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Firewood demand and energy policy in south-central Chile

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ABSTRACT

Firewood is the major fuel for household heating in south-central Chile and combustion of wood is the major source of air pollution by particulate matter (PM) emissions in this region. This paper discusses various strategies for lowering emissions from household wood combustion and their effectiveness in reducing air contamination. A survey of 2025 households and previous analysis performed with these data showed large consumption of wood fuel for heating in dwellings in Valdivia. The main variable identified is the low thermal efficiency of household envelope. Low efficiency of household envelope, low comfort, and a large share of income dedicated to energy, determines a high level of energy poverty. We have modeled the thermal retrofitting of dwellings under three efficiency scenarios, including stoves' and house's envelope improvements. Retrofitting houses led to energy poverty alleviation; in contrast, improvement of heating appliances alone does not alleviate energy poverty nor improve indoor comfort.

Introduction

Residential energy use varies widely across countries and even among regions within the same country. In Chile, the national production of energy depends on biomass, hydroelectric energy, and gas, accounting for 34% of the total energy available, with biomass representing 72% of the nationally produced energy resource. The major resources of oil, gas and coal are imported (66% of total) (IEA, 2016). This makes the country highly vulnerable to energy imports, while biomass is the cheapest energy resource. For instance, 95% of households in south-central regions use wood fuel for heating and partially for cooking (INFOR, 2012).

As wood fuel is the cheapest energy source in this region, not only the residential sector, but also the large public buildings like hospitals and schools depend on firewood for heating. Currently firewood is 4, 5 and 6 times cheaper than diesel, gas or electricity, respectively (Schueftan and González, 2013). Although human beings have been burning wood for heating purposes for over 500,000 years, doing so in a densely populated city such as those in south–central Chile is novel, and leads to serious environmental, economic and social consequences (Cereceda-Balic et al., 2012).

Our aim is to identify the major causes of air pollution and discuss the possible reasons that could account for the failure of current policies to reduce hazardous emissions and fuel poverty in south-central Chile. Once identified and their potential for improvement assessed quantitatively, the cost of the measures to reduce air pollution and a cost–benefit analysis was studied. Based on the observation of household mechanisms to ensure the satisfaction of heating demands, and given the current low thermal efficiency in building envelopes, we argue that the current programs have very limited potential for reducing air pollution. We seek to provide information that could be useful to policy-makers, so that they may shift their attention to those measures that could have a significant impact for reducing wood-fuel consumption and thereby reduce toxic emissions and improve indoor comfort in dwellings.

An outline of the paper is as follows. In the "Environmental issues" and "Economic and social issues" sections of the Introduction we present a literature review to understand the context of the problems related to the use of firewood, and in the "Current government subsidy programs" section we summarize the current programs to reduce air pollution that have been active for the last years. The "Methodology" section requires an extensive explanation ("Retrofit proposals and costs for households," "Emissions reduction," and "Energy expenditure in households"), as the effects of wood fuel use are related to current buildings' quality, climate, social status, and different levels of improvements related to government subsidies for refurbishments. In the "Results and discussion" section we present the results and discussions on retrofitting proposals and their costs for households, emissions reductions, the current energy poverty indicators and the decreases in firewood consumption obtained with energy efficiency improvements.

Environmental issues

Currently, in south-central Chile, the cities of Talca, Chillán, Los Angeles, Temuco, Valdivia, and Osorno, suffer from air pollution with

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concentrations of particulate matter PM_{10} and $PM_{2.5}$ (the subscripts relate to the size of particles present in air, including those smaller than 10 μm and smaller than 2.5 μm, respectively) that surpass both the international and Chilean standards. In Temuco, detailed spectroscopy analysis showed that the main contribution of air pollution is wood burning, to the extent that the city is considered a *monosource* pollution case (Cereceda-Balic et al., 2012), meaning that smoke contributions from wood burning are much greater than traffic or industrial sources. In winter, $PM_{2.5}$ usually accounts for 85% to 90% of the total PM_{10} counting, showing the influence of firewood used for residential heating. A similar PM pattern, with dominant firewood emissions, is shown by daily PM measurements in Valdivia and Osorno (SINCA, 2016). These two cities have been declared saturated of $PM_{2.5}$ in 2014, meaning that they experienced emissions above the Chilean standards for the past 3 years (Schueftan and González, 2015). Temuco has already been in this emergency category since 2013. The official declaration of PM saturation for a particular city is followed by the implementation of a government program intended to find strategies to mitigate air pollution.

A further aggravation of air pollution is the presence in the market of airtight residential wood-burning devices which allow a complete air-inlet choke. This operating mode, which allows for smoldering combustion, is used in most households, at the expense of higher particulate emissions. The measurements of Chilean (CNE, 2009) and Australian stoves' emissions (Jordan and Seen, 2005) demonstrated that choking the air-inlet increases PM emissions in up to a factor of ten, and that this increase occurs equally in new and old stoves. Other Organization for Economic Co-operation and Development (OCDE) countries have stricter regulations on airtight heaters to be sold in cities. For instance, stoves that allow choking are forbidden in New Zealand (Bosca, 2014). This common practice was found in almost all households in Valdivia: 68% respond to surveys that they completely choke their stoves, and 32% reported that they partially choke their stoves. This practice has economic and social consequences as households benefit from using less firewood; but higher emissions take their toll on health, requiring additional spending on public and private health services. Emissions also depend on the quality of the firewood that is used, but 97% is bought in the informal market so there is little control on the moisture content which directly affects the combustion process, as studied in a previous work (Schueftan and González, 2015).

Firewood combustion for heating has also consequences at a global level, contributing to greenhouse gases (GHG). Studies show that the residential heating system of Valdivia annually releases into the atmosphere 94,500 t of CO_2e,[1] when CO_2 in combustion is considered carbon neutral (2.2 t CO_2e/HH/year, meaning CO_2e per household per year), and 285,000 t of CO_2e when it is not considered neutral (7.1 t CO_2e/HH/year) (Reyes et al., 2015). The GHG emissions of firewood depend on the origin of the biomass that is used, being uncertain in the case of Valdivia, where most sources are from informal markets and not from forests managed in a sustainable way in order to be considered carbon neutral (Reyes et al., 2015; Schueftan and González, 2015).

