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Controlling air pollution in a context of high energy poverty levels in southern Chile: Clean air but colder houses?

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ABSTRACT

Firewood is the main fuel used for heating in Chile, but its inefficient use is producing severe episodes of air pollution. To address this issue, authorities implement Air Pollution Management Plans (PDAs), which include actions such as setting moisture requirements for firewood, replacing old wood-stoves, temporarily banning the use of firewood, and improving homes´ thermal insulation. However, PDAs do not focus on nor do they prioritize measures in relation to specific social contexts. This study assessed socio-economic variables, energy consumption and indoor environments in households located in the city of Valdivia, through surveys and the monitoring of temperatures and indoor air pollution levels. We found that, during the winter months, 68% of the time living room temperatures were below 21 °C, and $PM_{2.5}$ concentrations were above international standards. Furthermore, over 61% of households were to suffer a state of energy poverty. We urge decision-makers to consider social inequalities and energy consumption patterns in cities with high firewood consumption, prioritizing measures and focusing resources on reducing both air pollution and energy poverty. Thermal insulation of homes should be a priority in mid-to-low-income families, since these have the highest levels of energy demand. Other PDA´s measures could be economically regressive in these social-strata.

1. Introduction

Energy poverty has been extensively studied in developing countries, where it has been associated with a lack of access to clean energy sources; how this problem affects peoples´ health has consequently been widely researched (WHO, 2002; Liddell and Morris, 2010). On the other hand, developed countries are often able to avoid the problem of indoor air pollution, given that electricity, natural gas and other refined fuels are readily available. However, in such countries, many families must spend a high proportion of their income on energy, which may result in only a partial fulfillment of their basic needs (Bouzarovski et al., 2012). In these cases, energy poverty is associated with a limited ability to properly heat or cool homes (Aristondo and Onaindia, 2018).

Assessing energy poverty is a complex challenge, given the wide variety of social, environmental and cultural contexts where it occurs. Many frameworks and approaches have been proposed, from defining poverty levels to more comprehensive methods that consider multiple factors (Bravo et al., 1979; Goldemberg, 1990; Boardman, 1991; Foster et al., 2000; Khandker et al., 2010). Many authors have associated energy poverty with low income, while others have suggested that energy consumption beyond certain thresholds influences the availability of disposable income to fulfill other needs. While income can affect both energy consumption and welfare of family groups (cause and effect), these two factors can also affect income. For this reason, all three of these factors should be assessed together (Khandker et al., 2010). This is essential, as it allows for the incorporation of qualitative parameters associated with welfare when assessing energy poverty, making the interpretation of data pertinent to different cultural situations or contexts.

There are few studies on energy poverty in countries with intermediate GDP levels, such as Chile. The Chilean electrical grid covers almost 100% of households, and other sources of energy, like liquefied petroleum gas (LPG) and kerosene, are readily available, making the problem of energy poverty not so much about access to clean energy sources or indoor air pollution due to cooking practices. The problem in Chile is related to the very high consumption of firewood for heating: more than 80% of households use firewood in southern Chile, averaging from 6 solid[1] cubic meters per household year (m^3/hh/year) in the city of Temuco (Araucanía region, 38°45′S 72°40′W) and up to 27 m^3/hh/year in the town of Puerto Williams (Magallanes region, 54°56′S

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[1] 1 solid cubic meter = 1.56 stacked cubic meter.

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67°37′W), respectively[2] (Reyes, 2013; CDT, 2015), This is producing serious air pollution events. In order to control air pollution, authorities have started to implement Air Pollution Management Plans (PDAs) which provide families with different programs and subsidies oriented towards improving firewood quality, replacing old wood-stoves, and fostering household retrofits. Nonetheless, PDAs have been increasingly criticized,[3] because they are too focused on replacing firewood without considering socioeconomic dimensions.

This high firewood consumption is explained by a combination of various factors. The cold, rainy climate lasting at least 5 months (May–September) a year, coupled with thermally inefficient construction standards, result in high energy demands for heating (Schueftan and González, 2013). The poor performance of Chilean homes and buildings is not only because of thermal insulation, it is also due to thermal bridging, ventilation problems, moisture, the quality of doors and windows and their installation, etc. Furthermore, firewood is 4–5 times cheaper than kerosene, LPG or electricity per unit of energy. Although firewood is much cheaper than other energy sources, a large percentage of families cannot afford the amount of firewood they would need to adequately heat their homes, forcing them to live in cold, humid environments (Reyes et al., 2015). Income is so poorly distributed in Chile that while some families can afford the living standard of developed countries, most families find themselves in a precarious situation in terms of their heating alternatives (López et al., 2013). This results in a serious situation in terms of energy demand and household' thermal comfort levels.

This study aimed to assess energy poverty, examine how this interacts with the programs included in the PDA, and suggest measures to improve its performance, in the city of Valdivia, Chile. This was carried out by analyzing data regarding energy consumption, income, and indoor environmental conditions. Our postulate is that some of the measures included in the PDA may worsen energy poverty, indoor environmental conditions, and, in general, peoples´ well-being, because the PDA does not properly consider the social context of households nor their energy consumption habits. We provide data from 300 surveys carried out with the main decision-makers of households in different socioeconomic groups, in addition to indoor environmental data (temperature and $PM_{2.5}$ concentration) monitored in a subset of 80 homes for two months in the winter of 2017 (August and September). Together with information from other studies conducted in Valdivia, the present case study is relevant to other cities in south-central Chile which face similar problems.

1.1. Urban air pollution

Although most wood-stoves used in Valdivia are relatively modern, their abundance and intensive use have resulted in severe episodes of air pollution. Wood-stoves are normally located in the living room and heat spreads to the other rooms throughout the house. This layout is similar to what is seen in New Zealand (Howden-Chapman et al., 2009). Previous works in Valdivia have shown that the amount of particulate matter (PM) emitted is heavily dependent upon the user´s management of wood-stoves, common examples include the closing of air dampers and the use of firewood that is not dry enough (Schueftan and González, 2015). Molina et al. (2017) found that the concentration of fine particulate matter ($PM_{2.5}$) exceeds the threshold established by the World Health Organization (WHO) for at least 120 days a year in the Chilean cities of Rancagua, Rengo, Curicó, Talca, Chillan, Los Angeles, Temuco, Valdivia, Osorno, Puerto Montt, and Coyhaique. Fine particulate matter is produced as a result of firewood combustion and given its size it can reach deep into the human respiratory system. $PM_{2.5}$ can result in severe human health issues (Barría, 2012). For example, studies conducted in hospitals in south-central Chile have shown a higher prevalence of chronic bronchitis and cardiovascular diseases in the elderly (Gómez-Lobo et al., 2006). Leiva et al. (2013) also found a positive relationship between exposure to $PM_{2.5}$ and cerebrovascular damage (a 1.29% annual increase in damage per 10 μg/m^3 increase in $PM_{2.5}$).

