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Reduction of firewood consumption by households in south-central Chile associated with energy efficiency programs

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HIGHLIGHTS

- High firewood consumption and environmental pollution in cities of south-central Chile.
- High use of firewood due to inefficient constructions and soft thermal regulations.
- Potential reduction of energy consumption up to 77% with more demanding regulations.
- Policies should address building stock before thermal regulation, corresponding to 85%.

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ABSTRACT

Cities in the central-southern area of Chile face serious environmental pollution due to extensive use of firewood for heating. Low energy efficiency of constructions and cold climate increase the problem, which also affects native forests. The aims of this study are to characterize energy consumption in dwellings of this region, investigate the reduction potential, and study social and environmental consequences of high consumption of firewood. Actual energy consumption is studied with information from surveys, potential for reduction is modeled with software and other consequences are analyzed from previous studies. Results for the city of Valdivia show high firewood consumption per household, with a media bulk volume near 12 m^3/year. Thermal regulations are softer compared with other countries. Moreover, around 85% of buildings were built before enforcing codes in 2007, and has almost no thermal protection. The reduction potential due to thermal improvements is found to be very high (62%) if buildings are refurbished to comply with the present Chilean Norm of 2007, but it reaches a 77% reduction if refurbished according to stricter foreign regulations. Therefore, an energy efficiency program strongly addressing existing buildings has the largest potential for reducing firewood use, and therefore mitigate environmental and health impacts.

1. Introduction

Direct energy consumption in the residential sector in Chile in 2009 was 22% of the total energy used in the country (IEA, 2009). Chile is largely an energy importer, with 75% supplied from external sources. Biomass (mainly in the form of firewood) represents 18% of the total energy used, but it accounts for 54% of the energy produced in the country. In 2011, the residential sector derived 58% of the energy use from firewood (MINE, 2012), which is the main heating fuel in the regions of Araucanía, Los Ríos, and Los Lagos (central-south part of Chile), where temperate-cold and cold weather dominates.

At present, Chile faces a complex energy problem, including vulnerability of own resources to climatic changes and health issues associated with firewood-combustion smoke. As we will discuss in detail below, for the last decade, air pollution parameters in cities of central-southern Chile have shown concentrations of particulate material much larger than recommended limits. The situation is further stressed by a solid Gross Domestic Product (GDP) growth. From 1990 to 2007, energy use in Chile rose 320%, much faster than any other Latin-American country. In turn, CO_2 emissions also had a remarkable rise. Recently, Mundaca (2013) demonstrated that the rise in CO_2 emissions is better explained by affluence (measured by GDP per capita), rather than population or total GDP growth. Affluence led to larger percentage of population reaching medium incomes and requiring better

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standards of comfort. In the residential sector, where the building stock has low thermal efficiency, more comfort directly means more energy, and in central-south regions it means more firewood for heating. On the other hand, even though firewood is considered neutral on CO_2 emissions when burnt, there are emissions due to native forest perturbations by substantial logistics, transportations, and processing when delivering firewood into large modern cities like the one studied in the present work. A recent study in Australia also showed significant amount of carbon sequestered by m^3 of wood, which would not be contributing to CO_2 emissions if it is not burnt, but rather could store carbon by replacing other carbon intensive materials (England et al., 2013).

It is to note that Chile made an effort to switch from firewood into gas and electricity but failed. In the late 1990s a gas pipeline from Argentina was built across the Andes and a gas distribution network that provided a substitute for firewood was built in the central region of Chile. This pipeline network provided natural gas to industry, residential and power generation sectors. Gas import from Argentina rose 570% between 1996 and 2004. Cheaper electricity could also partially replace use of firewood even in medium and low income households. However, in 2003 Argentina began to have a shortage of gas supply and started in 2005 to lower the natural gas sold by pipeline to Chile, ending it completely in 2008 (CNE, 2013). Moreover, Chile has a smaller production of indigenous gas in the southernmost region of Magallanes. This provision is used mainly locally and there are price subsidies to compensate users for harsh cold conditions although subsidizing fuels seems to create an array of risks (González, 2013). For instance, an attempt to raise gas prices in 2011 by 15% in the Magallanes region ended up in a month-long protest and riots, to finally agree on just a 3% rise in price. On the other hand, subsidies on fuels in Argentina have shown to be major promoters of very high energy consumption and social inequalities on the access to energy (González et al., 2007). Subsidies for refurbishments, instead of subsidies on fuel prices, are long-term investments, rather than solving inefficiencies with the use of cheap energy (González, 2009).

On this matter, Chile has a program for thermal refurbishment for households in the low-medium and low income sectors. The program started in 2008, and has so far covered 0.6% of existing dwellings. The improvements covered by the subsidies could bring thermal efficiency of houses to the 2007 Norm, the latest thermal regulation for buildings in Chile. However, the 2007 Norm requires much less insulation than used in other OECD countries with similar climate. For instance, in the area of the present study, the 2007 Norm requires 2 cm insulation thickness for walls, 14 cm for roofs, and 5 cm for ventilated floors, but none for slabs on the ground, which are in fact very common. All buildings constructed after 2007 should comply with this regulation; however, the building stock previous to that date was built either with the 2000 Norm or with no specification, and accounts for around 85% of existing dwellings. The 2000 Norm was much softer in thermal requirements; regulating only the thermal transmittance of the roofing.

We will discuss below quantitative indicators showing that most dwellings in Valdivia have similar low efficiency as the ones already studied in the city of Bariloche, in the south of Argentina (González et al., 2007). The comparison between the Argentinean and the Chilean cases is interesting because, in spite of having similar building thermal efficiencies, they have different policies regarding energy prices. With few local exceptions, Chile does not subsidize fuels, but at present has programs to subsidize thermal refurbishments and modernization of heaters; however, these programs are limited and aimed only to low income households.

The present study aims to revise the information of actual energy situation for dwellings in south-central Chile, to investigate the potential for improvements, and to address proposals of energy policies for the region. Environmental, social and economic benefits of investments in energy efficiency will be considered.

