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Proposals to enhance thermal efficiency programs and air pollution control in south-central Chile

Alejandra Schueftan [a,*], Alejandro D. González [b]

[a] Escuela de Graduados, Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile, Box 567, Valdivia, Chile
[b] Instituto de Investigaciones en Biodiversidad y Medio Ambiente, CCT Patagonia Norte, CONICET y Universidad Nacional del Comahue, Bariloche, Argentina

HIGHLIGHTS

- High levels of $PM_{2.5}$ from wood combustion affect cities of south-central Chile.
- Current programs on dry wood fuel and stoves renewal have not reduced air pollution.
- Real operation of wood stoves strongly depends on user's behavior.
- Buildings' energy efficiency has greater potential for reducing emissions.
- Retrofit prevents degradation of native forest and improves indoor temperature.

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ABSTRACT

Major cities in South-central Chile suffer high levels of particulate matter PM_{10} and $PM_{2.5}$ due to combustion of solid fuels for heating. Exposure to these air pollutants is recognized as a major contribution to ill health in the region. Here we discuss new strategies to reduce air pollution. Regulations and subsidies focusing on improved combustion by providing drier wood fuel and better stoves have been in effect since 2007. However, air pollution due to combustion of wood fuel has been steadily rising, along with reports on health consequences. The paper analyzes a survey of 2025 households in the city of Valdivia, which found that wood fuel quality, stove renewal, and awareness of programs are strongly affected by income level, and that higher consumption of wood fuel is found in households already having better stoves and drier wood fuel. The analysis suggests that regulations intended to improve combustion are influenced by user's behavior and have limited potential for lowering pollution. We conclude that thermal refurbishment has a larger potential for improvement, not yet been implemented as an energy policy for the majority. Here we propose improvements and additions to current programs to enhance effectiveness and cover the whole social spectrum.

1. Introduction

Major cities in south-central Chile face a serious problem of air pollution, which has worsened the last ten years. Particulate matter (PM) in air has been increasing steadily in the last decade, and measurements and chemical analysis found that the main contribution is combustion of wood fuel in household stoves. For instance, data was so clear in attributing major air pollution to wood stove emissions that the city of Temuco was considered a mono-source contamination case (Cereceda-Balic et al., 2012). Besides, more than 93% of the PM from firewood burning corresponds to $PM_{2.5}$, which has the most serious effects on human health.

Up until this date, there have been three active programs to control contamination: (1) certification of retail wood fuel to insure dryness and origin; (2) subsidies for replacing old stoves with new models; and (3) subsidies for thermal refurbishment of dwellings for low-income sectors.

In (1), the certification intends to regulate forest management and commercialization, as well as providing wood fuel with maximum moisture content of 25%. So far, in the city of Valdivia only around 3% of wood fuel sold is from certified sources. In (2) a program for replacing old stoves and steel cook stoves used as heaters intended to incorporate new models which improve combustion due to secondary burners. In (3), thermal improvement of houses for the lowest income sector intends to refurbish dwellings to achieve a minimum thermal efficiency as stated in the Chilean Norm from 2007. In a previous work, a very large

* Corresponding author.
E-mail address: aschueftan@a2s.cl (A. Schueftan).

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potential for reducing firewood consumption through improved dwellings' efficiency was found (Schueftan and González, 2013).

The aim of the present article is to discuss current policies and possible reasons explaining their failure to reduce hazardous emissions. Based on the observation of households' mechanisms to ensure the satisfaction of heating demands, and given the current low thermal efficiency, we argue that the current programs have very limited potential for reducing air pollution. New strategies considering the actual behavior of household inhabitants, and including all social sectors, will be proposed. With this information, policy makers can focus on measures that could have greater impact for reducing wood fuel consumption and thereby toxic emissions.

2. Conceptual framework

2.1. Air pollution and wood-fuel consumption

As mentioned, according to data from recent studies in the city of Temuco, 93.6% of $PM_{2.5}$ comes from wood fuel combustion from the residential sector (MMA, 2013). In other locations of south-central Chile, an increasing number of cities have been declared saturated by either PM_{10} or $PM_{2.5}$, or both. Saturated zones are declared when at least one safety regulation for air quality has been surpassed according to measurements performed during a period of at least three years. The declaration is a requirement to design a decontamination plan (Chile, 1994). In the case of Temuco, a decontamination plan (PDA) for PM_{10} is operating since 2010 and a new one for $PM_{2.5}$ is being developed, as in 2013 the city was also declared saturated for this contaminant. During the past two years, the city of Osorno has suffered the largest PM counting of all cities in Chile. Osorno was declared saturated zone in 2012 and the PDA is still being developed. In 2014, Valdivia was also declared saturated zone and thus the development of a PDA is in progress. This city is the first to include participative instances through all the process of development of the PDA, and the first public activity with the social actors was held in July 2014.

The question is: what happened in the last decade in cities of south-central Chile that has led to increased use of wood fuel? The reason seems to be a combination of a fast growing economy and the availability of fuel at a much lower price than the alternatives. In addition, the improved income of a sector of the population did not yet reach the quality of buildings. A sharp and steady increase in Gross Domestic Product (GDP) since 1990 was paralleled with a 320% increase in energy use between 1990 and 2007. Much related to energy use, Mundaca (2013) showed that the increase in CO_2 emissions is explained by the increase in GDP per capita, i.e. affluence, rather than population or total GDP growth. Affluence demands higher levels of comfort, and at the present building thermal efficiencies, this requires higher residential energy use. Per unit of end-use energy, wood fuel in south-central Chile is four times cheaper than gas and six times cheaper than electricity. There is also a cultural component in the preference for wood fuel, which was traditionally plentiful and available mainly in the rural towns and communities in the region of interest in this study. Gomez-Lobo et al. (2006) showed higher consumption of firewood per household in smaller cities and even higher for rural areas. At present, air pollution is not systematically monitored in smaller cities.

