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Do we need complex and multidimensional indicators to assess energy poverty? The case of the Chilean indicator

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ABSTRACT

Energy poverty is a multidimensional and complex phenomenon, and several indicators have been developed to evaluate and quantify it. However, often greater complexity does not mean greater precision. In the case of Chile, the Energy Poverty Network established the Three-dimensional and Territorial Indicator of Energy Poverty (EPTTI in Spanish) to assess the energy poverty situation of Chilean families. The EPTTI is based on a multi-dimensional approach with 10 indicators. Although, their evaluation involves resources that may hinder a practical application. This study analyzed the consistency between the individual responses of an indicator and the adapted EPTTI evaluation, using a database of 641 families. The results show that the excessive energy expenditure and the type and energy source of heating systems indicators are the variables with the greatest influence on energy poverty assessments. These results served to both propose simplified approaches for energy poverty assessment with the indicator, and establish policies of action that regional governments should address to reduce the situation of energy poverty.

1. Introduction

1.1. Energy poverty: A twenty-first-century social issue

Energy is a key factor for the economic and social development of humanity, and it should be affordable, sustainable, and non-polluting [1]. In this sense, the built environment, which is responsible for about a third of all energy consumed in the world and about 40% of CO_2 emissions, plays an important role in the context of climate change and in decreasing environmental impact [2]. In the Chilean case, the residential, public, and commercial sector is responsible for 22% of the end energy use [3]. As a result, Chile has outlined different goals and commitments to reduce energy requirements in the built environment, in particular the Energy Policy 2050 [4]. However, energy efficiency is not the only dimension considered, since safe and quality access for all must be guaranteed. Energy consumption is considered an essential need linked to aspects of human well-being, so in the context of resource crisis and climate change, a sustainable energy requirement is sought, albeit one does not compromise occupant well-being.

Energy Poverty (EP) is a multidimensional and complex concept, usually understood as the inability to satisfy energy requirements or adequate environmental conditions [5–8]. However, operationalizing this concept and quantifying it has been and continues to be a challenge, in particular, because it is associated with the specific conditions of each context and place [6]. It has also been evidenced that EP has negative effects on people's health [9–11], is associated with cardiovascular, pulmonary, and respiratory diseases [12,13], as well as with excess deaths in summer and winter, thermal stress, anxiety, depression, and psychological stress [14–16]. Considering this, work has been done to understand the factors that produce it, to identify the risk of suffering it, and to generate measures to minimize it. It has been determined that it is a problem with an origin in multiple elements such as high energy prices, low family incomes, buildings with low energy efficiency, and inefficient appliances [17–21]. Efforts have also been made to quantify EP to size it and evidence it. However, measuring it is a challenge [6]. This is compounded by the limited availability of suitable data and indicators and the lack of consensus on how it should be conceptualized and measured [22].

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1.2. Existing indicators to quantify energy poverty

There are currently many definitions and indicators [23] and it has been stated that given EP's complexity it is difficult for a single indicator to consider all the associated factors, hence, it has been recommended to combine them for a holistic analysis [24]. Some studies have grouped these indicators into different categories, and although no consensus has been reached, it has been recognized that there are indicators based on household income and expenses, as well as multidimensional, self-reported, and econometric analysis ones, associated with energy efficiency, calculated based on thermal comfort and combined criteria [22,24,25].

Among the indicators based on income and expenses, perhaps the best known is the "ten percent rule", which defines that a household is in EP if it dedicates more than 10% of its income to energy expense payments [17]. This is a simple and easy-to-understand indicator, but it has been argued that it is not very accurate, and it has been questioned that it is an arbitrary threshold [26]. Seeking to clarify the definition of the threshold, the High share of energy expenditure in income (2 M) indicator emerged. It takes statistical conditions as a reference, considering domestic values, which allows making adjustments annually and assessing fluctuations. Thus, 2 M considers that a house is in a situation of EP when it doubles the median household energy expenditure or the average expenditure [25,27]. In some countries, such as Spain, this median expenditure coincides with the 10% established by Boardman [28]. The Minimum Income Standard (MIS) [29] also adjusts the way of evaluating the EP in terms of income, where the reference value is the income minus the minimum living costs, with those households that cannot cover energy expenditure with their remaining income being in EP. The MIS is a standard that must be defined domestically and is one that allows "having what you need to have the opportunities and choices needed to participate in society" [29]. However, none of these metrics identifies "false negatives", understood as those households who, due to the economic impossibility of covering the expenditure associated with energy, decrease their energy consumption, leading to thermal discomfort [27,30]. In addition, some households have irregular undeclared incomes, which also complicates its application. The Low Income, High Cost (LIHC) indicator is also associated with a minimum standard and states that EP occurs when "household income is below the monetary poverty threshold and energy consumption expenditure is higher than the threshold" [31]. In this sense, two thresholds must be determined: that of the poverty line and that of national expenditure, in addition to expenditure modeling, which hinders its application [32]. This metric, like the 2 M and MIS, corrects the "false positives" issue by focusing on the lower-income population. Nevertheless, this indicator does not take into account energy efficiency in homes or identify households that reduce their consumption on not being able to afford it. LIHC is not based on real household costs, but on costs that would be needed to keep housing comfortable. Similarly, the After Fuel Cost Poverty (AFCP) also allows identifying those households with lower incomes and expenses, defining that a household is in EP if its income after subtracting energy and housing costs is below the minimum acceptable income. It uses the MIS, the studies made by Heindl [33], and the applications carried out in Spain [34] and England [31], as a reference. Although it seeks that income is associated with well-being, it does not consider the thermal conditions required and the influence of behavior on energy consumption. Finally, the Hidden Energy Poverty (HEP) indicator makes it possible to identify "false negatives" by stating that EP occurs if the energy expenditure of a household does not reach a certain threshold. This can be a monetary reference value per month or a certain proportion of the national average absolute energy expenditure [25]. This indicator suggests that expenses are not necessarily indicative of meeting needs and recognizes that there are households that must choose between paying their utility bills or feeding themselves. It talks of "hidden" energy poverty in households that do not consume what they should because they cannot afford it. The HEP can identify these households, but cannot explain what happens in those that do not reach the expected expenditure. It also does not reflect those that have an "adequate" consumption but use adaptive strategies and actions that end up affecting their health.

These indicators are associated with economic aspects, but given their limitations, there are other types of indicators of a more qualitative nature, based on self-reports, or subjective conditions [6,35], which propose including data such as the presence of mold, the absence of central heating, and the ability to keep homes comfortable [35]. These indicators have been compiled in the European Union Survey on Income and Living Conditions to generate data on income, household conditions, and poverty [36]. This survey investigates the ability to heat the house on winter days, pay utility bills, and the physical conditions of the houses. In this way, problems to cover basic energy needs can be identified simply, but without great detail. The subjective and culturally dependent nature is acknowledged [37], but they can be used as complementary indicators.

Likewise, and in response to the fact that the economic aspect cannot represent EP alone, different multidimensional indicators have been suggested. These are more complex and require greater quantity and quality information as a basis. The Multidimensional Energy Poverty Index (MEPI) [38] approaches EP in terms of energy deprivation, considering different energy requirements, and assigns them an indicator and a deprivation threshold to subsequently perform a weighted total where it is determined whether the level of deprivation is acceptable or not [39]. According to its authors, MEPI is the result of the impact of EP and the quantification of its intensity, which allows understanding the state of households with a single number, but disregards other energy uses and its use outside the homes. Another indicator comprising several metrics is the Energy Development Index (EDI), developed by the international energy agency, which considers commercial energy consumption per capita, the share of commercial energy in total energy use, and the electrification rate [39]. It uses a weighted standard average of these three elements, and allows assessing the evolution of the domestic energy system, but does not identify the degree of energy deprivation of households [38]. The EDI includes commercial energy but does not adequately address household energy, since it focuses on the proportion of the population that has access to the electricity grid. The Energy Poverty Index (EPI), also integrates several aspects. It considers the energy deficit, a minimum percentage of energy consumption, and a measurement of the difficulty of access to energy [30,39], understood in different dimensions such as the frequency of purchase, distance, means of transport, and others, although it is limited to the home [30]. On the other hand, the Multi-Tier Framework for Measuring Energy Access (MTF), developed by the World Bank, is structured from a matrix that crosschecks five levels of access with different dimensions for each energy service. It is one of the most complete indicators [40]. It describes the realities of households better, considering both access to energy, as well as expenses and consumption [41], but it is complex and expensive to apply and does not integrate all the possible variables associated with EP [39]. The"Three-dimensional Energy Poverty Index" created by the Chilean Energy Poverty Network extends upon the MEPI, using the Multidimensional Poverty Indicator of the Chilean Ministry of Social Development as a methodological basis. The unit of analysis is the home and it understands the operationalization of energy poverty in four elements based on equitable and quality access to energy services. It is a territorialized index to synthetically account for EP conditions in Chile. The comfort and time range proposed, require local-level adaptation to consider occupation habits and housing use [41]. Its application has depended on the quantity and quality of information available and it does not incorporate the evaluation of qualitative data associated with users' thermal adaptation.