In the case of Valdivia, where an Air Pollution Management Plan (PDA) has recently been implemented to reduce the city´s air pollution level, an emissions' inventory determined that more than 90% of particulate matter (PM_{10} and $PM_{2.5}$) is produced by household firewood combustion. Other sources, such as industries and transportation, represent only 5% and 1% of the emissions, respectively (MMA, 2016). This means that most of the air pollution in Valdivia comes from a single source: residential firewood combustion. Air pollution worsens when the firewood used has a high moisture content, when wood-stoves are not efficient or when homes were precariously built and lack adequate thermal insulation (MMA, 2014).

Fig. 1 shows the fine particulate matter concentration in the city of Valdivia between 2013 and 2018, which evidences that the seasonality peaks are reached during the winter months, and that air pollution levels greatly exceed national and international standards. Fig. 1 thus summarizes the severity of the air pollution problem in Valdivia. The WHO determined that the daily concentration of $PM_{2.5}$ should not exceed 25 μg/m^3 (WHO, 2005), and the US Environmental Protection Agency (EPA) defined 35 μg/m^3 as their limit (EPA, 2016), whereas the Chilean air quality norm allows a maximum of 50 μg/m^3 (MMA, 2011). In the wintertime, 90% of the PM_{10} concentration comes from $PM_{2.5}$, while this figure drops to 40% in the summertime in Valdivia. The highest particulate matter concentration is reached between 6 p.m. and 2 a.m., when most people have returned from work and have lit their wood-stoves to heat their homes. This time frame also coincides with the most favorable atmospheric conditions for smoke accumulation: low temperature, thermal inversion and lack of wind (MMA, 2016).

1.2. Thermal regulations and the Air Pollution Management Plan in Valdivia

Chile lacks regulations and policies that specifically tackle the problem of energy poverty. In fact, this concept was only recently incorporated into the national energy agenda in the Energy Program 2050 (Ministerio de Energía, 2017). Even though heating systems are clearly precarious and inadequate for the cold, rainy winters in southern Chile, the topic of energy poverty is still new in this country and very few studies have addressed the topic and how it is related to household energy use (Reyes et al., 2015; Schueftan et al., 2016).

In contrast with the constant development and improvement of anti-seismic building regulations -Chile has world class building standards to withstand earthquakes- thermal regulation is still inadequate. Thermal regulation was incorporated into the Building Code in 2000, but it was poorly developed (Celis et al., 2012) and only included thermal insulation requirements for roofs. In 2007, a second stage of thermal regulations incorporated aspects related to walls, floors and windows, the latter restricting the total window area to a certain percentage of the house exterior, depending on the type of glass (MINVU, 2006). For the region studied here, wall insulation thickness required by the 2007 Norm was only 2 cm, and floor insulation only considered air ventilated floors but not those with concrete foundations.

This regulation was recently reviewed, improving the requirements for thermal insulation of roofs, walls, and floors. Furthermore, it incorporates new requirements regarding ventilation in order to reduce heat losses, moisture issues, and improve indoor air quality. These modifications were incorporated in 2017 for houses in areas saturated with particulate matter and where PDAs are in place, like Valdivia

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[2] Most urban households buy firewood, paying between US $38 and US $54 for a stacked cubic meter (INFOR, 2015; Reyes et al., 2018). Only a very small fraction of urban households collect the firewood they consume.

[3] August 6th, 2018. https://www.biobiochile.cl/noticias/nacional/region-de-los-rios/2018/08/06/diputado-ilabaca-ps-tildo-de-insuficiente-plan-de-descontaminacion-en-los-rios.shtml.

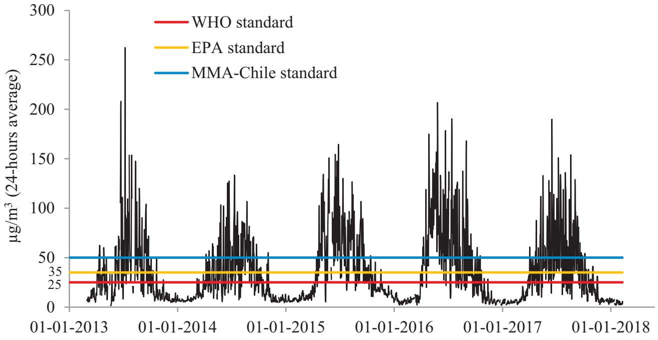

Fig. 1. Fine particulate matter concentration ($PM_{2.5}$) in the city of Valdivia between 2013 and 2018 (24-h average).
Source: based on SINCA (2017), EPA (2016), MMA (2011), WHO (2005).

(MMA, 2016). Starting in 2019, these requirements will be mandatory for the whole country. However, over 80% of the dwellings in Valdivia were built before 2000, and will not be required to comply with the regulation. Therefore, heating fuel demands will remain very high (Ortega et al., 2015).

Valdivia was declared a particulate matter saturated zone in 2014 since PM_{10} and $PM_{2.5}$ concentrations were recorded to be above the air quality standard between 2009 and 2013. This regulation sets the maximum daily concentration at 150 µg/m^3, the annual concentration at 50 µg/m^3 N for PM_{10}, and a daily limit of 50 µg/m^3 for $PM_{2.5}$. When a city is declared as a saturated zone, a PDA must be developed to reduce air pollution. This environmental management tool prescribes a set of measures to improve air quality, which include specific regulations regarding the use of firewood and its derived products, the improvement of heating systems, and the improvement of thermal insulation in homes, among others (MMA, 2016). Some of the measures that have been implemented in Valdivia include:

1) Subsidies to replace old wood-stoves with more efficient wood-stoves or heating systems that use a different type of fuel (kerosene, liquefied petroleum gas, or wood pellets);
2) A firewood certification system to guarantee low moisture levels and provide traceability;
3) Subsidies to improve the thermal insulation of existing houses and increase standards for new houses;
4) Prohibition of wood-stove use during periods of high air pollution levels, along with fines for non-compliance.

Nonetheless, the implementation of these measures has been slow and only partial, since, with the exception of measure 4, they are voluntary and depend on people´s interest. The effectiveness of measures 1 and 2 strongly depend on people´s practices, for instance, measure 1 is of little help when people close the wood-stove damper, as is measure 2 when people store firewood inappropriately. Diverse studies have demonstrated that improving the thermal insulation of homes can significantly reduce firewood consumption and pollution (Ortega et al., 2015, 2016; Schueftan and González, 2015; MMA, 2010, 2012) due to a 30–70% reduction in energy demand. More so, the effectiveness of thermal insulation does not depend on householders' practices. Although all of the measures included in the PDA are important to reduce air pollution levels, the PDA sets no clear stages or priorities, and, based on demand, attempts to implement all of the measures simultaneously. This means that the decision on what is done and how the PDA is implemented is based on each household's priorities, not on public policy. The PDA is consequently ineffective because the general public is unaware of the relative benefits of the various measures to improve air quality. As a result, although measures 1 and 2 (low cost with rapid implementation) are prioritized, they do not effectively tackle the ultimate cause of the high energy demand and do not therefore reduce air pollution. The PDA was initiated in Valdivia in 2014, and its failure to reduce PM emissions can be observed in Fig. 1, where no improvements can be seen since 2015. Furthermore, since most of these measures do not reduce the amount of energy required for heating, they keep many households in a situation of energy poverty. In particular, measure 4 may specially affect low income sectors as they cannot afford alternatives during the periods of wood burning prohibition, increasing health consequences due to increased cold and damp housing conditions.