Wood stoves and cook stoves in Chile have been of fair quality. Even though the combustion efficiency may differ widely, they all share a common important feature: they are smoke-tight for indoors. In Chile, it is very rare to find an indoor open fire or stove that leaks smoke into the house. Thus, the problem with the use of firewood in Chile is different than reported in other developing countries (Adrianzén, 2013). Although firewood smoke emission is large and serious in south-central Chile, it is mainly produced through the chimneys. In spite of this, high concentrations of smoke outdoors can reach household interiors by infiltrations found in doors, windows and even in defective structures. This failure in the quality of buildings is found very often in current dwellings in Chile, especially in lower income neighborhoods. In these locations houses are set in small lots and, the density of chimneys being high, inhabitants are exposed to large counts of PM both outdoors and indoors. Sealing of dwellings is essential to improve both the thermal performance and to prevent air pollution from getting inside and will be analyzed in more detail below. Nevertheless, from a policy point of view, it is relevant to stress that the presence of indoor smoke and the health consequences from breathing it are not due to leaky stoves but to building quality. The improved income levels over the last two decades in Chile seem to have reached certain essentials in the quality of households but not yet investments aimed at thermal efficiency in buildings.

Although there have been subsidy programs to improve household quality, for lower-income sectors since 2006, few subsidies have actually been delivered and only for the lowest income groups. Even in middle or higher income sectors, improved household economy has not influenced the thermal quality of buildings and, as we will see in detail, these sectors are large wood fuel consumers. Current policies are not influencing the wood fuel consumption of middle and higher income sectors. As will be shown, this is because the majority of this sector obtains wood fuel several months in advance of the heating season, they are already provided with modern stoves, and finally they are not eligible for the refurbishment subsidy.

2.2. Health issues

The effects on health from breathing air with high concentration of PM, especially $PM_{2.5}$, are well documented (Cereceda-Balic et al., 2012; Allen et al., 2009). In Chile, studies of hospital admissions in south-central regions, between the cities of Temuco and Puerto Montt, showed higher incidence of chronic bronchitis in the general population, and notable incidence of cardiac diseases during winter season in elders (Gómez-Lobo et al., 2006).

In addition to very high levels of PM, it is important to note that households in the south-central region of Chile are exposed to low indoor temperatures. While recommendations indicate indoor temperatures between 18 °C and 21 °C, studies have shown that household temperatures in cities from Concepción to Puerto Montt range from 14.3 °C to 16.5 °C during winter (Bustamante et al., 2009). This occurs in spite of high energy demand of wood fuel due to very low energy efficiency in buildings. Therefore, buildings with low thermal insulation affect health in two ways simultaneously: smoke emission leading to PM concentrations, and low indoor temperatures.

Studies in New Zealand linked low indoor temperatures to the approximately 1600 people over 65 dying each year, an excess winter mortality rate accounting for c.16% of winter deaths. There was also 8% excess winter morbidity. Additionally, it was found that there are more hospitalizations of people from low-income sectors where dwellings are of lower quality and indoor temperatures are the lowest (Howden-Chapman and Chapman, 2012). Sustaining an indoor temperature under 16 °C produces respiratory stress and if under 12 °C it can cause cardiovascular stress. Besides, cold dwellings are generally humid, generating growth of mold that affects the respiratory system. As commonly found, housing without thermal insulation and controlled ventilation systems have the inner envelope walls near dew point when the heating flux is not enough to compensate heat loses. In the

present conditions of thermal insulation, large heat fluxes are obtained due to high levels of wood fuel consumption. Stove improvements could help somehow, yet households with non-insulated walls require permanent heat flux due to lack of heat retention within the building.

2.3. Current programs

Policies in Chile have focused on four aspects: stove quality improvement, improved quality of wood fuels, thermal retrofitting of existing dwellings and education programs. Existing policies consider subsidies for stove replacement, thermal retrofit of dwellings in the low-income sector, as well as the implementation of a private-state certification system for retail wood fuel.

The subsidies for stove replacement mainly consider heating and cooking appliances. Recipients from these subsidies must assist educational workshops for training in proper stove operation. In addition, the installation of the new stove costs charged to households is US$230, which at present accounts for 75% of a minimum net salary. A relevant drawback for the implementation of the furnace exchange is that around 40% of households use the cooking wood stove also as space heater. Thus, the replacement of this device would dramatically change household energy practices. This change in the dynamics of practices has not been considered in the current program, which does not include support for the acquisition of a gas-cooking stove. This kind of omission has been previously addressed by Shove and Walker (2014) for other cases.

The stove-replacement subsidy only applies to houses, not to apartments, and is applied only once for each household (MMA, 2014). A norm has been developed, but not enforced, to regulate combustion efficiency and smoke emissions of stoves that should range between 2.5 g/h and 4.5 g/h in laboratory conditions (Chile, 2011), which rarely can be met by available equipment in the market (CNE, 2009). The greater obstacle for the enforcement of this regulation is the implementation of accredited laboratories to certify the compliance with the norm. Nevertheless, as shown by investigations in New Zealand (Scott, 2005), real-life operation produces larger emissions than laboratory values. In Chile, in addition, stoves are mostly operated in air-choking mode leading to unclean combustion due to lack of air. This choking of air is even possible in modern stoves, and has been experimentally demonstrated that could increase PM emissions by 10-fold (CNE, 2009; CONAMA, 2008).

