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Proposals for increasing thermal refurbishment subsidies for housing in the region XIV of Chile

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Abstract/Resumen

Fuel wood burning has been identified as the major source of air pollution in cities of Chile's south-central regions. Since 2007 particulate matter (PM) emissions were recorded and either daily or annual averages were well above the threshold known to promote a diversity of illnesses. In a previous study, we demonstrated that air pollution in the city of Valdivia is mainly due to high consumption of fuel wood in dwellings that have poor thermal insulation. In addition, the common practice of air-inlet choking produces incomplete combustion in stoves, aggravating emissions. This practice lets the wood burning last longer but increases PM emissions, and it is possible because of market availability of stoves that allow air choking. A limited number of subsidies to retrofit houses and to change stoves for new models are currently given through government programs. In the present work we investigate the provision of firewood, the quality of stoves, the characteristics of dwellings, the consumption of firewood in households in Valdivia, and different options for improving thermal efficiency of dwellings. In addition, we have performed an economic analysis disaggregating both private and public spending and benefits when efficiency improvements were done. Thermal retrofitting of dwellings has shown the best performance for both private and public sectors. From the private point of view, an option of changing only stoves for new models, in spite of lowering emissions, does lead to higher consumption of firewood due to the rebound effect, and thus increases fuel poverty and pressure on forest resources. On the other hand, studying the cost effectiveness for emissions, the option that changes stoves only without retrofitting, is the one that is more sensitive to user practices; on the contrary, the highest efficiency retrofit showed no sensitivity to stove quality or even to choking air inlet. The ROI analysis for a sample of 1,937 houses in Valdivia shows that all private and public spending shall be recovered in less than three years for the moderate retrofit option and in less than five years for the highest efficiency one. The NPV for private and public spending for the sample in Valdivia results in higher value for retrofit options over changing stoves only. We conclude that retrofit options show much better performance in economic, environmental and social issues regarding high consumption of firewood and low air quality in the cities of south-central Chile.

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Proposals for increasing thermal refurbishment subsidies for housing in the region XIV of Chile

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1. Introduction

Major cities in south-central Chile face a serious problem of air pollution, which has worsened [in / over] the last ten years. Particulate matter (PM) in the air has been increasing steadily in the last decade, and measurements and chemical analysis found that the main contributor 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 monosource contamination case (Cereceda-Balic et al., 2012). In addition, 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 the first program, the certification intends to regulate forest management and commercialization, as well as provide 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. The second program intends to incorporate new models that improve combustion due to secondary burners, as replacements for old stoves and steel cook stoves used as heaters. The third program, for 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 potential for reducing firewood consumption through improved dwellings' efficiency was found (Schueftan and González, 2013).

The aim of the present work is to identify major causes of air pollution and discuss possible reasons explaining the failure of current policies to reduce hazardous emissions. Once identified and their potential for improvement assessed quantitatively, the cost of the measures to reduce air pollution will be used to perform a cost-benefit analysis including their health consequences. Based on the observation of household 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. With this information, policy makers can focus on measures that could have greater impact for reducing wood fuel consumption and thereby toxic emissions.

1.1 Economic and social implications

When making a comparative analysis of fuel prices for consumers for 2013, the cost for obtaining 1 GigaJoule relative to firewood price is 3.6 for diesel, 5.2 for gas and 6.6 for electricity. According to this analysis, the only accessible fuel for medium- and low-income households is wood fuel (INFOR, 2012).

Despite the lower price of firewood, in a study conducted in the winter of 2007 and summer of 2008 for the determination of baseline energy consumption for heating and indoor temperature in households, it was found that the average heating time per day for households varies between 7 and 14 hours in the cities of south-central Chile. As for indoor temperature in households, the average air temperature was between 14.3 ° C and 16.5 ° C. Hence, it can be seen that the temperature conditions of households are below comfortable levels most of the time during winter days, a fact that is probably more critical for the low-income population. A comfortable temperature is considered to be between 18°C and 19°C (WHO, 2005).