Another negative environmental impact of the massive use of firewood is land reclamation and degradation of native forests. This is a problem that can be seen worldwide and is an increasing trend, as presented by Arabatzis et al. (2012). This aspect has also been studied for the case of Valdivia by Reyes et al. (2015) and it is very relevant, since forests are essential for local economy.

Economic and social issues

A comparative analysis of retail prices for fuel that was carried out in the year 2015 showed the following ratios for 1 GJ of energy, where 1 is firewood: 1:2.6 for diesel; 1:4.2 for gas; and 1:6.3 for electricity (Minenergía, 2015). The economic preference of firewood for heating is thereby obvious, especially in the context of the high energy consumption required by the low thermal efficiency of buildings. It is to note that the price of firewood varies for different species, which also differ in their calorific power. This is an important issue for polices related to the use of firewood, since price determines which species are being mostly harvested and the effect this could have on the forest ecosystem services as carbon storage (Zafeiriou et al., 2011), besides other environmental effects mentioned in the previous section.

Studies for the city of Valdivia found an average consumption of wood fuel near bulk 12 m^3 (ca. 8 m^3solid) per year, corresponding to an energy use of 300 to 540 kWh m^{-2} for heating (MMA, 2010, 2012). This energy demand is very high compared to climate indicators (Schueftan and González, 2013). The ratio of the heating energy used and the number of heating degree-days (HDDs[2]) were used as indicators of energy efficiency. Values around 40 MJ/year HDD were obtained for cities in Argentina and Chile (both countries with similar housing envelope thermal quality), compared to 13 MJ/year HDD obtained in the case of Stockholm, where constructions have better standards of energy efficiency (Schueftan and González, 2013).

In Chile, current building codes that regulate the thermal characteristics of a dwelling envelope (walls, roofs, floors and windows), have soft requirements compared to foreign regulations. The current norm was implemented in 2007, but most constructions were built before this implementation. For example, in the city of Valdivia, 85% of the houses were built before 2007 (Schueftan and González, 2013). Fig. 1 depicts usual house typologies found in the city of Valdivia and in general in south-central Chile, all of which have the same problems of inefficient thermal insulation in the envelope.

In addition to the very high levels of PM emissions, households in south-central regions of Chile are exposed to low indoor temperatures. While the recommended indoor temperatures are 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), in spite of the high wood-fuel consumption previously mentioned.

Therefore, the three main characteristics that define fuel poverty are found: 1) high prices of energy related to income; 2) inappropriate thermal performance of buildings and high energy consumption; and 3) low comfort standards (Healy and Clinch, 2004; Walker et al., 2012, 2014). An important consequence of fuel poverty is the trade-off that households have to make between keeping warm and paying for other basic needs such as clothing, food and education (Howden-Chapman et al., 2012).

In cities of south-central Chile, partial or total ban to burn firewood is enforced by authorities during air pollution emergencies, with serious consequences to those households which are not able to afford other fuels. During wood burning bans, households in the higher income levels turn to gas or electricity for heating; however, the lower income sectors that use firewood cannot afford the higher cost of gas and electricity, having to cope with the low indoor temperatures of their un-insulated dwellings and the pernicious consequences to health and life quality in general.

Therefore, buildings with low thermal insulation affect health in two simultaneous ways: smoke emissions leading to high PM concentrations, and low indoor air and wall temperatures. 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; Fuenzalida et al., 2013). In Chile, studies of hospital admissions in south-central regions, between the cities of Temuco and Puerto Montt, showed higher than average incidence of chronic bronchitis in the general population, and notable incidence of cardiac diseases during

[1] Tonnes of CO_2e indicates the total amount of the various GHGs emitted in a process, given in equivalent (e) units of CO_2.

[2] Heating degree-days (HDDs) account for the daily differences between actual outdoor temperature and 18.3 °C, considering empirically the outdoor temperature for which heating would not be needed; thus, HDD is an indicator of climate influence on heating needs.

Fig. 1. Common house typologies found in the city of Valdivia for low and medium income groups.

winter season in elders, due to the high concentrations of PM (Gómez-Lobo et al., 2006).

Additionally, low indoor temperatures affect health as well. Studies in New Zealand showed 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). Sustained indoor temperature below 16 °C produces respiratory stress and if under 12 °C it can cause cardiovascular stress (Howden-

Chapman et al., 2012). Besides, cold dwellings are generally humid. On cold days, even when heating is able to compensate indoor air heat loss, housing without thermal insulation and controlled ventilation systems has the inner face of envelope walls near dew point, generating growth of mold that further affects the respiratory system (Bustamante et al., 2009).

Current government subsidy programs

Despite some specific exceptions, Chile does not subsidize fuel, but there are programs (Chile, 2009) that focus on the reduction of air pollution. These include thermal refurbishment of dwellings, the availability of certified dry wood-fuel and a subsidy for the replacement of wood stoves for newer models. These programs, however, are mainly limited to the most vulnerable socio-economic sectors. The effects of the stove replacement program on air pollution have not yet been significant. On the contrary, it has created a further social problem by replacing wood-fueled cook-stoves (which also serve as heaters) with wood stoves that are not useful for cooking, while not supporting the acquirement of an alternative cooking device. Such alternative devices, nonetheless, would eventually increase fuel poverty by making the household dependant on gas and/or electricity for cooking (Schueftan and González, 2015).

The retrofitting program covers costs up to $cl 2,500,000,[3] which may be enough for small houses in low-income sectors. Household share of an initial cost for the retrofit was set at $cl 74,000 (minimum monthly salary in Chile is around $cl 185,000[4]). The subsidy for replacement of wood stoves and cook-stoves covers nearly two thirds of the cost and installation of a new improved stove. Households are charged around $cl 100,000. In the next section we will discuss in detail the various scenarios for retrofitting and stove-replacement, which depend on house typology and income groups.