Regarding the wood fuel market, there is a private–public initiative that promotes its regulation (Conway, 2012). The program for certified firewood has been in operation since 2007 and promotes the creation of a formal market, the regulation of the humidity content when sold (maximum 25% dry basis) and the implementation of management plans for its extraction. Currently, 86% of the firewood is extracted from native forests so this is a very important aspect to regulate (INFOR, 2012). It is not mandatory to use certified firewood and there are still few suppliers; in the city of Valdivia 24 have been identified (SNCL, 2014). The monitoring of humidity levels in firewood is simple, but it is very difficult for distributors to perform the drying process in a short time due to the humid climate of the region. To obtain dry wood, distributors should stock it in covered space and wait to sell it, which raises the final price, discouraging retail of certified wood fuel.

To improve the quality of dwellings there is a subsidy for thermal refurbishment, which aims to improve thermal insulation for households in order to save in heating and reduce interior condensation. The subsidy is part of a program called "Programa de Protección del Patrimonio Familiar" (Family Patrimony Protection Program), which includes three types of subsidies: (i) Subsidy for repairs and improvement of houses; (ii) subsidy for the expansion of the house; and (iii) subsidy for thermal refurbishment of houses (Chile, 2006). It targets families in social vulnerability based on instruments of social stratification and considers only social housing built by government plans. The price of the house should not exceed US$30300 (c.16.7 million Chilean $) and the household has to contribute with US$140. Each household can obtain the subsidy one time and must not have obtained other subsidies to improve house quality, like the above mentioned program for general improvement of dwellings, but not necessarily thermal improvements. The subsidy only considers the necessary retrofit to comply with the 2007 thermal regulation (Chile, 2006); shown to be a mild requirement for efficiency (Schueftan and González, 2013).

Besides, the 2007 Norm requires much less insulation than used in other OECD countries with similar climate (yearly 2000 Heating Degree-Days). For instance, in the area of the present study, the 2007 Norm requires only 2 cm insulation thickness for walls, 14 cm for roofs, and 5 cm for ventilated floors, but none for concrete floors set on the ground, which are in fact very common. Furthermore, vapor barriers and humidity barriers to improve sealing are not included in the thermal regulation and the retrofit subsidized program. These technical aspects help prevent not only condensation, which is a common problem in Valdivia, but also avoid PM pollution from getting inside the houses.

There were no thermal reference norms for buildings until 2000, and the 2000 Norm only required insulation in roofs. In the city of Valdivia, 85% of buildings were constructed before 2007, making this sector the largest wood fuel consumer and responsible for the majority of air pollution from the residential sector.

Despite the application of these policies, air pollution is still increasing, leading to the prohibition of firewood use in critical days during 2013and 2014. This is a very unpopular action since c.95% of dwellings use firewood for heating and a significant number are not able to pay for other resources like gas, kerosene, or electricity, with prices four to six times higher than wood fuel.

3. Methodology

The methodology considers data analysis and literature review on dwellings, stoves, fuels and pollution, and will use the city of Valdivia as a case study.

3.1. Current household energy status

In order to study the actual status of heating devices, use and dryness of wood fuel, and thermal quality of dwellings, we will analyze a survey of 2025 households in Valdivia performed during 2011 by the institute Certificación e Investigación de la Vivienda Austral (CIVA), Universidad Austral de Chile. The sample corresponds to the urban area of Valdivia, details on geographical aspects and household characteristics have been presented in a previous work (Schueftan and González, 2013) and details on firewood acquisition and storage practices are presented later in this article. The survey in Valdivia is part of a larger ongoing project that investigates housing quality and energy use in several cities in south-central Chile. Dwellings in the urban area built before the enactment of the 2007 building codes were considered. In a first stage of the project the most typical typologies were identified (MMA, 2010), and in the second stage a random selection of one-family dwellings of the most common typologies located throughout the city were surveyed (MMA, 2012). Households' energy practices on the use of stoves and on wood fuel acquisition are very important and were investigated to determine potential for reduction in energy consumption and policy implementation.

The survey by CIVA included 42 questions, of which 12 will be considered for the present work, related to: house value; information on fuels used for heating and amount yearly consumed; types of stoves and age; air-mode operation of stoves; period in which wood fuel is acquired as well as amount; whether certified or informal commercialized is preferred; house thermal quality; and level of consumer awareness on topics like wood moisture and subsidy options. Since income levels were not included in the survey, we will assume here that the house value is an indication of income, whenever needed for the analysis. Due to the house-value range criteria, the sample is associated with low to middle income sectors.

3.2. PM emission reduction potential

To study the impact that programs could have, we will compare different levels of improvement in firewood quality, stoves, and thermal refurbishments.

Detailed information on house typology and value, with plans and pictures of houses, was gathered in personal visits done by specialized surveyors (MMA, 2012). Thus, the expected reduction in energy demand and in the use of firewood by thermal refurbishment was obtained to comply as much as possible with the 2007 Norm. This approach considered the possibilities of intervention within the diversity of house typologies of existing constructions. The present work will compare this reduction potential to strategies including drier firewood and improved wood-stoves. In order to compare houses with higher efficiency thermal refurbishments and the potential to thereby reduce firewood consumption will also be obtained from a prototype social house, for either fully achieving the 2007 Chilean Norm or the stricter ASHRAE norm from the USA (Schueftan and González, 2013). These calculations were done with the official software CCTE CL v2 from the Ministry of Urbanism and Housing (MINVU, 2007a), and are relevant because the present subsidy for thermal retrofit only targets social housing.

Besides, two levels of efficiency and emissions for heating devices were considered: (1) cook stoves and old salamandra-type wood-fuel heaters; (2) improved wood-stoves with double air inlet corresponding to the equipment provided with the subsidy for replacement.

