to whether only this group could be affected by low temperatures, the World Health

Organization (WHO) has indicated that to not compromise the health of an adult, the indoor air temperature during cold seasons should be between 18°C and 21°C (adaptation to climate and adaptive behaviors were not considered in this approach). However, for vulnerable individuals (elderly, children, and people with preexistence diseases), it should be greater than 23°C [153, 185], which means that the elderly require more energy for their thermal comfort.

Other research is echoing the declaration made by the WHO that the elderly are vulnerable. In this research, it was stated that the elderly require higher temperatures because they are a population physically vulnerable to cold [180]. Individuals in a delicate state of health are vulnerable to extreme temperatures. People with conditions such as respiratory, cardiovascular, and arthritis diseases are at increased risk because a home that is too hot or too cold can exacerbate and increase their symptoms [34, 136, 186]. In Chile, 46% of the elderly (over 80 years of age) who assist in the control of healthcare declare to control a chronic disease, which is equivalent to 25% of total elderly of the fourth age (143,000 people). In addition, 35% declare physical difficulties and mobility. So, this group is exposed to the consequences mentioned previously [4].

Other researchers stated that efforts should be focused on families with children and single parents because they often rent their home, leaving them with less available resources [23]. In Chile, the Encuesta de Caracterizaci'on Socio-Econ'omica Nacional (2017 CASEN), which is a survey that determines the socio-economic condition of households (see Section 1.6.2), has shown that 22% of families with children (152,000 households) rent a property, with or without legal contract, and 16% (111,000 households) live in a property granted by relatives. So, 38% of the families with children live in a rented or granted home, a condition that could lead them to fall into EP.

Thus, part of the debate about the appropriate social definition is likely to be a political one, i.e., government spending is limited, and it needs to decide how best to target these resources, in this case either covering the relative needs of elderly households, who probably own their home outright, versus those who rent and have children [23]. It should be added that although low-income households are more likely to be in fuel poverty and low income is an important factor of vulnerability, it does not imply that families with middle income or above the median do not experience conditions associated with energy poverty [181]. This is because they could be living in low energy efficiency dwellings, that is, with poor insulation, leaks, and other intrusion points of the outside elements, which make it difficult to control indoor temperatures, leading to high bills and unsafe conditions [139, 188].

1.2 Consequences of EP

In this Section 1.2 the consequences of EP will be identified to consider the relevance of introducing energy efficiency measures in homes.

1.2.1 Diseases

There is a relationship between energy poverty and the health of people living in this condition. Energy poverty is a phenomenon in which people cannot afford energy services or have limited access. One of the consequences that individuals in cold climates experience due to this phenomenon is the prevalence of cold conditions within their home that cause health complications and a high number of deaths [136, 112, 124]. Cardiovascular symptoms [17], arthritis [107], pneumonia [35], asthma [90], and Alzheimer [111] are some of the reported diseases that are believed to be linked to inadequate heating in homes.

In most cases, cold inside of a dwelling intensifies a pre-existing disease. For example, people who have already been diagnosed with cardiovascular disease are more exposed to a higher risk of heart attack and stroke due to low temperatures [136, 34, 163]. Other research found similar results in relation to arthritis symptoms. These showed that symptoms intensified when individuals with the disease lived in cold properties [107]. Upper and lower respiratory diseases, such as coughing and wheezing, also worsen due to cold. Cold exposure has also been found to have a suppression effect on the immune system, increasing pneumonia rates and other infections mainly in children [35]. Some researchers have also identified that care providers have reported lower well-being rates and more frequent hospital visits among asthmatics who live in inadequately heated homes [90]. In addition, Alzheimers patients showed a higher rate of mortality due to a combination of physiological and behavioral factors due to cold [111].

Individuals in a delicate state of health are vulnerable to extreme temperatures. People with conditions such as respiratory, pulmonary, cardiovascular, and arthritis diseases are exposed to increased risk because a home that is too hot or too cold can exacerbate and increase symptoms [136, 34, 186]. According to The National Energy Services and its experience in working in fuel poverty, the elderly and people with reduced movements need warmer dwellings. Opinion that is confirmed and supported by medical and care professionals [166]. The Wold Health Organization suggests that vulnerable people should live in homes with a standard temperature greater than 23 degrees Celsius.

The heat or eat dilemma is another consequence of energy poverty. Some people have to reduce their caloric intake in the winter months because they have to decide between spending their resources in an adequate energy service or getting food because they cannot get both[146, 9, 19]. Therefore, children and adults from low-income families experience under-nutrition in winter, when they have more energy needs[146, 19]. Consequently, acute hospital visits, poor diabetes control, fatigue, and behavioral problems in children are obtained [100]. In response to high energy bills, people also opt out of medical and dental care, which can lead to worse health outcomes in the future [15].

Energy efficiency measures have been associated with improvements in indoor temperature, leading to an improvement in respiratory and cardiovascular health of the occupant. Insulation measures have shown the greatest improvement in respiratory and cardiovascular conditions, followed by alterations in windows and doors. Insulated homes were associated with 27% fewer emergency admissions to cardiovascular disease in older residents, fewer self-reports of wheezing, and absences from school and work. Although improvements in windows and doors were associated with 39% fewer emergency admissions for respiratory conditions [137]. It was also found that replacing gas or electric heaters or open fires with the most effective heating systems, such as non-polluting heating, can reduce winter school absence for asthmatic children by an average of 21%, or approximately 1.9 days over the middle two (winter) school terms [101].

1.2.2 Excess Winter Mortality

Excess winter mortality (EWM) is another measure used to indicate the consequences of experiencing cold inside the dwellings. The EWM is understood as the percentage of additional deaths generated in winter in comparison with the average of remaining months. The EWM rate reached average values of 20%, 28%, and 31% in Spain, Portugal, and Malta respectively for the period 2005-2014. In Spain, the 20% EWM rate is equivalent to approximately 24,000 additional annual deaths in the winter months [181]. In Chile, the Department of Statistics and Health Data reported 7,000 deaths from EWM in 2018. The World Health Organization Report stated that 30% of the additional mortality in winter is due to an inadequate heating condition in the dwellings [187].

In England and Wales, an average of 60,573 excess deaths by year attributable to cold were reported, corresponding to standardized excess mortality rates of 122 deaths every 100,000 people. The higher risk was found in older people. This group showed a higher susceptibility to non-optimal temperatures, with the 85-year or older age group having more than twice the mortality risk of people aged 0 to 64 years. The lowest mortality risk was found at temperatures ranging from 14.9 to 22.6 °C [105].

However, some researchers have questioned the EWM methodology. The methodology has been questioned because it arbitrary defines the winter months. Consider the period between December and March for all European nations without paying attention to climate differences between regions. Liddell proposed using calculations based on degree days of heating registered in each country as a criterion for defining cold months and thus calculating the EWM. According to this proposal, the EWM for countries with cold climates such as Norway and Iceland should be calculated using 8 months. The researchers argued that if a standard winter is applied (4 months), then the EWM would significantly underestimate additional mortality in winter in several countries located in the north and west of Europe [181]. A similar observation can be made for Chile, the numbers for EWM should be higher due to some thermal zones, especially those located to the south of the country, having a winter longer than the standard winter of 4 months considered.

1.2.3 Psychological impact

The reasons for mental health deterioration due to energy poverty can be multiple and diverse. The cause of mental health deterioration could be social, personal, or economic. From a social perspective, a person could experience a social exclusion sensation leading to social isolation as a result of a stigma sensation within the community that affects feelings of failure and shame [135, 182]. In addition, living in only one or two rooms that can be heated at an affordable price could lead to overcrowding conditions [135]. In a personal perspective, there could be concerns that cold damages physical health and a feeling of lack of control over the problem because a solution cannot be found [182, 174]. In an economic perspective, persistent concerns about debt and affordability could be experienced, feelings related to the experience of falling into debt, and constant sensations of damage to personal possessions due to damp and mold [9, 182]. In 2012, Gilbertson *et al.* [108] stated that the difficulty in paying the fuel bills was related to poorer well-being measured by their stress levels.

Improvements in energy efficiency are often associated with significant improvements in mental well-being [135]. Howden-Chapman *et al.* [123] made an intervention on ceiling and floor insulation and draft proofing in the homes of seven communities in New Zealand to find their association with mental health. The results indicated that residents of the dwellings that received energy efficiency measures reported better general health and a significantly lower probability of being classified as having poor mental health. The authors concluded that improving insulation in poorer quality homes was effective in improving quality of life. In other research, Bond *et al.* [24] examined the relationship between perceptions of housing and mental health. The results showed that the exterior appearance and the internal insulation were associated with better mental health. The most significant effects were associated with the exterior appearance of the home and the front door increasing the probability of high well-being for the double. The next most significant improvement was insulation, increasing thermal comfort. So, these findings suggest that energy poverty is a relatively complex problem that brings together comfort and esteem issues.

Improvements in insulation were associated with greater comfort and increased social interaction [137]. Older people who report being satisfied with the temperature of their home tend to go out more frequently for hobbies and social activities. Those who reported that their home was cold were more likely to report loneliness [50]. In addition, an increase in the use of rooms in the home was observed, which improved privacy and relationships within families because they were no longer in a small, heated area [189]. In addition, the ability to use more areas in the home for quiet study was found to have led to higher education aspirations and higher academic achievement in parents and children, as well as greater motivation to complete household chores [189]. Upgrades in the management of the heating system have also shown positive effects on mental well-being. The ability to rely on the control of the indoor temperature through the heating system has led to relief from anxiety and a positive feeling of empowerment, which can also be extended to greater control of fuel costs.

However, there have also been found cases where there is no clear relationship between improvements in energy efficiency and its impact on well-being. For example, Barton *et al.* [16] conducted a study in which they introduced improvements such as insulation, ventilation, heating installation, rewiring, and re-roofing in homes with the objective of measuring their impact on people's well-being. Although the intervention resulted in homes that were warmer, drier and more energy efficient, no statistically significant impact on overall well-being was demonstrated. Liddell & Guiney [135] stated that although there is consistent evidence in the relationship between mental well-being and cold and damp homes, to date there are not enough studies. So, more studies are needed to conclude this.

1.2.4 Summary

The prevalence of cold conditions inside a house leads to health complications, a high number of deaths in winter, and deterioration of mental health. The cold inside a residence intensifies a preexisting disease such as arthritis and cardiovascular and respiratory disease. The excess of deaths generated in winter due to cold inside the home reached 7,000 deaths in Chile in 2018. However, this number could be even higher if considered that zones located in the south of the country have winters longer than the four months proposed in the original definition.

Mental health deterioration has been detected through households that have persistent concern about debt and their ability to cover energy costs, affecting their well-being due to the high levels of stress experienced. In addition, some people must reduce their caloric intake in the winter months because they must decide between spending their resources on an adequate energy service or purchasing food because they cannot get both.

Comprehending the implications of energy poverty necessitates consideration of the significance of implementing energy efficiency measures in residential settings to mitigate these implications. This study employs a modeling approach to ascertain the magnitude of reduction in energy demand that households may experience upon the implementation of energy efficiency measures such as insulation of roofs, walls, and floors, double glazing, and enhancements in the efficiency of heating systems.

1.3 Main factors contributing to energy poverty

The inadequacy of sufficient energy resources within households can frequently be ascribed to a range of economic and demographic factors, such as income level, educational attainment, employment status, age, marital status, energy costs, the presence of individuals with poor health and/or chronic illnesses, as well as the reception of social assistance [126, 181]. An in-depth analysis of select determinants will be conducted in Sections 1.3.1 and 1.3.2, with the objective of clarifying their interrelations and significance in the context of energy poverty. This investigation will further aim to assess the factors that render Chilean households more prone to experiencing energy poverty.

1.3.1 Economic factor

1.3.1.1 Incomes

Low-income status is a significant determinant of vulnerability [181]. Households with low income levels frequently face the challenge of securing sufficient energy to meet domestic requirements in addition to other financial obligations [116, 9]. Furthermore, such households often experience difficulties managing housing expenses and are inclined to allocate a greater proportion of their income to energy costs compared to other socioeconomic demographics [21, 157]. Research indicates that in certain US cities, low-income households allocate, on average, between 10 to 20% of their income to energy expenses, while wealthier households, despite consuming more energy, allocate only approximately 1.5 to 3% of their income for the same purpose [131].

Research conducted in Canada revealed a parabolic relationship between energy consumption and socio-economic income levels. Households within the highest and lowest income brackets exhibited reduced energy consumption per unit of floor area, whereas those in the middle income bracket consumed the most. The underlying reasons for this phenomenon may vary; however, it is suggested that lower-income households may consciously reduce their energy use to reduce their energy bill liabilities by adopting practices such as lowering room temperatures during the heating season. In contrast, households with the highest income are likely to implement advanced energy efficiency techniques and control systems, resulting in a decrease in heating costs per unit of floor area [178]. The correlation between energy consumption and the levels of socioeconomic income has not yet been explored in the context of Chile. Consequently, this research will carry out a comprehensive analysis to discern the patterns exhibited by low-income households in this regard.

1.3.1.2 Educational attainment

This section elucidates the relationship between the educational attainment of adults within a household, along with its correlation with income, and energy poverty. In addition, it examines the impact of fuel poverty on individuals who undergo education, attributed to the living arrangements adopted to improve their comfort.

Initially, the level of educational attainment among adults within a household is linked to the state of energy poverty. Lower educational attainment adversely impacts income levels, thus increasing the likelihood of households experiencing energy poverty. As indicated in the 2018 Energy Poverty report conducted in Spain, households with primary income earners who have limited educational qualifications are more prone to experiencing energy poverty [181]. This vulnerability arises because individuals with lower educational credentials are often restricted to employment opportunities that offer lower income potential, thereby hindering their ability to meet energy expenses [48, 109].

Second, challenges in meeting energy payment obligations can adversely impact the performance of individuals engaged in an educational process, thereby influencing their educational attainment. Inability to meet energy costs induces stress, which is associated with behavioral problems in children, making them more susceptible to diminished academic motivation and increased difficulty maintaining concentration [92, 94]. In addition, some households adopt measures such as limiting energy usage to specific rooms to minimize energy expenses. This approach forces all residents to stay in the same room, causing distractions during homework and overcrowding, which consequently affects the potential educational achievement of children [126].

Thus, a lower educational attainment of household members results in decreased income, thereby increasing the likelihood that households experience energy poverty, which in turn adversely impacts the educational attainment of their offspring. This dynamic has the potential to become a recurring cycle that affects successive generations and may become embedded over time. However, while there exists a strong correlation between educational attainment and income, the correlation between income and energy poverty (EP) is considerably weaker, as income is not the only factor influencing EP.

1.3.1.3 Property tenure

Research conducted in the United States indicates that both renting and home ownership present distinct challenges that can exacerbate energy poverty [126]. Low-income groups are disproportionately affected by energy poverty because they often lack home ownership. Consequently, they reside in properties rented from landlords or managed by non-profit organizations [23, 181, 178].

The principal challenge facing low-income tenants is that the energy efficiency level of a residence is determined by the landlord. Low-income tenants have limited ability to persuade property owners to implement effective energy efficiency improvements [118, 115]. Furthermore, landlords generally prioritize generating a return on their investment, which results in a reluctance to undertake improvements that may neither increase rental income nor enhance property value. In the Netherlands, Hope & Booth [122] illustrated that landlords frequently exhibit a lack of financial motivation to improve the energy efficiency of rental properties, particularly for those aiming at low-income demographics. Their survey revealed that only 2% of the landlords rated the energy efficiency of their properties as excellent. Several constraints were cited, including substantial initial costs, the absence of direct personal benefits, and uncertainties regarding actual cost savings. Only 7% of the respondents indicated that a lack of government subsidies discouraged improvements. Some landlords also contended they are disinclined to upgrade properties due to tenant behaviors that have caused damage to the rented premises [117].

Many owners of rental properties refrain from or delay the implementation of energy efficiency improvements in their units, as they do not reside in the rented area and since their tenants often bear the responsibility of settling their own energy expenses [126]. Moreover, there is an absence of regulations that mandate a minimum efficiency standard, particularly in older housing constructed under building codes that placed less emphasis on sustainability [126]. Consequently, these decisions result in low-income renters often living in substandard homes without adequate weatherization and efficiency improvements [21]. In the UK, to address the issue of energy-inefficient housing faced by renters, the government has recently tried to require landlords to upgrade properties to Energy Performance Certificates (EPC) of C, thus altering market dynamics to favor tenants [11]. In contrast, in Chile, no additional requirements for energy efficiency have been instituted for rented dwellings, nor have there been any encouragement towards the improvement of thermal improvements to meet current thermal regulations.

1.3.1.4 Energy prices

Low-income households often face considerable challenges in providing enough energy to meet domestic needs while also covering other financial obligations [9, 116]. Substantial energy bills can result in delayed or missed payments, which may subsequently lead to service disconnections and temporary deprivation of essential services such as heating, lighting, hot water, and refrigeration. This persistent cycle can result in these households living in consistently cold homes due to the in-affordability of heating costs [126]. Furthermore, they may incur additional charges for the reinstatement of energy services and face higher monthly payments due to the discontinuation of equalized billing arrangements, which exacerbates their financial precariousness [178].

Fluctuations in energy prices correspondingly affect the proportion of people experiencing energy poverty (EP). Liberalization of the energy market in both developed and developing countries in 2008 precipitated an increase in energy prices [130]. Transformations within the electricity sector resulted in a 100% increase in electricity prices in certain European nations during the period 2000 to 2010, impacting 150 million individuals who consequently faced social exclusion and deprivation [45]. Consequently, households have been forced to reconceptualize their approach to energy consumption, moving from a paradigm of readily accessible energy to one characterized by financial constraints, compounded by the absence of previously available government subsidies [178]. Furthermore, it has been identified that the resistance to recovery varies according to the direction of transition. Although descent into EP occurs with relative ease, regaining a former state of financial stability proves challenging due to obstacles such as alterations in payment methods and incentives, which hinder the reacquisition of favorable energy deals that benefit prompt payers [178].

In Chile, the cost of electricity is among the highest in South America and occupies an intermediate level compared to OECD countries [60]. Regarding gas, there were significant price increases between 2009 and 2018, impacting the whole country, with the most pronounced effects observed in the central and southern regions, where prices increased by 59% and 64%, respectively [57]. There has been no previous identification of thermal zones with elevated energy prices or the disparities between them. This identification would be beneficial for detecting areas more susceptible to experiencing energy poverty, and consequently, this analysis will be presented later in this document.

The Chilean gas market has been the subject of controversy. In 2020, the National Economic Prosecutor's Office (FNE) indicated that there are valid reasons to believe that the gas market is not functioning effectively, primarily due to the high industry concentration (FiscalíaEconómica,[86]. Three companies, Gasco, Abastible, and Lipigas, control the importation, transportation, storage infrastructure, distribution, and sales of liquefied petroleum gas (LPG) within Chile. Limited competition in the gas market facilitated an increase in distributor profits during a period of declining gas prices from 2014 to 2020, without corresponding price reductions for end consumers. The FNE recommended that these companies stop distributing LPG and proposed reforms aimed at lowering gas prices. The FNE estimates that implementing these recommendations could result in a 15% reduction in the cost of bottled gas. Such a reduction would reduce consumers' energy bills, thus supporting efforts to lower economic pressures (EP).

The increase in energy prices can be addressed through a variety of strategies and measures. Some strategies involve interventions in energy tariffs, while others focus on the implementation of energy efficiency measures within dwellings. The French government suggests the introduction of social tariffs for low-income households, debt reduction, and other government benefits, in addition to promoting measures of energy efficiency [178]. Similarly, the Australian government offers payment arrangements and reduced tariffs for low-income households; however, researchers have criticized these measures as being overly restrictive, thus excluding many households suffering from energy poverty [178]. In Spain, while targeted support is provided to vulnerable households, comprehensive interventions such as energy retrofitting in dwellings have not been proposed [180]. In contrast, the

UK has made substantial investments in programs aimed at improving the thermal performance of social housing. These programs include measures such as exterior wall insulation, improved heating controls with new heating systems, boiler replacements, loft insulation, and glazing replacements, among others [87].

In Chile, while reduced tariffs have not been implemented for low-income households, certain energy efficiency initiatives have been implemented. The government has provided subsidies for energy retrofits in social housing, particularly in the southern regions of the country, including insulation upgrades and the replacement of old wood stoves with more efficient pellet-based heating systems [133]. Despite the improved efficiency of this heating system, the transition to pellet usage has resulted in increased operational costs as a result of the shift to a more economical fuel source, such as wood. Consequently, such programs have been suggested to focus on families that are able to afford more expensive fuel alternatives or introduce economic incentives such as reduced tax rates for cleaner fuels to improve affordability for low-income households [133]. In practical terms, most retrofit programs have been accessible to low-income households; for example, a minimum of 80% of the total resources allocated to the Coyhaique wood stove replacement program were directed toward the lowest income groups [49], yet no economic initiatives were incorporated, such as reduced tax rates for cleaner fuels.

In recent years, the Ministry of Environment initiated a program to replace wood stoves in areas that experience high levels of pollution attributable to the combustion of wood and charcoal particulate matter. This program was implemented without incorporating any socioeconomic assessments. Between 2011 and 2019, the program facilitated the replacement of 40,256 heating appliances, with pellets and kerosene emerging as the predominant fuel choices for installations between 2017 and 2019 [49]. Regrettably, during the winter of 2022, the central and southern regions of the country experienced a pellet shortage, attributed to an insufficiency of raw materials (specifically wood), resulting in volatility in both availability and pricing. Consequently, a portion of the 150,000 households that use pellets in 2022 faced challenges in maintaining adequate heating, alongside price spikes of up to 30% in certain regions due to the supply shortfall.

1.3.2 Socio-demographic factors

Empirical evidence indicates that elderly individuals and families with children should be designated as vulnerable households [150]. This is due to the fact that elderly people exhibit increased susceptibility to temperature fluctuations, making them more prone to hospitalization for respiratory and cardiovascular diseases. Furthermore, the findings reveal that households made up of elderly individuals allocate a substantial portion of their income to energy expenses, potentially leading to financial difficulties in addressing other necessities [137].

Numerous scholars claim that low-income elderly people living alone are susceptible to energy poverty [181]. In the UK, research indicates a high likelihood that low-income elderly residents of large dwellings, larger than 110 square meters, with low occupancy levels, experience energy poverty [154]. In Spain, the likelihood of energy poverty among households comprising elderly members with characteristics such as low income, under-occupation, and low energy efficiency increases to 97% [181]. This suggests that nearly all individuals living in such conditions are invariably affected by energy poverty.

1.3.3 Energy use behavior

The behavior of individuals who live within a household significantly influences energy consumption. Comprehending energy usage behavior is crucial for informed policy decision-making. This section elucidates two phenomena that contribute to understanding energy consumption: the prebound and rebound effects.

1.3.3.1 Prebound effect

The prebound effect quantifies the extent to which energy consumption is lower than anticipated prior to the implementation of retrofitting measures. This phenomenon supports the notion that the energy consumption of the occupants diverges from the assumptions embedded within standard computational methods to assess the energy consumption ratings of the dwellings. Substantial evidence of underconsumption prior to energy efficiency improvements has been documented in

Germany, France, the Netherlands, Belgium, and the United Kingdom. Notably, observations related to the prebound effect demonstrate that for any specific calculated consumption value, actual consumption values exhibit significant variability, with actual consumption averaging approximately 35% below calculated consumption [176]. This discrepancy increases as the calculated consumption increases, whereas in low-energy houses, with minimal calculated consumption, the discrepancy reverses (see Figure 1.1). In Chile, no examination has yet been conducted to discern the disparity between actual and projected energy consumption. This issue is of importance, as it has been suggested that addressing fuel poverty requires the identification of households characterized by a combination of a pronounced prebound effect and low income [176].

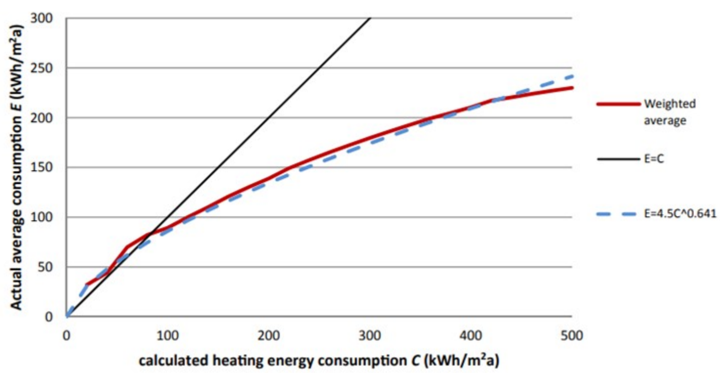


Figure 1.1: Composite plot of weighted average of 7 datasets, 3700 data points for actual and calculated heating consumption in German dwellings [176].

The factors contributing to the discrepancy between projected and actual energy consumption are varied. For example, low-income households have been observed to adopt specific strategies to minimize their energy expenditures. One such strategy involves limiting energy usage to particular rooms to compensate for inadequate heating systems. Consequently, most family members are obliged to share this confined space, resulting in overcrowding and potential distractions, among other issues [126]. In Chile, data from the 2018 Survey on Energy Use in Chilean Housing have indicated a distinct pattern of heating only occupied rooms in the central-north region of the country, while in the southern region, households tend to heat the entire home [40]. The extent of restrictions on energy use imposed by low-income households should be taken into account in the calculation of expected energy demand.

1.3.3.2 Rebound effect

Theoretically, the implementation of exceptionally high thermal standards has the potential to reduce net household heating demand to nearly zero, which, depending on initial conditions, is expected to yield substantial reductions in energy demand and consumption. However, the extent of this reduction is influenced by the behavior of the occupants.

The rebound effect denotes the situation in which a portion of the anticipated energy savings derived from the retrofit is offset by additional energy consumption. This may occur, for example, due to an increase in internal temperature that results in greater comfort, or the allocation of financial savings toward the purchase of new appliances [175]. Accurate measurement of the magnitude of the rebound effect presents challenges; however, it is estimated to range from 10 to 35%. Neglecting to account for the rebound effect has been identified as a factor contributing to shortcomings in the achievement of energy policy objectives and explains the discrepancies between actual energy savings and projected estimates that claim savings of 70-80% [176].

The rebound effect was identified in a study that examined how user behavior impacts energy consumption following the retrofitting of social housing in the UK. The findings indicated that although retrofitting substantially improved home conditions and reduced energy usage, it did not achieve the estimated £300 annual savings on household energy bills, with actual savings reaching only 30% of the projections. This shortfall can be attributed to ingrained habits of the residents, changes in preferences towards greater comfort, and the lack of information provided to help residents manage their home energy use after the renovation [87]. Another study yielded comparable results. Energy efficiency upgrades were implemented in social or rental housing units, yet energy consumption decreased only by a third of what was expected. The analysis indicated that residents increased their heating temperatures during winter, highlighting their thermal comfort [178].

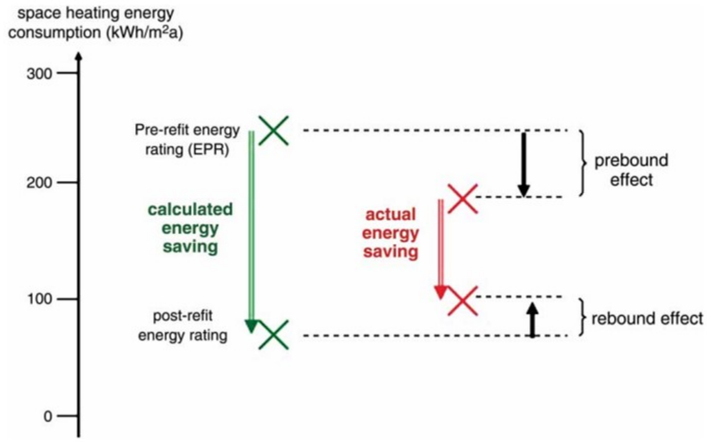


Figure 1.2: Schematic showing how the prebound and rebound effect may limit energy saving to be reduced from its theoretical amount [175].

A distinct pattern of behavior has been observed among low-income households after retrofitting interventions. Nicol and Humphreys conducted an analysis of resident behavior, revealing that low-income households were more frequently subjected to temperatures below 18°C compared to other groups [179]. Studies suggest that only a minority of households opt to achieve the warmth standards recommended by the World Health Organization, even when this could be achieved without incurring additional costs after the retrofit [152]. This observation may indicate a less pronounced rebound effect within certain low-income families. Further research demonstrated that, despite interventions aimed at improving heating and insulation, residents opted for reduced energy consumption. The findings suggest that these households continue to endure limited heating, even when they could achieve a warmer and drier living environment at no additional cost compared to prior conditions [108, 6].

Following the implementation of energy efficiency measures, the reactions of the occupants can vary significantly. For those experiencing energy poverty prior to these interventions, such measures might result in substantial energy savings, although potentially less than anticipated, while offering the potential for increased thermal comfort. Additionally, there exist households that, despite benefiting from these measures and reducing their energy expenditures post-retrofitting, do not clearly experience an enhancement in comfort compared to pre-measure conditions.

1.3.4 Housing energy inefficiency

Energy inefficiency in housing is a significant concern within the framework of energy poverty [126]. The interrelation between housing energy efficiency, energy poverty, and income was clarified through the findings of the English Housing Survey conducted in 1996 [23]. Low energy efficiency dwellings are characterized by insufficient insulation, leakage, and other defects that allow the intrusion of external elements, thus complicating the regulation of indoor temperatures and leading to increased utility costs and hazardous environments [139, 188]. In addition, these dwellings often exhibit additional deficiencies, such as the lack of air conditioning and the inability to provide effective ventilation [47].

A prominent contributor to energy poverty is the widespread occurrence of outdated housing structures. Households experiencing economic disadvantage are more inclined to live in older and lower quality homes, which are frequently marked by insufficient or absent insulation and high air infiltration rates, culminating in suboptimal indoor climatic conditions [5]. In the Spanish context, economically disadvantaged households that occupy government-supported multifamily dwellings, built between 1940 and 1980, are significantly associated with inadequate heating systems and inferior insulation standards [164].

Retrofitting represents a viable solution to address the issue of energy inefficiency in housing. This process improves the quality and efficiency standards of housing, thereby decreasing energy expenditures and increasing affordability. Furthermore, such interventions can contribute to improvements in health and well-being, raising comfort levels within residences and decreasing reliance on health services, which could lead to potential cost savings for National Health Services [137].

Enhancements in the building envelope, which include elements such as walls and roofs, have been identified as the most cost-effective measure to improve energy efficiency, thus addressing indoor environmental quality and energy consumption challenges in low-income households in Europe [137]. In the United Kingdom, the issue of energy demand within low-income households is predominantly addressed through the installation of insulation. Several non-profit housing projects, which were originally constructed with inadequate energy designs, underwent retrofitting measures. Subsequent post-construction research indicated that these improvements contributed to energy savings and significant improvements in the thermal comfort experienced by the occupants. According to the findings of Calderón & Beltrán [37], a retrofit that involved the installation of high-density mineral wool and contemporary double-glazed windows resulted in a 27% reduction in overall energy consumption.

In addition, interventions, such as the implementation of insulation, have been documented to exert a significant influence on indoor temperatures. During the winter season, indoor temperatures and thermal comfort levels were assessed in 2,500 low-income housing, both before and after renovation, as part of the UK's national Warm Front program. The average temperature in the reference buildings before any intervention was approximately 16.4°C, while it was observed at 17.6°C in the insulated dwellings. In centrally heated houses, the temperature recorded was 18.3°C, while in insulated and centrally heated dwellings, it was observed that it was 19.2°C. Furthermore, the temperature considered neutral by residents increased from 18.7°C in the reference houses to 18.75°C in the insulated ones. In centrally heated houses, this neutral temperature rose from 19.06°C to 19.32°C[121].

Despite the demonstrated advantages of retrofitting programs, they have not been prioritized by certain nations. According to Rezaei [161], residential retrofitting is rarely highlighted as a priority within energy poverty or climate change mitigation policies, as studies conducted in the United States and Canada have questioned the efficacy and comparatively high costs associated with such initiatives. In addition, policy and research often emphasize economic measures, such as subsidies, rather than structural strategies, such as energy efficiency upgrades or the integration of clean technologies [126]. In Chile, the Ministry of Housing has concentrated its efforts on mitigating heat losses in social housing by providing subsidies for thermal envelope improvements [133], but the effectiveness of these programs remains unexamined. This study addresses the need to explore and initiate the process of understanding the potential benefits of such measures through modeling.

1.4 Existing metrics of EP

The number of definitions of energy poverty and their respective measurement methods, which are translated into indicators or metrics, is steadily growing both in quantity and complexity [180].

Consequently, there are a wide variety of proposals in the international literature to classify a household as energy-poor. In the first place, there are indicators based on the comparison of energy expenditures with household income. In this group are included indicators such as ten per cent rule, minimum income standard, and low-income high-cost indicator. Second, the multidimensional indicator is an indicator that gathers a set of qualitative and quantitative indicators. Some of these indicators are based on interviews about how effectively people can meet comfort needs and their ability for payment, and others are focused on the comparison between energy expenditure and household income. In addition, there is a third type of indicator that is based on measurements of dwelling temperature in the indoor environment, also known as the direct approach [159]. These definitions or classification methods are discussed in Section 1.4.

1.4.1 Ten per cent rule (TPR)

The ten per cent rule (TPR) was defined in UK by Boardman. She stated that a household is energy poor when it spends more than 10% of their income on energy services [22, 166, 32]. The origin of the TPR concept is based on the results of a survey carried out in the UK in 1988 that showed that the average energy expenditure was 5% of monthly income and 30% of households with the lowest income spent at least 10%. The TPR has spread to other countries, but Boardman herself has warned against uncritically transferring this threshold, which is specific for the UK[23].

After those results were obtained, it was decided in the UK to start doing calculations of the expenditure predicted by building energy models. The information used to calculate those expenditures comes from the English Housing Condition Survey (EHCS) which is a survey that provides information related to condition and composition of the housing stock and the characteristics of the households living in different types of dwelling. Some examples of data collected in this survey are the age of the property, the number of rooms, the heating system, the size of the property, the demographics of the occupants and the patterns of use of energy of the occupants [171].

Then, the Building Research Establishment Domestic Energy Model (BREDEM), which is a highly simplified model, is used to predict the annual energy demand for housing based on their characteristics [8]. The model considers the energy required for space heating and water, lights, appliances, and cooking.

Therefore, it is this transition to the use of the energy model that led to the biggest difference between the method used in the UK and the method used in other countries. The UK method models the energy demand of the owners to achieve a standard (see equation 1.1), while other countries use actual energy data without considering specific characteristics of each house where the users live. Information such as location, property type (detached house, semidetached house, among others), or number of bedrooms is not included within the analysis. Consequently, it is not possible to define how much comfort they are experiencing due to it being only provided how much energy they consume.

$$Fuel\ poverty\ index = \frac{\sum(Fuel\ Price\ \times Modelled\ Fuel\ Consumption)\ +\ \sum Standing\ Charge}{Income} \tag{1.1}$$

In addition, it is a common error not to recognize the difference between actual and required energy expenditure, and it has been an issue of debate that has led to warning about the risks generated by unthinking production and interpretation of energy poverty indicators [180]. In general, it is agreed that actual energy expenditure is relatively easy to determine but is a poor indicator of energy poverty [144]. This is because vulnerable households tend to reduce their energy consumption, a phenomenon known as the prebound effect (see Section 1.3.3.1), to avoid high bills and falling into debt with energy providers. Thus, the actual energy expenditure is lower than the theoretical energy costs required for comfort [119]. The actual energy expenditure in English households is estimated to be between 66% and 82% of the theoretical energy costs required to satisfy an adequate level of thermal comfort [120]. In Spain, data collected by Pares showed that the energy consumption of vulnerable households is 30% lower than the theoretical energy costs required [145].

The method of predicting the required energy expenditure used in the UK is also problematic. First, the BREDEM model relies on multiple parameters such as modeled assumptions, simplifications of physics, and the use of heuristics [114]. Second, it has been found that there is a considerable difference between actual and estimated energy expenditures, and the magnitude of this difference is uncertain because people have rationed their consumption. This includes even the higher income deciles, where self-rationing should not be considered. The above could point out that there is an over-estimation of the manner in which occupants provide for their comfort needs equating to an overestimate of comfort.

In Chile, only one study has been conducted quantifying the number of people in energy poverty using the TPR. Data of actual expenditure in energy services provided by the 2013 Family Budget survey were used, and the results showed that 12.9% of households at the national level were affected by the EP, corresponding to 13. 4% for the metropolitan region and 12.3% for the rest of the regions[43]. The authors highlighted that the TPR indicator showed that there are middle- and high-income households that spend more than 10% of their income on energy services. This could be an indicator that due to a lack of adequate thermal conditioning, the dwelling could have a greater energy demand even when the income of the households is higher. Another alternative could be that they do not have significant demands on their income, i.e., they may have a large disposable income which gives them more ease to destine a higher proportion of their income to energy and therefore get comfort.

Nevertheless, the research made by Cerda et al. [43] shows several problems with the methods. They used the TPR but it is not clear that this is the appropriate threshold for all Chilean regions. This is because the country has diverse climates that can lead to different energy requirements. For example, households in the south could use a higher proportion of their income for energy, which could exceed the TPR. According to the authors, the reasons for this limitation could be explained by a lack of regional representation in the data provided by the Family Budget Survey that does not allow for an analysis by zone.

1.4.2 Minimum Income Standard (MIS)

Minimum Income Standard (MIS) was proposed in the UK in 2012 by Moore [144]. According to Moore, a household will be considered in energy poverty if, after deducting their actual housing costs and minimum living costs (defined by the MIS), they have insufficient residual income to meet their fuel costs (see Equation 1.2). The latter is calculated on the basis of the data provided by the English Housing Condition Survey [144].

$$Fuel\ costs < Net\ household\ income\ -\ Housing\ costs\ -\ minimum\ living\ costs\ (MIS) \quad (1.2)$$

MIS is comprised of several items, but excludes some as well. In general, MIS budgets include food, alcohol, clothing, council tax, household insurances, household goods, transport, social and cultural participation, among others [29]. Two important items are excluded from the budget: formal childcare costs and housing costs [144]. Formal childcare was excluded because its cost varies considerably throughout the country [183] and was also shown that up to two thirds of young families with the lowest income do not use it because they leave their children with friends or relatives [169]. Due to the variable nature of childcare costs and housing costs, these will be considered as variable costs for real households, adapting them according to each case [29].

Fuel poverty based on the MIS definition has shown some advantages. The definition of MIS provides a consistent, methodologically, and accurate measure of the affordability of fuel [144]. In addition, it takes into account a method to equivalise income to make household income comparable between them. Before the MIS definition was presented, the Organization for Economic Co-operation and Development (OECD) had proposed a scale to equivalise income between households which was adopted by national governments without any scientific basis. Then, because the results of the scale of income equivalisation are similar to those obtained from the square root of the number of people in the household, the latter was adopted as a formal measure to calculate the income equivalisation factors. However, the European Union statistical office (EUROSTAT) stated that these income equivalisation factors were overestimating the needs for children. So, the values of the square root that involve children were decreased. The reasons for this decision were not explained [29]. Unlike OECD, MIS proposes a scale to equivalise income in a more transparent way. MIS scale is based on actual results considering the different compositions of families. In the MIS scale, a distinction between income of singles-couples in working age and those who are retired was considered. In addition, the difference between families considering childcare and those who do not was considered. None of these parameters was contemplated on the OECD scale.

Although there still must be a detailed calculation of the fuel expenditure needed by each household to ensure that it has adequate heating and energy services in the home, the MIS definition provides, in principle, a much more direct and relevant measure of need. The threshold for fuel poverty in which total required fuel costs exceed the remaining available household income (difference between household income and housing cost and MIS) appears justifiable and could be easily adaptable to the different incomes and minimum living cost of other countries as long as the required energy costs are considered [144]. The fact that the method could be applied to any country seems to be, at least in part, because this method uses mainly gathered data (which could already be available) as opposed to predicted data.

Different organizations have conducted studies to determine the standard budget for households using the MIS method as a reference. MIS has been replicated in countries such as Australia, Belgium, Finland, France, Ireland, Japan, the Netherlands, and Portugal, among others. Some modifications were made to the original method, adapting it according to the country and the objectives and budget of the studies. For example, in Ireland, the objective was to generate a standard, based on a consensus reached by the population, that could be used as a benchmark in the public debate. In Belgium and the Netherlands, the objective was to socially validate the budgets that had already been developed by experts comparing them with the budget using the MIS method [51].

In Chile, the MIS could be applied, but some considerations must be considered to calculate the minimum living costs. First, the Chilean minimum wage cannot be used in the MIS definition because it is not a reference for the cost of living. According to the definition delivered by participants of the original MIS research in the UK, a minimum income standard of living in the UK should include but is more than just food, clothing, and shelter. It is about having a socially acceptable living standard and having what you need to have the opportunities and choices necessary to participate in society [29]. In contrast, the Chilean minimum wage is the lowest monthly amount that a worker may receive by her/his work [84], value that has reached $326,500 CLP in September 2020 ((£ 317 GB). This value is set by law and is the result of a process characterized as more political than technical as there are no formal criteria established by the government to calculate it. However, in practice, government and labor representatives annually propose a minimum wage rate based on inflation and increases in productivity [149]. Thus, the minimum wage is increased according to economic development, allowing for the compensation of a loss of purchasing power. Therefore, the Chilean minimum wage is an arbitrary value that is not designed to cover a list of needs, and even less if this amount of money covers satisfactorily the needs of a person considering a standard, which is the final goal of MIS.

Second, the poverty line could be used as a reference of minimum living costs but with some limitations. The poverty line is the lowest amount of money that a person needs to survive in Chile. The data provided by CASEN are used to calculate the total expenditure of the households with the lowest income. In this budget is included the basic food basket, which considers all the food required to cover a daily dietary of 2,000 calories per person, and goods and services acquired by 90% of the households with the lowest income [54]. Some of the items included in the basket are food and non-alcohol beverages, alcohol beverages, clothing and shoes, basic housing and services, equipment and home maintenance, health, transport, communications, culture and recreation, education, restaurants and hotels, and various services [70]. Therefore, the basket is made up of basic products, such as bread and rice, and recreation services such as sports entertainment, cinema tickets, and television [73]. However, unlike MIS, it does not have associated a certain level of standard of living or the level of well-being and satisfaction that a consumer obtains from them.

In Chile, the number of people affected by EP was quantified using the definition of MIS proposed in the UK. Some adjustments were made due to the availability of information. The minimum living cost was replaced by the poverty line provided by CASEN and fuel costs were obtained from the actual energy expenditure of households provided by the 2013 Family Budget survey. Expenditures for electricity, natural gas, LPG, paraffin, charcoal and wood were included. The results indicated that 15.7% of the population was affected by EP according to the definition of MIS [43]. The lowest income decile was highlighted to concentrate the largest part of the households affected by EP, reaching 66%.

1.4.3 Low Income High Cost (LIHC)

The Low Income High Cost (LIHC) indicator was adopted as an official metric of energy poverty in England in 2012 [120]. The LIHC indicator is a dual indicator. It determines the number of households that have both low income and high fuel costs; and determines the magnitude of fuel poverty that these fuel poor households experience, also known as the fuel poverty gap (see Figures 1.3 and 1.4). The fuel poverty gap represents the difference between the required fuel costs for each household and the nearest fuel poverty threshold [30]. It can also be understood as the amount in pounds by which the energy requirements assessed by fuel-poor households exceed the reasonable costs threshold[120].

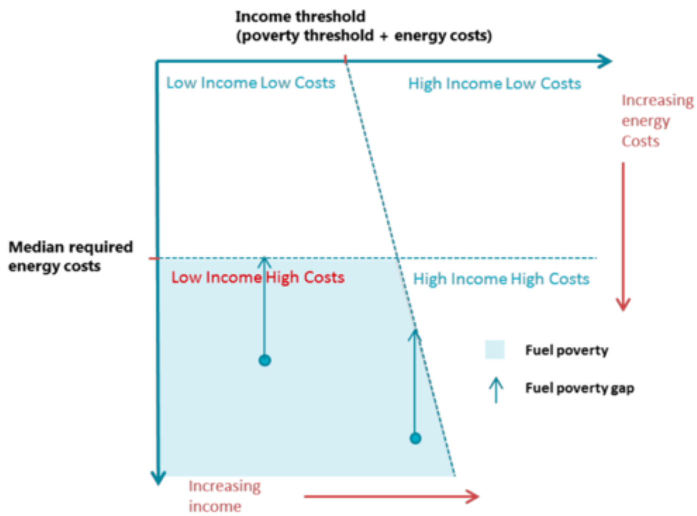


Figure 1.3: Low Income High Costs indicator [30].

