Title: Energy poverty risk mapping methodology, considering the user's thermal adaptability: the case of Chile.

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Abstract:

Today, identifying energy poverty is one of the scientific community's challenges. In this sense, panning through the country using Geographic Information Systems (GIS), assumes getting to know which areas are the most vulnerable. This study considers the development of a new territory energy poverty evaluation indicator, called Poverty Adaptive Degree Hourly Index (PADHI). The novelty of this indicator is that it combines the number of inhabitants in poverty with the hourly heating and cooling degrees of each climate, determined using adaptive thermal comfort limits based on ASHRAE-55-2017, i.e., that consider people's climate adaptation and that identify, based on adaptive degrees hourly, energy poverty situations. The area studied focuses on Chile and its 346 municipalities. The results show that, as a result of the country's climate variability, the application of the adaptive comfort model can exceed 90% in the north of the country and be below 20% in the most meridional areas. The results also outlined that the municipalities defined as PADHI's 10th decile are those which have a higher risk of energy poverty in their population, a higher percentage of income poverty and climatic severity. A cluster analysis was also run for this decile, identifying two risk groups with the aim of identifying the critical areas. This methodology applied to Chile, but international in nature, allows identifying priority areas on which the measures needed to reduce energy poverty can be focused.

Highlights:

- Development of the Poverty-Adaptive Degree Hourly Index (PADHI).
- Analysis of Chile's municipalities.
- It is detected that the country's southern municipalities have a lower energy poverty risk.
- The most populated areas and those with higher energy demands are the most vulnerable municipalities.

Keywords:
Poverty-Adaptive Degree Hourly Index, adaptive thermal comfort, poverty, degree hourly, municipalities

1. Introduction

The history of human progress has often been linked to the availability and to the consumption of energy in ever more intense ways [1–3]. As a result, energy for citizens, homes, governments, etc., has become a concern [4]. The policies, programs and campaigns position energy consumption as a need or essential right that must be covered, indicating that energy and welfare are interconnected. Currently, there is a significant divide between approaches to conceptualize and monitor the energy and welfare relationship in different parts of the world, particularly between more and less developed regions [5]; however, all of them are linked with the concept of energy poverty (EP). EP, also known as fuel poverty and energy vulnerability, occurs when homes are not capable of maintaining minimum thermal comfort temperatures or of having energy services either available or at an affordable cost [6–9]. It has also been linked with being unable to perform essential activities as a direct or indirect result of insufficient access to affordable, reliable and secure energy services [5].

The phenomenon has caught the attention of the scientific community and the society over recent decades, in light of its political and social implications [6,10,11]. There is broad consensus that EP is a consequence of the high energy prices, low family incomes, buildings with low energy efficiency and inefficient household appliances [12–14]; along with the energy needs, characteristics and practices of those living in the dwellings [15,16]. EP also has adverse effects on people's physical health [17–19], and has been associated to the excessive winter deaths in most European countries [20,21]. Likewise, when it is associated with using economic energy sources like wood, it can result in serious air pollution episodes [22,23].

Measuring EP is a complex challenge due to its social and environmental variability, its culturally sensitive and private nature, apart from it being temporary and dynamic [7]. It is a relative concept, where the relevance of its variables changes depending on the territory being observed [24]. This is worsened by the limited availability of suitable indicators and data and the lack of consensus about how it must be conceptualized and measured. For this reason, EP indicators are an important part of research into the matter [25]. Currently, there are several definitions and indicators that have been developed by countries like the United Kingdom, Ireland, France and Slovakia [26]. However, an official standard to assess EP has not been established and, therefore, in certain countries, this type of poverty has not yet been acknowledged as a social issue.

Different frameworks, approaches and indicators have been proposed around the world. Many authors have associated energy poverty with low incomes, while others have suggested that energy consumption above certain thresholds affects the availability of disposal income to satisfy other needs (see Table 1). Currently, different indicators and definitions are being used to analyze and assess EP, which can be divided into seven categories: (i) access, (ii) the income and expenses of the home, (iii) multidimension; (iv) self-reported conditions of the home, (v) econometric analysis, (vi) energy rating, and (vii) thermal comfort.

Table 1. Summary of existing indicators.

Type	Indicator	Reference
Access to energy	Lack of access to energy.	United Nations Development Program [25]
Based on the home's income and expenses	Ten Percent Rule	Boardman [12]
	The energy consumption expense is more than double the national median (2M)	Schuessler [27]
	Minimum Income Standard (MIS)	Moore [28]
	Low Income High Cost (LIHC)	Hills [29]
	After Fuel Cost Poverty (AFCP)	Heindl [30], Romero et al. [31]
	Hidden Energy Poverty (HEP)	Rademaekers et al. [32]
Based on multidimensionality	Energy Development Index (EDI)	International Energy Agency [33]
	Multidimensional Energy Poverty Index (MEPI)	Nussbaumer et al. [34]
	Energy Poverty Index (EPI)	Mirza and Szirmai [35]
	Multi-Tier Framework (MTF)	Bhatia and Angelou [36]
	Energy poverty 3D index (Chile)	Calvo et al. [37]
Based on self-reported home conditions	The inability to keep homes suitably heated during winter. Delays in paying energy bills. The dwelling has deficiencies, like moisture, damaged foundations or walls, and conditions like mold or rot.	European Commission [38]
Econometric analysis	The influence of different demographic, socioeconomic and physical factors in the likelihood of experiencing energy poverty.	Legendre and Ricci [39], Miniaci et al. [40]
Considering energy certification (CE)	The influence of the quality of the dwelling (energy consumption) on fuel poverty. Low quality dwellings cause an increase in energy consumption and trigger EP.	Florio and Teissier [41], Fabbri [42]
Thermal comfort analysis	Fuel poverty potential risk index (FPPRI).	Pérez-Fargallo et al. [8,9]
	% of hours the home is in thermal comfort.	Sánchez-Guevara Sánchez et al. [43]

The fight against EP depends on poorly defined goals, while accurately identifying areas with a higher probability of energy poverty is not possible. For this reason, part of the research into this issue has been focused on mapping energy poverty at both a domestic and a regional scale. In countries like Brazil, mapping has been made for low income populations associated to access, given that this is a challenge in many southern hemisphere countries [44]. Walker (2013) used Geographic Information System (GIS) techniques to evaluate the focalization of a small-scale domestic energy efficiency scheme in Northern Ireland using the fuel poverty risk index [45], which mainly uses social, economic and environmental variables [46]. In Scotland, research has also been made on how GIS can help locate areas that have a higher probability of having fuel-poor homes, using georeferenced energy efficiency data in the local housing stock [47]. Other investigations have made mapping by evaluating the potential of fuel poverty using data on income, education level, unemployment rate and the number of inhabitants over 65 years of age, with the heating and cooling gap estimated by typology [48]. Other indexes have also been made to identify critical areas to support domestic and local energy efficiency policies and instruments like the Energy Poverty Vulnerability Index. These allow EP mapping using the population's socioeconomic indicators, climatic variables (heating and cooling day-degrees), energy consumption levels, calculated energy demand for heating and cooling, types of air-conditioning systems and construction features of varied building typologies, which allows the indicator to assess the region's EP vulnerability [49]. However, this indicator does not consider two aspects: (i) the percentage of people who live in poverty; and (ii) the adaptive thermal behavior the users have. For this reason, this study outlines the development of a new territorial energy poverty evaluation indicator called Poverty-Adaptive Degree Hourly Index (PADHI). This indicator combines the number of inhabitants in poverty with the hourly cooling and heating degrees of each climate, determined based on the adaptive thermal comfort limits of the ASHRAE-55-2017. This follows the adaptive behavior of low-income users, who adjust their thermal comfort levels to reduce their energy consumption. Hence, the evaluation of energy poverty risk based on energy consumption is not a completely valid indicator [50]. Thus, by using PADHI, the intention is to have a methodology that allows evaluating the energy poverty vulnerability of cities considering inhabitants with low incomes and the climatic characteristics of the city and, in this way, establish priority actions in those cities with a higher risk. For this reason, part of the research also analyzed the most suitable methodology to set priority criteria in the cities analyzed.

The local municipalities of Chile were analyzed as the case study for this research. The choice of Chile as a case study is related to the political strategies of the region, where, in 2014, the Chilean Government's Energy Ministry presented its Energy Agenda. One of its main tasks was designing and implementing a long-term Energy Policy with a social, political and technical validation [51]. This energy policy, called "Energía 2050 or Energy 2050", was published at the end of 2015. Its main goal was attaining and maintaining reliability in the entire energy system, while complying with sustainability and inclusion criteria. The new Energy 2050 Policy is based on four pillars: (1) Supply quality and security; (2) Energy as the motor for development; (3) Environmental compatibility; (4) Energy education and efficiency. In the second pillar, one of the guidelines set out was defining the concept and measurement of energy poverty, aiming at establishing specific policies to reduce it. The goal was to reduce it by 50% by 2035 and completely eradicate it by 2050 [4]. As a result, it is essential to have indicators that, first of all, allow establishing a national scale where regions with greater EP problems can be outlined. The use of Chile as a case study is also of interest, given the country's current social-political framework, where its major internal conflicts are related to the population's economic inequality, among other factors [52].

2. Methodology

2.1. Case study: Chile

Chile is defined as a tricontinental country and comprises three geographic areas: continental, insular (set of Pacific islands) and Antarctic territory. The first of these, continental Chile, comprises a strip of land on the west coast of the Southern Cone running between the 17°29'57 S and 56°32'12 S parallels, mainly from the southeastern shores of the Pacific Ocean to the highest peaks of the Andes mountain range. The country is 4,270 km long, with its broadest part being 445 km wide at 52°21' S and its narrowest, 90 km at 31°37' S. Continental Chile has a very high climatic variability, with climates ranging from dry arid and semi-arid (BWk, BWk´, BWn, BSks, BSk´s, BSn), template with rain in winter or all year-round (Csb, Csbn, Csbn´s, Csc, Cfb, Cfbs, Cfc, Cfcs) to cold both with tundra and ice (ETI, ETH, EFH) [53] (See figure 1). This makes EP conditions especially difficult to study, given their ties to the climate.