Regarding the firewood market, there is a private–public initiative that promotes its regulation (Conway, 2012). The program for certified firewood has been in operation since 2007 promoting the creation of a formal market, which intends to regulate the moisture 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 12 have been identified (SNCL, 2016). The monitoring of humidity levels in firewood is simple, but it is very difficult for distributors to perform the seasoning process due to the humid climate of the region. To obtain dry wood, distributors would need to stock it in warehouses and delay the sale, raising the final price, and thereby discouraging retail of certified wood-fuel.

Methodology

Retrofit proposals and costs for households

The methodology consists of an assessment of the technical aspects and cost for improving thermal performance of households. Based on the data from a survey of 2025 households in Valdivia we performed a detailed energy modeling and analysis of the costs for different intervention strategies. The survey was performed by the institute Certificación e Investigación de la Vivienda Austral (CIVA), Universidad Austral de Chile (MMA, 2012). Dwellings in the urban area built before the implementation of the 2007 building codes and having a maximum house value of USD 80,000 were considered. In the sample, 1937 households (95%) use wood fuel for heating.

The modeling considers different variables, which are not independent, such as house typology and status, income sectors, wood-fuel consumption, climate and indoor comfort, government subsidies, and the resulting correlation to energy expenditure when the refurbishments are achieved.

The costs and emissions reduction potential of improved thermal performance of dwellings were studied with three different scenarios: (1) no thermal insulation retrofitting, but replacement of existing wood stoves with new “low-emissions” models of wood stoves; (2) house retrofit complying with the 2007 Norm (NT2007); (3) an energy efficient option similar to European standards (EE). Options 2 and 3 also include the replacement of the heating devices and cook stoves for new models.

The modeling of the energy demand for the different scenarios was performed according to the heating requirements in the area. The official climatic data from Dirección Metereológica de Chile (Meteo, 2014) averaged over the period 1971–2000 was used. Since the official station is in Pichoy Airport, 30 km north from Valdivia, we adjusted average temperatures by using available official data for Valdivia from 1994 to 2002 (Meteo, 2014). Our calculations were performed for an indoor temperature of 18 °C, as internationally recommended (WHO, 2005).

In order to study the costs of different retrofit proposals, technical solutions were studied with construction materials commonly found on the market and considering simple labor. Also, the utility for the construction firm that performs the retrofit was calculated assuming a large-scale intervention. Solutions were developed so as to be applied in inhabited dwellings and were designed so that installation would not be invasive for the households.

As found in previous studies (Schueftan and González, 2015), there are high levels of energy demand for all income-levels and housing typologies and there is a high correlation between the surface area of the dwelling and the consumption of energy per square meters. Therefore, a retrofit cost per square meters was obtained for the different scenarios and different typologies of walls and roofs. We studied one dwelling for each income level[5] with the most common architectonic typology and with the average area obtained from the survey (C2 = 119 m^2, C3 = 85 m^2, D = 51 m^2 and E = 41 m^2). These values were used to perform the economic analysis, and it is important to note that 75% of the sample corresponds to D and C3 income groups. The survey did not include households in the highest income group ABC1, so we have not considered these incomes for the retrofitting analysis.

Thermal refurbishment costs were estimated for different income groups, and private households were assumed to receive the government subsidy up to the maximum amount established in current policies. All households in income groups C2, C3, D and E are assumed eligible for this subsidy. The private cost of retrofit considered is the amount necessary to achieve each of the two efficiency levels, scenarios 2 and 3, minus the government subsidy. Efficiency levels require different investments, some are below and some are above the maximum subsidized amount; therefore, for those households with retrofit costs below the subsidy we have considered only the fixed required private investment of $cl 74,000; and for those households with retrofit costs above the subsidy we estimate the total private investment as the cost for retrofitting plus $cl 74,000 minus the maximum amount of the subsidy. A similar situation of private–public shared investment occurs with stove renovations. The subsidy covers $cl 200,000 and private households are required to pay additional $cl 100,000 to purchase and install a new wood stove. The former amount counts as public investment and the latter as private household investment.

[3] 1 USD = $cl 688 average rate for August 2015. We chose to report in local currency ($cl, Chilean pesos) because Chilean inflation is under 5% annually, but the USD exchange rate in Chile varies largely up and down; for instance, between 537 and 704 in the two-year period 2014/2015. Thus, prices reported here in $cl are more consistent than they would be if expressed in USD.

[4] All monetary figures throughout the article are due August 2015.

[5] Based on income, the government office Instituto Nacional de Estadísticas (INE, 2013) established five socio-economic levels: ABC1, C2, C3, D and E, from higher to lower income, respectively.

According to previous works, indoor winter temperatures in social housing average 14.5 °C (Bustamante et al., 2009). In order to include rebound effect, we have estimated income-dependent current indoor temperatures. We have assumed the following present temperatures for housing: 15 °C for income-level E, and 18 °C for income-level C2, the highest considered in this study, which is reasonable due to housing quality and firewood consumed. For intermediate income levels, D and C3, we have assumed 16 °C and 17 °C indoor winter temperature average, respectively. The difference in firewood consumption by rebound effect was thus obtained by comparing the heating degree-days (from meteorological data averaged over 30 years) (Meteo, 2014) needed with the present winter temperatures and with a desirable level of 18 °C for all income groups.

To assess the cutback in firewood consumption ostensibly related to new stoves, we have used data from the Ministry of New Zealand that experimentally studied "real-life" efficiency of commercial stoves (NZ, 2008). The average efficiency for current stoves is 61.4%, 51% for cook-stoves and 66.7% for new ones. It is important to note that, due to different proportions in income groups of older heating stoves and wood fired cook stoves, the various income groups experience different levels of efficiency improvements when replacing stoves. The range is between 8% and 20% reductions, from C2 to E, respectively.

Savings in wood-fuel were thus obtained from a modeling of firewood consumption according to each scenario of thermal performance enhancement, and across income groups. The baseline consumption of firewood was obtained from the survey. The consumption of firewood was considered for the 6-month period from April to September, which usually corresponds to the consumption of firewood in Valdivia. The price of non-certified firewood was used, since, as shown in a previous work, the use of certified firewood is under 3% in the surveyed households (Schueftan and González, 2015).