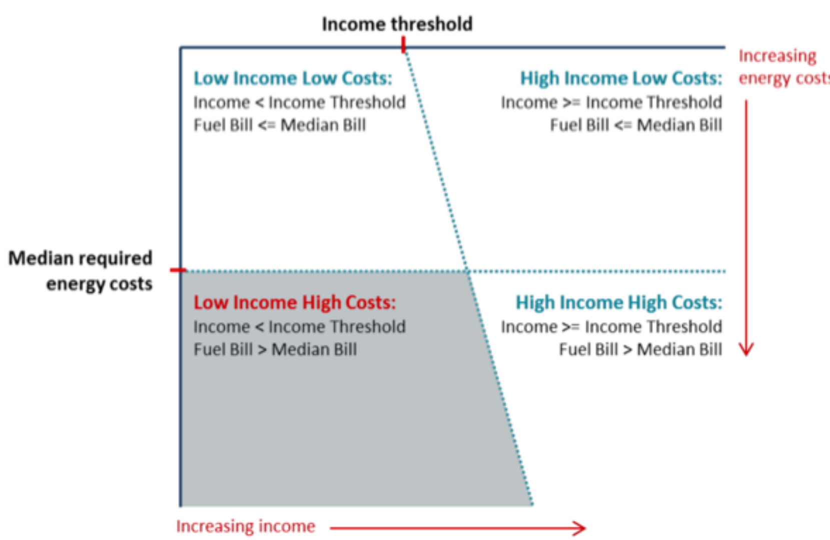


Figure 1.4: Low Income High Costs matrix classification [30].

According to the LIHC indicator, a household is fuel poor if they have required fuel cost above the national median level and also if they spend that amount, a residual income below the official poverty line is left. Therefore, the LIHC definition is a relative indicator because it compares households with the national median fuel costs and income, reflecting current trends [30].

LIHC indicator is comprised by three components: income, energy consumption, and fuel prices [30]. In a similar form to the TPR, the information comes from the EHCS and their responses are used in the BREDEM model [170] that calculates the energy required for space and water heating, lights, appliances (including requirements for pumps, fans and electric showers, and energy generated by renewables) and energy for cooking [30].

The English annual Fuel Poverty Statistics indicate that the proportion of households in fuel poverty decreased to 10% in 2018 (from 11% in 2017) and the average fuel poverty gap was estimated at £334 per year[172]. It was also identified that, in line with the 2020 fuel poverty target, 93% of all fuel-poor households live in properties with an energy efficiency rating of Band E or better, being E the minimum level of energy efficiency requested by the government [110].

In Chile, only one study has been conducted quantifying the number of people in EP using LIHC. The median required energy cost was calculated using data provided by the 2013 Family Budget survey and the poverty line reported by CASEN was used. The results showed that 5% of the population was affected by EP according to this metric[43]. However, these findings have the limitation that the data reported by the Family Budget survey only allowed to determine the percentage of households affected by EP at national level because it does not provide data by regional area.

1.4.4 Low Income Low Energy Efficiency (LILEE)

The Low-Income Low Energy Efficiency (LILEE) indicator was adopted as an official metric of EP in England in 2021, replacing the LIHC indicator proposed in 2012 [31]. The LILEE is also a dual indicator. It determines the number of households that have low incomes and low energy efficiency; and determines the depth of fuel poverty among these fuel poor households, measured through a fuel poverty gap (see Figures 1.5 and 1.6). The fuel poverty gap is defined as the difference between current fuel costs and the fuel costs modeled for a household at the band C threshold (Fuel Poverty Energy Efficiency Rating, FPEER 69); or the difference between disposable income after fuel costs and the low income threshold, whichever is smaller [31].

According to the LILEE indicator, a household is fuel poor if they have an FPEER of band D or below and if they spend their modeled energy costs, a residual income below the official poverty line is left (60% of the median disposable income) [31]. Therefore, the LILEE indicator sets an absolute energy efficiency threshold, making it easier to identify the impact of changes in energy efficiency. Differently, the relative nature of the income threshold makes it harder to see the impact of changes in income and the contribution of prices, since this requires an assessment of how household income and fuel costs change relative to median income [173].

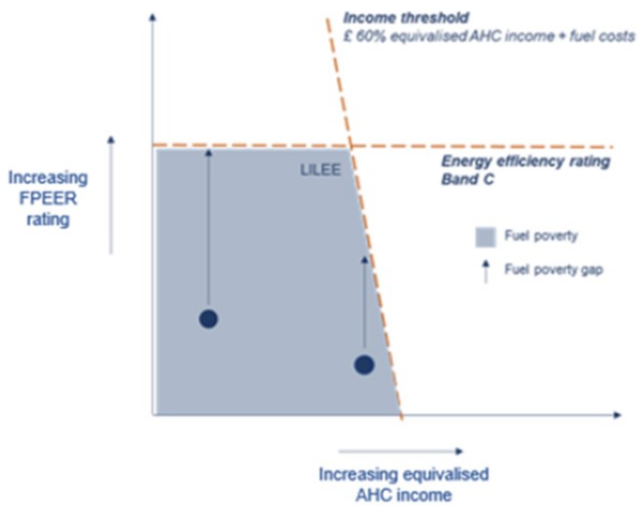


Figure 1.5: Fuel poverty under the Low Income Low Energy Efficiency indicator [30].

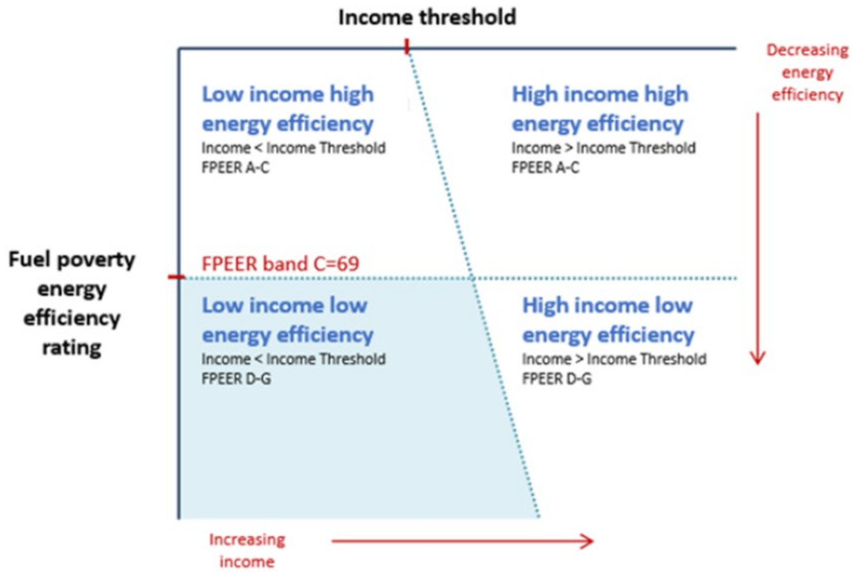


Figure 1.6: Classifications under the Low Income Low Energy Efficiency matrix [30].

In the LILEE indicator, it is intended to capture the three key drivers of fuel poverty: income (after housing costs), fuel prices, and energy efficiency. Similarly to TPR and LIHC, the information to calculate this metric comes from EHS and their responses are used in the BREDEM model to calculate the cost of energy for households (see Sections 1.4.1 and 1.4.3).

The Government Standard Assessment Procedure (SAP) is used to evaluate the energy performance of domestic properties (FPEER). In this methodology, an energy efficiency rating is generated from 0 (lowest) to 100 (highest). Then, this rating is translated into an energy efficiency band which moves from G (lowest) to A (highest).

The English annual Fuel Poverty Statistics indicate that the proportion of households in fuel poverty under LILEE decreased to 13.2% in 2020 (from 13.4% in 2019) and the average fuel poverty gap was estimated at £223 per year (£229 in 2019) [173]. It was also identified that, in line with the 2030 fuel poverty target, 52.1% of all fuel-poor households in 2020 (14.6% in 2010) live in properties with an energy efficiency rating of band C or better, being C the minimum level of energy efficiency requested by the government [173]. This reflects the improvement in energy efficiency in dwellings between 2010 and 2020 which has brought more low-income households up to band C which removes them from fuel poverty.

FPEER has been considered an absolute form of measurement. However, in practice, SAP has been observed to consider policies such as the Warm Home Discount (WHD) within its calculation of the FPEER band, discounting money from households' energy bills. For example, if a household has a band D and gets £140 deducted from their energy bill due to receipt of the WHD, this could move them into an FPEER band C. This is because households who live in energy efficiency band D properties have an average gap of £115. So, government subsidies could impact the property efficiency rating incorrectly because some properties will be classified as band C in the short term, but in practice this is not a permanent solution because if they do not receive that subsidy anymore, their property would be classified as band D. Considering that WHD was provided to more than two million households in 2021 [173], the introduction of this government measure to tackle poverty could mask the number of fuel-poor households because if they no longer receive a subsidy they will fall into band C, and the number of fuel-poor will increase, making these measures not a permanent solution.

1.4.5 Direct approach

The direct approach is based on the comparison between the level of domestic energy services achieved and a specific standard previously determined. The most common example of this approach is temperature measurements in a house that look to compare results with standards to ensure comfortable indoor temperatures. The most widely used reference temperatures were provided by the World Health Organization (WHO) in 1987 [153, 185]. The standard temperature proposed by the WHO varies between 18°C and 21°C (in winter conditions) because this range was found to be not associated with health risks for healthy adults using appropriate clothing, humidity and other factors. Higher temperatures were recommended for the physically vulnerable population to cold, such as the elderly, people affected by diseases, and children [180].

However, studies have suggested that few households choose to achieve the standards of warmth recommended by the WHO, even when doing so would not cost them more money than before performing a retrofit [152]. In terms of income, a research in Canada found that energy consumption had a parabolic relationship with socio-economic group. The highest and lowest income levels showed lower energy consumption per square meter of floor, while the middle income levels consume the most. Reasons for this may vary, but it might easily demonstrate that the lower income household could be voluntary in reducing their energy consumption in an attempt to reduce the amounts due on their energy bills and consequently reduce room temperatures during the heating season [178]. In Spain, low-income households were found to be more frequently exposed to temperatures below 18 ^{o} C than other socioeconomic groups [179].

In Chile, a preliminary examination of real-time indoor temperatures performed in 297 housing units located throughout the country showed that indoor temperatures were generally found to be cold when the European adaptive thermal comfort model is used. Like previous studies conducted in Canada and Spain, it was also found that low socioeconomic groups lived in colder dwellings than those belonging to a mid and high socioeconomic group [143]. Another study carried out in 300 homes located in a city in the southern part of the country, Valdivia, also showed that 68% of the time the temperature in the living room was less than 21 ° C in the winter months [96].

1.4.6 Multidimensional approach

The multidimensional approach has been proposed by the EU Energy Poverty Observatory (EPOV) in 2016. EPOV is a project led by the University of Birmingham and the University of Manchester whose objective is to improve access to available sources of information on energy poverty and to propose indicators that could be applied to all European countries [27].In parallel, the directive of the EU Electricity Market, which is a legislative act that aims to have competitive prices and high standards for electricity services for all final customers of the EU, has developed in the 29 article that each member state should have an EP measure system and the number of households affected by EP should be reported to the European Commission every two years [89]. As a result, EPOV proposed a multidimensional approach.

EPOV proposal consists of four main metrics and a series of secondary indicators. The EPOV project proposes four EP metrics, two based on expenditure-income focus (based on the Family Budget Survey) and two based on perception of dwelling, also known as direct or consensual focus (based on the European Survey on Income and Living Conditions, EU SILC) [113, 112]. Disproportional expenditure on energy services (also known as 2M) and hidden energy poverty (HEP) are the two main metrics based on the focus on expenditure-income. The first one is focused on people that spend (actual) an amount greater than the double of the national median on domestic energy services, suggesting that they occupy very hard to heat homes, or they like to be very warm, which could be the case of households that contain vulnerable members. The second is concentrated in vulnerable households that spend less than half of the national median in domestic energy services, i.e., these households have unusual low energy bills that might be associated with underheating scenarios (see Figure 1.7). The percentage of population unable to keep warm their home and arrears in their energy bills are the two main metrics based on perceptions of the dwelling. In addition, energy prices, building certification, energy use by quintile, available heating and cooling equipment, and complementary aspects are proposed as secondary indicators [181].

EPOV proposed an indicator capable of capture all the diversity of experiences and intensities of energy poverty, admitting that each indicator has some weakness. The original EPOV proposal contemplates each indicator in an independent manner and each indicator has the same level of importance as the other indicator [180]. So, the number of energy poor are analyzed by each indicator independently. More recently, in the Spain Energy Poverty report it was proposed that all indicators should be considered additively[181], which means that the total number of households affected by EP will be the sum of total households affected by EP by each individual indicator, avoiding double accounting of households who are in EP under more than one indicator.

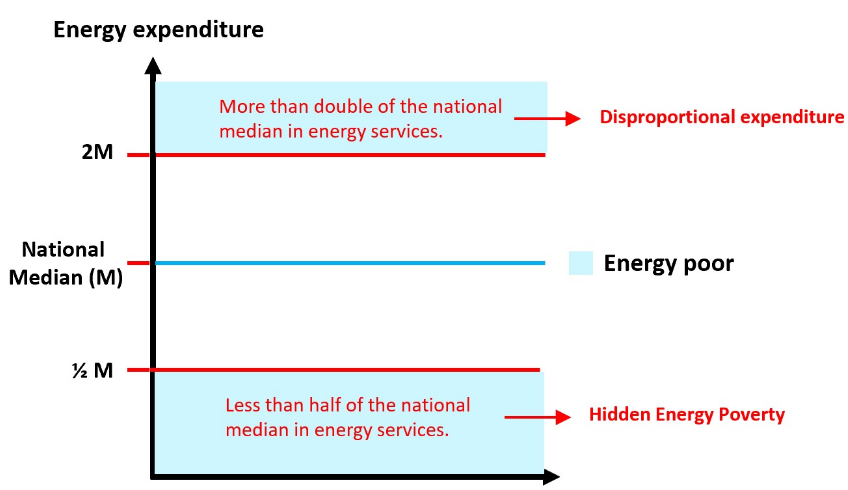


Figure 1.7: Disproportional expenditure (2M) and Hidden Energy Poverty (HEP).

The EPOV proposal was applied for the first time in Spain. The results showed that domestic energy expenditure was disproportionally high for 17% of the residents (8 million of the population), extremely low for 12% (5.4 million), 4.6 million cannot keep their house at a suitable temperature and 3.6 million were affected by bills due in 2016. Thus, if all these criteria are considered together, 41% of residents of Spain (19.1 million) would be affected by some of the proposed indicators. This percentage is considerably higher than it was considered for each indicator independently. Therefore, the results could lead to a debate about how indicators overestimate the EP numbers [181].

1.4.7 Poverty Adaptive Degree Hourly Index (PADHI)

The Poverty Adaptive Degree Hourly Index (PADHI) was proposed in Chile by Pérez-Fargallo et al. [155] in 2020. This is a risk indicator for the EP that combines the number of inhabitants in poverty and the required degrees per hour of heating and cooling according for each territory, considering the wide variety of climates of Chile. Most buildings were assumed to have low levels of thermal performance because technical requirements were recently included in construction codes, so they can be represented by a single building type. In terms of the limits of thermal comfort, the standard of thermal environmental conditions for human occupancy (ASHRAE 55-2017) was used considering an adaptive thermal comfort model. This means that the limits of comfort temperature will depend on the mean outdoor air temperature, resulting in a different temperature for each place that is being evaluated. Data for outdoor air temperature to feed the ASHRAE 55 were obtained from the Chilean Ministry of Energy. However, this model can be applied only if the outdoor temperature is between 10°C and 33.5°C. This condition was achieved 90% of the days of the year in cities located in the north, but in the south of the country this condition was only reached 20% of the days of the year, forcing to set a fixed temperature in this zone.

According to the authors, the PADHI value will be the result of multiplicate the number of people in poverty (obtained from the National Institute of Statistics, INE) and the degrees needed to climatize a building. BREDEM models used in the UK are also based on degree days but make use of them as input to a building energy model. According to PADHI, the higher the value of the result, the place will be at increased risk of energy poverty. The results of this research have shown that EP in Chile is mainly produced by the need for heating. It was also found that the risk of being in EP is higher in the centre of the country because there is a greater number of people in poverty. Although in the south of the country the risk was found to be lower because although they have major energy requirements (higher degrees required to climatize a building) due to low outdoor temperatures, a lower amount of people experience poverty, resulting in a lower PADHI value than that obtained for cities located in the centre of the country[155].

However, this method quantifies the risk of EP in an over-simplified manner. Multiplying variables such as the number of people in poverty and the degrees needed to climatize a building lead to ambiguous and not comparable results, prioritizing those places where there is a greater concentration of people in poverty condition in detriment of those who can be a minority confronting adverse climatic zones. This indicator could be clearer if the number of people in poverty was indicated with respect to the total population by region and independent of the energy requirements for heating and cooling by region. In addition, significant variables such as energy prices, household income and building design (different materials used throughout the country), which are crucial in determining EP were ignored.

1.5 Chilean context

The purpose of this chapter is to understand the use of residential energy in the Chilean context and to analyze where efforts should be focused to confront energy poverty. In pursuit of this objective, this chapter delineates the context related to climate (Section 1.5.1), economic factors (Section 1.5.2), national energy consumption (Section 1.5.3), the energy market (Section 1.5.4), energy policy concerning housing stock (Section 1.5.5) and energy poverty within Chile (Section 1.5.6).

1.5.1 Introduction

Chile is located in South America, flanked by the Pacific Ocean to the west, the Antarctic Circle in the south, and the Andes Mountain range to the east. The mainland territory is occupied by 19 million people, most of whom (41%) are concentrated in the capital city, Santiago, with a housing stock of 2.4 million dwellings [66]. The country is 4,270 km long and has a wide variety of climates. Desert climates in the northern part of the country are characterized by extremely low rainfall and significant daily temperature fluctuations. Toward the center of the country, mild and Mediterranean climates can be observed, described by four distinct seasons, dry summers, and relatively rainy winters. More rainy temperate climates are found in the south, allowing extensive areas of vegetation and native trees. Finally, sub-polar and ice climates can be found in the extreme south of Chile. The weather in this zone is rainy and cold and windy on the coast and in Patagonia *pampa*. Finally, where the continent ends, temperatures and precipitations tend to decrease [20].

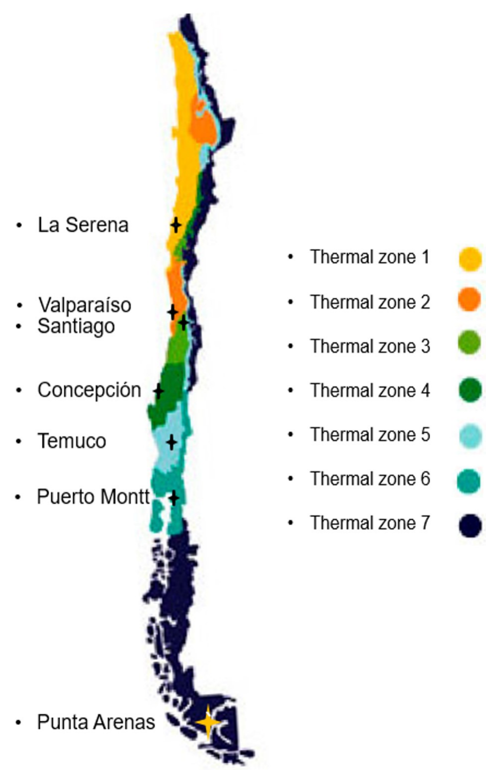


Figure 1.8: Chilean thermal zones proposed by the Ministry of Housing. [158]

Given the variability in climates, the Ministry of Housing proposed dividing the Chilean territory into seven *thermal* zones (see Figure 1.8). These zones were defined according to the annual heating degree-days (HDD)[82]. More recently, in 2019, the National Institute of Standardization [75], the entity responsible for the study and preparation of national technical standards, proposed nine thermal zones to facilitate the design of buildings. In addition, relevant information on the location is taken into account, such as temperature, solar radiation level, relative humidity, and cloudiness. However, this new classification has not been included in the building and construction code yet, and the seven thermal zones proposed by the Ministry of Housing are still in force [80].

1.5.2 Chilean economy

Chile experienced rapid economic growth between 2000 and 2015, and so poverty fell from 26% to 8% of its population [14]. However, economic growth declined by 5% between 2011 and 2019 [14] due to various causes, such as the introduction of tax reform [18], a decrease in the price of copper in 2014, the commodity comprising 10% of the gross domestic product (GDP) and the social upheaval faced by the country at the end of 2019 [14]. In addition, the COVID-19 pandemic has produced a strong economic contraction, resulting in high social and economic costs. The fiscal deficit increased to 8% of GDP in 2020, the highest in the last decades. Consequently, projections estimate a new increase in poverty, from 8% to 12%, equivalent to 780,000 additional people that will see affected their ability to meet basic needs, such as access to food, water, and energy services [13]. These figures are relevant, especially considering that poverty rates are directly related to energy poverty [9, 116], a phenomenon that is exacerbated by additional variables such as the quality of housing [126], the climatic region, and the difficulties in maintaining healthy levels of comfort.

1.5.3 National energy consumption

The Comisión Nacional de Energía (CNE) reported in 2018 a national energy consumption of 350 TWh per year. The largest consumers were the industrial and mining sector (38%), transport (36%), and commercial, public and residential sector (22%) [57]. In 2014, the CNE found that 72% of the energy used by the commercial, public, and residential sectors correspond to the residential area, accounting for 16% of the national energy consumption, or 55 TWh [56]. Similarly, a report on end-use energy made by the Ministry of Energy through the Corporación de Desarrollo Tecnológico (CDT) in 2018 found that the total energy consumption in the residential sector was 51 TWh.

At national level, the end use of residential energy is mostly distributed between space heating (53%), water heating (20%), refrigeration and freezing food (5%) and other appliances, such as those for cooking, washing clothing, lighting, and watching television (see Figure 1.9). Although a high percentage of the energy is used to heat the space, a preliminary study, using real-time data of indoor temperatures of 297 dwellings, revealed that indoor temperatures are generally found to be cold compared to the European adaptive thermal comfort model (EN 15254)[143]. Another study carried out in 300 homes located in Valdivia reinforces this idea, showing that 68% of the time the temperature in the living room was lower than 21° C in the winter months [96].

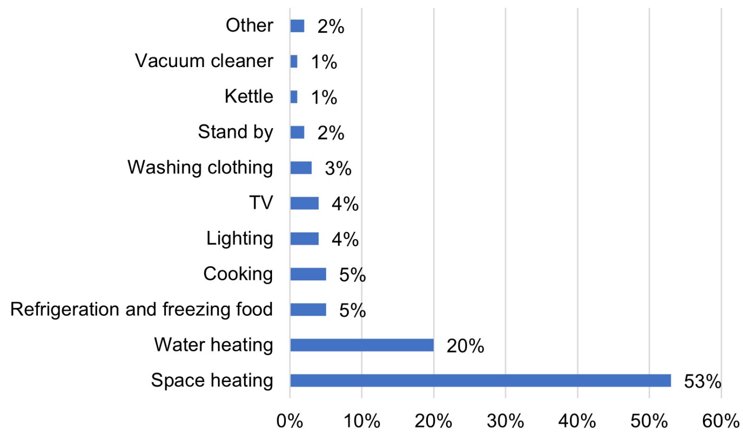


Figure 1.9: National distribution of energy consumption by end-use [41].

The total energy consumption in the residential sector is distributed primarily in 40% in wood, 31% gas (LPG and natural gas) and 26% electricity [41]. The high use of wood as fuel in the residential sector is mainly due to its use as heating in the south of the country, which is corroborated by the elevated presence of wood stoves in thermal zones 4, 5 and 6 where the tenancy of wood stoves reached 60%, 90% and 91%, respectively. However, the high rate of wood combustion in these zones has caused many cities in the south of the country to be affected by atmospheric pollution; especially PM2.5 particles, which are fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller [2, 58], which affects the health and well-being of the inhabitants. Factors such as high moisture in wood, low efficiency stoves, and the low presence of insulation in homes are the main causes.

Consequently, big cities such as Temuco, Valdivia, Osorno and Coyhaique have adopted atmospheric decontamination plans (known as PDA) to decrease pollution. These PDAs propose measures such as the replacement of wood stoves for more efficient models, or the use of different fuel sources, wood certification to guarantee a low moisture content, thermal improvement of dwellings, and inspection of wood stoves during episodes of pollution [58]. However, despite the introduction of these measures, the results have not been successful. For example, the level of pollution in Temuco is still dangerous and emergency episodes have persisted. The causes could be related to the high informality of the firewood market, which makes it difficult to control the quality of the wood (see Section 1.5.4.1). Its low price also gives few incentives for households to opt for other sources of energy and, some populations have shown a lack of confidence in the availability of other fuel sources as well as concern in the possible increase in energy expenditure to achieve the thermal comfort they are used to.

1.5.4 Energy market

Understanding the particular characteristics of the markets for different fuels helps quantify how market forces influence the adoption of certain fuels and the cost to this reliance on the consumer.

1.5.4.1 Firewood market

Wood is a highly consumed resource in the country, but the firewood market is highly informal in production, distribution, merchandising, and consumption [58]; around 80% of firewood sellers are considered informal.

The informal trade and consumption of firewood was studied by the Ministry of Energy in 2015 [55]. The results, based on 4,015 individual cases, showed that national firewood consumption in the Residential, Commercial, and Public sectors (RCP) ranged between 18 and 23 TWh per year, of which 99% corresponds to the residential sector. These results were similar to those reported by 2018 CDT shown in Section 1.5.3. The greatest use of firewood was found in the southern cities of the country, where it is used mainly for heating. The maximum demands were recorded in the Bio-Bio and Los Lagos regions, concentrating around 17% and 32% of the national consumption, respectively.

A previous study by CNE in 2013 estimated that the wood energy consumption of the RCP sector was 41 TWh per year, which is between 1.8 and 2.2 times higher than the value reported by the Ministry of Energy in 2015. The difference in results would be explained by a better representativeness of the data obtained in the field in the study conducted in 2015 and a higher precision in conversion factors, such as the use of the calorific value according to the type of specie and humidity. Consequently, due to the huge difference detected in the study, CNE decided to decrease the energy consumption of wood for the RCP sectors by 28% (27 TWh) in the 2014 CNE report and subsequent reports to be consistent with the study conducted in 2015 by the Ministry of Energy [55].

The Ministry of Energy has shown that the cheapest energy source for heating at the national level is wood (20 $/kWh), followed by pellets (50$/kWh), diesel (65 $/kWh) and kerosene (70 $/kWh). The most expensive sources are gas (95 $/kWh) and electricity (165 $/kWh), which are around 5 and 8 times the cost of wood, respectively [61]. Therefore, there is a considerable difference in the prices of energy sources and few incentives for people to opt for other sources, leading to many families continuing to use wood despite the negative health consequences they may experience. The wood market has been characterized by a consumer who has two different offers: wood with uncertain quality and low price, and another certified but with higher price [53]. In addition, wood has shown a considerable increase in its price in recent decades. In regions located to the south of the country such as Araucanía and Aysén have been found increases of 40% and more than a 100%, respectively, between 2005 and 2016 (adjusted by CPI)[58].

However, although the price of wood has increased in recent years, its price is still low compared to alternative fuel sources such as natural gas and LPG [55]. In addition, there are budget restrictions that lead households to refuse cleaner fuel sources because they are more expensive[97]. For example, measures have been developed to improve access to more efficient technologies for heating, such as wood stove replacements. However, these programs have not been exempted from problems due to a lack of confidence in the population in the availability of these new fuel sources in the region, the increase in energy expenditure to reach the thermal comfort to which they are used, and the challenges they will face in applying this benefit. In addition, there is an investment barrier to changing from one fuel to another; for example, the cost of replacing the furnace if it does not get the benefit, which makes the energy transition process difficult [97].

1.5.4.2 Hydrocarbons market

Hydrocarbons are the second most consumed energy source by the housing stock. These resources are imported. In 2019, the most imported energy sources were oil (33%), followed by natural gas (19%) and diesel (18%) [57]. Oil and gas are commercialized through a free market, but gas is regulated by the National Commission of Energy (CNE), the entity that plans the production and use of resources. Exceptionally, the regions located in the south of the country, such as the Magallanes region and the Chilean Antarctica, have a fixed tariff for gas due to a monopoly. It has been observed that the average price of $19.3\,\mathrm{m}^3$ gas (equivalent to 15 kg of LPG) has had substantial increases in central-south areas such as Metropolitan Region (54%), Valparaiso (54%), Bío-Bío (69%) and Araucanía (85%) between 2009 and 2018. A similar situation was found in the average price of LPG packaging (15 kg), which has experienced a considerable increase during the same period, affecting the whole country, but more noticeably in the central and southern zones with an increase of 59% and 64%, respectively [57]. Therefore, fuel sources, such as wood (see Section 1.5.4.1), gas and LPG, have shown an overarching pattern of price increases. However, wood and gas have considerable differences in their prices, so if their prices increase, there is still a huge gap in their prices that makes the possibility of changing from one fuel type to another difficult.

1.5.4.3 Electricity market

The Chilean electricity market is developed by private enterprises and the National Commission of Energy (CNE) is the public body responsible for analyzing the prices, tariffs, and technical standards that companies should respect in the production, generation, transport, and distribution of energy. Based on this information, the CNE advises the government on appropriate tariffs and provides technical and legal guidance, when required.

The national electric system reached 77 TWh of gross annual electricity generation in 2019, which represents 99% of the total generated by the country [57]. This total generation is composed of 56% thermoelectricity (derived 38% from charcoal and 18% from imported natural gas), 25% conventional hydraulics and 19% non-conventional renewable energies. Although the average price in the electricity market has experienced a slight increase in previous years, more recently it has increased 8% between February 2019 and February 2021. This situation is considered worrying because Chile has the highest electricity prices in South America and is at an intermediate level with respect to other countries in the Organization for Economic Cooperation and Development (OECD) [60]. In addition, the cost of electrical energy is the most expensive compared to other fuel sources available in the country. This is relevant when it comes to the decision to change from one fuel to another while meeting energy needs. A high price could be a barrier for households with a limited budget. Section 2.3.4.6 shows that the energy consumed by lights and appliances tends to be relatively stable in all households in the country, so it represents a basic requirement for households for which cost is a relevant factor.

1.5.5 Chilean Energy policy for housing stock

1.5.5.1 Thermal regulation

The government's justification for mandating insulation standards was predicated upon the advantages of enhancing the population's quality of life in an economically viable manner, reducing energy consumption in residential buildings, minimizing both indoor and outdoor pollution, and preventing damage to building materials resulting from temperature fluctuations and excessive humidity. In addition, the implementation of these measures aimed to improve the thermal performance of homes during winter, particularly in low-income households [36].

Dwellings constructed prior to 2001 lacked thermal requirements and are generally regarded as uninsulated. The thermal regulation was carried out by the Ministry of Housing in two stages. The initial stage began in 2001, where minimum requirements were defined to mitigate heat loss through the roof, primarily focusing on the necessity to maintain warmth. The subsequent stage, supplementing the previous, was instituted in 2007. It established requirements to limit heat loss through walls, ventilated floors, and windows. The window sizes are restricted according to their thermal transmittance (see Table 1.1).

Table 1.1: Minimum requirements for roof, walls, ventilated floors and windows in different thermal zones [82].

Zone	Roof		Walls		Ventilated floors		Windows: % Maximum of glass surface respect to vertical parameters of enclosure.		
	U (W/m^2K)	Rt (m^2K/W)	U (W/m^2K)	Rt (m^2K/W)	U (W/m^2K)	Rt (m^2K/W)	Simple Glass	Double Glass $2.4 < U \leq 3.6$	Double Glass $U \leq 2.4$
1	0.84	1.19	4.0	0.25	3.60	0.28	50%	60%	80%
2	0.60	1.67	3.0	0.33	0.87	1.15	40%	60%	80%
3	0.47	2.13	1.9	0.53	0.70	1.43	25%	60%	80%
4	0.38	2.63	1.7	0.59	0.60	1.67	21%	60%	75%
5	0.33	3.03	1.6	0.63	0.50	2.00	18%	51%	70%
6	0.28	3.57	1.1	0.91	0.39	2.56	14%	37%	55%
7	0.25	4.00	0.6	1.67	0.32	3.13	12%	28%	37%

1.5.6 Energy Poverty in Chile (EP)

The Chilean Energy Policy for 2050 expressed the need to introduce the concept of energy poverty (EP), which according to the literature can be defined as the inability to provide adequate warmth due to inefficiency of the home [22]. The energy required to provide adequate lighting, cooking, and typical domestic appliances in a dwelling is also considered [85]. Several countries have implemented measures and policies to mitigate EP because these measures can lead to improvements in population health and well-being, increasing comfort levels at home and reducing the use of health services, therefore having potential cost savings for National Health Services [137]. However, the greatest challenge has been to create policies that include most of the population affected by this phenomenon. Most of the policies created have focused on specific groups, such as families with children or pensioners, relying on a political decision rather than technical ones, and leaving out other demographics of the population that could be experiencing EP, but do not meet the requirements to receive support [23].

In Chile, the government has stated that there is a need to define and quantify EP to detect the most vulnerable population and promote its reduction through policies[60]. It has been stated that policies should be in line with the objective of decreasing the amount of greenhouse gases contributed to the environment (30% reduction by 2030)[60] and considering the diversity of the geography, climate, population and economy of the country. However, no guidelines have been given on how this should be carried out. In addition, it should be taken into account that tackling the EP could mean a greater demand for energy. If this is not matched with energy efficiency measured, then it will place pressure on climate change policies.

1.6 Existing data sources in Chile

The data sources incorporated in this study include the Census of Population and Housing, the National Socio-Economic Characterization Survey, the Family Budget Survey, the Basket of Goods and Services, the Uses of Energy in the Chilean Housing Survey and the National Network of Housing Monitoring.The analysis will involve a comprehensive assessment of the intrinsic strengths and limitations of each data source, with a particular emphasis on the computation of energy poverty metrics in Chile.

1.6.1 Census of population and housing

This section will address the most recent censuses conducted in Chile, specifically those of 2002, 2012, and 2017. It will examine the methodological irregularities present in the 2012 Census and their repercussions on the reliability of the reported data. Furthermore, an analysis of the pertinent variables related to EP, as identified in these censuses, will be undertaken.

Census of population and housing is the most important statistics operation that has been performed by the National Statistics Office (INE) since 1952, with a frequency of approximately ten years. All citizens of the country participate in this survey, so its results can be considered statistically representative. The data obtained from this resource are highly valuable because they allow one to count with essential information to propose policies and make decisions in both the private and public sectors [63].

However, the census is not exempt from criticism. There has been found to be a significant difference between the methods and questionnaires used in the 2002 and 2012 census. The 2012 Census has several irregularities in the distribution by gender and age of the population, which were expressed in an inexplicable descent of the male population showing highly heterogeneous results at the national level [65]. In the same census, it was also found out that the non-response rate at national level reached to 9.6% which is considerably higher than the 3.8% reached in the 2002 census [65]. A further audit dictated that these results have a significant difference from the results achieved in other previous censuses. Therefore, information within the database was considered not valid for making decisions in public policy because there was a high probability that imprecise estimations were obtained [65].

In relation with EP, in the 2002 census only one variable that could be related to EP was included, which is the type of fuel used for cooking. Then, in 2012, this question was kept in the census and was also included the type of fuel used for heating water and space [62, 64]. However, in the 2017 census none of these questions were included [67]. So, it is suggested to be cautious with the continuity of the questions to allow an adequate comparison. In addition, as the government sees EP as a metric they need to understand in order to develop policy, the census should be considered as an effective way of obtaining the data they need.

It is proposed that the Census questionnaire incorporate items enabling respondents to report their average monthly expenditures on fuel utilized for cooking, water heating, and space heating. This addition would facilitate the computation of actual household energy expenditures across national, regional, and municipal levels, employing metrics like the Ten Percent Rule (TPR). Presently, data on energy expenditures are sourced from the 2017 Family Budget Survey (see Section 1.6.3), which presents constraints in data granularity as it only distinguishes between the Metropolitan region and other regions.

1.6.2 National socio-economic characterization survey (Encuesta de Caracterizacion Socio-económica Nacional,CASEN)

The CASEN survey, a cross-sectional study initiated in 1987 by the Ministry of Social Development, is conducted approximately biennially or triennially. The primary objective of this survey is to ascertain the socio-economic status of households across dimensions such as family composition, education, health, housing conditions, employment, and income. It constitutes the principal data source for assessing poverty and inequality in Chile. In 2017, the survey encompassed 70,948 households residing in private dwellings across both urban and rural settings in 15 regions of the country, which expanded to 16 regions post-2017, thus ensuring national representativeness [38]. Concerning energy poverty (EP), the dataset comprises information on net and gross income for both dependent and independent workers, the type of dwelling of the respondents, availability of electricity, and primary fuel usage, among other aspects [42]. Nevertheless, the absence of data on energy expenditures or comprehensive dwelling conditions necessary for modeling energy requirements [184] poses a significant limitation. This gap hinders the precise calculation of EP using indices such as the TPR, MIS, or LIHC.

1.6.3 Family Budget survey (Encuesta de Presupuestos Familiares, EPF)

The EPF is a socio-economic survey devised by the National Statistics Office (INE), aimed at gathering data on actual household expenditure and income within the metropolitan region and key cities across various regions. The most recent iteration of this survey was conducted in 2022, encompassing approximately 25,000 households. The data collection period spans one year, and the survey is administered quinquennially in accordance with the directives of the Organization for Economic Cooperation and Development (OECD) [72].

The method used to determine expenditure consists of interviewees using a daily journal to record their expenditures for two weeks and receiving four visits from the interviewer to keep track of their register [20]. A notable limitation of this approach is the potential for participants to underreport their expenses; this occurs when they may exclude certain expenditure items depending on the season in which the interview takes place. For example, participants might omit fuel expenditures that are typically incurred during the winter if the interview is conducted in a different season [43]. Consequently, such expenditures may be underrepresented in the data reported by the EPF.

This survey provides significant data regarding energy poverty. The database encompasses income data for both dependent and independent workers, as well as pension details for retirees. For dependent workers, comprehensive data are supplied, including gross income, contributions to health and social security, income tax, overtime compensation, allocations, incentives and awards, bonuses, and earnings for food and beverages. Conversely, for independent workers and retirees, the focus is on net income figures.

Regarding energy expenditure, participants in the interview were requested to present payment receipts or bills from the preceding month relative to the survey date. Consequently, only the expenditures incurred within that month, excluding arrears and interest, were documented [69]. They were required to provide bills for electricity, pipeline gas, bottled gas, charcoal, wood, and the total costs associated with common expenses. Common expenses pertain to the costs associated with the management, maintenance, and repair of shared property elements within a building or condominium such as elevators, stairs, roofs, facades or exterior walls, gardens, barbecues, event halls, parking areas, and essential services like water, electricity, or heating, whether for communal or individual use [77].

In the EPF database, it is recommended to exercise caution regarding common expenditures, as the questionnaire initially aimed to capture the amounts associated with water and space heating separately. However, the database records only aggregate these amounts under common expenses without disaggregation. Consequently, for the short-term calculation of any metrics based on these data, it is recommended to adopt certain assumptions regarding the breakdown of common expenditures such that the calculations exclusively reflect the expenditures pertinent to household electricity and space heating. In the long term, it is imperative to reformulate this questionnaire item to discern common expenditures associated with community needs, such as administrative costs, maintenance, and energy expenses for communal facilities, from those pertinent to individual needs, namely energy expenses for lighting, and space and water heating. All responses recorded during the survey application should subsequently be seamlessly transferred to the database.

The data encapsulated within the EPF is of significant utility in the computation of metrics such as Ten Percent Rule (TPR), Disproportional expenditure (2M), and Hideen Energy Poverty (HEP), all of which are part of the multidimensional approach (see Table 2.1). Although the low-income, high-cost metric could be applied, certain considerations must be addressed initially. Specifically, the required energy demand should be substituted with the actual energy demand, given that the EPF does not record the characteristics of the home necessary to model energy requirements. In addition, the EPF provides data to calculate comprehensive income and housing costs, including rent and mortgage. However, this metric involves an equivalence factor for housing costs that is tailored to the UK, necessitating an examination of its applicability within the Chilean context, as no prior study has been conducted on this matter. Similarly, equivalence factors for energy, akin to housing costs, warrant scrutiny as to their suitability in Chile. Lastly, the poverty line essential for the calculation of this metric could be sourced from the Goods and Services Basket (see Section 1.6.4).

1.6.4 Basket of goods and services

The composition of the goods and services basket is determined by analyzing the expenditure patterns on goods and services of households in capital regions, as obtained from the Family Budget Survey (EPF) and developed by the National Statistics Office (INE) [73]. This basket comprises goods and services, termed products, and totaling 303 items. These products are selected based on their prevalence of consumption in at least four of the five population quintiles, representing a broad array of socioeconomic groups [71]. The composition and weighting of the basket are stabilized over a five-year period, with monthly modifications only to the prices assigned to each product [71]. To facilitate these price adjustments, the INE employs interviewers who conduct monthly registrations of product prices from various sources such as stores, fruit markets, supermarkets, and stores, in addition to visiting households to record rental and service prices [71]. In terms of categorization, products are systematically organized into 12 divisions derived from the EPF survey [73]. These divisions encompass categories such as food and non-alcoholic beverages, alcoholic beverages, clothing and footwear, essential home services, maintenance and equipment, health, transport, communications, culture and recreation, education, restaurants and hotels, and miscellaneous services [70]. Consequently, the basket encompasses both essential goods, such as bread and rice, and recreational services, including sports entertainment, cinema tickets, and television [73].

The basket serves as the basis for the National Statistics Office to calculate the Consumer Price Index (CPI) on a monthly basis [73]. The CPI is an economic metric that quantifies the temporal price variations of the basket and is a crucial indicator of inflation. In addition, it is used routinely to adjust financial obligations such as rents, loans, and essential services governed by the state, including electricity and water [73]. Although electricity pricing is related to the CPI, considerations of fuel poverty are omitted in its determination. The CPI is often regarded an indirect measure of the cost of living (ICV). However, the ICV evaluates expenditure on goods and services within the basket concerning the degree of well-being and satisfaction derived by consumers [70], while the CPI simply accounts for the products predominantly consumed by Chilean households without assessing whether these items adequately meet their needs.

The calculation of the Minimum Income Standard (MIS) metric can be derived from this source; however, certain considerations must be addressed. Data from the EPF should serve as a complementary component in the calculation of this metric (refer to Table 2.1). It is necessary to substitute the required energy demand with the actual energy demand due to the absence of home characteristic data in the EPF, which hinders the modeling of energy requirements. The EPF also provides data pertinent to the estimation of full income and housing costs. The application of the MIS definition (minimum living costs) utilizing the basket of goods and services must take into account that it serves as an indirect measure of the cost of living and fails to incorporate the level of well-being and satisfaction achieved by households upon fulfilling their needs. Additionally, it is important to note that within the EPF structure, the category of dwelling and basic services encompasses rent, water, common expenditures, electricity, gas, charcoal, paraffin, wood, among other goods and services [70]. Thus, to prevent double counting, if the basket is implemented, rent and basic services should be excluded.

1.6.5 The Uses of Energy in Chilean Housing survey

The Uses of Energy in Chilean Housing Survey is administered by the Ministry of Energy via the Corporation for Technological Development (Corporación de Desarrollo Tecnológico, CDT), which is responsible for producing the reports. The survey aims to analyze the consumption patterns of energy within the Chilean residential sector. It seeks to quantify the annual energy demand based on usage and fuel type, as well as to evaluate the types of equipment and the implementation of energy efficiency measures in homes. The resulting data will enable the government to make informed decisions by formulating public policies that promote the integration of energy-efficient practices in the residential sector, thereby decreasing both energy demand and emissions of pollutants[41].

The first report was published in 2010 [39], covering an analysis of 3,220 houses, including detached and semi-detached houses, as well as apartments located in the seven thermal zones of the country. The subsequent and most current report was published in 2018, which included a study of 3,500 households strategically distributed in seven statistically representative thermal zones determined by the Ministry of Housing [41].

The survey included data related to the socioeconomic status of the participants, their type of housing, the year of construction, construction materials, and the appliances used for cooking, lighting, space heating and water heating. Using the results obtained, the energy requirements for cooking, lighting, and both space and water heating were determined. In addition, household incomes were recorded according to various income brackets, enabling the calculation of the proportion of income allocated to energy per household. Consequently, this survey provides essential data that facilitate the calculation of the Ten Percent Rule (refer to Table 2.1).

The computation of the Low Income High Costs (LIHC) metric using this survey is subject to certain limitations (refer to Table 2.1). Firstly, while data pertaining to income are incorporated, information concerning housing costs, such as rent or mortgage payments, is absent. Conversely, data on energy consumption are available. The LIHC employs energy equivalisation factors that have been specifically developed for the United Kingdom, yet these may serve as a reference point given the absence of equivalent data in Chile. Upon application of the energy equivalisation factors, the energy consumption data can be utilized to determine the fuel cost threshold, defined as the weighted median of the equivalised total energy cost for the entire sample. Nonetheless, this metric's calculation is constrained by the aforementioned missing data.