In addition, there is a significant problem of energy poverty due to high household demand. Previous studies show that 52% of households spend more than 15% of their income in energy and another 27% spend almost 10% (Schueftan and Gonzalez, 2015b). In spite of the high levels of consumption, indoor temperatures are much lower than recommended as explained above; if indoor temperatures were appropriate, levels of energy poverty would be even higher. The common problem is the high price of fuels compared to income and a high energy demand, mainly due to inadequate levels of efficiency in dwellings.

1.2 Environmental pollution and health issues

The negative 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 the elderly (Gómez-Lobo et al., 2006; Fuenzalida et al., 2013).

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. As mentioned, studies have shown that household temperatures in cities from Concepción to Puerto Montt range from 14.3ºC to 16.5ºC during the 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 phenomenon of 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 16ºC produces respiratory stress and if under 12ºC it can cause cardiovascular stress. Additionally, cold dwellings are generally humid, generating growth of mold, which affects the respiratory system. As commonly found, housing without thermal insulation and controlled ventilation systems has inner envelope walls that are near dew point when the heating flux is not enough to compensate for heat losses. In the present conditions of thermal insulation, large heat fluxes are produced due to high levels of wood fuel consumption. Stove improvements could help somewhat, yet households with non-insulated walls require permanent heat flux due to lack of heat retention within the building.

1.3 Current Programs

Policies in Chile have focused on four aspects: (1) stove quality improvement, (2) improved quality of wood fuels, (3) thermal retrofitting of existing dwellings and (4) education programs. Existing policies offer 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 cover 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. The subsidy only applies to houses, not to apartments, and is applied only once for each household (MMA, 2014).

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, promoting the creation of a formal market, which intends to regulate 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; thus, 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 a covered space and wait to sell it, a practice that in turn raises the final price, thereby discouraging retail sales of certified wood fuel.

To improve the quality of dwellings there is a subsidy for thermal refurbishment, which aims to improve thermal insulation in order to save on 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 that are rated socially vulnerable based on instruments of social stratification, and considers only social housing built by government. The price of the house should not exceed US$30.300 (c.16.7 million Chilean $) and the household has to contribute US$140. Each household can obtain the subsidy one time and must not have obtained other subsidies for the improvement of house quality, e.g., the above-mentioned program for general improvement of dwellings, but not necessarily including thermal improvements. The subsidy only covers the necessary retrofit to comply with the 2007 thermal regulation (Chile, 2006), which is shown to be a soft requirement for efficiency (Schueftan and González, 2013).

Also, the 2007 Norm requires much less insulation than used in other OCDE countries with a climate similar to Chile's (yearly 2,173 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 in the ground, which are in fact very common. 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 during critical days in 2013 and 2014. This is a very unpopular measure, 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 that of wood fuel.

2. Methodology

The methodology was divided into two phases: the first one deals with the general problem and technical issues related to thermal retrofit, stove characteristics, user behavior and emissions reduction. These results were already published and more detail can be found in the corresponding reference (Schueftan and Gonzalez, 2013 and 2014).

The second phase contains the economic analysis for different strategies that were re-defined and expanded according to results obtained in Phase 1.

2.1 Methodology Phase 1

The first phase of the methodology considered data analysis and the literature review on dwellings, stoves, fuels and pollution, and used the city of Valdivia as a case study. An extensive literature review and data mining was done, both on Chilean reports and on international information. Official reports on the fields of emissions and health costs from PM concentration from the Chilean Ministries of Environment and Ministry of Energy were revised for the present work.

For phase 1 we also analyzed a survey of 2,025 households in Valdivia, administered in 2011 by the *Instituto de Certificación e Investigación de la Vivienda Austral* (Institute for Housing Certification and Research), or CIVA, headquartered at the Universidad Austral de Chile. Dwellings in the urban area built before the enactment of the 2007 building codes were considered. In the 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). The survey included 42 questions, of which 12 were 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 of operation of combustion stoves; period in which firewood is acquired; whether certified or informal commercialized firewood is preferred, and amount; 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 assumed 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. The large survey we have studied was done for housing of middle- and low-price range. We cannot assign income to house value, but it is an indication of socio-economical status. In any case, by far the largest problems of air pollution are suffered in neighborhoods of middle and low house values, with high population density, high emission source density and worst house quality.