Emission factors for stoves in real household operation were obtained from experimental studies ordered by The Ministry for the Environment in New Zealand (Scott, 2005; Kelly et al., 2007). In these studies, emissions in real-life conditions were found to be four to five times higher than ideal laboratory measurements. The large difference is attributed to: mode of operation, transient cool period when starting and wood quality. Cook stoves were not measured in the same conditions. However, since ideal laboratory measurements both in Chile and New Zealand have obtained similar emissions than for stoves (CNE, 2009; ESSE, 2014), the same base value for emissions is assumed, but corrected by the lower efficiency observed in cook stoves with respect to heating stoves.

To assess the influence of firewood quality, the results from the survey on probable moisture content where combined with information on enhanced emissions due to moisture content. Following present regulations, firewood is considered dry with 25% moisture content, and semi-humid in a range 25–35%. A study from CONAMA (2008) showed that wood fuel used for heating in the city of Temuco was rarely over 40% humidity, and mostly present a moisture content under 25%–30% due to storage and drying during a period of approximately four months before burnt. These moisture contents are in agreement with previous studies in Denmark for drying firewood (Nord-Larsen et al., 2011). The increase in emissions as a function of wood-fuel moisture was obtained from experimental studies by Kelly et al. (2007).

The reduction of $PM_{2.5}$ emissions were calculated for the prototype house considering the three strategies and the characteristics of households in the survey: (i) thermal refurbishment, (ii) stove replacement and (iii) use of drier firewood. With this information the effect of each program and the different combinations will be discussed.

4. Results and discussion

4.1. Moisture content of firewood

The survey of 2025 households in Valdivia showed that 96% of these use firewood for heating, of which 93% declared to know how to recognized dry firewood. This is in line with the long tradition of firewood management in the south-central part of Chile where households are active stakeholders in the improvement of conditions for combustion of firewood. Buying it in advance is one of their strategies.

Fig. 1 depicts the preferred month of the year and the frequency in which households in the survey buy firewood. Purchases between the months of October and April (spring to autumn) are stocked in sheds for using during winter.

Three steps in this mode of buying firewood are commonly found in the city of Valdivia. In the first step firewood is offered by medium size trucks from distributors directly to households at the dwellings' doors, where sectioned logs of around 1 m long are downloaded (Fig. 2a). This step is very important to consider on wood quality. The seller offers the firewood on a truck at the house door, and the customer inspects and decides on quality. After agreement, it is unloaded and there is a further check on quantity and quality before paying. The second step comprises the hiring of a contractor that provides a transportable motorized saw and cut firewood in pieces of ca. 0.33 m long, and usually the same crew moves the firewood inside the house lot, commonly stacked it up in a backyard shed.

Around 62% of households prefer to buy in advance between October and April, following this procedure for a number of reasons: (a) better price is obtained before the heating season; (b) a selection of wood dryness and wood quality is offered; (c) early buying is likely to obtain denser native wood. Large private and public buildings also prefer to buy firewood in advance, but were not included in the survey (Fig. 2b). To our knowledge, there is no systematic measurement of moisture content in stored firewood. We will discuss this below in relation to policy improvements. Depending on the time of purchase, and on the quality of the shed, firewood bought informally could even be drier than the certified

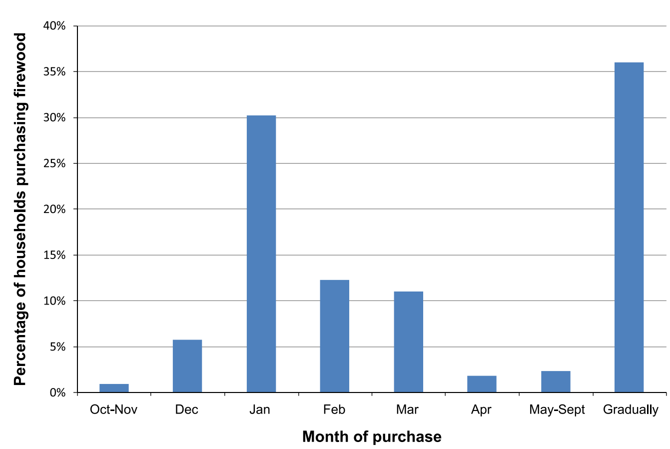

Fig. 1. Percentage of households purchasing firewood as a function of preferred period.

Fig. 2. Firewood purchased in summer piled outdoors in cities of the XIV Region of Chile: (a) for a house, (b) for a school building.

firewood sold under government regulation with a maximum of 25% moisture (CONAMA, 2008).

In Fig. 1, it can be seen that 2% of households buy firewood from May to September, and 36% answered that they gradually purchased as needed. These groups risk a high degree of moisture. The logistic of the gradual purchase is usually different than the advanced purchase described above. Firstly, as we will see in detail in the next section, it turns out that advanced purchasers reported house values, in average, 64% higher than gradual purchasers. Thus, the decision to buy gradually may be a combination of low income and lack of house facilities to safely store firewood. Secondly, there are several options to buy low moisture firewood anytime, even in winter. The certified wood program is one option, and in the survey accounted for 2.7% of the total firewood used. Other options are firewood stored by sellers and sold either by bulk or in sacks of 25 kg. In any case, although it cannot be concluded definitely from the survey, it is clear that the 38% of households buying gradually or in winter time are not all purchasing high moisture firewood. Based on the percentage of firewood bought in advance, and the fact that households know the disadvantages of moist firewood and how to recognize it, and additionally that 4% of gradually purchasers bought some certified wood, we estimate that 10%–15% of households may be gradually provided with firewood below 25% moisture. Therefore, together with the 62% of the advanced-purchase group, a total of 70%–75% of households are very likely provided with fairly dry firewood, and the rest (25%–30%) can be considered as possibly using firewood with more than 25% moisture.