Chile's territorial organization is made dividing the country into regions, provinces and municipalities. This organization is descending in nature, where one region covers several provinces, while there are a series of municipalities in each province. In total, there are 16 regions, 56 provinces and 346 municipalities (see Table 2). It is important to highlight that municipalities correspond to the cities in the country, so this territorial division can be of great use to detect cities with a higher energy poverty risk. To run the spatial analysis, it was necessary to obtain climate data of all Chilean municipalities. For this reason, hourly temperature data was obtained, that were monitored throughout an entire year by the Chilean Energy Ministry.

Table 2. Distribution of the 346 Chilean municipalities by region.

Region	Municipalities
Arica y Parinacota	Arica, Camarones, General Lagos, Putre
Tarapacá	Alto Hospicio, Iquique, Camiña, Colchane, Huara, Pica, Pozo Almonte
Antofagasta	Antofagasta, Mejillones, Sierra Gorda, Taltal, Calama, Ollagüe, San Pedro de Atacama, María Elena, Tocopilla
Atacama	Chañaral, Diego de Almagro, Caldera, Copiapó, Tierra Amarilla, Alto del Carmen, Freirina, Huasco, Vallenar
Coquimbo	Canela, Illapel, Los Vilos, Salamanca, Andacollo, Coquimbo, La Higuera, La Serena, Paihuano, Vicuña, Combarbalá, Monte Patria, Ovalle, Punitaqui, Río Hurtado
Valparaíso	Isla de Pascua, Calle Larga, Los Andes, Rinconada de Los Andes, San Esteban, Limache, Olmué, Quilpué, Villa Alemana, Cabildo, La Ligua, Papudo, Petorca, Zapallar, Hijuelas, La Calera, La Cruz, Nogales, Quillota, Algarrobo, Cartagena, El Quisco, El Tabo, San Antonio, Santo Domingo, Catemu, Llaillay, Panquehue, Putaendo, San Felipe, Santa María, Casablanca, Concón, Juan Fernández, Puchuncaví, Quintero, Valparaíso, Viña del Mar
Libertador General Bernardo O'Higgins	Codegua, Coínco, Coltauco, Doñihue, Graneros, Las Cabras, Machalí, Malloa, Olivar, Peumo, Pichidegua, Quinta de Tilcoco, Rancagua, Requínoa, Rengo, San Francisco de Mostazal, San Vicente de Tagua Tagua, La Estrella, Litueche, Marchigüe, Navidad, Paredones, Pichilemu, Chépica, Chimbarongo, Lolol, Nancagua, Palmilla, Peralillo, Placilla, Pumanque, San Fernando, Santa Cruz
Maule	Cauquenes, Chanco, Pelluhue, Curicó, Hualañé, Licantén, Molina, Rauco, Romeral, Sagrada Familia, Teno, Vichuquén, Colbún, Linares, Longaví, Parral, Retiro, San Javier de Loncomilla, Villa Alegre, Yerbas Buenas, Constitución, Curepto, Empedrado, Maule, Pelarco, Pencahue, Río Claro, San Clemente, San Rafael, Talca
Ñuble	Bulnes, Chillán, Chillán Viejo, El Carmen, Pemuco, Pinto, Quillón, San Ignacio, Yungay, Cobquecura, Coelemu, Ninhue, Portezuelo, Quirihue, Ránquil, Treguaco, Coihueco, Ñiquén, San Carlos, San Fabián, San Nicolás
Bio-Bío	Arauco, Cañete, Contulmo, Curanilahue, Lebu, Los Álamos, Tirúa, Alto Biobío, Antuco, Cabrero, Laja, Los Ángeles, Mulchén, Nacimiento, Negrete, Quilaco, Quilleco, San Rosendo, Santa Bárbara, Tucapel, Yumbel, Chiguayante, Concepción, Coronel, Florida, Hualpén, Hualqui, Lota, Penco, San Pedro de la Paz, Santa Juana, Talcahuano, Tomé

Araucanía	Carahue, Cholchol, Cunco, Curarrehue, Freire, Galvarino, Gorbea, Lautaro, Loncoche, Melipeuco, Nueva Imperial, Padre Las Casas, Perquenco, Pitrufquén, Pucón, Saavedra, Temuco, Teodoro Schmidt, Toltén, Vilcún, Villarrica, Angol, Collipulli, Curacautín, Ercilla, Lonquimay, Los Sauces, Lumaco, Purén, Renaico, Traiguén, Victoria
Los Ríos	Futrono, La Unión, Lago Ranco, Río Bueno, Corral, Lanco, Los Lagos, Máfil, Mariquina, Paillaco, Panguipulli, Valdivia
Los Lagos	Ancud, Castro, Chonchi, Curaco de Vélez, Dalcahue, Puqueldón, Queilén, Quellón, Quemchi, Quinchao, Calbuco, Cochamó, Fresia, Frutillar, Llanquihue, Los Muermos, Maullín, Puerto Montt, Puerto Varas, Osorno, Puerto Octay, Purranque, Puyehue, Río Negro, San Pablo, San Juan de la Costa, Chaitén, Futaleufú, Hualaihué, Palena
Aysén del General Carlos Ibáñez del Campo	Aysén, Cisnes, Guaitecas, Cochrane, O'Higgins, Tortel, Coyhaique, Lago Verde, Chile Chico, Río Ibáñez
Magallanes y Antártica Chilena	Antártica, Cabo de Hornos, Laguna Blanca, Punta Arenas, Río Verde, San Gregorio, Porvenir, Primavera, Timaukel, Natales, Torres del Paine
Metropolitana de Santiago	Colina, Lampa, Tiltil, Pirque, Puente Alto, San José de Maipo, Buin, Calera de Tango, Paine, San Bernardo, Alhué, Curacaví, María Pinto, Melipilla, San Pedro, Cerrillos, Cerro Navia, Conchalí, El Bosque, Estación Central, Huechuraba, Independencia, La Cisterna, La Granja, La Florida, La Pintana, La Reina, Las Condes, Lo Barnechea, Lo Espejo, Lo Prado, Macul, Maipú, Ñuñoa, Pedro Aguirre, Cerda, Peñalolén, Providencia, Pudahuel, Quilicura, Quinta Normal, Recoleta, Renca, San Miguel, San Joaquín, San Ramón, Santiago, Vitacura, El Monje, Isla de Maipo, Padre Hurtado, Peñaflor, Talagante

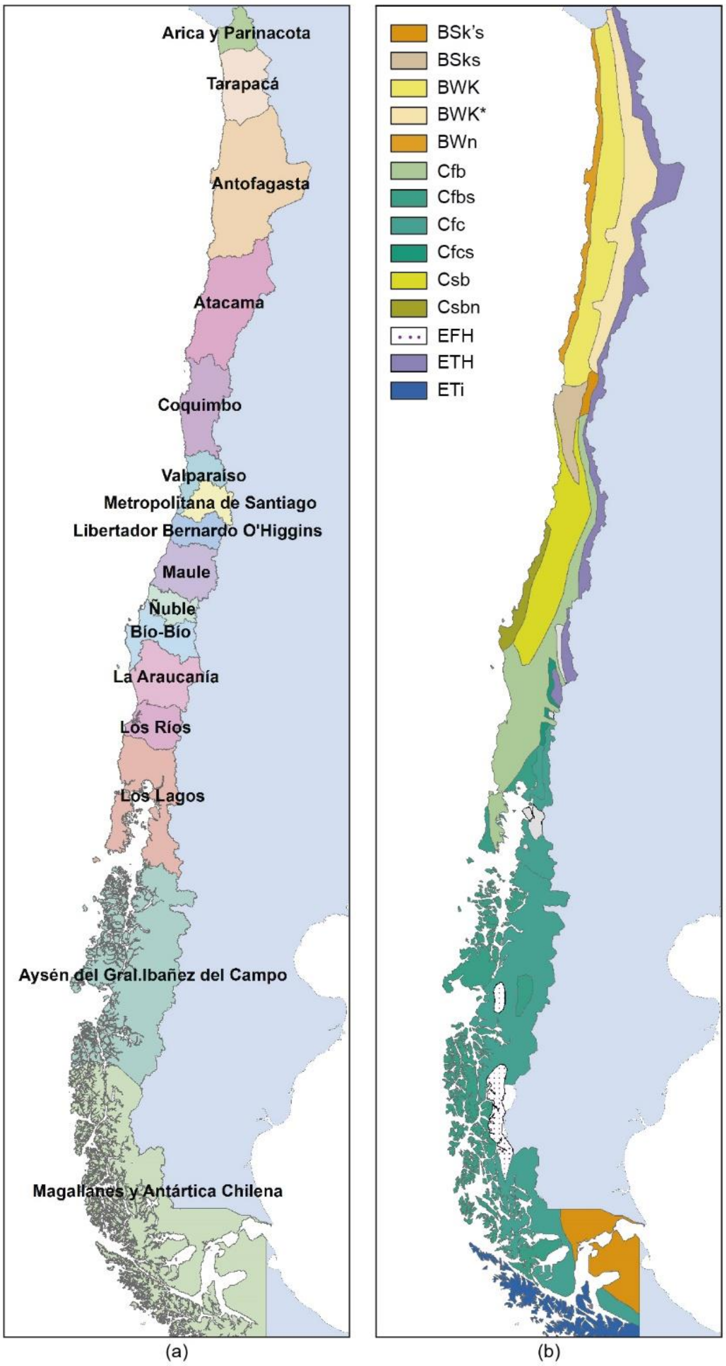

Figure 1. Distribution of regions (a) and Köppen climates (b) in Chile.

2.2. The climate-based energy poverty potential evaluation indicator: Poverty-Adaptive Degree Hourly Index.

The Poverty-Adaptive Degree Hourly Index (PADHI) looks to evaluate the risk that a region can have in energy poverty cases. For this reason, the intention is to use statistical and climatic parameters that allow having a general understanding of an entire country, to be able to establish pertinent government measures. It is for this reason that the indicator is going to be based on two parameters: the number of people in poverty risk and the degrees hourly of heating and cooling based on adaptive comfort limits.

On one hand, the first of the parameters can be determined by analyzing the statistical information collected by the statistics institutes of each country. In the case of Chile, for example, the Chilean National Statistics Institute has accurate information of the percentage of people in poverty by income in each region.

On the other hand, the degrees hourly of heating and cooling will be obtained from the thermal gradient there is between the outdoor temperature and the thermal comfort limits. It will be necessary to use an adaptive thermal comfort model for this that regulates the thermal expectations of users. In this sense, adaptive thermal comfort models are developed by different investigations [50,54] and standards [55–58]. One of the best developed models used and with a more international application is ASHRAE-55-2017 [55], as in its development, data from 160 buildings located on 4 continents was used [59].