Another approach to address EP is econometric analysis, which rather than being indicators to diagnose a specific area, is a statistical model that seeks to identify vulnerable groups based on demographic, socioeconomic, and physical factors, even if the household is not classified in EP according to indicators such as LIHC and the 10% rule, among others. These analyses have been conducted in France [42] and Italy [43], and assess the influence of these factors on the likelihood of falling into EP. However, the studies made, focus on the influencing factors rather than on the identification of EP as such.

Similarly, energy efficiency has been established as a strategy to solve EP [44,45]. However, it is usually approached only from the consumption to thermally condition the house and does not include lighting and equipment expenses, which can generate discrepancies. It is also usually based on energy simulations, which can have performance gaps. This has been attributed in part to occupant behavior and is relevant considering that vulnerable households often resort to adaptive actions to regulate consumption that they cannot afford. For this reason, simulation-based indicators may have significant mismatches regarding the consumption of lower-income households [46,47].

In the same vein, it is important to highlight that energy consumption is associated with certain environmental conditions and despite this, there are not many energy poverty studies that consider thermal comfort. The Fuel poverty potential risk index (FPPRI)" [7,8] integrates the ASHRAE adaptive thermal comfort model into Chilean social housing consumption simulations using the 10% indicator. It also looks at the urban context and the characteristics of the building to measure the risk of suffering energy poverty considering the income decile of the family living there and allows making future predictions by applying climate change models [8]. However, this indicator also does not integrate consumption for needs other than thermal conditioning. On the other hand, the percentage of hours in comfort has also been used [48] as an indicator, where those households with the longest time outside comfort are considered more vulnerable than others. This is based on the relationship between outdoor and indoor temperatures rather than adjusted consumption. In both cases, simulation data is relied on and could be optimized if monitored data and/or self-reported conditions were added. It can be seen that there are many important indicators and more are being developed. This is because EP characteristics are associated with the specific conditions of each place and context [49]. This has generated many developments from the Boardman indicator in 1991 (TPR) to 56 indicators in 6 areas (Climate, Facilities/housing, Mobility, Socio-economic aspects, Policy and regulatory framework, Participation and awareness raising) of the Energy Poverty Advisory Hub (EPAH) [50]. Therefore, it has been seen that the indicators have become increasingly complex due to the multidimensionality of the phenomenon, but also because of the complexity of having available information. As a result, the EPAH indicates, referring to the use of the 56 indicators that "It's recommended to start with them and identify which ones, among all of them, can be relevant to characterize your specific local energy poverty and a way for you to monitor whether the challenges are growing or if you are on track to eradicate energy poverty in your municipality". In this sense, the advantages and disadvantages of using the indicators may be associated with different aspects such as the characteristics of the region of study, the existing information collection tools, and the databases, etc. A simple indicator may be useful in those countries, regions, or municipalities with few information sources which are looking to implement measures, and a complex indicator for those with more substantial information sources that allow for greater accuracy. However, to date, no research has been made on the capacity of simple indicators to handle multidimensional indicators to identify the phenomenon.

1.3. Adapted indicator for Chile: The three-dimensional and Territorial Indicator of Energy Poverty

The Three-dimensional and Territorial Indicator of Energy Poverty (EPTTI, in Spanish) is an indicator developed for Chile [51,52] to address the weaknesses detected, both nationally and internationally, in existing indicators. Thus, EPTTI includes variables associated with energy and the country's climatic variability, as well as income fluctuations and economic inequalities [51]. This results in a holistic indicator adapted to the characteristics of Chile with 4 dimensions [51]: 1) Food and hygiene; 2) Lighting and electrical appliances; 3) Air conditioning of the dwelling; and 4) Equity of energy expenditure (based on energy expenditure). The number of indicators needed to make evaluations in the country was chosen in each of these dimensions, resulting in 18 indicators to be used [51]. The EPTTI's dimensions and indicators are summarized in Fig. 1. EPTTI understands that a dwelling will be in EP when the following 2 situations occur: (i) the dwelling has a dimension with all its indicators below the energy poverty threshold (Table 1), or (ii) the dwelling does not exceed the threshold in four of the indicators regardless of its dimension.

Recently, EPTTI was adapted (See Fig. 1) to be applied in social housing settings with similar characteristics (e.g., built the same year) [52]. In these cases, EPTTI had a limited application with indicators that were sensitive to larger scales (e.g., at a national scale). Hence, the proposed modification looks to increase the indicator's sensitivity. In this sense, the results obtained in previous studies showed the effectiveness of the indicator for making energy poverty assessments in social housing. In any case, the large number of dimensions and indicators could limit its wider application as obtaining information on all indicators can be an elusive challenge for social workers and technical staff in charge of energy poverty assessment. All this leads to questions about the need or not for complex and multidimensional indicators. Is there a practical difference when it comes to classifying households as energy poor?

For this reason, this study looks to determine the most influential variables considered in the adapted EPTTI and simplify this indicator for a more accurate and effective application in real cases.

2. Methodology

2.1. Dataset used

For this research, a dataset was generated with real social housing data. Social housing was chosen from the Michaihue residential neighborhood in San Pedro de la Paz (Chile). This neighborhood was recently identified by the Ministry of Housing and Urbanism of Chile (MINVIU, in Spanish) as a neighborhood with several problems, such as the poor condition of the buildings, high population density, and concentration of poverty. For this reason, the setting chosen was suitable to assess the adapted EPTTI, in particular, the neighborhood's La Estrella (with 274 homes) and Michaihue Complexes (with 716 dwellings) (Fig. 2).

To assess the ETTPI, the technical evaluation was combined with door-to-door surveys made to the families. The format of the surveys and their questions was made by the authors. The questions and answers format made it possible to assess most of the dimensions and indicators (Fig. 3). Specifically, the results of the survey were used to evaluate D1-I1, D1-I2, D2-I1, D2-I2, D2-I3, D3-I2, D4-I1, and D4-I2 (Fig. 1). 641 valid surveys were obtained, 64.8% of the homes in the area of analysis. This information was then incorporated into the dataset.

A different procedure was used to analyze D3-I1 (indoor temperature) and D3-I3 (indoor relative humidity). D3-I3 was obtained from information in Chile's National Air Quality Information System (NAQIS) [53], while D3-I1 was obtained through energy simulations. The energy simulations were performed using EnergyPlus. For this, representative housing typologies of most of the analysis area's constructions were chosen (Fig. 4). In the case of the Michaihue complex, the predominant construction is residential blocks with 2-bedroom apartments, with an average floor surface area of 38.5 m^2. For La Estrella, the predominant typology is the single-family house. However, there are different typologies that vary in both the envelope surface and distribution. For this study, the 5 typologies indicated in Fig. 4 were considered. The number of bedrooms in each house varies: (i) dwelling-1 (Dw-1) has 1 bedroom; (ii) Dw-2 and Dw-3 have 2 bedrooms; and (iii) Dw-4 and Dw-5 have 3 bedrooms. The number of people assigned for the simulations was