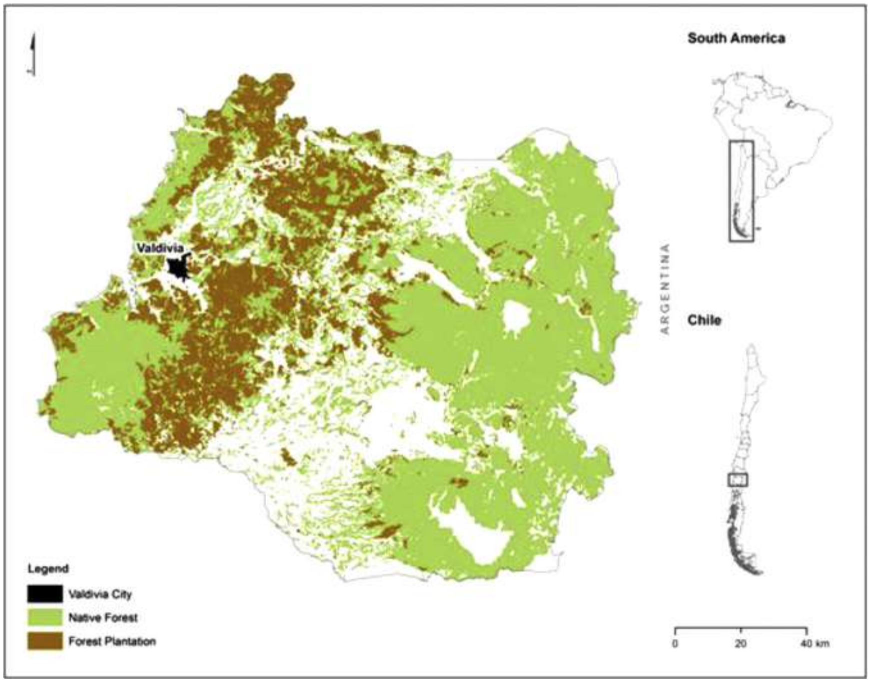

Fig. 2. Study area.
Source: based on CONAF (2017).

2. Study area

The climate in Los Rios Region is wet and temperate with an average annual temperature of 12 °C and abundant precipitations, especially in coastal areas (such as Valdivia), that can exceed 2000 mm per year (Castillo, 2001; Fig. 2). The cold season lasts from April to November, with the coldest temperatures in July. The average winter temperature is 8 °C, and the maximum temperature rarely exceeds 18 °C. This maximum corresponds to the minimum indoor temperature that the WHO suggests to maintain a healthy life (WHO, 1987). The combination of climatic conditions and envelope characteristics of houses results in a high energy demand for heating which is covered by firewood produced from native forests and exotic tree plantations (mostly *Eucalyptus* spp.).

The city of Valdivia (capital of Los Rios Region, 39°48′30″S, 73°14′30″W) is about 15 m above sea level, among three rivers: Valdivia, Cau-Cau, and Calle-Calle, and is surrounded by wetlands and hills, only 15 km (9 miles) from the Pacific Ocean. Approximately 155,000 people live in Valdivia (INE, 2017), on a plain of 2000 ha (4940 acres). The economy of Valdivia is based on forestry (wood and cellulose production from *Pinus radiata* and *Eucalyptus* spp.), tourism, education (universities) and services. Large sawmills and pulp-mills are located just over 50 km (30 miles) from the city.

3. Methods

Data required to perform this study were collected in two stages. In the first stage, 300 households were surveyed between May and June 2015. These surveys considered the following aspects: demographic data, characteristics of the main decision-makers (schooling, age, etc.), income, household energy consumption (heating and cooling, cooking, appliances, lighting and hot water), heating systems, firewood supply, technology (wood-stoves and others), and dwellings characteristics. The total family income was estimated by adding each family member´s income (those with jobs or pensions/subsidies). When a decision-maker did not want to provide information regarding income, it was estimated by using information about family member´s activities (regional averages for different kinds of jobs/activities, which were declared by decision-makers).

Households were randomly chosen based on a point grid overlaid on satellite imagery of Valdivia, by using ArcGIS®. Once a point was selected, the house closest to it was surveyed, following an established sampling protocol (INFOR, 2015). This protocol established that when a decision-maker was contacted, and before performing the survey, an informed consent letter was read to him/her by researchers in order to inform him/her about the institution carrying out the study (name and phone number of the main researcher), the research goals, the use of the information, and the surveyed people´s rights in terms of confidentiality and participation. After this conversation, each decision-maker decided to participate (or not) in the study. If he/she declined participating, the closest house was chosen as a replacement (leftward houses had the priority), and so on. When a decision-maker was not at home, a second visit was scheduled. If he/she was not available on the second visit, the replacement protocol was utilized. A total of approximately 75 houses were replaced before completing the sample size of 300.

The second stage was conducted during August and September 2017 (winter), when households´ firewood consumption is very high because of the low temperatures. During these months outdoor and indoor temperatures significantly differ, allowing us to show the impact of energy poverty on indoor environmental conditions more clearly. In this stage, a sub-sample of 80 households was randomly selected to monitor indoor temperatures and fine particulate matter concentrations ($PM_{2.5}$). These households were contacted to assess their willingness to participate in this stage. Outdoor particulate material concentrations were obtained from the public air quality monitoring system of Valdivia (SINCA, 2017), while outdoor temperatures were obtained from the local weather station (DMC, 2017). One stacked cubic meter of certified (dried) firewood was provided to the families who decided to participate in this stage of the study, in order to a) encourage their participation following the rules that were stipulated by researchers (mainly, do not manipulate the sensor during the research), and b) reduce the bias associated to firewood quality (humid firewood produces less heat and more $PM_{2.5}$). Indoor environmental conditions were monitored by using Speck® sensors (INFOR, 2017), which have been successfully used for this purpose in other studies (Taylor and Nourbakhsh, 2015). Study participants explicitly agreed to not manipulate the sensors installed in their homes. Forty homes were monitored in August and another 40 in September. The sensors were installed in living rooms, at a minimum of two meters from the wood-stove and safely out of the reach of children, pets or other factors that could disturb them or alter their functions. The location of each sensor was agreed to with the inhabitants of each home. Given that the sensor is in close proximity to the wood-stove, its data can be considered as the maximum household temperature. Sensors were installed after conducting a survey to update household information. The same informed consent letter as in stage 1 was used before performing the survey with decision-makers.