Emissions reduction

As reported in a previous analysis (Schueftan and González, 2013), the mean annual emissions of $PM_{2.5}$ vary according to climate; thus, we have obtained a better estimate for the city of Valdivia by averaging $PM_{2.5}$ over a 4-year period based on official data provided by SINCA (2016). The annual 4-year average is 37 μg m^{-3}, of which we assumed 28 μg m^{-3} corresponding to wood burning, and 9 μg $m^{-3}$to transport and industry. The latter estimate was possible by averaging $PM_{2.5}$ emissions in the period from December to April when space heating is not used. No measures have been taken so far to decrease emissions from transport and industry, so we assumed them constant. The maximum annual mean of $PM_{2.5}$ allowed by the Chilean norm is 20 μg m^{-3}; however this figure is under revision as it doubles the maximum recommended by WHO (2005). Therefore, to analyze the impact of future efficiency improvements we have assumed a maximum recommended value of 15 μg/m^3; accounting for traffic and industry (9 μg m^{-3}), the goal for household emission from wood burning would be an annual 6 μg m^{-3}. Therefore, improvements to lower PM emissions from wood-fuel combustion should aim at an annual reduction of 22μg m^{-3}.

In order to calculate the emissions reduction potential for the stove-replacement options the current stove was considered at a rate of emissions of 13 gPM kg^{-1} of firewood burnt and a new efficient one at a rate of 6.5 gPM kg^{-1}. The values for the emissions were obtained from the experimental studies done in New Zealand with similar wood stoves (Scott, 2005; Kelly et al., 2007) and were explained in a recent article (Schueftan and González, 2015).

Stove operation with choked air-inlet is frequent (68% according to survey, MMA, 2012). Emissions in choked mode vary according to user behavior and there is no definitive data on this subject. As a reference of the magnitude in choking-setting variations we used the data from Jordan and Seen (2005) in Australia, who compared emissions of modern stoves with those of older wood-fueled equipment. These authors found that the modern stoves have indeed low emissions (2.6 gPM kg^{-1}) when the air inlet is open, but produce 35 gPM kg^{-1} with closed air-inlet. Such rates of emissions surpass those of older stoves in the same choked mode (33 gPM kg^{-1}), which performed at a rate of 13.5 gPM kg^{-1} with an open air-inlet. This large increase of emissions with closed air-intake was also measured in Chilean-made stoves tested in Switzerland (CNE, 2009). Choking the air-intake is a widespread practice, done in order to slow combustion and make firewood last longer, dramatically increasing emissions.

Energy expenditure in households

We studied the current levels of energy poverty generated by the high rate of firewood consumption for household heating. The definition of energy poverty first appeared in England at the beginning of the 1990s, defined as the inability of a household to obtain an adequate amount of energy services with 10% of their income. When energy for heating or cooling is included, the amount of energy to maintain an indoor temperature between 18 °C and 21 °C must be considered, with heating being available for 9 h on weekdays and 16 h on weekends, as recommended by WHO (2005).

The estimation of energy poverty levels is based on energy consumption for heating, electric appliances, lighting and hot water (Walker et al., 2014). The firewood consumption including the rebound effect to achieve 18 °C average temperature indoors, was obtained for incomes C2, C3, D and E as explained in the "Retrofit proposals and costs for households" section, and for the income groups ABC1 was obtained from Instituto Nacional de Estadísticas (INE, 2013). Note that for energy poverty estimations we considered the five income groups as defined by official sources; however, since data available in the survey for Valdivia covers the four incomes C2, C3, D and E, we have excluded ABC1 from the retrofitting study. Data for gas and electricity consumption for the different groups was obtained from a study performed by Cámara Chilena de la Construcción (CDT, 2010). The information presented in this study corresponds to the whole country according to income levels; there are no big differences in consumption of gas and electricity due to climatic differences because, as it has been mentioned before, these fuels are not widely used for heating, gas is used for cooking and heating water and electricity for lighting and appliances. There are no fuel subsidies in the city of Valdivia and the types of fuels, prices and their availability were obtained from official information from ministries and research centers (MINVU, 2007; CDT, 2010; INFOR, 2012). Interior wall temperatures were not considered in this work, although they are relevant to thermal comfort.

Using the consumption of firewood cost for each of the three scenarios when improvements would be achieved, we assessed the effect of retrofitting in energy poverty alleviation. For this analysis we focus on the sample of 1937 houses that use wood fuel for heating, therefore energy consumption for heating changes in the retrofitting scenarios but gas and electricity use is assumed to remain constant.

In addition, we have compared the operating cost of replacing firewood with natural gas and electricity, on the one hand, and the cost of retrofit and stove renewal for the defined three scenarios in the city of Valdivia. This analysis was motivated by the fact that in Chile there have repeatedly been proposals to subsidize fossil fuels and/or electricity to mitigate harmful PM emissions, and thus to promote the replacement of firewood for an alternative government-subsidized energy resource (Senado, 2014, 2015; Pacheco, 2014). Energy alternatives to firewood, as gas and electricity, would require new installations and networks to operate. Gas piping is not provided in the cities considered here, and eventual electricity used as space heating would require new wiring to provide high power outputs, both in electric wiring of the city and within households wiring. The present average wood stove power is ca. 10 kW; considering efficiency improvements in electric heating appliances, 6 kW would be sufficient. Yet, this power requirement exceeds threefold the present residential electric power connections, so major rewiring would be needed in order to implement electric heating. To simplify the analysis, we do not account for installation costs of gas piping and electric wiring.

Results and discussion

Energy poverty

Table 1 shows a summary of the annual energy requirements and their expense for households in Valdivia according to the official classification of income levels (ABC1, C2, C3, D and E). The average firewood consumption in the survey was bulk 11 m^3, but modeling showed that to obtain an indoor temperature of 18 °C the average consumption would be higher, so this consumption was used for calculations, according to the definition of fuel poverty.