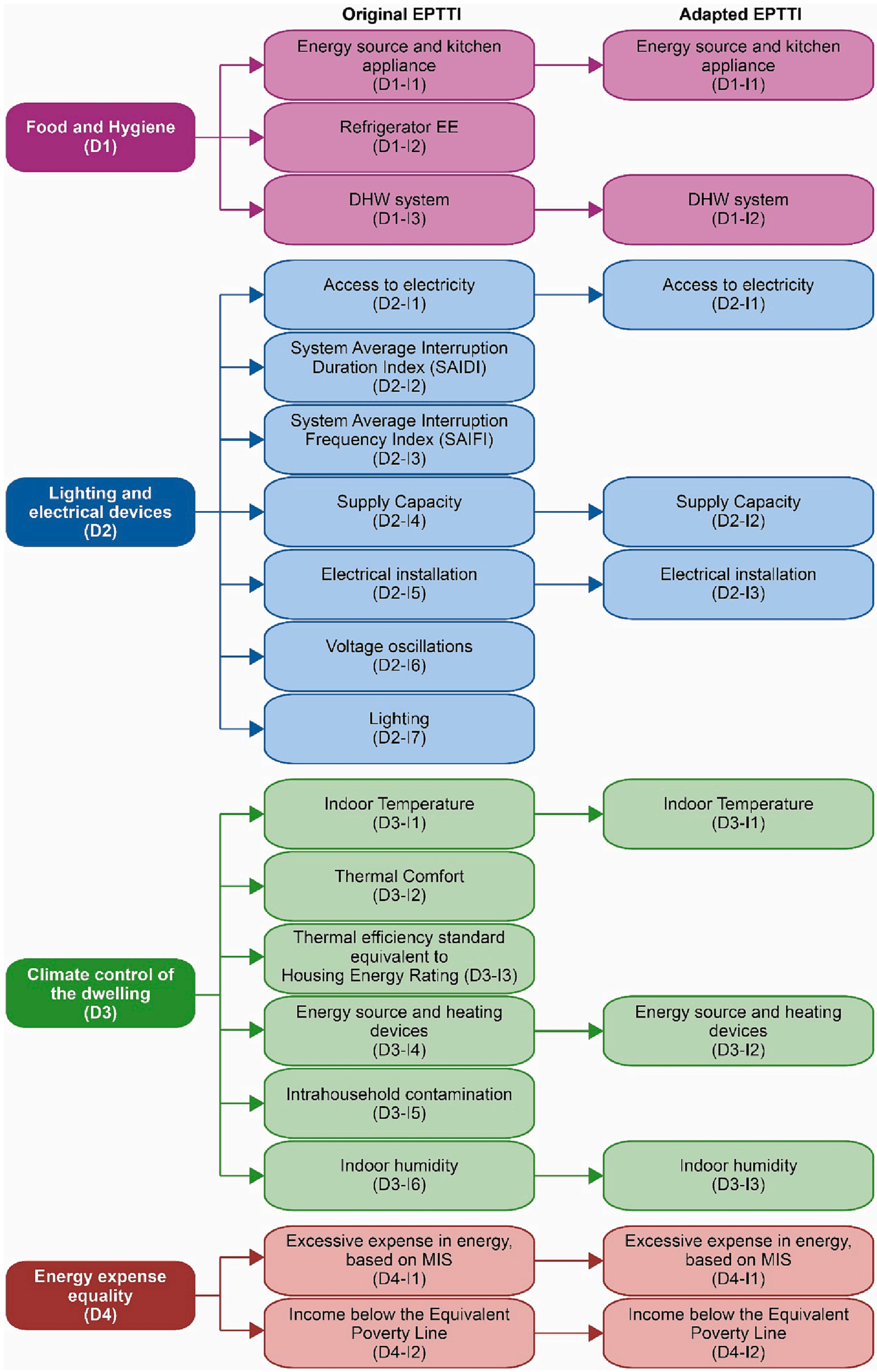

Fig. 1. Dimensions and indicators of the EPTTI [51] and adapted EPTTI [52].

Table 1
Thresholds of the adapted EPTTI's indicators.

Dimension	Indicator	EP	EP Exceedance
Food and Hygiene (D1)	Energy source and kitchen appliance (D1-I1)	Kerosene, coal, wet firewood or waste with open combustion	Gas, electricity, firewood, pellet, solar energy, and closed combustion
	DHW System (D1-I2)	Does not have DHW or has an electrical system not authorized by the SEC	Has DHW
Lighting and electrical devices (D2)	Access to electricity (D2-I1)	Not connected to grid, illegal connection or uses own generator whose fuel is bought more than an hour away	Connected to grid with an unaltered panel
	Supply Capacity (D2-I2)	Has 2 or fewer electrical circuits	Has 3 or more electrical circuits
	Electrical installation (D2-I3)	Irregular or home-made electrical installations	There are no irregular or home-made electrical installations
Climate control of the dwelling (D3)	Indoor Temperature (D3-I1)	The home is not kept under the lower limit of ASHRAE 55:2017 adaptive thermal comfort model, more than 46.8% of the year	The home is kept under the lower limit of ASHRAE 55:2017 adaptive thermal comfort model, less than 46.8% of the year
	Energy source and heating devices (D3-I2)	Kerosene, coal, firewood or waste for heating	Gas, electricity, dry firewood, pellet, logs and/or solar energy
	Indoor humidity (D3-I3)	There are floods, leaks or presence of humidity inside the dwelling, that favor the presence of mold	There are no floods, leaks or presence of humidity inside the dwelling, that favor the presence of mold
Energy expense equality (D4)	Excessive expense in energy, based on Minimum Income Standard (MIS) (D4-I1)	Available income of home – (costs of dwelling + energy expense of home) < equivalent poverty line	Available income of home – (costs of dwelling + energy expense of home) > equivalent poverty line
	Income below the Equivalent Poverty Line (D4-I2)	Income of home is below equivalent poverty line	The rest of the indicators must be assessed together

established using the criteria established in the Sustainable Housing Construction Standards [54] (ECSV in Spanish). It was established that the number of people was equal to the number of bedrooms plus 2 (Table 2). The load and temperature setpoint values also used the values established in the ECSV. The absolute values established for occupancy and lighting loads, ventilation flow rate, and temperature setpoint for the heating installation are indicated in Table 3, while the percentage distributions throughout the day are indicated in Fig. 5. It is important to note that the buildings in the area do not have cooling systems, hence these have not been considered in the simulations. The thermal properties of the buildings' envelope are indicated in Table 4.

2.2. Sensitivity analysis

The database was analyzed in its entirety (N = 641), classifying housing between energy poor and not poor, using the adapted EPTTI indicator. According to the thresholds defined in Table 1, it is established that a house is in energy poverty when it does not exceed the threshold established in 4 of the 10 indicators, or if there is a dimension where all its indicators do not exceed the threshold.

Subsequently, 4 groups were created based on the expenditure percentage, to evaluate the differences between using the indicator solely based on the expenditure percentage and the simplified one. The distribution of the sample in subgroups based on income-expenditure looks to generate intentional subsamples to analyze the variables in each one of these, to finally discard, as on evaluating the entire dataset, variables associated with certain income or expenditure conditions and/or associated Hidden Energy Poverty, are left hidden. The groups were established to have a similar number of families in the different groups and with thresholds rounded to whole numbers. Table 5 shows the groupings made.

The EPTTI variable was analyzed for the other variables starting with a complete analysis of the data without separating into groups, and then with analysis discriminated by group. The following steps were used:

1. Study of the complete data, with all the variables compared to EPTTI. For this, the variables that had agreement above 0.21, using the kappa coefficient, were chosen. The kappa coefficient (κ) is used to evaluate the consistency or reproducibility of measuring instruments whose result is categorical (2 or more categories). It represents the proportion of agreements observed beyond chance compared to the maximum possible agreement. κ = 0 is associated with a poor agreement, from 0.21 is considered acceptable, and over 0.81, is almost perfect [55]. The kappa consistency index is expressed and calculated using the following formula:

$$K = \frac{P_0 - P_e}{1 - P_e} \quad (1)$$

Where, P_0 is the proportion of agreements observed (Eq. (2)) and P_e is the proportion of expected agreements (Eq. (3)).

$$P_0 = \frac{NEP_{EPTTI-Variable} + EP_{EPTTI-Variable}}{N} \quad (2)$$

$$P_e = \frac{NEP_{EPTTI} \bullet NEP_{Variable} + EP_{EPTTI} \bullet EP_{Variable}}{N^2} \quad (3)$$

Where $NEP_{EPTTI-Variable}$ are the homes that are not in EP according to EPTTI, classified as not energy poor homes with the analyzed variable; $EP_{EPTTI-Variable}$ are the homes in EP according to EPTTI, classified as homes in EP with the analyzed variable; NEP_{EPTTI} is the total number of not energy-poor dwellings according to EPTTI; EP_{EPTTI} is the total number of homes in EP according to EPTTI; $NEP_{Variable}$ is the total number of not energy-poor dwellings with the analyzed variable; $EP_{Variable}$ is the total number of dwellings in EP with the analyzed variable; and N is the total number of dwellings.