In the case of Chile, different studies have assessed the possibility of applying the adaptive thermal comfort limits of this standard for low-income Chilean users, since they have the highest risk of suffering EP [50]. ASHRAE-55-2017 establishes two types of limits depending on the acceptability percentage of the users: 80% and 90%. ASHRAE-55-2017, when facing this situation, recommends using 80% limits, as the 90% acceptability level is unlikely to be reached and limits the use of these models [55]. Apart from this, low income users have a higher thermal acceptability [50]. The lower and upper limits where the operative temperature must be, are obtained using dependent linear correlations of the prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) (see equation (1)). $\overline{t_{pma(out)}}$ is a weighted mean temperature of the daily outdoor temperatures ($T_{ext,d}$) of the previous days. The determination of $\overline{t_{pma(out)}}$ will allow determining, first of all, whether the adaptive model is applicable (in the case of ASHRAE, this is when $\overline{t_{pma(out)}}$ is between 10 and 33.5°C) and, secondly, it allows determining the users' upper (see Eq. (2)) and lower (see Eq. (3)) thermal expectation limit.

$$\overline{t_{pma(out)}} = 0.4 \cdot \sum_{d=1}^{n} \left(0.6^{(i-1)} \cdot T_{ext,d}\right) \quad (1)$$

$$Upper\ acceptability\ limit = 0.31 \cdot \overline{t_{pma(out)}} + 21.3 \quad (2)$$

$$Lower\ acceptability\ limit = 0.31 \cdot \overline{t_{pma(out)}} + 14.3 \quad (3)$$

The determination of the degrees hourly is based on the heating degree days (HDD) and cooling degree days (CDD) indexes to determine the heating and cooling demands needed to condition the buildings. Both HDD and CDD are determined by the difference between daily mean outdoor temperature and a base temperature. However, for the purposes of the methodology developed in the research, it was decided to determine the degree hours needed to condition the building: heating degree hours (HDH) and cooling degree hours (CDH). This is because they allow having a better understanding of the energy demands that the real estate stock of a region can have on facing climatic factors like the daily thermal oscillation. As an example, the variation of considering degree hours versus degree days was analyzed in the climate data used in the study. Figure 2 represents the scatter plots obtained using a base temperature of 20°C for heating and 25°C for cooling. As can be seen, considering an hourly scale allows analyzing energy demands in buildings that cannot be analyzed on the daily scale. In this sense, cooling degree days in most cities obtained values of 0 or of few degrees, while on the hourly scale, degrees of up to 9.210°C were detected. In the case of heating degrees, a certain linear trend is detected between daily and hourly degrees that could allow using daily data, but at the highest demand values, it can be confirmed how there is not a linear trend and a logarithmic growth is detected which reflects a higher demand on an hourly scale that is not detected on the daily scale.

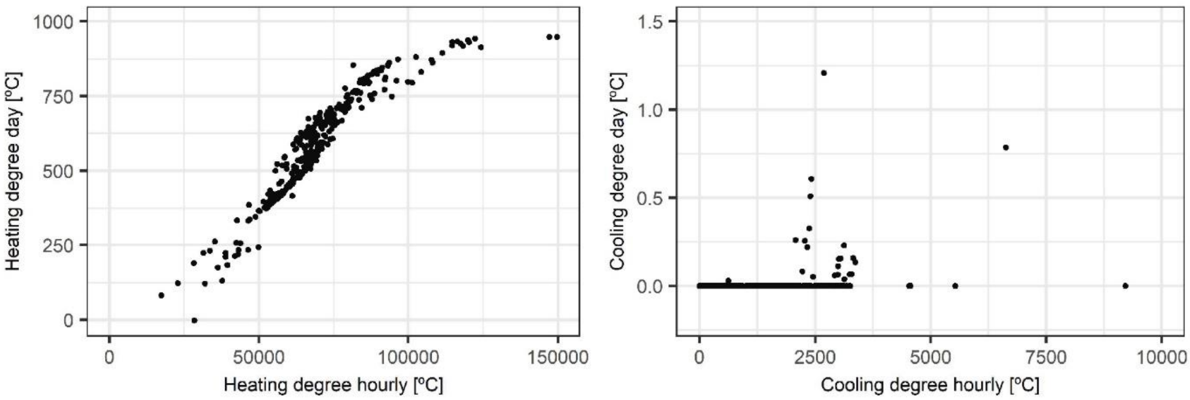

Figure 2. Comparative graph between HDD and HDH and between CDD and CDH. It is appropriate to highlight that the scales on the X and Y axis are not equal to facilitate the display of the data.

As such, an analysis of the heating and cooling degrees on an hourly scale allow having a more accurate understanding of the energy demand of buildings. The following novel aspect of the methodology in this study is considering that the HDH and the CDH are determined based on an adaptive base temperature, that is to say, the base temperature varies depending on the upper and lower limits determined using ASHRAE-55-2017, obtaining heating adaptive degrees hourly ($HDH_{Adaptive}$) and cooling adaptive degrees hourly ($CDH_{Adaptive}$). This consideration is a result of the trends detected in different studies in the region where an adaptive behavior to the climate by low-income users is confirmed [50]. As an illustration, the graphical representation of $HDH_{Adaptive}$ and $CDH_{Adaptive}$.are shown. Just as can be seen in the graph, the red points correspond to hourly values where the region's temperature is below comfort limits so, for the purposes of calculating the $HDH_{Adaptive}$ and $CDH_{Adaptive}$, a value of 0 would be assigned to these hours (i.e. there is no energy demand in the building). Likewise, it can be seen how the blue points correspond to hours where there is thermal discomfort and, thus, it will be necessary to use HVAC systems. The thermal gradient there is between each point and the thermal comfort limit will be added in the total annual degrees. The position of the outdoor temperature versus the limits will be determined on whether the demand is for heating or for cooling: it will be heating if it is below the lower limit and cooling if it is above the upper limit. Thus the $HDH_{Adaptive}$ and $CDH_{Adaptive}$.would be determined through Eqs. (4) and (5), to determine the severity of the heating and cooling of each municipality.

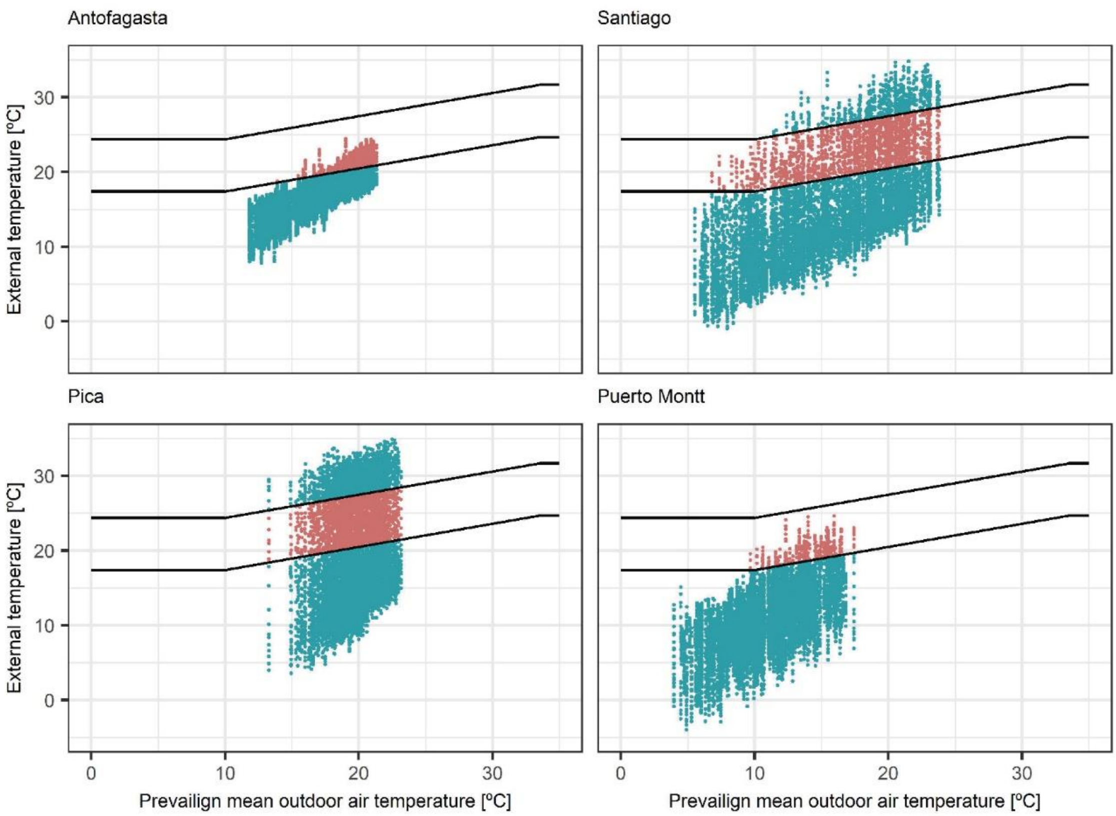

Figure 3. Example of the distribution of the hourly outdoor temperature values versus the adaptive thermal comfort limits of ASHRAE 55-2017 (represented by the black line). The red represents the hourly values within the adaptive thermal comfort limits, while the blue represents those that are outside these.

$$HDH_{Adaptive} = \sum_{i=1}^{8760} (T_{ext,i} - T_{AH,i}) \cdot X_{HA} \quad X_{HA} = 1 \; if \; T_{ext,i} < T_{AH,i} \tag{4}$$

$$CDH_{Adaptive} = \sum_{i=1}^{8760} (T_{AC,i} - T_{ext,i}) \cdot X_{CA} \quad X_{CA} = 1 \; if \; T_{ext,i} > T_{AC,i} \tag{5}$$

Where $HDH_{Adaptive}$ is the annual total of the HDH using the lower limit of ASHRAE-55-2017 [°C] as the base temperature; $CDH_{Adaptive}$ is the annual total of the CDH using the lower limit of ASHRAE-55-2017 [°C] as the base temperature; $T_{AH,i}$ is the daily adaptive base temperature determined with the lower limit of ASHRAE 55-2017 [°C]; $T_{AC,i}$ is the daily adaptive base temperature determined with the upper limit of ASHRAE 55-2017 [ºC]; and X_{HA}, X_{CA} are logic values that will be worth 1 when the condition given in the equations is met and 0 when said condition is not.