2. Methodology

The present work comprises a multi-thematic investigation on the efficiency and consequences of firewood use in cities with populations over 100,000 inhabitants. The study focuses on the city of Valdivia, in the region of los Ríos, one of the fifteen administrative district regions in Chile. It is situated in the central-south region of Chile. This is a latitude-wide area comprising from the region of Araucanía to the region of Los Lagos (Fig. 1), and sharing similar weather requirements and solutions for households' energy needs. The region of Los Ríos where the city of Valdivia is located was created in the year 2005 and previously belonged to the region of Los Lagos. For this reason some previous studies mentioned the region of Los Lagos when presenting data that also included Valdivia.

The methodology for the present work is a literature and data review of economic, social and environmental aspects related to energy efficiency of dwellings. Data for fuelwood consumption and housing status in Valdivia was obtained from studies at the Universidad Austral de Chile (details below). Data for air pollution and health implications are based on official documents and reports from other public entities, such as the Ministry of Environment and Ministry of Health. In addition, scientific publications were revised to obtain information of international cases that served as benchmarks for this study. Sections 2.1–2.4 give details on the methodology for the issues considered.

2.1. Energy consumption assessment

This research will use Valdivia as a case study, one of the major cities in the south-central part of Chile. In 1960 Valdivia suffered the strongest earthquake ever recorded (magnitude 9.5). Due to seismic risks, building practices take into account the geological instability of the region. Therefore, one-family houses are usually light and wood-framing and cavity walls are common, as well as ground floor with masonry walls but second and third floors in light-frame wood.

The research unit Centro de Investigación de la Vivienda Austral (CIVA-UACh), Universidad Austral de Chile, has surveyed the actual consumption of firewood in 310 single-family households in Valdivia. The study assessed heating demand as well as addressing proposals for thermal improvements (CIVA-UACh, 2010).

The survey included a set of questions to identify consumption patterns and housing construction features, and was performed at random in dwellings built before the year 2000 in the city of Valdivia. The city was divided in 35 areas according to the housing typology, and 62 typologies were identified. A total of 5 surveys were performed for each typology, thus there was information gathered for 310 dwellings, some examples are shown in Fig. 2.

The thermal performance of these dwellings was modeled with the software CCTE-MINVU. This software is the official tool to certify thermal behavior of buildings, created by the Chilean Ministry of Housing and Urbanism (MINVU, 2007). The CCTE-MINVU is a steady-state calculation engine that delivers monthly and annual results based on predetermined thermal comfort conditions. The energy demand is compared with a baseline that corresponds to the same building under conditions in which the elements of the envelope possess the maximum thermal transmittance values required by the thermal regulation. The software incorporates climate data for 107 different areas throughout the country.

Before the year 2000 there was no regulation for the thermal characteristics of dwellings that were built in Chile, and the actual regulation has been implemented in stages. The first stage was implemented in the year 2000 and regulated only the thermal transmittance ("*U*" value) of the roofing. The second stage was implemented in the year 2007 and also considers the thermal transmittance of walls and floors. To determine requirements regarding thermal transmittance this regulation divides the country into seven regions according

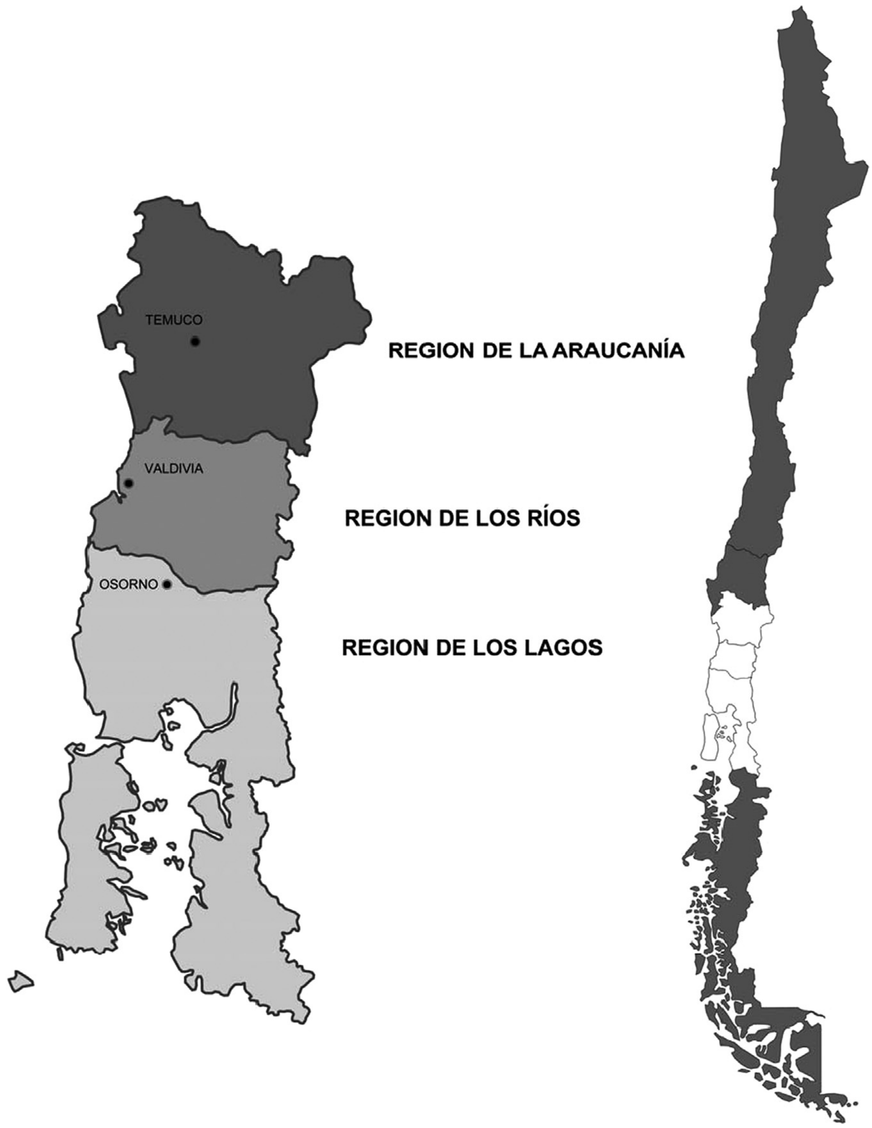

Fig. 1. Regions of south-central Chile.

to climatic characteristics. The city of Valdivia corresponds to climatic zone 5, so the recommended heat transfer coefficients are as shown in Table 1.