Energy poverty was assessed by using an alternative approach of the 10% threshold proposed by Boardman (1991). This approach considered the net income instead of the gross income, because a very high proportion of Valdivian families pay rent or a mortgage (Moore, 2012). This implies that less income is available to meet the family´s needs. Furthermore, instead of using the amount of money that would be needed to cover the household´s energy needs, this approach used the amount of money that was actually spent on energy. Thus, the 10% line built in this study shows families that has already spent more than 10% of their net income on energy, representing a minimum level of energy poverty in the city (the proportion of families in a state of energy poverty would be higher). Spending more than 10% of the family´s income on energy may negatively affect their ability to fulfill other needs.

A second approach to energy poverty, proposed by Khandker et al. (2010), was also used in this analysis. This method suggests a relative threshold instead of an arbitrary one (10% line). This relative threshold corresponds to the point at which family energy consumption starts to increase with a certain income increase. Authors point out that at very low income levels income increments do not immediately result in more energy consumption (inelastic), nonetheless there is always a point at which additional income does result in increased energy consumption. Below this line, families would be considered to live in energy poverty. Yet another interpretation could also be proposed: the point at which energy consumption decouples from income (higher income levels) would correspond to the point at which energy poverty disappears (below that point people would be using less energy since they could not afford to use more). Both interpretations were considered in this analysis.

All of these approaches to energy poverty were compared to the measures included in Valdivia's PDA. The energy deficit of each household was also assessed, considering the amount of heat needed to maintain a comfortable temperature at home throughout the day. The deficit was established as the number of Celsius degrees needed to reach 18 °C on an average day. This was the sum of the differences between the recommended temperature and the average temperature recorded inside each house, every time the former exceeded the latter (sum of deficits).

4. Results

4.1. Characteristics of heating systems

The urban residential sector of Valdivia consumes 767 GW h/year in heating, cooking, bathing, lighting, and electronics, which averages

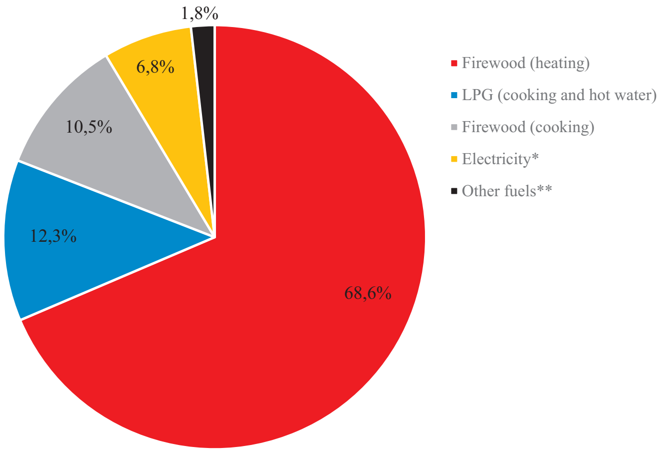

Fig. 3. Final energy consumption in Valdivia´s households. * A small fraction of the electric consumption is used for heating. ** Other fuels used for heating are kerosene, liquefied petroleum gas, diesel and wood pellets. Note: This graph does not include transportation.
Source: based on INFOR (2015).

4948 kW h/person/year. This figure represents the end user consumption and does not include the energy used in production, transportation and distribution. Most of this energy (71%) is used for heating (Fig. 3), which averages 206 kW h/m^2/year, and 95% of households use firewood for heating. Fig. 4 shows the most commonly used wood-stoves found in Valdivia. The energy consumption for heating varied depending on the dwelling´s size. The energy used for heating houses smaller than 60 m^2 averaged 271 kW h/m^2/year (standard error = 21 kW h/m^2/year), which correlated with lower income households (Fig. 5). The average consumption in houses between 60 and 120 m^2 reached 180 kW h/m^2/year (standard error = 8 kW h/m^2/year), and descended to 120 kW h/m^2/year in larger homes (standard error = 10 kW h/m^2/year).

Wood-stoves are not automated and are used intermittently to save fuel (they are allowed to die down and are relit throughout the day). Most of the particulate matter emitted by wood-stoves occurs during the first 30 min of operation because they need higher temperatures to burn pollutants (Vicente et al., 2015). Therefore, intermittences not only affect heating quality, but also increase outdoor air pollution. This occurs even with modern wood-stoves (certified wood-stoves) that have emission reduction devices (Calvo et al., 2015). Another behavior intended to “save firewood”, which also increases outdoor air pollution, is that of closing the wood-stove damper. This allows firewood to “last longer” especially at night when people go to bed (Ortega et al., 2016).

In general, most families buy the total volume of firewood required for the whole winter in the previous spring and summer (Fig. 6). Once firewood is delivered to the home it is chopped and stored in woodsheds and under roofs. This behavior allows people to buy firewood at lower prices, because of the volume, and keep it drier (lower moisture content). Yet, lower-income families cannot afford this expense. They subsequently tend to buy firewood in small quantities throughout the year, which implies higher prices and firewood with a higher moisture content (Reyes and Frene, 2006; INFOR, 2015). Furthermore, low income households generally lack space to properly store and maintain dry firewood, which can reabsorb moisture.

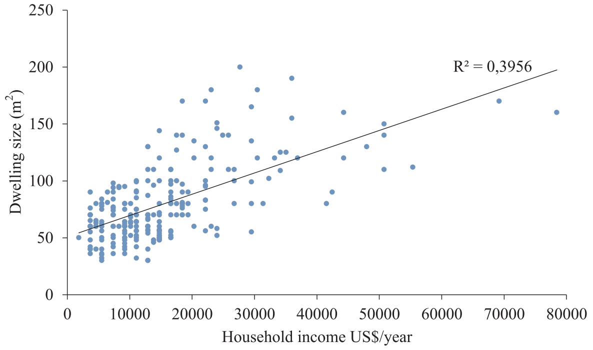

Fig. 5. Household income versus dwelling size.
Source: own elaboration.

4.2. Indoor and outdoor temperatures

Fig. 7 shows indoor and outdoor temperatures. In August and September, the outdoor temperature averaged 8.3 and 8.4 °C, respectively, fluctuating between 0 and 14 °C in August and 0 and 18 °C in September. By contrast, when taking into account all of the monitored houses (40-houses on average), indoor temperatures averaged 19.5 °C in both months, this was nonetheless highly variable among homes (Fig. 8). When using the average of the 40 homes, 68% of the time living room temperatures were below the thermal comfort threshold of 21 °C, which is recommended by the World Health Organization (WHO, 1987). In general, indoor temperatures surpassed the 21 °C threshold for only some hours each day.