Income levels were identified as C2, C3, D and E and represent the typical socio-economical classification according to income, place of residence and consumer habits. C2 corresponds to the highest income group and E to the lowest. There are also higher income groups (ABC1) that were not included in the analysis because they are not represented in the survey, and account for only 6% of the population in Valdivia.

The expected reduction in energy demand and in the use of firewood by thermal refurbishment was calculated. A prototype social house was studied, for either fully achieving the 2007 Chilean Norm or the stricter ASHRAE norm from the USA (Schueftan and González, 2013). These calculations are relevant because the present subsidy for thermal retrofit only targets social housing. We also considered the intervention possibilities within the diversity of house typologies of existing constructions according to a previous study performed by CIVA (MMA, 2012). The 2000 Norm, which only considered insulation for the roof, was used as the baseline. The reduction potential was compared to various strategies, including drier firewood and improved stoves.

Additionally, two levels of efficiency for heating devices were considered: 1) cook stoves and old salamandra-type stoves, and 2) improved stoves with double air inlet, corresponding to the equipment provided with the subsidy for replacement. In addition, different levels of firewood moisture, as well as user preferences when using stoves and purchasing firewood were analyzed in detail.

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

Therefore, our research focused first on understanding wood stoves, user behavior and influence of wood moisture in emissions, to allow us to find reliable data. After this first phase we obtained a solid base of knowledge and scientific references so that we could properly assess a comparison between stove replacement, firewood moisture, and thermal retrofitting strategies, and thereby design the scenarios for economic valuation of health and policy enforcement.

2.2 Methodology phase 2

For the second phase of the study we performed an economic valuation of the programs we studied in the first phase, with a detailed analysis of the costs for each intervention.

Levels of energy poverty for Valdivia were studied, which in this case are levels directly related to the high consumption of firewood by households. The definition of energy poverty first appeared in England at the beginning of the 1990s as the inability of a household to obtain an adequate amount of energy services as much as spending 10% of their income. When energy for heating or cooling is included, the amount of energy to maintain an indoor temperature between 18ºC and 21ºC must be considered, with heating being available for 9 h on weekdays and 16 h at weekends.

Households in fuel poverty do not meet this thermal standard; fuel poverty has been found to be associated with excess winter mortality and morbidity (Howden-Chapman et al., 2012).

The estimation for energy poverty levels should include heating, electric appliances, lighting and hot water. An important consequence of fuel poverty is the trade-off that households have to make between keeping warm and other basic needs as clothing, food and education.

The costs and emissions reduction of thermal improvements for dwellings were studied for four different levels of efficiency: (1) the base house as it is, but replacing existing fuel wood stoves with new models with lower emissions; (2) house retrofit complying with the 2007 Norm (NT2007); (3) the 2007 norm improved with double-glazed windows, sealing of doors and active ventilation systems (NT2007 I); and (4) an energy efficient option complying with European standards (EE). Options 2, 3 and 4 also include the replacement of the heating devices and cooking stoves for the same new models as in option 1.

Since the operation of fuel wood stoves has been shown to greatly influence emissions, a sensitivity analysis with household practices of choking was performed. Thus, costs and emissions reduction of each efficiency option were calculated for the current stove and for the efficient model, with different levels of choking for both stoves.

The modelling of the energy demand for the different retrofit levels was performed according to ASHRAE methodology with degree-days method for the heating requirements. 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 18ºC, as internationally recommended (WHO, 2005).

2.2.1 Energy Poverty

Fuel poverty due to high levels of energy consumption was studied for Valdivia. Income data for different socio-economic levels was obtained from the *Instituto Nacional de Estadísticas* (National

Statistics Institute) (INE, 2013). Data for gas and electricity consumption for the different groups were obtained from a study performed by *Cámara Chilena de la Construcción* (Chilean Construction Chamber) (CDT, 2010). This information corresponds to the whole country according to income levels, but there are no significant differences in consumption of gas and electricity due to climatic differences, because, as has been previously mentioned, firewood is mostly used for heating, gas for cooking and heating water and electricity for lighting and appliances.

There are no fuel subsidies in the city of Valdivia; the types of fuels, prices and their availability were obtained from official information from various ministries of energy and air pollution in south-central Chile and from university studies.