The survey incorporated two inquiries regarding the thermal comfort of residents during winter and summer [41]. Notably, this study prioritizes the issue of maintaining warmth and omits considerations of energy poverty associated with cooling needs. Consequently, the inability to adequately heat a residence, a metric that forms part of the multidimensional approach (Section 1.4.6), can be ascertained through the survey. The incorporation of intensity levels in these questions is regarded as an enhancement over the original indicator. The proportion of households indicating that their residence was cold or very cold during winter varies nationwide: 35% (equivalent to 956,300 households) reported such conditions in thermal zone 3 (Metropolitan region), 42% (or 489,600 households) in thermal zone 4, 28% (or 153,000 households) in thermal zone 5, 5% (or 14,100 households) in thermal zone 6 (Los Lagos), and 19% (or 22,900 households) in thermal zone 7 (Magallanes) [40]. It is important to acknowledge that these responses are subjective and may differ based on the socioeconomic status and perceived comfort level of the respondents [181].

1.6.6 National network of housing monitoring (Red Nacional de Monitoreo de Viviendas, RENAM)

The National Housing Monitoring Network, initiated by the Chilean Ministry of Housing in 2015, aims to establish and maintain a valuable, enduring, and publicly accessible database. This facilitates informed decision-making by governmental bodies and individuals interested in enhancing the quality of life for residents of national housing stock. The project provides real-time data on temperature, humidity, noise, and air quality both inside and outside specific residences [160].

The inaugural stage of this project entailed the deployment of sensors within private and social properties situated in six urban areas in Chile: Antofagasta, Valparaíso, Santiago, Rancagua, Temuco, and Coyhaique (refer to Figure 1.8). Subsequently, a preliminary survey was conducted to document data encompassing the year of construction, type of dwelling, surface area, orientation, construction materials, type of heating, presence of insulation in the perimeter walls and roof, as well as the location of measurement devices. Additionally, inquiries regarding thermal comfort within the residence during autumn, winter, spring, and summer were incorporated. In subsequent phases, the project aims to encompass additional building typologies, including public, commercial, and non-residential structures.

With respect to energy poverty, temperature data represent a potentially valuable resource for the implementation of the direct approach (see Section 1.4.5). However, the current application of this approach is impeded by the lack of a sufficient number of active cases on the RENAM platform to be deemed representative. In 2017, data registration was reported for 101 dwellings in the country, with 38 cases located in Santiago and 25 and 23 cases in Temuco and Valparaiso, respectively. The remaining cases were allocated between Antofagasta and Coyhaique. By 2021, the number of active cases at the national level had declined to 35 dwellings.Therefore, to effectively apply the Direct approach, it is recommended to increase the number of cases within each thermal zone to achieve results that may be considered representative.

1.6.7 Summary

Energy poverty metrics, such as the Minimum Income Standard (MIS) and Low Income High Costs (LIHC), are presently challenging to implement due to the absence of a singular information source that compiles all necessary data for metric calculation. Additionally, these metrics traditionally model energy demand to achieve standardized outcomes; however, replacing this with actual energy consumption makes it difficult to ascertain the occupants' comfort level, as it solely reflects the quantity of energy utilized. Furthermore, the compilation of goods and services that may represent minimum living costs, as with the MIS, fails to incorporate the satisfaction and well-being experienced when individual needs are met, aspects central to the original MIS concept, but instead merely reflects the lowest financial requirement for survival in Chile. Moreover, the application of the LIHC metric is constrained by the lack of income or energy equivalisation factors specific to Chile, resulting in an absence of a methodology to compare both income and energy expenditures across households of varying sizes. Consequently, additional studies are warranted.

Payment arrears represent the sole aspect of the multidimensional strategy that cannot be assessed due to a lack of accessibility, despite the availability of such data to electricity energy companies. Consequently, governmental intervention may be necessary to acquire these data for comprehensive analysis.

The EP metric that can be implemented without delay is the Ten Percent Rule (TPR). For this purpose, two distinct combinations of data sources may be employed: the Family Budget Survey (EPF) and the Uses of Energy Chilean Housing Survey. Despite inherent limitations associated with each source, the existing literature indicates their robustness in the face of data gaps, and prior research has demonstrated their capability to accommodate all necessary data. Thus, the methodology for calculating the TPR will be explained in the following chapter 2 (section 2.2).

1.7 Research gap

The concept of energy poverty was first defined by Boardman in 1991 as the inability to afford adequate warmth due to inefficient housing. This chapter highlights the complexity of energy poverty, which encompasses physical, economic, and behavioral dimensions. The significant health consequences of energy poverty are elucidated, including the exacerbation of diseases such as cardiovascular disease, arthritis, pneumonia, asthma, and Alzheimer's, as well as excess winter mortality and psychological impacts such as social isolation and debt stress.

Key factors contributing to energy poverty include low income, educational attainment, property tenure, energy prices, demographics, and energy-inefficient housing. Older dwellings, in particular, exhibit the most significant problems due to lower insulation levels and higher air infiltration rates. Retrofitting programs have been proposed to address these issues, showing positive results such as energy savings and improved thermal comfort for the occupant. However, some countries have not prioritized retrofitting programs due to doubts about their effectiveness and high implementation costs.

Energy poverty is a major challenge for the European Union today. Initially addressed by the UK, the problem has now expanded to other countries, leading to the development of various methodologies to determine the number of people affected by energy poverty. Metrics such as the Ten Percent Rule (TPR), Minimum Income Standard (MIS), Low Income High Cost (LIHC), Low Income Low Energy Efficiency (LILEE), direct approach, multidimensional approach, and Poverty Adaptive Degree Hourly Index (PADHI) have been discussed. These methodologies share common factors, including income, energy prices, and energy efficiency of dwellings.

In Chile, diverse climates and economic challenges have been described, with significant residential energy consumption primarily for heating. This focus on heating links energy poverty to the challenge of keeping warm. In the south of Chile, a high proportion of households use wood for heating, leading to critical atmospheric pollution conditions. Measures such as replacing wood stoves with more efficient models, wood certification, and thermal improvement of dwellings have been proposed. Despite these measures, pollution levels remain dangerous and emergency episodes persist, possibly due to the informal nature of the firewood market and the cost difference between wood and cleaner energy sources.

Energy poverty is a recent concept in Chile, and the government recognizes the need to define and quantify it to establish policies for its reduction. However, no official definition has been adopted yet. Existing metrics and data sources such as the Census of Population and Housing, the

National Socioeconomic Characterization Survey (CASEN) and the Family Budget Survey (EPF) were presented in this chapter.

Energy inefficiency in housing is an prevalent issue that contributes to energy poverty. Retrofitting has been used to improve housing quality and efficiency standards, reduce energy costs, and improve affordability. However, some nations have hesitated to implement retrofitting programs due to uncertainties about their efficacy and high costs. In Chile, the Ministry of Housing has focused on mitigating heat loss in social housing by providing subsidies for thermal envelope improvements, although the effectiveness of these initiatives has yet to be empirically evaluated.

This research aims to address this gap by initiating a modeling-based analysis to understand the potential benefits. The goal is to determine the consequences of energy demand reduction interventions on energy poverty in the Chilean housing stock. The research will assess the number of households affected by energy poverty in Chile, identify the main contributing factors, and describe the Chilean housing stock and representative archetypes. Data on building physics models and relevant input will be collected to determine the energy demand of the most predominant housing group within the region at highest risk of entering energy poverty. The proposed interventions aimed at reducing energy demand will undergo a thorough analysis to evaluate their effects on energy heating demand.

CHAPTER 2

Methodology

2.1 Main factors contributing to EP in Chile

This investigation uses a mixed methods approach to systematically examine the factors that contribute to energy poverty (EP) in Chile. The research design integrates quantitative data analysis with qualitative insights to provide a comprehensive understanding of the determinants and consequences of EP across various regions and socio-economic groups.

The main source of quantitative data was the 2017 Family Budget Survey, which provides comprehensive information on household energy expenditures, income levels, educational attainment, property tenure, and sociodemographic variables, including family size and composition, throughout Chile. Furthermore, data from the 2017 national census were used to derive additional information on household composition, which is essential to understand the sociodemographic determinants influencing EP. An analysis of electricity and gas tariffs from 2018 to 2023, sourced from electrical suppliers and the National Energy Commission (CNE), was performed to examine trends and regional disparities in energy costs. In addition, qualitative data were acquired from the findings of the 2018 study on energy usage within the Chilean residential sector, offering in-depth insights into strategies employed by residents to manage energy expenses, such as the selection of heating spaces.

Quantitative analysis involved the use of descriptive statistics, correlation analysis, and multiple regression models. The descriptive statistics served to summarize the main characteristics of the data set, which included the calculation of the mean, median, and standard deviation of household energy expenditures and income. A correlation analysis was conducted, using Pearson's correlation coefficients, to evaluate the relationship between household income and energy expenditure. Meanwhile, the regression analysis used multiple regression models to determine the main predictors of energy expenditure and quantify the influence of various factors such as income, household size, and educational attainment. Qualitative data were subjected to content analysis to discern patterns and extract meaningful insights, facilitating triangulation with quantitative findings.

Households were systematically selected based on criteria that included income levels, geographic distribution, and energy expenditure patterns. The sample encompasses a wide range of households from various thermal zones and socio-economic contexts to ensure representativeness. Although there are potential limitations, such as the reliance on self-reported survey data which can introduce reporting biases, this methodology offers a robust framework to interpret the intricate dynamics of energy poverty in Chile. Furthermore, while the study attempts to provide a comprehensive analysis of energy poverty in Chile, the conclusions drawn may not be readily applicable to other nations with divergent socio-economic and climatic conditions. The results of this analysis are presented in Section 3.1.

2.2 The current state of energy poverty in residential housing in Chile.

In the subsequent section, the methodology for assessing the current state of energy poverty in Chilean residential housing will be elucidated. Initially, the data collected for the metrics (refer to Section 1.4) and the data sources currently available in Chile (refer to Section 1.6) were overlaid to distinguish between the metrics that can be quantified currently and those that require additional data for future quantification. Table 2.1 provides a comprehensive summary of available and missing data within each source for the calculation of each metric. The existing information sources that could support the evaluation of energy poverty in Chile will be briefly described later in this section.

Table 2.1: Applicability of EP metrics with Chilean sources.

Metric	Required data to apply metric	Source	Data available	Missing data to apply metric
Ten per cent rule	•Energy required (modelled) or actual energy demand (expenditures). •Fuel price. •Household income.	Family Budget Survey(EPF).	•Actual energy demand. •Household income.	•No data to calculate energy requirements using a model.
		Uses of energy in Chilean housing survey.	•Energy required (modelled). •Fuel price.	• Detailed income gap for each socio-economic group.
Minimum Income Standard (MIS)	•Energy required (modelled). •Fuel price. •Household income. •Housing costs. •Minimum living costs (MIS).	Family Budget Survey(EPF).	•Actual energy demand. •Household income. •Housing costs	•No data to calculate energy requirements using a model. •Minimum living costs (MIS).
		Uses of energy in Chilean housing survey.	•Energy required (modelled). •Fuel price.	• Detailed income gap for each socio-economic group. • Housing costs. •Minimum living costs (MIS).
		Basket of Goods and Services.	•Minimum living costs (including housing costs).	•No data to calculate energy requirements using a model. •Fuel price. •Household income. •Satisfaction or well-being is not considered in minimum living costs.
Low Income High Cost (LIHC)	•Energy required (modelled). •Fuel price. •Household income. •Poverty line.	Family Budget Survey(EPF).	•Actual energy demand. •Household income. •Housing costs (either rent or mortgage).	•No data to calculate energy requirements using a model. •Minimum living costs (MIS).
		Uses of energy in Chilean housing survey.	•Energy required (modelled). •Fuel price.	• Detailed income gap for each socio-economic group. • Housing costs. •Minimum living costs (MIS).
		Basket of Goods and Services	•Poverty line.	•No data to calculate energy requirements using a model. •Fuel price. •Household income.
Direct approach	•Indoor temperature.	National network of housing monitoring (ReNaM).	•Indoor temperature.	•Increase the number of dwellings measured to at least 400 per region to make it representative.
Multidimensional approach				
1. Excessive expenditure on energy services.	•Actual energy demand (expenditures).	Family Budget Survey(EPF).	•Actual energy demand.	-
2. Hidden energy poverty (HEP)	•Actual energy demand (expenditures).	Family Budget Survey(EPF).	•Actual energy demand.	-
2. Inability to keep warm their home.	•Question asking over the inability to keep warm home.	Uses of energy in Chilean housing survey	•Thermal comfort in a dwelling in winter.	-
3. Arrears in energy bills.	•Question asking over arrears in energy bills.	No data	-	•Database including information of arrears in energy bills.

Based on Table 2.1, the present condition of energy poverty within Chilean residential housing will be evaluated according to the ten per cent rule metric. Two different data sources will be utilized: i) the Family Budget Survey (conducted in 2017 and 2022), and ii) the Uses of Energy in Chilean Housing Survey (2018). These sources exhibit variations in the categorization of information by geographic region and in the methodology used to determine energy expenditures, resulting in differences in the calculation of the TPR. Consequently, while the methods of calculation differ, juxtaposing the results from both sources will provide insight into the general conclusions of this study or understanding of potential variability.

2.2.0.1 Family Budget Survey (2017 and 2022)

Initially, the 2017 Family Budget Survey (EPF)compiles data by comunas, the fundamental administrative units in Chile. In the Metropolitan region, 35 out of 52 comunas were included in the sample, constituting 76% of all households in this area [66]. Conversely, for the remaining regions, the sample comprised 28 out of 293 comunas, all from the 15 capital regions, accounting for 36% of the households. Despite the 2017 EPF collecting data by comuna, the reported data is divided into two broad categories: the Metropolitan region (zone 1) and all other regions (zone 2). This classification results in the loss of valuable information for the other regions, as they are grouped together, hindering the analysis of variations in residential energy demand in different regions.

Table 2.1 demonstrated that the data essential for the computation of the TPR includes actual energy demand (expenses) alongside household income. The website of the National Statistics Office (INE) provides access to the EPF databases, providing information on energy expenditures and net household income separately (see details in Figure 2.1). Energy expenditure data encompass electricity expenses, pipeline gas, bottled gas, wood, charcoal, liquid fuels, and common expenditures. The data on net income and energy expenditure were consolidated into a single database (Excel format), linked by the unique folio assigned to each household. Within this database, 174 of the 7,956 cases in the metropolitan region sample were excluded due to their net income showing a standard deviation equal to or greater than three ($Z \geq 3$). In other regions, 100 out of 7,284 cases were excluded for similar reasons. Subsequently, the Excel database was exported to SPSS Statistics for the calculation of the TPR.

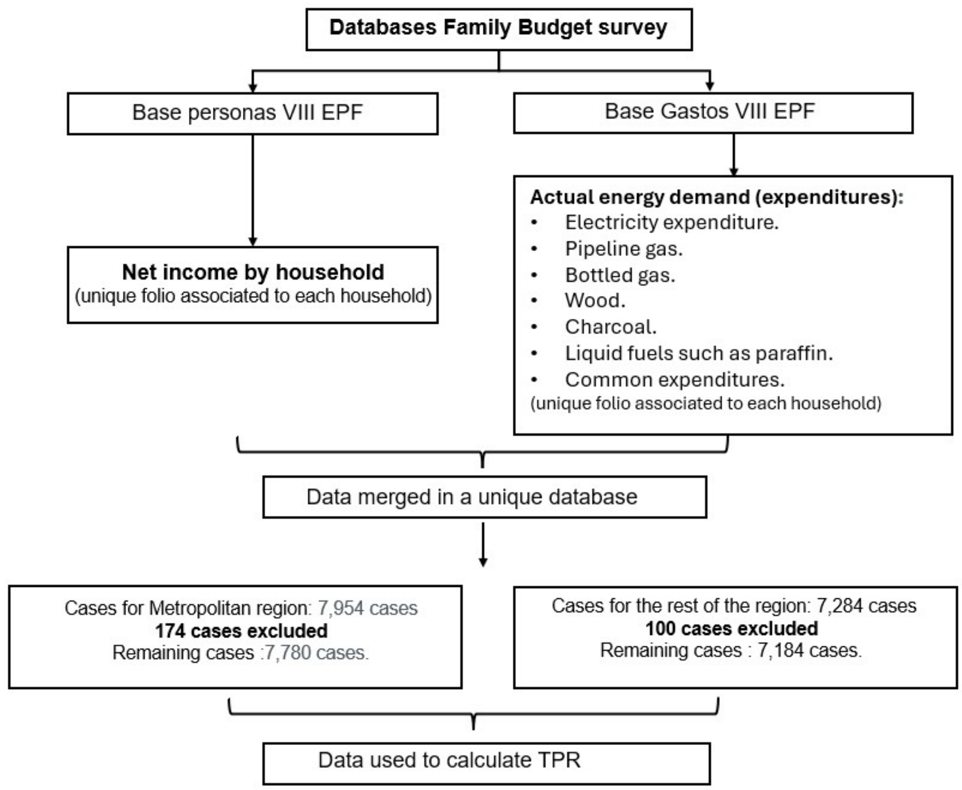


Figure 2.1: Procedures for processing EPF databases to ascertain TPR.

The TPR is determined as the ratio of actual energy expenditure to net income. The elements that comprise the actual energy expenditure include the costs associated with electricity, gas, charcoal, liquid fuels, and wood. Common expenditures have been omitted from this calculation because they relate to service charges pertinent to multi-residential buildings, such as apartment complexes. These charges are allocated for the management, maintenance, and repair of shared facilities within a building, and essential services such as water, electricity, and heating for communal or individual use [77]. Regrettably, the lack of itemized data within the provided data set hinders the ability to distinguish costs specifically associated with electricity and heating.

In addition, only a single study has preliminarily investigated the distribution of common expenses. The results obtained from two buildings located in the metropolitan region reveal that the majority of common expenses are allocated to employees (48%) and essential services such as water, electricity and gas (30%) [162]. Among the funds designated for basic services, 68% is attributed to gas utilized to heat space and water, and 29% to electricity. However, this does not constitute a representative sample of building common expenditures, necessitating further research to accurately allocate the distribution of these expenses. Consequently, common expenses will be excluded from the calculation, which is likely to result in an underestimation of the EP, as expenditures associated with heating are not considered. This exclusion might affect up to 19% of the households surveyed in the metropolitan region, as this proportion of the population reported having common expenditures.

The results of the 2022 Family Budget Survey have been published recently. Consequently, the condition of energy poverty within Chilean residential housing will be evaluated using the ten percent rule metric. The calculation method remains largely consistent with that used in the 2017 survey. The sole distinction lies in the manner of data reporting. In this iteration, the data is segmented into four major categories: the north, the metropolitan region, the central, and the south. This restructuring could signify an improvement in mitigating the loss of critical information related to the various regions of the country, as mentioned above. However, it simultaneously renders the results non-comparable with those obtained in 2017, hindering the traceability of the findings. The results of both iterations of the survey will be thoroughly presented in Section 3.2.

2.2.0.2 2018 Uses of Energy in the Chilean Housing Survey

The second source used for the estimation of the EP originated from the results of the 2018 Energy Uses in the Chilean Housing Survey (see Section 1.6.5), which was disclosed by the Under Secretary of Energy in accordance with the transparency law. The database provides information on the socioeconomic classification of each household into distinct categories and a modeled estimate of the corresponding energy requirements per household. The survey asked for information on household income, categorizing it into eight distinct income brackets as outlined in Table 2.2. The classification will serve as the basis for calculating the TPR.

Data on annual energy demand for electricity, gas, paraffin, wood, and pellets were sourced from the 2018 Energy Uses in the Chilean Housing Survey. The fuel sources prices were derived from the study 'Curva de Conservación de la Energia', which is cited in the 2018 final report [41].

Table 2.2: Categories of household income included in the survey.

	Income bands (Chilean pesos,$)		Class mark (Chilean pesos,$)
1	-	100,000	50,000
2	100,001	250,000	175,001
3	250,001	500,000	375,001
4	500,001	750,000	625,001
5	750,001	1,000,000	875,001
6	1,000,001	1,500,000	1,250,001
7	1,500,001	2,000,000	1,750,001
8	2,000,000	-	2,000,000

The aggregate energy expenditure per household is calculated by adding the product of the energy demand of each fuel and its respective price. Table 2.3 details the fuel prices used in this calculation.

Table 2.3: Fuel prices by thermal zone [40].

Thermal zones	Fuel prices (CLP $/kWh)			
	Electricity	LPG	Natural gas	Wood
Zona 1	153	94	102	24
Zone 2	153	94	102	24
Zone 3	126	97	88	22
Zone 4	126	97	88	22
Zone 5	126	97	88	22
Zone 6	154	100	12	19
Zone 7	154	100	12	19

Following this, the database encompassing data on income and total energy expenditure was transferred to SPSS Statistics. It is important to note that typically each survey sample, representing a household in this instance, corresponds to a specific number of households within the entire population, which are converted into weighting factors. Such weighting factors were not provided in the 2018 Uses of Energy in the Chilean Housing Survey. Consequently, the method used in the 2010 survey was utilized to determine these weighting factors. This involved an examination of the distribution of the housing stock according to thermal zones, geographic setting (urban or rural), and classification of buildings (house or apartment). Consequently, the representativeness of the survey, considered as a weighting factor, was determined as the quotient of the total housing stock by the type of building and the number of surveys conducted for that particular type of building.

2.3 Archetypes

2.3.1 Housing stock models

Housing stock models (HSM) are generally categorized as top–down or bottom-up, working at aggregated and disaggregated levels, respectively. Both methods can be subcategorized by their application of statistical (for example, regression techniques) or physical modeling methods [129].

2.3.1.1 Top-down approach

Top-down models assess long-term changes in energy consumption using macroeconomic (GDP, income, energy prices) and environmental factors. They are normally carried out by fitting historical or time series data at an aggregated level but are limited to the given variables. For example, top-down models might predict changes in house energy demand or pollutant concentrations from changes such as variations in energy prices or weather conditions, but they cannot explain these changes in detail [129]. Therefore, some of the disadvantages of this model is that there is no detailed information for individual energy end-use. Consequently, they cannot assess the impact of new technologies.

2.3.1.2 Bottom-up approach

The bottom-up modeling approach uses disaggregated data to estimate the energy demands of individual units or entire housing stocks. This methodology employs housing archetypes as representative models of a housing stock. Archetypes have been widely used to model the energy demand of existing buildings, conduct Life Cycle Assessment (LCA), and evaluate Indoor Air Quality. These calculations generally require considerable computational and temporal resources, which can be alleviated by using a series of archetypal buildings to represent the entire housing stock of a nation.

Modeling an individual building or a set of buildings representing a proportion of the stock is a faster and economic assessment method than in situ measurements. Furthermore, it is preferred due to its ability to assess multiple scenarios, and it is considered a suitable approach in contrast to using energy bills, as it allows for the easy detection of impacts from modifications in building parameters. For example, the model can be utilized to evaluate the impacts of a new intervention policy by examining the effects of alterations in a component's conditions, such as a U-value, or by comparing a set of components between different building types,such as building type A versus B.

A robust model should be able to estimate the energy performance precisely because these results could be used to estimate other outcomes such as those related to national energy demand, expenditures, climate change impact, etc. [12, 25, 44]. Consequently, the model requires detailed input and typical data input includes dwelling attributes such as geometry, structure, equipment, appliances, location, occupancy, lighting, and operation schedules, among others. In the absence of specific data, the model may rely on empirical data or assumptions to characterize each component of the home.

2.3.2 Segmentation methods

The classification of archetype segmentation methodologies can be categorized into three principal approaches: deterministic, probabilistic, and clustering [127].

2.3.2.1 Deterministic

Deterministic segmentation is the most widely used approach. It consists of a classification of building stock by categorical variables. These archetypes are developed by aggregating relevant characteristics known as factors. The selection of these factors depends on their availability within the data set and their impact on the calculations of the energy demand for a dwelling. The chosen factors enable the clustering of housing stock data entries into groups or cells. As a result, the available housing stock data is organized into categories that share common characteristics. Following this classification, the attributes of each group are used to delineate the archetypes. Therefore, each archetype corresponds to a specific segment of the housing stock. Certain factor values occur with greater frequency in the dataset, leading to the formation of larger cells, whose conglomeration of factors represents a more significant proportion of the housing stock [26].

2.3.2.2 Probabilistic

The probabilistic segmentation approach involves a statistical determination of the most pertinent variables for the fragmentation of the building stock, using historical data on energy consumption as an auxiliary indicator [91, 52]. Although employing this method for building stock fragmentation may more accurately capture the diversity of building stock when compared to deterministic approaches, there is a paucity of studies adopting it. This is mainly attributable to the extensive data requirements concerning buildings, along with the need for measured data on energy use, which is often inaccessible due to the confidentiality policies maintained by energy supply companies [26].

2.3.2.3 Clustering

The cluster segmentation approach consists of the application of clustering methods and building characteristics as cluster classifiers to divide the building stock [165]. This unsupervised classification data mining method consists in classification into groups following a pattern [125], in such a way that objects in a particular cluster are as similar as possible, while objects in different clusters are as different as possible. One of the strengths of the cluster approach compared to the previous ones is that the building classification results from hidden structures, since membership information is not used as a prior input. Although clustering techniques have been applied in many contexts and disciplines, including specific areas of the building sector, it is a rather recent concept in the field of building archetype development. In fact, due to its novelty, research works focus mainly on identifying the most suitable building-related variables and clustering algorithm to perform clustering analysis [177].

2.3.3 Representative buildings or archetypes

The use of archetype application was observed in the United States, as well as in several European countries, including Germany, Italy, France, and the United Kingdom. In 2006, the United States developed 209 archetypes, which constituted 80.2% of the US housing stock. National databases related to residential buildings were used to characterize the housing stock, taking into account variables such as location, type of building, year of construction, floor area, and household size.

The clusters were established through a factorial design, specifically by integrating a category from each of the selected variables. Consequently, 848 clusters were created, of which the distribution showed that 209 of these clusters (or archetypes) represented 80% of the housing stock [156]. In England, a selection of 15 representative buildings was used to investigate the phenomenon of overheating within the London housing stock. These structures collectively represented 76% of the housing stock in two specified locations within the city. Variables such as type of building (detached, semi-detached, terraced, and flat), year of construction, and infiltration rate were considered in the archetype development process [151].

In 2018, European nations undertook efforts to establish a suite of prototypical buildings to facilitate the assessment of energy demand and potential savings. The number of buildings required to adequately represent the housing stock of each nation varied, with Hungary necessitating 11 buildings, while Germany required 62. Specifically, for Montenegro, Albania and Serbia, 15, 20, and 24 archetypes were developed, respectively [147]. A concurrent study in Italy, directed towards energy planning, resulted in the construction of 12 archetypes intended to represent the Sicilian housing stock [93]. The derivation of these archetypes required an analysis of relevant housing stock variables and classification based on attributes such as type of building, year of construction, climate zones, building service systems and energy sources.

In Chile, the Ministry of Housing (MINVU) in 2018 launched a tender to characterize the Chilean housing stock based on various factors influencing their energy demand [76]. This tender was awarded to the Pontificia Universidad Catolica de Valparaiso. The analysis and selection of influential factors was informed by census data sets and the housing energy rating (CEV). Established since 2012, the CEV is a voluntary process that assigns an energy label to housing based on their design. Key factors pertinent to the calculation of the energy demand for heating were extracted from these sources. In general, nine categories or factors were identified, including thermal zone classification, house geometry, number of floors, building materials, floor area, periods of construction, and type of windows. A total of 13 archetypes have been identified that represent the entirety of the Chilean housing stock, comprising 5 detached houses, 4 semidetached or terraced houses, and 4 apartments. However, the manner in which the results were reported poses challenges in accurately quantifying the number of dwellings by archetype and thermal zone, as well as in determining the proportion of each archetype relative to the total housing stock within each thermal zone.

A study conducted by the University of Nottingham in 2019 [142] identified a series of archetypes and sub-classifications. Using a variety of data sources, such as censuses and building permits, the research aimed to develop archetypal Chilean houses with statistically significant representative values for design parameters relevant to energy demand and indoor air quality. The study identified eight categories or factors, including the type of house, the construction period, the number of zones, the floor area, the number of stories, the number of bedrooms, the number of bathrooms, and the number of occupants. The results indicated that 496 archetypes can adequately represent the entire Chilean housing stock, while only 90 archetypes suffice to represent 95% of the stock. However, significant issues were identified in the calculation of the distribution between groups and subgroups, resulting in inaccuracies in the calculated weighting factors. Consequently, this led to errors in the estimation of the number of dwellings per archetype, as well as in the proportion of each archetype relative to the total housing stock. Therefore, based on these findings, the determination of Chilean archetypes will be revisited in this chapter.

2.3.4 Stock characterization

This section will provide a comprehensive overview of the Chilean housing stock, encompassing the total number of homes and their geographical distribution, physical geometry, construction materials, year of construction, and floor area. In addition, it will examine the energy consumption patterns within the residential sector and the associated fuel sources. This analysis will facilitate the creation of representative archetypes of the Chilean housing stock, presented in Section 2.3.5.

2.3.4.1 Dwelling quantity and distribution

Chile is divided into 16 administrative regions and incorporates 7 thermal zones, classified according to the climatic conditions observed within each zone (see Figure 1.8). The use of thermal zones as a framework presents a pragmatic and straightforward approach that enhances the modeling of the housing stock, optimizes the simulation process, and facilitates data analysis. Consequently, the subsequent analysis will proceed on the basis of thermal zones rather than administrative regions.

The correspondence between thermal zones and administrative regions is illustrated in Table 2.4.

Table 2.4: Regions that compose each thermal zone. Source: Self-elaboration.

Thermal zones	Regions	Population	Degree days of heating (2022)
Zone 1	XV. Arica	226,068	412
	I. Tarapacá	330,558	
	II. Antofagasta	607,534	
	III. Atacama	286,168	
	IV. Coquimbo	757,586	
Zone 2	V. Valparaíso	1,815,902	1,798
Zone 3	Metropolitana	7,112,808	1,723
	VI. O´Higgins	914,555	
Zone 4	VII. Maule	1,044,950	1,947
	VIII. Bío-Bío	1,556,805	
Zone 5	IX. La Araucania	957,224	2,615
	XIV. Los Rios	384,837	
Zone 6	X. Los Lagos	828,708	2,975
Zone 7	XI. Aysén	103,158	4,097
	XII. Magallanes	166,533	

In 2017, the Chilean housing stock consisted of approximately 5.5 million residential units [66]. Most of these units are located in the central region of the country, specifically within thermal zones 2 (10.8%), 3 (44.7%), and 4 (18.3%). These zones correspond to the main cities of the country, namely Valparaiso, Santiago, and Concepcion, respectively.

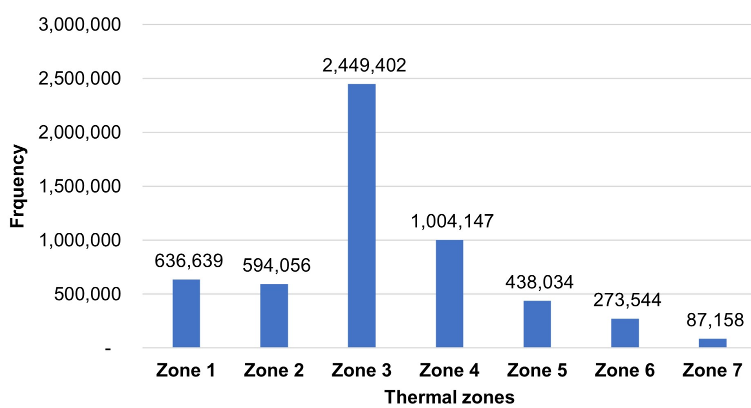


Figure 2.2: Housing stock distribution by thermal zone [66].

2.3.4.2 Geometry

Relevant data for understanding the geometry of the housing stock have been provided by the Chilean census. Despite inconsistencies in the questionnaire regarding housing geometry (see Section 1.6.1, the 2012 Census provided data that enabled determining the proportion between detached and semi-detached houses (see Figure 2.3). This ratio was later extrapolated to the results of the 2017 Census.

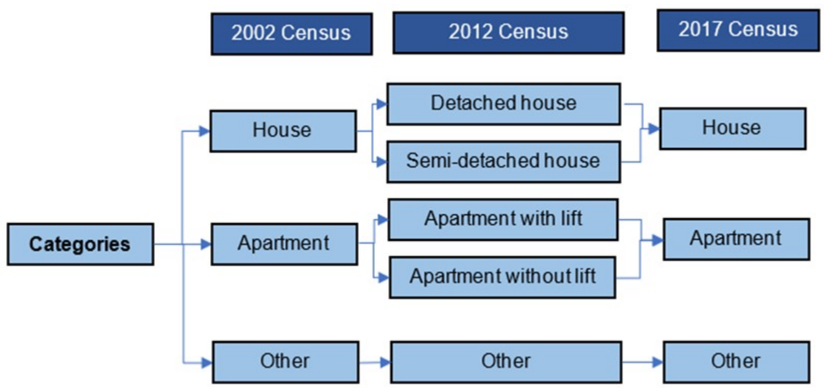
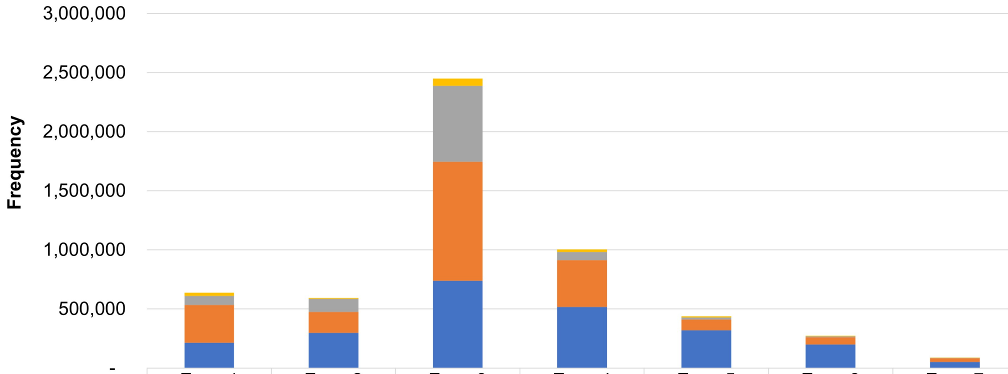


Figure 2.3: Categories for geometry of the house in the Chilean censuses [62, 64, 66].

According to the 2017 Census, 4.4 million dwellings, representing 80. 6% of the total housing stock are classified as houses. Among these, 2.3 million are classified as detached houses, while 2.1 million are classified as semi-detached houses. The residual housing stock is comprised of 0.9 million apartments and 0.1 million units designated for emergency use or as rooms occupied by residents of older dwellings.

The configuration of housing types is influenced by geographical location. As illustrated in Figure 2.4, there is a higher prevalence of semi-detached houses in the central and northern regions of the country, whereas detached houses are predominantly found in the southern areas. Most apartment buildings are located within thermal zones 2 (0.1M) and 3 (0.6M). This distribution can be attributed to the availability of land and the population density within each zone. Consequently, areas with a substantial number of residents, particularly thermal zone 3, favor semi-detached houses or apartments, as this housing typology optimizes space utilization in highly sought-after zones and is more cost-effective than detached homes.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Other	26,826	9,445	60,551	22,738	9,853	5,103	1,205
Apartment	75,565	109,889	643,253	68,780	18,104	8,762	2,447
Semi-detached House	319,431	177,992	1,007,991	395,208	89,256	60,044	33,023
Detached House	214,817	296,730	737,607	517,421	320,821	199,635	50,483

Thermal zones

Figure 2.4: Type of house by thermal zone [66].

2.3.4.3 Wall material

The composition of the national housing stock can be categorized by wall construction materials. As illustrated in Table 2.5, the most prevalent categories are semi-detached masonry houses (26%), wood-detached houses (17%), detached masonry houses (14%), and reinforced concrete apartments (12%).

The characteristics of the building materials of the housing stock vary throughout the country (see Figure 2.5). Toward the center-north of the country there is a greater variability of materials used for walls, such as masonry, wood, and reinforced concrete. In the south there is a considerable predominance of wood buildings. The variability in material selection could be explained by the local climate and the availability and affordability of building materials.

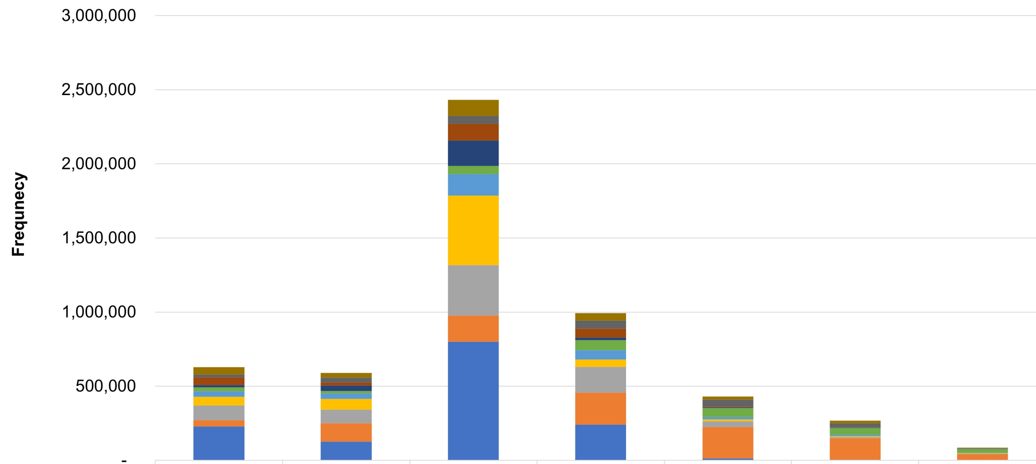
Thermal zones 3 and 5 are utilized to demonstrate the variation in wall construction materials. Thermal zone 3, which concentrates most of the national housing stock (2.4 million), pre-

Table 2.5: Distribution of housing stock by type of house and wall material [66].

House type		Percent	Frequency	Wall material	Percent	Frequency
House	Detached house	43%	2,337,515	1. Reinforced concrete	6%	308,119
				2. Masonry	14%	753,295
				3. Wood	17%	953,867
				4. Internit	4%	237,675
				5. Mud and recycling materials	2%	84,559
	Semi-detached house	38%	2,082,944	1. Reinforced concrete	5%	252,026
				2. Masonry	26%	1,418,519
				3. Wood	5%	296,165
				4. Internit	1%	55,812
				5. Mud and recycling materials	1%	60,422
Apartment		17%	926,800	1. Reinforced concrete	12%	672,053
				2. Masonry	5%	254,747
Other		2%	135,721		2%	135,721
Total		100%	5,482,980	Total	100%	5,482,980

dominantly employs masonry (54%), reinforced concrete (30%), and wood (9%) as construction materials. Based on building geometry, notable categories include semi-detached masonry houses (0.8 million), reinforced concrete apartments (0.5 million), and detached masonry houses (0.3 million). In contrast, thermal zone 5, located in the southern region of the country with a housing concentration of 0.4 million dwellings, mainly uses wood (62%), followed by masonry (13%) and internit (11%). In terms of building geometry, the significant groups are wood detached houses (0.2 million), wood semi-detached houses (0.1 million), and internit detached houses (0.05 million).

The data collected within this section constitute a significant resource for the development of archetypes that accurately represent each thermal zone. These archetypes will serve as a reference, and the necessary inputs for modeling will be allocated to them.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Other.	49,340	32,174	109,002	49,061	20,820	17,180	3,125
Internit detached house	20,407	31,531	53,182	56,088	45,838	26,427	4,201
Reinforced concrete semi-detached house	50,672	21,581	111,744	59,001	5,027	2,323	1,678
Masonry apartment	16,052	37,622	172,945	18,373	5,865	3,261	629
Wood semi-detached house	25,961	16,756	54,274	67,526	60,128	46,201	25,318
Reinforced concrete detached house	37,515	36,547	144,340	63,409	15,677	8,434	2,197
Reinforced concrete apartment	59,513	72,267	470,308	50,407	12,239	5,501	1,818
Masonry detached house	98,199	92,110	339,305	172,924	38,184	9,173	3,400
Wood detached house	42,347	123,628	175,963	214,724	213,123	145,249	38,834
Masonry semi-detached house	229,175	126,360	800,966	241,906	12,788	3,429	3,895

Thermal zones

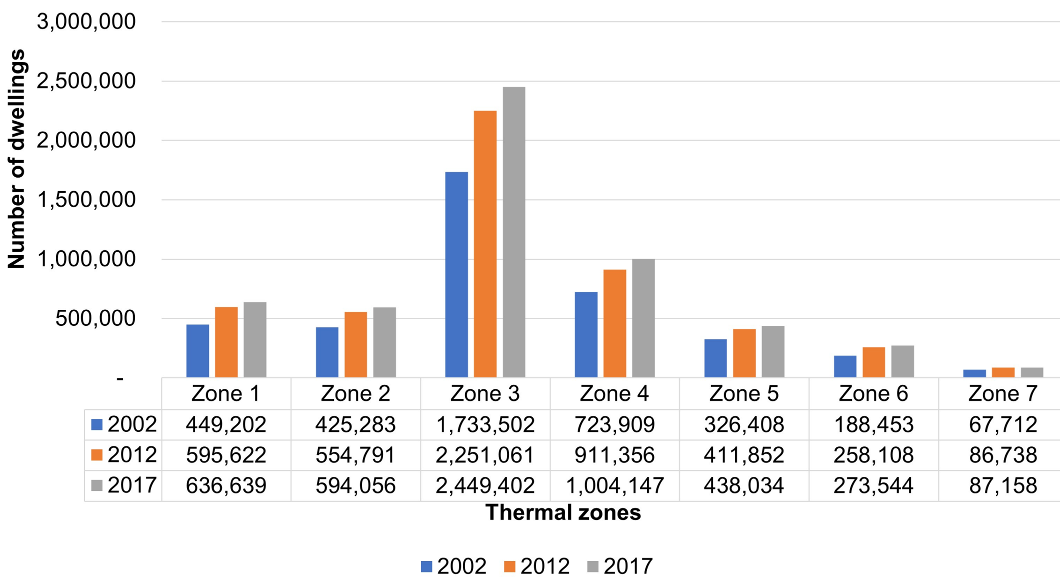
Figure 2.5: Type of wall material of Chilean housing stock by thermal zones [66].

2.3.4.4 Period of construction

In Chile, there is currently a lack of documentation on the age of buildings; however, estimations can be derived from data provided by the 2002, 2012, and 2017 Censuses. Gaining insight into the construction years of these buildings will enable an assessment of the extent to which the Chilean housing inventory has incorporated the thermal specifications mandated by the Ministry of Housing. This information will later be used to develop archetypes in Chapter 2.3.5.

Figure 2.6 illustrates the distribution of the housing stock by thermal zone, as reported by the three censuses. The data shown in Figure 2.6 facilitate the visualization of the increase in housing stock as presented in Figure 2.7. This analysis is pertinent to determine the degree to which the Chilean housing stock has adhered to thermal requirements over time. The initial and second phases of thermal regulation were enacted in 2001 and 2007, respectively (see Section 1.5.5). Thus, it is essential to determine the number of dwellings constructed up to these years.

To quantify the size of the housing stock based on the level of insulation acquired, the housing stock was classified into three groups according to the construction year, each corresponding to the level of insulation present in the dwellings. It was assumed that all housing stock constructed prior to 2001 lacked insulation, despite the fact that some may have included it independently. Given that the 2002 Census was conducted in March 2002, a mere three months after 2001, this date has been used as the starting point for the first stage of thermal regulation. Consequently, the number of dwellings constructed in 2007 was estimated by interpolation. It is important to acknowledge a potential limitation of this methodology, the possibility of data lag. For example, there may be a delay of several years before the housing approved under the new regulation is completed. Conversely, dwellings sanctioned under the previous regulation could take several years to be completed, and as a result, be counted as new dwellings under the post-regulation phase.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
2002	449,202	425,283	1,733,502	723,909	326,408	188,453	67,712
2012	595,622	554,791	2,251,061	911,356	411,852	258,108	86,738
2017	636,639	594,056	2,449,402	1,004,147	438,034	273,544	87,158

Figure 2.6: Number of dwellings in Chile through the time [62, 63, 66].

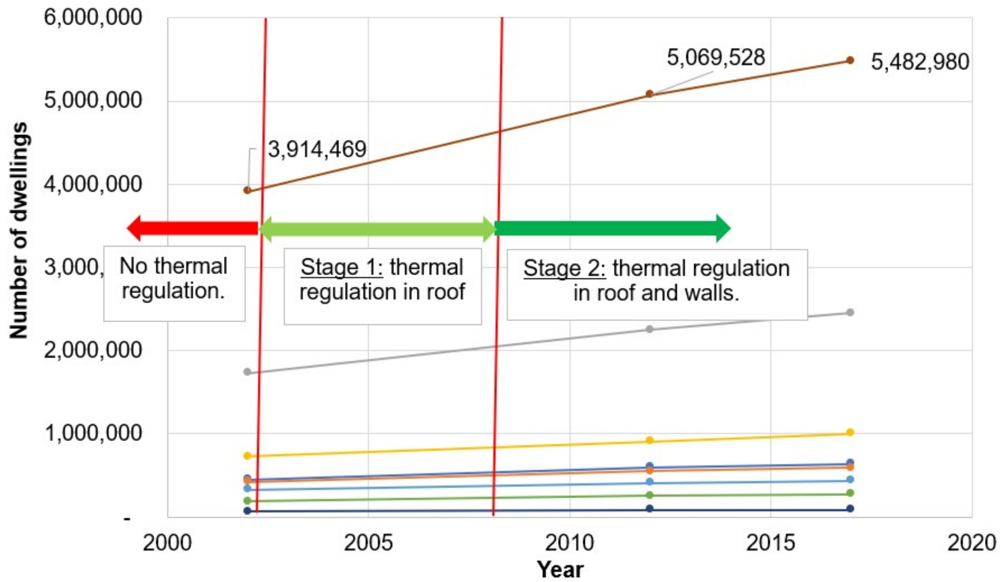


Figure 2.7: Number of dwellings built in Chile through the time[62, 63, 66].