According to the surveys, on average, a family in Valdivia keeps the wood-stove burning for 12 h/day (heating period). Considering this, we estimated the energy deficit in homes, which represents the amount of heat needed to reach a constant state of thermal comfort throughout the day. We found that the energy deficit decreases when income increases in houses built before 2000 (year when the first thermal regulation was created), this was not the case in houses built after 2000 (Table 1). The

Fig. 4. Most common wood-stoves used in Valdivia. Note: (a) “salamandra” wood-stove, (b) wood-burning cooking stove, and (c) slow-burning wood-stove.
Source: own elaboration.

Fig. 6. Firewood bought in the spring and summer in Valdivia.
Source: own elaboration.

heating period does not necessarily mean that people were cold the rest of the time (they may not have been at home); however, intermittent use of the wood-stove implies colder periods inside the home. Consequently, if the residents were home, this would have reduced their comfort level.

4.3. Indoor and outdoor air pollution

Fig. 9 shows indoor and outdoor fine particulate matter concentrations (24-h average of $PM_{2.5}$). The daily outdoor $PM_{2.5}$ concentration repeatedly exceeded 50 $\mu g/m^3$, which is the maximum value allowed by the Chilean air quality standard. In fact, values exceeded this standard on 26 out of the 56 days of monitoring (from 08/01 to 09/28). If this analysis were performed with the WHO air quality standard (25 $\mu g/m^3$ daily average; WHO, 2005), the number of days above the threshold would increase to 41.

On average, the indoor $PM_{2.5}$ concentration estimated from the 40 homes (40-houses on average) was much lower than that found outdoors. The range was between 20 and 30 $\mu g/m^3$ (24-h average), although we recorded up to 100 $\mu g/m^3$ for shorter time intervals (1-h average). These peaks are likely related to other activities that produce particulate matter, like smoking or lighting the fire (Barría, 2012). The WHO standard was exceeded on 36 out of the 56 days of monitoring indoor $PM_{2.5}$.

Unlike temperature, we found that the average indoor $PM_{2.5}$ concentration did not significantly correlate with income and dwelling age (which was related to thermal insulation, Table 2). This suggests that indoor air pollution is found across the board, with no distinction in terms of income (Fig. 10), although this may have been influenced by the study design (sample size and allocation). Higher-income families living in suburbs or on higher grounds that have lower housing density and are better ventilated may be exposed to lower outdoor $PM_{2.5}$ concentrations than those reported in this study.

4.4. Energy poverty

The average household income in Valdivia is US$ 15,528 per year, and the median US$ 12,923 per year. Families that fall into the first income decile earn an average of US$ 3804 per year (standard error = US$ 120), while the average household´s income in the highest decile reaches US$ 40,932 per year (standard error = US$ 2562) (Fig. 11).

Household income is relatively constant throughout the year, but the heating expense is concentrated in the winter months. Fig. 12 shows the proportion of the household income is spent on energy expenses for each household. The left-hand graph shows that 61% of families spend more than 10% of their real incomes on energy in the winter (dots above the horizontal line), which decreases to 25% of families in the summer (right-hand graph). In both cases, families start spending more than 10% of their incomes when they earn less than US$ 18,000 per year.

Fig. 13 shows the relationship between household income and energy consumption during the winter months. We found no difference in

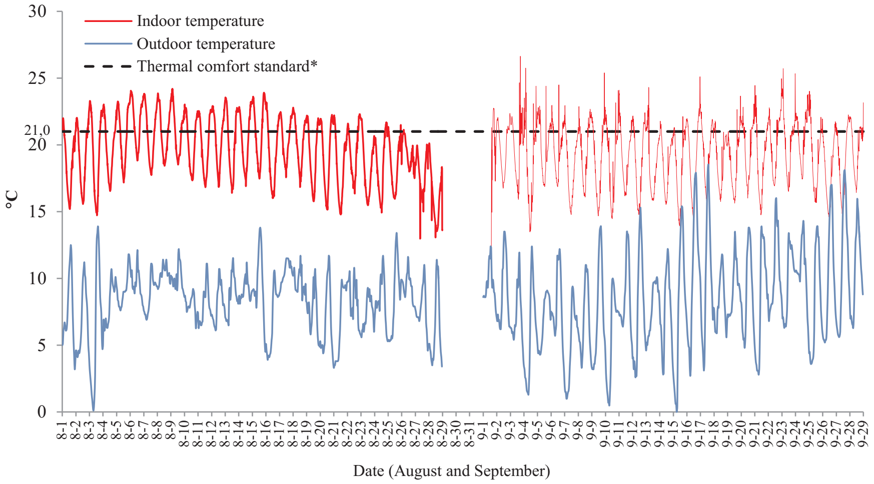

Fig. 7. Indoor (40-house average) and outdoor temperatures in August and September 2017. *WHO recommends 21 °C in the living room and 18 °C in the rest of the house (WHO, 1987).
Source: based on DMC (2017) and own data.