The PADHI value of a region will be obtained by multiplying the number of persons living in poverty per income (NPLPI) by the degrees needed to climatize the building. It is appropriate to highlight that, in this point, three PADHI typologies are distinguished considering the type of degrees analyzed: heating ($HDH_{Adaptive}$), cooling ($CDH_{Adaptive}$) and total ($TDH_{Adaptive}$) (obtained from the sum total of $HDH_{Adaptive}$ and $CDH_{Adaptive}$). Eqs, (6) – (8) indicate the calculation procedure. It is necessary to mention that to facilitate handling the PADHI values obtained, it was decided that the NPLP units and the degrees were in thousands (i.e., NPLP has as a unit, the thousands of people who live in poverty). It is important to underscore that PADHI is developed to be used in countries or regions that have similar characteristics in their real estate stocks. In the case of Chile, its real estate stock in general does not have a suitable energy performance. This is because the first construction codes in Chile did not include technical requirements for energy efficiency [60]. Likewise, the current regulatory framework could generate property development lacking energy efficiency, which could force revising new buildings in the not so distant future [61].

$$PADHI_{HDH} = NPLPI \cdot HDH_{Adaptive} \tag{6}$$

$$PADHI_{CDH} = NPLPI \cdot CDH_{Adaptive} \tag{7}$$

$$PADHI_{TDH} = NPLPI \cdot TDH_{Adaptive} \quad (8)$$

Thus, to run the study, it is necessary to have information about the degrees hourly and the NPLPI. The degrees hourly were obtained using the hourly data described in subsection 2.1 and what was used in Figures 1 and 2. Hence, the missing data that needs explaining is NPLPI. For this reason, the data about the population and the percentage of people in poverty in each one of the municipalities was collated. The population data of each municipality was obtained through the census made by the Chilean National Statistics Institute. Concretely, the data used in this study is from 2017 [62], which is the most recent data available when this research was carried out. The NPLPI value was determined through the estimations of the percentage of people in poverty in 2017, determined by the Chilean National Statistics Institute [63].

Figure 4 represents the population data obtained. As can be seen, the population spread in the municipalities has no relationship with their latitude. In this sense, a Pearson correlation coefficient of 0.18 was obtained for the total population of 0.10 for the people in poverty. This means that there is not a direct relationship between the coldest areas (low latitudes) and the low number of inhabitants, since municipalities like Punta Arenas have over 130,000 inhabitants, while municipalities in the north of the country, like Taltal, have a lower number of inhabitants. This aspect reflects the difficulty to set out palliative measures to confront energy poverty due to the variable nature of the population in the different cities across the country, without a pattern for the latitude of the city.

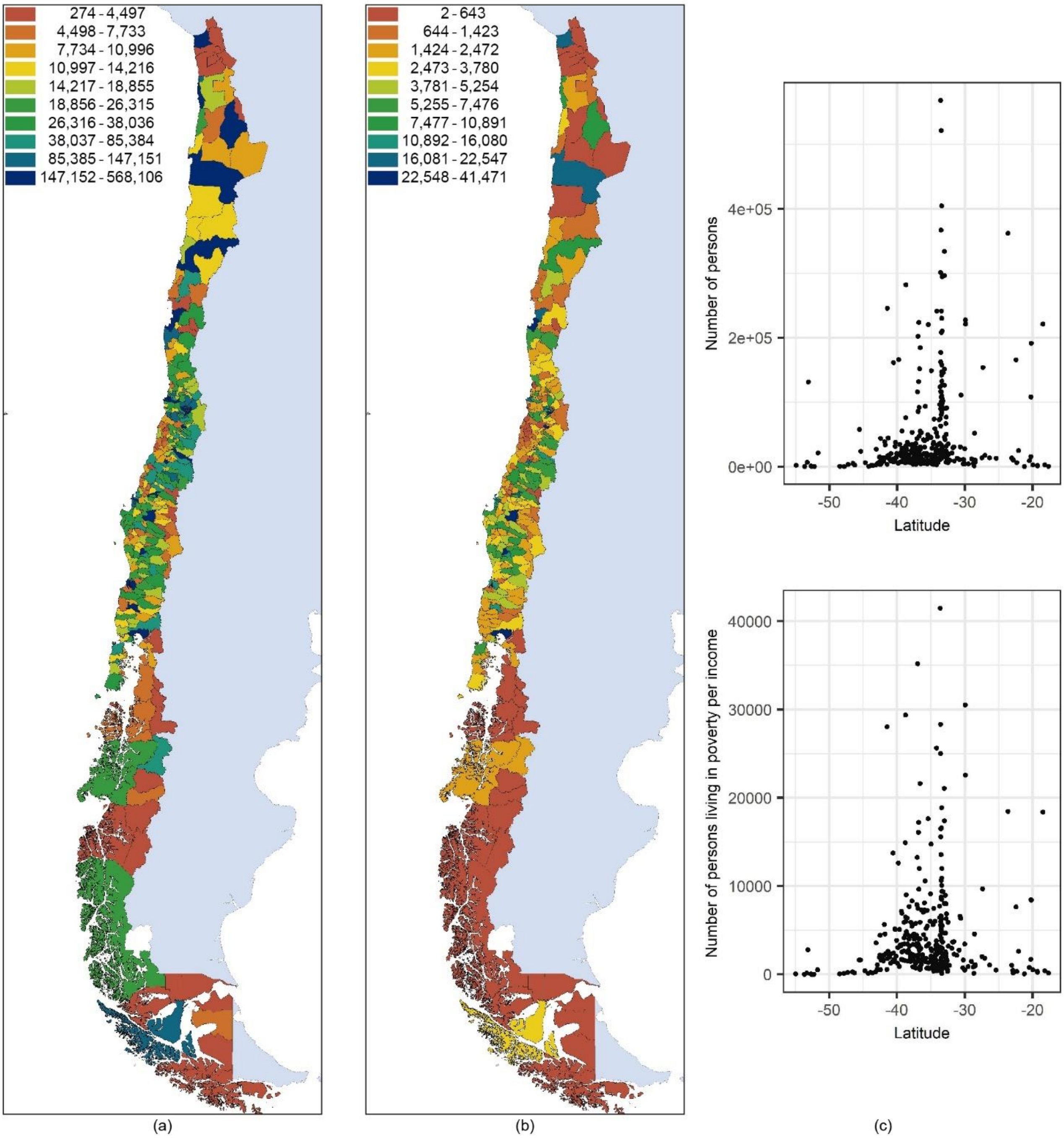

Figure 4. Population graphs of the municipalities: (a) total population, (b) people in poverty, (c) scatter plot between the population data and the latitude of the municipality.

3. Results and discussion

First of all, it was decided to evaluate the possibility of applying the adaptive thermal comfort model in each one of the municipalities. For this, it is good to remember that the ASHRAE-55-2017 adaptive thermal comfort model can be applied when $\overline{t_{pma(out)}}$ is between 10 and 33.5°C. Given that the application depends on a daily scale variable, the analysis of the possibility of application must be done over all the days of the year. Figure 5 represents the spatial distribution of the percentage of days of the year where the adaptive thermal comfort model can be applied. Just as can be seen, the application of the adaptive thermal comfort model is different in Chile. In this sense, it was detected that there is an upward trend in the application of the adaptive thermal comfort model from the lowest to the highest latitudes (see Figure 6.) where, the regions of the north of the country, like Antofagasta or Atacama, showed how most of their municipalities had an application of the adaptive model over 90% of the days of the year, while in the south, applications are below 20% of the days of the year. These results match those obtained in the application study made for the entire planet, where this same application trend for the ASHRAE-55-2017 was detected [64].

It is worth mentioning that in municipalities with a low application, this does not mean that a base temperature obtained with the ASHRAE-55-2017 adaptive thermal comfort model cannot be used to calculate the $HDH_{Adaptive}$ and $CDH_{Adaptive}$, but rather that the value used in most of the cases will be the value obtained from the horizontal extension in the limit conditions. Hence, in these cases, the base temperature will correspond to a static behavior pattern by the users due to difficulties in adapting to the climate, although the base temperature value to condition the spaces corresponds to a more representative value regarding the typical behavior guidelines of the users [50].

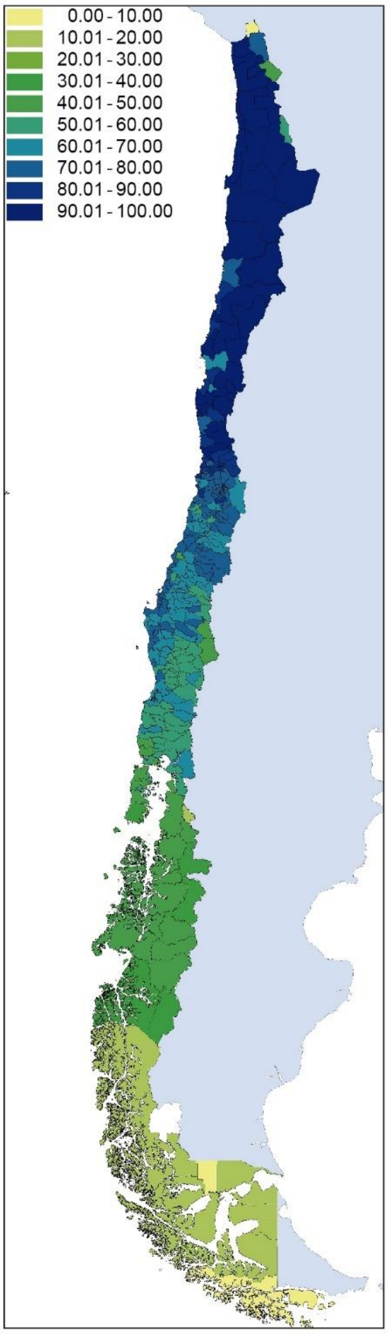

Figure 5. Percentage of the days of the year where the ASHRAE-55-2017 adaptive thermal comfort model can be applied in Chilean municipalities.