In the survey, 13.4% of households reported to have bought some certified firewood (answering quantities from 1% to 100%), and 57% acknowledged knowing what it is. In Fig. 3, the number of households that bought different percentages of certified firewood in their annual supply is depicted. Only around 1.4% of households bought 100% certified firewood.

With the percentages of purchased certified wood and the total amount of wood informed by the corresponding household, one is able to estimate that 2.7% of the total firewood was from certified origin. This result is in agreement with previous reports (SNCL, 2014). Although, as seen above, this lack of interest in certify wood-fuel does not mean that households do not care for dry firewood. On the contrary, high quality firewood is acquired through different commercialization channels, and the best possible quality is obtained depending on affordability and households' facilities for storage.

From the aforementioned, we can conclude that the large majority of households knew about the relevance of using dry wood, and actively purchased in advance and with the best possible conditions in price and dryness. Thus, although the program of certification may have contributed to create consciousness on the advantages of using drier firewood, at present and towards the

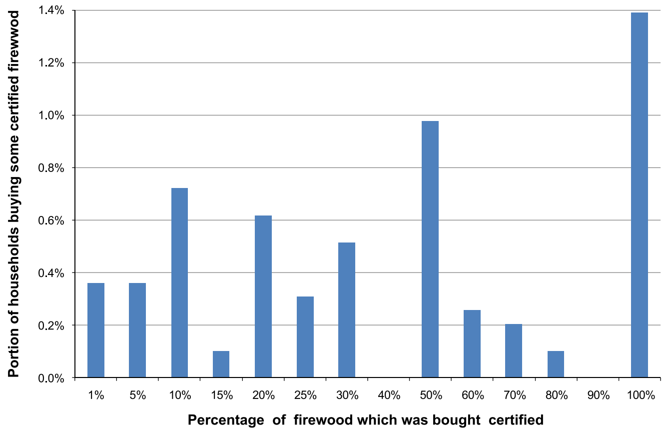

Fig. 3. Percentage of households that bought different amounts of certified firewood.

future, the program is very likely to have limited effect on air pollution. On the other hand, the program does have positive effects on other topics regarding the formal commercialization of firewood and the sustainability of forests (Conway, 2012). However, regarding air pollution, the evidence for moisture content of firewood in Valdivia showed that the certification program will not help significantly to improve combustion and reduce emissions, and the reason seems to be that the majority of households are aware and already provided with fairly dry firewood. Our understanding is that the assumption of the certification policy to consider that most firewood was highly moist was wrong, and these beliefs, and the publicity given to it, caused the certification program to reach the public with no credibility. The result would probably have been different had proper measurements and statistics, not done yet, shown the public whether the real moisture content of their firewood was or not worrisome. The results presented above show that not considering the actual dynamics of demand can lead to policy recommendations that might not be meaningful to households to improve energy practices (Shove and Walker, 2014).

4.2. House-value dependence of firewood and wood-stove quality

The survey did not provide information regarding income-level, but included the value of the dwellings and the models of heating devices used, both items related to income status. In Table 1, parameters describing firewood purchase preferences and consumption, house value and type of heating devices are shown. The data in Table 1 is very interesting, depicting strong dependence on firewood preference and quality with economical status.

The group that purchased firewood in advance is associated with average house value 64% higher than gradual purchasers; and with 67% having modern stoves in comparison to 32% of gradual purchasers. The average wood-fuel consumption of households buying in advance is 41% higher than the consumption of gradual purchasers. This fact, together with the higher incidence of modern stoves within this higher income group, thwart the potential reduction of air pollution intended in both programs, namely firewood certification and stove renewal.

Regarding certification, 57% of households using firewood declared to be aware of the availability of certified firewood, while 43% reported they did not know. Strikingly, these two groups also present significant differences in house value, firewood consumption and efficient stoves: the group knowing about certification consumes in average 30% more firewood, their house value is 40% higher, and 66% have modern heaters. The dependence on income status of firewood purchase practices, as well as the use of wood fuel and access to information, shows that the efficiency of energy practices is related to socio-economical status. In the case of Valdivia, these results show a poorer performance of the education programs on social sectors with lower economical status, which are in fact the sectors aimed by the programs.

In Table 2, a similar comparison is done for the stove characteristics. The survey gave information on the main household's wood-heater, with detailed brand, model, and age. This information could also be analyzed according to economic status by using the house value provided.

Households with modern improved-combustion wood-heaters (55%; 7-years average age) are associated with house value in average 90% higher than those using traditional cook stoves and 123% higher than those with even less developed salamandra-type heaters. These last two pieces of equipment are made either from cast iron or steel, or a combination of both. Note the significant variation of wood-fuel consumption in the three different stove-type users: modern stove owners are the larger fuel consumers, with 10% higher firewood consumption than traditional cook stoves and 53% higher consumption than those using salamandra-type heaters. If the aim is to reduce air pollution due to wood-fuel combustion, we must also concentrate efforts upon the sectors with the greatest annual consumption; that is, home owners who already have improved modern equipment as well as access to dry wood-fuel. The striking difference in house values suggest that it is very likely that the higher consumption is due to higher incomes, in agreement with increased energy-use driven by affluence (Mundaca, 2013). These facts are strongly associated with poor thermal insulation in buildings: if affluence does not reach building quality, then higher comfort is satisfied with higher energy consumption.

Table 2 also shows that the program for stove replacement could have limited consequences on air pollution, due to the fact that 55% already have modern equipment. As mentioned in Section 2.3, even with the subsidy there is a cost to replace older

Table 1
Fuel consumption, house value, and stove type for different firewood purchase choices.