The Norm does not consider key issues for the energy performance of homes and indoor environmental quality such as thermal bridges, vapor barriers and ventilation systems to prevent condensation on building components.

2.2. Energy reduction potential

Recently, Schueftan (2012) investigated the thermal performance and improvement potential for the most common social housing typology. This social housing in Valdivia is built with complete wood structure and according to the technical characteristics required by the Chilean Ministry of Housing and Urbanism (MINVU, 2006). A house of 44 m^2 of living area and 6.8 m^2 of windows with south-west orientation (neutral in terms of solar gain) was studied. A number of 5 inhabitants were considered in the house. The 44 m^2 dwelling used for thermal simulations is considered to be representative for the building stock in Valdivia because the 2000 norm was considered as baseline for this house. This corresponds to constructive characteristics of most existing dwellings in Valdivia (85%). Surveys conducted by CIVA also showed that different house typologies have similar energy demand per m^2, and thus the studied dwelling gives a fair reduction potential for the city.

The energy demand calculation was performed considering three different refurbishment levels, according to the following thermal regulations: (1) 2000 Chilean Norm; (2) 2007 Chilean Norm; and (3) ASHRAE 2005. The latter considers lower *U*-values than the Chilean norms, for instance 0.57 W/m^2 K for walls (ASHRAE, 2005) against 1.6 W/m^2 K as in the 2007 Chilean Norm, and the elimination of thermal bridges. An indoor temperature of 18.3 °C was considered a comfort level for Valdivia. ASHRAE norm is compared with the Chilean thermal regulation because it is considered of broad knowledge, and used widely in certifications in Chile to demonstrate energy efficiency in buildings, for instance, in LEED certification (Leadership in Energy and Environmental Design). ASHRAE proposes stricter and complete standards and requirements, as well as European norms; however, the ASHRAE is frequently used in Chile.

Outdoor mean temperatures averaged over 1970–2000 were obtained from the official meteorological service (Meteo, 2001), and are depicted in Table 2. Heating Degree-Days (HDD) were calculated on 18.3 °C base.

The different refurbishment levels allowed assessing the costs and benefits associated with each reduction potential. Currently, in the city of Valdivia there are approximately 54,500 dwellings, of

Fig. 2. Sample of common one-family housing typologies.

which around 38,500 were built before the enactment of the thermal regulation of 2000 (INE, 2012). Therefore, 70% of the residential housing stock does not meet the basic requirements of thermal conditioning, making retrofitting of existing buildings a major issue.

Table 1
U-value (W/m^2 K) required by the 2007 Chilean Code for different climate regions. The city of Valdivia corresponds to zone 5.

Zone	Roof	Exterior wall	Ventilated floors
1	0.84	4.0	3.60
2	0.60	3.0	0.87
3	0.47	1.9	0.70
4	0.38	1.7	0.60
5	**0.33**	**1.6**	**0.50**
6	0.28	1.1	0.39
7	0.25	0.6	0.32

2.3. Heating fuels

The main heating fuel in the city of Valdivia is firewood, with as much as 95% of households using it for heating. Native forests provide the largest part of firewood consumed (86%) (INFOR, 2012), and there is almost no use of forest residues for heating. The wood is processed in 1 m logs with a section between 0.10 m and 0.30 m, then transported into cities by truck and sold according to different measurement systems depending on the city (Fig. 3). It is sold to consumers by the volume, and in Valdivia the unit is usually called “m^3”. In International Units this is the stereo or stacking volume (st). The st of firewood approximately equals a bulk volume of 1 m^3 of fairly round logs, and it is considered as equivalent to 0.56–0.65 m^3 solid wood for measuring the amount of fuelwood. The standard humidity is assumed at 25%, and the calorific value of firewood is estimated at 1540 kWh/st.

Households buying firewood from this source have it piled up at the sidewalks (Fig. 3), and other workman services cut it with chainsaws in smaller pieces, usually 0.33 m long, convenient to carry into the house's wood shed. Afterwards, the wood must be split longitudinally into pieces suited for the dimensions of the furnaces. The cut and split wood is then stored in a shed within the property, and brought into the house in amounts suitable for daily or weekly use.

Table 3 depicts the fuels available for households in Valdivia and the actual cost, including all taxes. The comparative analysis of fuel prices show that the consumer cost for obtaining 1 GJ of firewood is around 3 times lower than for diesel or kerosene, 4 times lower than LPG (Liquified Petroleum Gas), and as much as 5 times lower than electricity. Briquettes are not commonly used but they are readily available in the market, and their energy price is around 2 times higher than firewood. Clearly, fuelwood use has economic advantages for all users, but it is also the only accessible heating fuel for low-income households. An even larger asymmetry in fuel prices was found in Argentina for subsidized natural gas and other available households' energy resources (González et al., 2007). Having one energy source at much lower price than others usually has consequences in thermal efficiency, as we will see below.

Efforts have been made from institutions to create conditions for consumers to buy certified wood. This type of wood is regulated to have a maximum humidity (25%) and the provision should be from renewable cultivars with management plans and forest improvement criteria. In the region of Los Ríos only 1.2% of the firewood sold is certified wood (SNCL, 2010). Only three districts of the region (La Unión, Corral and Valdivia) consume certified wood. Although the city of Valdivia consumes the highest percentage compared to other communities (2.8%), it still represents a small fraction of all the firewood that is used (SNCL, 2010).

On the other hand, the participation of the firewood market in the development of local economies accounts for 1.2% GDP share

Table 2
Monthly mean temperature (T_{MM}) (Meteo, 2001), and Heating Degree-Days for Valdivia (18.3 °C base).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
T_{MM}	18.2	17.8	15.7	12.7	10.5	8.1	7.8	8.8	10.7	12.8	14.8	17.1	12.9
HDD	3	14	81	168	242	306	325	295	228	171	105	37	1974

Fig. 3. Typical firewood delivered to the door of one-family houses.

Table 3
Energy sources for households in Valdivia: retail prices, calorific value, and energy prices.

	Purchase unit	Price/unit[a] ($)	Energy/unit (MJ)	Price per GJ ($/GJ)
Electricity	kWh	0.23	3.6	65
Kerosene	liter	1.40	36	38
Gas (LPG)	kg	2.60	49	52
Diesel	liter	1.40	38	36
Briquette	kg	0.41	18	23
Firewood	st	66	5540	12

[a] Price corresponds to households and includes all taxes and fix costs. Rate of Chilean Peso and US$ was 470 CLP to US$ 1.