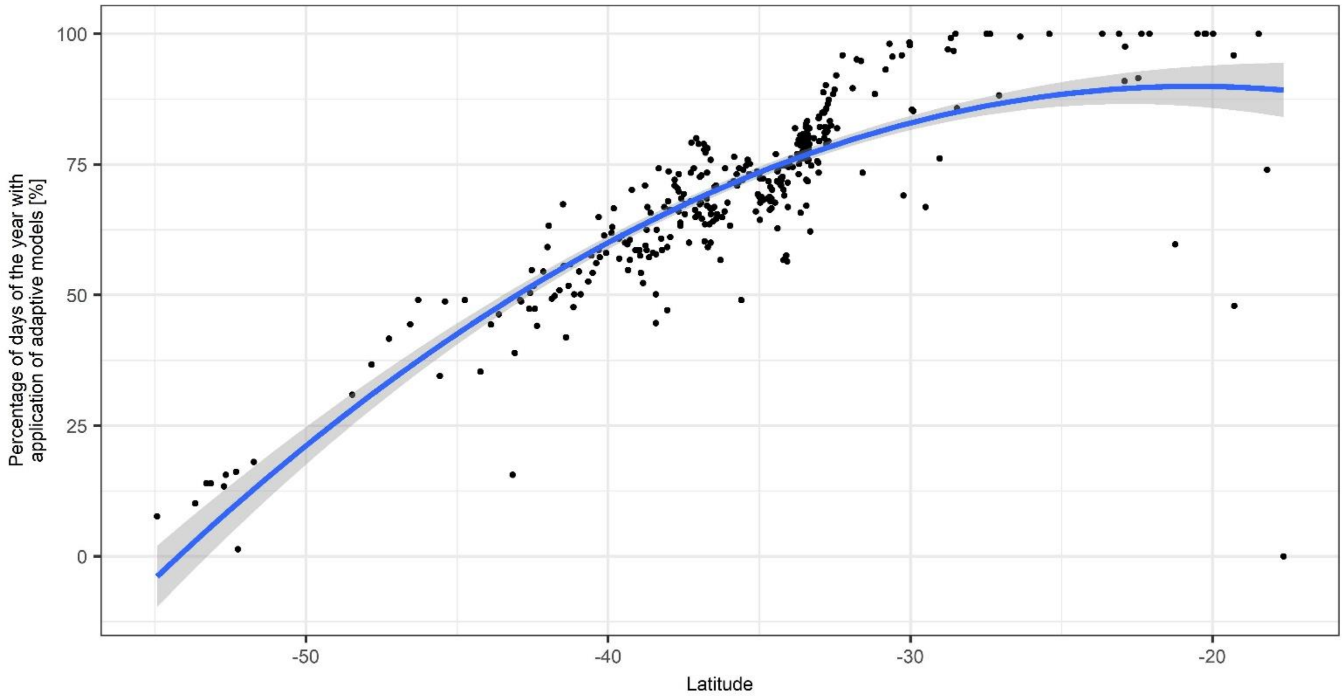

Figure 6. Scatter plot between the percentage of the days of the year where the ASHRAE 55-2017 adaptive thermal comfort model can be applied and the latitude of each municipality in Chile.

Once the application potential of the adaptive thermal comfort model was analyzed, the $HDH_{Adaptive}$, $CDH_{Adaptive}$ and $TDH_{Adaptive}$ values were obtained for each municipality to obtain the PADHI values. Figure 7 shows the PADHI values obtained from the three types of hourly degrees analyzed. Just as can be seen, the deciles obtained for $PADHI_{HDH}$ and for $PADHI_{TDH}$ were very similar, while a different distribution was obtained for $PADHI_{CDH}$. This is caused by the low incidence that the cooling degrees have in the total degrees of each municipality. In this sense, most of the municipalities showed that the heating degrees contributed more than 97.5% of the total degrees, and only some municipalities had a lower percentage. This despite that, in all cases, the heating contribution was significantly higher than cooling. This means that the energy poverty risk in the region is practically due to heating. In this sense, it was detected that only 2.89% of the municipalities had a change in the decile they were grouped in for $CDH_{Adaptive}$: the municipalities of Alto Hospicio, Antofagasta, Curepto, Empedrado and Providencia reduced the decile level, while the municipalities of Cerrillos, Pica, Recoleta, Rinconada and Tierra Amarilla rose in decile. Likewise, it is important to highlight the potential using PADHI has, since it will be able to detect those municipalities that really have an energy poverty risk. In this sense, the municipalities in the south of Chile are characterized on having a high heating demand due to the low outdoor temperatures. However, most of the municipalities have a low number of people in poverty (see Figure 4 (b)), so the poverty risk in these areas is low. Only the city of Punta Arenas would have a high risk among the municipalities in the south of Chile. It is also detected that there is a concentration of one municipality with an elevated risk located in the center of the country, mainly due to the high number of people in poverty. The main cities of the country are in these regions, namely Santiago, Concepción and Valparaíso, which have the highest number of inhabitants in the entire country. This high number means that the number of inhabitants in risk of poverty is higher than other regions, so this increases the needs of establishing government measures in these municipalities.

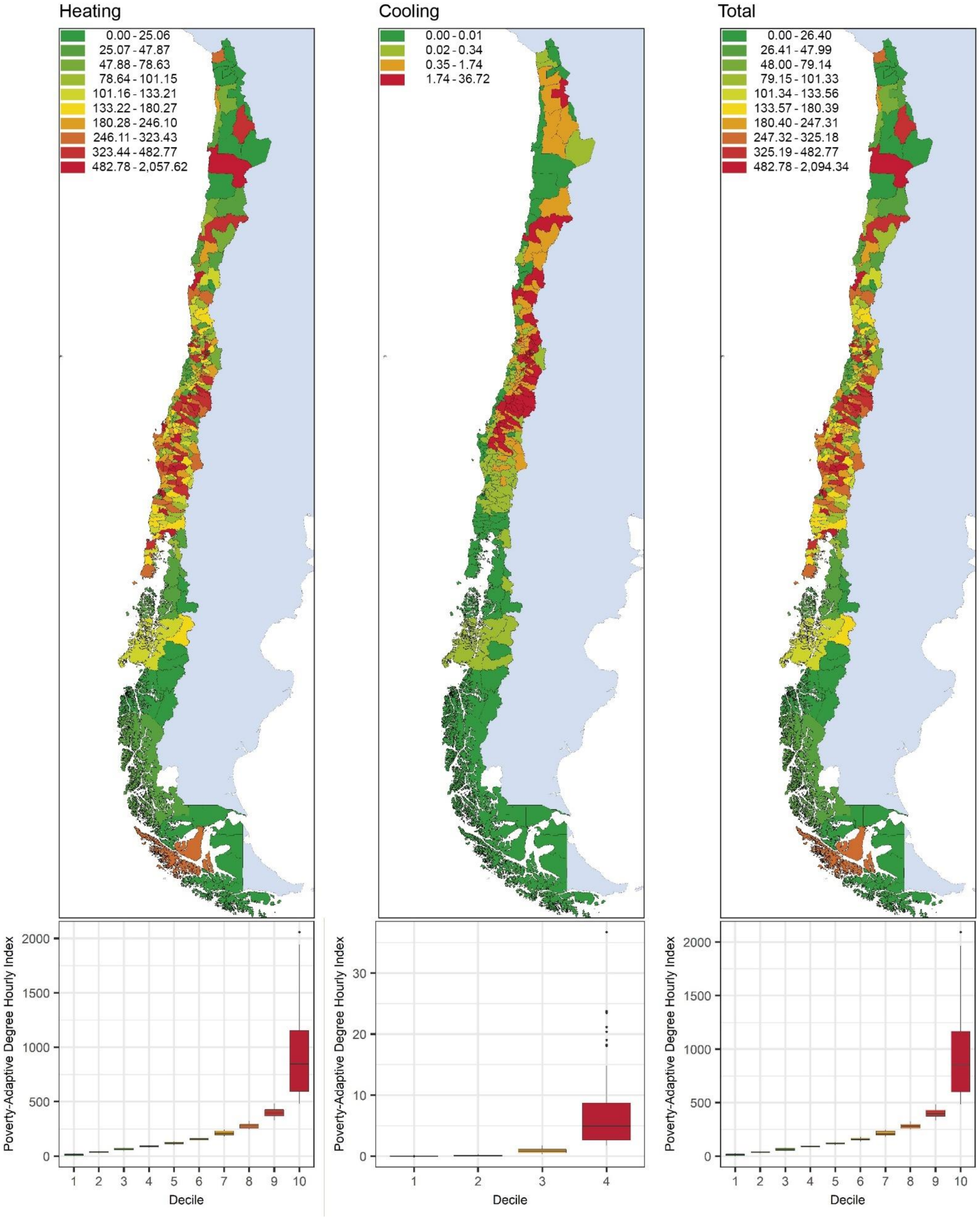

Figure 7. Distribution of the $PADHI_{HDH}$ (heating), $PADHI_{CDH}$ (cooling), and $PADHI_{TDH}$ (heating and cooling) values in Chilean municipalities. The lower part of the box diagrams represents each one of the deciles the municipalities are divided into considering the PADHI value obtained.

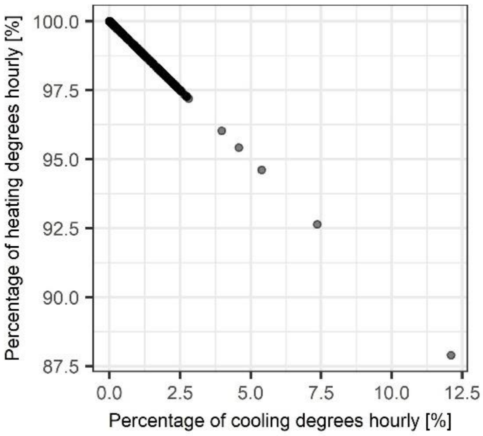

Figure 8. Scatter plot between the $HDH_{Adaptive}$ and $CDH_{Adaptive}$ percentage regarding the total.