2.2.2 Retrofit proposals

To study the costs of different retrofit proposals, technical solutions were developed with construction materials commonly found in the market and considering simple labor. Also, the utility for the construction firm that performs the retrofit was calculated assuming a large-scale intervention.

The retrofit proposals according to the energy efficiency levels have the following technical aspects:

The retrofit of the floors was not considered, since these are inhabited houses and intervention in floors has not been included in the current subsidy programs for the same reason (MINVU, 2013). All interventions for walls are performed from the exterior of the house so they do not affect inhabitants. Also, insulation in the exterior of the wall prevents condensation, which is very common in the cities of south central Chile due to its cold and humid climate. This produces mold, which aggravates health problems as do air pollution and low temperatures.

For all cases new sheathing was considered for wooden walls because we found that it was cheaper than re-installing and fixing the existing sheathing after the installation of insulation. A moisture barrier under the sheathing and painting for exterior finishing are also added. The option of installing the insulation over the existing wall was also studied, but the cost was very similar and with more technical difficulties, so it was not considered in the retrofit proposals.

To comply with the 2007 Norm in the cases of houses with masonry walls in the ground floor, the insulation is installed covering the existing wall and over it a board with a stucco finishing, to maintain the original image of the house. For wooden walls commonly used in the second floors, the sheathing is taken away and the insulation is installed between the wooden studs. Even though the thermal regulation only requires 20mm of insulation, the most common insulation thickness found in the market is 50mm; this happens to be the size of the wooden studs so it is easier to install the insulation between them.

To avoid the intervention of the roof from the exterior, the insulation is installed through the ceiling and considered a vapor barrier to prevent condensation. As in the case of walls, commercial products for insulation are commonly found in 120mm even though the norm requires less. Furthermore, this is the thickness that has been used in all the previous retrofit programs in the region because it is easier to find in the market (MINVU, 2013).

For the improved 2007 Norm, windows were changed for double-glazed ones, sealing of exterior doors was considered, and the installation of a mechanical ventilation system to regulate the air changes per hour was added.

For the EE retrofit the same solution as the 2007 Norm was used for masonry walls, but with an insulation of 100mm. In the case of wooden walls, the same technical solution as in the 2007 Norm was also considered, but over it wooden guides were installed perpendicular to the existing studs to minimize thermal bridges, and to add another 50mm of insulation between them. Furthermore, 10mm of continuous insulation with a moisture barrier was considered below the new sheathing to eliminate thermal bridges.

The ceiling in the EE retrofit has an insulation of 150mm with a vapor barrier that is continuous over the beams, eliminating thermal bridges, and is installed (as in the 2007 Norm) from the interior of the house. Also, in the EE retrofit the replacement of windows for double-glazing and PVC frames is added, together with the sealing of exterior doors and a system of mechanical ventilation.

The price of maintenance was not considered because it would be the same for all retrofit cases, as well as the cleaning of fuel wood stoves and chimneys that will have the same maintenance requirements for the different equipment.

As found in previous studies (Schueftan and Gonzalez, 2014), there are high levels of energy demand for all income levels and housing typologies and there is a high relation between the area of the dwelling and the consumption per m^2. Therefore, a retrofit cost per m^2 was obtained for the different levels of efficiency and different typologies of walls and roofs. We studied one dwelling for each income level with the most common architectonic typology and with the average area (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.

2.2.3 Emissions Reduction

To calculate the emissions reduction, the firewood consumption for the baseline with a new stove and for the three retrofit levels, a modeling was performed. The baseline consumption of firewood was obtained from the survey. The consumption of firewood was considered for the six-month period from April to September, which usually corresponds to the consumption of fuel wood in households. Modeling was performed for the different retrofit and stove options and for all income levels.

To calculate the emissions reduction for the stove replacement, the current stove was considered with emissions of 13gPM/kg of firewood burnt and an efficient new stove with 6.5 gPM/kg firewood. The values for the emissions were obtained from experimental studies done in New Zealand with similar fuel wood stoves (Scott, 2005; Kelly et al., 2007) and were explained in a recent article (Schueftan and González, 2015a).