Table 4
Safety limits of PM on 24-h and annual mean. See text for references.

	PM_{10} ($\mu g\ m^{-3}$)		$PM_{2.5}$ ($\mu g\ m^{-3}$)	
	24-h	Annual mean	24-h	Annual mean
WHO AQ Guideline	50	20	25	10
WHO IT3 level	75	30	37	15
Chilean Primary Norm for PM	150	50	50	20
EPA US	150	50	35	12

for the region of La Araucanía and 0.9% for the region of Los Lagos (Gómez-Lobo et al., 2006). However, since only 1–3% of consumers buy certified wood, there is a major tax loss due to the informality of the fuelwood market. According to previous studies the tax loss for south-central Chile is between US$14.5 and US$16.3 million per year (Gómez-Lobo et al., 2006).

A significant threat to the native forest is a consequence of the minimum amount of wood extracted with management plans and having the appropriate moisture content. Since most fuelwood is sold with no certification, a high level of humidity is commonly found, more quantity is needed for heating requirements and more particulate emissions the combustion produces. The regional office of the Ministry of Environment posted in its website recommendations to buy and use fuelwood, and availability of certified wood in the area (MMA, 2013a).

2.4. Environmental pollution and health issues

In the present work, we use data from the official website of the Ministry of Environment, which has equipment monitoring particulate matter hourly in major cities (SINCA, 2013). The use of large quantities of firewood for heating is not exclusive to households but also to public buildings and commercial sectors. Large buildings burn fuelwood in boilers, while households use it mainly in individual iron made furnaces. Both boilers and furnaces have chimneys releasing smoke directly outdoors. Catalytic or filters are extremely rare in the equipment currently provided. As a consequence, the largest cities south of Temuco have surpassed the upper tolerance limit for $PM_{2.5}$ and PM_{10} particulate for several consecutive years (SINCA, 2013).

Table 4 depicts upper limits of PM_{10} and $PM_{2.5}$ for health risks according to the World Health Organization (WHO, 2005), the Chilean Norm for air quality (MMA, 2013b), and the US safety limit (EPA, 2013). Values averaged over a day (24-h mean), and over a year (annual mean) are indicated and will be use to discuss results in Section 3.2. The WHO (2005) stated 4 different safety levels according to risk. This procedure was not followed by the other two norms depicted in Table 4. Then, we show two levels of risk stated by WHO (2005): the Air Quality Guideline (AQG), and the second risk level IT3.

It is to note that, based on extensive scientific review on health impacts, EPA has recently lowered the $PM_{2.5}$ annual mean from $15\ \mu g\ m^{-3}$ to $120\ \mu g\ m^{-3}$, closely approaching the value recommended as safe by WHO (2005). On PM_{10} for 24-h, the relatively large value set by EPA is joined by a regulation stating that it can only be surpassed once a year.

3. Results and discussion

3.1. Current firewood consumption

Table 5 depicts results obtained from the study mentioned in Section 2.1 (CIVA-UACh, 2010). The first column indicates the range of fuelwood consumed annually, the second column the number of households in the surveyed that reported that range of consumption,

Table 5
Fuelwood consumption in 310 one-family dwellings in Valdivia, and projections for the total number of houses built before 2007.

Firewood/year (st)	No. surveys	Percentage (%)	Total dwellings	Total firewood/year (st)
3	5	1.29	607	1821
4	5	1.29	607	2428
5	25	6.46	3036	15,180
6	13	3.36	1578	9472
7	17	4.39	2064	14,452
8	35	9.04	4250	34,005
9	3	0.78	364	3279
10	130	33.59	15,788	157,880
11	1	0.26	121	1335
12	42	10.58	5100	61,209
13	3	0.78	364	4736
14	5	1.29	607	8501
15	44	11.37	5343	80,155
16	4	1.03	485	7772
17	2	0.52	242	4129
18	8	2.07	971	17,488
20	33	8.53	4007	80,155
25	10	2.58	1214	30,361
30	2	0.52	242	7286
	387	100	47,000	541,698

the third column is the percentage of those households surveyed. Then, the fourth and fifth columns show a prediction for the consumption of fuelwood by all houses in Valdivia built before the 2007 Norm. This is estimated by assigning the percentage of households having a given level of consumption to the total 47,000 dwellings built before 2007.

The statistical analysis of Table 5 led to a mean firewood consumption of 11.4 st/year with a standard deviation of 5. The same surveyed households were modeled with the software mentioned in Section 2.1, and the result was a mean of 13.5 st of firewood per year for each household. This difference is attributed to the choice of comfort indoor temperature in the simulations (18.3 °C). In practice, most houses do not reach the minimum level of comfort. This is a very important aspect to consider in health and social issues, especially in the study of social housing where indoor temperatures are lower.

Fig. 4 depicts the annual consumption of fuelwood as a function of income level for the surveyed households (CIVA-UACh, 2010). Group 1 corresponds to the higher income and group 4 corresponds to the lower income. The 4 income groups represent typical socio-economical classification according to income, place of residence and consumer habits in: ABC1, C2, D and E. There is a clear relation between income level and firewood consumption from surveys. Lower fuel consumption, along with lower thermal efficiency in lower income dwellings, led to indoor temperatures below comfort.

It is to note that recently, on the event of sanitary alarms for air quality in Temuco, the Minister of Environment called middle and higher incomes to replace firewood by gas, arguing that higher income homes consume the most, and have the means to pay for cleaner energy resources (Benítez, 2013). Restrictions for fuelwood consumption in certain neighborhoods assumed to be of higher incomes have been recently implemented in Temuco.