Figure 2.8 indicates that 71.4% of the national housing stock lack any form of insulation, while 9.5% includes roof insulation and 19.1% features both roof and wall insulation. Figure 2.9 illustrates the adoption of thermal requirements by thermal zone, revealing that the proportions are comparable between these zones.

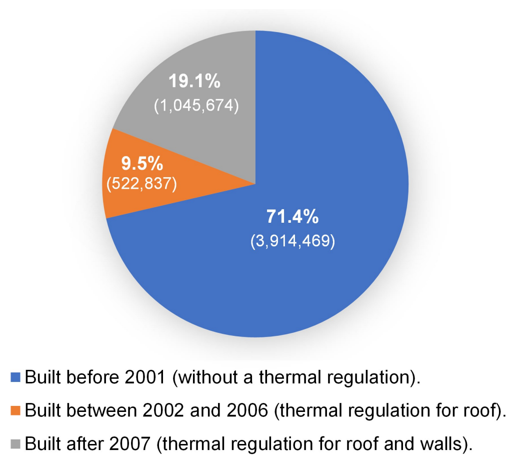
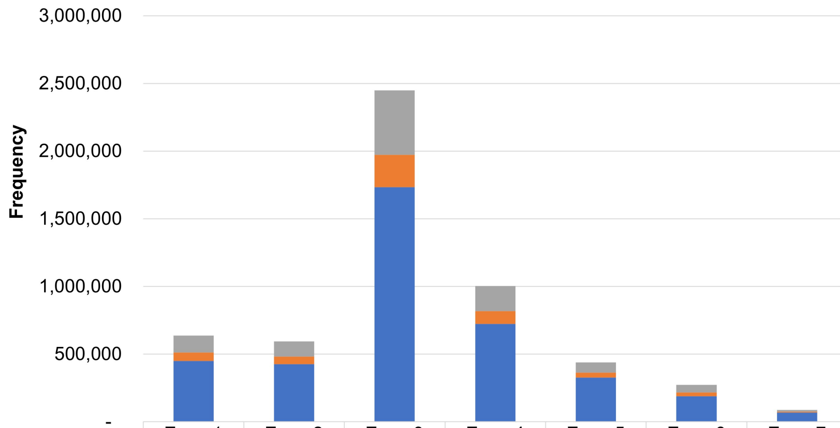


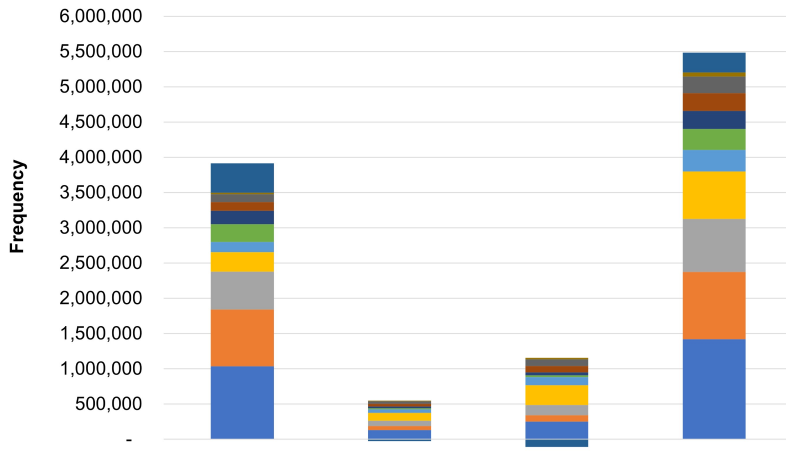
Figure 2.8: Distribution of national housing stock considering thermal regulation[62, 63, 66].



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Built after 2007.	124,958	112,515	477,267	186,825	74,417	56,727	12,964
Built between 2002 and 2006.	62,479	56,258	238,633	93,413	37,209	28,364	6,482
Built before 2001.	449,202	425,283	1,733,50	723,909	326,408	188,453	67,712

Figure 2.9: Distribution of housing stock according to incoporation of thermal requirements[62, 63, 66].

Subsequently, the entire housing stock is categorized according to house type, defined by geometry and wall material, as well as by year of construction (see Figure 2.10). This categorization was carried out using the distribution of Chilean housing stock based on the type of wall material according to the thermal zone, as shown in Figure 2.5, and then applying the distribution according to the year of construction as demonstrated in Figure 2.8. Within the cohort constructed before 2001, which constitutes 71% of the national housing stock, the most predominant typologies are semi-detached masonry (26%), wood detached houses (21%) and masonry detached houses (14%). In contrast, the housing stock constructed post-2001 also includes masonry semidetached and detached houses; however, there is a notable rise in the prevalence of reinforced concrete for apartments and semi-detached houses. This phenomenon is potentially related to the insights discussed in Section 2.3.4.2 concerning the costs of land and the densification of urban development. Consequently, it is logical that the housing stock built after 2001 predominantly comprises semidetached houses and apartments, facilitating space conservation in areas with high population concentration and demand.

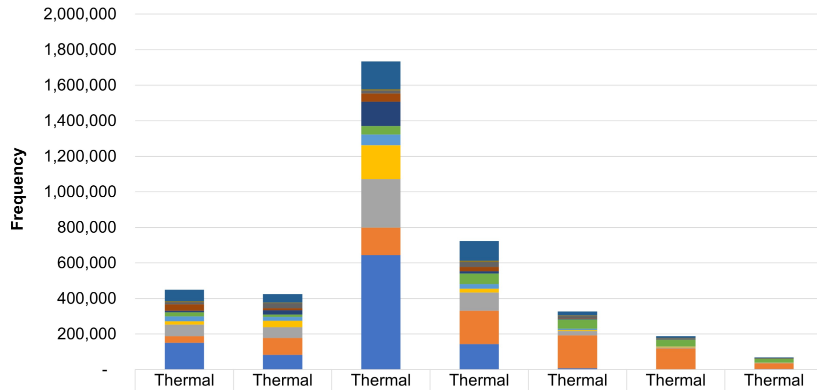


	Before 2001	Between 2002 and 2006	After 2007	Total
Other.	416,764	-26,101	-109,961	280,702
Internit semi-detached house	23,321	9,369	23,122	55,812
Internit detached house	107,649	37,869	92,156	237,675
Reinforced conc. semi-det. house	124,139	37,687	90,199	252,026
Masonry apartment	189,735	22,480	42,532	254,747
Wood semi-detached house	251,944	18,098	26,123	296,165
Reinforced concrete detached house	145,883	47,474	114,763	308,119
Reinforced concrete apartment	278,246	113,189	280,618	672,053
Masonry detached house	534,833	72,781	145,681	753,295
Wood detached house	805,672	59,809	88,386	953,867
Masonry semi-detached house	1,036,283	130,181	252,055	1,418,519

Year of construction

Figure 2.10: Housing stock distribution by dwelling type and year of construction[62, 63, 66].

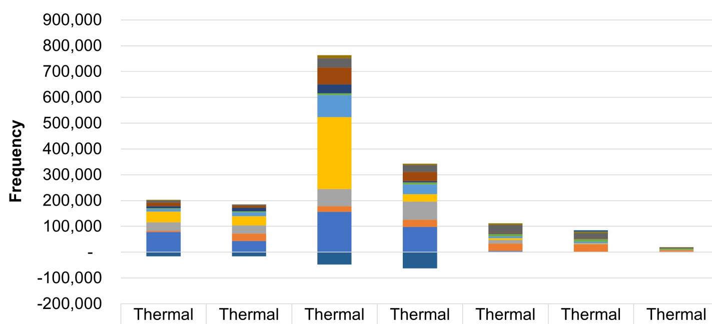
Figures 2.11 and 2.12 illustrate the distribution of the housing stock constructed prior to and after 2001, respectively. These figures facilitate the determination of the predominant types of dwelling within each thermal zone and enable the identification of changes in construction patterns, such as the increased use of specific materials. In thermal zone 3, a significant increase is observed in the application of reinforced concrete for the construction of apartments, as well as detached or semi-detached houses. In contrast, in the southern regions of the country, there is a marked proliferation of detached housing utilizing fiber cement construction boards (also known as internit) to encase structural steel frames. It is pertinent to clarify that the negative values presented in Figure 2.12 refer to dwellings that have been demolished.



	Thermal zone 1	Thermal zone 2	Thermal zone 3	Thermal zone 4	Thermal zone 5	Thermal zone 6	Thermal zone 7
Other	65,033	48,053	156,482	111,411	21,215	10,997	3,573
Internit semi-detached house	4,396	3,083	5,624	5,638	2,506	1,416	658
Internit detached house	12,028	27,938	17,217	29,478	13,768	5,880	1,340
Reinforced concrete semi-det. house	37,260	12,809	46,065	23,834	2,581	584	1,006
Masonry apartment	7,893	24,131	138,343	13,602	3,903	1,477	386
Wood semi-detached house	23,283	12,824	47,412	58,984	51,962	36,940	20,539
Reinforced concrete detached house	27,585	21,693	59,502	25,615	8,050	2,121	1,317
Reinforced concrete apartment	18,197	36,142	191,506	21,648	5,854	3,902	997
Masonry detached house	64,656	60,711	273,057	102,604	24,271	6,554	2,980
Wood detached house	37,977	94,614	153,714	187,561	184,170	116,133	31,503
Masonry semi-detached house	150,894	83,285	644,580	143,534	8,128	2,449	3,413

Thermal zones

Figure 2.11: Distribution of housing stock built before 2001 (71.4% of housing stock) [62, 63, 66].



	Thermal zone 1	Thermal zone 2	Thermal zone 3	Thermal zone 4	Thermal zone 5	Thermal zone 6	Thermal zone 7
Other	-15,693	-15,879	-47,480	-62,350	-395	6,183	-448
Internit semi-detached house	3,062	397	11,749	5,090	5,839	4,950	1,405
Internit detached house	8,379	3,593	35,965	26,610	32,070	20,547	2,861
Reinforced concrete semi-det. house	13,412	8,772	65,679	35,167	2,446	1,739	672
Masonry apartment	8,159	13,491	34,602	4,771	1,962	1,784	243
Wood semi-detached house	2,678	3,932	6,862	8,542	8,166	9,261	4,779
Reinforced concrete detached house	9,930	14,854	84,838	37,794	7,627	6,313	880
Reinforced concrete apartment	41,316	36,125	278,802	28,759	6,385	1,599	821
Masonry detached house	33,543	31,399	66,248	70,320	13,913	2,619	420
Wood detached house	4,370	29,014	22,249	27,163	28,953	29,116	7,331
Masonry semi-detached house	78,281	43,075	156,386	98,372	4,660	980	482

Figure 2.12: Distribution of housing stock built after 2001 (28.6% of housing stock) [62, 63, 66].

2.3.4.5 Floor area and number of rooms

The floor area corresponding to each type of house is essential to characterize the various housing archetypes within the country. Furthermore, the floor area will serve as a fundamental parameter in calculating the energy demand for heating associated with each archetype. The 2018 survey on energy use in Chilean housing provides comprehensive data on dwelling areas classified by house type, geometric configuration, and wall material (as illustrated in Table 2.6). These findings are aligned with those documented in the 2002 Census, in which the mean and median floor areas are reported to be 81 m^2 and 79 m^2, respectively.

Table 2.6: Median dwelling size by type of house [40].

House type		Wall material	Median dwelling size (m2)
House	Detached	1. Reinforced concrete	80
		2. Masonry	80
		3. Wood	72
		4. Internit	72
	Semi-detached	1. Reinforced concrete	77
		2. Masonry	75
		3. Wood	70
		4. Internit	70
Apartment		1. Reinforced concrete	80
		2. Masonry	68

A weak correlation between the floor area of the dwellings and the number of occupants has been identified [40], indicating that the floor area of the dwellings does not increase substantially with the number of occupants. This conclusion is supported by the findings of the 2002 Census, which also revealed a low correlation between the number of occupants and the number of rooms in a home [62]. Table 2.7 illustrates that there is only a minor increase in the number of rooms as the number of inhabitants of a dwelling increases. In Chile, most households consist of one to five people (refer to Section 1.3.2). Consequently, households that contain one to three occupants typically have a median of four rooms, consisting of a combined living and dining area, a separate kitchen, and two bedrooms. In contrast, households with four to five occupants generally have a median of five rooms, which includes three bedrooms in total. Thus, there is minimal variation in the size of the house relative to the number of occupants. Furthermore, the modest increase in the size of the residence by occupant number may explain the weak correlation observed between energy expenditure and the floor area of the residence in all thermal zones of the country [40]. This suggests only a limited variation in energy expenditure in relation to floor area.

Table 2.7: Number of rooms by household size[62].

Household size	Number of rooms		
	Mean	Median	Standard Deviation
1	4.0	4.0	1.8
2	4.4	4.0	1.6
3	4.5	4.0	1.5
4	4.8	5.0	1.5
5	5.1	5.0	1.7
6	5.4	5.0	1.9
7	5.7	5.0	2.1
8	6.0	6.0	2.3

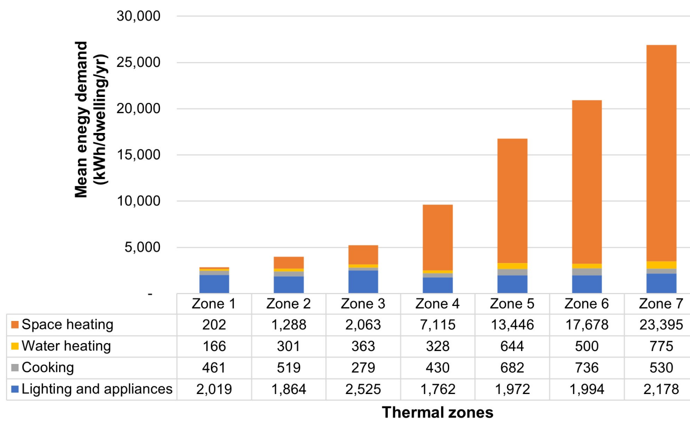
2.3.4.6 Energy end-use in residential housing stock

Various studies have documented the national average energy consumption per dwelling. In 2010, an analysis of the final uses and trends in energy conservation within the Chilean residential sector indicated that the national average energy consumption per dwelling was 10,232 kWh annually, covering all forms of energy for space heating, water heating, lighting, cooking and appliance use [39]. The energy consumption of the residential sector was distributed among different sources as follows: 47% consisted of wood (4,773 kWh); 21% was liquefied petroleum gas (LPG) (2,186 kWh); 18% derived from electricity (1,806 kWh); 10% from natural gas (1,035 kWh); 3% was attributed to paraffin (344 kWh); and 1% to charcoal (84 kWh) [39].

Subsequently, the comprehensive report on energy consumption within Chilean households, published in 2018, indicated that the national average consumption per household amounted to 8,083 kWh annually, encompassing all energy sources such as space heating, water heating, lighting, cooking and appliances. This figure is significantly lower than the estimates calculated in 2010. The disparities are attributed to the application of different methodologies in the evaluation of heating, water heating, and cooking [41]. According to this study, the energy sources utilized by the Chilean residential sector are predominantly composed of 40% wood (3,201 kWh); 20% liquefied petroleum gas (LPG) (1,644 kWh); 26% electricity (2,074 kWh); 11% natural gas (892 kWh); 3% paraffin

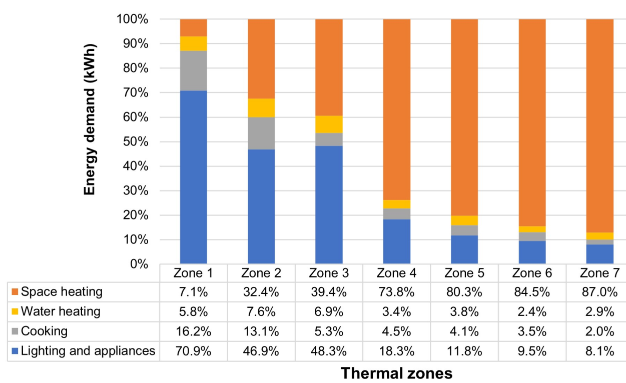
(211 kWh); and 1% pellet (63 kWh).

Data from the 2018 Chilean Energy Use Housing Survey facilitated the analysis of end use of energy within the residential housing sector throughout the country. The energy consumption for lighting and appliances demonstrates relative stability in different thermal zones compared to space heating. In contrast, space and water heating show substantial variability which can be ascribed to the climatic heterogeneity of the country, with pronounced increases observed in the southern regions (see Figure 2.13) [41].



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Space heating	202	1,288	2,063	7,115	13,446	17,678	23,395
Water heating	166	301	363	328	644	500	775
Cooking	461	519	279	430	682	736	530
Lighting and appliances	2,019	1,864	2,525	1,762	1,972	1,994	2,178

Figure 2.13: Mean annual energy demand per dwelling by end-use [40].

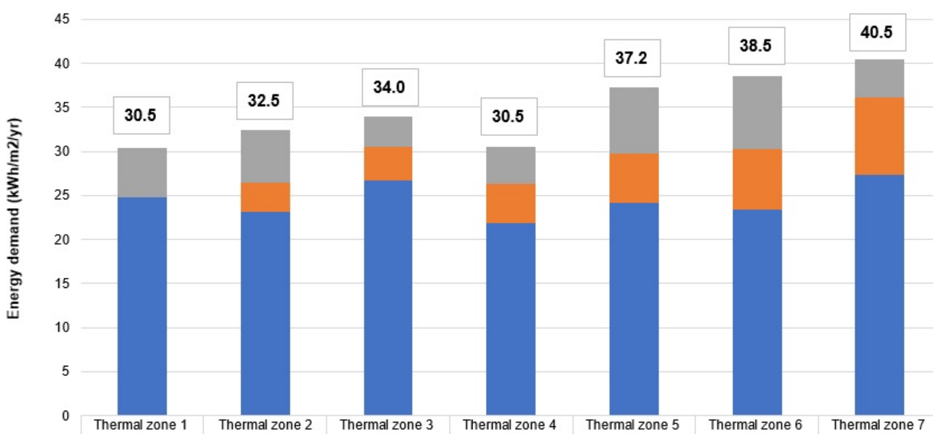


	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Space heating	7.1%	32.4%	39.4%	73.8%	80.3%	84.5%	87.0%
Water heating	5.8%	7.6%	6.9%	3.4%	3.8%	2.4%	2.9%
Cooking	16.2%	13.1%	5.3%	4.5%	4.1%	3.5%	2.0%
Lighting and appliances	70.9%	46.9%	48.3%	18.3%	11.8%	9.5%	8.1%

Figure 2.14: Distribution of energy demand per dwelling by end-use [40].

Figure 2.15 illustrates that the energy requirements for lighting and appliances, cooking and hot water range from 30.5 to 40.5 kWh/m^2/year, exhibiting an increasing trend towards the southern regions. The majority of the energy demand is allocated to lighting and appliances, with a distribution of 20% for lighting and 80% for appliances [40].

Figure 2.16 further indicates that there is minimal variability in the energy demand for lighting throughout the country. This low variability can potentially be attributed to the fact that despite the substantial variation in daylight duration throughout the year in different thermal zones, the average number of waking hours requiring illumination remains quite consistent when assessed annually. Consequently, the additional energy consumption associated with lighting during the winter months (with shorter daylight hours) is offset by the reduced energy usage in the summer months (with longer daylight hours).



	Thermal zone 1	Thermal zone 2	Thermal zone 3	Thermal zone 4	Thermal zone 5	Thermal zone 6	Thermal zone 7
Cooking	5.6	6.1	3.4	4.2	7.4	8.3	4.4
Hot water	-	3.3	3.8	4.5	5.6	6.8	8.8
Lighting and appliances	24.8	23.1	26.8	21.8	24.2	23.4	27.3

Figure 2.15: Median energy demand for cooking, hot water and lighting and appliances [40].

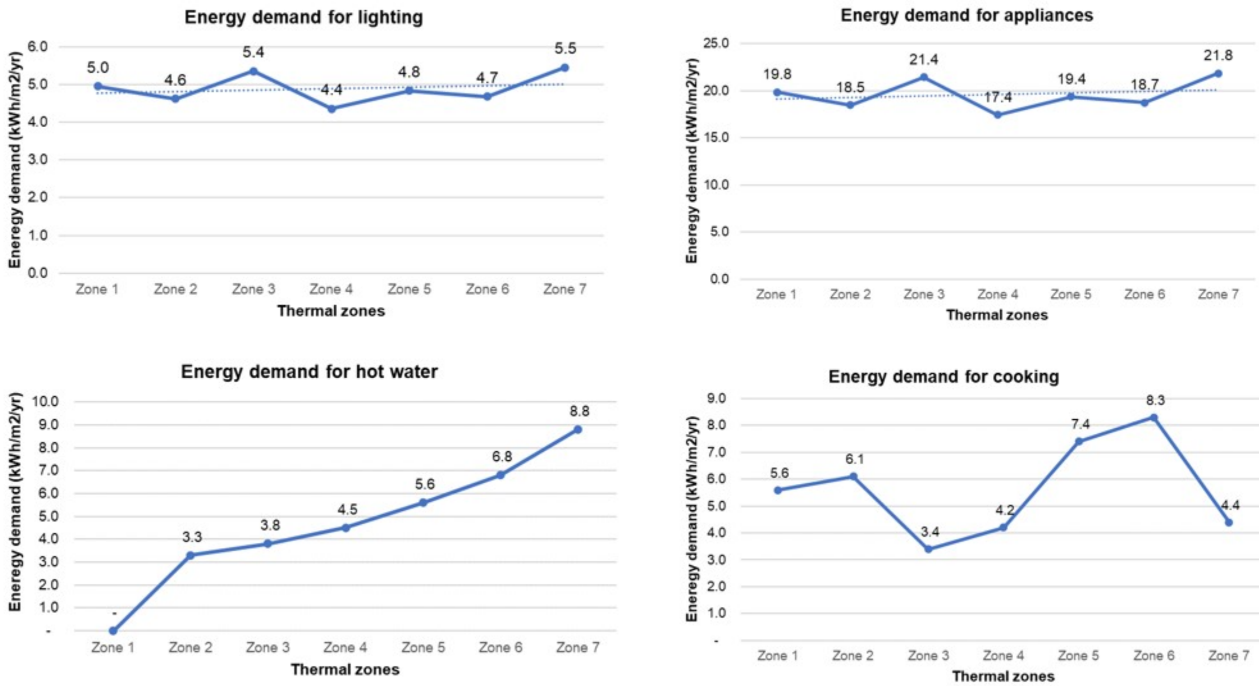
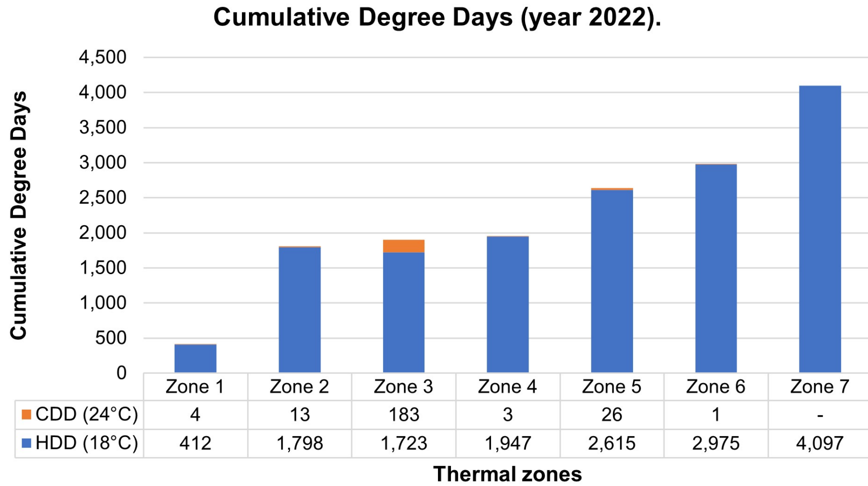


Figure 2.16: Energy demand by type of use: lighting, appliances, hot water, and cooking [40].

It is pertinent to note that although the demand for heating is substantial and exhibits considerable variation throughout the country, the energy demand for cooling remains minimal. Degree days serve as a tool to illustrate this phenomenon. Degree days are a simplified representation of ambient air temperature data, which facilitates the assessment of how warm or cold a location is by comparing the mean outdoor temperature of a location to a standardized temperature [1]. Figure 2.17 illustrates that most thermal zones predominantly require heating, with the exception of thermal zone 3, which requires cooling for a limited number of days annually. Furthermore, the 2018 Chilean housing energy use survey revealed that only 4.5% of the households in thermal zone 3 reported experiencing excessive heat in their homes during the summer and only 4.6% had air conditioning [41]. These findings suggest that overheating and comfort cooling are not significant concerns within the Chilean context and therefore do not warrant consideration. Consequently, this thesis will focus on heating and the challenge of energy poverty associated with maintaining warmth.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
CDD (24°C)	4	13	183	3	26	1	-
HDD (18°C)	412	1,798	1,723	1,947	2,615	2,975	4,097

Figure 2.17: Cumulative Degree Days (year 2022) [168].

The energy requirements of residential buildings are intrinsically linked to climatic conditions. Consequently, a comprehensive understanding of the relationship between energy consumption and climate is essential, as it facilitates the identification of populations susceptible to energy poverty and enables comparative analyzes. This relationship is quantified by comparing the mean energy consumption for heating per dwelling with the heating degree days. By normalizing the heating energy demand in relation to the degree days of heating in various thermal zones, the variation in the energy demand nationwide is scrutinized, demonstrating a correlation with external air temperatures.

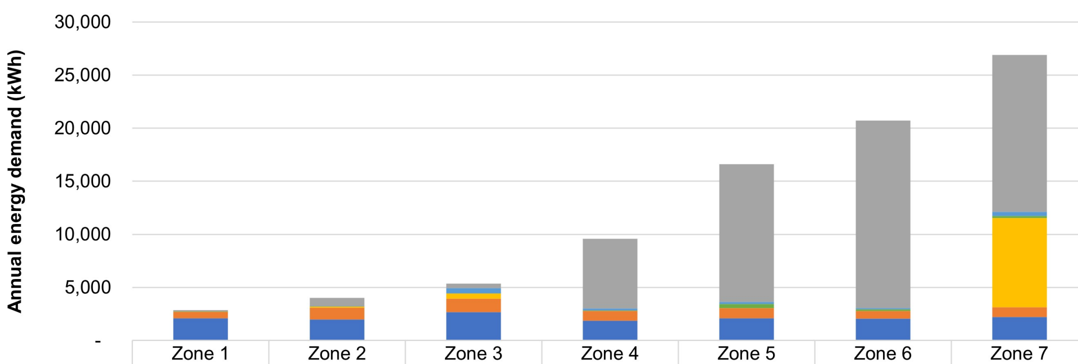
The analysis reveals a gradient in the intensity of the energy demand attributed to climate, which escalates from the north to the south (see Table 2.8. This variation is moderate in the northern and central thermal zones, but increases markedly in the southern zones. For example, the energy demand for heating in thermal zone 7 exceeds that of thermal zone 2 more than eight times and exceeds that of thermal zone 4 1.5 times, thus providing a framework for examining the variability in the energy demand induced by climate.

Table 2.8: Relationship between energy demand and climate (kWh/degree days)

Thermal zones	kWh/degree day	Heating system [42]	Efficiency [88]
Zone 1	0.5	-	-
Zone 2	0.7	Gas heater	92%
Zone 3	1.2	Gas heater	92%
Zone 4	3.7	Wood stove	65%
Zone 5	5.1	Wood stove	65%
Zone 6	5.9	Wood stove	65%
Zone 7	5.7	Combination of gas heater and wood stove	92% 65%

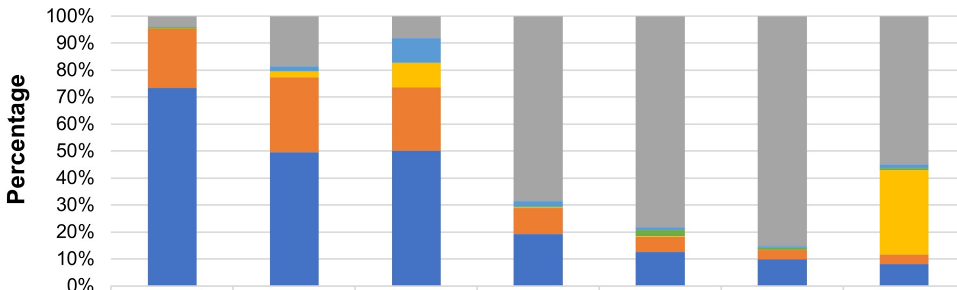
2.3.4.7 Fuel sources

The types of fuel sources utilized by the residential sector exhibit variation across the various regions of the country (see Figure 2.18). The demand for energy in the forms of electricity and natural gas tends to demonstrate relative stability across the different thermal zones. In contrast, there is a noticeably higher consumption of wood in the southern regions of the country.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Wood	112	744	433	6,561	12,977	17,640	14,775
Paraffin	0	71	483	196	174	129	374
Pellet	18	3	2	32	393	131	207
NG	1	85	494	19	7	8	8,398
LPG	625	1,114	1,263	931	937	729	914
Electricity	2,090	1,989	2,684	1,847	2,109	2,062	2,217

Figure 2.18: Annual energy demand per dwelling by fuel sources [40].



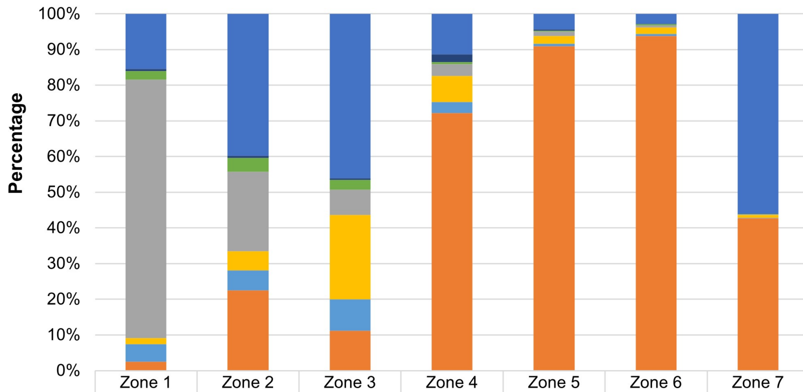
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Wood	4%	19%	8%	68%	78%	85%	55%
Paraffin	0%	2%	9%	2%	1%	1%	1%
Pellet	1%	0%	0%	0%	2%	1%	1%
NG	0%	2%	9%	0%	0%	0%	31%
LPG	22%	28%	24%	10%	6%	4%	3%
Electricity	73%	50%	50%	19%	13%	10%	8%

Thermal zones

Figure 2.19: Distribution of annual energy demand per dwelling by fuel sources [40].

Empirical evidence indicates that in the northern regions, there is a higher prevalence of households lacking a heating system (refer to Figure 2.20) [83]. The most pronounced instance occurs in thermal zone 1, where approximately 73% of residences are without a heating system, and only 15% utilize gas for heating purposes. This suggests that heating may not be essential in this zone. Conversely, in the central region of the country, there is a notable increase in the utilization of fuel sources such as gas (46%) and paraffin (24%). Additionally, it is important to note that 7% of households in this area also lack a heating system for their homes.

In the southern regions of the country, wood constitutes the primary source of fuel for heating. The Magallanes region, aligned with thermal zone 7, represents a notable exception in which households use wood or gas, attributed to the presence of a natural gas energy network in this area [20]. As reported in the 2015 CASEN, 43% of households employ wood as a heating fuel source, while 56% rely on gas [42]. The predominant use of wood is observed in thermal zones 5 and 6, with 91% and 94% of households using this type of fuel, respectively.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Gas	15.4%	39.8%	46.0%	11.3%	4.4%	2.8%	56.0%
Other	0.6%	0.5%	0.5%	2.1%	0.3%	0.1%	0.1%
Does not use fuel	2.4%	3.9%	2.8%	0.6%	0.2%	0.4%	0.1%
Does not have system	72.5%	22.3%	7.0%	3.3%	1.3%	0.5%	0.1%
Paraffin	1.7%	5.3%	23.7%	7.4%	2.3%	1.8%	0.8%
Electricity	4.9%	5.7%	8.8%	3.1%	0.7%	0.6%	0.2%
Wood	2.5%	22.5%	11.2%	72.2%	90.9%	93.8%	42.7%

Thermal zones

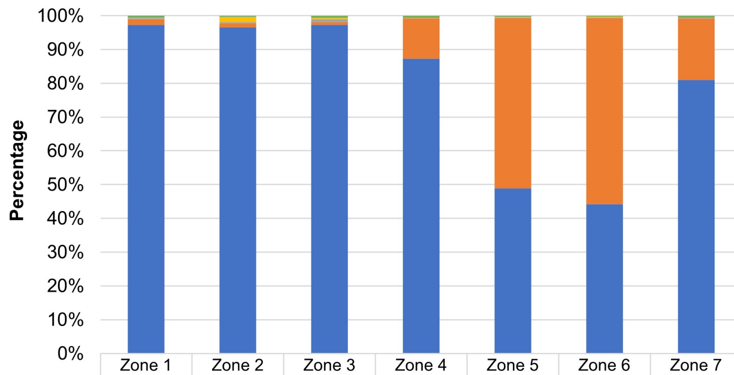
Figure 2.20: Type of fuel used for space heating by thermal zone [83].

The duration and frequency of heating utilization are contingent upon the thermal zone. The duration of heating usage progressively increases across the thermal zones, culminating in a year-round requirement in thermal zone 7. The mean duration of heating use was derived from data provided by the 2018 Energy Uses in the Chilean Housing Survey [40], exclusively considering households that reported using heating. Table 2.9 denotes the duration in months of heating usage and the hours of heating utilization per thermal zone that were analyzed.

Table 2.9: Duration of heating utilization and hours of operation by thermal zone[40].

Thermal zones	**Mean heating hours**	**Months of heating**
Zone 1	-	-
Zone 2	4.2	Jun to Aug
Zone 3	4.0	May to Aug
Zone 4	7.2	May to Sep
Zone 5	8.5	Apr to Oct
Zone 6	7.4	Mar to Oct
Zone 7	7.2	Jan to Dec

The energy sources used for cooking demonstrate geographic variation (refer to Figure 2.21). Households located in the northern region of the country, encompassing thermal zones 1, 2, and 3, predominantly use gas for cooking purposes. In contrast, a disparate pattern emerges in the southern region of the country. In thermal zones 5 and 6, both gas and wood are utilized with equal prevalence. Thermal zone 7, comprising the Región de Aysén and the Región de Magallanes, shows gas as the primary fuel for cooking with a usage rate of 81%, followed by wood at 18%. However, when evaluating the Región de Aysén and the Región de Magallanes separately, notable distinctions in consumption patterns are evident. In the Región de Aysén, 60% of the households use gas and 39% rely on wood, while in the Región de Magallanes, 95% of the households use gas for cooking and 4% use wood.



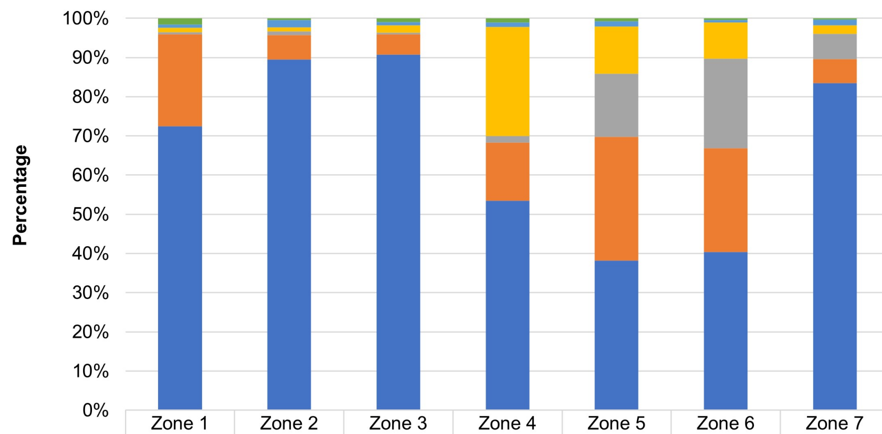
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Other	0.5%	0.3%	0.6%	0.5%	0.3%	0.3%	0.6%
Does not have system	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Does not use fuel	0.2%	1.4%	0.3%	0.1%	0.1%	0.2%	0.0%
Electricity	0.2%	0.3%	0.9%	0.1%	0.1%	0.1%	0.1%
Wood	1.8%	1.3%	0.8%	11.9%	50.5%	55.2%	18.3%
Gas	97.2%	96.5%	97.3%	87.2%	48.9%	44.1%	81.0%

Thermal zones

Figure 2.21: Type of fuel used for cooking by thermal zone [83].

At the national level, the primary fuels used for water heating are predominantly gas and wood; however, a significant portion of the population lacks access to a water heating system (see Figure 2.22). In the northern region of the country, the majority of households utilize gas for heating water, yet 23% of households in thermal zone 1 report the absence of such a system. These observations are explicable given that this thermal zone is characterized by a temperate climate, which may diminish the necessity for hot water, thus allowing for the increased use of cold water.

In the southern regions of the country, three distinct behavioral patterns are evident. In thermal zone 4, 53% of the households use gas, followed by 28% who rely on electricity, while 15% report lacking a hot water system. In thermal zones 5 and 6, approximately 39% of households employ gas, 19% use wood, and 30% lack a hot water system. The latter figure is particularly concerning, given the extreme cold climate of these zones and the fact that a substantial proportion of households without a system are located in rural areas (66% and 55% in thermal zones 5 and 6, respectively). It is plausible that these households are using cooking equipment, predominantly wood stoves, to heat water. It is important to note that the energy consumption data for cooking presented in Figure 2.13 remain unaffected by these observations, as the data in the Chilean Housing Survey segregate each fuel according to its specific end use.



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Other	1.6%	0.4%	1.0%	1.1%	0.8%	0.4%	0.3%
Does not use fuel	0.8%	2.0%	0.8%	1.2%	1.3%	0.6%	1.5%
Electricity	1.1%	1.0%	1.9%	27.8%	12.0%	9.2%	2.1%
Wood	0.6%	0.9%	0.4%	1.7%	16.1%	22.9%	6.5%
Does not have system	23.4%	6.2%	5.2%	14.8%	31.6%	26.5%	6.1%
Gas	72.5%	89.5%	90.7%	53.5%	38.2%	40.3%	83.4%

Thermal zones

Figure 2.22: Type of fuel used for water heating by thermal zone [83].

2.3.5 Representative housing archetypes

In the previous section, the characteristics of the Chilean housing stock were elucidated, classified by geometry, building materials, year of construction, floor area, end-use energy and fuel sources.

This information aims to facilitate the development of archetypes, which will be explored in this section 2.3. These archetypes will later serve as a basis for modeling the energy demand of dwellings.

2.3.5.1 Method

This section elucidates the methodology employed to establish Chilean archetypes at both the national level and by thermal zones. A bottom-up approach has been adopted, utilizing archetypes to articulate the characteristics of the Chilean housing stock (see Section 2.3.1.2). The development of these archetypes was informed by data sourced from censuses conducted in 2002, 2012, and 2017, as well as the information provided by the 2018 survey on energy use within the Chilean residential sector. Following the data collection phase, a segmentation process is initiated, which aims to determine the optimal number of archetypal buildings necessary to accurately represent the stock of residential buildings across various scales. Using the available data set, a deterministic segmentation methodology was adopted (see Section 2.3.2.1).

The existing literature reveals a consensus on the fundamental factors critical to the categorization of building stock into typologies. These factors encompass the type of building, construction materials, construction period, floor area, climatic conditions, and building service systems, such as heating and cooling systems [93, 98]. For example, specific scholars have elucidated the reasons why the type of building and the construction period are significant factors for the segmentation of the housing stock. The classification of building type is generally derived from the layout of the house and its spatial arrangement relative to adjacent structures, including detached, semi-detached, and terraced houses or apartments. This classification is considered vital for building energy modeling, which is attributed to the variation in energy demand dependent on the building type. For example, detached, semi-detached, and terraced houses are likely to exhibit distinct cooling and heating requirements [140].

The construction period is closely related to the building regulations in effect at the time, as well as the technological advancements that were then available, resulting in buildings of the same period exhibiting uniform characteristics in their construction materials [26]. The year of construction serves as a critical determinant of the energy performance of a building. Generally, older buildings tend to exhibit higher levels of energy consumption than newer constructions, which capitalize on contemporary technologies engineered for energy efficiency. Thus, the age of a building serves as a fundamental factor in the classification of building archetypes [128].

In this study, the selection of factors was based on the concordance between insights derived from the existing literature and the data available within the datasets. The elements incorporated into the archetype development process encompass climatic conditions (ranging from thermal zones 1 through 7), types of buildings (including detached houses, semi-detached houses, apartments, and other categories), wall construction materials (such as reinforced concrete, masonry, wood, internit, and additional varieties), periods of construction (categorized as prior to 2001, from 2001 to 2007, and post-2007), and floor area. The exclusion of building systems and materials, such as windows and roofing materials, from the categorization of building stocks was due to the absence of these factors in the data sets. Furthermore, critical data for energy modeling, including the window-to-wall area ratio and the orientation of buildings and glazing, were also unavailable. However, these aspects will be elaborated upon subsequently for the specific cases selected for modeling. Figure 2.23 illustrates the classification of the housing stock according to the selected factors, showcasing the categorization of housing stock both at the national level and by thermal zones. This bifurcated approach enables the identification of the most representative building typologies on a national scale and the most prevalent building typologies within specific thermal zones.

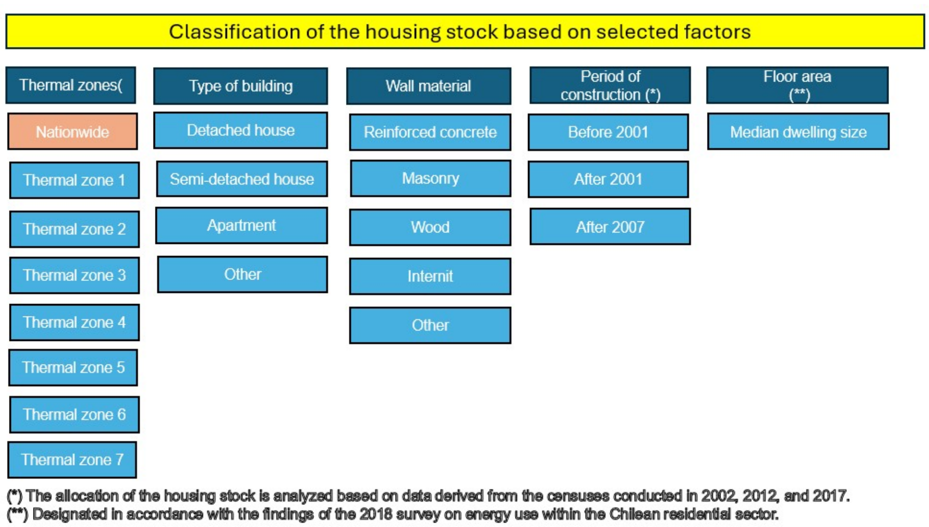


Figure 2.23: Classification of the housing stock based on selected factors.

(*) The allocation of the housing stock is analyzed based on data derived from the censuses conducted in 2002, 2012, and 2017.
(**) Designated in accordance with the findings of the 2018 survey on energy use within the Chilean residential sector.

Figure 2.24: Segmentation for detached houses.

The classification of the housing stock by type of building and wall materials was derived from the 2017 census. Subsequently, the distribution of the housing stock by construction period, sourced from the 2002, 2012, and 2017 censuses, was carried out according to Section 2.3.4.4 (see Figure 2.9). Furthermore, the allocation of floor area by housing type was informed by data reported in the 2018 survey on energy use within Chilean housing (see Table 2.6). Furthermore, Figure 2.24 presents an excerpt of the classification process carried out for detached houses. An analogous methodology is applied in the classification of semidetached houses and apartments.

2.3.5.2 Quantification of the housing stock

This section presents an analysis of the quantification of housing stock, both on a national scale and stratified by thermal zones. The preceding data indicate that a collection of 18 archetypes accounts for 80% of the Chilean housing stock, with merely four archetypes comprising approximately 50% (see Figure 2.25). The most relevant typologies of buildings at the national level are ranked according to their frequency observed in descending order in Table 2.10. The most prevalent archetype encompasses 19% of the housing stock and is characterized as a semi-detached uninsulated house constructed from clay bricks. The second most prevalent archetype represents 15% of the housing stock and is described as a detached, uninsulated house constructed of wood.