The results show high levels of energy poverty, with 52% of households spending more than 14.8% of their income on energy. In addition, income level C3, which accounts for 27% of households in Valdivia, spends 9.4%, which is very near the 10%-limit for energy poverty. This fact will be relevant in the following analysis to decide on energy strategies affecting household's spending on firewood and their implications on policy.

Private costs of improvements in households

Private cost includes the initial retrofit and stove replacement investment not covered by the subsidies, and increases yearly due to wood-fuel purchase. Fig. 2 shows private costs for four income levels, C2, C3, D and E.

The total cost of reforms and the savings on wood fuel depend strongly on household income. The variations are due to: 1) different costs for retrofitting larger or smaller houses; that is, different coverage of subsidies for improvement; 2) various levels of rebound effect; that is, lower income housing is reported to have present colder indoor rooms; therefore, a larger rebound effect is expected here; and 3) different efficiency improvements, due to larger number of older equipment in the lower income strata.

Fig. 2 shows the total cost of each improvement scenario per household as a function of time for the four income groups considered. The first scenario, simple replacement of wood-stoves (diamonds) has the lowest initial cost for all incomes, but operating costs remain relatively high. The second scenario (retrofitting to the NT2007 plus stove renovation), represented by squares, becomes more cost-effective just in the first year. For income groups E and D, the government subsidy for retrofitting covers most initial costs, making the third scenario of thermal performance enhancement (EE) most cost-effective in less than 1 year for income E and in 3.5 years for income group D. Subsides for retrofitting at level EE do not cover the whole initial cost for dwellings in income groups C2 and C3; therefore, initial costs for these households are higher. For income group C2, it takes 7.5 years for the third scenario to be more cost-effective than the first (simple stove replacement), and 9.5 years for it to be more cost-effective than the second scenario (retrofitting to the lower level NT2007); while the same periods of time are 3.5 and 6.5 years, respectively, for income group C3.

Due to government subsidies, initial retrofit and stove costs are small in the first and second scenarios. The third scenario has a larger initial cost, but after a number of years it becomes the most cost-effective regardless of income group. The third scenario, therefore, is most convenient after 9 years for C2, after 6 years for C3, after 3 years for D, and after less than 1 year for income group E. Very large savings in firewood purchase in the retrofitted scenarios lead to relative decreases in total private costs. For all incomes, and from the first year, the second scenario (meeting NT2007 standards) is more convenient than only replacing stoves.

As shown in the “Energy poverty” section, the two income levels D and E are currently in fuel poverty, thus, an important consequence derived from the analysis of Fig. 2 is that the simple stove replacement (scenario number one) is not a sustainable alternative for private households within income groups D and E. For these income groups the cost of wood fuel actually increases to achieve 18 °C indoor temperature; hence, fuel poverty will only increase.

Based on these group costs we calculated the total cost for the sample of 1937 houses in Valdivia, as depicted in Fig. 3.

Although the second and third scenarios have higher initial costs, in less than half a year the second scenario (meeting NT2007 standards) becomes the most cost-effective, and after 5 years the third scenario becomes the most cost-effective. After only 2 years the first scenario of simple stove replacement leads to the highest costs, due to higher firewood demand.

Reduced wood-fuel consumption and emissions

Table 2 depicts reduction in wood fuel consumption and PM emissions for the various options of efficiency improvements in Valdivia. The estimates were based on the 1937 households in the survey that use firewood. The second column shows savings on wood. In the first scenario, where only the stove is replaced and house envelope remains as it is, the negative result means larger than current consumption of wood fuel. A combined limited stove efficiency improvements and the rebound effect to achieve a minimum of 18 °C indoor temperature, led to larger fuel consumption. In other words, without improving the house thermal envelope, the better efficiency of new stoves would not compensate for the rebound effect. In the second scenario, where not only the stove is replaced, but the house quality is improved to comply with the Chilean norm NT2007, total annual savings would be an estimated bulk 171,000 m^3. The third scenario, seeking to comply with the thermal efficiency standards similar to the European Union (EE), would lead to even larger firewood savings. The present annual wood fuel consumption estimated for all households in Valdivia is around bulk 460,000 m^3 (ca. 170,000 t), therefore the reduction potential in consumption and emissions obtained with retrofitting options is substantial. The enormous potential for reduction reflects the fact that buildings lack thermal efficiency. At present, Valdivia has an average heating energy consumed per square meter as high as Stockholm, Sweden, where monthly average temperatures in winter are around 0 °C, which is much colder compared to the monthly average between

Table 1
Energy expenses and percentage of income needed to cover them for the average household in Valdivia according to different socio-economic status.

Income group	ABC1	C2	C3	D	E
% of households within the income group	6%	15%	27%	37%	15%
Firewood (in $cl)	540,000	371,119	351,353	312,183	318,113
LPG (in $cl)	168,873	199,377	198,395	163,049	152,845
Electricity (in $cl)	351,543	262,337	211,804	182,414	159,881
Total household energy (in $cl)	1,060,416	832,832	761,832	657,646	630,849
Household income (in $cl)	38,543,556	15,136,296	8,066,988	4,440,756	2,024,256
% of income on energy	2.8%	5.5%	9.4%	14.8%	31.2%

$cl means Chilean pesos, August 2015 average rate, 1 USD = $cl 688.