Operation with air inlet choked is a frequently used mode (68% according to survey, CIVA 2012). Emissions in choking mode vary according to user behavior and there is no precise data about the air inlet or testing for this option. As a reference of the magnitude in variations we have the study of Jordan and Seen (2005) in Australia, which compared very low emissions for a modern stove with older equipment. These authors found that the modern stove indeed have low emissions (2.6 gPM/kg) when the air inlet is open, but produces 35 gPM/kg with the air inlet closed, which are even larger emissions than older stoves in the same choking mode (33 gPM/kg), while these older models with air inlet open showed emissions of 13.5 gPM/kg. This large increase of emissions with air inlet closed was also measured in Chilean-made stoves tested in Switzerland (CNE, 2009). It is relevant to note that when operating with the air inlet choked, modern and older stoves rise to similar emissions, blurring the advantages that new modern equipment could certainly introduce. This is due to the low temperature in the combustion chamber when lacking a proper air inlet, and thus secondary combustion, which is the advantage in the design of modern stoves, does not work properly. The choking of air inlet is a practice done by a large majority in Chile, in order to let fuel burn slowly and last longer; however, the practice dramatically increases emissions.

In order to include the possible (and very likely in the present case study) rebound effect, we have estimated income-dependent current indoor temperatures. According to previous works, indoor winter temperatures in social housing average 14.5ºC (Bustamante et al., 2009). Based on house typologies, we have assumed 15ºC for present housing in incomes E and 18ºC present indoor temperatures for incomes C2, the highest considered here, which is reasonable due to housing quality and fuel wood consumed. For intermediate incomes, D and C3, we have assumed 16ºC and 17ºC winter average. The difference in firewood consumption by rebound effect was thus obtained by comparing the heating degree-days (from meteorological data averaged over 30 years) needed with the present winter temperatures and with a desirable level of 18ºC for all income groups.

As mentioned, we have considered three levels of efficiency improvements; however, for each there are also options of two different stove emissions (the present ones and the best low emissions possible). Rebound effect was considered for all cases. To assess the lowering of firewood consumed due to better 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 cooking stoves and 66.7% for new ones. It is important to note that, due to different proportions of older heating stoves and fuel wood cooking stoves, the various income groups experience different efficiency improvements when replacing stoves. The range is between 8% and 20% in reductions, from C2 to E, respectively.

To study the increase in emissions by air choking, even that allowed in new stoves, we have analyzed the effectiveness in PM-saved emissions for the sample of 1,937 houses in Valdivia assuming different scenarios of choking. PM saved per cost unit and the effectiveness were compared between retrofitted houses at levels NT2007, NT2007 improved and EE provided with new and old stoves, as well as for houses without retrofit but with new stoves with choking as they operate achieving one-half and one-quarter the reduction in emissions when changing stoves.

2.2.4 Household economic analysis

Household private cost for each level of retrofit depends on income groups that where identified through house average typology and area for the group. The total cost of retrofit can be then partially or totally covered by public subsidies. Replacement of stoves is even for all income groups as the cost for new equipment and the subsidy does not vary across incomes. The purchase of fuel wood is totally private as there are no fuel subsidies in the region considered here.

The cost of retrofit has been estimated for different income groups, as described in section 2.2.2, and private households were assumed to receive the government subsidy according to current policies. All households in the income groups considered are eligible for this subsidy. In February 2015, the subsidy for the region of Valdivia was set at a maximum amount of $cl 2,453,300 ($cl, Chilean pesos), and the recipient was required to pay an additional $cl 73,600. The private cost of retrofit considered is the amount necessary to achieve every efficiency level, 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 73,600; and for those households with retrofit costs above the subsidy the difference plus $cl 73,600 was the total private investment.

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 fuel wood stove. The former amount counts as public investment and the latter as private household investment.

Health costs were obtained from Gomez-Lobo et al., (2006); the cost for reducing 1 µg/m3 per inhabitant was calculated for the average for the city of Valdivia of four inhabitants per household. Other studies were analyzed (Fuenzalida et al., 2013), all of which had similar values for hospital admissions, but Gomez-Lobo et al. (2006) considered more items than other studies as loss and restriction of labor.