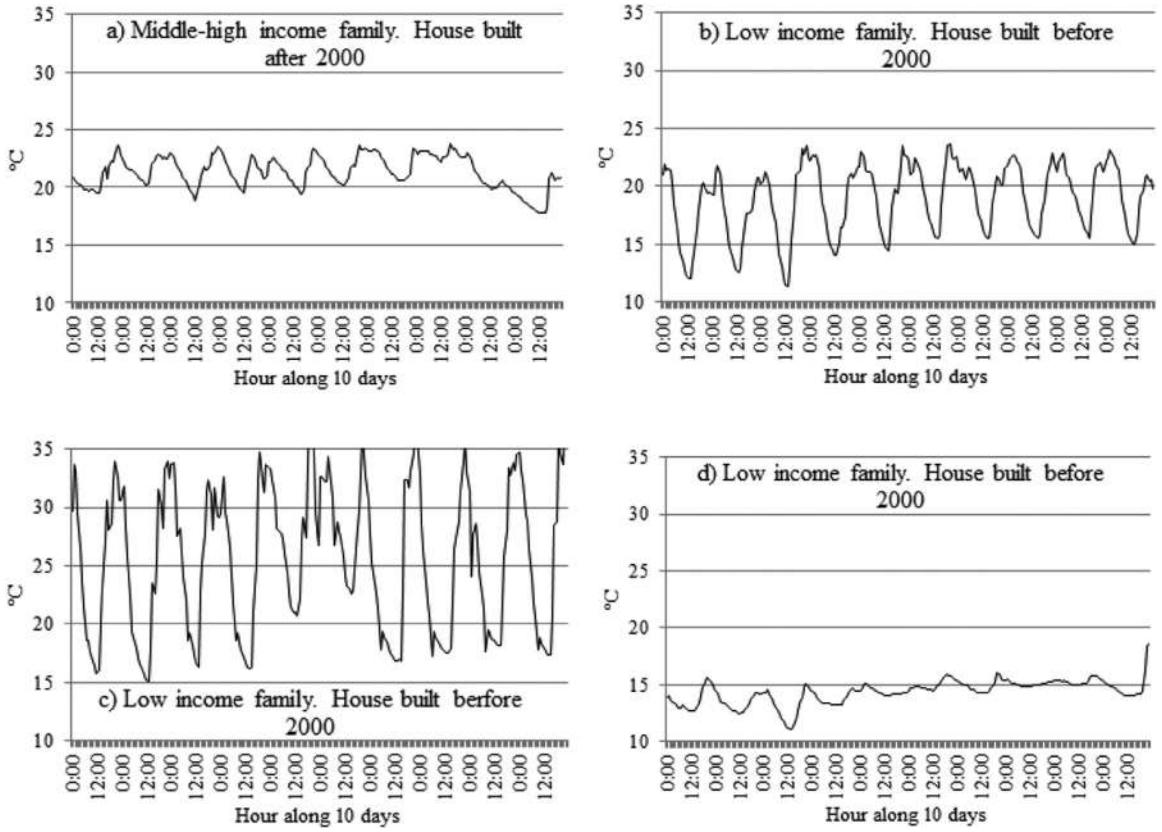

Fig. 8. Cases showing different trends of indoor temperature (August 1st–10th, 2017). Note: House "a" was built after 2000, so it has some thermal insulation, and is inhabited by two people (a woman and her son younger than 4 years old). House "b" was built before 2000, so it does not have thermal insulation, and is inhabited by two retired people. House "c" is the only one where people also cook with firewood. This house is inhabited by four people (one of them is younger than 4 years old). Finally, House "d" is inhabited by two middle aged people (with primary education) who work most of the day outside of the home. Houses in the other three cases are permanently inhabited.
Source: own elaboration.

Table 1
Energy deficit, household income, and dwelling age.
Source: authors´ own calculation.

Year the house was built	Energy deficit	Income (US$/household/year)		
		< 9240	9240–18,480	> 18,480
Before 2000[a]	Average (accumulated degrees/day)[b]	20.2	17.5	13.4
	Standard error	3.6	4.5	3.8
	Sample size	23	11	9
After 2000	Average (accumulated degrees/day)	10.5	14.0	9.9
	Standard error	8.1	3.8	4.0
	Sample size	4	9	3

Note: an exchange rate of 650 Chilean pesos per US dollar was used in the analysis.

[a] There were no thermal building regulations in Chile before 2000.

[b] Average Celsius degrees needed to reach a permanent state of thermal comfort.

energy consumption for the first two income deciles (inelastic), which means that increases in income do not translate into an increase in energy expenditure. There is a steady increment in energy consumption as income increases between deciles 3 and 8, a pattern that did not hold for the top two deciles (decoupling).

5. Discussion

The amount of energy used for heating in the city of Valdivia (206 kW h/m^2/year) is less than that in the neighboring city of Bariloche, Argentina (410 kW h/m^2/year),[4] where subsidized natural gas is the main fuel (González, 2009). This is nonetheless much greater than that which is consumed in other regions of the world with similar or even colder climates. This is the case of New Zealand, where about 30–50 kW h/m^2/year are used for heating, the states of Oregon and Washington in the Pacific Northwest of the United States of America (about 40–100 kW h/m^2/year), and Sweden (120 kW h/m^2/year), among others (EIA, 2009; González, 2009; Isaacs et al., 2010). This highlights the thermal inefficiency of homes in Valdivia. Schueftan and González (2013) found that small investments in thermal insulation, aiming to reduce heat losses through roofs, doors and windows can reduce energy consumption, air pollution, and expenditure on heating by 30–70%.

Valdivian residences high energy consumption proved not to provide adequate thermal comfort in most dwellings, as shown in Fig. 7. Inadequate temperatures are more frequent in lower income families living in dwellings built before 2000. This shows that replacing current wood-stoves for heaters that use another more expensive type of fuel, as is proposed in Valdivia´s PDA, may end up exposing to low-income families to severe health hazards by increasing the number of hours they suffer cold conditions inside their homes. A low quality living environment for people reduces their general wellbeing and the time they are able to allocate to study, work, or leisure (Khandker et al.,

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[4] Although when energy consumption values are adjusted by degree-days, both locations are similar in terms of energy consumption for heating (Schueftan and González, 2015).

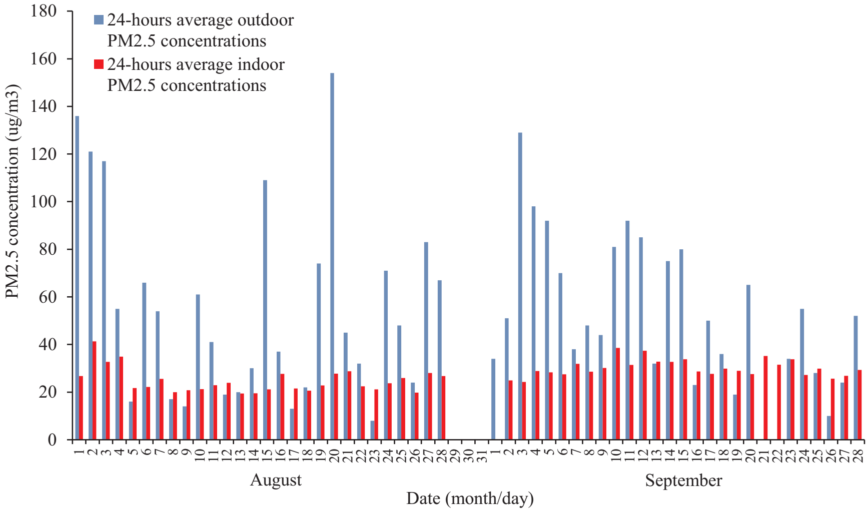

Fig. 9. Daily indoor (40-house average) and outdoor fine particulate matter ($PM_{2.5}$) concentrations.
Source: based on SINCA (2017) and own data.

Table 2
Average indoor PM2.5 concentration, household income, and dwelling age.
Source: authors´ own calculation.

Year the house was built	Indoor $PM_{2.5}$ concentration	Income (US$/household/year)		
		< 9240	9240–18,480	> 18,480
Before 2000[a]	Daily (24-h average, $\mu g/m^3$)	27.8	23.9	29.8
	Standard error	2.6	2.4	5.5
	Sample size	23	11	9
After 2000	Daily (24-h average, $\mu g/m^3$)	33.0	24.3	30.2
	Standard error	4.7	3.3	1.3
	Sample size	4	9	3

Note: An exchange rate of 650 Chilean pesos per US dollar was used in the analysis.
[a] There were no thermal building regulations in Chile before 2000.

2010), as well as having important effects on people's health (Baker et al., 2012). Despite their importance, impacts such as lower productivity, more time required for primary care, among others, have not yet been properly studied.