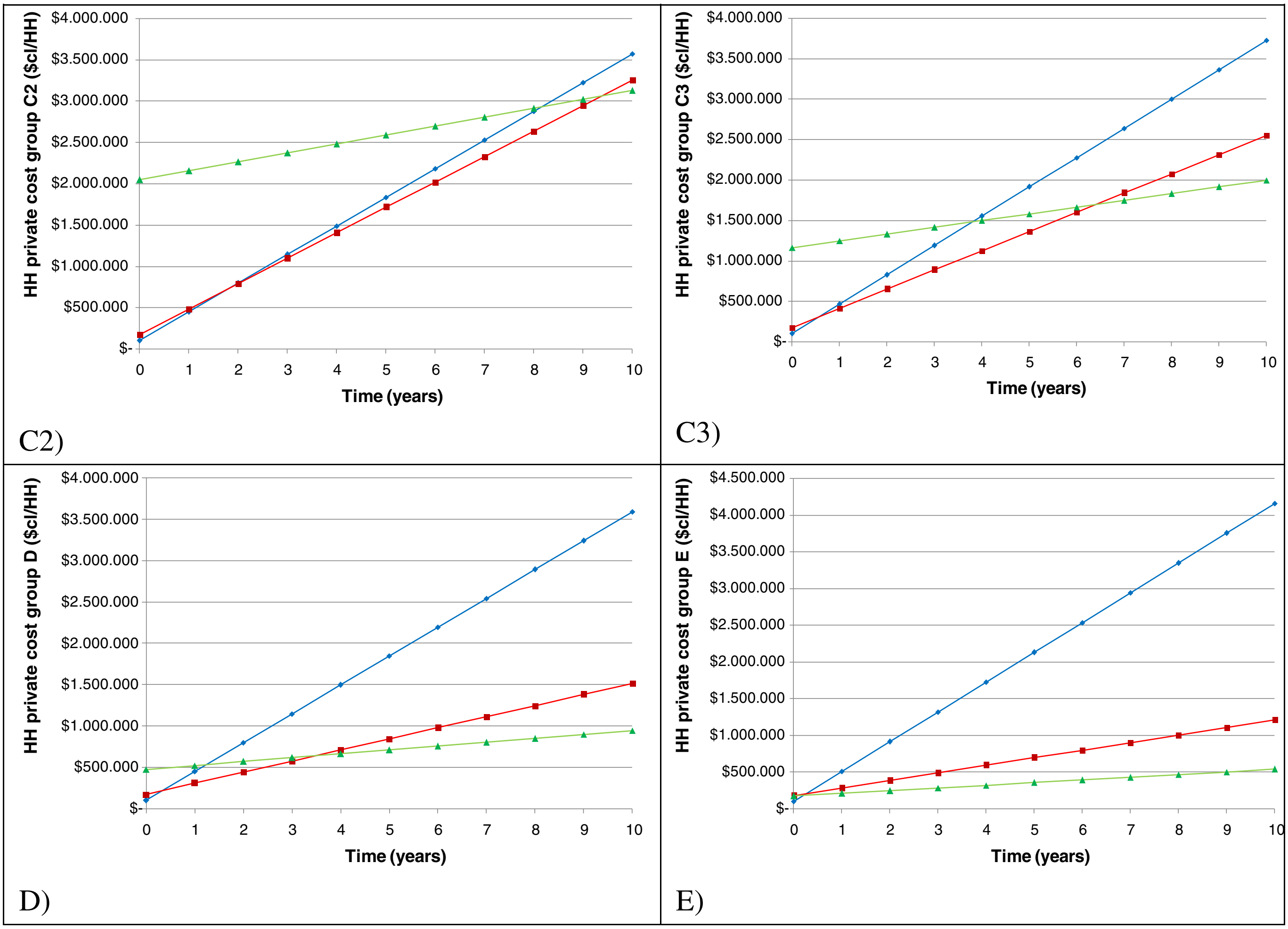

Fig. 2. Private cost for households (HH) for income groups C2, C3, D and E, and for the three scenarios studied (see text).

7.6 °C and 10.4 °C observed in winter in Valdivia. Very large potential for improvements are always found when the baseline of building efficiency is extremely low (González, 2009).

The first scenario – stove replacement – leads to total annual emissions higher than the maximum of 15 μg/m^3 recommended, while the other two scenarios satisfy the requirement. In addition to air pollution

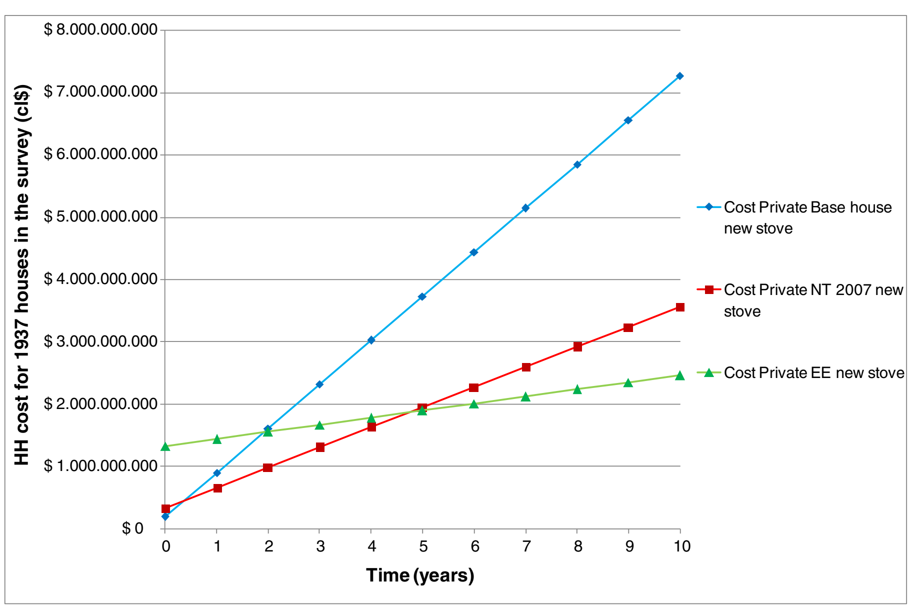

Fig. 3. Total cost of efficiency improvements and wood-fuel expenditure in the sample of 1937 households (HH) using wood-fuel in Valdivia.

Table 2
Annual savings on firewood expenditure and PM emissions for Valdivia, based on different levels of improvements in surveyed dwellings.