Health costs due to PM emissions for the income groups considered (C2, C3, D and E) are mainly public, according to previous studies. However, Chilean current public health system differentiates income groups: C2 has a share of 20% of health costs at public hospitals; income group C3 has a 10% share, and D and E incomes have no private costs at public hospitals. Total public health costs per household are explained below in section 2.2.5; here, the percentages for C2 and C3 were applied.

The cost of health insurance includes avoided private and public health costs. Medicament private cost and private health care are not considered since most households in the sample use the public health system. In addition, loss of working days are considered as a public cost and not differentiated between public and private, since that information is not available. As shown in Gómez-Lobo (2006), the factor that most affects health costs is the loss of working days and as we used this data for the calculations, this issue is included in our analysis. In the D and E groups all the cost for loss of working days is considered as public, but there could be households that have a private cost when they are unable to work. In the C2 and C3 groups, the incidence is shown in the percentage they pay for health (10% and 20%, respectively).

Savings in fuel wood were obtained from estimations based on efficiency improvements for the various retrofitting levels, and were accounted for in $cl, considering fuel wood prices of February 2015.

To perform the calculations for the return of the private investment (ROI) in households, we define it here as: (cost of retrofit + cost of new stove + cost of health insurance) – (savings in fuel wood). As mentioned, cost for maintenance is not included because it is similar in the improved and the base condition.

2.2.5 Public economic analysis

When the retrofit is applied there is also an improvement in comfort levels and in indoor temperature. Studies have shown that higher indoor temperatures would reduce the risks of several diseases and this would reduce associated health costs. However, these possible benefits have not been included because there is no data available.

As explained above, dwellings for different income groups and for different retrofit levels require a large range of investments, and there are maximum amounts given through the government subsidies. Here, to assess public spending in retrofitting we have considered the maximum amount given for those cases in which retrofit costs are higher, the rest being charged to private households. In cases in which the cost of retrofit is lower than the maximum subsidy, we have considered that public spending is just the cost of the retrofit, and households in this category do not have private costs. Therefore, retrofitting costs are dependent on income groups and housing level of retrofit. Public spending for replacing fuel wood stoves is simpler, as a fixed amount is given ($cl 200,000) to all households eligible. All income groups in our analysis are eligible for both retrofit and stove improvements.

Public costs of health burdens derived from PM emissions have been studied previously. In the present work we use a health costs estimation by Gómez-Lobo et al. (2006), which was published in units of $cl / per μg/m^3 of PM emissions, which is in excess of recommended levels. Results from 2005 were inflation adjusted by using official inflations data for Chile. PM emissions in excess were estimated from data published by the Ministry of Environment in Chile (sinca.mma.gov.cl) for the city of Valdivia (at a fixed located measuring station). Daily averages let us compare summer (Dec. to Feb. months) levels to annual averages, subtracting an estimate of traffic and industry PM emissions from fuel wood smoke. Using a four-year average, we obtained an annual incidence of traffic and industry as large as 9 μg/m3, and an annual count from fuel wood smoke of 28 μg/m3, leading to a total PM2.5 annual dailyaverage of 37 μg/m3. The maximum recommended value from the WHO is 10 μg/m3, whilst the Chilean Norm established a 20 μg/m3 maximum (under revision). We have assumed a need for improvement, considering an intermediate recommended maximum of 15 μg/m3, and that traffic and industry will follow business-as-usual values, as there are currently no programs to reduce PM emissions from traffic and industry in Valdivia. Therefore, we estimate a need to reduce 22 μg/m3 of PM 2.5 from fuel wood burning, which is associated with a cost of $cl 5,060 per capita and per μg/m3 PM in excess. For the average household of four in Valdivia, the total annual public health spending of 22 μg/m3 excess has a cost of $cl 441,330 per year and per household. It is noteworthy that the similarity of this amount compared to private yearly fuel wood costs by households.

Income groups in our study (C2, C3, D, E) use mostly the Chilean public health care (known by its acronym FONASA); previous studies showed that hospital visits associated with PM emissions are mostly in public hospitals. FONASA has four categories based on income, and we assumed C2 and C3 income groups in the categories D and C, which have a private share cost of 20% and 10%, respectively. Thus, public health costs are also dependent on income level.