Sensitivity and specificity were also evaluated in the analysis. Sensitivity is the probability of correctly classifying a not energy poor home, that is, the ability of the test to detect not being in energy poverty (Eq. (4)). The sensitivity ranges from 0 to 1 (0 to 100%). The higher the numerical value, the better the ability to detect not energy-poor homes;

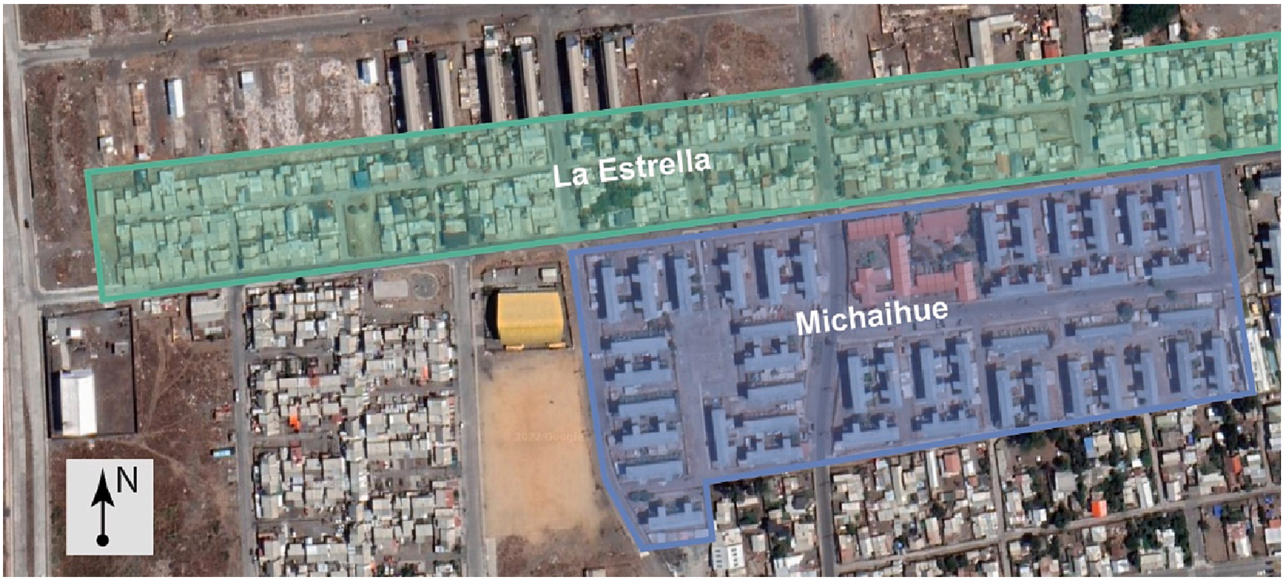

Fig. 2. Housing complexes from the Michaihue neighborhood considered in the research.

and (ii) the specificity, the probability of correctly classifying an energy-poor home, that is, the ability of the test to detect the energy poor (Eq. (5)). The specificity ranges from 0 to 1 (0 to 100%). The higher the numerical value, the better the ability to detect homes in energy poverty.

$$\text{Sensitivity} = \frac{True''NotEP''}{True''NotEP'' + False''EP''} \tag{4}$$

$$\text{Specificity} = \frac{True''EP''}{True''EP'' + False''NotEP''} \tag{5}$$

2. Combined analysis of the variables that meet the condition of a kappa above 0.21 [55]. The analysis was carried out independently both for the entire dataset and for the established expenditure groups.

3. Results

3.1. Total set of dwellings: classification between EP and not EP according to EPTTI.

The entire set of homes analyzed was evaluated with the adapted EPTTI, detecting that 71.6% of the households analyzed were in a situation of energy poverty. Using these evaluations, the level of agreement between the EPTTI evaluations and the evaluation provided by each indicator was then analyzed. Considering the evaluation of each indicator as the only means to determine whether or not the household was in EP, Table 6 summarizes the values obtained in the Kappa coefficient, as well as the sensitivity and specificity. As can be seen, the values obtained with the kappa coefficient had a wide range of values from 0.046 to 0.592. Considering the threshold of 0.21 for a mean agreement between EPTTI and the indicator [55], it could be seen how most indicators obtained values below this threshold. In this sense, only D3-I2 (energy sources and heating devices) and D4-I1 (excessive expense in energy, based on MIS) obtained values greater than 0.21. Thus, it was possible to establish an agreement between the individual energy poverty classifications of each indicator and the final evaluation provided by EPTTI. This aspect is of great interest since it could mean that EPTTI evaluations could be simplified in certain cases by using just 2 indicators. In any case, it should be noted that the agreements obtained by D3-I2 and D4-I1 were not from the same dwelling, since D4-I1 obtained an agreement value that was 238.71% higher than that obtained by D3-I2.

The sensitivity and specificity coefficients were analyzed once the agreements obtained between the indicators and the EPTTI had been evaluated (Table 6). As can be seen, the sensitivity and specificity coefficients obtained different ranges of values. While the sensitivity ranged from 0.301 to 0.640, the specificity did so from 0.736 to 0.923. Since sensitivity is the ability to correctly evaluate the cases that were not in energy poverty, it can be seen how the indicators have little effectiveness when evaluating households that were not in energy poverty. Therefore, from this analysis, it can be seen how the indicators tended to find more situations of energy poverty than those actually established by EPTTI. For the indicators with the highest level of agreement (D3-I2 and D4-I1), it can be noted that D4-I1 obtained the highest level of sensitivity (0.640), thus detecting that excessive energy expenditure allows better distinguishing whether the home may or may not be in EP.

Despite this low capacity to detect not energy poor households with the individual application of the indicators, the analysis was complemented by the combined use of the 2 indicators with the highest level of agreement. As a result, the statistical parameters for the values established by D3-I2 and D4-I1 compared to EPTTI were then assessed. To do this, if the household was classified as not EP for both indicators, it was classified as not EP, and if it was classified as EP in either of the two variables, it was classified as EP. Fig. 6 shows the confusion matrix obtained, as well as the statistical coefficient values. As can be seen, the agreement with the 2 variable combination was greater than with the individual analysis of each indicator. Thus, while D3-I2 and D4-I1 obtained values of 0.248 and 0.592, respectively, the 2 indicators combined obtained a kappa of 0.629. Thus, the agreement of the 2 indicators' evaluations allowed obtaining responses closer to those of the EPTTI. This can be seen in the agreements shown in the confusion matrix: (i) for households that were not in energy poverty, there were 111 agreements compared to the 182 classified by EPTTI; and (ii) for households that were in EP, there were 442 compared to a total of 459. Apart from these agreements, errors were observed in the estimates provided, such that 71 not-poor households were classified as EP and 17 poor households were classified as not EP. Again, the same tendency to classify more EP cases was detected, as was observed with the individual application of the indicators. However, in this case, it was possible to appreciate how the combination of the 2 indicators allowed making more suitable estimates of the families' situations. This aspect can be

Dimension	Indicator	Source of Information
D1	D1-I1	Survey
	DI-I2	Survey
D2	D2-11	Survey
	D2-I2	Survey
	D2-I3	Survey
D3	D3-I1	Thermal assessment of case study
	D3-I2	Survey
	D3-I3	NAQIS
D4	D4-I1	Survey
	D4-I2	Survey