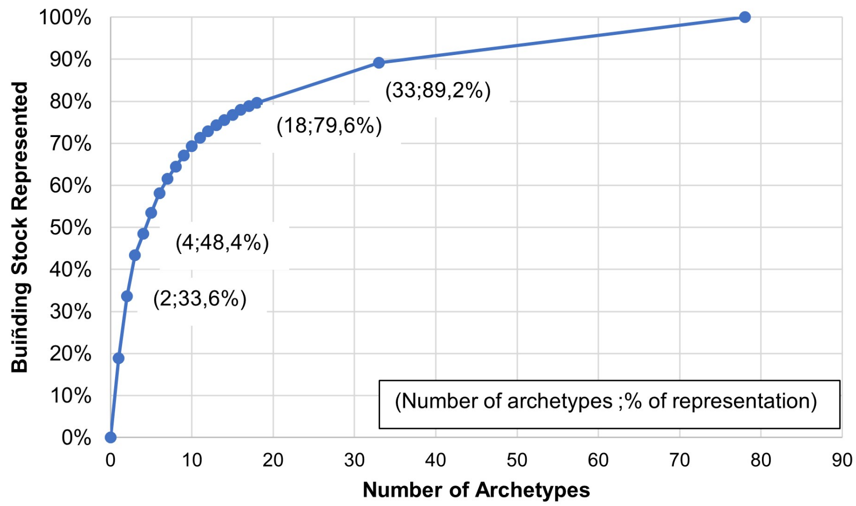


Figure 2.25: Cumulative frequency distribution of percentage of the housing sotck represented by archetypes.

Table 2.10: Relevant building typologies at the national level [62, 63, 66, 40].

N.	Type of dwelling	Wall material	Period of construction	Floor area (m²)	Frequency	Percent
1	S	M	1	75	1,036,283	19%
2	D	W	1	72	805,672	15%
3	D	M	1	80	534,833	10%
4	A	RC	2,3	80	278,802	5%
5	A	RC	1	80	278,246	5%
6	S	W	1	70	251,944	5%
7	A	M	1	68	189,735	3%
8	S	M	2,3	75	156,386	3%
9	D	RC	1	80	145,883	3%
10	S	RC	1	77	124,139	2%

[1]D: Detached house; S: Semi-detached house; A: Apartment.
M: Masonry; W: Wood; RC: Reinforced Concrete.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

The distribution of archetypes throughout the country is influenced by climatic conditions, as well as accessibility and cost-effectiveness of materials (see Section 2.3.4.3). Consequently, understanding the typologies of the buildings within specific thermal zones is essential. In addition, this understanding facilitates the identification of the most pertinent building typologies within each thermal zone.

- North zone

The housing stock of thermal zone 1 corresponds to 11.6% of the national housing stock. 10 archetypes represent 82% of the thermal zone 1 housing stock. Masonry and reinforced concrete are the predominant materials observed in this thermal zone. The housing stock in the north is mainly characterized by semi-detached and detached masonry houses with different levels of roof insulation (see Table 2.11). The most abundant archetype represents a 24% of the thermal zone 1 housing stock, and is a semi-detached uninsulated house, constructed with clay bricks.

Table 2.11: Distribution of housing stock in the northern zone (thermal zone 1) [62, 63, 66, 40].

N.	**Type of dwelling**	**Wall material**	**Period of construction**	**Floor area (m^2)**	**Frequency**	**Percent**
1	S	M	1	75	150,894	24%
2	S	M	2,3	75	78,281	12%
3	D	M	1	80	64,656	10%
4	A	RC	2,3	80	41,316	6%
5	D	W	1	72	37,977	6%
6	S	RC	1	77	37,260	6%
7	D	M	2,3	80	33,543	5%
8	D	RC	1	80	27,585	4%
9	O		N/A		26,826	4%
10	S	W	1	70	23,283	4%

[2]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

- Centre zone

The central region of the country, which includes thermal zones 2, 3, and 4, comprises 73.8% of the national housing stock, with thermal zone 3 alone containing 44. 7%. The housing stock in thermal zone 2 accounts for 10.8% of the national housing stock. Within thermal zone 2, 11 archetypes constitute 82% of the housing stock. This zone exhibits a greater diversity of building typologies, encompassing semi-detached and detached masonry houses, detached wood houses, and reinforced concrete apartments, all exhibiting varying degrees of roof insulation (see Table 2.12). The most prevalent archetype accounts for 16% of the thermal zone 2 housing stock and consists of a detached uninsulated house constructed with wooden panels.

Table 2.12: Distribution of the housing stock in thermal zone 2 [62, 63, 66, 40].

N.	**Type of dwelling**	**Wall material**	**Period of construction**	**Floor area (m^2)**	**Frequency**	**Percent**
1	D	W	1	72	94,614	16%
2	S	M	1	75	83,285	14%
3	D	M	1	80	60,711	10%
4	S	M	2,3	75	43,075	7%
5	A	RC	1	80	36,142	6%
6	A	RC	2,3	80	36,125	6%
7	D	M	2,3	80	31,399	5%
8	D	W	2,3	72	29,014	5%
9	D	I	1	72	27,938	5%
10	A	M	1	68	24,131	4%
11	D	RC	1	80	21,693	4%

[3]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete; I: Internit.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

In thermal zone 3, the predominant construction materials are masonry and reinforced concrete. Nine archetypes account for 81% of the housing stock in this thermal zone. The housing stock is predominantly composed of semi-detached and detached masonry houses, which exhibit varying levels of roof insulation, as well as a significant presence of reinforced concrete apartments (see Table 2.13). The most prevalent archetype constitutes 26% of the Thermal Zone 3 housing stock and is an uninsulated semi-detached house constructed with clay bricks.

The housing stock within thermal zone 4 constitutes 18.3% of the national housing inventory. A total of 13 archetypes account for 82% of the thermal zone 4 housing stock. This stock is predominantly characterized by uninsulated semi-detached and detached houses, primarily constructed from masonry and wood materials (see Table 2.14). The most prevalent archetype comprises 19% of the thermal zone 4 housing stock and is identified as a detached uninsulated house, constructed

Table 2.13: Distribution of the housing stock in thermal zone 3 [62, 63, 66, 40].

N.	Type of dwelling	Wall material	Period of construction	Floor area (m^2)	Frequency	Percent
1	S	M	1	75	644,580	26%
2	A	RC	2,3	80	278,802	11%
3	D	M	1	80	273,057	11%
4	A	RC	1	80	191,506	8%
5	S	M	2,3	75	156,386	6%
6	D	W	1	72	153,714	6%
7	A	M	1	68	138,343	6%
8	D	RC	2,3	80	84,838	3%
9	D	M	2,3	80	66,248	3%

[4]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete; I: Internit.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

Table 2.14: Distribution of the housing stock in thermal zone 4 [62, 63, 66, 40].

N.	Type of dwelling	Wall material	Period of construction	Floor area (m^2)	Frequency	Percent
1	D	W	1	72	187,561	19%
2	S	M	1	75	143,534	14%
3	D	M	1	80	102,604	10%
4	S	M	3	75	68,236	7%
5	S	W	1	70	58,984	6%
6	D	M	3	80	48,778	5%
7	D	RC	2,3	80	37,794	4%
8	S	RC	2,3	77	35,167	4%
9	S	M	2,3	75	30,136	3%
10	D	I	1	72	29,478	3%
11	A	RC	2,3	80	28,759	3%
12	D	W	2,3	72	27,163	3%
13	D	I	2,3	72	26,610	3%

[5]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete; I: Internit.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

with wooden panels. The second most prevalent archetype is an uninsulated semi-detached house, constructed from clay bricks, representing 14% of the thermal zone 4 housing stock.

- South zone

The southern region of the country comprises 14.6% of the national housing stock. In these areas, the most prevalent type of buildings are detached and semi-detached houses constructed with wooden panels (see Tables 2.15, 2.16, and 2.17). A significant proportion of these dwellings lack insulation. For example, within thermal zone 5, which accounts for 8.0% of the national housing stock, seven archetypes constitute around 80% of the housing stock in this zone, and only four of these archetypes represent 68%, predominantly consisting of uninsulated detached and semi-detached houses built with wood.

Table 2.15: Distribution of the housing stock in thermal zone 5 [62, 63, 66, 40].

N.	**Type of dwelling**	**Wall material**	**Period of construction**	**Floor area (m^2)**	**Frequency**	**Percent**
1	D	W	1	72	184,170	42%
2	S	W	1	70	51,962	12%
3	D	I	2,3	72	32,070	7%
4	D	W	2,3	72	28,953	7%
5	D	M	1	80	24,271	6%
6	D	I	1	72	13,768	3%
7	O		N/A		9,853	2%

[6]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete; I: Internit.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

Table 2.16: Distribution of the housing stock in thermal zone 6 [62, 63, 66, 40].

N.	**Type of dwelling**	**Wall material**	**Period of construction**	**Floor area (m^2)**	**Frequency**	**Percent**
1	D	W	1	72	116,133	42%
2	S	W	1	70	36,940	14%
3	D	W	2,3	72	29,116	11%
4	D	I	2,3	72	20,547	8%
5	O		N/A		10,352	4%
6	S	W	2,3	72	9,261	3%

[7]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete; I: Internit.
Period of construction: [1] Before 2001, [2] Between 2002 and 2006, [3] After 2007.

Table 2.17: Distribution of the housing stock in thermal zone 7 [62, 63, 66, 40].

N.	**Type of dwelling**	**Wall material**	**Period of construction**	**Floor area (m^2)**	**Frequency**	**Percent**
1	D	W	1	72	31,503	36%
2	S	W	1	70	20,539	24%
3	D	W	3	72	4,802	6%
4	S	M	1	75	3,413	4%
5	S	W	3	70	3,131	4%
6	D	M	1	80	2,980	3%
7	D	W	2	72	2,529	3%
8	D	I	3	72	2,030	2%

[8]D: Detached house; S: Semi-detached house; A: Apartment; O: Other.
M: Masonry; W: Wood; RC: Reinforced Concrete; I: Internit.
Period of construction: [1] Before

2.4 Energy modeling

2.4.1 Energy demand calculations

Energy demand calculations can be categorized into two principal approaches: steady-state and dynamic. The steady-state calculation represents a simplified technique, requiring minimal inputs that are clearly defined through visual mathematical processes, thus facilitating an intuitive and succinct identification of the relationships between data inputs and outputs [95]. However, this simplified methodology does not adequately represent the dynamic performance of complex building system controllers.

Dynamic simulations incorporate temporally varying variables and advanced modeling capabilities to evaluate fluctuations in energy performance over time, along with integrated performance evaluations of parameters such as thermal comfort, indoor environmental quality (IEQ) and daylighting. Furthermore, they facilitate the evaluation of innovative building designs and systems, such as double-skin facades, which are not adequately addressed by steady-state analysis [190].

2.4.2 Energy modeling and analysis tool

2.4.2.1 House energy rating (Calificación Energética de Viviendas, CEV).

The Chilean house energy rating, also known as Calificación Energética de Viviendas (CEV) is applied to rate and evaluate the energy requirements of new or existing buildings in terms of space heating, water heating, lighting and cooling. The energy requirements for cooking and appliances are not considered in the model because most certifications are for new buildings, which may not have appliances. In addition, the energy required for cooking and appliances depends on the behavior of the occupants.

The first version of CEV was applied in 2012 by the Ministry of Housing and was updated in 2018. CEV was voluntarily applied until 2021, and then it was declared mandatory for new buildings (residential, public, and commercial buildings) through the Chilean law 21.305. Access to the complete code or calculation method is not allowed, which makes it difficult to understand the calculation method and assumptions made during the process. The house energy rating handbook indicates that aspects such as envelope transmittance (roof, walls, floor, windows, and doors), thermal inertia, building orientation, thermal bridges, infiltration, and type of ventilation are considered to calculate the energy demand. The temperature required for heating during daylight is based on the method of adaptive thermal comfort, which varies by season and thermal zone, while for night time it is considered a minimum temperature of 17 ° C. All these elements lead to the calculation of the energy demand of the dwelling which is compared with the reference building that complies with the minimum standard required by the Ministry of Housing. Thus, the building is rated with a letter between A+ and G, where G the least efficient and E is the minimum standard required [79]. According to MINVU, a social housing built since 2007 can achieve an E score.

2.4.2.2 EnergyPlus

EnergyPlus is an open-access dynamic energy simulation tool for buildings, used to model heating, cooling, lighting, ventilation, and other related systems [148]. The calculations are based on the heat-balancing method as recommended in the Fundamentals of the ASHRAE Handbook. This tool was initially developed in 1996 through a collaborative effort involving the Berkeley Lab Simulation Research Group, the University of Illinois at Urbana-Champaign, and the U.S. Army Construction Engineering Research Laboratory. The primary audience comprises designers and architects who aim to determine appropriate-sized HVAC equipment, formulate retrofit studies for life cycle cost analyses, and improve energy performance optimization, among other objectives.

The determination of the heating and cooling loads necessary to maintain the thermostat set points is made based on the parameters specified by the user. The simulation requires various data inputs, such as location, schedules, construction materials, building geometry, occupancy levels, orientation, infiltration rates, ground temperature, and systems, among others. Assessment of building energy performance can be performed using the Ideal Load Air System (ILAS), which assumes an infinitely capable system that can meet the energy demands. To simplify the process, the user is not required to design a complete HVAC system, including air ducts, water ducts, and other mechanical components; instead, only zone controls, equipment, and thermal loads are necessary.

The advantage of using EnergyPlus is that the method for calculating, and the variables involved are described in a transparent manner [103]. Therefore, the results obtained with EnergyPlus can be replicated and compared to the housing stocks of other nations. Detailed inputs are required to generate output files, but the interface makes it easier for users to enter data and parameters of buildings. In addition, EnergyPlus has shown proper sizing of equipment without oversizing, generally saving energy as the equipment is operated near optimal loads [148].

2.4.3 Method

A bottom-up methodology was used to evaluate the impact of implementing interventions aimed at reducing energy demand on heating requirements of a dwelling (see Section 2.3.1.2. This methodological choice is justified by the approach's ability to incorporate archetypes that facilitate the modeling of diverse scenarios. Such modeling aids in the identification of improvements in building performance, potentially leading to substantial reductions in energy demand and, consequently, a decrease in energy expenditure, thus contributing to a reduction in energy poverty.

To construct a comprehensive model, the archetype delineated in Section 2.4.4 will be used to represent a standard dwelling (baseline). Baselines establish an initial reference by aggregating the comprehensive energy consumption of a building before implementing any modifications. Therefore, this baseline will be juxtaposed against a house that incorporates numerous enhancements to the building envelope, including improvements to the roof, floor, walls, and windows, along with improvements in system efficiency.

Crucial information necessary for the modeling process, including details on the location and environment of houses, as well as physical parameters such as geometry, structural attributes, pertinent areas, height, and energy demand parameters, will be expounded in Section 2.4.4. It is imperative to acknowledge that, due to the potential substantial variability in the input data and the resultant outcomes, a validation process is essential. This process helps to demonstrate the degree to which the predicted energy behavior correlates with that of actual buildings utilizing statistical regressions [132]. The validation phase of this research method is thoroughly examined in Section 4.4.4.

The energy demand calculations in this research will be carried out using a dynamic methodology (refer to Section 2.4.1). The rationale behind selecting a dynamic approach lies in its superior capability to accurately depict energy flows and dynamics by modulating building parameters. Furthermore, it includes auxiliary variables that cannot be effectively and precisely represented by the steady-state method. Therefore, a dynamic energy simulation tool such as EnergyPlus was chosen (see Section 2.4.2.2). This tool offers the advantage of having its computational method and the variables involved explained in a transparent manner.

It is important to note that, while Chile has an energy model (CEV) for calculating the heating energy demand of buildings, the lack of complete access to the code impedes a comprehensive understanding of the calculation method, the variables involved and the assumptions made throughout the process (see Section 2.4.2.1).

2.4.4 Identification and Characterization of the Archetypes

This section provides a detailed account of the archetypes chosen for the simulation of heating energy demand. The input data are systematically segmented into three categories: Section 2.4.4.1 elucidates the inputs relevant to the geographical and environmental context. Section 2.4.4.2 gives an explanation of the physical parameters derived from the quantification of the housing stock as presented in Section 2.3.5.2. Following this categorization, the attributes of each group serve to delineate the archetypes selected in greater detail, attributing factors such as overall dimensions, U-values for construction materials, orientation, infiltration, among others. Lastly, Section 2.4.4.3 enumerates the parameters associated with the calculation of the energy demand for heating, including temperature settings, scheduling, and heating systems.

2.4.4.1 Location and environment of the houses

- **Location**

  The thermal zones selected for this investigation are zones 5 and 7, with Temuco and Punta Arenas serving as representative cities, respectively (see Figure 1.8 for geographical locations).

A detailed exposition of the criteria used for the selection of these thermal zones will be provided in a later section of this document (see Section 3.3.1). For modeling purposes, the most substantial group within the housing stock in these thermal zones will be designated as the standard dwelling (baseline). The predominant form of housing in both thermal zones is the uninsulated detached house, constructed of wooden panels, which constitutes 42% and 36% of the housing stock in thermal zones 5 and 7, respectively (refer to Tables 2.15 and 2.17).

- **Weather**

Meteorological data serve as a critical input for EnergyPlus simulation software[148]. EnergyPlus utilizes EnergyPlus Weather (EPW) files, which are formatted in a straightforward text-based structure as comma-separated values (CSV). These files encapsulate the environmental conditions pertinent to a specific location, including coordinates (latitude, longitude, time zone, altitude), dry-bulb temperature, solar radiation, relative humidity (RH), wind speed, sky cover, atmospheric pressure, precipitation, among other factors. The EPW file is generated through the comprehensive analysis of a typical meteorological year (TMY), which comprises 20 to 30 years of hourly solar radiation data[46].

The generation of these files was carried out by the US National Climatic Data Center, which collected data from meteorological stations distributed throughout the world. The US Department of Energy maintains a repository of over 2,500 weather datasets accessible through Climate.OneBuilding.Org [46]. In this investigation, two specific EPW weather files were used, corresponding to the cities of Temuco and Punta Arenas, which are located in thermal zones 5 and 7, respectively.

2.4.4.2 Physical parameters

- **Overall dimensions**

The detailed dimensions of the dwelling serve as essential parameters for assessing the energy demand via EnergyPlus. In thermal zones 5 and 7, the predominant housing type is an uninsulated detached house constructed with wooden panels. Subsequently, it is assumed that the overall dimensions and physical characteristics of the standard dwelling (baseline) situated in thermal zone 5 are analogous to those in thermal zone 7.

The determination of the wall area by orientation is essential for assessing the heat loss within the model. In the context of this analysis, it is supposed that the house exhibits a rectangular configuration characterized by a block aspect ratio, defined as the quotient of the house's length and width, which is equal to 2. This implies that the length of the dwelling is twice its width (12m x 6m). A representative illustration and layout for detached dwellings are provided in Figure 2.26.

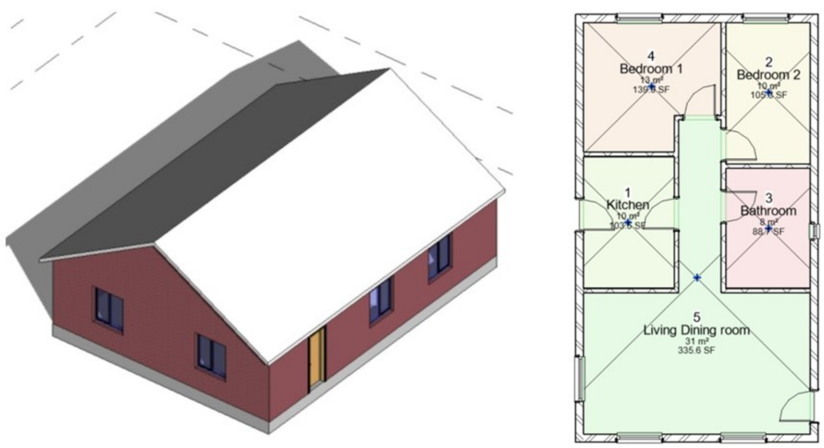


Figure 2.26: Reference appearance of detached houses

The wall area for each façade was determined according to the previously defined dwelling dimensions and the aspect ratio of the block. In the absence of precise information regarding the window areas and their placement, it was assumed that standard windows, with dimensions of 1.35m by 1.2 m, are distributed within areas such as the living room, dining room, and bedrooms. A smaller window size of 0.5m by 0.8m was selected for the bathroom. This configuration has demonstrated a window-to-wall ratio of 14%, which adheres to the maximum allowed glass surface area for single glazing as stipulated by the Ministry of Housing. The standard dimension attributed to the door area is 1.9 m x 0.9 m, while the height of the dwelling is assumed to be 2.3 m, according to the regulations specified in the Chilean building code [78]. The areas and orientations of the walls, windows and doors are thoroughly detailed in Table 2.18.

Table 2.18: Dimensions and alignment of the walls, windows, and doors.

Surface type	Area [m^2]				
	North	East	South	West	Total
Wall	8.9	22.7	10.6	27.2	69.4
Windows	3.2	3.2	3.2	0.4	10.0
Door	1.7	1.7	0.0	0.0	3.4

- **Physical properties standard dwelling (baseline)**

The thermal characteristics of the building envelope are indispensable inputs for assessing energy demand using EnergyPlus. This software requires a comprehensive description of each layer of construction, including specifications such as the name of the layer, thermal conductivity, thickness, density, and specific heat capacity. To accurately calculate the thermal resistance of the construction component, it is crucial that the layers of the envelope are entered in order from the external to the internal surface.

In line with these considerations, the physical attributes of the standard dwelling are extensively delineated in Table 2.19. The parameters for thermal conductivity, density and specific heat are extracted from the construction solutions document released by the Ministry of Housing of Chile [74]. The thermal resistance associated with each construction component has been calculated using the methodology outlined by NCh 853, the standard pertinent to thermal envelopes [74].

The roof is constructed from a series of sequentially arranged layers from the outermost to the innermost component, starting with fiber cement tiles secured to a wooden frame structure, which supports an OSB wood board with a thickness of 11 mm. The horizontal ceiling consists of a wooden frame clad with a standard 10 mm plasterboard, as depicted in Figure 2.27. In addition, the thermal resistances of both the interior and exterior have been incorporated according to the guidelines provided by NCh 853[74]. The total thermal transmittance of the roof, referred to as the U-value, is calculated to be 2.23 W/m^{2}K. The model presumes that the residence is entirely exposed to sunlight, thus excluding any external shading that could impede solar radiation.

Table 2.19: Physical attributes of the standard dwelling (baseline) [74]

Material description	Thickness (m)	Conductivity (W/mK)	Density (kg/m3)	Specific Heat (J/kgK)	Thermal resistance (m2K/W)	Thermal transmittance (W/m2K)
Roof components						
Interior surface thermal resistance					0.09	
Fibre cement tiles	0.006	0.23	920	837	0.03	
Oriented Strand Board (OSB)	0.011	0.11	800	2093	0.10	
Non-ventilated air chamber					0.14	
Standard plasterboard	0.010	0.26	700	840	0.04	
Exterior surface thermal resistance					0.05	
					0.45	2.23
Exterior wall components						
Exterior surface thermal resistance					0.05	
Radiata pine wood	0.010	0.104	410	2805	0.10	
Oriented Strand Board (OSB)	0.011	0.106	800	2093	0.10	
Standard plasterboard	0.010	0.26	700	840	0.04	
Interior surface thermal resistance					0.12	
					0.41	2.45
Floor components						
Interior surface thermal resistance					0.17	
Reinforced concrete slab	0.120	1.63	2400	920	0.07	
Exterior surface thermal resistance					0.05	
					0.29	3.41
Windows						
Exterior surface thermal resistance					0.05	
Single glazing	0.006	1.05	2500	750	0.01	
Interior surface thermal resistance					0.12	
					0.18	5.69
Doors						
Exterior surface thermal resistance					0.05	
Pine wood	0.05	0.104	410	2805	0.48	
Interior surface thermal resistance					0.12	
					0.65	1.54
Interior walls						
Interior surface thermal resistance					0.12	
Pine wood	0.010	0.104	410	2805	0.10	
Air					0.14	
Pine wood	0.010	0.104	410	2805	0.10	
Exterior surface thermal resistance					0.12	
					0.57	1.70

Figure 2.27: Roof constructive solution for standard dwelling (baseline)[141].

The exterior wall consists of an outer layer of radiata pine wood affixed to a frame made of the same wood species. This assembly also includes an oriented strand board (OSB) with a thickness of 11 millimeters and a standard plasterboard with a thickness of 10 millimeters. In line with the recommendations provided by NCh 853, both internal and external thermal resistances are taken into account. The exterior wall has a thermal transmittance (U-value) of 2.45 W/m^{2}K. Figure 2.28 illustrates a section of the exterior wall, detailing the composition of its layers.

Figure 2.28: Wall constructive solution for standard dwelling (baseline).

The ground floor consists of a reinforced concrete slab with a thickness of 120 mm and a density of 2400 kg/m^3. In addition, it accounts for the interior and exterior thermal resistance as recommended by NCh 853. The total thermal transmittance (U-value) for the ground floor is calculated to be 3.41 W/m^{2}K. This slab is placed directly on the ground without the inclusion of insulation.

The window type considered for the standard dwelling (baseline) consists of a single glazing window with a thickness of 6 mm and a metal frame, exhibiting a U-value of 5.69 W/m^2K. This selection reflects the most prevalent solution in the country. New alternatives, such as double glazing and PVC frames, have only recently been introduced [76]. For exterior doors, the chosen material is pine wood, which has a U value of 1.54W/m^2K.

- **Physical properties including energy demand reduction interventions**

Interventions aimed at reducing energy demand in standard dwellings (baseline) include roof, exterior walls, and floor insulation, as well as the replacement of single glazing with double glazing. These interventions are outlined in the official document for thermal conditioning construction solutions issued by the Ministry of Housing [81]. This document recommends various insulation thicknesses for roofs, walls, and floors. In this study, the insulation selections will comply with the minimum requirements specified by the Ministry of Housing for the building envelopes according to the thermal zone (see Table 1.1). In addition, a sensitivity analysis of the insulation thickness will be performed to assess its impact on home heating demand. As Table 1.1 reveals, the U-values for roofs, walls, and floors exhibit variation across thermal zones. Consequently, the incorporation of improvements will be individually considered for thermal zones 5 and 7. Additionally, it is imperative to note that these enhancements will be addressed separately to evaluate their individual effects in contrast to the baseline, and, subsequently, all measures will be implemented concurrently.

Improvements in standard dwelling located in thermal Zone 5

Table 2.15 delineates the specified enhancements considered for the standard dwelling located in thermal zone 5. The Ministry of Housing has stipulated a maximum roof U-value of 0.33 W/m^2K for this thermal zone. Upon installation of 120mm of glass wool insulation in the roofing structure, the resulting total U-value reduces to 0.30 W/m2K, thus meeting the prescribed regulatory standard.

The suggested U-value for walls is 1.60 W/m^2K. Incorporating a 50mm layer of expanded polystyrene results in a decrease in the U-value from its baseline of 2.45 W/m^2K to 0.63 W/m^2K. For flooring, the required U-value is 0.50 W/m^2K. Employing an 80mm layer of expanded polystyrene achieves a U value of 0.45 W/m2K, as opposed to the baseline U-value of 3.41 W/m2K.

The Ministry of Housing did not establish explicit U-value specifications for windows; however,

Table 2.20: Energy demand reduction interventions applied on standard dwelling (baseline) on thermal zone 5.

Element	Improvement	Description	Total U-value (W/m2K)
Roof	Insulation	Glass wool (120 mm)	0.30
Wall	Insulation	Expanded polystyrene (50mm)	0.63
Floor	Insulation	Expanded polystyrene (80mm)	0.45
Window	Double glazing	Two panels (6mm)	0.30

it provided a guideline that restricts the maximum permitted glass area in relation to the wall area. Alternatively, this study advocates for the replacement of single glazing, which has a thermal transmittance of 5.69 W/m^{2}K, with double glazing, which exhibits a thermal transmittance of 0.30 W/m^{2}K, to assess its influence on heating demand.

Improvements in standard dwelling located in thermal Zone 7

Table 2.21 provides a detailed account of the planned enhancements for the standard dwelling (baseline) located within thermal zone 7. The Ministry of Housing stipulates a U-value requirement of 0.25 W/m^{2}K for roofs in thermal zone 7. Incorporating glass wool with a thickness of 160 mm in the roof achieves a total U-value of 0.23 W / 2K, thus meeting the regulatory requirement. With respect to walls, the U-value should not exceed 0.60 W/m^{2}K. The use of expanded polystyrene with a thickness of 60 mm reduces the U-value from the baseline of 2.45 W/m^{2}K to 0.55 W/m^{2}K after the suggested modification. Regarding the floor, the U-value must adhere to a maximum of 0.32 W/m^{2}K. Introducing expanded polystyrene at a thickness of 120 mm results in a U-value of 0.31 W/m^{2}K, contrasting with the baseline value of 3.41 W/m^{2}K.

Ultimately, analogous to the approach utilized in thermal zone 5, this study advocates for the replacement of single glazing, defined by a thermal transmittance of 5.69 W/m^{2}K, with double glazing, which exhibits a thermal transmittance of 0.30 W/m^{2}K, in order to assess its impact on the heating demand.

Table 2.21: Energy demand reduction interventions applied on standard dwelling (baseline) on thermal zone 7.

Element	Improvement	Description	Total U-value (W/m2K)
Roof	Insulation	Glass wool (160 mm)	0.23
Wall	Insulation	Expanded polystyrene (60mm)	0.55
Floor	Insulation	Expanded polystyrene (120mm)	0.31
Window	Double glazing	Two panels (6mm)	0.30

- **Orientation**

The orientation of a building is a significant factor as it can influence the building's ability to receive light and solar radiation, which affects its heating demand. Ideally, the building's orientation should be such that it maximizes exposure to intense light for extended periods, capitalizing on the solar path to reduce heating demand. For instance, the optimal orientation for dwellings situated in the Northern Hemisphere is towards the south, whereas in the southern hemisphere it is oriented in the opposite direction.

In the southern hemisphere, dwellings with a southern orientation receive solar radiation predominantly during the early morning and late afternoon hours. This limited exposure to natural light necessitates an increased demand for electricity and heating, owing to the reduced duration of solar illumination. Dwellings facing east, akin to those oriented northward, experience adequate levels of light and solar radiation, albeit for fewer hours and with diminished intensity, as they receive sunlight primarily from sunrise until midday throughout the year. In contrast, dwellings oriented westwards obtain solar radiation from midday to sunset, resulting in elevated energy demands during the winter months due to the inability to retain thermal energy past midday, exacerbated by the subsequent reduction in solar radiation.

In Chile, there is a lack of prior studies that have quantified the impact of building orientation on energy demand. This research aims to evaluate this parameter, identifying the worst-case scenario for the standard dwelling as the baseline.

- **Infiltration rate**

Infiltration refers to the uncontrolled movement of air through the building envelope, which affects both the cooling and heating loads [167]. Typical sources of infiltration come from the operation of exterior doors, the presence of gaps around windows, and even minor cracks in building materials. The infiltration rate is quantified by the unit air changes per hour (ach).

Although EnergyPlus is not a computational fluid dynamics tool, it performs infiltration calculations using the equation outlined in the ASHRAE Fundamentals Handbook [7]. This equation accounts for variables such as the infiltration design flow rate, the temperature difference between indoor and outdoor environments, and the speed of the wind. The design infiltration rate is defined as the volumetric flow rate for each air-conditioned zone. In EnergyPlus, this rate can be determined using five different methods: flow per zone, flow per area, flow per exterior area, flow per exterior wall area, and air change per hour.

In this study, the infiltration design flow rate was estimated using the air change per hour method. The infiltration rate has not been empirically measured within the Chilean housing stock; therefore, reference values provided by the ASHRAE Fundamentals Handbook, Chapter 26, have been utilized for modeling purposes. This document recommends an infiltration rate of 0.1 ach for new, energy-efficient dwellings and 0.9 ach for older, low-income residences. Given that households in energy poverty typically reside in older, low-income housing, a standard infiltration design flow rate of 0.9 ach has been adopted as the baseline for the typical dwelling. Furthermore, a sensitivity analysis will be conducted to assess the impact of infiltration rates on heating demand.

2.4.4.3 Energy demand parameters

Table 2.22 delineates the parameters utilized in EnergyPlus to evaluate the heating demand of the standard dwelling (baseline) and subsequently with the integration of improvements. The settings for the heating temperature must be specified in EnergyPlus. In this analysis, a consistent temperature of 23 ° C was applied in both thermal zones. This specific temperature was selected according to the WHO recommendation to maintain environments above 23°C, especially for vulnerable populations, including the elderly, children, and individuals with pre-existing health conditions, as detailed in Section 1.1. These groups are the most susceptible to EP, and this study aims to determine the potential advantages that may result from the implementation of enhancements. The temperature was assumed to be constant and uniform in all rooms.

Table 2.22: Parameters for calculating heating demand for dwelling in thermal zones 5 and 7.

Parameters	Thermal zone 5	Thermal zone 7
Temperature settings	23°C	23°C
Heating schedule	April to October (20.00pm to 4.30am)	Jan. to December (20.00pm to 3.10am)
Heating system	Wood stove	Wood stove
Efficiency heating system	70%	70%

EnergyPlus necessitates a detailed scheduling framework to delineate the operational hours of the heating system and its daily regimen. This framework is structured around a calendar format that indicates the system's operational status, ranging from 0 (indicating no operation) to 1 (indicating full operation). The schedule can be articulated to reflect usage hours across different timescales such as days, weeks, and months, thereby accommodating variations for specific design days like those for summer and winter [148].

In Chile, empirical data on the patterns of heating usage within Chilean households is currently unavailable. However, insights derived from the 2018 Uses of Energy in the Chilean Housing Survey allowed us to determine the duration and months during which heating systems are used (see Section 2.3.4.7). For the purpose of modeling, it was hypothesized that in both thermal zones, heating systems are activated around 20:00, the time when families are typically at home after work or school. This heating pattern was considered consistent for both weekdays and weekends.

The heating system must be delineated in EnergyPlus, with particular attention to its efficiency. The specific fuel sources used for the heating of the space within each thermal zone are outlined in Section 2.3.4.7. In particular, thermal zones 5 and 7 are predominantly defined by their dependence on wood as a fuel source. Consequently, a wood stove was employed for modeling purposes. The efficiency assessment of this heating system is derived from the 2012 SAP model corresponding to 0.7 [88].

CHAPTER 3

Results

3.1 Main factors contributing to EP in Chile

This study will explore the manifestation of primary factors that influence energy poverty (EP) in the Chilean context. By doing so, it aims to identify the thermal zones and populations most vulnerable to EP. The analysis will present findings on the main contributing factors, including income levels, educational attainment, property tenure status, energy prices, household size, and energy efficiency of the home.

3.1.1 Economic factor

3.1.1.1 Incomes

In Chile, empirical evidence on energy expenditure, as collected from the 2017 Family Budget Survey, reveals that households with higher income levels incur higher energy expenditures. The relationship between energy expenditure and income is best described by a natural logarithmic function, in which energy expenditure exhibits a notable growth in particular income ranges until an inflection point is reached, beyond which the rate of increase gradually stabilizes (refer to Figure

3.1).

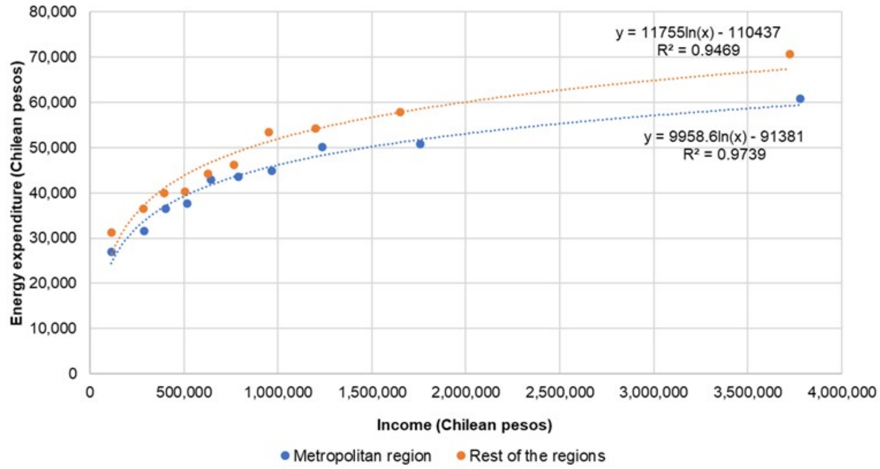


Figure 3.1: Energy expenditure versus income by household [68].

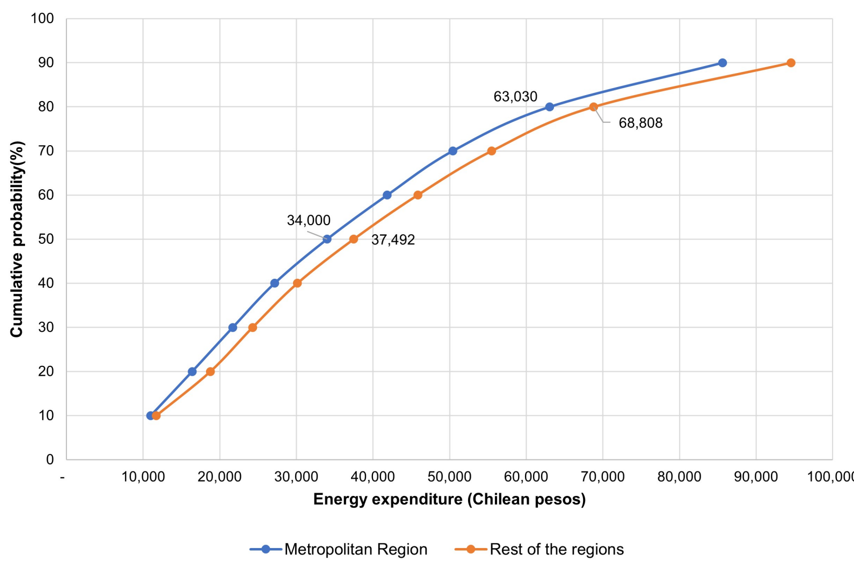


Figure 3.2: Cumulative probability of energy expenditure [68].

Figure 3.2 indicates that 80% of households in the Metropolitan Region (MR) incur energy expenses less than CLP 63,030, while in other regions this threshold is CLP 68,808. The median household energy expenditure is CLP 34,000, which represents 6.6% of income in the MR, and CLP 37,492, which represents 7. 1% of income in other regions. The median household income is reported as CLP 712,330 in the MR and CLP 688,950 in the other regions [68].

The disparity in energy expenditures between the Metropolitan region and other regions does not reach statistical significance ($p \leq 0.05$). However, these findings may be confounded by the substantial climate variability in the other regions, which range from low energy demands in the north to high energy demands in the south of the country. This climatic diversity may result in a compensatory effect when thermal zones are aggregated.

Low-income households in Chile allocate, on average, between 9 and 24% of their income to energy bills in the Metropolitan Region (MR), and between 10 and 27% in other regions. In contrast, affluent households spend between 1.6 and 4% in MR and between 1.9 and 4.5% in the rest of the regions, despite the fact that their energy bills are more than twice as much as those of low-income households (see Tables 3.1 and 3.2). Furthermore, the unit cost of energy remains uniform for all residents within a region since the energy company applies a single tariff rate to all residential consumers. These findings may suggest that low-income households tend to reduce their energy consumption, thereby potentially compromising their thermal comfort compared to medium- and high-income households.

Table 3.1: Energy expenditure by income decile, Metropolitan region [68].

	Income gap		Energy expenditure		Proportion of income destined to energy
			Mean	Median	
1	-	225,108	27,041	20,725	24.0%
2	225,108	346,900	31,634	25,150	11.1%
3	346,900	455,307	36,588	30,000	9.1%
4	455,307	578,000	37,688	31,050	7.3%
5	578,000	712,330	42,864	34,000	6.6%
6	712,330	864,000	43,531	34,250	5.5%
7	864,000	1,069,557	44,963	37,758	4.7%
8	1,069,557	1,404,469	50,088	41,832	4.0%
9	1,404,469	2,107,111	50.825	42,698	2.9%
10	2,107,111	-	60,801	49,600	1.6%

Furthermore, it was observed that the impact of EP varies according to the income decile to which a household belongs. In the metropolitan region, 87% of households that allocate more than 10% of their income to energy expenses are located within the lower income deciles (deciles 1 to 5),

Table 3.2: Energy expenditure by income decile, Rest of the regions [68].

	Income gap		Energy expenditure		Proportion of income destined to energy
			Mean	Median	
1	-	230,000	31,333	24,176	27.2%
2	230,000	340,000	36,544	28,000	12.8%
3	340,000	446,125	39,933	31,000	10.2%
4	446,125	563,105	40,259	32,000	8.0%
5	563,105	688,950	44,241	36,036	7.1%
6	688,950	846,144	46,189	37,296	6.0%
7	846,144	1,054.,548	53,451	41,922	5.6%
8	1,054,548	1,346,865	54,240	44,185	4.5%
9	1,346,865	1,957,689	57,867	47,195	3.5%
10	1,957,689	-	70,737	57,000	1.9%

and the first and second deciles alone constitute 51% of the population (see Figure 3.3). Comparable results were identified in other regions.

Table 3.3: Households affected by EP (TPR) by income decile[68].

N.	Income decile	Metropolitan region		Regions	
		Number of households	Percentage	Number of households	Percentage
1	I	120,116	30%	108,499	28%
2	II	84,743	21%	75,045	20%
3	III	64,639	16%	65,325	17%
4	IV	46,061	12%	45,434	12%
5	V	37,409	9%	30,741	8%
6	VI	22,395	6%	23,056	6%
7	VII	11,197	3%	15,371	4%
8	VIII	10,179	3%	10,850	3%
9	IX	2,799	1%	4,747	1%
10	X	254	0%	3,391	1%
	Total	399,793	100%	382,459	100%

Drawing upon the 2015 CASEN survey [83] concerning household income, the mean household income for each thermal zone was determined. This computation involved averaging household incomes across regions within each thermal zone, with weights assigned based on the population size of each region. The mean and median household incomes by thermal zone are detailed in Table 3.4. The median household income was chosen as it reflects a central tendency that is more representative of the Chilean context.

Household income data categorized by thermal zones can act as an indicator of economic disparities and help identify thermal zones where households are more likely to face significant challenges with energy expenditures. Table 3.4 indicates a substantial variation in household income throughout the country. The highest median income is observed in thermal zone 3, predominantly associated with the metropolitan region. Conversely, thermal zone 5, situated in the southern region of the country, exhibits the lowest median household income.

Table generated by Excel2LaTeX from sheet 'Income'

Table 3.4: Mean and median income by household by thermal zone [83].

Thermal zones	**Regions**	**Mean (CLP$)**	**Median (CLP$**
Zone 1	XV. Arica	814,660	590,834
	I. Tarapacá		
	II. Antofagasta		
	III. Atacama		
	IV. Coquimbo		
Zone 2	V. Valparaíso	760,084	540,000
Zone 3	Metropolitana	1,096,988	715,000
	VI. O´Higgins		
Zone 4	VII. Maule	633,827	443,333
	XVI. Nuble		
	VIII.Bío-Bío		
Zone 5	IX. La Araucania	617,915	408,333
	XIV. Los Ríos		
Zone 6	X. Los Lagos	695,310	500,000
Zone 7	XI. Aysén	1,080,957	741,667
	XII. Magallanes y Antártica Chilena		

However, additional factors may also play a role in contributing to EP. This assertion can be supported by an analysis of raw data realted to energy expenditure and income. Figures 3.3 and 3.4 illustrate the absence of a discernible pattern. In fact, a low correlation was identified between energy expenditure and income. In the MR, only 47.3% of the variation in energy expenditure can be attributed to income (Pearson correlation), while the remaining regions demonstrate an even lower correlation of 33.5%. These results underscore the need for a more comprehensive understanding of the determinants of residential energy demand. Although there exists a certain degree of correlation between income and energy expenditure, numerous other factors, such as housing quality, energy prices, and human behavior, may contribute to or influence energy expenditure.

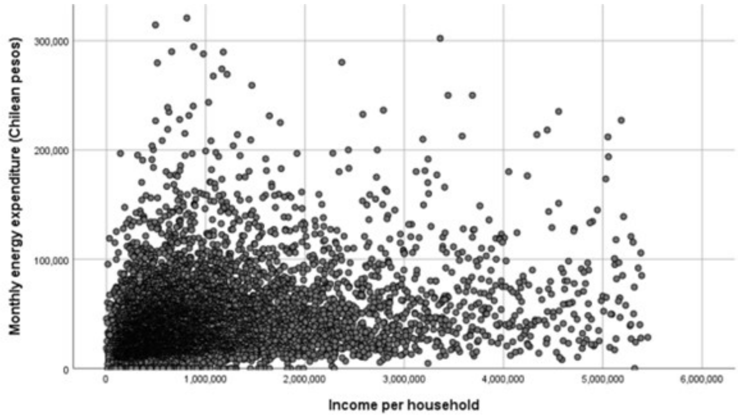


Figure 3.3: Energy expenditure versus income by household, Metropolitan region [68].