Here, we define the return on investment (ROI) for the public sector to improve energy efficiency as: "(subsidy for retrofit + subsidy new stove) – (savings in public health due to reduction in PM emissions)."

2.2.6 Effectiveness

We define cost effectiveness of each kg of PM saved as: the amount of PM saved (measured in kg) divided by the total cost (in $cl, whether carried out by the private sector, by the public, or by both). Both quantities, cost ($cl) and PM saved (kg PM/year) depend strongly on the income group and on the level of retrofit done. Thus, we have estimated effectiveness for the sample of 1,937 dwellings in Valdivia that use firewood and were included in the studied survey.

The following options were studied: 1) the base house with new stove, 2) the NT2007 retrofit level, and 3) the highest efficiency retrofit EE level. In addition, we have included the option of retaining old stoves in retrofitted houses, and two different levels of choking as explained in section 2.2.3.

2.2.7 Net Present Value

We have calculated the net present value (NPV) for private (household) and public spending on refurbishing dwellings, stoves, firewood and healthcare. Different income levels were considered as explained before, and the sample of 1,937 houses surveyed in Valdivia analyzed.

NPV is defined as the sum of the net cash flow for each year divided by the discount factor for the period of years considered (www.financeformulas.net/Net_Present_Value.html). In the present case the value at time zero is negative, as it represents the spending in improvements. The interest rate used was 5.18%, which is the past-10-year average for no-risk savings, as published by the Central Bank of Chile. The four options of efficiency improvements, as defined in previous sections, were considered. Private cash out-flows include spending on retrofit, and cash in-flows are savings in healthcare and in purchase of fuel wood. Public out-flows are subsidies given for improvements, and in-flows are the savings in public health costs.

3. Results and discussion

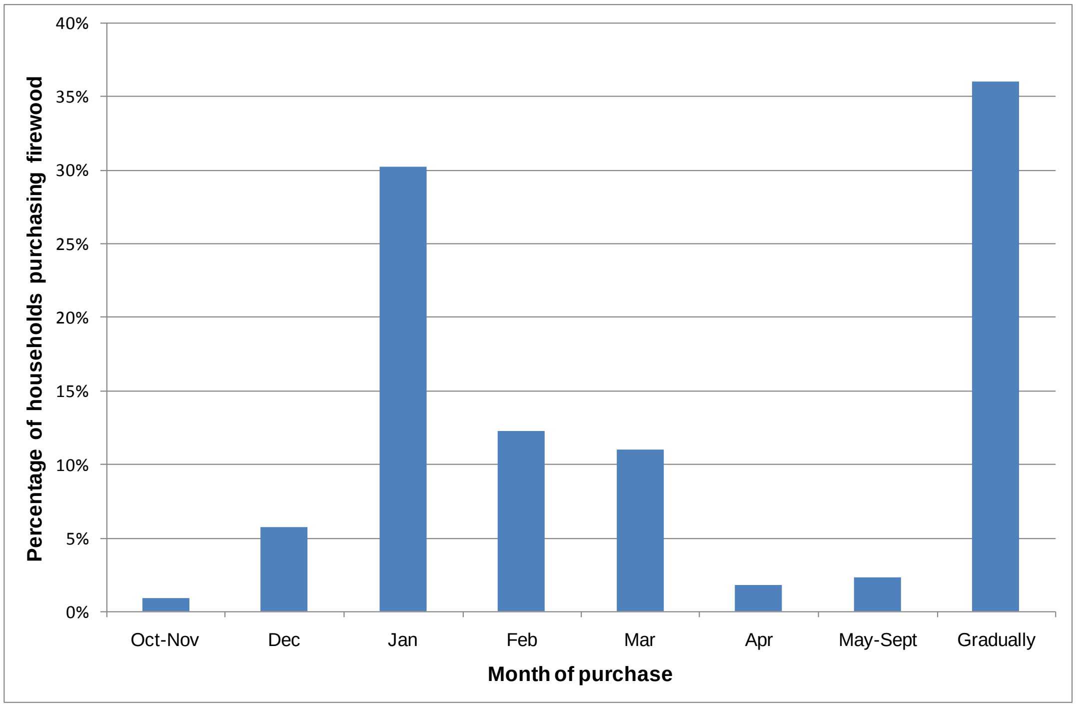
3.1 Results Phase 1

3.1.1 Moisture content of firewood

The survey of 2,025 households in Valdivia showed that 96% of them use firewood for heating and 93% of them declared knowing how to recognized dry firewood. This follows 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.