Indicator	Question	Reponse
D1-I1	Presence of gas cylinder	Yes No
D1-I2	Presence of Boiler	Yes No
D2-I1	Indoor electrical panel	Yes No
	Home-made modification of electrical panel	Yes No
D2-I2	Number of electrical circuits inside it	Number
D2-I3	Presence of electrical conditions conducive to fires	Yes No
	State of cabling inside the dwelling	Loose and visible Closed and visible Embedded
D3-I1	Main orientation of the dwelling	North South East West
	Usage time of dwelling	Morning-Night All day long
D3-I2	What fuel do you use for heating?	Wood Electricity Liquid Gas Natural Gas Kerosene Coal Does not use
	Problems of the dwelling. Moisture in bedrooms.	Yes No
	Problems of the dwelling. Water leaks.	Yes No
	Flooding due to rain on first and top floor	Yes No
D3-I3	Presence of humidity: Walls	Yes No
	Presence of humidity: Roof	Yes No
	Rainwater leaks through windows	Yes No
D4-I1	What is your monthly income?	Amount
D4-I2	How many people live in the dwelling?	Amount
	What is the situation of the dwelling?	Own paid Own, paying Rented with contract Rented without contract Transferred Usufruct Irregular Loan for use
	How much do you approximately pay for the mortgage of this dwelling? (US$)	<282 282–423 424–564 565–705 706–847 >848
	How much do you approximately pay in rent for this dwelling? (US$)	<141 142–282 283–423 424–564 >565
	How much do you pay monthly for administration fees? (US$)	<7 8–14 15–21 22–28 29–35 36–42 43–49 >50 Doesn't pay administration fees
	How much do you spend monthly in the summer on…?	<14 15–21

Fig. 3. Data source of the EPTTI variables and survey format.

observed in the values obtained for the sensitivity and specificity coefficients, with values above 86%. Therefore, the combined evaluation of energy sources and heating devices (D3-I2) and excessive expense in energy (D4-I1) could provide a similar response to that expected with EPTTI. This aspect may be relevant for EPTTI applications since it would allow assessing families faster by simplifying the application of a multidimensional indicator on using the indicators that have the greatest impact.

3.2. Differences between family unit groups

The agreement analysis showed that the D3-I2 and D4-I1 indicators had the greatest similarity with the assessments provided by EPTTI. However, there may be differences if the study sample is grouped into income expenditure clusters, as has been observed in state-of-the-art works [56,57]. For this reason, the analysis was complemented by the agreement assessments between the different indicators and the groups established in Table 4.

First the results obtained for group 1 (income expenditure percentage less than or equal to 5%) were analyzed. Table 7 shows the values obtained in the statistical coefficients with the individual application of the indicators. In this case, it can be seen that the agreement threshold of 0.21 is only exceeded by D4-I1. Thus, D3-I2 does not have the level of agreement with EPTTI obtained with the total dataset. This shows that the excessive energy expenditure indicator could be used to make an assessment similar to those of EPTTI in families with an income expenditure of less than 5%. In this sense, the values observed for sensitivity and specificity with D4-I1 were higher than 79%, so the indicator could classify, in a very similar way to EPTTI, both the households in an EP situation and those that were not. For the rest of the indicators, it was remarkable that an increase in sensitivity of between 0.4 and 18.4% was detected, while the specificity decreased between 3.5 and 22.8%. Therefore, all the indicators ranked households in EP worse than in the case of using the entire dataset. This aspect can be attributed to a greater similarity in the percentages of cases in each group: 55% of the families were in EP, while the remaining 45% were not. Despite this,

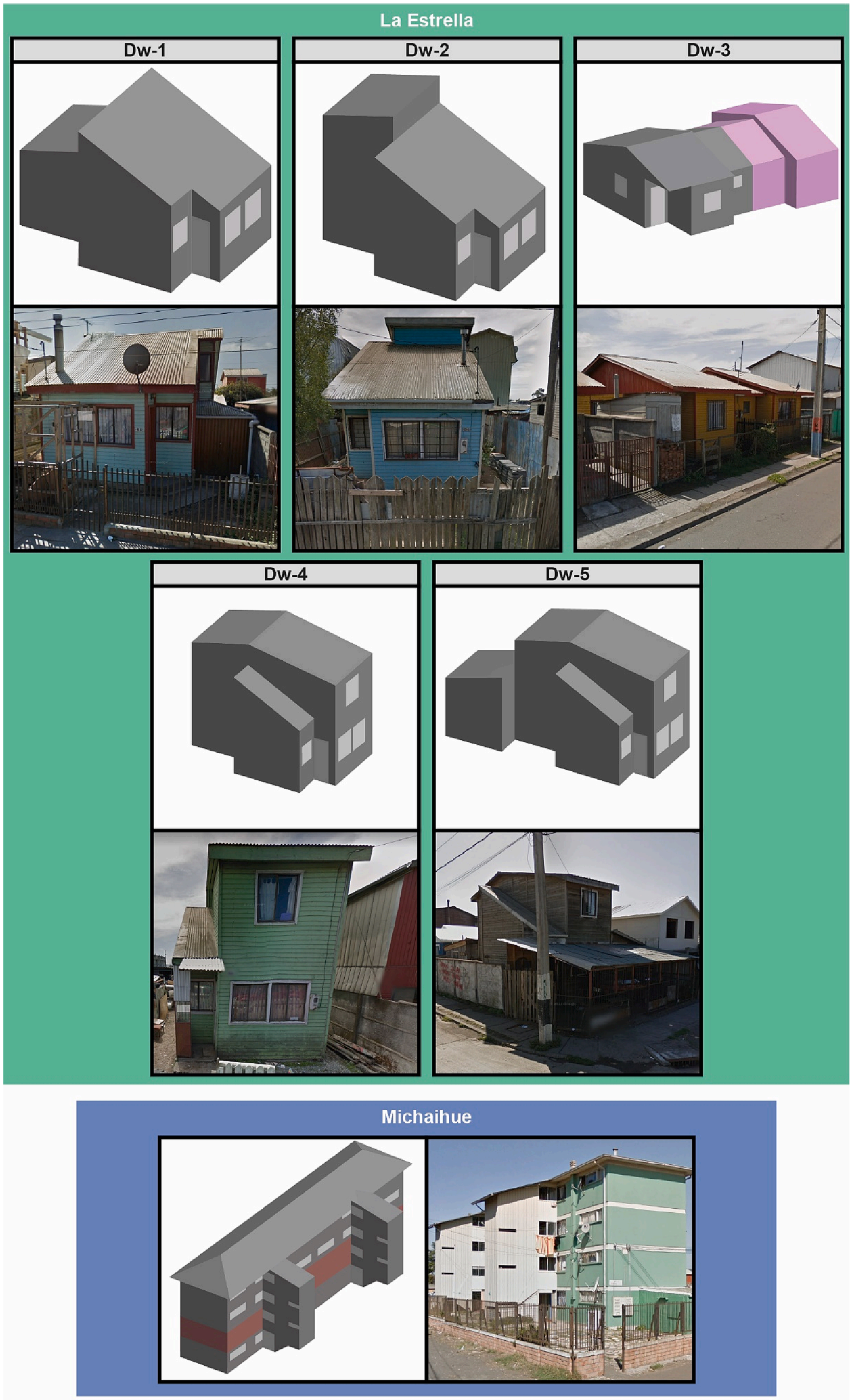

Fig. 4. Constructive typologies considered in the study.

Table 2
Area and number of inhabitants in the simulated housing typologies.

Residential complex	Typology	Floor surface area (m^2)	Number of people
Michaihue	–	38.50	4
La Estrella	Dw-1	24.78	3
	Dw-2	35.42	4
	Dw-3	35.98	4
	Dw-4	45.65	5
	Dw-5	52.83	6

Table 3
Loads considered in indoor spaces of the analyzed buildings.

Dwelling	Occupation load (m^2/person)	Lighting load (W/m^2)	Ventilation (l/s)	Heating setpoint temperature (°C)
Michaihue	8.94	1.5	18	18
Dw-1	8.26	1.5	14	18
Dw-2	8.85	1.5	18	18
Dw-3	8.99	1.5	18	18
Dw-4	9.13	1.5	21	18
Dw-5	8.81	1.5	31	18

the best performance rates were obtained with D4-I1. It should be noted that in this case, unlike in the analysis of all the groups, the combined use of several indicators was not feasible due to the low agreement observed. Therefore, for families with income expenditure percentages of less than or equal to 5%, the excessive energy expenditure indicator

Table 4
Thermal properties of the buildings' envelope.