	Wood fuel saved	$PM_{2.5}$ from wood fuel after efficiency improvement	$PM_{2.5}$ baseline traffic and other	$PM_{2.5}$ after improvements	Further reductions needed to accomplish max. 15 μg/m³
	m³st/year	μg/m³	μg/m³	μg/m³	
First scenario (stove replacement)	−52,300[a]	13	9	22	7
Second scenario (NT 2007 and new stove)	171,000	6.4	9	15.4	0.4
Third scenario (EE and new stove)	358,000	1	9	10	0

[a] Negative value means there is more wood fuel consumption than at present.

control, retrofit reforms would substantially improve public health, as PM emissions would drop sharply. Related health costs would drop as well, mainly for the public sector (Fuenzalida et al., 2013; Gómez-Lobo et al., 2006). The options with higher efficiency would alleviate PM-related public health costs, while basic stove replacement would still carry a burden related to the 7 μg/m³ of excess annual emissions.

As shown in Table 2, only replacing stoves lowered PM emissions, and in this matter the government initiative for subsidizing stove replacement is a positive air pollution measure. However, it is essential to note that this option leads to higher energy poverty because firewood consumption would actually increase in order to achieve the minimum comfort temperature. If this comfort level would be assumed as not necessary, then we could also assume that firewood consumption would effectively decrease; yet, the health hazards related to low indoor winter temperatures would still place this scenario within the spectrum of energy poverty.

The cases in which both the thermal performance of the house and the stove was replaced led to substantial reductions of emissions and wood fuel consumption, maintaining indoor comfort. Therefore, scenarios two and three would result in energy-poverty alleviation; the degree of alleviation will be discussed in the next section.

Energy poverty alleviation through efficiency improvements

As discussed above, the effect of thermal insulation and stove replacement on energy poverty can be estimated. Table 2 showed that a reduction of 37% in firewood can be assumed for the minimum retrofit improvement required to comply with the Chilean code NT2007, and 77% reductions could be obtained if the higher standard of insulation, based on European Union standards (EE) is performed. For incomes C2, C3, D and E, improvements to achieve the NT2007 level would be fully covered by the present thermal-insulation subsidy programs, while income group E would gain from complete coverage from subsidies to achieve also the highest efficiency-standards given by the EE scenario. Households in income groups D, C3, and C2 would need to spend the equivalent of 2, 5, and 8 minimum salaries, respectively, in addition to subsidies given by the government programs, in order to complete in the first year the improvements needed to meet the highest EE efficiency level. Table 3 shows household energy expenditure for income levels, considering the three scenarios for improvements and the current baseline consumption.

Fig. 4 shows the percentage of household income spent on energy according to each thermal refurbishment scenario and differentiated by income groups. The results depicted in Fig. 4 were obtained with data for annual income from Table 1 and energy costs from Table 3. The horizontal axis at 10% level represents the expenditure above which the income group is in energy poverty.

Fig. 4 provides two major results: a) the first thermal refurbishment scenario (wood stove replacement) results in increased energy poverty due to higher firewood expenditure (rebound effect); and b) both thermal refurbishment scenarios that include retrofitting actually lower energy poverty.

The higher efficiency of new stoves is marginal compared to the energy necessary to achieve minimum comfort; this is why energy poverty with simple stove replacement only increases. In the second scenario (NT 2007), the C3 income group falls below the energy-poverty line (10% income spent on energy), D is placed near the limit, while income group E remains in energy poverty. In the third scenario, where thermal refurbishment meets EE standards, all income groups emerge from energy poverty, except for the lowest income group, E, which would still be spending 17.8% of income on energy, though with a substantial reduction from the previous 31.7%. In the third scenario about 15% of households would remain in energy poverty, a sharp improvement when compared to the 52% of the baseline.

It should be noted that a large percentage of the total energy expenditure is on gas for cooking and water heating and electricity for lighting and appliances. In the two scenarios that include retrofitting – thus, actual reduction of expenditure on firewood – the relative percentage of income spent on energy for cooking, hot water and lighting increases. It is out of the scope of the present work to include further reductions by implementing solar energy for sanitary water heating and more efficient lighting systems; however, these measures would lead to additional increases in comfort and reductions in fuel poverty.

Energy subsidies vs. house improvements

Table 4 shows, on one hand, the total private and public costs of thermal refurbishment in scenarios two and three plus annual cost of firewood according to different socio-economic status; and on the other hand the annual cost of gas or electricity for the same heating requirements if firewood was replaced. Taken these values, we compare the costs of thermal refurbishment scenarios two and three with the costs of subsidizing the fuels. The hypothetical energy subsidies would have to cover the difference between the actual cost of other fuels for heating and the actual cost of firewood. Also, Table 4 shows the number of years it would take for the economic resources spent on energy subsidies to equal the initial investment on thermal refurbishment (private plus public), according to the different income groups and the different retrofitting scenarios.

The results from Table 4 are conclusive: the initial investment on thermal refurbishment amortizes itself in an average of less than 3 years, when compared to subsidies that would compensate for the difference in price between firewood and alternative gas or electricity. Therefore, under the present dwelling thermal quality, subsidizing fuels to substitute wood-fuel would incur in a relevant economic burden for Chile, mostly on imported resources.

Table 3
Annual spending on household energy according to each of the three scenarios and different income groups.

Income group	C2	C3	D	E
Baseline, firewood ($cl)	371,119	351,230	312,183	318,113
Only stove replacement, firewood ($cl)	344,842	360,252	340,679	387,777
Retrofit to level NT 2007, firewood ($cl)	308,129	237,868	134,253	103,995
Retrofit to level EE, firewood ($cl)	107,943	83,330	47,031	36,431
LPG baseline ($cl)	199,377	198,695	163,049	152,845
Electricity baseline ($cl)	262,337	211,804	182,414	159,881

$cl means Chilean pesos, August 2015 average rate, 1 USD = $cl 688.

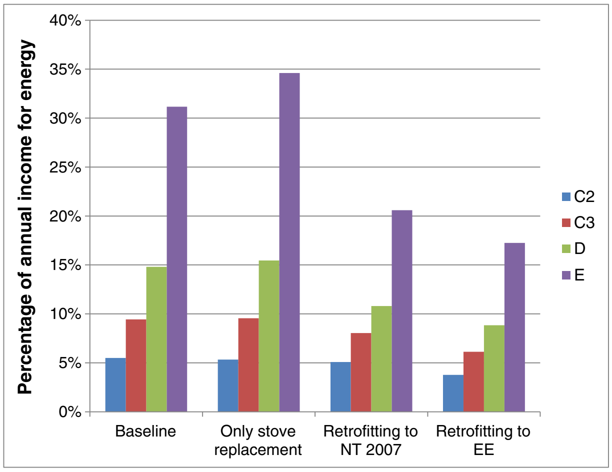

Fig. 4. Percentage of annual income spent on energy by income groups C2, C3, D and E, and for different retrofitting scenarios.