	Number of households	Annual firewood consumed (m^3 st)	Average house value (million $cl)[a]	Cook stove and salamandra[b] (%)	Improved modern stove[c] (%)
Purchase firewood October to April	1200	12.3	24	33	67
Purchase firewood gradually	743	8.7	14.6	68	32
Knows about certificate firewood	1142	12.1	23.1	34	66
Does not know about certificate firewood	849	9.3	16.5	60	40

[a] $cl means Chilean pesos. Rate of exchange $cl 550 = USD 1.
[b] Steel and iron old models of salamandra-type wood-heaters and cook stoves.
[c] Modern double chamber air-tight steel stove.

Table 2
Stove characteristics related to house value, wood-fuel consumption and age of equipment.

Type of stove	Number of households	Annual firewood consumed (m^3 st)	Average house value (million $cl)[a]	Average age of equipment (years)
Modern improved combustion stove[c]	1072	11.5	25.7	7
Traditional steel cook stoves[b]	814	10.5	13.5	12.2
Primitive steel salamandra-type heaters[b]	51	7.5	11.5	11.2

[a–c] as in Table 1.

stoves, and the large difference in house value shown in Table 3 suggests that the subsidy program could be enlarging inequalities even further, in agreement with previous findings by Chávez et al. (2011).

On the other hand, the lower consumption of the groups with older stove models could indicate of low indoor temperature in households that cannot afford more fuel. In a previous work, we have pointed out income-related differences in fuel consumption and comfort (Schueftan and González, 2013). Thus, the lower fuel consumption found for the groups with older equipment suggests that, in order to improve comfort, it is likely that when changing stoves, these groups could either stay constant or increase firewood consumption, thereby partially compensating any possible air pollution reductions.

Nevertheless, it is not yet clear how much better the overall efficiency and pollution control of the new stoves is, since one of the main causes of PM emissions is air choking, which has not been solved with the new models provided. At present, the majority of models offered in the market are air tight, meaning that users can choke completely the air inlet, a practice that is common to let firewood burn slowly and last longer. The serious drawback of this practice is that choked combustion emits more PM. In the survey, 68% responded that they choke completely the air inlet, 32% that they partially choked it, and a negligible number let it open. We have found no difference in fuel consumption between completely choked and partially choked groups, suggesting that answers on partially choked might imply mostly choked, as it is easy to assess in practice where the damper is closed but it is not easy to assess intermediate unmarked positions. Air-choking is a relevant issue in air pollution control, and at present a further regulation was proposed that should enforce manufacturers to redesign air dampers to avoid complete choking. This prospective enforcement to change the mode in which furnaces are actually run will surely help to reduce emissions in new heating devices. The results obtained from the survey analysis depicted a high potential of improvement with respect to the present air-choked mode. In other countries, for instance New Zealand, a similar regulation is applied but manufacturers are enforced to sell no-air-choked stoves in cities, while regulations for rural areas are not as strict (Bosca, 2014). The relevance of user's behavior on air choking shows that households' efficiency practices must be considered when analyzing the potential for reduction in energy use due to different policies. As discussed above for wood fuel purchase and for cooking stove replacement, current policies have not considered energy efficiency practices, misleading the goals of programs and subsidies. The case study presented here is an example of a policy problem previously described by Shove (2012).

Table 3
Emissions of $PM_{2.5}$ for the sample in Valdivia as function of thermal retrofit, heating devices and firewood moisture.

# of Heaters	$PM_{2.5}$ emissions (tons/year)					
	Dry firewood (25%)		Semi-humid firewood (25–35%)		Estimated total emissions in the survey	Total emissions with improved stoves and dry wood
	346 Cook stoves	643 Improved stoves	519 Cook stoves	429 Improved stoves		
N 2000	39	61	75	52	227	187
N 2007 (CIVA)	17	26	32	22	97	81
N 2007	15	23	29	20	87	72
ASHRAE	9.1	14	17	12	53	44

According to other studies (Allen et al., 2009), changing firewood stoves for more efficient technology did not consistently reduce indoor concentrations of $PM_{2.5}$. This is due to the high level of infiltration in houses. Even if some heating devices are changed, the emissions from the rest of the dwellings still produce indoor pollution due to high levels of infiltrations. This shows that substantial wood smoke exposure reductions may only be possible if a large proportion of the equipment is replaced or removed. Note that so far, in the city of Valdivia only 365 subsidies for stove replacement were assigned, from a total estimated of 8200.

4.3. Thermal retrofitting reduction potential

In the studied survey we found high wood-fuel consumption for heating per household, with 11 m^3 st/year average (m^3 st is a stack volume of 1 m^3 firewood), equal to around 16,940 kWh/year. As mentioned in the Methodology, the typologies in the survey were modeled considering the refurbishment to comply with the 2007 Norm, giving an average energy consumption for the retrofitted dwelling of 10,740 kWh/year (MMA, 2012), which is 37% lower than the present average consumption. In a previous work, we have reported the study for a prototype social house which resulted in similar consumption of 9596 kWh/year by retrofitting to comply with the 2007 Norm (Schueftan and González, 2013). These reductions would imply a saving of 4–5 m^3 st of firewood per household, with significant consequences in air pollution.

Nevertheless, the 2007 Norm is a moderate improvement and previous studies have shown that the current retrofit interventions focused on roofs with 74% of the interventions, in walls 34%, windows on 20%, and 0% in the case of floors (MINVU, 2013). Hence, we performed thermal modeling with software to obtain the energy reduction potential for a level of retrofit closer to OECD standards, namely the ASHRAE 2005. This retrofit level would lower the consumption of the social prototype to 5830 kWh/year and would lead to 65% savings, representing a reduction of 7 m^3 st/year of wood-fuel for heating purposes in comparison to the present average (Schueftan and González, 2013).

At a national level, other studies have assessed the implementation of a national retrofit plan comprising 20% of dwellings built before the year 2000 and have estimated savings of 10.4% in energy consumption for the whole residential sector, and 2.5% for the total energy consumption in the country. Currently, in Chile there are 4,207,972 dwellings that do not comply with the 2007 Norm (MINVU, 2007b).