Residential	Element		Thermal transmittance (W/(m^2K))
Michaihue	Façade	Brickwork Mq Hv (140 mm) and Plasterwork (25 mm)	1.75
	Roof	Pine structure (1 × 4′) + Mineral Wool (40 mm)	0.744
	Floors	Reinforced concrete (80 mm)	3.71
La Estrella	Façade	OSB Smart panel (11 mm) + Struct. Pine 2″× 3″ + Indoor drywall	2.69
	Floors	Concrete	3.315

Note: The windows have a thermal transmittance of 3.8 (W/m^2K) and a solar factor of 0.70.

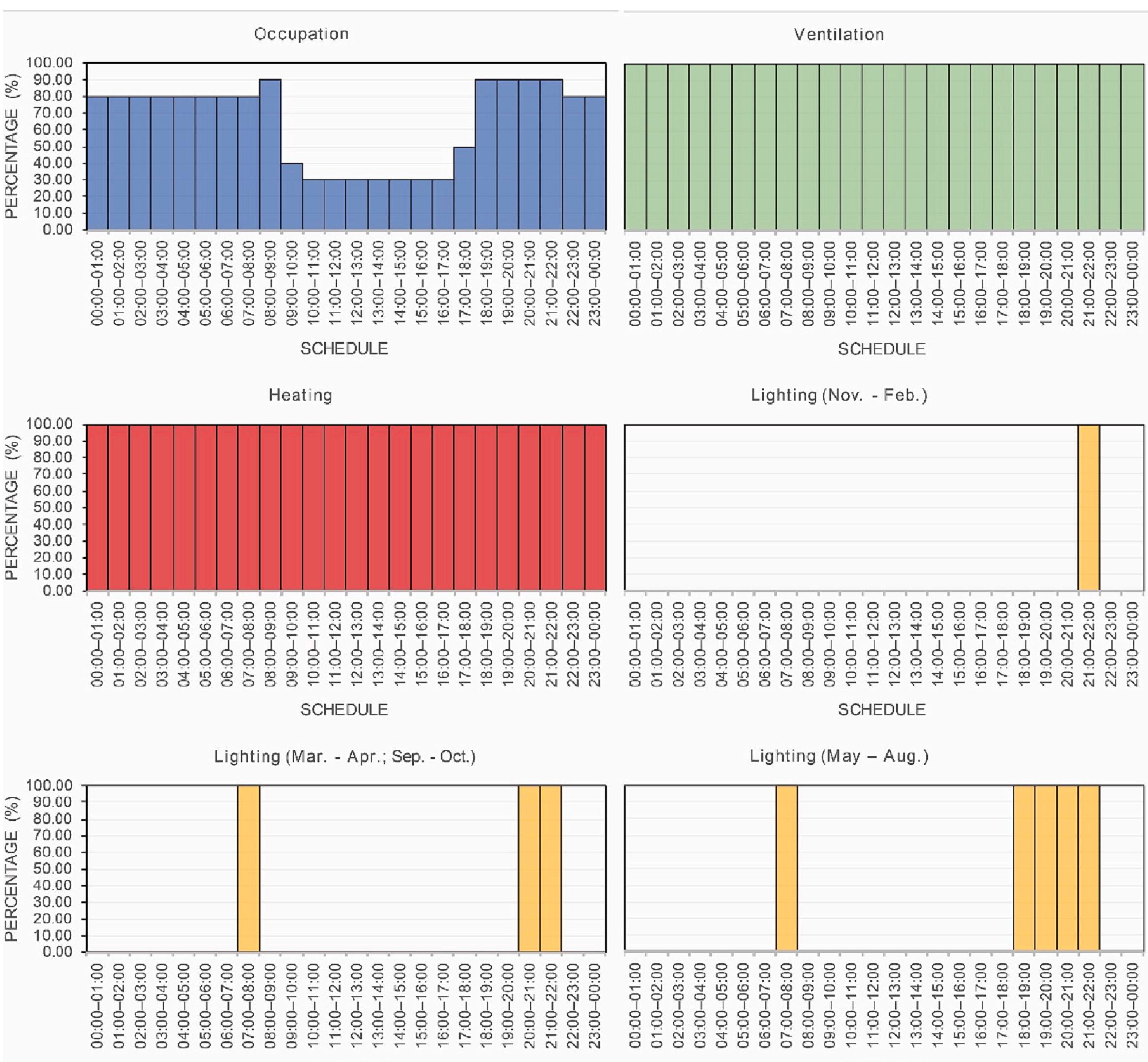

Fig. 5. Load distribution percentage throughout the day.

Table 5
Groupings using the income-expenditure percentage of the surveyed families.

Group	Income expenditure (%)	N
1	≤ 5%	129
2	(5%, 9%]	196
3	(9%, 14%]	157
4	> 14%	159

Table 6
Kappa, sensitivity, and specificity obtained for the total set of dwellings depending on the indicator. In bold, the Kappa values with agreement above 0.21.

Dimension	Indicator	Kappa	Sensitivity	Specificity
D1	D1-I1	0,046	0,301	0,935
	D1-I2	0,095	0,321	0,892
D2	D2-I1	0,094	0,321	0,862
	D2-I2	0,079	0,349	0,736
	D2-I3	0,172	0,355	0,892
D3	D3-I1	0,169	0,369	0,801
	D3-I2	**0,248**	0,404	0,853
	D3-I3	0,190	0,478	0,758
D4	**D4-I1**	**0,592**	0,640	0,923
	D4-I2	0,075	0,320	0,758

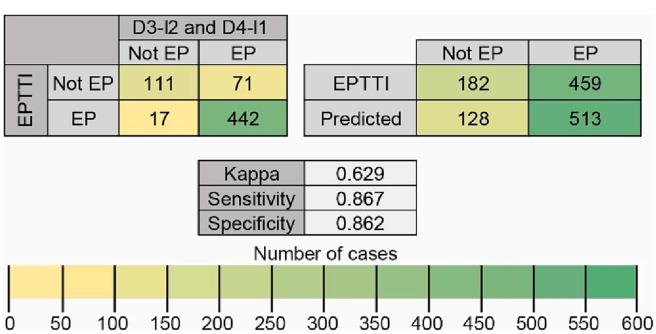

Fig. 6. Contingency table between the adjusted EPTTI and combining the D3-I2 and D4-I1 indicators.

Table 7
Kappa, sensitivity, and specificity obtained for group 1 dwellings depending on the indicator. In bold, the Kappa values with agreement over 0.21.

Dimension	Indicator	Kappa	Sensitivity	Specificity
D1	D1-I1	0,097	0,471	0,900
	D1-I2	0,188	0,505	0,808
D2	D2-I1	0,167	0,500	0,742
	D2-I2	0,028	0,469	0,567
	D2-I3	0,193	0,510	0,758
D3	D3-I1	0,112	0,500	0,612
	D3-I2	0,097	0,481	0,625
	D3-I3	0,103	0,482	0,636
D4	**D4-I1**	**0,673**	0,790	0,881
	D4-I2	0,037	0,453	0,667

Table 8
Kappa, sensitivity, and specificity obtained for group 2 dwellings depending on the indicator. In bold, the Kappa values with agreement above 0.21.

Dimension	Indicator	Kappa	Sensitivity	Specificity
D1	D1-I1	0,044	0,282	0,933
	D1-I2	0,041	0,281	0,889
D2	D2-I1	0,081	0,297	0,868
	D2-I2	0,064	0,318	0,750
	D2-I3	0,130	0,319	0,885
D3	**D3-I1**	**0,213**	0,369	0,849
	D3-I2	**0,240**	0,381	0,868
	D3-I3	0,018	0,500	0,737
D4	**D4-I1**	**0,516**	0,568	0,918
	D4-I2	−0,017	0,259	0,714

may be sufficient to provide an accurate estimate of their situation.