In previous works, we have defined a simple indicator of energy efficiency in housing, and compared efficiencies in locations of Argentina and Sweden (González, 2009). The indicator is the ratio of the heating energy used and the number of heating degree-days at the location. In Table 6 we compared the energy consumption for household heating in Valdivia with cities studied in Argentina and Sweden. The similar values in the range of 40–42 MJ/year. HDD obtained for La Plata and Bariloche indicate a similar low heating efficiency, in contrast with Stockholm which has a value of 13 for the same indicator. The consumption found in Valdivia (38 MJ/year.HDD) is much higher than cities in developed countries, such as Stockholm, but slightly lower than cities in Argentina. Housing heating efficiency is about the same in Argentina and Chile, however, in Argentina natural gas is the main heating fuel and the price is heavily subsidized (US$2/GJ), making energy consumption and indoor temperature higher. In developed countries, stronger thermal regulations along with fuels at international prices result in households using much less energy for heating. In the case of Argentina, fuel subsidies result in very low prices causing no investment or subsidies for improvements in the construction quality; this is the reason for having the same efficiency for temperate-warm La Plata and very-cold Bariloche (González, 2009). The same thermal low quality in two different climatic regions is compensated by gas consumption to achieve indoor comfort. In any case, Table 6 makes clear the large difference in the use of energy in Sweden and in the two Latin American countries compared.

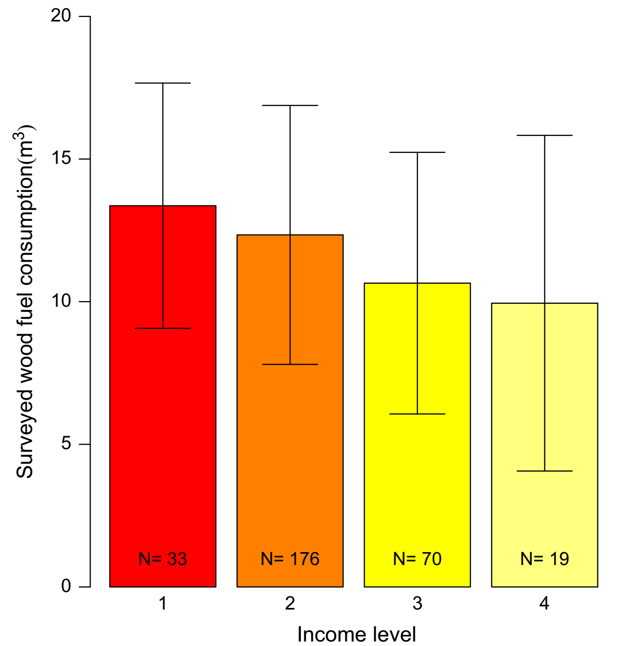

Fig. 4. Fuelwood consumption per year in one-family households surveyed in Valdivia, as a function of income level.

Table 6
Heating energy used per unit of climate requirement, in MJ per Heating Degree Days (HDD), for one-family houses in Chile, Argentina and Sweden.

	Valdivia	La Plata	Bariloche	Stockholm
Latitude	39°S	34°S	41°S	59°N
Annual mean temperature (°C)	12.9	15.5	8	7
Heating degree-days (HDD) (°C, base line 18.3 °C)	1974	1170	3620	4070
Energy for heating (MJ/year)	75,000	50,000	144,000	53,000
Heating energy per unit of climatic heating degree-day (MJ/year HDD)	38	42	40	13

3.2. Air pollution

The need for heating in the region studied extends from 7 to 8 months yearly. As mentioned, the amount of firewood consumed, and the way it is burnt, is responsible for large quantities of particulate PM_{10} and $PM_{2.5}$. Fig. 5 shows daily measurements of

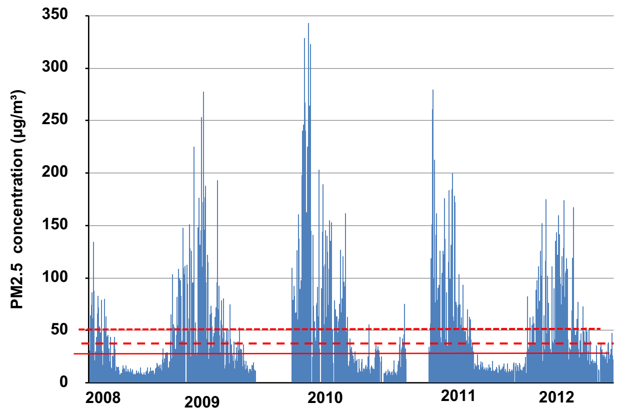

Fig. 5. 24-h mean $PM_{2.5}$ for Valdivia. Solid red line, safety guideline by WHO; dash red line, safety level by EPA-US; and dot red line safety level by the Chilean Primary Norm (see text and Table 4 for references). (For interpretation of references to color, the reader is referred to the web version of this article.)

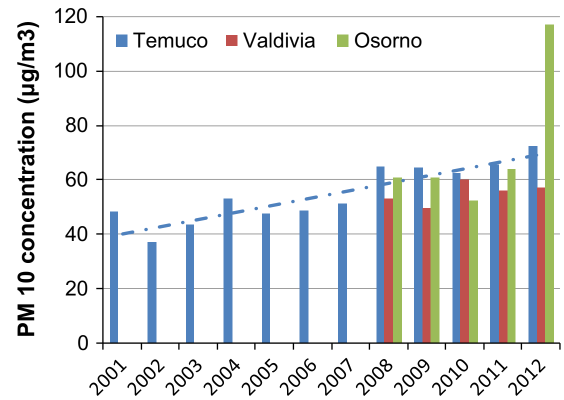

Fig. 6. PM_{10} concentration, annual mean daily values, for three cities. The dot-dash line is the fitting of Temuco data (see text for details).

$PM_{2.5}$ in the city of Valdivia (SINCA, 2013), compared with the safety level of the three norms discussed in Section 2.4.

It is clear that the level of PM pollution is extremely high during the cold season, surpassing safety levels of all air quality norms. Not shown here, the PM_{10} 24-h is also frequently above safety levels in the cities of the region considered (SINCA, 2013). Either for PM_{10} or $PM_{2.5}$, the study of the 24-h means of daily exposures clearly depicts the cold season with concentrations several times higher than warmer months of spring or summer. Therefore, it seems like firewood smoke, and not traffic, is the main reason for the excessive particulate found in the region.

In Fig. 6 the annual mean of daily concentration of PM_{10} for the cities of Temuco, Valdivia, and Osorno is shown (SINCA, 2013). For all years and the three cities, the limit has been far higher than the recommended level by WHO (2005) for not having health consequences (AQG = 20 μg m^{-3}), and currently, the three cities have higher annual means than all norms recommend. We have no explanation for the extremely high level experienced by Osorno in 2012, except that the year was drier and average temperatures were lower, and heating was used even until December 2012, which is the starting of the summer season. In addition, Osorno has experienced a steady economic growth, and in 2013 is considered in environmental emergency, because there have been several years with saturated particulate pollution.