4.4. Emissions reduction by the three strategies

For the three strategies promoted by current programs, the emission reduction for a prototype dwelling was calculated. Four levels of thermal insulation were considered: N 2000 is a previous Chilean norm that includes only some insulation in roofs; N 2007 is the current Chilean norm; N 2007 CIVA is the norm applied to the typologies of the survey; and ASHRAE is the US standard from 2005. Each level of insulation determines the consumption of firewood required to maintain 18 °C indoors (Schueftan and González, 2013).

Two options of heating devices were considered following the wood-stove exchange program, which allows households to exchange steel cook stoves and salamandra-type heaters for improved modern stoves. Emissions factors are expressed in grams (g) of PM in smoke per kg of firewood burnt, and for the different equipment these factors were obtained from studies performed by the Ministry for the Environment of New Zealand (Scott, 2005; Kelley et al., 2007). These emissions factors have large uncertainties, as ideal laboratory results could change significantly in real households' running conditions (Scott, 2005; CONAMA, 2008). For instance, a Chilean stove was experimentally investigated in Switzerland under different operation conditions. PM emissions ranging from 2 to 79 g/kg firewood were obtained, concluding that air inlet, firewood moisture and stoking influence emissions greatly. In these experiments, air choking was found to have the largest influence on emissions, with an increase up to 10-fold with respect to the excess air mode (CNE, 2009; CONAMA, 2008). As shown above, complete air-choking is used by 68% of households in the survey to prevent firewood from burning fast, and 32% partially choked air in an undetermined degree.

Regarding steel cook stoves used as heaters, experiments in the laboratory SERPRAM, in Chile, demonstrated that a cook stove running with plenty of air inlet have PM emissions of 1.7 g/kg firewood, which is lower than modern stoves. Although the thermal efficiency found for the cook stove was 19% lower than the average for five different modern stoves, PM emissions were 43% lower (CONAMA, 2008; CNE, 2009). Experimental results for cook stoves in New Zealand also led to low PM emissions (2.7 g/kg wood-fuel), and lower efficiency (51%). The fact that laboratory values obtained for emissions are similar for cook stoves and wood-stoves, allow us to assume the same real-life emissions for both appliances, although corrected by the difference in efficiency.

Table 3 depicts results for $PM_{2.5}$ emissions for different heaters, firewood moisture, and thermal insulation level. The emission factors used in Table 3 per kg of firewood were 15.5 g/kg for steel cook stoves and salamandra-type, and 13 g/kg for a modern furnace. The latter was obtained from Scott (2005), and the former was estimated as 19% higher due to lower thermal efficiency of cook stoves. On the other hand, if the cook stove is simultaneously used for cooking, sanitary water heating, and space heating, the overall efficiency would improve. The qualified experimental data available suggest that projections of pollution reduction based on ideal laboratory conditions may be far from reality due to uncontrolled households' operational variables (Scott, 2005; CONAMA, 2008). For instance, cook stoves, which are targeted to be replaced; running air-rich combustion may lead to lower emissions than choked-air modern stoves, thereby contradicting the program's goals.

The firewood moisture considered includes the maximum of 25% and a second option with humidity range 25–35%. A factor of 1.27 increasing emissions for the second option was estimated from experimental results, and corresponds to the average between 1.15 (rise from 25% to 30% in moisture content) and 1.4 (rise from 25% to 40% in humidity content) found by Kelley et al. (2007). There is controversy in the reports available in Chile on this factor. According to the MMA (2013) a factor of 1.6 should be used. However, this reference cites CONAMA (2008) as source, and studying carefully this report it addressed to Laundhardt (2002), who showed a factor of 1.3 raise in emissions when moisture content increased from 20% to 40%. Extrapolating data points we estimate that increasing moisture from 25% to 35% could be well represented by a factor between 1.2 and 1.3, also in agreement with Kelly et al. (2007). Households that very likely stock dry firewood may be conservatively estimated in 60% for modern stoves and 40% for the older equipment (Section 4.1 and Table 1).

The last two columns show that improving the thermal insulation from the baseline to 2007 Norm, which is what the subsidy currently finances, leads to emissions 48%–54% lower than performing both heaters' renewal and using dry wood-fuel. Additionally, this reduction would not depend on user's behavior. Changing the heating device and using dry certified wood would reduce emissions by 21% even without retrofitting, but this choice maintains very high energy demand by thermal losses, with the associated problem of native forest degradation and low indoor temperatures in households that cannot afford to buy enough firewood. Retrofitting to ASHRAE level leads to the largest reductions.

5. Conclusions and policy implications

The results shown above suggest a diversity of reasons for which policies so far have not had the desired effect on lowering air pollution in south-central cities of Chile. The authorities of environment, housing, energy and health are strongly focusing firstly on enforcing firewood certification, and secondly on stove replacement. However, these two strategies strongly depend on households' behavior. Inappropriate air choking and handling and storage of firewood can diminish benefits from improving stoves and wood quality. The fact that substantial potential for reduction lies on thermal refurbishments, and that these reductions would not depend on user's behavior, have not yet been recognized. For instance, during May 2014, and following the recent declaration of Valdivia as PM-saturated city, there has been a strong controversy on how to prevent high PM levels. The health and environment authorities proposed a ban on firewood burning when high levels of PM occur (Diario La Tercera, 2014). This was rejected by households and by the mayor preventing on consequences from low indoor temperatures; but the very important fact was that none of these relevant stakeholders considered other than firewood moisture as the reason for high PM count, and none had communicated that pollution is related to the excessive consumption of firewood in non-insulated buildings. Regarding health, it is relevant to note that the proposed bans on firewood are enforced during 6 h in the evening if $PM_{2.5}$ counting rises above 110 $\mu g/m^3$, so-called "preemergencia" levels by the environmental authority (SINCA, 2014). Strikingly, this level is twice as much as the highest allowed by the Chilean Air Quality Norm and four to five times higher than the maximum recommended by the World Health Organization (WHO, 2005), These levels of emissions, which would theoretically allow implementation of the ban, are not reached instantly; rather, after a whole day of "preemergencia" recordings. Therefore, alleviation of health hazards is limited since pollution loads above the norms' limits are not prevented beforehand.