For group 2 (families with an income expenditure percentage between 5 and 9%), a different trend could be observed in the statistical parameters (Table 8). Here the agreement of 0.21 was exceeded by 3 indicators: D3-I1, D3-I2, and D4-I1. Hence, it was observed that the indicators that obtained a high agreement with EPTTI for all the families, repeat with the families of group 2. Although, indoor temperature (D3-I1) appears as another option for EPTTI. Despite this, the level of agreement between the indicators and EPTTI is lower than those obtained in the total dataset. In this sense, the kappa coefficient decreases its range from 0.002 to 0.172, with the sole exception of D3-I1 which increased its kappa by 0.044. Regarding the sensitivity and specificity values, it could be seen that the values obtained were very similar to those for the entire dataset, with absolute variations between 2.2 and 7.2% in sensitivity, and between 4.4 and 4.8% in specificity. Therefore, the indicators showed a greater tendency to classify the families of group 2 in a situation of energy poverty. Given that these 3 indicators had an agreement level above 0.21, it was decided to analyze their combined use. To do this, the combined use of D3-I2 and D4-I1 (also performed on the total dataset) was evaluated (Fig. 7), and the combined use of D3-I1, D3-I2, and D4-I1 was analyzed (Fig. 8). For D3-I2 and D4-I1, it was possible to verify how the combination increased the agreement with EPTTI, with a kappa of 0.604. Likewise, the sensitivity increased by combining the indicators, with a value of 80%. This represented a clear improvement compared to the individual indicators (with sensitivities of 38.1 and 56.8%), although the specificity decreased slightly. Thus, it was possible to appreciate the great similarity obtained in the evaluations of the indicators compared to EPTTI, since only 28 families received different evaluations. However, for the combined use of D3-I1, D3-I2, and D4-I1, the performance was worse. In this case, the agreement was lower than the D3-I2 and D4-I1 combination due to the effect of indoor temperature. This meant that the sensitivity and specificity values were similar to those of the indicators individually. Hence, errors in the assessment of not energy-poor families were high. Consequently, the use of the energy sources and heating devices and excessive energy expenditure variables is the most suitable way to make quick estimates of EPTTI in the families of group 2.

For groups 3 and 4, the same trends were detected (Tables 9 and 10). From the agreement by indicators analysis, it was appreciated how D3-I2 and D4-I1 were once again the indicators with a Kappa above 0.21. This aspect followed what was observed in the group analysis. The difference was in the kappa value, which ranged between 0.024 and 0.111 compared to the dataset. For the not energy-poor households' assessment, the same downward trend in the sensitivity value was detected in

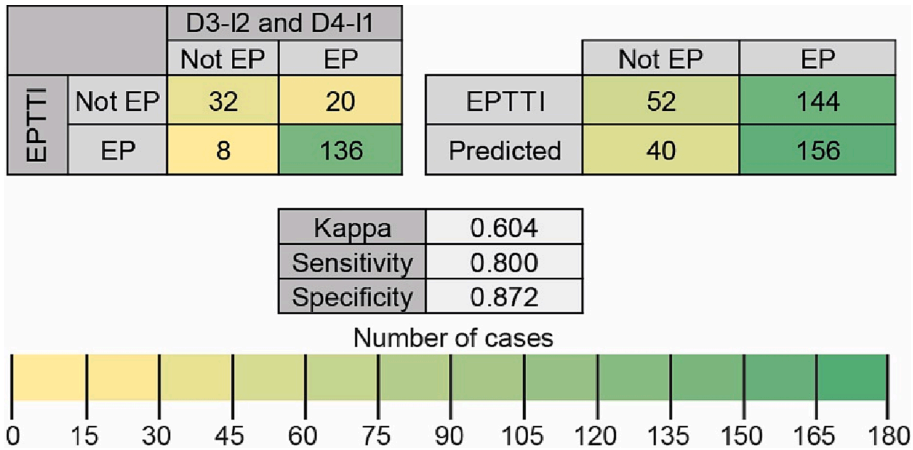

Fig. 7. Contingency table between the adjusted EPTTI and combined D3-I2 and D4-I1 indicators in group 2.

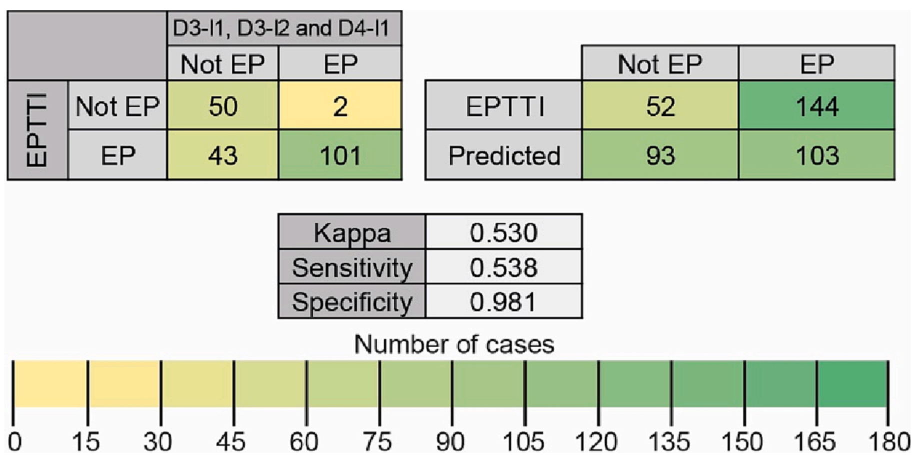

Fig. 8. Contingency table between the adjusted EPTTI and combined D3-I1, D3-I2, and D4-I1 indicators in group 2.

Table 9
Kappa, sensitivity, and specificity obtained for group 3 dwellings depending on the indicator. In bold, the Kappa values with agreement below 0.21.

Dimension	Indicator	Kappa	Sensitivity	Specificity
D1	D1-I1	0,035	0,206	0,938
	D1-I2	0,118	0,245	0,909
D2	D2-I1	0,097	0,233	0,946
	D2-I2	0,134	0,279	0,842
	D2-I3	0,188	0,276	0,981
D3	D3-I1	0,158	0,267	0,901
	D3-I2	**0,359**	0,385	0,946
	D3-I3	−0,012	0,000	0,808
D4	**D4-I1**	**0,549**	0,519	0,971
	D4-I2	0,080	0,234	0,839

Table 10
Kappa, sensitivity, and specificity obtained for group 4 dwellings depending on the indicator. In bold, the Kappa values with agreement below 0.21.

Dimension	Indicator	Kappa	Sensitivity	Specificity
D1	D1-I1	0,024	0,279	1,000
	D1-I2	0,059	0,293	1,000
D2	D2-I1	0,066	0,296	0,875
	D2-I2	0,102	0,367	0,752
	D2-I3	0,170	0,342	0,896
D3	D3-I1	0,197	0,377	0,811
	D3-I2	**0,222**	0,374	0,868
	D3-I3	0,192	0,480	0,769
D4	**D4-I1**	**0,616**	0,688	0,910
	D4-I2	−0,013	0,250	0,727

all indicators, with decreases of between 1.9 and 47.8%. This meant a worse estimate of the families that were not in energy poverty. For households in EP, the specificity percentages showed slight increases. Regarding the possibility of combining D3-I2 and D4-I1 to improve the predictions, the results obtained with these combinations are summarized in Figs. 9 and 10. Combining the indicators improved the sensitivity in both groups, which meant a better classification of households that were not in energy poverty. This aspect, as well as having high specificity values, allowed having a low percentage of erroneous evaluations: 7% in group 3, and 16.9% in group 4.

4. Discussion

As a result, it has been possible to confirm how EPTTI can have a simpler approach to make accurate assessments of families' situations. Through the analysis made, it has been possible to verify how energy

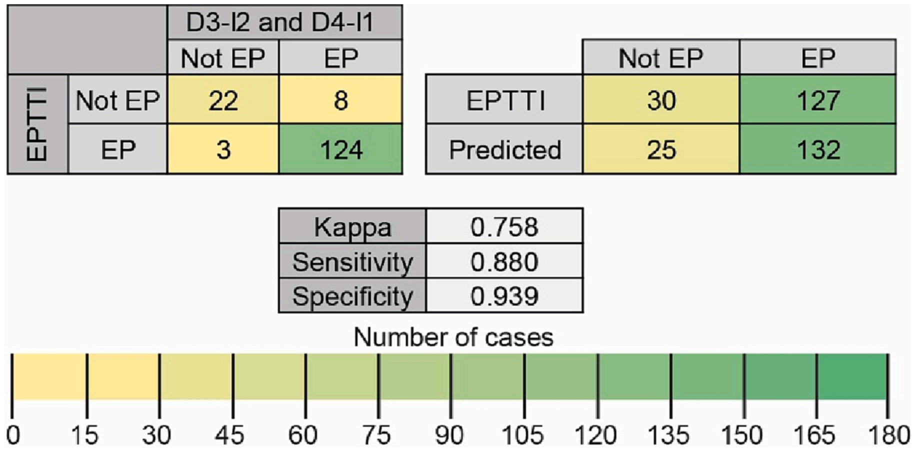

Fig. 9. Contingency table between the adjusted EPTTI and combined D3-I2 and D4-I1 indicators in group 3.