Temuco has been monitored for longer time, and it let us make a linear regression in Fig. 6. The result is the dot-dash line in Fig. 6, which has a slope of 2.7 (R^2 = 0.80). The meaning of the slope is an increase of particulate concentration of 2.7 μg m^{-3}/year averaged between 2001 and 2012. The trend for Osorno and Valdivia is also upward but there is not enough data to make a reliable fit.

Fig. 7 depicts the concentration of $PM_{2.5}$ averaged annually for the cities of Temuco, Valdivia and Osorno. In this case, the different air quality guidelines state a safety limit of 10 μg m^{-3} (WHO, 2005), 12 μg m^{-3} (EPA, 2013), and 20 μg m^{-3} (MMA, 2013b). The three cities are well above the tolerance limits for the 4-year period shown.

In all south-central major cities smoke from burning fuelwood is clearly seen and smelled most days of the cold season.

The social benefit of reducing in 1 μg the concentration of fine particulate matter ($PM_{2.5}$) has been estimated between US$8 and US $34.5 per person (Gómez-Lobo et al., 2006). The benefit of reducing the concentration of one microgram of $PM_{2.5}$ just in the city of Temuco and surrounding areas could reach between US$2.2 and US $10 million, depending if the effects on mortality from long-term exposure are considered or not. If the exercise is extended to all the urban population in the central-south of the country, the benefits reach between US$11.2 to US$51.3 million. These figures and

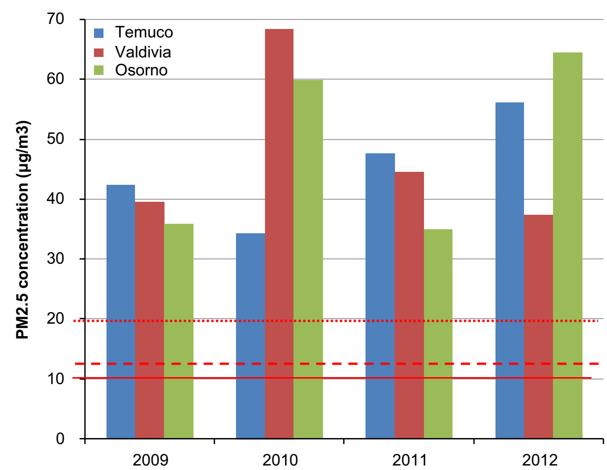

Fig. 7. Annual mean of daily concentration of $PM_{2.5}$ in three cities. Solid-red line, safety level by WHO; dash-red line, safety level by EPA-US; dot-red line safety level by Chilean Primary Norm (see text and Table 4 for references). (For interpretation of references to color, the reader is referred to the web version of this article.)

parameters can be used to assess the costs and benefits of different policies to reduce air pollution in the cities of the central-south of Chile (Gómez-Lobo et al., 2006).

3.3. Reduction potential by efficiency retrofits

In a recent work, Schueftan (2012) found a large potential for thermal improvement in social housing of Valdivia. Table 7 shows the consumption of energy for heating a 44 m^2 one-family household with and indoor temperature averaging 18.3 °C. Three thermal qualities were studied. The least restrictive is the 2000 Chilean Norm, which represents an upper limit of thermal status for around 85% of existing dwellings built before 2007. A second option considered was the thermal standard of the 2007 Chilean Norm, and the third was a more restrictive following the US code ASHRAE 2005.

In the first and most common option the energy consumption for heating is estimated in 25,000 kWh/year for each household. This corresponds to 16 st of fuelwood, which is higher than the average 11.4 st found in the surveys. This difference is explained by the setting of indoor temperature higher than what most people currently have. When the standards required by the 2007 Norm are applied, the consumption dropped sharply to 9600 kWh/year per household. This amount of energy corresponds to around 6 st of firewood, which is half the surveyed average consumption. Based on these data it can be clearly seen that with the application of thermal refurbishment just to comply with the 2007 Norm, the entire housing stock built between

Table 7
Total heating energy (kWh) required per month and per year for a 44 m^2 one-family dwelling in Valdivia, for different house thermal quality option.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
NT 2000	591	668	1219	2048	2852	3254	3545	3378	2807	2139	1496	979	24,980
NT 2007	96	156	398	805	1178	1357	1484	1389	1126	813	517	277	9596
ASHRAE 2005	74	107	250	487	706	812	888	833	679	495	321	181	5833

2000 and 2007 in Valdivia would present a reduction in consumption of energy for heating of around 62%, which also means 62% reduction in firewood burnt. The reduction for dwellings built before 2000 with no Norm restrictions would be even larger, but not considered quantitatively here as only the different Norm levels were set for the study. Therefore, a minimum reduction in firewood consumption just in the city of Valdivia can be estimated in 340,000 st/year for dwellings that do not comply with the 2007 Chilean Norm.

We also investigated the option of increasing the requirements according to foreign regulations, which are viable options requiring similar roofing and floors but a reasonable *U*-value of 0.5 for walls and the elimination of thermal bridges. The result was energy consumption in heating of 5800 kWh/year for each household, which represents a further reduction to less than 4 st of fuelwood per year. This intervention would lead to 77% reduction in firewood consumption.

As of price levels of 2013, the thermal retrofit for the accomplishment of the 2007 Norm in the house investigated has a cost of US $3800 and the thermal retrofit to meet the standards of ASHRAE (USA thermal regulation) has a cost of US$7200. These values are slightly higher than the existing refurbishment subsidies that range between US$4,800 and US$ 6300 depending on the region (MINVU, 2006).

There is also an impact to the environment caused by CO_2 emissions due to the use of wood from non-renewable sources. A reduction in emissions of 6.8 t CO_2e/year for the 44 m^2 social house was estimated when retrofit measures meet the 2007 Norm (Schueftan, 2012). If this amount is considered for the residential stock built before 2007 in Valdivia, the total emissions reduction would be 320,000 t CO_2e. This is a conservative estimation considering that households with a greater income and bigger houses would have a higher consumption, thus a higher reduction potential.