Houses built before 2000 reported the most serious deficiencies in thermal insulation, especially those owned by lower income families; the highest energy deficit for heating was found in these homes. Lower-income families are forced to spend a greater percentage of their income on energy expenses, while also suffering more frequently from cold conditions inside their homes than higher-income families. Therefore, it is important to realize that a share of any household retrofit oriented to improve energy efficiency in these households could produce only a small reduction in firewood consumption, because of people would tend to prioritize their thermal comfort instead of reducing heating demand (rebound effect). Anyway, this group should be a priority for a public policy (Galvin and Sunikka-Blank, 2016). In higher incomes levels (middle-low and middle income groups), rebound effect may be less intense (Webber et al., 2015). By contrast, houses built after 2000 showed a lower energy deficit, which did not change in relation to income level. Consequently, policies that aim to improve the thermal insulation of homes not only reduce energy consumption and air pollution, but also help to reduce social differences in thermal comfort.

At the same time, the thermal insulation of houses was not directly related to differences in indoor $PM_{2.5}$ concentrations. These pollutants were not correlated with income and the construction year, and more likely would depend upon people´s behavior concerning their heating systems as well as the household´s location within the city. Average indoor $PM_{2.5}$ concentrations were relatively steady throughout August and September, regardless of outdoor pollution levels. The daily average $PM_{2.5}$ concentration recorded inside homes in August (25 $\mu g/m^3$) was significantly lower than that recorded outside homes (56 $\mu g/m^3$). However, some homes showed higher concentration levels (24-h average), which vary between 20 and 80 $\mu g/m^3$ (Fig. 10), although most of values fluctuate between 10 and 40 $\mu g/m^3$. These levels were still high and could lead to severe health consequences when people are permanently exposed (WHO, 2005; Bernstein et al., 2008). This would not be the case, since $PM_{2.5}$ concentrations should fall between October and March, when the climate is warmer and drier and firewood consumption decreases, although this was not monitored in this study.

Regarding social terms, we found that over 61% of the sample was defined to be in energy poverty in the winter because they reported spending more than 10% of their net family income on energy (heating was the main component of their energy expenditure). These families recounted that they buy as much firewood as they can without significantly affecting their other, more basic needs, such as buying food, paying health and education bills, etc. Some of these families have developed alternative methods to fulfill their heating needs, such as firewood collection inside and outside the city (5% of households; INFOR, 2015), burning of wastes (wooden remains, cardboard, etc.; CDT, 2015), illegal electricity connections to the power grid,[5] or simply withstanding the cold and damp conditions inside their homes. In the summer, when heating is not a component of the energy bill, at least 25% of the sample proved to remain in energy poverty. This percentage coincides with what other authors have described as the "true dimension of poverty in Chile" (income poverty) (Durán and Kremerman, 2017; Ministerio de Desarrollo Social, 2017).

However, when the relationship between income and energy expenditures was analyzed under the framework proposed by Khandker et al. (2010), we found that families in the lower two income deciles spent on energy regardless of their income (more income does not turn into more energy). On the contrary, in the next five deciles, an increase in income did translate into higher energy expenditures; nonetheless, such a relationship was not found in the top two income deciles (Girod and de Haan, 2010). According to this analysis, most of households in Valdivia are in a state of energy poverty, which could reach 80%, with

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[5] http://www.soychile.cl/Puerto-Montt/Sociedad/2016/10/02/421372/Impulsan-campana-para-combatir-las-conexiones-electricas-ilegales.aspx.

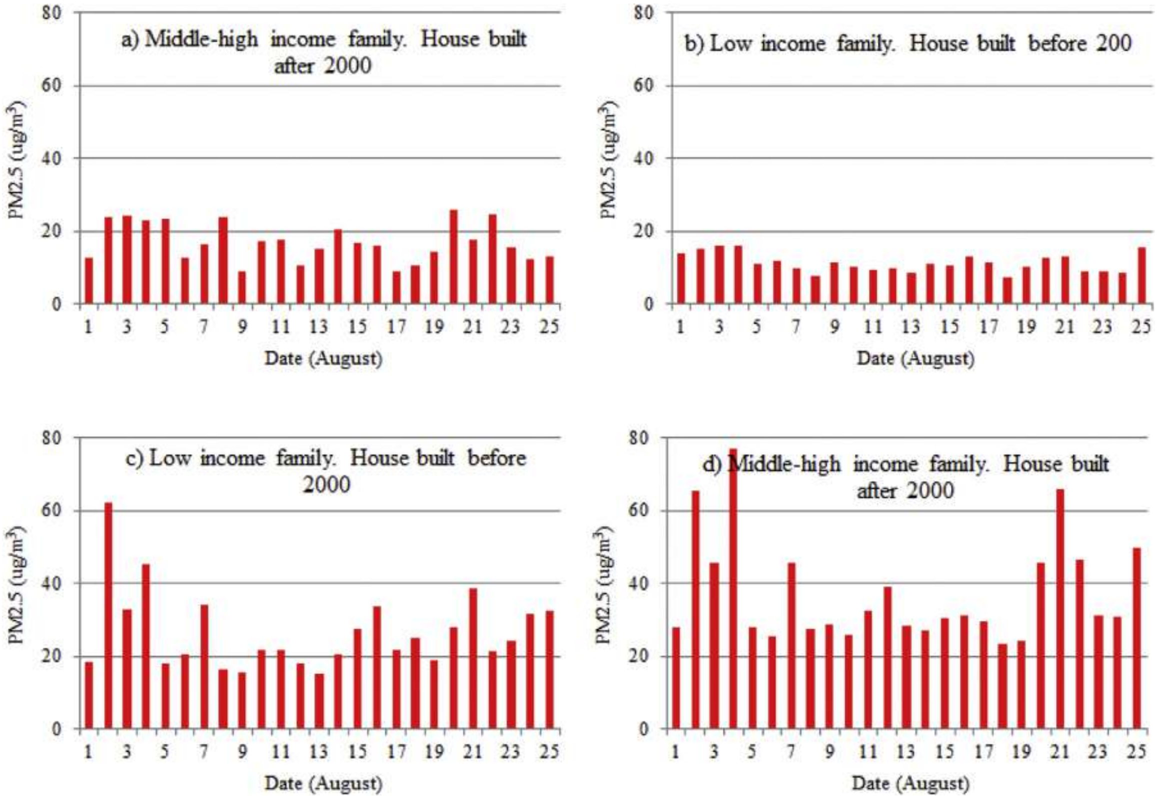

Fig. 10. Cases showing different trends of indoor $PM_{2.5}$ concentrations (24-h average) (August 1st–25th, 2017). Note: House "a" was built after 2000, so it has some thermal insulation and is inhabited by two people (a woman and her son younger than 4 years old). House "b" was built before 2000, so it does not have thermal insulation and is inhabited by two retired people. House "c" is inhabited by two middle aged people (with primary education). Finally, House "d" was built after 2000 and belongs to a middle-high income family (with university education), which is inhabited by three adults. Houses a) and b) people´s presence at home is permanent, unlike the House c). In the case of the House "d", the dwelling is used in a more irregular way.
Source: own elaboration.