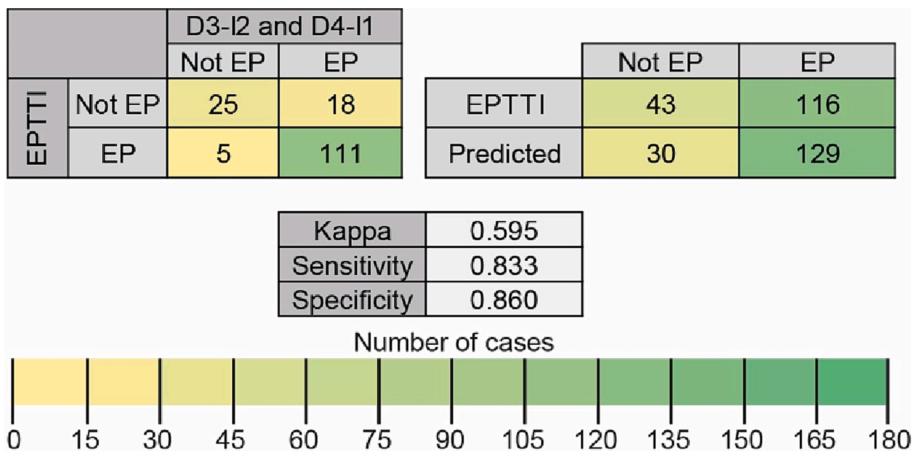

Fig. 10. Contingency table between the adjusted EPTTI and combined D3-I2 and D4-I1 indicators in group 4.

sources and heating devices, as well as high energy expenditure, can be used as accurate indicators of energy poverty assessment for Chilean families. The only exception detected was the case of families with really low-income expenditure percentages, where the only indicator consistent with EPTTI was excessive energy expenditure, seeing differences, just as in other studies, if several clusters of the sample are generated [56,57]. With these results, a faster assessment of families could be achieved as well as priority indicators for countries or regions, for example, for the 56 indicators of EPAH [50]. Thus, with the results of the study, it has been shown that variables such as kitchen equipment and DHW systems could be eliminated from assessments if sufficient resources are not available. This does not mean that they should be completely discarded if there are sufficient resources for the evaluation of EPTTI, but a simplified option with D3-I2 and D4-I1 could be considered if needed.

Currently, there is no international consensus about how to measure or identify energy poverty. There are many indicators; however, despite the complexity of the phenomenon, many simple indicators are used due to difficulties in finding information [58]. Many studies have highlighted the difficulties in having the data needed to make energy poverty assessments with these indices [59,60]. In addition, the lack of data impedes a generalized use, and can delay the implementation or assessment of energy policies [61], or the transfer to and application of the indicators in other realities.

In the case of Latin America, and more specifically, Chile, efforts are being made to contextualize, measure, and identify EP [58,62–66]. The results show that in the case study, EP is mainly linked to indicators based on excessive energy expenditure (D4-I1) and the type and source used for heating (D3-I2), unlike in other studies such as that of Santillan et al. [62] in Colombia, the Dominican Republic, Guatemala, Haiti, Honduras, Mexico, and Peru, where EP is mainly linked to access.

In the case of Chile, Urquiza et al. [65] highlight the importance of establishing a three-dimensional framework for EP, given the diversity of the phenomenon [65]. However, since many of the existing approaches are based on multidimensional analysis [67,68], there may be difficulties in a consistent and adequate application in real situations. [59,60]. For example, Pereira et al. [64], in Argentina, Brazil, Uruguay, and Paraguay, identify that the results of the application of CEPI are very sensitive to the selection of different weights for the different approaches proposed for the analysis of energy poverty. Likewise, Hernandez et al. [63], assign similar weights to the indicators to multidimensionally measure EP in Colombia. The results of this research show that with application to specific cases it is possible to have greater knowledge of multidimensional indicators considering local contexts. Therefore, the use of the methodology of this study could make it possible to prioritize, assign weights, improve, and simplify many of the indicators found in scientific literature to assess energy poverty. Finally, it is necessary to highlight the relevance of this study's results for the rest of the indicators in the scientific literature for EP assessment.

5. Conclusions

The assessment of energy poverty is complex due to the large number of dimensions that must be considered. Many indicators in the scientific literature are based on a multidimensional approach. In this study, the Three-dimensional and Territorial Indicator of Energy Poverty (EPTTI in Spanish), used by the Chilean Energy Poverty Network to assess families with fewer economic resources, was evaluated. Given that determining the EPTTI's 10 indicators can be difficult in real applications, this study looked to verify the existing agreements between individual evaluations of the indicators and the global response given by EPTTI.

Through the analysis of a study sample of 641 social housing units, it was possible to verify how the use of indicators based on excessive energy expenditure (D4-I1) and the type and source used for heating (D3-I2) could obtain similar answers to those obtained with EPTTI. For this, a combined application of these 2 indicators is needed. This is because individual valuations tend to classify more families in situations of energy poverty. However, the use of a combined assessment of the 2 indicators tends to obtain sensitivity and specificity values closer to 100%.

This would imply savings from not assessing the other 8 indicators that EPTTI needs, meaning that the assessment time could be shorter for technical staff and social workers. This can even be simplified further if the group of income expenses that the family has is considered. In this sense, it has been possible to verify how in families that have a low expenditure percentage (less than 5% of income), the only indicator that obtains a similar response to EPTTI is excessive energy expenditure. Thus, the approach can be simplified further still. In any case, for other expenditure groups, it would be necessary to also evaluate the type and source of heating systems. It should be noted that the simplified 2-indicator approach is an option to speed up evaluations. However, an accurate assessment of EPTTI is obtained with all the indicators. In cases where resources and time allow, and depending on the objective and scale of the analysis, the entire EPTTI could be applied for greater accuracy, given the small errors there may be with the simplified 2-indicator approach. In any case, the time required to obtain all the indicators can be lengthy. In this sense, surveys need to be carried out by visiting each of the homes and it may be difficult to obtain all the data requested in them (e.g., the family may be unaware of some aspects). It is also possible that the use of statistical data may not always be available. Hence, the use of a simplified indicator is beneficial and could lead to obtaining assessments from a greater number of families.

The results of this study are also relevant in terms of their political implications. They highlight that the use of multidimensional approaches can be simplified if there is greater detail on the social, economic, and technical characteristics of the built environment. This knowledge can lead to establishing the highest priority action measures to reduce cases of energy poverty. In this regard, the results of this study suggest that excessive energy expenditure and heating systems are the main determinants of the energy poverty situation of families. Establishing action measures to reduce the energy expenditure of families (e.g., with financial aid to pay the electricity bill) and improve heating systems (e.g., replacement of boilers and the contribution of self-consumption sources), could significantly reduce the number of families in energy poverty in Chile. Taking into account the objectives laid out by the Chilean Government to act on energy poverty by 2050 and the large number of the country's resident population estimated to be in this situation, it is essential to have instruments that allow technical staff and social workers to make accurate assessments. It should also be noted that these results could occur in other regions, if the characteristics of the built environment, climate, and families are similar to those of Chile.

Finally, it should also be noted that the results of this study highlight the need to make evaluations of the multidimensional indicators in the scientific literature so that they have a more practical approach. Many of these indicators are based on analyzing a series of variables that often have limitations for their practical application in real cases. In this sense, many studies have made reflections on the limitations these indicators may have due to the difficulty in assessing each of the variables they use. The methodology used in this research could be extrapolated for other indicators to assess their simplified application for the characteristics of different regions, as well as to establish the most important lines of action. This aspect should be addressed in future work on the topic.

CRediT authorship contribution statement

Alexis Pérez-Fargallo: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Laura Marín-Restrepo:** Conceptualization, Investigation, Formal analysis. **Sergio Contreras-Espinoza:** Visualization, Formal analysis, Validation. **David Bienvenido-Huertas:** Visualization, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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