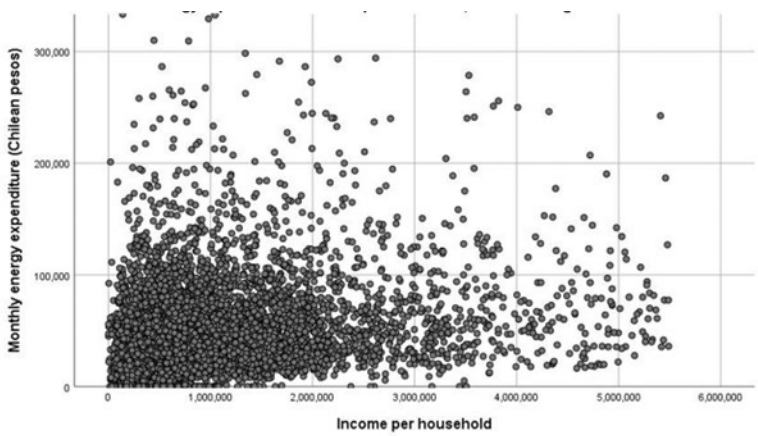


Figure 3.4: Energy expenditure versus income by household, regions [68].

3.1.1.2 Educational attainment

In Chile, the analysis reveals that among individuals allocating more than ten percent of their income to energy expenses, approximately 60% have primary and secondary education, while 33% have pursued professional or technical careers in the metropolitan region (see Figure 3.5 for details). In contrast, in other regions, the proportion of people with primary and secondary education increases to 76%, with only 18% having pursued professional or technical careers (see Figure 3.6 for details). Hence, lower educational attainment can contribute to limited income, which in turn can result in challenges in meeting energy payment obligations.

Table 3.5: Maximum level of educational attainment of householders affected by EP, Metropolitan region [68].

Maximum level of educational attainment		Frequency	Percent (%)	Total (%)
Secondary education	Scientific-Humanism	81,859	21	37
	Technical-Professional	42,676	11	
	Old system	16,642	4	
Primary education	Current system	47,132	12	23
	Old system	39,533	10	
Professional (4 or more years of study)		74,027	19	19
Technical career (1 to 3 years of study)		53,238	14	14
Other		28,690	7	7
Total		383,797	100	100

Table 3.6: Maximum level of educational attainment of householders affected by EP, rest of the regions [68].

Maximum level of educational attainment		Frequency	Percent (%)	Total (%)
Secondary education	Scientific-Humanism	98,339	27	48
	Technical-Professional	47,612	13	
	Old system	27,953	8	
Primary education	Current system	58,900	16	28
	Old system	42,132	12	
Professional (4 or more years of study)		35,779	10	10
Technical career (1 to 3 years of study)		28,964	8	8
Other		21,313	6	6
Total		360,992	100	100

In Chile, the pattern of energy consumption is contingent upon the thermal zone (see Table 3.7). In thermal zones 1, 2, and 3, it is observed that the majority of households predominantly heat only the used rooms, usually the living and dining room, while in other parts of the country there is a tendency to heat the entire home [40]. This trend is mirrored by the general population and those impacted by energy poverty (EP). These findings suggest that harsher climatic conditions may require heating of entire homes, potentially facilitated by the greater availability of low-cost fuel resources in these regions. However, it is essential to acknowledge that a considerable proportion of households continue to heat only the spaces in use. Specifically, this comprises 38% households in thermal zone 4, 24% in thermal zone 5, 20% in thermal zone 6, and 32% in thermal zone 7 [40]. Thus, it is possible that some of these households include members engaged in educational endeavors, which can be adversely affected by the repercussions of overcrowding.

Table 3.7: Proportion of spaces heated by households by thermal zone [40]

Thermal zones	Spaces heated	Percent (%)
Thermal zone 2	Whole House	28
	Only rooms in use	72
	Total	100
Thermal zone 3	Whole House	12
	Only rooms in use	88
	Total	100
Thermal zone 4	Whole House	62
	Only rooms in use	38
	Total	100
Thermal zone 5	Whole House	76
	Only rooms in use	24
	Total	100
Thermal zone 6	Whole House	80
	Only rooms in use	20
	Total	100
Thermal zone 7 (wood fuelled)	Whole House	62
	Only rooms in use	38
	Total	100
Thermal zone 7 (gas fuelled)	Whole House	75
	Only rooms in use	25
	Total	100

3.1.1.3 Property tenure

Table 3.8 illustrates the distribution of property tenure within the Metropolitan region compared to the remainder of the regions, aiming to analyze property tenure in Chile for 2017. The predominant category is comprised of individuals who are homeowners, either having fully paid for their property or in the process of payment, accounting for 62% in the Metropolitan region and 59% in the rest of the country. This is followed by households that rent, constituting 23% in the Metropolitan region and 24% in the rest. The disparity in housing tenure between the Metropolitan region and other regions is not statistically significant, as evidenced by a chi-square test with a p-value of 0.99. Furthermore, no significant variations were observed in housing tenure across different income deciles within the Metropolitan region (refer to figure 3.9).

Table 3.8: Property tenure of households located in Metropolitan region and regions [68].

Tenure	Metropolitan region		Rest of the regions	
	Frequency	Percent	Frequency	Percent
Owner (fully paid)	1,103,619	46%	1,829,761	44%
Owner (in process of payment)	371,044	16%	597,557	15%
Rent (with contract)	344,881	15%	622,284	15%
Rent (without contract)	190,279	8%	370,898	9%
Assigned by relative or friend	166,494	7%	407,987	10%
Shared inheritance or succession	142,709	6%	218,417	5%
Other	61,841	3%	74,180	2%
Total	2,378,490	100%	4,121,084	100%

Table 3.9: Housing tenure by income deciles, Metropolitan region [68].

	Income gap		Tenure							
			Owner (fully paid)	Owner (in process)	Rent (contract)	Rent (no contract)	Assigned by relative	Inheritance/ succession	Other	Total
1	-	225,108	47%	15%	15%	8%	7%	6%	3%	100%
2	225,108	346,900	47%	15%	14%	8%	7%	6%	3%	100%
3	346,900	455,307	52%	12%	12%	9%	7%	5%	3%	100%
4	455,307	578,000	46%	12%	17%	8%	8%	7%	2%	100%
5	578,000	712,330	46%	12%	17%	8%	8%	7%	2%	100%
6	712,330	864,000	44%	16%	14%	6%	7%	10%	3%	100%
7	864,000	1,069,557	50%	15%	13%	6%	7%	6%	3%	100%
8	1,069,557	1,404,469	43%	17%	15%	9%	9%	6%	2%	100%
9	1,404,469	2,107,111	46%	15%	15%	9%	8%	5%	3%	100%
10	2,107,111	-	46%	16%	16%	11%	6%	4%	2%	100%

The tenure status of households affected by energy poverty (TPR) in Chile indicates that the majority are homeowners, with 61% in the Metropolitan Region and 64% in other regions (see Table 3.10). Conversely, there are distinct groups that reside in rented accommodations, comprising 22%

in the Metropolitan Region and 15% elsewhere, or in dwellings provided by relatives or friends, accounting for 7% in the Metropolitan Region and 13% in other regions.

The information presented in Tables 3.8 and 3.10 offers significant insights into the widely acknowledged hypothesis articulated in Section 1.3.1.3, which asserts that low-income groups are disproportionately affected by energy poverty. This condition is attributed primarily to their frequent inability to own homes, consequently compelling them to inhabit properties leased from landlords. In the Metropolitan Region, the probability of a renter being affected by energy poverty can be determined by comparing the number of total households that rent and experience energy poverty (88,116 households) with the overall number of renting households (535,160 households), resulting in a probability of 16.5%. For homeowners, the population affected by energy poverty (243,665 households) relative to the total number of homeowners (1,474,663 households) also results in a 16.5% probability, suggesting an equivalent likelihood of being affected by energy poverty. In contrast, in other regions, the data demonstrates a more favorable outcome for tenants, with 10.1% of homeowners affected by energy poverty compared to only 5.5% of tenants. These findings infer that within Chile, the propensity for renters to be disproportionately impacted by energy poverty is not greater than that of homeowners.

Table 3.10: Housing tenure of households affected by EP [68].

	Metropolitan region		Rest of the regions	
Tenure	Frequency	Percentage (%)	Frequency	Percentage (%)
Owner (fully paid)	175,930	44%	217,966	57%
Owner (in process of payment)	67,735	17%	26,772	7%
Rent (with contract)	53,971	13%	33,274	9%
Rent (without contract)	34,145	9%	21,035	6%
Assigned by relative or friend	28,360	7%	51,250	13%
Shared inheritance or succession	28,537	7%	27,920	7%
Other	11,137	3%	4,207	1%
Total	399,973	100%	382,459	100%

3.1.1.4 Energy prices

In Chile, the average market price of electricity has increased slightly in recent years. However, in response to the social upheaval experienced in October 2019 and the subsequent economic and social impacts of the COVID-19 pandemic, authorities resolved to implement a freeze and a deferral in the escalation of electricity prices for a duration of five years. Although the tariffs were supposed to freeze, the data provided by the electricity supplier companies for 2018 and 2023 indicate that while the fixed charges remained relatively stable, the base energy and additional winter energy tariffs increased (see Tables 3.11 and 3.12). The most significant increases were observed in the metropolitan region, at 21% and 19%, respectively. Currently, projections indicate that, on the national scale and after the presumed tariff suspension, electricity rates are expected to escalate by an average of approximately 62% by January 2025[104]. This anticipated increase is attributed to the economic and social implications of the COVID-19 pandemic and the broader international economic context shaped by the conflict in Ukraine, which has led to a higher exchange rate and subjected the country to elevated inflationary pressures.

Furthermore, it is evident that the electricity rates vary according to geographic location (see Table 3.11). The highest energy prices are observed in Región de la Araucanía, Región de Los Rios, Región de Los Lagos, and Región de Aysén, which are situated within thermal zones 5, 6, and 7. Conversely, the Metropolitan region (thermal zone 3) exhibits the lowest fixed charge and base energy tariff. The discrepancy between the lowest and highest fixed charges can reach up to 110%, whereas the disparity in the base energy tariff is up to 35%. Nevertheless, the proportion of total energy demand attributable to electricity is 47% in a dwelling within the Metropolitan region (see Figure 2.14), while it is merely 8% in the Region de Aysén. Consequently, despite the significant cost differences, the proportion of electricity in the total energy cost remains relatively small in the Region de Aysén..

Recent CNE data indicates that although gas prices remain relatively stable up to 2020, a significant increase occurred in 2021, affecting the entire country with increases ranging from 14% to 32% (see Figure 3.5). Variations in gas prices are geographically observable. The highest prices were recorded in Región de Los Rios, Los Lagos, and Aysén, all situated in the southern region of the country, corresponding to thermal zones 5, 6, and 7, respectively. In contrast, the lowest energy price was identified in Regi'on de Magallanes, located in thermal zone 7 (see Section 1.5.4.2 for an explanation). The price disparity between the lowest price in (Regi'on de Magallanes) and the highest in (Regi'on de Los Lagos) can reach 36%. The most significant price fluctuations between 2018 and 2021 were observed in Region de Arica (32%), O'Higgins (28%), and Los Lagos (25%).

Natural gas is used primarily for cooking and water heating applications, with its allocation

Table 3.11: Electricity tariff for residential consumers at national level (October,2018). Source: Electricity supplier company.

Thermal zones	Region	Fixed charge (CLP/month)	Base energy (CLP/kWh)	Additional winter energy (CLP/kWh)	Backbone usage charge (CLP/kWh)
Zone 1	XV. Arica	1140.0	127.8	127.8	12.3
	I. Tarapaca	1322.2	127.8	127.8	12.3
	II. Antofagasta	1075.5	101.7	112.3	13.3
	III. Atacama	1058.4	103.0	138.8	17.6
	IV. Coquimbo	1322.2	122.2	170.8	17.6
Zone 2	V. Valparaiso	1302.5	127.9	174.2	13.7
Zone 3	XIII. Metropolitana	818.4	100.1	133.9	11.5
	VI. O'Higgins	1042.9	105.3	140.6	17.3
Zone 4	VII. Maule	1046.8	112.6	154.4	17.3
	XVI. Nuble	1190.1	124.4	178.5	17.3
	VIII.l Biobio	1323.3	120.4	175.8	17.3
Zone 5	IX. Araucania	1365.7	126.8	185.2	17.3
	XIV. Los Rios	1377.8	130.1	189.0	21.9
Zone 6	X. Los Lagos	1489.6	130.3	189.9	14.0
Zone 7	XI. Aysen	1718.0	135.4	209.3	2.1
	XII. Magallanes	1322.2	133.3	226.1	0.0

Table 3.12: Electricity tariff for residential consumers at national level (March,2023). Source: Electricity supplier company.

Thermal zones	Region	Fixed charge (CLP/month)	Base energy (CLP/kWh)	Additional winter energy (CLP/kWh)	Backbone usage charge (CLP/kWh)
Zone 1	XV. Arica	1150.9	139.6	139.6	22.4
	I. Tarapaca	1324.4	141.3	141.3	22.4
	II. Antofagasta	1079.3	106.9	117.0	22.8
	III. Atacama	1062.3	121.4	160.5	24.3
	IV. Coquimbo	1324.4	141.2	193.0	24.3
Zone 2	V. Valparaiso	1305.1	144.2	198.2	13.4
Zone 3	XIII. Metropolitana	823.7	121.4	158.7	17.4
	VI. O'Higgins	1046.9	125.9	163.9	27.6
Zone 4	VII. Maule	1050.9	132.5	176.5	27.6
	XVI. Nuble	1194.5	142.8	196.1	27.6
	VIII.l Biobio	1328.1	134.8	186.2	27.6
Zone 5	IX. Araucania	1364.4	142.0	195.8	27.8
	XIV. Los Rios	1324.4	145.0	202.4	33.3
Zone 6	X. Los Lagos	1369.1	145.4	205.1	28.3
Zone 7	XI. Aysen	1771.5	149.2	228.1	0.7
	XII. Magallanes	1239.8	147.3	134.5	227.4

relative to the overall energy demand ranging from 5% to 8% in thermal zones located in the southern region of the country (see Figure 2.14). However, although natural gas accounts for a relatively small proportion of energy consumption relative to heating in these areas, the high costs of electricity and gas predispose households to energy poverty, resulting from their propensity to allocate more than 10%.

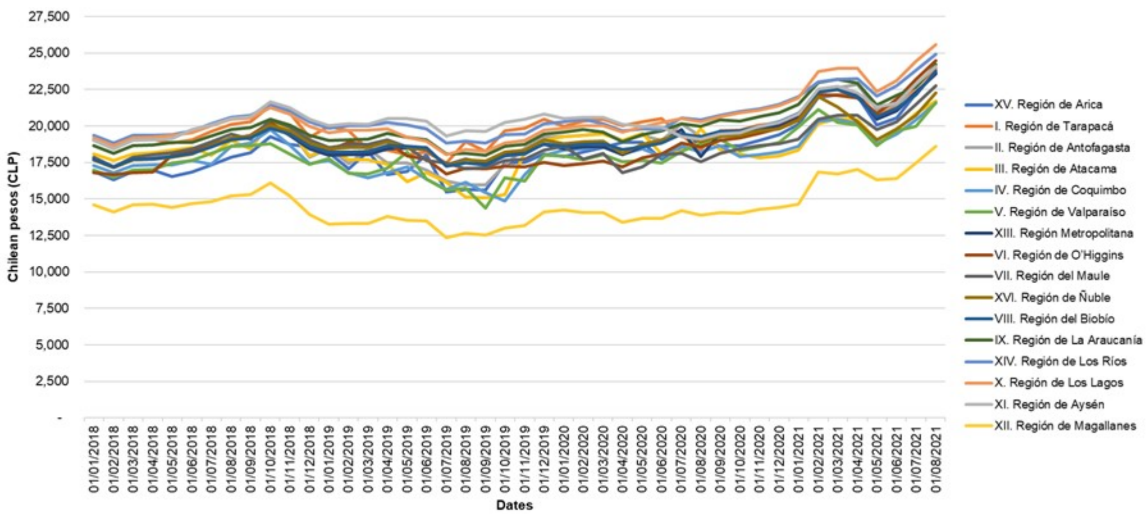


Figure 3.5: Bottled gas price evolution at national level (15 kg) [59].

3.1.2 Socio-demographic factors

According to data from the 2017 Census, the national household count was recorded at 5,275,372. The distribution of households includes mainly those with 1 (15.7%), 2 (22.9%), 3 (22.0%), and 4 (18.8%) members, with an average household size of 3.3 members, as shown in Figure 3.6. The composition of these households varies depending on their size, as illustrated in Figure 3.14. Specifically, 57.9% of single-person households consist of adults, while the remaining portion is comprised of elderly individuals. In two-person households, the predominant compositions include adult couples (43. 0%), elderly couples (22. 6%) and mixed adult and elderly pairs (22.0%). Households with three people consist mainly of adults and minors (41.2%) or adults and elderly individuals (24.5%). Among households of four people, the most common configuration is that of adult couples

Table 3.13: The pricing of 15 kg bottled gas across various regions of the nation for the years 2018 and 2021, respectively (tariff in Chilean pesos)[59].

Thermal zones	**Region**	**Dates**		**Variation**
		01/08/2018	01/08/2021	
Zone 1	XV. Región de Arica	$17,875	$23,620	32.1%
	I. Región de Tarapacá	$20,097	$23,947	19.2%
	II. Región de Antofagasta	$19,183	$23,530	22.7%
	III. Región de Atacama	$19,017	$21,680	14.0%
	IV. Región de Coquimbo	$18,600	$21,547	15.8%
Zone 2	V. Región de Valparaíso	$18,593	$21,600	16.2%
Zone 3	XIII. Región Metropolitana	$19,168	$23,607	23.2%
	VI. Región de O'Higgins	$19,093	$24,463	28.1%
Zone 4	VII. Región del Maule	$19,467	$22,738	16.8%
	XVI. Región de Ñuble	$19,173	$22,267	16.1%
	VIII. Región del Biobío	$19,040	$23,750	24.7%
Zone 5	IX. Región de La Araucanía	$19,750	$24,233	22.7%
	XIV. Región de Los Ríos	$20,590	$24,917	21.0%
Zone 6	X. Región de Los Lagos	$20,450	$25,583	25.1%
Zone 7	XI. Región de Aysén	$20,507	$24,100	17.5%
	XII. Región de Magallanes	**$15,200**	**$18,600**	22.4%

with children (61.3%).

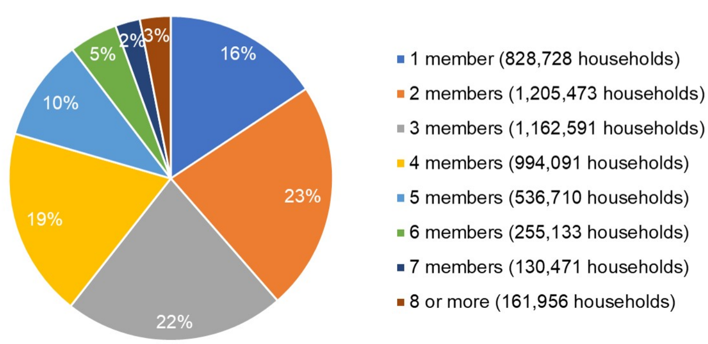


Figure 3.6: National distribution of household size [66].

The 2017 EPF findings indicate that energy expenditure increases progressively with the addition of members to a household (refer to Figure 3.7). Nevertheless, the increase in household energy expenditure is not proportional to the number of members. This phenomenon occurs because household members share activities and services, such as heating and the energy used for

Table 3.14: Family composition at national level [66].

Number of members	Family composition	Frequency	Percent
1 member	Adult	480,068	58%
	Elderly	347,832	42%
	Minor	828	0.1%
	Total	828,728	100%
2 members	Two adults	518,906	43%
	Two elderlies	273,087	23%
	Adult and elderly	265,333	22%
	Adult and minor	138,777	12%
	Elderly and minor	9,370	1%
	Total	1,205,473	100%
3 members	Two adults and minor	478,711	41%
	Three adults	227,903	20%
	Two adults and an elderly	143,159	12%
	Adult and two elderly	141,955	12%
	Adult and two minors	83,298	7%
	Adult, minor and an elderly	54,589	5%
	Other	32,976	3%
	Total	1,162,591	100%
4 members	Two adults and two minors	404,060	41%
	Three adults and a minor	205,762	21%
	Four adults	104,254	10%
	Two adults, minor and an elderly	69,391	7%
	Three adults and an elderly	61,639	6%
	Two adults and two elderlies	58,393	6%
	Adult, minor and two elderlies	28,596	3%
	Adult and three minors	24,701	2%
	Other	37,295	4%
	Total	994,091	100%
5 members	Two adults and three minors	125,268	23%
	Three adults and two minors	112,194	21%
	Four adults and minor	84,117	16%
	Three adults, minor and elderly	43,195	8%
	Two adults, two minors and elderly	40,165	7%
	Five adults	28,996	5%
	Two adults, minor and two elderlies	28,863	5%
	Four adults and an elderly	22,676	4%
	Three adults and two elderlies	20,907	4%
	Other	30,329	6%
	Total	536,710	100%

cooking, which results in a per capita cost reduction. Economies of scale in energy consumption are represented through equivalisation factors, which are metrics that enable the comparison of energy consumption across households of varying sizes. In this analysis, the reference unit considered is a household consisting of two individuals, with adults and children deemed equivalent. These equivalisation factors are depicted in Figure 3.8 below.

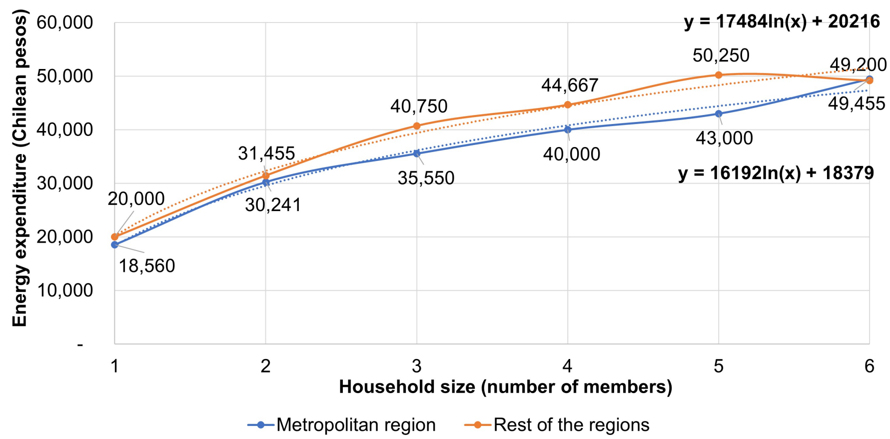


Figure 3.7: Median energy expenditure by household size [68].

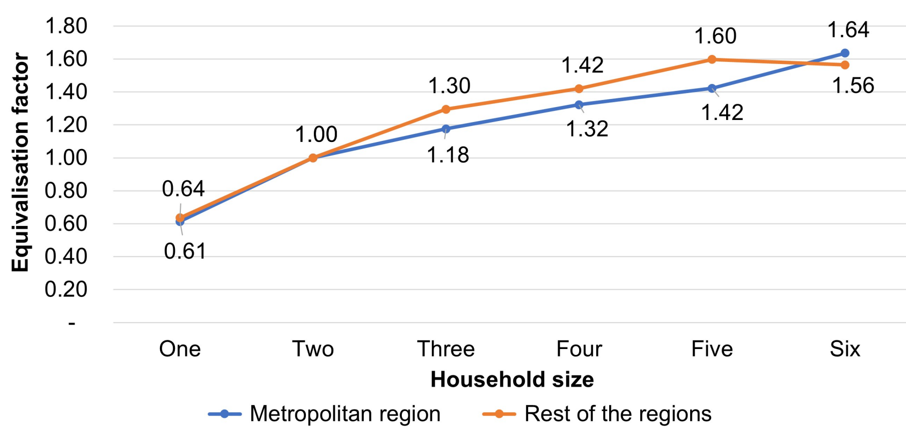
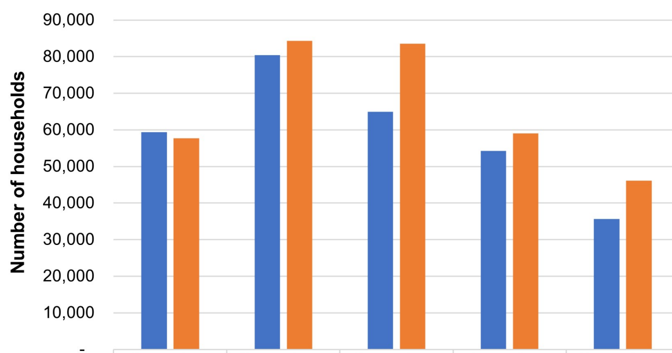


Figure 3.8: Chilean equivalisation factors [68].

Data provided by the 2017 EPF was utilized to investigate correlations within the population data, particularly examining the size and composition of households impacted by EP. The household sizes most affected by EP are those consisting of one to three members in both Metropolitan and regional areas. Table 3.15 presents the detailed family composition of these households. Within single-person households, EP has significantly influenced the elderly demographic. This group constitutes 77% and 64% of single-person households affected by EP in Metropolitan and regional areas, respectively. Similarly, in two-person households, the groups most affected by EP include those comprising elderly individuals, both adults and elderly, and adults. Households of larger size predominantly consist of families with children or families where adults and elderly individuals cohabit.



	1 member	2 members	3 members	4 members	5 members
Metropolitan region	59,411	80,394	64,954	54,244	35,694
Rest of the regions	57,727	84,278	83,501	59,065	46,099

Figure 3.9: Household sizes most affected by EP (TPR) [68].

In Chile, Law 19.828 classifies individuals aged 60 and above as elderly. Consequently, 16.2% of the Chilean population, amounting to 2.9 million individuals, are considered elderly [66]. The majority of this demographic resides in thermal zones 2, 3, and 4, situated in the central region of the country, mirroring the distribution pattern of the general population (refer to Table 3.16). At present, EP is projected to impact approximately 390,000 elderly individuals.

Table 3.15: Family composition of households affected by EP (TPR) [68].

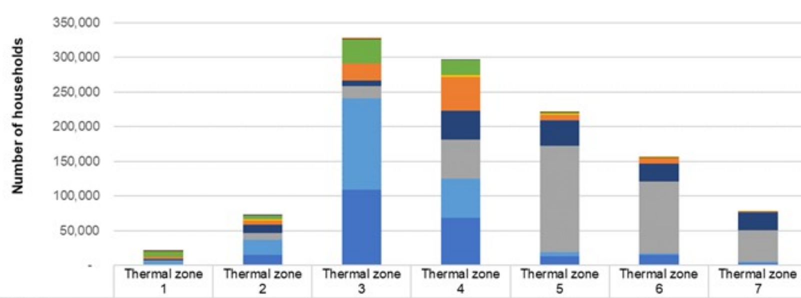
Number of members	Family composition	Metropolitan region		Rest of the regions	
		Frequency	**Per cent**	**Frequency**	**Per cent**
1 member	Elderly	45,747	77%	36,766	64%
	Adult	13,664	23%	20,961	36%
	Total	59,411	100%	57,727	100%
2 members	Two elderlies	29,455	37%	28,875	34%
	Adult and elderly	21,317	27%	18,417	22%
	Two adults	20,126	25%	25,634	30%
	Adult and minor	8,611	11%	11,041	13%
	Elderly and minor	885	1%	309	0%
	Total	80,394	100%	84,278	100%
3 members	Two adults and minor	18,570	29%	32,086	38%
	Adult and two elderly	11,193	17%	10,705	13%
	Two adults and an elderly	11,126	17%	12,172	15%
	Three adults	7,725	12%	16,871	20%
	Adult, minor and an elderly	6,721	10%	2,994	4%
	Adult and two minors	6,628	10%	6,756	8%
	Three elderlies	1,930	3%	834	1%
	Other	1,061	2%	1,082	1%
	Total	64,954	100%	83,501	100%
4 members	Two adults and two minors	20,074	37%	20,395	35%
	Three adults and a minor	13,452	25%	12,828	22%
	Two adults, minor and an elderly	5,045	9%	4,527	8%
	Adult and three minors	3,472	6%	3,912	7%
	Four adults	3,395	6%	4,813	8%
	Three adults and an elderly	3,264	6%	2,687	5%
	Adult, minor and two elderlies	2,489	5%	2,509	4%
	Two adults and two elderlies	2,170	4%	5,278	9%
	Other	883	2%	2,118	4%
	Total	54,244	100%	59,065	100%
5 members	Two adults and three minors	7,637	21%	13,111	28%
	Three adults and two minors	7,321	21%	9,332	20%
	Four adults and minor	3,741	10%	6,017	13%
	Two adults, two minors and elderly	3,693	10%	6,176	13%
	Adult, two minors and an elderly	2,975	8%	612	1%
	Three adults, minor and elderly	2,277	6%	5,698	12%
	Two adults, minor and two elderlies	2,092	6%	1,174	3%
	Five adults	1,622	5%	1,054	2%
	Adult and four minors	1,068	3%	1,198	3%
	Three adults and two elderlies	1,067	3%	961	2%
	Other	2,201	6%	767	2%
	Total	35,694	100%	46,099	100%

Table 3.16: Distribution of elderlies at national level [66].

Thermal zones	Regions	Number of elderly	Percent	Percent
Zone 1	XV. Arica	34,973	1.2%	10.9%
	I. Tarapacá	38,781	1.4%	
	II. Antofagasta	70,276	2.5%	
	III. Atacama	41,301	1.4%	
	IV. Coquimbo	126,227	4.4%	
Zone 2	V. Valparaíso	342,035	12.0%	12.0%
Zone 3	Metropolitana	1,095,901	38.5%	43.9%
	VI. O´Higgins	155,975	5.5%	
Zone 4	VII. Maule	183,040	6,4%	18.8%
	XVI. Ñuble	90,964	3.2%	
	VIII.Bío-Bío	261,673	9.2%	
Zone 5	IX. La Araucania	167,612	5.9%	8.3%
	XIV. Los Ríos	68,102	2.4%	
Zone 6	X. Los Lagos	131,104	4.6%	4.6%
Zone 7	XI. Aysén	13,997	0,5%	1.5%
	XII. Magallanes y Antártica Chilena	28,210	1.0%	
Total		2,850,171	100.0%	100.0%

3.1.3 Housing energy inefficiency

Based on 2018 data on energy consumption in the Chilean residential sector, it is evident that households that allocate more than 10% of their income to energy in thermal zones 1 to 4 predominantly occupy structures constructed of reinforced concrete and masonry (see Figure 3.10). In contrast, within thermal zones 5 to 7, the majority of such households reside in detached wooden houses. Moreover, 55% of the households that dedicate more than 10% of their income to energy expenses live in non-insulating dwellings.



	Thermal zone 1	Thermal zone 2	Thermal zone 3	Thermal zone 4	Thermal zone 5	Thermal zone 6	Thermal zone 7
Reinforced concrete apartment	-	-	-	-	1,182	1,371	986
Masonry apartment	962	1,173	-	1,173	886	412	55
Adobe semi-detached house	1,261	0	2,237	-	-	-	-
Reinforced concrete semi-detached house	7,566	5,616	34,918	22,212	948	-	276
Adobe detached house	-	1,872	-	2,222	1,895	-	-
Reinforced concrete detached house	3,783	5,616	24,447	48,803	7,580	8,045	553
Wood semi-detached house	1,758	12,076	7,760	41,559	36,263	25,357	25,983
Wood detached house	497	10,204	17,855	56,447	153,583	104,183	45,754
Masonry semi-detached house	5,045	21,436	131,912	57,106	6,633	2,103	2,212
Masonry detached house	1,261	14,977	108,673	67,881	12,558	14,829	2,525

Figure 3.10: Type of house where households affected by EP live according to TPR [40].

3.2 The current state of energy poverty in Chilean residential housing.

3.2.0.1 Family Budget Survey (2017 and 2022)

This section outlines the findings concerning the current state of energy poverty within the residential housing sector in Chile. According to the 2017 EPF survey, 2.6 million individuals, representing 12% of the Chilean population, are affected by energy poverty. Among households in the metropolitan region, 17% were identified as experiencing energy poverty, which is approximately 400,000 households. This figure extrapolates to an estimated 1.3 million individuals, assuming an average household size of 3.3 persons [66]. Conversely, a lower incidence of energy poverty was observed in other regions, with a prevalence rate of 9%, which corresponds to approximately 380,000 households or 1.3 million individuals.

Table 3.17: The population impacted by EP as reported in the 2017 EPF.

Area	Number of households represented	Percentage of households affected by EP	Number of households affected by EP	Number of people affected by EP
Metropolitan Region	2,378,490	16.8%	399,973	1,319,910
Rest of the regions	4,121,084	9.3%	382,459	1,262,114
National level	6,499,574	12.0%	782,431	2,582,024

The 2022 EPF survey reveals that 3.7 million individuals, accounting for 25% of the Chilean population, are impacted by the EP, indicating an increase compared to the 2017 survey. The prevalence of households experiencing EP exhibits a pronounced escalation from north to south (see Table 3.18). The central region of the country, particularly the metropolitan area, alongside the southern zones, registers the highest concentration of households affected by EP, with a substantial 42% of the households confronting EP. The metropolitan region, serving as a comparative baseline between the two survey periods, demonstrates a considerable rise in the proportion of households grappling with EP, escalating from 17% in 2017 to 23% in 2022.

Table 3.18: The population impacted by EP as reported in the 2022 EPF.

Area	Number of households represented	Percentage of households affected by EP	Number of househoolds affected by EP	Number of people affected by EP
North	535,653	19.3%	103,113	340,274
Metropolitan region	2,491,960	23.4%	583,119	1,924,292
Central	1,032,249	27.6%	284,901	940,172
South	361,185	42.2%	152,420	502,986
National	4,421,047	25.4%	1,123,553	3,707,724

3.2.0.2 2018 Uses of Energy in the Chilean Housing Survey

Based on the findings of the 2018 Chilean Housing Survey on energy use, approximately 4.5 million individuals, representing 22% of the Chilean populace, experience energy poverty (EP) at the national level, with 2 million residents of the metropolitan area. Similarly to the 2022 EPF, the incidence of households experiencing EP shows a marked increase from north to south (see Table 3.19). In particular, 85% of these households are located in thermal zones 3, 4, 5, and 6. The highest proportion of households affected by EP is found in thermal zones 4 (22%), 5 (35%), 6 (48%), and 7 (55%).

Table 3.19: Quantification of individuals impacted by EP, utilizing data from the 2018 uses of energy Chilean Housing Survey.

	Number of households represented by zone	Percentage of households affected by EP	Number of households affected by EP	Number of people affected by EP
Zone 1	554,747	9%	51,591	170,252
Zone 2	912,138	10%	87,565	288,965
Zone 3	2,731,681	22%	602,882	1,989,511
Zone 4	1,157,266	22%	254,946	841,321
Zone 5	540,314	35%	190,244	627,807
Zone 6	265,627	48%	127,581	421,016
Zone 7	118,703	55%	65,844	217,287
National	6,280,476	22%	1,379,821	4,553,408

Consequently, based on the evidence presented in these sources, the findings demonstrate an overall upward trend in the number of households affected by EP in recent years. Although a substantial number of households within the metropolitan region are impacted by EP, the most considerable proportion is observed in the southern regions of the country, with particular emphasis on thermal zones 5, 6, and 7.

3.3 Energy modeling

This section elucidates the outcomes of implementing energy demand reduction strategies across different building archetypes, derived from simulations conducted with EnergyPlus. Initially, the rationale for selecting specific thermal zones for the simulation process is detailed in Section 3.3.1. Subsequently, the outcomes pertaining to the baseline energy requirements of the archetypes are presented in Section 3.3.2, and ultimately, the findings that incorporate the energy demand reduction strategies are delineated in Section 3.3.3.

3.3.1 Selection of thermal zones

This section elucidates the comprehensive rationale underpinning the selection of thermal zones 5 and 7 for archetype simulations. The selection of these particular thermal zones is predominantly informed by an analysis of five principal factors: the energy demand pertinent to residential dwellings, household income levels, the cost of energy, inefficiencies inherent within the housing stock, and the widespread occurrence of energy poverty.

3.3.1.1 Thermal zone 5

Households situated within thermal zone 5 face a series of factors including considerable energy demands, widespread inefficiencies in housing, high energy costs, and the lowest median income on a national scale, which collectively contribute to their vulnerability to energy poverty.

The significant demand for heating can be attributable to the high incidence of uninsulated wooden houses, together with the exposure to one of the nation's most severe climates (see Figures 2.9 and 2.8). In thermal zone 5, uninsulated wooden houses constitute 54% of the housing stock (see Table 2.17). The climate in this region is among the harshest in the country, as indicated by the correlation between energy demand and degree days (see Table 2.8). This is further evidenced by the substantial use of heating, which averages 87% between April and October, with an average daily usage of 8.5 hours (see Table 2.9). Mostly, wood serves as the main heating fuel, utilized by 90.9% of the households (see Figure 2.20). Moreover, 76% of the households heat the entire house, while only 24% heat solely the spaces in use (see Table 3.7).

Furthermore, data provided by electricity suppliers in 2018 showed that the electricity price in Regi'on de la Araucan 'ia (thermal zone 5) is one of the highest in the country (see Table 3.11), only surpassed by Regi'on de Los Lagos (thermal zone 6) and Regi'on de Ays 'en (thermal zone 7). The National Commission of Energy documented similar findings in 2018 on bottled gas prices (see Table 3.13). This situation is particularly concerning, given that this area also has the lowest median income in the nation (see Table 3.4). These observations may also explain the high percentage of households experiencing energy poverty (TPR) in this thermal zone, recorded at 35% according to the Chilean 2018 Energy Use Survey (see Table 3.19.

Consequently, the aforementioned factors, coupled with the intrinsic likelihood of households experiencing energy poverty under the prevailing conditions, render this thermal zone pertinent for evaluating the impact of enhancements in residential properties. The largest cohort of residences within thermal zone 5 has been selected for modeling. This cohort constitutes 42% of the housing stock in thermal zone 5 and comprises detached, uninsulated wooden houses, as detailed in Section 2.4.4.

3.3.1.2 Thermal zone 7

Households located within thermal zone 7 are subject to conditions similar to those of thermal zone 5, making them particularly susceptible to energy poverty. This zone experiences the most severe climate in the nation, as evidenced by the correlation between energy demand and degree days (see Table 2.8) and is further manifested by the extensive use of heating (see Table 2.9). In this thermal zone, heating is used continuously throughout the year, from January to December, with approximately 79% of households utilizing heating during these months and reporting an average daily usage of 7.2 hours (see Table 2.9).

In thermal zone 7, two distinct populations have been identified, differentiated by their choice of heating fuel, wood or natural gas (see Figure 2.20). These groups show divergent profiles with respect to heating energy demand, which is influenced by a combination of factors, including their choice of fuel source, the cost of fuel, the efficiency of the heater, and household income. One demographic is composed of households using subsidized natural gas, characterized by relatively high heating efficiency and substantially greater household income compared to their counterparts. In particular, the income of those that use natural gas is more than double that of households that rely on wood for heating [40]. In contrast, households dependent on wood heating encounter higher fuel costs, operate less efficient heaters, and have an income approximately half that of natural gas users.

Therefore, the demographic most susceptible to energy poverty in thermal zone 7 comprises households reliant on wood for heating. This is attributed to the confluence of increased energy costs relative to gas, inefficient heating systems, and reduced income levels. Furthermore, 60% of the housing inventory in thermal zone 7 consists of uninsulated wooden houses (see Table 2.17. This condition may exacerbate their vulnerability to energy poverty, as inefficient homes require increased energy consumption. In fact, this could also elucidate the highest prevalence of households enduring energy poverty, with an observed rate of 55%, as reported by the Chilean 2018 Energy Use Survey (see Table 3.19).

Consequently, the factors previously mentioned, along with the inherent probability that households face energy poverty due to current situations, make this thermal zone essential to assess the effects of improvements in residential buildings. The most significant group of homes in thermal zone 7 has been chosen for modeling. This group represents 36% of the housing stock in thermal zone 7 and consists of detached wooden houses without insulation, as explained in Section 2.4.4.

3.3.2 The baselines energy consumption of archetypes

3.3.2.1 Sensitivity analysis

Sensitivity analyzes (SA) have been widely employed in academic endeavors across a wide range of disciplines, including engineering, physics, economics, social sciences, and medical studies [102]. These analyses are classified into three distinct types: mathematical, statistical, and graphical. Mathematical logic is used to evaluate the sensitivity of model outcomes to a range of input values [33]. In statistical analyzes, probability distributions are assigned to variables and the effects on the outcome are assessed by systematically altering one or more inputs [10]. Finally, graphical analysis refers to the representation of sensitivity through visual graphics or graphs [106].

In the domain of building energy modeling, sensitivity analysis (SA) functions as an instrument to determine the parameters that wield the most substantial influence on energy performance. It also helps to verify and validate a model throughout its developmental and refinement phases, thus improving the reliability of the results [99]. This study will take into account the inputs detailed in Sections 2.4.4.2 and 2.4.4.3 to support the model, followed by a comprehensive sensitivity analysis (SA) on various parameters to identify the most suitable inputs to configure the base dwelling in both thermal zones. Factors such as infiltration rate, building orientation (north, south, east, west), and heating temperature settings will be considered. Subsequently, SA will be used to evaluate interventions designed to mitigate energy demand applied to the baseline dwelling, incorporating variables such as improvements in the building envelope (insulation thickness), the adoption of double glazing and the efficiency of the heating system. These analyses aim to assess their effect on heating demand.

- **Infiltration rate**

The energy demand for heating per square meter is significantly influenced by the infiltration rate, as depicted in Figure 3.11. An infiltration rate ranging from 0.1 ACH to 1 ACH was considered, where lower values denote more energy-efficient dwellings, whereas higher values indicate dwellings that are less energy-efficient, often older, and typically occupied by low-income households, as outlined in the ASHRAE fundamentals handbook [7]. Consequently, the energy demand for heating ranges from 174 to 219 kWh/m^2 for the dwelling baseline located in thermal zone 5, and from 377 to 459 kWh/m^2 for the dwelling baseline located in thermal zone 7.

This study focuses on households that are potentially affected by energy poverty and are, therefore, more vulnerable to this condition. Accordingly, the infiltration rate for the baseline dwelling in both thermal zones is established at 0.9 ACH, considering that these households generally inhabit energy-inefficient dwellings with insufficient insulation, as outlined in Section 3.1.3, and also fall within the lowest income brackets, as shown in Table 3.3.

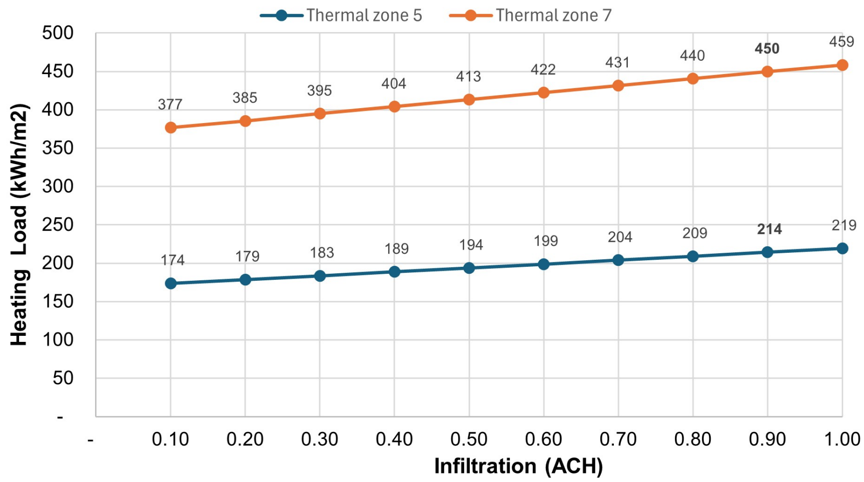


Figure 3.11: Infiltration-related heating requirements.

- **Orientation**

In Chile, there is a lack of prior studies that have quantified the impact of building orientation on energy demand. This research aims to evaluate this parameter, identifying the worst-case scenario for the standard dwelling as the baseline. Table 3.20 presents the heating energy demand of the dwelling in thermal zones 5 and 7 according to the orientation. The data do not reveal significant differences in energy demand attributable to the orientation of the dwelling. However, the highest heating demand is recorded for a dwelling oriented southward. Consequently, this orientation is selected for the baseline dwelling, as it represents the worst-case scenario.

Table 3.20: Heating energy demand by building orientation.