On the other hand, a deputy for the region was proposing a subsidy on certified firewood to alleviate household expenditures (Berger, 2014). It is well known that subsidies on fuels increase risks and do not solve the underlying problem of low efficiency (González, 2013). In Valdivia, a subsidy on firewood will very likely increase air pollution. Due to contamination emergencies in the

larger cities of Chillán and Los Angeles, senators and cabinet ministers proposed subsidies to natural gas for installation and provision to replace firewood (Navarro, 2014; Pacheco, 2014). To implement this proposal the region would require the building of a gasification port to receive Liquefied Natural Gas by vessels, and build the pipeline network for distributions. The option for thermal efficient dwellings was, again, conspicuously absent.

Given the air pollution emergency that is occurring in all regions of south-central Chile, and the fact that the measures so far could neither reduce air pollution nor create incentives to massively improve thermal quality, we propose here a set of improvements for existing policies based on the above analysis:

(a) Establish an agenda on priority tasks and involve universities to create national and regional laboratories for research on equipment and techniques, and design a method to measure the real level of moisture in firewood currently in the market. It is urgent to have reliable empirical data on users' practices regarding firewood, equipment, houses, and social receptiveness of proposed changes.
(b) Implement continuing education and assistance programs in every city. The creation of technical offices for every city sector could assist and train neighbors, and coordinate requirements and suggestions. This is a way to encourage social participation in the process of improving energy efficiency and communitarian and associative initiatives in neighborhoods. Social sectors able to afford improvements could be also encouraged by the continuing assistance and education initiative.
(c) The emphasis on policy should shift from firewood certification and wood-stove quality to thermal refurbishments, which has the largest potential for lowering air pollution by dramatically reducing heating needs. In addition, improving sealing by implementing vapor barriers should be acknowledge as an effective mean to both reduce consumption of wood fuel and to avoid indoors pollution by incoming outdoor smoke.
(d) It is urgent to investigate the effects of air-choked equipment on PM emissions and work on it together with industry and commerce. This will lower chimney smoke significantly but, given the low thermal efficiency of current households, proper air inlet would increase wood-fuel consumption. Besides, heaters are located in one room of the house, so even with a replacement for a better technology, indoor temperatures and associated health problems will not improve considerably if the house does not have proper thermal insulation. Therefore changes towards better stoves and house retrofits cannot be separate initiatives, along with changing in practices on the use of stoves.
(e) The premises and goals of the certification program should be critically revisited. Feasible future goals may merge with a more practical and simple starting strategy focusing in moisture and quality of firewood.
(f) There is no systematic measurement of wood moisture. It is urgent to help both householders and the informal firewood market to regularly monitor moisture and achieve proper moisture content. This will also help households to improve their current practice on firewood purchase.
(g) The current thermal efficiency subsidy for low incomes should include those that already have been beneficiaries of non-thermal house improvements; and should be extended to all social vulnerable sectors disregarding social housing plans.
(h) The limitations on income levels to be eligible for the thermal insulation subsidy should be more lenient so as to include assistance of mid-level income social sectors. It is more likely for medium-income sectors to invest in thermal refurbishment, since low-income sectors are not able to afford it and high-income sectors have less incentive to do so (Howden-Chapman et al., 2012).
(i) Monitoring and verification protocols should be implemented so results can be verified, not only the number of subsidies have to increase, but also their correct execution. Surveys of households after the retrofit show improvements in condensation, mold reduction, and lifetime of materials, but other problems as infiltrations and thermal bridges were not solved with the thermal refurbishment (MINVU, 2013). The same study shows that sometimes the subsidy is used for other improvements in the dwellings that are not related with the thermal performance.
(j) Prioritize the elements of the envelope to be retrofitted: nowadays it is common to see investments with the subsidy financing double glass in dwellings that do not even have insulation in the roof.
(k) In social housing the building extensions made by the owners are not considered in the subsidy; thus, only the original social house is retrofitted. Extensions are in fact very common and found in over 71% of dwellings (MINVU, 2013). If this extension is not thermally insulated, the overall effectiveness decreases considerably, in some cases even invalidating the effect of the retrofit.
(l) Raising the price of firewood has been proposed by some studies, but this would increase sharply fuel poverty, as currently the average annual energy bill in Valdivia accounts for around four minimum wages. In countries that have a similar energetic situation in the residential sector like New Zealand it has proven to increase inequality in the access to energy, fuel poverty and health problems due to low indoor temperatures (Howden-Chapman et al., 2012).
(m) Householders with no income capacity to afford replacement of old cook stoves should be provided with alternative cooking and water heating devices, and not just a new space heater, otherwise they will continue opting out of the program as presently occurs.

House retrofitting, in spite of having by far the highest potential for reducing firewood consumption, improving air quality, improving indoor comfort, and slow forest degradation, is not yet recognized as a priority. According to the study conducted here, the two current main strategies will have limited potential for improving air quality: (i) acceptance of certificated firewood is very low; and (ii) stove replacement has low impact if wood-heaters with an option of air-choking are still provided. Further acknowledgment on households' realities and further public–private interaction could speed the process needed to combine successfully the three strategies studied.

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