This shows the advantages of using PADHI as it allows considering, in the same indicator, the energy poverty risk for the population in a situation of poverty and the energy demand considering the climate the buildings have. As a result, the actions can be concentrated in regions with a higher indicator, placing special importance on municipalities in the 10^{th} decile. It is worth highlighting the importance that the grouping of municipalities by deciles has, regarding the PADHI value, as it allows grouping the energy poverty risk in the region into ten levels. In this sense, the 10^{th} decile corresponds to the group of municipalities with a higher risk and where the government action measures against energy poverty must be focused on. However, it can be seen how the distribution of $PADHI_{TDH}$ values in the 10^{th} decile has a great variability, oscillating between 484.53 and 2,094.33 inh °C. This can generate complications when outlining suitable measures, as actions could be implemented for a municipality with a lower PADHI. For this reason, it was decided to run a single-dimensional cluster analysis of the municipalities from the 10^{th} decile to establish priority groups. The algorithm *k*-means was used for this. This is an iterative reallocation algorithm based on the concept of centroid of a group of individuals [65] that classifies individuals (in this case, the municipalities of the 10^{th} decile) into *k* groups. The essential factor to apply the algorithm is to determine the number of *k* that allows generating groups with a suitable independence and entity regarding the rest of the groups. In this way, it is guaranteed that the municipalities are within the suitable group. For the optimal selection of the number of groups, the Elbow method was applied (see Figure 9) and the silhouette index was analyzed (s(i)) (see Figure 10). The Elbow method consists of the selection of the optimal number of *k*, minimizing the total within-cluster sum of squares [66]. This consists in applying *k* means for different *k* values and in calculating the total within-cluster sum of squares. The path of the curve of the total within-cluster sum of squares allows detecting the elbow of said curve that indicates the optimal number of groups. Just as can be seen in Figure 9, the elbow detected in the graph corresponds to 2 groups, so this should be the number of groups that stand out in the 10^{th} decile. However, to ensure the suitability of this number, the *s(i)* value obtained was checked. *s(i)* shows the similarity of an individual with the rest of the individuals of the same group on a scale of -1 to 1, thus it reflects the quality of the grouping made. The value is obtained at an individual level for each municipality and is discussed with the average value obtained in all the municipalities. This allows seeing the general quality of the grouping. By analyzing the average result in Figure 10, it can be seen how the value obtained is an indicator that the municipalities are properly grouped.

In this way, the cluster analysis identified the two groups there are in the 10^{th} decile (see Table 3). Using this complementary analysis, it was detected that there are two risk groups, with the one with more risk formed by 9 municipalities grouped in a cluster with a centroid of 1,607.81 (that is to say, with an average PHADI value of 1,607.81 inh°C), and the rest of the municipalities of the most vulnerable decile are grouped in a cluster with PHADI values between 484.53 and 1,093.09 inh°C. As a result, the municipalities with the highest risk of energy poverty in Chile can be detected using this methodology (see Figure 11). The regional and municipal governments must establish measures for these municipalities to reduce energy poverty, be this by improving the income level of the most vulnerable families, by improving the energy performance of the existing stock, or by allocating support for energy purposes. These results can become more relevant on facing the current precarious situation of incomes and high expenses that is generating internal conflict in the country [52]. Likewise, the potential international implementation of the methodology is worth highlighting, since the information used does not correspond to the specific data of Chile, but rather that these can be obtained in other countries or regions. Therefore, PADHI on using data of people in poverty and heating and cooling degrees considering the climate, allows setting up a methodology that can be extrapolated to other regions.

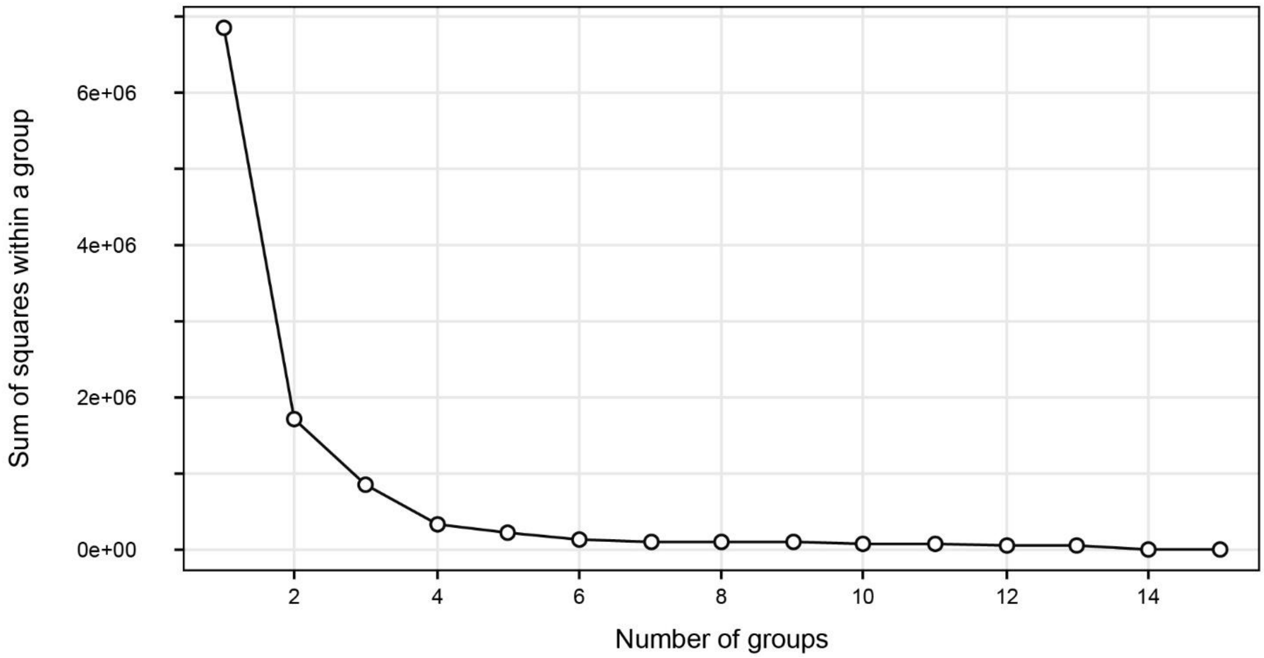

Figure 9. Representation of the total within-cluster sum of squares curve used to apply the elbow method.

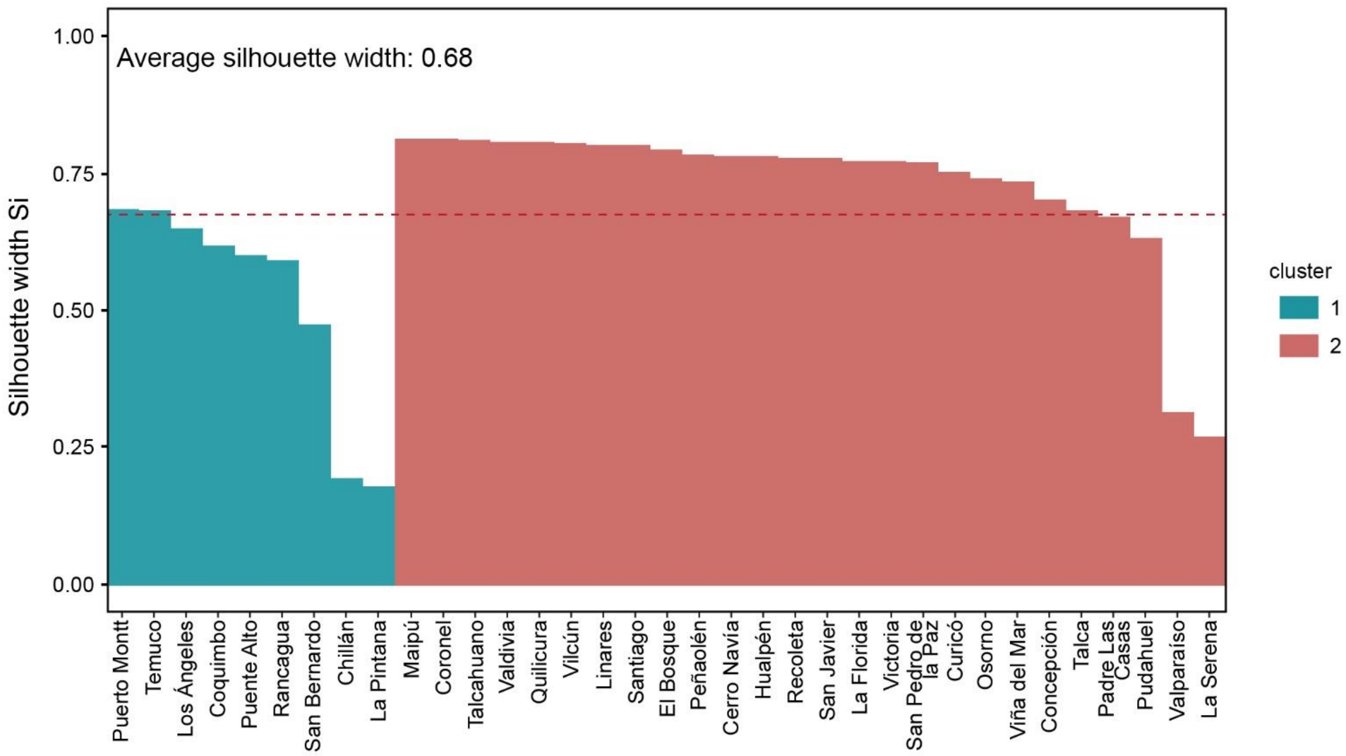

Figure 10. *s(i)* values obtained in the municipalities of the 10th decile, using two groups.

Table 3. Groupings of the municipalities in the 10th decile.