4. Policy discussion

4.1. Current related policies

With minimum exceptions, there are no energy subsidies for households in Chile. The southernmost region of Magallanes has subsidies on natural gas, and the city of Coyhaique have a subsidy of 1 m^3 of firewood for the 40% most vulnerable families. In both cases it represents a very small portion of energy used in the residential sector.

There is a subsidy for the replacement of wood-burning heaters with pilot plans implemented for the cities of Chillán, Temuco, Valdivia, Osorno and Coyhaique. These subsidies aim to improve furnace efficiency, reduce the expense for the families in fuel, and reduce pollution. It consists of partly paying the cost of a new furnace (around 40–50% of retail price), given in exchange for the old one. This action does not solve the underlying problem of high energy consumption due to the house envelope efficiency.

To address this issue a recent program of subsidies for home thermal improvements was implemented. The subsidy helps improve insulation in dwellings which have a valuation that does not exceed US$31,500, allowing the beneficiary families to reduce their heating costs. The subsidy amounts to between US$4800 and US$6300 according to the region in which the dwelling is located. It targets families in social vulnerability and is based on instruments of social stratification (MINVU, 2006). This subsidy was developed for houses that were built before the enactment of the thermal regulation of 2007, and finances the thermal refurbishment necessary to become compliant with these regulations. From 2008 to 2012, approximately 30,000 subsidies where granted nationwide. This corresponds to an investment of US$72 million and the plan is to grant approximately 59,000 subsidies by 2020, corresponding to US$142 million.

As mentioned, in other OECD countries thermal regulations are more demanding than in Chile. To illustrate this, the thermal transmittance for walls is 0.57 W/m^2 K for USA, 0.3 W/m^2 K for Sweden, but as much as 1.6 W/m^2 K for zone 5 in Chile, where cities like Valdivia and Temuco are located (Table 1). The Chilean thermal regulation does not require thermal protection standards for unventilated floors. Especially in cool or cold climates, the presence of this protection involves an important decrease of heat loss.

Another issue not considered in the Chilean thermal regulation is condensation, which occurs on the inner surface of walls, windows, ceiling, floor, thermal bridges and other elements of the envelope (cold surface condensation). To prevent condensation it is necessary to limit the production of humidity in the interior while keeping the environment with permanent ventilation, according to the standards required by the size and number of people living in the household. To ensure good control of indoor air quality in social housing, including moisture content, the most effective method is mechanical ventilation (Bustamante et al., 2009).

It is also necessary to incorporate in the Norm protection for thermal bridges. Their presence, along with generating additional heat loss in winter, also generates condensation problems on the inner surface, thus accelerating degradation of the building systems and causing habitability problems (Bustamante et al., 2009).

Air infiltration is also a relevant issue for the energy performance of dwellings that is not considered in the present regulation. Measurements of air infiltration of dwellings in the region of Bio-Bio obtained values up to 8.3 volumes per hour for wooden houses (Bobadilla, 2009). Various studies and stricter thermal regulations consider air exchange of 1.0 volume per hour as an optimum value. Therefore, present heating energy demand is strongly affected by air infiltration, and could be as much as between 24% and 73% of the total demand.

It is also necessary to study the level of implementation of the thermal regulation in social housing projects and perform a monitoring process to verify compliance with the standards. This control should have a concrete answer on complementary policies to current thermal regulations and certification of quality systems that aim to evaluate the architectural and subsequent stages in the construction and operation of buildings (Bustamante et al., 2009).

In addition to the low thermal standards there are other reasons that affect the high energy consumption: (1) Original dwelling does not work as designed, due to changes made by users; (2) modifications are made with no technical criteria, only in response to the need of increasing the usable area of the dwelling; (3) the thermal performance of the original construction is different from the later constructions, so dwellings are thermally heterogeneous; (4) usually they do not have a suitable ventilation standard, and (5) have been inhabited without information on maintenance or operation, resulting in misuse and deterioration (CIVA-UACh, 2010). This is a problem that must be addressed when proposing energy efficiency strategies for households, since it would ensure the maintenance of energy performance of dwellings over time.

The large energy reduction potential through thermal refurbishment would lower emissions of particulate in almost half, even considering present conditions for stove efficiency and wood quality. If these two issues were also included in the improvement, the reduction of PM emissions could be estimate in 60–70%, and thus safety levels could be reached.

A decontamination plan for the conglomerate Temuco and Padre Las Casas came into effect in 2010. The plan considered the regulation of the following aspects: sale and use of dry wood, prohibition of open hearth fireplaces, emission regulations for commercial and industrial boilers, prohibition of agricultural and outdoor burning, and surveillance of air quality. The plan did not provide regulation for the energy demand of buildings, which has been shown as a key aspect of the high concentrations of particulate matter. According to data shown in Figs. 6 and 7, both PM_{10} and $PM_{2.5}$ emissions kept risen in 2011 and 2012, and therefore there has been no improvement in this respect since the enactment of the decontamination plan.

This issue is very important in designing strategies for cleaner energies. The present case-study gives a unique opportunity to address not only the advantages of the possible renewable resource (which is not the case here because 86% of fuelwood is from native forests) but also the drawbacks. If building efficiency is not achieved, renewable biomass might not be suitable for large conglomerates.

4.2. Policy proposals

As explained above, there are government policy instruments functioning and reaching low income population to improve homes and to make thermal refurbishments. However, the pace and the number of thermal subsidies are disproportionate to the urgency to solve air pollution and excessive use of native forest resources as fuelwood.

There are no policies targeting medium and high income homes. These sectors might not need economical help but they certainly need to understand the problem and possible means to solve it. As mentioned, an average refurbishment to achieve a moderate but effective heating energy saving would cost around US$4000. At present, in Chile, this amount is equivalent to two salaries in low to medium pay university jobs, or two salaries of a young engineer just starting a career. It means a large number of people probably have the means to afford reforms either as savings or as loan capacity, but there seems to be barriers to do it. Moreover, in some proposals we noticed confusion on the relevance of thermal improvements on building stock. Independently on what is done on new constructions, repairing the building stock is vital and urgent, because 85% of homes are in this category. A large part of it are not low incomes that might be reached by government subsidies, but rather medium and higher incomes that, as we have shown above, consume even more firewood than other social sectors. This confusion is materialised in excessive official focusing on changing furnaces, promoting dry wood, and calling for stricter thermal codes. These measures will do little on PM emissions due to the 70% of dwellings with almost no thermal insulation, because they were built before 2000.