On the other hand, intensifying the subsidy program for long-term investment on household thermal refurbishment would lead to actual reduction in total energy requirements. Such requirements could be covered with firewood at safe levels of total emissions and no economic burden, since wood is a local, abundant and potentially renewable resource. Recently, Reyes et al. (2015) demonstrated the sustainability of using wood fuel in Chile, as well as its potential to mitigate climate change. The challenge, therefore, is to reduce the air pollution that results from abuse of firewood in un-insulated households, while enhancing the potential of firewood to reduce GHG emissions and its contribution to resilient local economies.

Conclusions and policy implications

We have investigated technical and economic aspects of wood-burning for household heating in south-central Chile. The analysis of a sample of 2025 households in Valdivia, of which 1937 use wood fuel for heating, shows high firewood consumption correlated to low thermal efficiency of building envelopes. We have studied a variety of techniques and materials for retrofitting existing houses for them to comply with current building codes regulating thermal efficiency, as well as higher standards corresponding to the European Union's standards. It was found that thermal retrofitting has enormous potential for lowering wood-fuel consumption and reducing particulate matter (PM) emissions, within viable economic bounds and in accordance with the socio-economic importance of firewood production.

The results presented above show various social and economic implications to be considered in public policies to reduce air pollution, as follows:

- *Household thermal refurbishment*: has the highest potential to reduce air pollution by sharply reducing heating requirements: total expenditure on energy is reduced and energy poverty is alleviated. In addition, after retrofitting the household envelope with thermal insulation, the general impact of stove mode of operation becomes less relevant. Social benefits include improvement in levels of indoor comfort, increasing indoor temperatures, and reducing humidity problems.
- *Stove-replacement subsidy*: the results presented above show that the improved efficiency of new equipment is not enough to compensate for minimum comfort requirements in lower incomes D and E. Therefore, this program has no foreseeable potential to reduce firewood consumption and energy poverty. Due to the fact that even with new wood-fuel stoves PM emissions depend strongly on the operation mode, stove-replacement could be partially, but not significantly, successful in reducing PM emissions.
- *Subsidizing other fuels*: as shown in the "Energy subsidies vs. house improvements" section, subsidies for refurbishments are more convenient than subsidies on fuel prices, repaying retrofit investments in short periods. In the neighboring country of Argentina, gas and electricity subsidies have led to sharp increases in energy consumption and social inequalities upon access to energy (González, 2013, 2009). On the other hand, energy production based on firewood has important social and financial effects in regions where agriculture and forestry are major economic activities (Zafeiriou et al., 2011; Reyes et al., 2015), which is the case of most cities in the south central region of Chile.
- *Rising prices of firewood*: fuel prices are valid instruments of energy policy, and rising prices of wood fuel is sometimes proposed as a measure to discourage excessive consumption in households. However, the economic and social context should be carefully considered. We have shown that the present population in fuel poverty in Valdivia is at least 52%, corresponding to income groups E and D. Additionally, income group C3 is nearly spending 10% of income in energy. The foreseeable outcome of rising firewood prices would be tipping the entire income group C3 below the energy poverty line, deepening social and economic burdens for income groups E, D and C3, which account for around 70% of the population in Valdivia. The foreseeable outcome would only be lower indoor household temperature with continued exposure of the population to hazardous levels of air pollution. In countries where the residential sector has a similar energetic situation, like New Zealand, rising prices of fuels has only proven to increase inequality in the access to energy, as well as fuel poverty and health problems due to low indoor temperatures (Howden-Chapman et al., 2012).
- *Sustainable use of firewood*: studies have shown that the use of firewood should not be prohibited or substituted by subsidized fossil fuels (Reyes et al., 2015), as it has been proposed by several policy-makers (Senado 2014, 2015; Pacheco, 2014). The use of firewood is important to the socio-economic context of south-central Chile, which has a large availability of forest resource and where the

Table 4
Total private and public refurbishment costs compared to present operating cost of firewood and its possible replacement by gas or electricity.

	C2	C3	D	E
NT2007 + stove cost ($cl)	2,434,917	1,772,667	1,674,131	1,312,220
EE + stove cost ($cl)	4,628,933	3,744,540	3,055,297	2,587,588
Present annual firewood cost ($cl)	371,119	351,353	312,183	318,113
Annual gas cost to replace firewood ($cl)	1,341,492	1,270,043	1,128,455	1,149,890
Period NT 2007 + stove equals gas subsidy (years)	2.5	1.9	2.1	1.6
Period EE + stove equals gas subsidy (years)	4.8	4.1	3.7	3.1
Annual electricity cost to replace firewood ($cl)	1,394,517	1,320,244	1,173,059	1,195,341
Period NT 2007 + stove equals electricity subsidy (years)	2.4	1.8	1.9	1.5
Period EE + stove equals electricity subsidy (years)	4.5	3.9	3.5	2.9

$cl means Chilean pesos, August 2015 average rate, 1 USD = $cl 688.

activity is a contribution to local economies. In addition, the biomass is the largest energy resource produced in Chile, while the possible fossil fuel substitutes would be imported. A combination of policy interventions that include energy efficiency strategies and the sustainable production of firewood would maintain firewood as the primary fuel for this region, mitigating air pollution and enhancing the positive aspects of promoting forest biomass-based energy systems. (Reyes et al., 2015).

The results shown above suggest a diversity of reasons for which current policies so far have not had the desired effect of 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 household practices. Thermal retrofits, in spite of requiring larger initial investments have the greater potential for reducing energy demand and PM emissions, and enhancing the populations' quality of life.

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