Group	Municipalities	Centroid of the indicator	Minimum and maximum range of values
1	Chillán, Coquimbo, La Pintana, Los Ángeles, Puente Alto, Puerto Montt, Rancagua, San Bernardo, Temuco	1,607.81	1,237.46-2,094.33
2	Cerro Navia, Concepción, Coronel, Curicó, El Bosque, Hualpén, La Florida, La Serena, Linares, Maipú, Osorno, Padre Las Casas, Peñalolén, Pudahuel, Quilicura, Recoleta, San Javier, San Pedro de la Paz, Santiago, Talca, Talcahuano, Valdivia, Valparaíso, Victoria, Vilcún, Viña del Mar	731.02	484.53-1,093.09

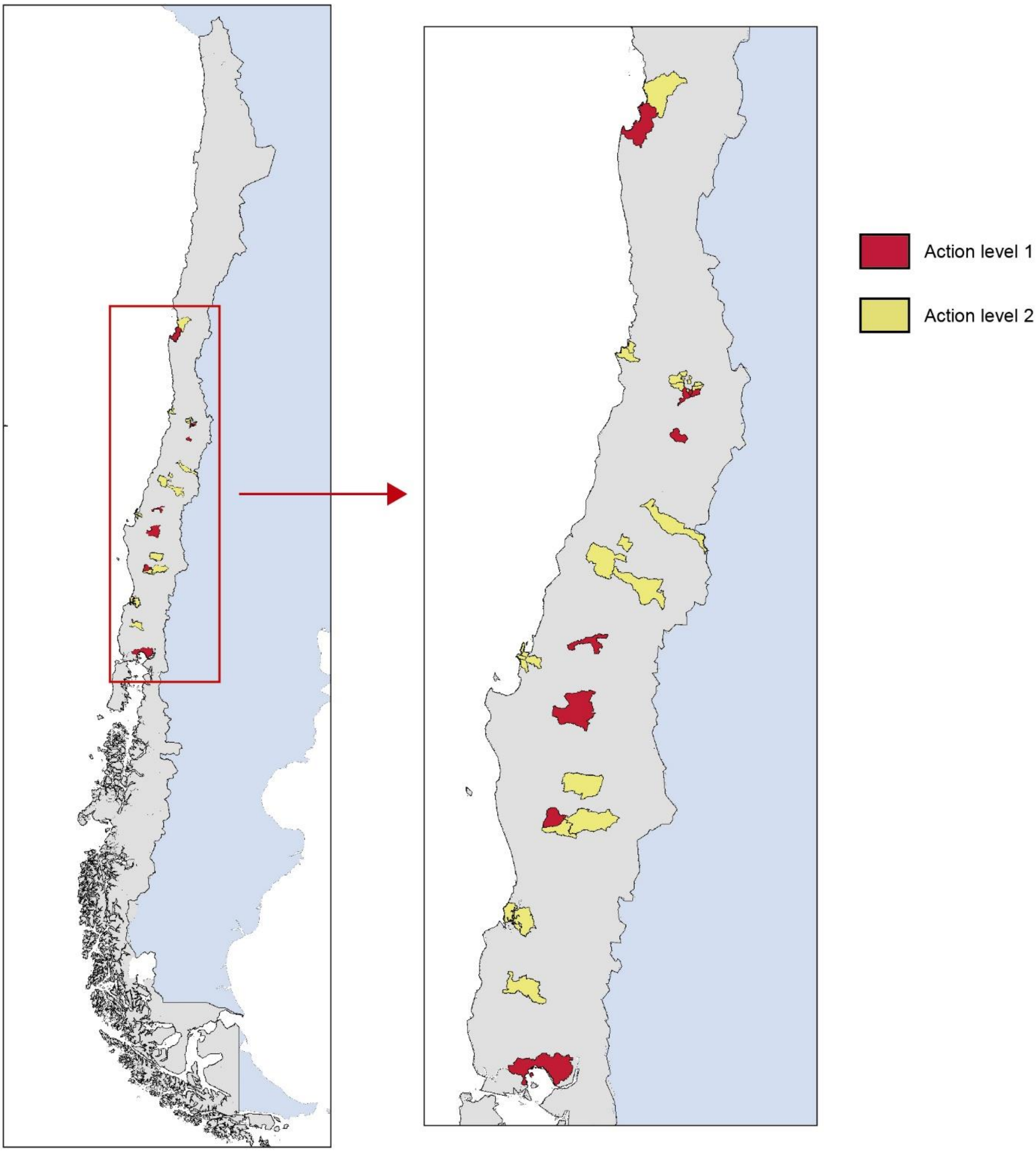

Figure 11. Municipalities with higher risk of energy poverty detected (10th decile) and action levels needed.

4. Conclusions

Energy poverty is a growing concern internationally, with harmful consequences for health and welfare in the home, as well as economic and political issues for the countries. Locating and eradicating energy poverty is a difficult task given its temporary, social and environmental variability and its private nature. Internationally, mainly in the northern hemisphere, different frameworks, approaches and indicators have been developed to measure and identify energy poverty. However, accurately identifying homes or regions with energy poverty issues is even more difficult. For this reason, some researchers have been working on the use of regional indicators to identify areas that are likely to have energy poverty issues [47,49,67,68]. However, in the southern hemisphere, the indicators based on demands, consumptions or statistical data are not applicable, as users adjust their comfort to reduce their consumption as much as possible [50]. They also use cheaper fuels like wood or kerosene [69], and there are no georeferenced databases with the energy data of dwellings that allow mapping easily, while in other cases, the problem is the access [44].

The definition and localization of energy poverty is the first step towards energy equality and the eradication of energy poverty [37]. For this reason, in this document we have moved forward in the development of a methodology to identify, at a country level, the areas with the highest probability of energy poverty-associated problems appearing, using two basic pieces of information like the climate and the level of income poverty of each municipality.

The empirical test of the methodology was done for the 364 municipalities of continental Chile. The methodology combines socioeconomic and climate indicators, applying adaptive thermal comfort models using the Poverty Adaptive Degree Hourly Index (PADHI) to assess the risk a region may have in cases of energy poverty.

The results show that the energy poverty risk in the region is practically due to heating, finding the municipalities with the highest risk in the center of the country, fundamentally due to the climate and the higher percentage of people in income poverty compared to other studies where it has been associated to cooling issues [49]. However, the municipalities in the south of Chile that are characterized on having a high heating demand due to low outdoor temperatures have a lower risk on having a lower number of people in a situation of poverty. Even so, it is necessary to mention that a low risk does not imply that there may not be problems related, for example, to the cheapest energy sources like Escobar & Bosso have identified [69,70].

The mapping and index, together, show aspects that stand out to recognize problems associated with climate-related income poverty, which could imply a lower indoor thermal comfort, thus identifying the critical municipalities for in-depth study of energy poverty or for Government action, and also for the application of other types of indicators at the building level, like the Fuel Poverty Potential Risk Index or its evolution linked with climate change [9,71]. The municipalities which have been defined as in falling into the 10^{th} decile of PADHI are those which have a higher risk of energy poverty for their population, a higher percentage of income poverty and climatic severity. This decile has also been analyzed by cluster to identify groups and locations with a higher risk. This allows governments to identify the critical points to run in-depth studies to establish the measures needed to reduce energy poverty and comply with the goal of eradicating energy poverty by 2050 [4]. It is also worth highlighting the potential international implementation of the methodology, since the data used can be obtained in other countries or regions where there is data about income poverty and climate.

5. Acknowledgements

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References

[1] L.A. White, Energy and the Evolution of Culture, Bobbs-Merrill Indianapolis, 1949.
[2] L. Mumford, Technics and human development: the myth of the machine, vol. I, Harvest Books, 1971.
[3] B. Sorensen, A history of energy: Northern Europe from the Stone Age to the present day, Routledge, 2013.
[4] Ministry of Energy (Chile), Energía 2050. Política Energética de Chile, Santiago de Chile, Chile, 2017.
[5] R. Day, G. Walker, N. Simcock, Conceptualising energy use and energy poverty using a capabilities framework, Energy Policy. 93 (2016) 255–264. https://doi.org/10.1016/J.ENPOL.2016.03.019.
[6] S. Bouzarovski, S. Petrova, A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary, Energy Res. Soc. Sci. 10 (2015) 31–40.
[7] H. Thomson, S. Bouzarovski, C. Snell, Rethinking the measurement of energy poverty in Europe: A critical analysis of indicators and data, Indoor Built Environ. 26 (2017) 879–901. https://doi.org/10.1177/1420326X17699260.
[8] A. Pérez-Fargallo, C. Rubio-Bellido, J.A. Pulido-Arcas, M. Trebilcock, Development policy in social housing allocation: Fuel poverty potential risk index, Indoor Built Environ. 26 (2017). https://doi.org/10.1177/1420326X17713071.
[9] A. Pérez-Fargallo, C. Rubio-Bellido, J.A. Pulido-Arcas, F. Javier Guevara-García, Fuel Poverty Potential Risk Index in the context of climate change in Chile, Energy Policy. 113 (2018) 157–170. https://doi.org/10.1016/J.ENPOL.2017.10.054.
[10] D.S. Shonali Pachauri, Energy Use and Energy Access in Relation to Poverty, Econ. Polit. Wkly. 2004. 39 (2004) 271–278.
[11] M. González-Eguino, Energy poverty: An overview, Renew. Sustain. Energy Rev. 47 (2015) 377–385. https://doi.org/10.1016/J.RSER.2015.03.013.
[12] B. Boardman, Fixing fuel poverty: challenges and solutions, Routledge, 2013.
[13] J. Rosenow, R. Platt, B. Flanagan, Fuel poverty and energy efficiency obligations - A critical assessment of the supplier obligation in the UK, Energy Policy 2013. 62 (2013) 1194–1203. https://doi.org/10.1016/j.enpol.2013.07.103.