From our analysis, a pressure for increasing fuelwood prices could appear as a valid economical policy instrument. This would do wrong in Chile because of the very large income gap among populations. A large percentage of people live on minimum or nearly minimum wages (around US$400 per month in 2013). If firewood price increases, a large number of people would suffer significantly and their quality of life could drop dramatically.

Another valid policy instrument is enforcing thermal codes. As we have seen, this would have advantages and we endorse it for new constructions, but does not solve inefficiencies on the majority of existing buildings, whether households or businesses. In addition, in new buildings, besides respecting thermal codes, central heating systems using pellets, gas or diesel are common, and therefore they do not add to the increasing problem of pollution and resource depletion. Then, clearly, policy should be directed to improve existing buildings, either homes or large public and private facilities which at present use firewood and lack thermal efficiency.

One way to extend the program of thermal refurbishment is to create a financing model. A possibility of financing part of these investments is the Clean Development Mechanism of the Kyoto Protocol or other voluntary markets. Reduction of CO_2 emissions generated from energy efficiency programs can be sold in the carbon market.

The carbon market appears to be an opportunity for a public–private funding model to develop large scale refurbishment projects for cities in central-south Chile. The main fuel for heating in the studied cities is firewood, generally considered carbon neutral, but, as shown in previous sections, the firewood used is mostly not certified and around 85% comes from native forests. The CDM methodology used in these cases would be "Energy efficiency measures in applications of non-renewable biomass". The application procedure should first achieve an assessment of carbon savings in non-sustainable forest management in the region, with the additional carbon emission savings that retrofitting measures would save from using alternative fuels. Although health issues would be hard to translate into carbon trading advantages, joining public initiatives could act as complementary. There is a successful experience in South Africa with the Kuyasa CDM project which involves the retrofitting in over 2300 low-cost homes in Khayelitsha, Cape Town, which included solar water heaters, insulated ceilings and energy efficient lighting (Kuyasa, 2009). The Kuyasa project considers funding from the municipality, the Certified Emissions Reductions (CERs) and the users of houses that have to pay a small amount each month, thus ensuring sustainability over time. The model also considers training of users in refurbishment and maintenance of the houses, creating new job opportunities (Goldman, 2010).

In Chile, there are several successful CDM projects; however, energy efficiency projects represent only 4% of CDM projects and they correspond to generators and distributors, not final users (MMA, 2013c). Reductions of energy consumption in buildings are small compared to other types of CDM projects, making total carbon savings uncompetitive. Nevertheless, there is a new tool of CDM, which allows grouping a set of unlimited activities of similar characteristics into a single Program of Activities (PoA). The PoA seems as a good opportunity to group energy efficiency projects and compete in the carbon market, especially social housing projects. In Chile this tool has already been used in renewable energy projects (MMA, 2013c). More research is needed on a funding model which combines subsidies, CERs and private investment in order to achieve high levels of energy efficiency for the residential sector.

It is also important to have private bank financing with soft loans so the retrofit measures can be applied by emerging sectors that are not eligible for subsidies. In spite of it, previous to the measures there must be a public will to make the reforms, and this is not at all the case at present.

In the education to the public we see a win–win situation. Real cost for not doing the improvements includes health and disability, natural ecosystem loss, decrease of a vital resource which comprises 57% of the energy produced in Chile, while all alternative options for heating at present involve energy imports. Therefore, an intensive education program could mobilize social forces that would trigger individual and group initiatives to improve thermal quality. Giving the situation as it is, we find that a government initiative on education via TV, radios, newspapers, conferences, and neighborhood delegations with proposals to help with know-how, would trigger public awareness and hopefully actions. Health, environment, sustainability, resilience, are obviously subjects for a win–win program to convince large portions of the population to invest in the future. Such a program should include technical assistance organized by cities and neighborhood associations with government support.

The mobilization of large number of households able to pay for the materials and jobs for refurbishment would generate wealth in local and regional industry and labor, which would return revenues to the government. There is an interesting question for future works: would the extra taxes collected from materials and labor pay for the cost of the public education program including technical offices?

The measures to be implemented should be designed locally and it is imperative to develop studies at national, regional and local levels so knowledge can result in political transformation. Knowledge transfer to management and public action is necessary to link energy efficiency to priority issues in the local agenda like air quality. Municipalities as the basic unit of local management must take this issue and include it in local development plans.

Cities should not necessarily cause environmental problems. These are the result of poor or inadequate planning and management, and existing governance structures. By contrast the cities have enormous potential for the development of solutions as they are centers of innovation and drivers of change, concentrating population and resources.

5. Conclusions

We have investigated the links between thermal efficiency in envelopes of dwellings in cities of south-central Chile and air pollution. Results showed low energy efficiency of dwellings, high consumption of firewood for residential heating, and high concentration of particulate matter in cities of south-central Chile.

The present Chilean Norm, from 2007, regulating thermal quality of buildings was compared to foreign standards, finding relatively low level of requirements of the Chilean Norm for thermal transmittance. In addition, relevant technical issues present in foreign regulations such as the elimination of thermal bridges and the inclusion of ventilation systems and vapor barriers are not considered in the Chilean Norm. These would increase the efficiency of insulation, improve environmental indoor quality within the households and prevent condensation on building components. However, enforcing better codes would not solve the problem since around 70% of existing constructions where built before the enactment of any thermal regulation, lacking even minimum efficiency standards. Therefore, improving thermal efficiency of existing buildings is essential to achieve significant reductions in fuelwood burnt and particulate emissions.

The reduction potential in energy consumption for heating in social housing is shown to be very large, reaching 62% reduction compared to the current Chilean Norm from 2007 and 77% if stricter regulations would be targeted. It is an urgent issue to extend the coverage of existing subsidies and encourage population to take action in improving efficiency of constructions for all income sectors.

An intensive education to the public program is suggested as complementary policy to the present one reaching low incomes with retrofit subsidies. Medium and higher incomes might not need subsidies but to understand the problem and the options to solve it.

Technical solutions to refurbish all types of constructions already exist, but we lack a system of management, financing and education to achieve the potential improvement in energy efficiency in the cities of south-central Chile. These strategies would solve to a large degree the serious problem of air pollution that they are currently facing and improve significantly quality of life of people in this region.

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