Building orientation	Thermal zone 5 (kWh/m2)	Thermal zone 7 (kWh/m2)
North	210.8	442.2
South	214.2	449.6
East	211.1	445.9
West	213.0	444.4

- **Temperature settings**

The configuration of the temperatures within the heating systems constitutes a critical factor affecting energy consumption. The analysis covers a temperature range from 18°C to 23°C (see Figure 3.12). This selected range is based on the World Health Organization recommendation of a standard temperature in winter conditions, which suggests values between 18°C and 21°C. This range was determined not to pose health risks to healthy adults provided that they wear adequate clothing and consider humidity and other environmental factors. In particular, elevated temperatures were suggested for demographic groups that are more susceptible to cold, including the elderly, people with illnesses, and children [180].

This research focuses on households that may be susceptible to the impacts of energy poverty, as well as the conditions that exacerbate their vulnerability. Energy poverty has notably affected the demographics of the elderly and children (see Section 3.1.2). Specifically, elderly individuals constitute 77% and 64% of single-person households affected by energy poverty in metropolitan and regional areas, respectively. In contrast, larger household sizes are predominantly composed of families with children or those where adults and elderly members reside together. Therefore, a temperature setting of 23°C is adopted for the standard dwelling as the baseline. Consequently, the baseline residence located in thermal zones 5 and 7 demonstrates an energy requirement for heating quantified at 214 kWh/m2 and 450 kWh/m2, respectively. These values will act as the baseline for the energy consumption of the evaluated archetypes, upon which interventions designed to mitigate energy demand will be implemented.

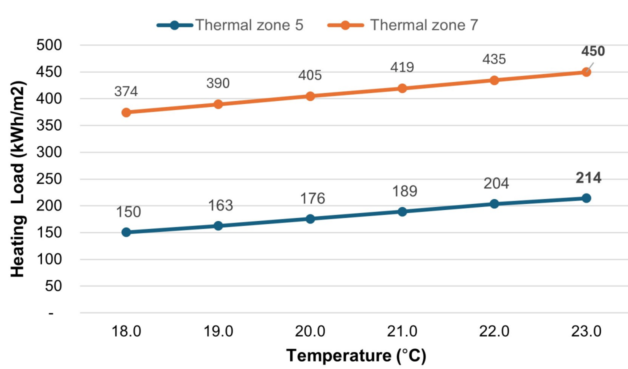


Figure 3.12: Variation in heating energy demand by temperature settings.

3.3.3 Energy demand reduction interventions

This section presents the results of interventions aimed at reducing energy demand as applied to the reference dwelling. The variables considered include improvements to the building envelope, such as roof, wall, and floor insulation, the implementation of double glazing, and improvements in the efficiency of the heating system, all of which are analyzed to assess their impact on heating demand. The analysis will be conducted independently for each reference dwelling within each thermal zone.

3.3.3.1 Thermal zone 5

- **Roof insulation**

The effect of incorporating roof insulation in the reference dwelling is presented in Table 3.21. Various insulation thicknesses, ranging from 40 to 200 mm, were analyzed, resulting in energy reductions between 19.0% and 28.5%. According to the thermal regulation proposed by the Ministry of Housing, the maximum recommended U-value for roofs in thermal zone 5 is 0.33 W/m^{2}K (see Section 1.5.5.1). Consequently, it is recommended to implement an insulation thickness of 120 mm to meet this standard, achieving a U-value of 0.30 W/m^{2}K, which is below the required threshold. This enhancement results in a 26.3% reduction in heating demand.

It should be noted that while the addition of insulation significantly decreases the demand for heating energy, the marginal benefit diminishes with increasing insulation thickness (see Figure 3.13). This observation is crucial for identifying the most cost-effective solution, particularly in contexts where strategies are targeted toward households with limited income, making cost considerations fundamental.

Table 3.21: Impact of incorporating roof insulation in the reference dwelling on heating energy demand.

Thickness (mm)	Rt (m^2K/W)	U-value (W/m^2K)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
0	0.45	2.23	15,381	214.2
40	1.4	0.71	12,461	173.5
60	1.88	0.53	11,992	167.0
80	2.35	0.43	11,694	162.8
100	2.83	0.35	11,492	160.0
120	3.31	0.30	11,333	157.8
140	3.78	0.26	11,222	156.3
160	4.26	0.23	11,131	155.0
180	4.73	0.21	11,061	154.0
200	5.21	0.19	11,000	153.2

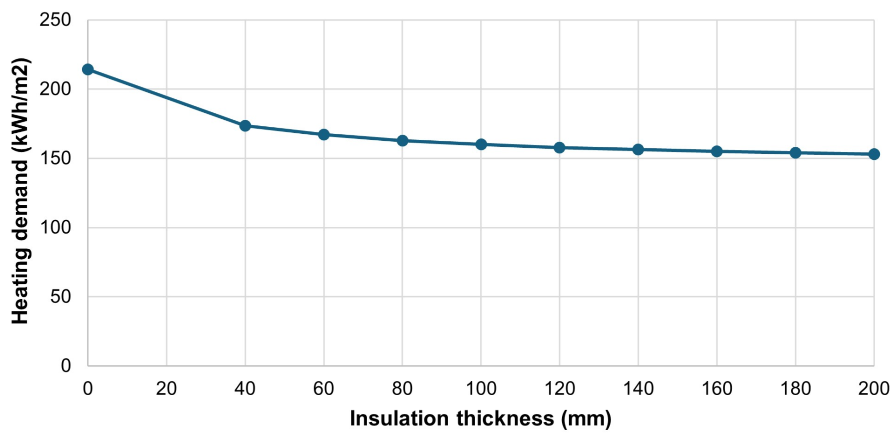
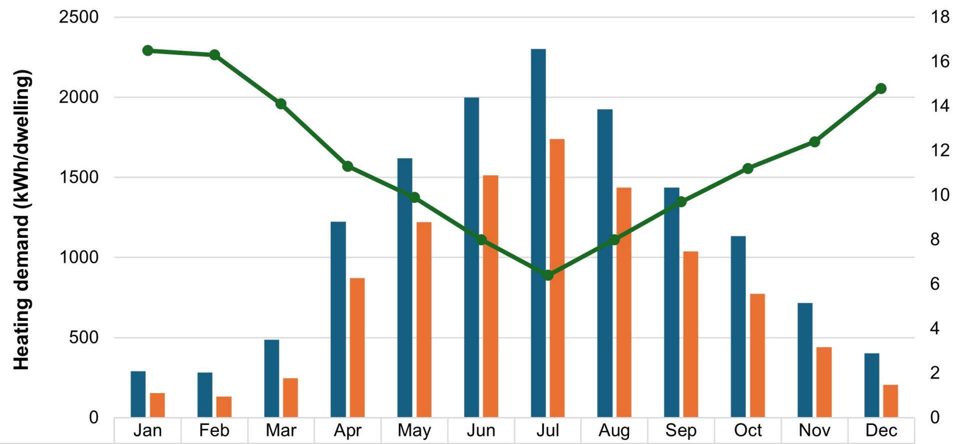


Figure 3.13: Energy demand for heating with the addition of roof insulation.

Figure 3.14 presents a comparative analysis of the annual heating energy demand for the baseline dwelling, represented by blue bars, and a dwelling incorporating a roof insulation with a thickness of 120mm, indicated by orange bars. The observed data elucidates the impact of incorporating roof insulation, especially during the winter months, when the average outdoor temperature can decrease to 6.4°C.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (non-insulated roof)	290	281	488	1224	1619	2000	2301	1924	1438	1135	717	401
Insulated roof (120mm).	155	132	247	872	1220	1514	1739	1435	1039	773	441	207
Average Outdoor Temperature (°C)	16.5	16.3	14.1	11.3	9.9	8	6.4	8	9.7	11.2	12.4	14.8

Figure 3.14: Analysis of variations in heating demand between the baseline and the roof-insulated dwelling.

- **Wall insulation**

The impact of incorporating wall insulation within the reference dwelling is illustrated in Table 3.15. An analysis of various insulation thicknesses, ranging from 20 to 80 mm, indicated energy reductions between 10.5% and 18.0%. According to the thermal regulation proposed by the Ministry of Housing, the maximum recommended U-value for walls in thermal zone 5 is 1.6 W/m^{2}K (see Section 1.5.5.1). However, the official document on thermal conditioning construction solutions issued by the Ministry of Housing advocates for an insulation thickness of 50 mm [81], which produces a U-value of 0.65 W/m^{2}K, which is significantly lower than the stipulated threshold. This enhancement results in a 15.7% reduction in the heating demand.

It is imperative to recognize that while the addition of insulation decreases the energy required for heating, increasing the thickness beyond a certain point does not result in substantial reductions in energy demand (see Figure 3.22). This knowledge is vital to formulate the most cost-effective strategy, particularly for households with limited financial resources where expenditure is a primary concern.

Table 3.22: Impact of incorporating wall insulation in the reference dwelling on heating energy demand.

Thickness (mm)	Rt (m^2K/W)	U-value (W/m^2K)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
0	0.33	3.03	15,381	214
20	0.81	1.23	13,769	192
30	1.06	0.94	13,406	187
40	1.3	0.77	13,156	183
50	1.54	0.65	12,964	181
60	1.78	0.56	12,808	178
70	2.02	0.50	12,700	177
80	2.27	0.44	12,608	176

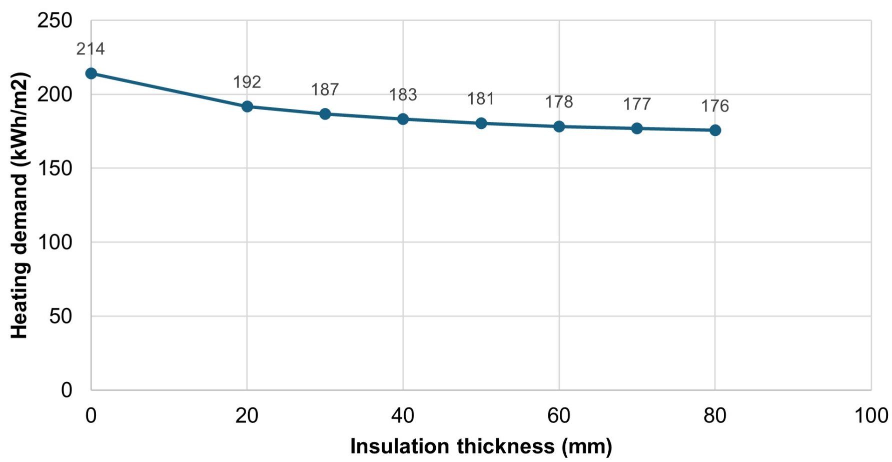
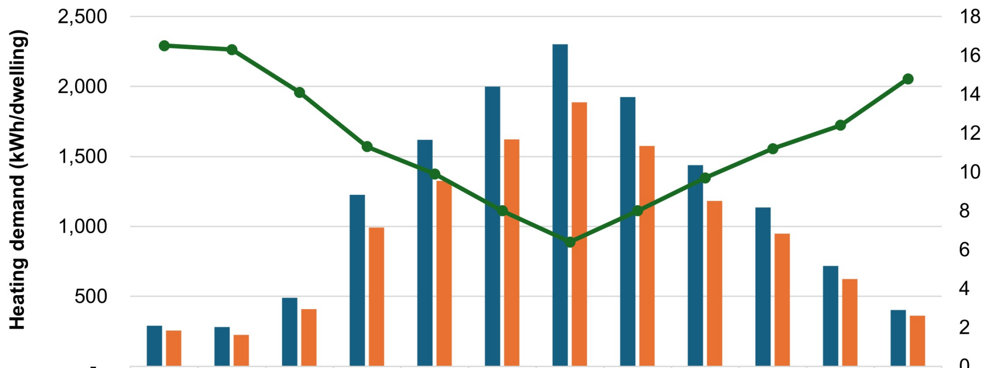


Figure 3.15: Energy demand for heating with the addition of wall insulation.

Figure 3.16 shows a comparison of the annual heating energy requirements for the baseline dwelling, represented using blue bars, and a dwelling enhanced with 50mm thick wall insulation, shown by orange bars. The data highlights the influence of wall insulation, particularly throughout the winter months when the average outdoor temperature may drop to 6.4°C.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (non-insulated wall)	290	281	488	1,224	1,619	2,000	2,301	1,924	1,438	1,135	717	401
Insulated (50 mm)	255	225	407	992	1326	1622	1887	1576	1181	950	623	361
Average Outdoor Temperature (°C)	16.5	16.3	14.1	11.3	9.9	8	6.4	8	9.7	11.2	12.4	14.8

Figure 3.16: Comparison of heating demand between the baseline and wall-insulated dwelling.

- **Floor insulation**

The effect of incorporating floor insulation in the reference dwelling is depicted in Table 3.23. An analysis of various insulation thicknesses, ranging from 30 to 140 mm, revealed energy reductions between 0.5% and 1.5%. According to the thermal regulation presented by the Ministry of Housing, the maximum recommended U-value for flooring in thermal zone 5 is 0.5 W/m²K (see Section 1.5.5.1). Thus, it is advisable to implement an insulation thickness of 80 mm to comply with this standard, attaining a U-value of 0.45 W/m²K, which is below the mandated threshold. This improvement results in a 1.0% reduction in heating demand.

The limited reduction in heating demand can be partially explained by the configuration within EnergyPlus, which uses a fixed temperature value of the ground 18°C. This configuration results in a relatively minor temperature gradient between the interior environment and the ground, which leads to a lower assessment of heat loss through the floor. Consequently, the incorporation of insulation does not significantly contribute to a reduction in energy demand. Enhancements in the representation of ground temperature by EnergyPlus could potentially improve these results. However, the limited impact observed in the reduction in heating demand highlights the importance of prioritizing other measures to reduce energy demand, relegating floor insulation to a lower priority.

As illustrated in Figure 3.17, the diminished effect of floor insulation on energy demand is evident throughout the year.

Table 3.23: Impact of incorporating floor insulation in the reference dwelling on heating energy demand.

Thickness (mm)	Rt (m^2K/W)	U-value (W/m^2K)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
0	0.29	3.41	15,381	214
30	1.02	0.98	15,306	213
40	1.26	0.79	15,289	213
50	1.50	0.67	15,269	213
60	1.75	0.57	15,259	212
80	2.23	0.45	15,225	212
100	2.71	0.37	15,194	212
120	3.20	0.31	15,172	211
140	3.68	0.27	15,156	211

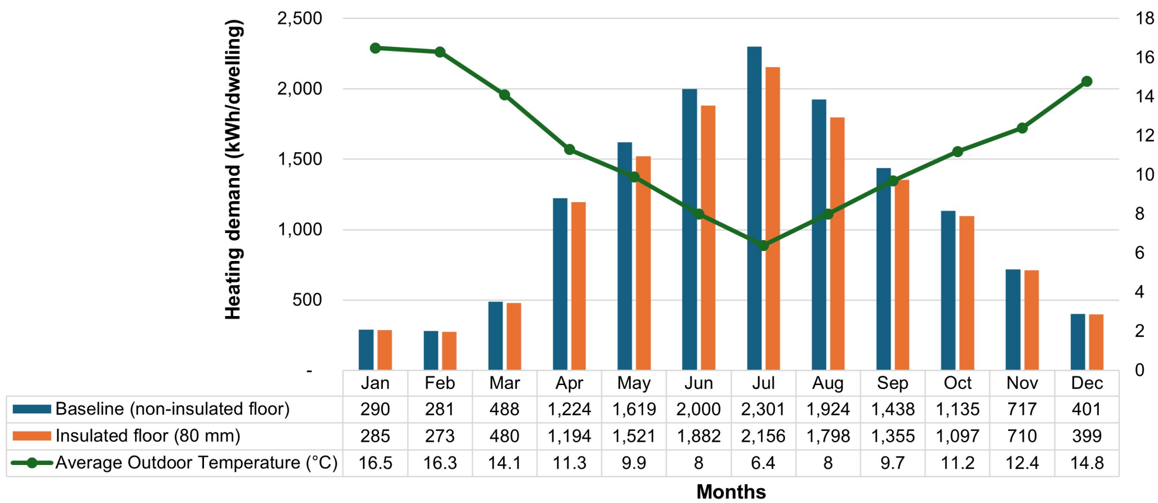


Figure 3.17: Analysis of variations in heating demand between the baseline and the floor-insulated dwelling.

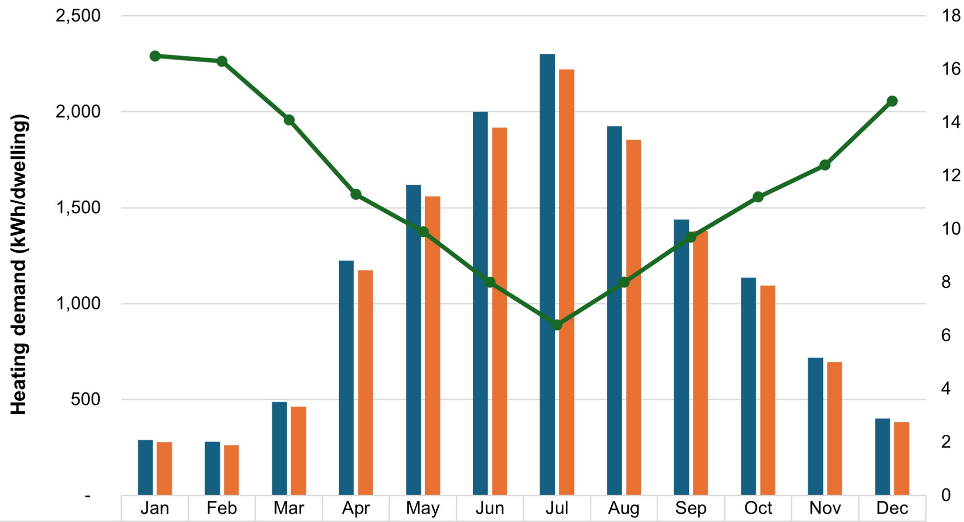
- **Double glazing**

The thermal regulations stipulated by the Ministry of Housing specify a maximum permissible glass surface area in relation to the parameters of the vertical envelope, depending on the type of glazing, single or double. Since the residence already complies with the requirement of a maximum of 18% single glazing regarding the vertical enclosure parameters for thermal zone 7, the reference dwelling has been fitted with double glazing to assess its impact on heating demand.

The influence of incorporating double glazing within the reference dwelling is documented in Table 3.24. Various thicknesses between the panes, ranging from 6 to 15 mm, were analyzed, demonstrating reductions in heating energy demand between 3.1% and 4.2%. The minimal effect observed when substituting single glazing for double glazing can be mainly attributed to the limited proportion of glass surface area in relation to the dimensions of the vertical envelope, which only accounts for 10%, thus resulting in minimal heat loss through this element. Moreover, due to the unavailability of specific data on glazing for the Chilean housing stock, assumptions regarding the glazing size were necessary. Consequently, the impact on energy demand may be more substantial if these assumptions have underestimated the actual size of the glazing. The reduced impact of double glazing on energy demand throughout the year is also illustrated in Figure 3.18.

Table 3.24: Impact of incorporating double glazing in the reference dwelling on heating energy demand.

	Thickness (mm)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
	0	15,381	214.2
Air	6	14,903	207.5
	8	14,847	206.7
	10	14,806	206.2
	12	14,769	205.7
	15	14,736	205.2



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (non-insulated floor)	290	281	488	1,224	1,619	2,000	2,301	1,924	1,438	1,135	717	401
Double glazing (8mm gap)	278	262	463	1175	1558	1918	2221	1854	1380	1095	696	384
Average Outdoor Temperature (°C)	16.5	16.3	14.1	11.3	9.9	8	6.4	8	9.7	11.2	12.4	14.8

Months

Figure 3.18: Analysis of variations in heating demand between the baseline and the double-glazed dwelling.

- **Efficiency of the heating system**

This section evaluates the effect of replacing a wood-burning stove with a pellet stove. Initially, the reference residence was modeled with a wood-burning stove that exhibits an efficiency rate of 70%, as indicated by the SAP model [88]. Subsequently, a pellet stove was selected for replacement, with its efficiency, as documented by the Certified Wood Stove Database of the U.S. Environmental Protection Agency (EPA), varying between 70 and 84% [3].

The effect of replacing a wood burner stove with a pellet stove on heating demand is detailed in Table 3.25. The efficiency of the heating system considered in the modeling process ranges from 72 to 84%, demonstrating reductions in the heating energy demand between 0.4% and 2.4%. This indicates that replacing a wood-burning stove with a pellet stove has a negligible impact on the reduction of heating energy consumption, which may be attributed to the minimal variation in the efficiency of both heating systems.

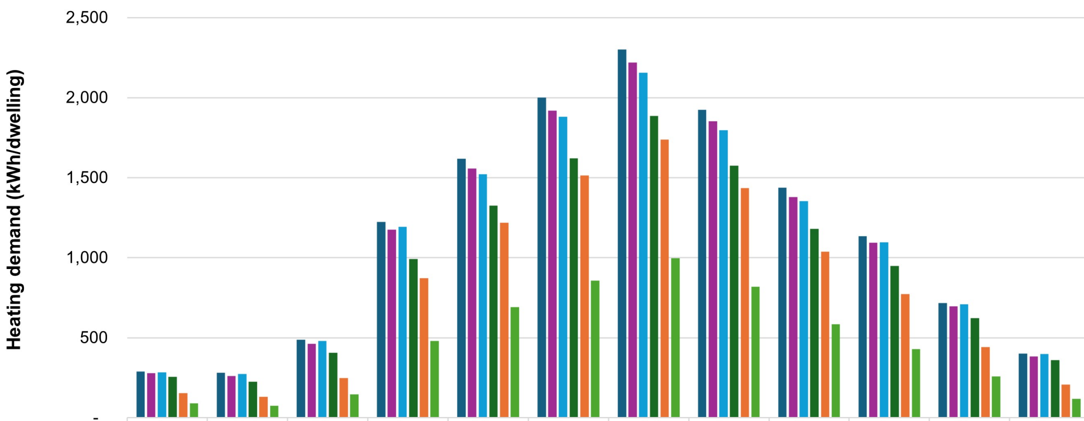
Table 3.25: Impact of substituting wood-burning stoves with pellet stoves on heating demand.

Efficiency of the heating system	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
70%	15,381	214.2
72%	15,319	213.3
74%	15,261	212.5
76%	15,206	211.7
78%	15,153	211.0
80%	15,103	210.3
82%	15,056	209.6
84%	15,011	209.0

- **Total reductions**

This section examines the potential impact on heating demand when measures such as roof insulation, wall insulation, floor insulation, and double glazing are applied concurrently to the reference dwelling. These measures adhere to the minimum standards prescribed for the building envelope as outlined in the thermal regulations for thermal zone 5. Consequently, the insulation thicknesses for the roof, walls, and floors are 120 mm, 50 mm, and 80 mm, respectively. Furthermore, a separation of 8 mm between the panes is considered for the double glazing.

Figure 3.19 illustrates the impact of individual interventions independently, as well as the comprehensive set of measurements concurrently applied to the reference dwelling (baseline). The results indicate that the concurrent application of all these interventions could lead to an annual reduction in heating demand of up to 46.5%. Figure 3.19 also facilitates the identification of strategies that exert the most substantial influence on the reduction of heating demand. Roof insulation emerges as having the most pronounced effect, followed by wall insulation. In contrast, floor insulation and the implementation of double glazing exhibit only marginal contributions. Thus, this analysis provides a framework for informed decision-making regarding the adoption of strategies to confront energy poverty.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	290	281	488	1,224	1,619	2,000	2,301	1,924	1,438	1,135	717	401
Double glazing (8mm gap)	278	262	463	1,175	1,558	1,918	2,221	1,854	1,380	1,095	696	384
Floor insulation (80mm)	285	273	480	1,194	1,521	1,882	2,156	1,798	1,355	1,097	710	399
Wall insulation (50mm)	255	225	407	992	1,326	1,622	1,887	1,576	1,181	950	623	361
Roof insulation (120mm)	155	132	247	872	1,220	1,514	1,739	1,435	1,039	773	441	207
Total reductions	90	75	146	481	692	858	999	820	584	430	258	118

Months

Figure 3.19: Impacts of interventions to mitigate energy demand on heating.

3.3.3.2 Thermal zone 7

- **Roof insulation**

The effect of incorporating roof insulation in the reference dwelling located in thermal zone 7 is presented in Table 3.26. Various insulation thicknesses, ranging from 40 to 200 mm, were analyzed, resulting in energy reductions between 17.7% and 26.0%. According to the thermal regulation proposed by the Ministry of Housing, the maximum recommended U-value for roofs in thermal zone 7 is 0.25 W/m^{2}K (see Section 1.5.5.1). Consequently, it is recommended to implement an insulation thickness of 160 mm to meet this standard, achieving a U-value of 0.23 W/m^{2}K, which is below the required threshold. This enhancement results in a 25.3% reduction in the heating demand.

Although it is essential to recognize that adding insulation greatly reduces heating energy requirements, the incremental advantage decreases as the insulation thickens (refer to Figure 3.20). This insight is vital for determining the most cost-effective approach, especially in scenarios where the focus is on providing solutions for low-income households and cost is a critical factor.

Table 3.26: Impact of incorporating roof insulation in the reference dwelling on heating energy demand.

Thickness (mm)	Rt (m^2K/W)	U-value (W/m^2K)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
0	0.45	2.23	32,292	449.6
40	1.4	0.71	26,586	370.2
60	1.88	0.53	25,706	357.9
80	2.35	0.43	25,156	350.2
100	2.83	0.35	24,775	345.0
120	3.31	0.30	24,492	341.0
140	3.78	0.26	24,294	338.3
160	4.26	0.23	24,125	335.9
180	4.73	0.21	23,997	334.1
200	5.21	0.19	23,894	332.7

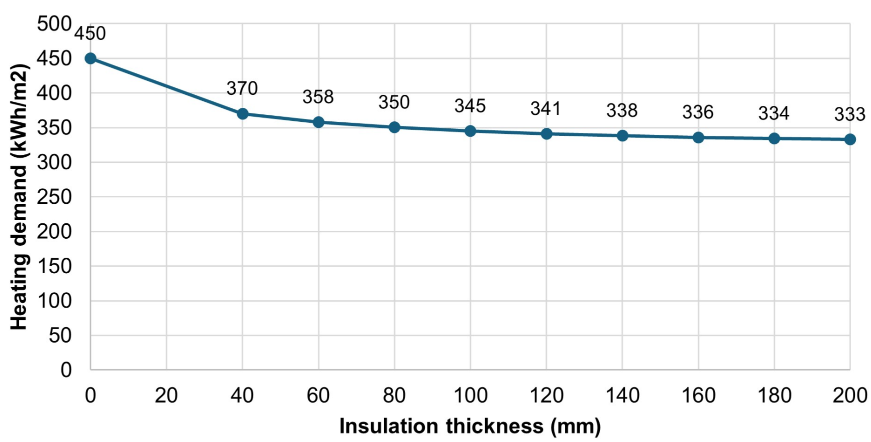
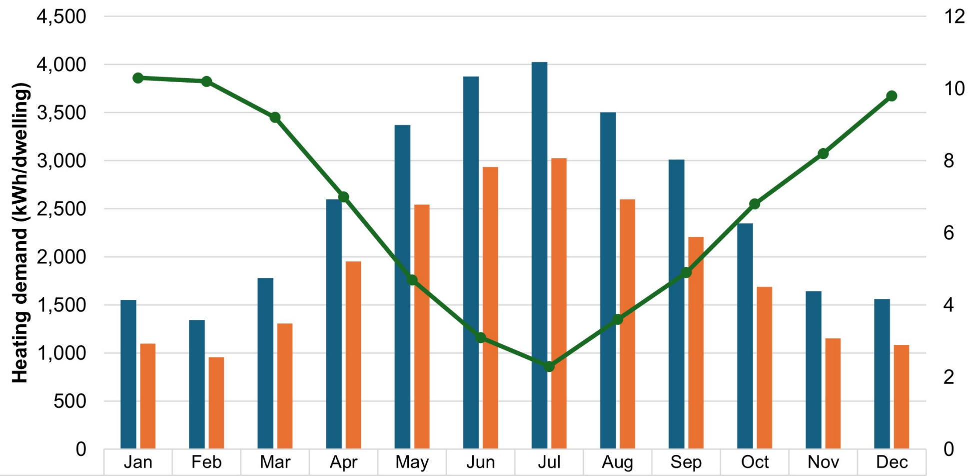


Figure 3.20: Energy demand for heating with the addition of roof insulation.

Figure 3.14 presents a comparative analysis of the annual demand for heating energy for the baseline dwelling, represented by blue bars, and a dwelling incorporating a roof insulation with a thickness of 160mm, indicated by orange bars. The observed data elucidate the impact of incorporating roof insulation, especially during the winter months, when the average outdoor temperature can decrease to 2.3°C.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (non-insulated roof)	1556	1345	1782	2601	3371	3878	4028	3503	3011	2348	1645	1564
Insulated roof (160mm).	1100	957	1307	1954	2544	2938	3028	2600	2209	1690	1152	1087
Average Outdoor Temperature (°C)	10.3	10.2	9.2	7	4.7	3.1	2.3	3.6	4.9	6.8	8.2	9.8

Months

Figure 3.21: Analysis of heating demand variations between baseline and roof-insulated dwelling.

- **Wall insulation**

The impact of incorporating wall insulation within the reference dwelling is illustrated in Table 3.27. An analysis of various insulation thicknesses, ranging from 20 to 80 mm, indicated energy reductions between 11.8% and 20.4%. According to the thermal regulation proposed by the Ministry of Housing, the maximum recommended U-value for walls in thermal zone 7 is 0.6 W/m²K (see Section 1.5.5.1). Consequently, it is recommended to implement an insulation thickness of 60 mm to meet this standard, achieving a U-value of 0.56 W/m²K, which is below the required threshold. This enhancement results in an 18.8% reduction in heating demand.

It is imperative to recognize that while the addition of insulation decreases the energy required for heating, increasing the thickness beyond a certain point does not result in substantial reductions in energy demand (see Figure 3.22). This knowledge is vital to formulate the most cost-effective strategy, particularly for households with limited financial resources where expenditure is a primary concern.

Table 3.27: Impact of incorporating wall insulation in the reference dwelling on heating energy demand.

Thickness (mm)	Rt (m^2K/W)	U-value (W/m^2K)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
0	0.33	3.03	32,292	450
20	0.81	1.23	28,497	397
30	1.06	0.94	27,608	384
40	1.3	0.77	27,000	376
50	1.54	0.65	26,561	370
60	1.78	0.56	26,214	365
70	2.02	0.50	25,936	361
80	2.27	0.44	25,711	358

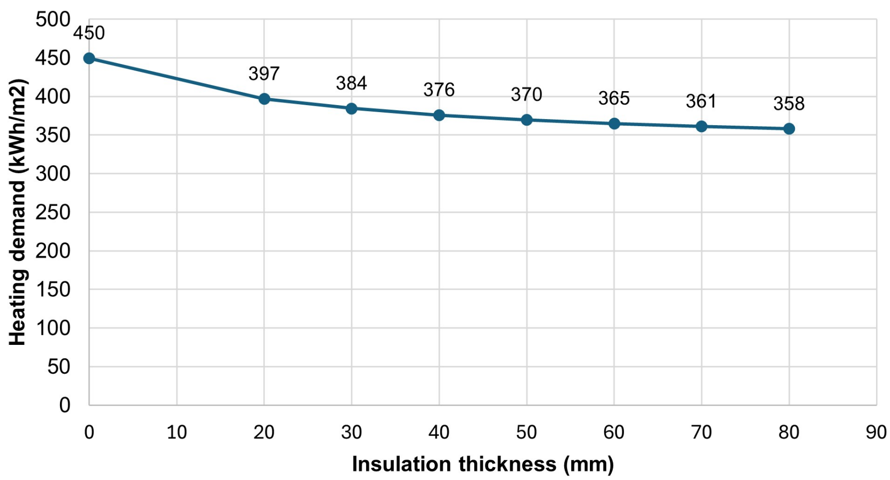
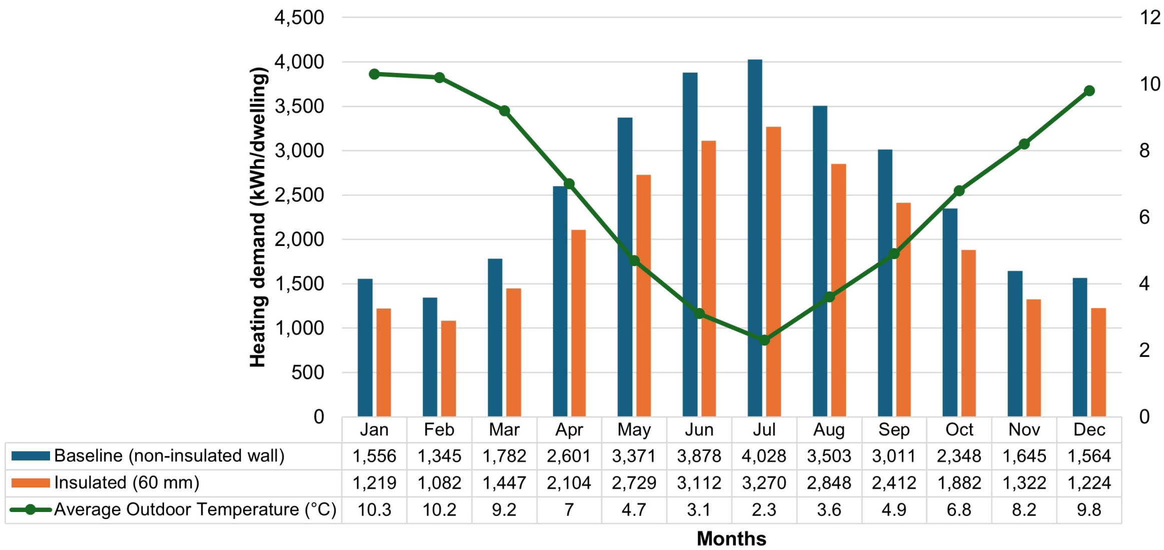


Figure 3.22: Energy demand for heating with the addition of wall insulation.

Figure 3.23 presents a comparative analysis of annual heating energy requirements for the standard home, depicted by blue bars, in contrast to a home enhanced with 60 mm wall insulation, illustrated by orange bars. The data elucidate the impact of wall insulation, especially during the winter months, when the average outdoor temperature has the potential to decrease to 2.3°C.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (non-insulated wall)	1,556	1,345	1,782	2,601	3,371	3,878	4,028	3,503	3,011	2,348	1,645	1,564
Insulated (60 mm)	1,219	1,082	1,447	2,104	2,729	3,112	3,270	2,848	2,412	1,882	1,322	1,224
Average Outdoor Temperature (°C)	10.3	10.2	9.2	7	4.7	3.1	2.3	3.6	4.9	6.8	8.2	9.8

Figure 3.23: Comparison of heating demand between the baseline and wall insulated dwelling.

- **Floor insulation**

The effect of incorporating floor insulation in the reference dwelling is observed in Table 3.28. An analysis of various insulation thicknesses, ranging from 30 to 140 mm, revealed energy reductions between 5.2% and 9.4%. According to the thermal regulation presented by the Ministry of Housing, the maximum recommended U-value for flooring in thermal zone 7 is 0.32 W/m^{2}K (see Section 1.5.5.1). Thus, it is advisable to implement an insulation thickness of 120 mm to comply with this standard, attaining a U-value of 0.31 W/m^{2}K, which is below the mandated threshold. This improvement results in a 9.1% reduction in the heating demand.

The limited reduction in heating demand can be partially attributed to the configuration within EnergyPlus, where a constant temperature value of the ground is employed (18°C). The constant temperature value may exceed the actual ground temperature, thereby establishing a relatively diminished temperature gradient between the interior environment and the ground. This results in an underestimated calculation of heat loss through the floor, which consequently affects the quantification of the impact derived from the incorporation of floor insulation. Enhancements in the representation of ground temperature by EnergyPlus could potentially improve these results.

When the latter consideration is excluded, the results derived from EnergyPlus reveal only a minor decrease in heating demand attributed to floor insulation. This implies the advisability of favoring alternative strategies to reduce energy demand, thus reducing floor insulation to a lower priority. As illustrated in Figure 3.25, the diminished influence of floor insulation on energy demand is evident year round.

Table 3.28: Impact of incorporating floor insulation in the reference dwelling on heating energy demand.

Thickness (mm)	Rt (m^2K/W)	U-value (W/m^2K)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
0	0.29	3.41	32,292	450
30	1.02	0.98	30,597	426
40	1.26	0.79	30,333	422
50	1.50	0.67	30,133	420
60	1.75	0.57	29,969	417
80	2.23	0.45	29,714	414
100	2.71	0.37	29,519	411
120	3.20	0.31	29,369	409
140	3.68	0.27	29,247	407

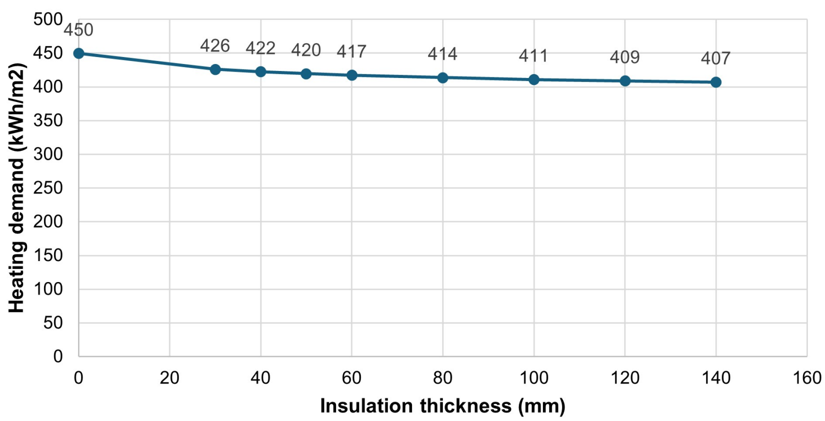


Figure 3.24: Energy demand for heating with the addition of floor insulation.

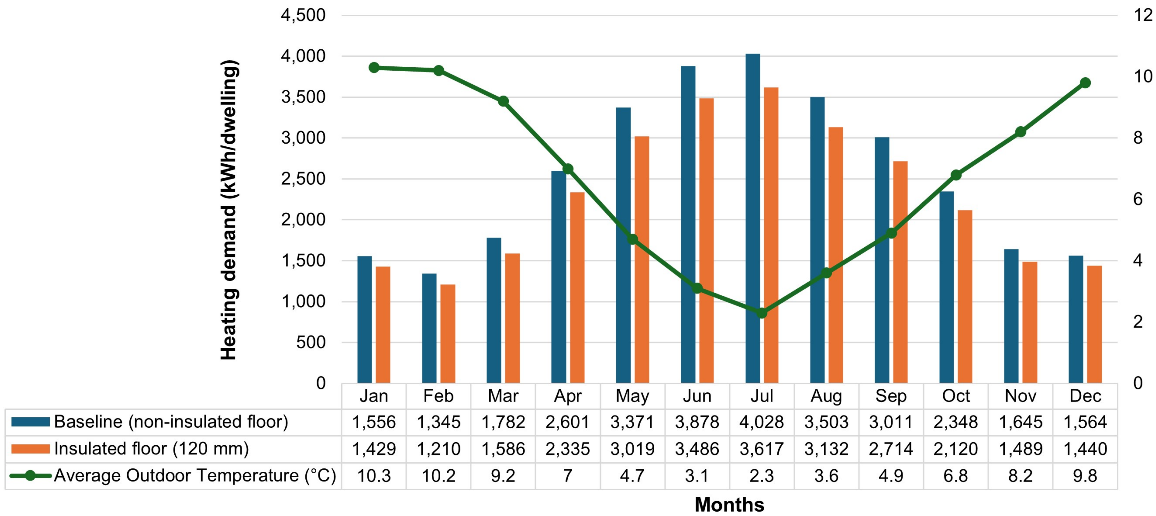


Figure 3.25: Analysis of variations in heating demand between the baseline and the floor-insulated dwelling.

- **Double glazing**

The thermal regulations stipulated by the Ministry of Housing specify a maximum permissible glass surface area in relation to the parameters of the vertical envelope, depending on the type of glazing, single or double. Since the residence already complies with the requirement of a maximum of 12% single glazing regarding the vertical enclosure parameters for thermal zone 7, the reference dwelling has been fitted with double glazing to assess its impact on heating demand.

The impact of incorporating double glazing in the reference dwelling is presented in Table 3.29. This analysis examined various inter-pane thicknesses, ranging from 6 to 15 mm, and reported reductions in heating energy demand between 3.6% and 8.2%. Despite the fact that the effect of replacing single glazing with double glazing is more pronounced than that observed in the reference dwelling in thermal zone 5, the influence depicted in Figure 3.26 remains modest when compared to other enhancements such as roof or wall insulation. This can primarily be attributed to the limited glass surface area relative to the dimensions of the vertical envelope, which constitutes only 10%, leading to minimal heat loss through this component. Furthermore, due to the lack of specific data on glazing for the Chilean housing stock, it was necessary to make assumptions regarding the glazing size. Consequently, the impact on energy demand could be greater if these assumptions underestimated the actual dimensions of the glazing. The reduced influence of double glazing on energy demand throughout the year is also shown in Figure 3.27.

Table 3.29: Impact of incorporating double glazing in the reference dwelling on heating energy demand.

	Thickness (mm)	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
	0	32,292	449.6
Air	6	31,122	433.3
	8	30,761	428.3
	10	30,400	422.2
	12	30,039	417.2
	15	29,639	411.7

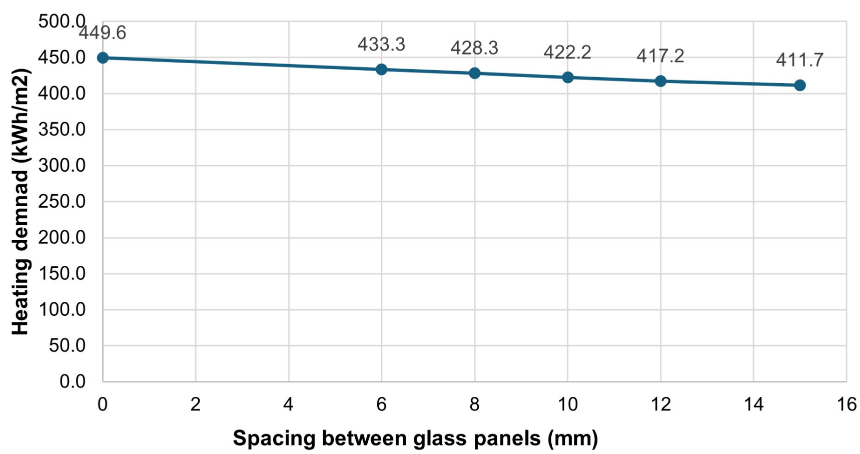
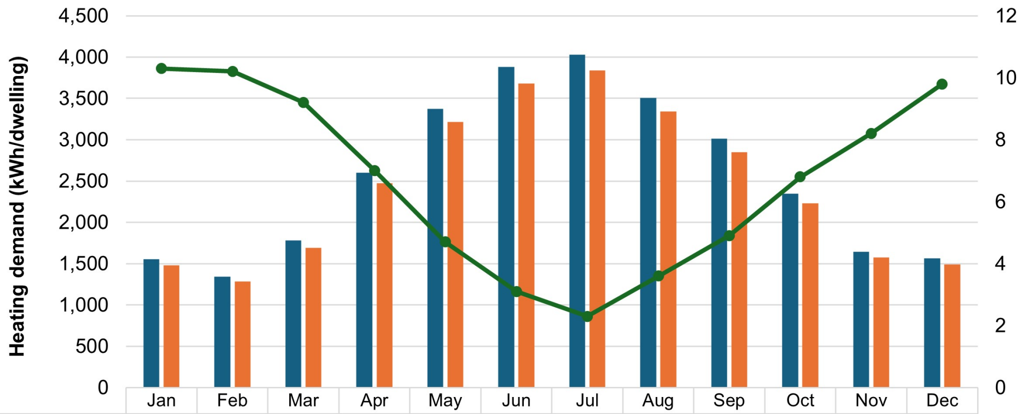


Figure 3.26: Energy demand for heating with the addition of double glazing.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (single glazing)	1,556	1,345	1,782	2,601	3,371	3,878	4,028	3,503	3,011	2,348	1,645	1,564
Double glazing (8mm gap)	1,481	1,285	1,694	2,473	3,212	3,681	3,839	3,343	2,851	2,233	1,577	1,489
Average Outdoor Temperature (°C)	10.3	10.2	9.2	7	4.7	3.1	2.3	3.6	4.9	6.8	8.2	9.8

Months

Figure 3.27: Analysis of variations in heating demand between the baseline and the double-glazed dwelling.

- **Efficiency of the heating system**

This section evaluates the effect of replacing a wood-burning stove with a pellet stove. Initially, the reference residence was modeled with a wood-burning stove that exhibits an efficiency rate of 70%, as indicated by the SAP model [88]. Subsequently, a pellet stove was selected for replacement, with its efficiency, as documented by the Certified Wood Stove Database of the U.S. Environmental Protection Agency (EPA), varying between 70 and 84% [3].