[14] A.R. Ambrose, Improving energy efficiency in private rented housing: Why don't landlords act?, Indoor Built Environ. 24 (2015) 913–924.
[15] J. Love, A.C. Cooper, From social and technical to socio-technical: Designing integrated research on domestic energy use, Indoor Built Environ. 24 (2015) 986–998.
[16] C. Snell, M. Bevan, H. Thomson, Justice, fuel poverty and disabled people in England, Energy Res. Soc. Sci. 10 (2015) 123–132.
[17] K.-M. Brunner, M. Spitzer, A. Christanell, Experiencing fuel poverty. Coping strategies of low-income households in Vienna/Austria, Energy Policy. 49 (2012) 53–59.
[18] C. Liddell, C. Guiney, Living in a cold and damp home: frameworks for understanding impacts on mental well-being, Public Health. 129 (2015) 191–199.
[19] L. Middlemiss, R. Gillard, Fuel poverty from the bottom-up: Characterising household energy vulnerability through the lived experience of the fuel poor, Energy Res. Soc. Sci. 6 (2015) 146–154.
[20] C. Liddell, C. Morris, H. Thomson, C. Guiney, Excess winter deaths in 30 European countries 1980–2013: a critical review of methods, J. Public Health (Bangkok). 38 (2016) 806–814.
[21] M. Braubach, D.E. Jacobs, D. Ormandy, Environmental burden of disease associated with inadequate housing, WHO Regional Office for Europe, Copenhagen, 2011.
[22] A. Schueftan, A.D. González, Reduction of firewood consumption by households in south-central Chile associated with energy efficiency programs, Energy Policy. 63 (2013) 823–832. https://doi.org/10.1016/J.ENPOL.2013.08.097.
[23] R. Reyes, A. Schueftan, C. Ruiz, A.D. González, Controlling air pollution in a context of high energy poverty levels in southern Chile: Clean air but colder houses?, Energy Policy. 124 (2019) 301–311. https://doi.org/10.1016/J.ENPOL.2018.10.022.
[24] S. Scarpellini, P. Rivera-Torres, I. Suárez-Perales, A. Aranda-Usón, Analysis of energy poverty intensity from the perspective of the regional administration: Empirical evidence from households in southern Europe, Energy Policy. (2015). https://doi.org/10.1016/j.enpol.2015.08.009.
[25] Programa de las Naciones Unidas para el Desarrollo, Pobreza energética: análisis de experiencias internacionales y aprendizajes para Chile, Santiago de Chile, 2018.
[26] H. Thomson, C. Snell, C. Liddell, Fuel poverty in the European Union: a concept in need of definition?, People, Place Policy Online 2016. 10/1 (2016) 5–24. https://doi.org/10.3351/ppp.0010.0001.0002.
[27] R. Schuessler, Energy Poverty Indicators: Conceptual Issues., Cent. Eur. Econ. Res. (ZEW), Discuss. Pap. Ser. 2014. 14 (2014) 37.
[28] R. Moore, Definitions of fuel poverty: Implications for policy, Energy Policy 2012. 49 (2012) 19–26. https://doi.org/10.1016/j.enpol.2012.01.057.
[29] J. Hills, Getting the measure of fuel poverty. Final Report of the Fuel Poverty Review. Centre for the Analysis of Social Exclusion., London, 2012.
[30] P. Heindl, Measuring Fuel Poverty: General Considerations and Application to German Household Data., Finanz Arch 2015. 71 (2015) 178–215. https://doi.org/10.1628/001522115X14285723527593.
[31] J.C. Romero, P. Linares, X. López Otero, X. Labandeira, A. Pérez Alonso, Energy poverty in Spain. Economic analysis and proposals for action., Madrid, 2015.
[32] K. Rademaekers, J. Yearwood, A. Ferreira, S. Pye, I. Hamilton, P. Agnolucci, D. Grover, J. Karásek, N. Anisimova, Selecting Indicators to Measure Energy Poverty, Rotterdam, 2014.
[33] International Energy Agency (IEA), World Energy Outlook 2015: Methodology for Energy Access Analysis, París, 2015. https://doi.org/http://dx.doi.org/10.1787/weo-2015-en.
[34] P. Nussbaumer, M. Bazilian, V. Modi, Measuring energy poverty: Focusing on what matters, Renew. Sustain. Energy Rev. 16 (2012) 231–243. https://doi.org/10.1016/j.rser.2011.07.150.
[35] B. Mirza, A. Szirmai, Towards a new measurement of energy poverty: A cross-community analysis of rural Pakistan, 2010. https://doi.org/10.1111/j.1467-629X.1980.tb00220.x.
[36] M. Bhatia, N. Angelou, Capturing the Multi-Dimensionality of Energy Access, Livewire. (2014).
[37] R. Calvo, C. Amigo, M. Billi, A. Cortés, P. Mendoza, R. Tapia, M.A. Urquieta, A. Urquiza, ACCESO EQUITATIVO A ENERGÍA DE CALIDAD EN CHILE. HACIA UN INDICADOR TERRITORIALIZADO Y TRIDIMENSIONAL DE POBREZA ENERGÉTICA, Santiago de Chile, 2019.
[38] European Comission, European Union Statistics on Income and Living Conditions (EU-SILC)., Eurostat. (2014).
[39] B. Legendre, O. Ricci, Measuring fuel poverty in France: which households are the most vulnerable?., Energy Econ. 2014. 49 (2014) 620–628. https://doi.org/10.1016/j.eneco.2015.01.022.
[40] R. Miniaci, C. Scarpa, P. Valbonesi, Fuel Poverty and the Energy Benefits System: The Italian Case., Milano, 2014.
[41] P. Florio, O. Teissier, Estimation of the Energy Performance Certificate of a housing stock characterised via qualitative variables through a typology-based approach model: A fuel poverty evaluation tool, Energy Build. 89 (2015) 39–48. https://doi.org/10.1016/j.enbuild.2014.12.024.
[42] K. Fabbri, Building and fuel poverty, an index to measure fuel poverty: An Italian case study, Energy. 89 (2015) 244–258. https://doi.org/10.1016/j.energy.2015.07.073.
[43] A. Sánchez-Guevara Sánchez, Carmen; Neila Gonzalez, Francisco Javier and Hernández Aja, Towards a fuel poverty definition for Spain, in: World Sustain. Build. Conf., World Sustainable Building Conference 2014, Barcelona, 2014: pp. 11–17.
[44] J.C. Piai Paiva, G.D.M. Jannuzzi, C.A. de Melo, Mapping electricity affordability in Brazil, Util. Policy. 59 (2019) 100926. https://doi.org/10.1016/J.JUP.2019.100926.
[45] R. Walker, P. McKenzie, C. Liddell, C. Morris, Area-based targeting of fuel poverty in Northern Ireland: An evidenced-

based approach, Appl. Geogr. 2012. 34 (2012) 639–649. https://doi.org/http://dx.doi.org/10.1016/j.apgeog.2012.04.002.
[46] R. Walker, C. Liddell, P. McKenzie, C. Morris, Evaluating fuel poverty policy in Northern Ireland using a geographic approach, Energy Policy 2013. 63 (2013) 765–774. https://doi.org/10.1016/j.enpol.2013.08.047.
[47] C. Morrison, N. Shortt, Fuel poverty in Scotland: Refining spatial resolution in the Scottish Fuel Poverty Indicator using a GIS-based multiple risk index, Health Place. 14 (2008) 702–717.
[48] S.G. Simoes, V. Gregório, J. Seixas, Mapping Fuel Poverty in Portugal, Energy Procedia. 106 (2016) 155–165. https://doi.org/10.1016/J.EGYPRO.2016.12.112.
[49] J.P. Gouveia, P. Palma, S.G. Simoes, Energy poverty vulnerability index: A multidimensional tool to identify hotspots for local action, Energy Reports. 5 (2019) 187–201. https://doi.org/10.1016/J.EGYR.2018.12.004.
[50] A. Pérez-Fargallo, J.A. Pulido-Arcas, C. Rubio-Bellido, M. Trebilcock, B. Piderit, S. Attia, Development of a new adaptive comfort model for low income housing in the central-south of chile, Energy Build. 178 (2018) 94–106. https://doi.org/10.1016/j.enbuild.2018.08.030.
[51] Ministerio de Energía, Agenda de Energía. Un desafío país, progreso para todos, 2014.
[52] K. Sehnbruch, S. Donoso, Social protests in Chile: inequalities and other inconvenient truths about Latin America's poster child, Glob. Labour J. 11 (2020) 52–58. https://doi.org/10.15173/glj.v11i1.4217.
[53] Pontificia Universidad Católica de Chile, Cartografía interactiva de los climas de Chile, (n.d.).
[54] L.A. López-Pérez, J.J. Flores-Prieto, C. Ríos-Rojas, Adaptive thermal comfort model for educational buildings in a hot-humid climate, Build. Environ. 150 (2019) 181–194. https://doi.org/10.1016/j.buildenv.2018.12.011.
[55] American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy, Atlanta, GA, United States, 2017.
[56] European Committee for Standardization, EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics, Brussels, Belgium, 2007.
[57] Ministry of Housing and Urban-Rural Development (China), Evaluation Standard for Indoor Thermal Environment in Civil Buildings (GB/T 50785), Beijing, China, 2012.
[58] Instituut Voor Studie En Stimulering Van Onderzoek, ISSO 74 Thermische Behaaglijkeid, Publication 74, Rotterdam, Netherlands, 2004.
[59] S. Carlucci, L. Bai, R. de Dear, L. Yang, Review of adaptive thermal comfort models in built environmental regulatory documents, Build. Environ. 137 (2018) 73–89. https://doi.org/10.1016/j.buildenv.2018.03.053.
[60] C. Rubio-Bellido, A. Pérez-Fargallo, J.A. Pulido-Arcas, M. Trebilcock, Application of adaptive comfort behaviors in Chilean social housing standards under the influence of climate change, Build. Simul. 10 (2017). https://doi.org/10.1007/s12273-017-0385-9.
[61] W. Bustamante, R. Cepeda, P. Martínez, H. Santa María, Eficiencia energética en vivienda social: un desafío posible, in: Camino Al Bicenten. Propuestas Para Chile, 2009: pp. 253–282.
[62] Instituto Nacional de Estadística (Chile), Censos de Población y Vivienda, (2020).
[63] Instituto Nacional de Estadística (Chile), Estimaciones del Porcentaje de Personas en Situación de Pobreza por Ingresos a Nivel Comunal, año 2017, mediante Metodología de Estimación para Áreas Pequeñas, (2020).
[64] D. Bienvenido-Huertas, C. Rubio-Bellido, A. Pérez-Fargallo, J.A. Pulido-Arcas, Energy saving potential in current and future world built environments based on the adaptive comfort approach, J. Clean. Prod. (2019) 119306. https://doi.org/10.1016/J.JCLEPRO.2019.119306.
[65] J.A. Hartigan, M.A. Wong, Algorithm AS 136: A k-means clustering algorithm, J. R. Stat. Soc. Ser. C (Applied Stat. 28 (1979) 100–108.
[66] D.J. Ketchen, C.L. Shook, The application of cluster analysis in strategic management research: An analysis and critique, Strateg. Manag. J. 17 (1996) 441–458. https://doi.org/10.1002/(sici)1097-0266(199606)17:6<441::aid-smj819>3.0.co;2-g.
[67] W. Baker, G. Starling, D. Gordon, Predicting fuel poverty at the local level, Final Rep. Dev. Fuel Poverty Indic. Cent. Sustain. Energy. (2003).
[68] W. Baker, V. White, I. Preston, Quantifying rural fuel poverty, Cent. Sustain. Energy. (2008).
[69] À. Boso, C. Oltra, Á. Hofflinger, Participation in a programme for assisted replacement of wood-burning stoves in Chile: The role of sociodemographic factors, evaluation of air quality and risk perception, Energy Policy. 129 (2019) 1220–1226.
[70] B.Á. Escobar, Á.B. Gaspar, Representaciones sociales de la contaminación del aire y las estufas de leña en diferentes niveles socioeconómicos de la ciudad de Temuco, Chile, Rev. Int. Contam. Ambient. 34 (2018) 527–540.
[71] A. Pérez-Fargallo, C. Rubio-Bellido, J.A. Pulido-Arcas, M. Trebilcock, Development policy in social housing allocation: Fuel poverty potential risk index, Indoor Built Environ. 26 (2017) 980–998. https://doi.org/10.1177/1420326X17713071.