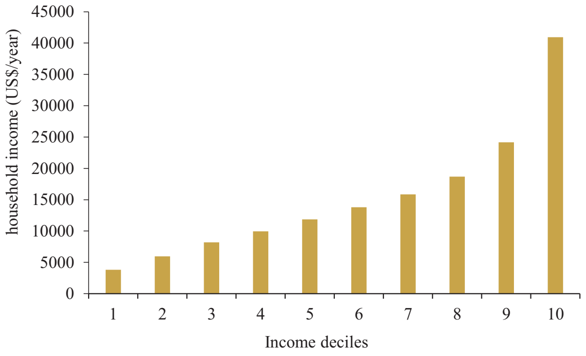

Fig. 11. Household income distribution in Valdivia based on the sample.
Source: own elaboration.

20% of households falling into the category of permanently income poor.

6. Conclusions and policy implications

Air quality improvement policies, implemented through the PDA, should take socio-economic factors into account in order to avoid increasing energy poverty. This is extremely important in Valdivia, Chile, where we found that over 61% of sampled households were defined to be in energy poverty in the winter.

Concerning the dry firewood program, this must certify that firewood actually complies with the 25% moisture content. If this is achieved, the program could complement other measures in order to reduce air pollution, although people´s behavior concerning firewood storage and use will always remain a key factor influencing the real contribution of this program. If firewood is used, in the end, at higher moisture contents since it reabsorbs humidity, all investments and efforts dedicated to this program would be questionable and could lead to negative social outcomes, as buying dry firewood increases the heating cost (Conway, 2012). Similarly, the wood-stove replacement program should be focused on people who can afford the cost of more expensive fuels (wood-pellets, kerosene, LPG or electricity). Since 2014, this program has replaced about 300 wood-stoves per year (with more than 2000 applicants each year), which is exiguous in comparison with the 50,000 wood-stoves that exist in the city. Nevertheless, a significant increment in the rate of replacement should occur in the coming years.

Moreover, the real value of the PDA's "environmental alerts", when environmental authorities forbid the use of firewood at the risk of a fine, must be thoroughly reviewed. During these alerts, people are expected to use an alternative source of energy for heating. However, this is virtually impossible for lower-income families. These "environmental alerts" have thus resulted in increased heating expenses and colder indoor environments. Even though this measure reduces the negative impact of air pollution on people's health, it also exposes people to cold, humid environments inside their homes, making them vulnerable to other health issues, such as bronchitis, asthma, etc. (WHO, 1987; Howden-Chapman et al., 2012).

Thermal building regulations have only recently been implemented, resulting in a complex scenario: more than 80% of homes are highly energy inefficient (Ortega et al., 2015). As shown above, the lack of thermal efficiency particularly affects low-income families living in older and more precarious dwellings, which require more energy to reach a healthy indoor temperature. The household thermal retrofit

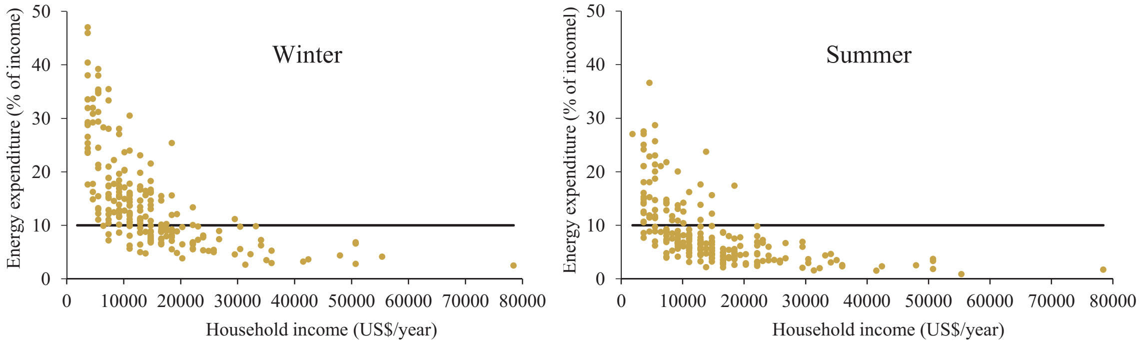

Fig. 12. Household income and energy expenditure.
Source: own elaboration.

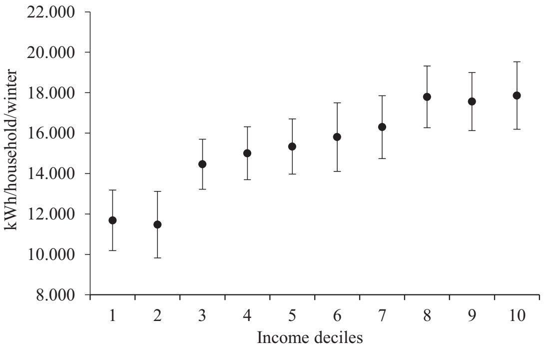

Fig. 13. Energy consumption versus household income (deciles). Note: average and standard error.
Source: own elaboration.

program, as well as enhanced thermal requirements for new homes could significantly improve the indoor environmental conditions and reduce energy demands for heating (Howden-Chapman et al., 2009). These measures would effectively tackle one of the ultimate causes of air pollution in Valdivia and other cities in south-central Chile (Fissore and Colonelli, 2013), with positive effect on people's health and welfare (Schueftan et al., 2016; Preval et al., 2018). More research is needed to determine other potential benefits regarding income, school performance and other indicators. The household thermal retrofit program would mainly benefit low and middle-low income families.

Household thermal retrofit could also have synergistic effects on the other PDA measures, such as the replacement of wood-stoves and the dry firewood program. By reducing energy consumption, heating costs would also be reduced, thus increasing the affordability of other fuels, such as electricity, wood pellets, and others, whose functioning can be automated. This would improve people´s comfort and health (Howden-Chapman et al., 2008). The household retrofit program should be the backbone of the PDA, especially for lower income families, where levels of thermal discomfort and health hazards are the highest. Thermal retrofit should also consider controlled air ventilation to reduce the accumulation of particulate matter (Cortés and Ridley, 2013). Future extension onto existing homes should also follow the standards of thermal retrofitting to obtain the same positive effects (Viggers et al., 2017).

The design and implementation of public policies that aim to solve the problem of air pollution that affects cities in south-central Chile should consider all the previous aspects; especially since air pollution is a much deeper and more complex problem than just heating. It is the result of complex issues related to poverty and inequality. Under this framework, PDAs should not only center on reducing $PM_{2.5}$ concentration, but also on promoting welfare for families by increasing thermal efficiency and therefore reducing their spending on fuel, and ultimately, reducing air pollution.

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