The effect of replacing a wood burner stove with a pellet stove on heating demand is detailed in Table 3.30. The efficiency of the heating system considered in the modeling process ranges from 72 to 84%, demonstrating reductions in the heating energy demand between 0.1% and 0.9%. This indicates that replacing a wood-burning stove with a pellet stove has a negligible impact on the reduction of heating energy consumption, which may be attributed to the minimal variation in the efficiency of both heating systems.

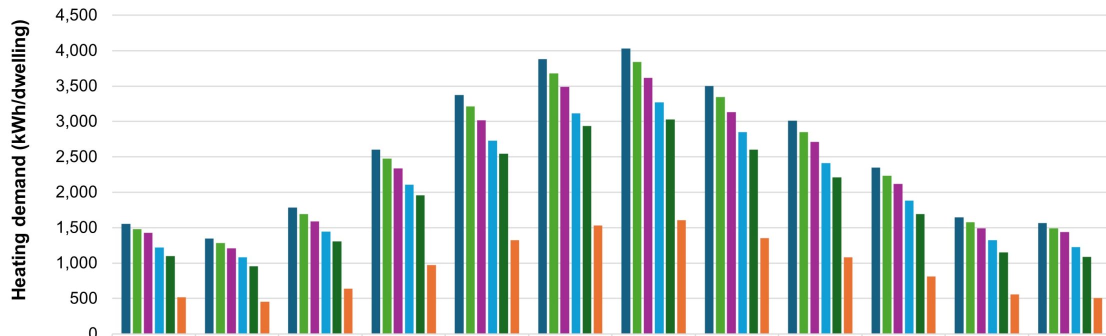
Table 3.30: Impact of substituting wood-burning stoves with pellet stoves on heating demand.

Efficiency of the heating system	Annual heating demand (kWh/year)	Heating demand per square meter(kWh/m^2)
70%	32,292	449.6
72%	32,244	449.0
74%	32,200	448.3
76%	32,156	447.7
78%	32,117	447.2
80%	32,078	446.6
82%	32,039	446.1
84%	32,006	445.6

- **Total reductions**

This section examines the potential impact on heating demand when measures such as roof insulation, wall insulation, floor insulation, and double glazing are applied concurrently to the reference dwelling. These measures adhere to the minimum standards prescribed for the building envelope as outlined in the thermal regulations for thermal zone 7. Consequently, the insulation thicknesses for the roof, walls, and floors are 160 mm, 60 mm, and 120 mm, respectively. Furthermore, a 8mm separation between the panes is considered for double glazing.

Figure 3.28 illustrates the impact of individual interventions independently, as well as the comprehensive set of measurements applied concurrently to the reference dwelling (baseline). The results indicate that the concurrent application of all these interventions could lead to an annual reduction in heating demand of up to 57.9%. Figure 3.28 also facilitates the identification of strategies that exert the most substantial influence on the reduction of heating demand. Roof insulation emerges as having the most pronounced effect, followed by wall insulation. In contrast, floor insulation and the implementation of double glazing exhibit only marginal contributions. Thus, this analysis provides a framework for informed decision-making regarding the adoption of strategies to confront energy poverty.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline	1,556	1,345	1,782	2,601	3,371	3,878	4,028	3,503	3,011	2,348	1,645	1,564
Double glazing (8mm gap)	1,481	1,285	1,694	2,473	3,212	3,681	3,839	3,343	2,851	2,233	1,577	1,489
Floor insulation (120mm)	1,429	1,210	1,586	2,335	3,019	3,486	3,617	3,132	2,714	2,120	1,489	1,440
Wall insulation (60mm)	1,219	1,082	1,447	2,104	2,729	3,112	3,270	2,848	2,412	1,882	1,322	1,224
Roof insulation (160mm)	1,100	957	1,307	1,954	2,544	2,938	3,028	2,600	2,209	1,690	1,152	1,087
Total	518	451	640	971	1,321	1,529	1,607	1,353	1,082	812	556	504

Months

Figure 3.28: Effects of energy demand mitigation interventions on heating requirements.

CHAPTER 4

Discussion

4.1 Main factors contributing to EP in Chile

This section discusses the various factors that contribute to energy poverty in Chile, with a focus on low income, educational attainment, property tenure, energy prices, and sociodemographic variables such as household size and composition.

4.1.1 Incomes

Low income is an important factor of vulnerability. Low-income households tend to spend a higher portion of their income on energy bills when compared to other socio-economic groups, despite of being lower energy consumers. Chilean low- income households spend on average from 9 to 24% of their income on energy bills in MR, and 10 to 27% in the rest of the regions. On contrast, wealthier households spend on average from 1.6 to 4% in MR, and 1.9 to 4.5% in the rest of the regions, even when their energy bills are more than double of low-income energy bills. In addition, the cost of the unit of energy considered is the same for the whole population within a region because the energy company considers a unique tariff for all residential consumers. So, these results could give an idea of how low-income households tend to reduce their energy bills, and therefore their thermal comfort when compared to medium and high-income households.

Furthermore, an analysis of household income data by thermal zones reveals economic disparities and identifies regions that are likely to encounter difficulties regarding energy expenditure. Thermal zone 3, corresponding to the metropolitan area, exhibits the highest median income, while thermal zone 5 in the southern region demonstrates the lowest. Although income is recognized as a significant vulnerability factor that influences energy expenditure, the correlation between income and energy expenditure was found to be minimal. Consequently, these findings suggest that while there exists a certain degree of relationship between income and energy expenditure, additional factors are likely to contribute to or impact energy expenditure.

4.1.2 Educational attainment

The educational attainment of adults within a household is correlated with income levels and, consequently, with energy poverty. A lower level of educational attainment adversely affects income, thus increasing the likelihood of households being affected by energy poverty. In Chile, 60% of the households affected by energy poverty (EP) in the Metropolitan Region (MR) have completed primary and secondary education, while 33% have pursued a professional or technical career. In other regions, the percentage of households with only primary and secondary education increases to 76%, with only 18% having followed a professional or technical career. In addition, challenges in meeting energy payments can impair the educational performance of individuals engaged in academic endeavors, thus negatively influencing their educational attainment. Certain households implement strategies such as restricting energy use to one specific room to maintain a low-cost energy bill. This forces all residents to occupy the same room, leading to distractions during homework and overcrowding, which adversely affects the potential educational attainment of children. In Chile, households located in thermal zones 1 to 3 typically heat only the rooms they are occupying, unlike other parts of the country where heating the entire house is more common. However, a notable proportion of households in the southern regions also heat only the rooms in use: this represents 38% of households in thermal zone 4, 24% in thermal zone 5, 20% in thermal zone 6, and 32% in thermal zone 7. Therefore, a portion of these households may have members involved in educational activities who are potentially affected by overcrowding.

Thus, reduced educational attainment among household members typically results in reduced income levels, which increases the likelihood that households experience energy poverty. This, in turn, negatively impacts the educational prospects of their children. As a result, this scenario has the potential to become a cyclic pattern that affects subsequent generations, potentially perpetuating over time. However, while there is a strong correlation between educational attainment and income, the association between income and energy poverty is less pronounced. This is attributed to the multifactorial nature of energy poverty, which cannot be solely explained by income levels.

4.1.3 Property tenure

Property tenure is a variable that has been associated with energy poverty (EP). Low-income households have been shown to be more susceptible to EP due to the frequent absence of home ownership. However, in Chile, evidence suggests that renters are not more predisposed to EP than homeowners. In the metropolitan region, the proportion of renters experiencing EP is identical to that of homeowners (16.5%), indicating an equivalent probability of being affected by EP for both groups. In contrast, in other regions, the proportion of homeowners in EP is 10. 1%, while the proportion of renters is 5.5%. Thus, both homeowners and renters may encounter financial constraints that warrant addressing to mitigate energy poverty.

4.1.4 Energy prices

Energy prices are a key determinant in households' capacity to manage their energy expenditures. In recent years, there has been a notable increase in global energy prices. In Chile, the average market price of electricity for residential consumers was frozen from 2020 to 2025, and despite recent increases, projections indicate that electricity rates are expected to increase by an average of approximately 62% by January 2025. Gas prices have also witnessed substantial increases in 2021, with national increases ranging from 14% to 32%. The highest electricity and gas prices have been recorded in the southern regions of the country, specifically thermal zones 5, 6, and 7. Consequently, the high costs of electricity and gas impose a significant burden on households in these regions, making them alarmingly vulnerable to the harsh realities of energy poverty. This vulnerability starkly highlights the geographical areas within the country that face the most severe challenges when grappling with the ever-escalating energy prices,

4.1.5 Socio-demographic factors

Socio-demographic variables, including household size and family composition, are pertinent to energy poverty (EP). With the addition of more household members, energy expenditure tends to increase; however, this rise is not linear, as members often share activities and services such as heating and energy utilized for cooking, thereby reducing the cost per capita. In Chile, the households most affected by EP are those consisting of one to three members. EP has a pronounced effect on the elderly population, currently impacting approximately 390,000 older adults. In particular, this demographic accounts for 77% and 64% of single-person households affected by EP in the metropolitan and regional areas, respectively. This phenomenon may be attributed to factors such as inefficient energy performance of their homes, under-occupation, or limited financial resources (low income). Therefore, it becomes imperative to recognize the elderly population as a critically vulnerable demographic that urgently deserves prioritization in the formulation and implementation of policies designed to combat energy poverty.

4.2 The current state of energy poverty in Chilean residential housing.

In this section, the current state of energy poverty in Chilean residential housing is discussed. The ten per cent rule was used to assess the present state of energy poverty within the Chilean residential sector due to the possibility of obtaining data on household income and energy expenditure in databases such as the Family Budget Survey (EPF) and the Uses of Energy in the Chilean Housing Survey. Calculating EP using alternative metrics such as the Minimum Income Standard (MIS) and Low-income High Cost (LIHC) was not feasible due to the absence of essential data. Specifically, MIS requires information on minimum living costs, while LIHC requires the availability of energy and income equivalization factors, none of which are currently accessible in the databases. In addition, both metrics require additional input for the calculation of required fuel costs. Therefore, it is recommended that future studies focus on investigating these variables within the Chilean context to enable the application of these metrics. Furthermore, it is imperative for the EPF to collect additional data necessarily for modeling fuel costs, as this source could potentially consolidate modeled energy requirements, income, and housing costs.

As previously articulated, the ten per cent rule metric was applied. According to the findings derived from the 2017 EPF, 0.8 million households in Chile, representing 12% of the total, were affected by the EP. In contrast, the 2018 survey on energy consumption in Chilean households indicated that 1.4 million households, or 19% of the total, were affected by this condition. The discrepancy between these figures may arise from differences in methodologies employed by data collectors, which exhibit variations in the classification of information by geographic region, as well as in the methodologies utilized to determine energy expenditures, resulting in divergences in the calculation processes.

The methodologies utilized by data collectors diverge. The survey of energy uses in Chilean housing collects data to inform a model that estimates energy requirements and consequently calculates fuel costs. This model is based on several assumptions and simplifications of physical principles, which can lead to an overestimation of household energy requirements. This potential overestimation could indicate a miscalculation in assessing how occupants meet their comfort needs, resulting in inflated figures in EP.

In contrast, the EPF acquires empirical data on energy consumption, yet it also notes several observations. For example, the EPF faces limitations due to the methodology used in conducting the survey, which is administered at different intervals throughout the year. Consequently, if data are collected outside the heating season, the energy expenditure associated with heating can be underestimated, leading to a possible underestimation of the number of people experiencing energy poverty. Furthermore, the EPF lacks the disaggregation of common expenditures, which complicates the allocation of funds directly tied to household energy consumption. As a consequence, common expenses have been omitted from the calculations, likely resulting in an underestimation of energy poverty. This occurs because expenditures dedicated to heating by households with communal expenses, representing 19% of households in the metropolitan region, are not taken into account. Despite discrepancies in the calculation methods, comparing the findings from both sources elucidates the study's overarching conclusions and facilitates comprehension of the potential variability in the population impacted by energy poverty.

The classification of information by geographic region varies according to the source. The data provided by the 2017 EPF is divided between the metropolitan region and other regions, resulting in the loss of detailed information for each specific region. This is of significance due to the substantial variation in climate zones, which leads to differences in the nature and magnitude of energy consumption. Furthermore, a consequence of this limitation is that the population in the Metropolitan region will be represented with relative accuracy, while greater error margins will exist for the other regions. However, the lack of detailed regional information noted in the 2017 EPF was addressed in the 2022 iteration, which systematically organized data by the northern and metropolitan regions, as well as the central and southern zones. Meanwhile, the classification scheme used in the 2018 study on energy consumption in the Chilean housing survey demonstrated a more effective method to visualize the results in the seven thermal zones.

This investigation has identified two notable patterns. Firstly, through an analysis of the 2017 and 2022 EPF data, there is a marked increase in the number of households affected by EP within the nation in recent years, corresponding to the concurrent increase in fuel prices during the same time frame. Secondly, the results provide critical insight into the thermal zones necessitating prioritization to mitigate EP, highlighting primarily the thermal zones located in the southern regions of the country, such as the thermal zones 5, 6, and 7, which have shown a higher proportion of households impacted by EP. Households in these thermal zones experience increased energy requirements due to their geographical latitude, leading to exposure to more severe climatic conditions, characterized by cold and precipitation. Consequently, these households are compelled to allocate more than ten percent of their income to energy expenditures.

4.3 Chilean archetypes

This section provides an analysis of the sources of information and archetypes introduced in Sections 1.6 and 2.3, along with a comparison with previous studies specifically related to Chilean archetypes.

4.3.1 Information sources

The selection of pertinent variables to predict energy demand is one of the most challenging aspects in the development of archetypes. This challenge arises from the direct impact that the quality and relevance of the input data exert on the predictive accuracy of the model. Section 1.6 indicates that several data sources describe Chilean residential buildings and their occupants, and the quality of the data is adequate to derive archetypes. However, improvements in certain areas could mitigate the uncertainties associated with specific parameters. These parameters include dwelling attributes such as geometries (floor area and volume), window area and glazing type, construction year, insulation level, orientation, and type of heating system fuel. In addition, a deeper understanding of occupant behaviors, such as the schedule and duration of heating use, would enhance the predictions of energy demand and greenhouse gas emissions.

4.3.2 Archetypes

The Chilean housing stock is characterized through the use of archetypes, as detailed in Section 2.3. The development of these archetypes was carried out using a bottom-up approach, drawing upon data derived from censuses and energy surveys. The number of archetypes is indicative of the level of resolution offered by the data sets and the attributes of the selected parameters. Therefore, identifying key parameters is crucial for the classification of housing stock. In this research, energy demand was integrated into the selection process; therefore, its influence must be recognized when these archetypes are used to evaluate alternative criteria. The classification took into account various factors, including climatic conditions, building types, wall construction materials, construction periods, and floor area.

The findings indicate that a total of 18 archetypes collectively constitute 80% of the Chilean housing stock, with a mere four archetypes composing approximately 50%. The two most prevalent archetypes pertain to a semi-detached, uninsulated house constructed from clay bricks and a detached, uninsulated house constructed of wood, accounting for 19% and 15% of the housing stock, respectively. Furthermore, the housing stock was analyzed according to thermal zones. For instance, within thermal zone 5, situated in the southern region of Chile, results revealed that seven archetypes make up approximately 80% of the housing stock specific to this zone, with only four of these archetypes comprising 68%, predominantly featuring uninsulated detached and semi-detached houses constructed with wood. The intent behind determining the proportion or sizing of the archetypes by thermal zone was to enable an appreciation of the diversity in the building stock throughout the country and to assess the significance of each archetype within each thermal zone.

4.3.3 Archetypes comparison

In Section 2.3.3, a study conducted by the University of Nottingham in 2019 [142] is referenced, where various archetypes and subclassifications were identified. Notwithstanding, this study displayed methodological inaccuracies, resulting in incorrect estimations regarding the number of dwellings per archetype and the proportion of each archetype relative to the overall housing stock. Consequently, it is not suitable to compare the results of this research with those of the study in question.

As an alternative, the research conducted by the Pontificia Universidad Catolica de Valparaiso, commissioned by the Ministry of Housing (MINVU) as mentioned in Section 2.3.3, will serve as a reference. This research identifies 13 archetypes that encapsulate the Chilean housing stock, comprising 5 detached houses, 4 semidetached or terraced houses, and 4 apartments. This identification reflects a slight reduction from the number of archetypes proposed herein, justified by the similar methodologies of classification, categorization, data manipulation, and data analysis employed in both studies. The study also encountered issues related to dataset quality and noted similar typographical and coding errors, although the criteria for data cleaning and selecting representative values differ. Moreover, while the geometry of the archetypes is comparable in both investigations, variations exist in the number of storeys.

Section 2.3.5.1 delineates the classification process, indicating that five categories or key parameters were employed, in contrast to the nine utilized in MINVU's process. While both investigations account for pertinent parameters necessary for the calculation of energy use related to heating, the selection criteria for the variables in MINVU's study remain unexplained. Noteworthy similarities were observed in the classification process, including the designation of thermal zones as the primary factor, which offers an advantage due to its impact on energy consumption. Additionally, variables such as geometry, building material, year of construction, and housing size were considered.

However, notable discrepancies were identified, particularly in the sources of information analyzed and the categorization methodologies employed for data aggregation. The MINVU integrated two supplementary datasets: the first originating from the council tax department (SII), and the second pertaining to properties undergoing a voluntary certification process to obtain an energy label based on design features (CEV). The primary data set lacked additional information, while the latter provided data on windows of 37,724 properties constructed after 2009, reflecting a mere 0.7% of the existing housing stock. The authors did not undertake an assessment of the dataset's quality; however, specific details such as the material of the window frame are available. However, there exists a potential bias against older properties, as the dataset predominantly comprises newer constructions that generally incorporate more energy-efficient measures. Hence, the application of these data may pose challenges, necessitating an uncertainty analysis.

Moreover, this study has identified variations in the classification of dwellings based on floor area. Three distinct categories of floor area were analyzed. However, this classification is deemed redundant due to the weak correlation between energy consumption and the floor area of residences across all thermal zones of the country, as discussed in Section 2.3.4.5. This suggests that the variation in energy expenditure concerning floor area is minimal.

Ultimately, although the MINVU research has demonstrated a generally robust development of the methodology, the final results encountered challenges in interpretation. This is due to the manner of reporting, which poses difficulties in accurately quantifying the number of dwellings by archetype and thermal zone, as well as in determining the proportion of each archetype relative to the overall housing stock within each thermal zone.

4.4 Energy modeling

This Section examines the input used in the model, the modeling tool, the interpretation of the results related to the incorporation of energy efficiency measures into the housing stock, and a comparative analysis with the findings from other studies.

4.4.1 Model inputs

EnergyPlus operates as a deterministic model that employs a singular set of input parameters to generate a single prediction. However, by systematically varying these inputs within predefined boundaries and executing numerous calculations, it becomes feasible to investigate the uncertainty associated with the outputs, such as the energy demand necessary for heating. Therefore, understanding the uncertainty in the outputs requires awareness of the inherent uncertainty in the inputs. In situations where information about certain inputs is scarce, assumptions must be made. This section examines the constraints associated with the selection and application of input data within the model and their consequent impact on the results.

4.4.1.1 Weather data and local environment

Due to the restricted availability of weather data across various locations, the simulations were conducted utilizing meteorological data from the capital city of each region, which serves as the primary population hub. Consequently, this simplification may limit the accuracy in representing the diverse climatic conditions inherent to each region. However, expanding the climatic characterization will necessitate a considerably higher number of simulations to satisfy the convergence criteria, thereby leading to augmented computational demands in terms of time and resources.

4.4.1.2 Period of construction

In Chile, the current deficiency in documentation concerning the chronological age of buildings necessitates reliance on estimations derived from data sourced from the Censuses conducted in 2002, 2012, and 2017. The complete housing stock has been segmented into three categories to evaluate their degree of compliance with the thermal specifications mandated by the Ministry of Housing. It is assumed that all residences constructed prior to 2001 were devoid of insulation, notwithstanding the possibility that some may have adopted insulation independently. Considering that the 2002 Census was conducted in March 2002, a mere three months subsequent to 2001, this date has been adopted as the inception point for the initial stage of thermal regulation. Accordingly, the quantification of dwellings constructed by 2007 has been estimated by means of interpolation.

It is pertinent to acknowledge a potential limitation inherent within this methodology, namely the potential for data lag. For instance, there may be a delay extending over several years before housing approved under the new regulation is completed. Conversely, dwellings authorized under the previous regulation may take several years to be finalized, thereby resulting in their classification as new dwellings within the post-regulation phase.

4.4.1.3 Infiltration rate

The infiltration rate within the Chilean housing stock has not been empirically determined; consequently, values from the ASHRAE Fundamentals Handbook, Chapter 26, have been employed for modeling purposes. This reference suggests an infiltration rate of 0.1 ach for new, energy-efficient dwellings and 0.9 ach for older, low-income residences. Considering that households experiencing energy poverty predominantly occupy older, low-income housing, a standard infiltration design flow rate of 0.9 ach has been adopted as the baseline for a typical dwelling. However, to address this knowledge deficit, more data collection is imperative. Pressurization tests employing the blower door method, which is capable of calculating an infiltration rate, have been extensively applied in countries such as France, the United States and the UK. Regulations, guidelines and protocols are available for this purpose, and some have already been implemented in Chile. In addition, the creation of an open source national platform is vital for synthesizing these data, the results of the tests, and the additional physical parameters of the housing stock.

4.4.1.4 Floor area

The residential floor area utilized for the development of the archetypes was sourced from the 2018 survey on energy use in Chilean housing. This survey provides median dwelling areas classified by house type, geometric configuration, and wall material. As a weak correlation between energy expenditure and the floor area of residences was identified across all thermal zones of the country, it suggests only a limited variation in energy expenditure concerning floor area. Consequently, for simplification and to minimize the number of simulations, this variable is held constant, with discrete values assigned to the archetypes. An additional parameter that could be integrated into future surveys is the height of the dwelling, given its significance in calculating room volume.

4.4.1.5 Dwelling orientation and window area

The orientation of the dwelling represents an area of epistemic uncertainty due to the lack of available information. Therefore, alternatively it was considered that the house faced four cardinal directions (north, south, east, and west) and the average energy demand for heating was calculated considering all these directions. The model assumes that the residence is fully exposed to sunlight, thus excluding any external shading that might obstruct solar radiation.

In the absence of detailed information regarding the dimensions and positioning of window areas, it is assumed that standard windows, measuring 1.35 meters by 1.2 meters, are allocated in spaces such as the living room, dining room, and bedrooms. A smaller window size, measuring 0.5 by 0.8 meters, has been selected for the bathroom. The type of window used for the standard house (baseline) is characterized by a single glazing window of 6 mm thickness, featuring a metal frame, with a U-value of 5.69 W / m2K. This choice reflects the most common solution in the country.

It is important to note that if the actual window area exceeds that proposed in the model, the model would underestimate the demand for heating energy due to the increased heat loss through the windows. As these factors are not comprehensively captured by national censuses or other surveys, incorporating them into future data collection efforts would be beneficial.

4.4.1.6 Time of heating use

The duration of heating utilization constitutes a crucial parameter in calculating the heating energy demand. In Chile, the 2018 survey on energy use in Chilean housing provided pertinent data regarding the number of daily hours and months of heating usage, disaggregated by thermal zones, which exhibit substantial variation across different zones. However, a subsequent study with an expanded sample size specific to each thermal zone is warranted, along with a more precise characterization of the heating use patterns. This includes, for instance, distinctions in heating use between weekdays and weekends, as well as a more accurate depiction of daily schedules.

4.4.2 The modeling tool

In this study, EnergyPlus is used as a dynamic energy simulation tool to model heating systems within buildings situated in thermal zones 5 and 7. The essential attributes of EnergyPlus, which encompass its origin, operational mechanisms, necessary inputs, and advantages, are discussed in Section 2.4.2.2. Some limitations of this tool were identified during the computational processes. In particular, EnergyPlus presumes a constant ground temperature of 18°C throughout the year, which can considerably affect the accuracy of energy prediction. Although there has been a documented reduction in heating energy demand due to the implementation of floor insulation in both thermal zones, the reductions could be even more pronounced if the actual ground temperatures specific to these zones were considered. This observation stems from the fact that the temperature difference between the ground floor and the indoor environment, particularly in these zones characterized by lower external temperatures and consequently lower ground temperatures, could lead to more substantial reductions in heating demand with improved floor insulation. There are speculations that the limited development of EnergyPlus on floor heat transfer could be due to the complexities inherent in floor heat transfer and soil modeling techniques [134]. This limitation was not addressed in this study and merits consideration in future research endeavors.

4.4.3 Predicted outcomes

The most significant reduction in energy demand is achieved by incorporating insulation into the roof in both thermal zones. This is attributed to the fact that the roof represents the largest surface area exposed to the external environment; thus, the addition of insulation effectively mitigates heat loss. The substantial reduction in heat loss is mainly due to the composition of the uninsulated roof, which is composed solely of fiber cement tiles attached to a wooden frame structure. This structure, in turn, supports a thin OSB wood board, and the horizontal ceiling is constructed from a wooden frame clad with a standard plasterboard. Consequently, the total thermal transmittance of the roof, known as the U-value, is determined to be 2.23 W/m^2K.

In thermal zone 5, the integration of roof insulation ranging from 40 to 200 mm into the baseline dwelling results in energy reductions between 19.0% and 28.5%. Specifically, compliance with thermal regulations requires the installation of 120 mm of glass wool insulation, which reduces the U value to 0.30 W/m2K and results in a reduction in energy demand of 26.3% due to improved thermal resistance. In contrast, in thermal zone 7, the addition of roof insulation within the same range to baseline dwellings results in energy savings that fluctuate from 17.7% to 26.0%. To meet the requirements suggested by the thermal regulations in this zone, 160 mm of glass wool insulation is required, which decreases the U-value to 0.23 W/m^{2}K and leads to a reduction in energy demand by 25.3%.

The impact of wall insulation on the reduction of heating energy demand is notably less significant compared to that of roof insulation. The exterior wall of the reference dwelling consists of an outer layer of radiata pine wood affixed to a frame comprised of the same wood species. This structure is further integrated with an oriented strand board (OSB) and conventional plasterboard, resulting in a thermal transmittance (U-value) of 2.45 W/m^{2}K. An analysis of wall insulation incorporation was conducted in thermal zone 5, with insulation thicknesses ranging from 20 to 80 mm yielding reductions between 10.5% and 18.0%. For instance, the addition of a 50 mm insulation layer results in a U-value of 0.65 W/m^{2}K, effecting a 15.7% reduction in heating demand. Conversely, in thermal zone 7, insulation thicknesses ranging from 20 to 80 mm produce energy reductions between 11.8% and 20.4%. Specifically, an insulation thickness of 60 mm facilitates achieving a U-value of 0.56 W/m^{2}K and leads to an 18.8% reduction in heating demand.

The impact of integrating floor insulation in the reference dwelling was evaluated within thermal zones 5 and 7. The ground floor is composed of a reinforced concrete slab with a thickness of 120 mm, characterized by a total thermal transmittance (U-value) of 3.41 W/m^{2}K. In thermal zone 5, varying insulation thicknesses ranging from 30 to 140 mm demonstrated energy reductions between 0.5% and 1.5%. An insulation thickness of 80 mm is recommended to adhere to thermal regulations, whereupon the U-value achieved is 0.45 W/m^{2}K, corresponding to a 1.0% reduction in heating demand. Conversely, in thermal zone 7, the addition of insulation with thicknesses between 30 and 140 mm resulted in energy reductions ranging from 5.2% to 9.4%. Consequently, an insulation thickness of 120 mm is recommended to meet this standard, resulting in a U-value of 0.31 W/m^2, thereby effecting a 9.1% decrease in heating demand.

The constrained reduction in heating demand due to the addition of floor insulation can be partially ascribed to the configuration within EnergyPlus, wherein a constant temperature value of the ground is utilized (18°C). This constant temperature value may surpass the actual ground temperature, thereby creating a relatively diminished temperature gradient between the interior environment and the ground. Consequently, this could lead to an underestimated calculation of heat loss through the floor, which affects the quantification of the impact derived from the incorporation of floor insulation. Therefore, advancements in the representation of ground temperature by EnergyPlus have the potential to enhance these results.

The transition from single to double glazing and the enhancement of heating system efficiency occupy a less significant role when compared to earlier energy demand reduction measures such as roof, wall, and floor insulation. This is attributed to findings which indicate that, for instance, the substitution of a single glazing window with a thickness of 6 mm and a metal frame with double glazing of pane thicknesses ranging from 6 to 15 mm can yield reductions in heating energy demand ranging from 3.1% to 4.2% in thermal zone 5 and from 3.6% to 8.2% in thermal zone 7. This is primarily due to the limited proportion of glass surface area relative to the overall dimensions of the vertical envelope, which represents merely 10%, resulting in minimal heat loss through this component. Furthermore, due to the unavailability of specific data on glazing for the Chilean housing stock, assumptions concerning glazing size were necessary. Consequently, the impact on energy demand could be more substantial if these assumptions underestimated the actual dimensions of the glazing.

The substitution of a wood-burning stove with a pellet stove was similarly determined to have a limited effect. The initial efficiency of the wood-burning stove was established at 70%, whereas the efficiency of the pellet stove ranged from 70% to 84%. The modeling process exhibited reductions in heating energy demand of 0.4% to 2.4% in thermal zone 5 and 0.1% to 0.9% in thermal zone 7, respectively. This suggests that the transition from a wood-burning stove to a pellet stove exerts a minimal impact on decreasing heating energy consumption, potentially due to the slight variance in the efficiencies of both systems.

The impact of simultaneously implementing measures such as roof insulation, wall insulation, floor insulation, and double glazing on the heating demand of the reference dwelling was evaluated. In thermal zone 5, the prescribed insulation thicknesses for the roof, walls, and floors are 120 mm, 50 mm, and 80 mm, respectively, with a separation of 8 mm between the panes considered for double glazing. These interventions comply with the minimum standards for building envelope specifications as defined by the thermal regulations for thermal zone 5. The findings suggest that the combined implementation of these measures may result in an annual heating demand reduction of up to 46.5%. In thermal zone 7, the insulation thicknesses for the roof, walls, and floors are 160 mm, 60 mm, and 120 mm, respectively, with an 8 mm separation between the panes for double glazing. The results indicate that these concurrent interventions could yield an annual reduction in heating demand of up to 57.9%. The analysis elucidates the strategies offering the most considerable impact on minimizing heating demand, identifying roof insulation as the most significant, followed by wall insulation. Conversely, floor insulation and double glazing contribute only marginally. Consequently, this analysis serves as a framework to enable informed decision-making in mitigating energy poverty.

4.4.4 Comparison with other studies

In Chile, there is a lack of both empirical and theoretical research regarding the impact of energy demand reduction interventions, including insulation for roofs, walls, and floors, the replacement of single glazing with double glazing, and enhancements to heating system efficiency. Therefore, the results derived from this study cannot be directly compared to investigations under similar local conditions. Nonetheless, studies conducted in other countries may serve as a general point of reference.

Prior research has demonstrated that enhancements to the building envelope, encompassing components such as walls and roofs, represent the most economically efficient strategy to augment energy efficiency. This approach addresses challenges related to indoor environmental quality and energy consumption in low-income households across Europe [137]. Consistent with these findings, the current study reveals that the incorporation of roof and wall insulation exerts the most significant influence on energy reduction when compared to other interventions such as the installation of double glazing or advancements in heating system energy performance.

In the United Kingdom, the challenge of energy demand within low-income households is addressed primarily through the implementation of insulation measures. Subsequent post-construction analyzes have shown that these enhancements contribute to energy conservation and substantial improvements in thermal comfort experienced by the occupants. As reported by the U.S. Department of Energy, the addition of insulation to attics, floors, and basements can result in up to a 20% reduction in average heating and cooling costs. According to the findings of Calderón & Beltrán [37], a retrofit that included the installation of high-density mineral wool and modern double-glazed windows led to a 27% decrease in overall energy consumption. In northern Germany, research has indicated that the addition of wall insulation to old detached houses built before 1970 can lead to a 15% reduction in the energy demand for heating [138].

The results align with the findings of this study, indicating that the incorporation of roof insulation can result in energy reductions ranging from 19% to 29% in thermal zone 5, and from 18% to 26% in thermal zone 7. Furthermore, the addition of wall insulation can produce energy savings between 11% and 18% in thermal zone 5, and between 12% and 20% in thermal zone 7. It is crucial to consider that these reductions in energy demand are specific to the zones analyzed, as each case should be examined independently due to varying conditions such as location and building materials.

4.5 Applications of outcomes and future work

The acquired knowledge is expected to exert a positive impact by identifying the critical factors contributing to energy poverty in Chile; assessing the current status of energy poverty within the nation; characterizing the Chilean housing stock and introducing a set of archetypal buildings to represent it; presenting a model and modeling framework for assessing potential improvements in the Chilean housing stock; contextualizing and interpreting the results; demonstrating how the model and its predictions can inform and evaluate the impact of new policies on enhancing the energy performance of dwellings; and recognizing the necessity for future measurement, surveying, and data collection efforts.

This section is structured into four primary segments, wherein the application of outcomes and prospective directions for each segment will be elucidated.

4.5.1 Main factors contributing to energy poverty

Energy poverty presents a significant challenge due to the complexity and multitude of variables involved. In the context of Chile, variables identified as pertinent to energy poverty include fluctuations in fuel prices and income disparities across the country, behavioral patterns related to energy consumption, inefficiencies in housing energy usage (notably a low prevalence of insulation), and the specific demographic characteristics of households impacted by energy poverty.

This study provides pertinent information on populations potentially impacted by energy poverty and offers guidance for policy making decisions. Specifically, Section 3.1.1.4 indicates that the southern regions of the country experience the highest energy prices, with a nationwide trend of increasing energy costs in recent years. Consequently, this is an indicator of regions that policy initiatives should prioritize, for example, by implementing energy efficiency measures, to facilitate reduced energy demand and, thereby, lower energy expenditures.

The study also provided pertinent information on demographic groups that should be prioritized when policies are implemented. Section 3.1.2 identified elderly individuals and families with children as the most vulnerable populations to energy poverty. These groups allocate a disproportionate amount of their financial resources to energy expenses. In addition, older adults are particularly susceptible to temperature fluctuations due to potential health conditions that can be exacerbated by such variations. Thus, having this information enables institutions, such as the Ministry of Housing, to strategically allocate their limited resources to these groups.

4.5.2 The current state of energy poverty

Evaluating the state of energy poverty necessitates not only the examination of existing informational sources but also the metrics available for its assessment. This process has resulted in identifying gaps in the information that hinder the calculation of specific metrics, whereas in other instances, the data is available, yet recommendations are made for enhancements in future data collection to achieve more assured outcomes.

The 2017 Family Budget Survey encountered difficulties with respect to the geographical classification of the data, as it was limited to differentiating only between the metropolitan region and all other regions collectively. This approach led to the aggregation of valuable data from various other regions, thus impeding a nuanced analysis of the variations in residential energy demand in these areas. Although the 2022 iteration of the survey addressed this issue by categorizing data into four groups: north, metropolitan region, central, and south, it is recommended that future surveys allocate information more specifically by region. This is due to the country's diverse climatic conditions, which would enable a more precise analysis for each region and facilitate comparisons with findings from the Chilean households' energy consumption survey.

Despite the challenges encountered in the search for information, the current state of energy poverty was determined employing the ten percent rule. The 2018 Chilean Housing Energy Usage Survey provided pertinent data on which thermal zones should be prioritized by the government based on the proportion of households affected by energy poverty (EP). The findings indicate that the southern thermal zones, specifically zones 5, 6, and 7, exhibit the highest prevalence of households experiencing EP. This trend is consistent with the elevated energy prices and the significant energy demands associated with the climate in these regions. Subsequent research efforts could focus on establishing an appropriate benchmark for categorizing households as energy-poor. This is justified by observations in the southern region of the country, where a substantial proportion of households are affected by energy poverty. The prevalent criterion, wherein ten percent of household income is allocated to energy expenses, might be easily met by many, thereby diluting the intended focus of policies designed to assist those most susceptible to energy poverty rather than the entire population.

4.5.3 Chilean archetypes

The characterization of the Chilean housing stock is critical to understand the diversity of the housing, and they serve as a research tool and may be applied to other modeling and field studies, such as forecasting and assessing the effects of policies on indoor air quality and energy demand, or to inform future data collection initiatives. This investigation revealed that 18 archetypes account for 80% of the Chilean housing stock, with only 4 archetypes that make up approximately 50%. The predominant archetype, accounting for 19% of the housing stock, is a semi-detached, uninsulated house constructed of clay bricks. The second most prevalent archetype comprises 15% of the housing stock and is a detached, uninsulated house constructed from wood.

However, analysis of national data sources indicates significant knowledge deficiencies in categorical descriptors and occupant behaviors, as well as insufficient granularity in physical data. However, enhancements in certain domains could potentially reduce uncertainties related to specific parameters. These parameters encompass dwelling attributes, such as window area and glazing type, year of construction, orientation, and infiltration rate. Furthermore, advanced understanding of occupant behaviors, such as the schedule and duration of heating use, would facilitate improved predictions of energy demand and greenhouse gas emissions. To address these gaps, national surveys should be enhanced and complemented by fieldwork.

4.5.4 Energy modeling

The simulations and sensitivity analyses yield estimations of the impacts of energy efficiency retrofits on energy demand and provide a foundational data source to inform the formulation of national policies regarding housing energy efficiency retrofits. The results facilitate the evaluation and prioritization of various strategic interventions based on their relative effectiveness in reducing energy demand. For instance, the implementation of roof and wall insulation demonstrates the most significant effect in diminishing energy consumption, whereas interventions such as replacing single glazing with double glazing and substituting wood stoves with pellet stoves exhibit the least impact on energy demand reduction.

The modeling of an individual building or a collection of buildings, which collectively represent a fraction of the building stock, is a more expedient and cost-effective assessment approach compared to on-site measurements. Nonetheless, this method entails certain disadvantages or limitations, primarily due to the multitude of assumptions inherent in the process. These assumptions include, but are not limited to, the duration of heating usage, equipment efficiency, the inputs considered for building physics, and temperature settings. Such assumptions can result in discrepancies when calculating the energy demand for heating. As previously mentioned, a more profound understanding of these parameters is necessary to attain more accurate results in future research endeavors.

CHAPTER 5

Conclusion

This research has meticulously examined the consequences of energy demand reduction interventions on energy poverty within the Chilean housing stock. The study has underscored the multifaceted nature of energy poverty, which includes physical, economic, and behavioral dimensions. Energy poverty, defined as the inability to afford adequate warmth due to housing inefficiency, also includes the energy required for lighting, cooking, and typical domestic appliances. The Sustainable Development Goals of the United Nations aim for universal access to modern energy services by 2030, focusing on affordable costs and improvements in electricity and appliances.

The analysis identified several key factors contributing to energy poverty in Chile. Economic factors, particularly low income, emerged as significant determinants of vulnerability. Households with lower income levels tend to allocate a higher proportion of their income to energy expenses, although the amount of money destined is lower than wealthier households. However, the correlation between income and energy expenditure is weak, indicating that other factors also play a role. Educational attainment was found to adversely affect income levels, increasing the likelihood of households experiencing energy poverty. A significant proportion of households affected by energy poverty have only primary or secondary education.

The property tenure status influences susceptibility to energy poverty. Although renters are often thought to be more vulnerable, the study found that in Chile, the likelihood of renters being affected by energy poverty is not significantly higher than that of homeowners. Energy prices, particularly electricity and gas, vary geographically and have increased significantly in recent years. Higher energy prices exacerbate the financial burden on households and contribute to energy poverty. Sociodemographic factors, such as household size and composition, also affect energy expenditure. Single-person households, particularly elderly individuals, are significantly impacted by energy poverty. Larger households, often composed of families with children, also face challenges.

Housing energy inefficiency is a prevalent issue contributing to energy poverty. A substantial portion of the Chilean housing stock lacks adequate insulation, leading to higher energy demands for heating. The prevalence of uninsulated wooden houses in southern regions contributes to the high incidence of energy poverty. The study used a bottom-up approach using archetypes to model the energy demand of representative dwellings in thermal zones 5 and 7. Interventions included improvements in the building envelope, such as roof, wall, and floor insulation, the implementation of double glazing, and improvements in efficiency of the heating system.

Adding roof insulation significantly reduces the demand for heating energy. In thermal zone 5, a 120mm thickness of glass wool insulation resulted in a 26.3% reduction, while in thermal zone 7, a 160mm thickness led to a 25.3% reduction. Wall insulation also contributes to the reduction of energy demand. In thermal zone 5, a 50mm thickness of expanded polystyrene resulted in a reduction of 15.7%, while in thermal zone 7, a thickness of 60mm led to a reduction of 18. 8%. The impact of floor insulation on heating demand is minimal. In thermal zone 5, an 80mm thickness of expanded polystyrene resulted in a reduction of 1.0%, while in thermal zone 7, a thickness of 120mm led to a reduction of 9. 1%.

Replacement of single glazing with double glazing has a modest impact on heating demand. In thermal zone 5, the reductions ranged from 3.1% to 4.2%, while in thermal zone 7, the reductions ranged from 3.6% to 8.2%. Replacement of a wood burning stove with a pellet stove has a negligible impact on heating demand, with reductions ranging from 0.4% to 2.4% in thermal zone 5 and 0.1% to 0.9% in thermal zone 7. The concurrent application of all interventions led to substantial reductions in heating demand. In thermal zone 5, the combined measures resulted in a reduction of 46. 5%, while in thermal zone 7, the reduction was 57.9%. Roof insulation emerged as the most effective measure, followed by wall insulation, with floor insulation and double glazing contributing marginally.

The findings of this research have significant implications for policy-making decisions aimed at reducing energy poverty in Chile. The study underscores the importance of customized interventions based on regional characteristics and types of housing. Policymakers should prioritize measures that offer the most substantial impact on reducing energy demand, particularly roof and wall insulation. Future research should focus on improving the accuracy of data on parameters such as infiltration rates, building orientation, and heating usage patterns. In addition, more studies are needed to explore the long-term benefits of energy efficiency measures on health and well-being, as well as their economic feasibility for low-income households. Energy poverty is a complex and multifaceted issue that requires comprehensive and targeted interventions. This research has demonstrated the potential benefits of energy demand reduction measures in alleviating energy poverty in Chilean housing stock. By addressing the key factors contributing to energy poverty and implementing effective interventions, policy makers can improve the quality of life of vulnerable populations and promote sustainable energy practices.

CHAPTER 6

Limitations of the study

Despite the comprehensive nature of this research, several limitations must be acknowledged. First, reliance on self-reported survey data, such as the Family Budget Survey (EPF), introduces potential biases. Respondents may underreport or omit certain expenditures, particularly those incurred during different seasons, leading to inaccuracies in the data. Furthermore, the geographical classification of the data in the 2017 EPF was limited to the metropolitan region and other regions collectively, resulting in the aggregation of valuable data from various regions and preventing a nuanced analysis of regional variations.

Secondly, the study's methodology involved numerous assumptions, particularly in the modeling of energy demand reduction interventions. Assumptions about the duration of heating usage, equipment efficiency, and building physics inputs may not accurately reflect real-world conditions, potentially affecting the validity of the results. Furthermore, the lack of detailed regional information in the 2017 EPF was addressed in the 2022 iteration, which systematically organized data by the northern and metropolitan regions, as well as the central and southern zones. However, discrepancies in the calculation methods between different sources may still lead to variability in the findings.

Third, the study's focus on specific thermal zones (5 and 7) may limit the generalizability of the results to other regions with different climatic conditions and housing characteristics. Although these zones were selected based on their high prevalence of energy poverty and housing inefficiency, the findings may not be directly applicable to regions with less severe climates or different compositions of housing stock.

Fourth, the bottom-up approach used in this study, while effective in modeling energy demand for representative archetypes, entails certain limitations due to the multitude of assumptions inherent in the process. These assumptions include the inputs considered for building physics, the efficiency of heating systems, and the impact of various interventions. The accuracy of the results is contingent upon the validity of these assumptions, which may not fully capture the complexity of real-world scenarios.

Fifth, the study did not account for the potential data lag in the estimation of housing stock characteristics based on construction periods. There may be delays in the completion of housing approved under new regulations, leading to inaccuracies in the classification of dwellings by insulation levels. This limitation could affect the assessment of the impact of thermal regulations on energy demand.

Sixth, the study's reliance on existing data sources, such as the Chilean Housing Survey on energy use, may introduce limitations related to the representativeness and accuracy of the data. The survey methodology and sample size may not fully capture the diversity of the Chilean housing stock, potentially affecting the validity of the findings.

Seventh, the study did not explore the long-term benefits of energy efficiency measures on health and well-being. Although the research demonstrated the potential for substantial reductions in heating demand, more studies are needed to assess the broader impacts of these interventions on the quality of life of vulnerable populations.

Lastly, the conclusions drawn from this research may not be readily applicable to other nations with divergent socio-economic and climatic conditions. Although the study provides a comprehensive analysis of energy poverty in Chile, the findings may not be directly transferable to countries with different energy markets, housing characteristics, and policy frameworks.

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