Figure 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 use during winter.

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



This process of buying firewood, commonly used in Valdivia, consists of three steps. In the first step, firewood is offered via medium-sized trucks from distributors directly to households at the dwelling door, where sectioned logs of around 1 m long are unloaded (Figure 2a). This step is very important to consider regarding wood quality. The seller offers the firewood from 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 hiring a contractor who provides a transportable motorized saw and who then cuts the firewood into pieces of ca. 0.33 m long; usually that same crew moves the firewood inside the house lot, commonly stacking it up in a backyard shed.

Approximately 62% of households prefer to buy in advance between October and April, following this procedure for a number of reasons: a) 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 (Figure 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 firewood sold under government regulation with a maximum of 25% moisture (CONAMA, 2008).

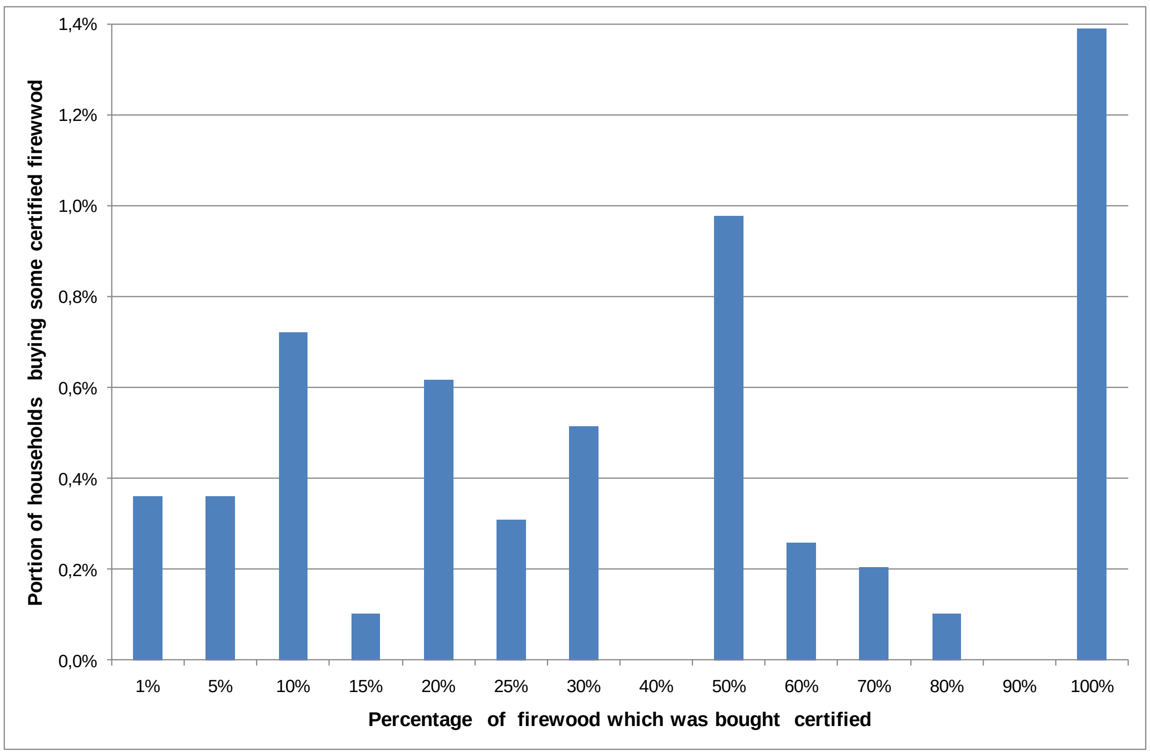
Figure 2: Firewood purchased in summer piled outdoors in cities of the XIV Region of Chile: a) for a house, b) for a school building.

a)  b) 

In Figure 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, on 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 for buying 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 25kg. In any case, although it cannot be definitively concluded from the survey, it is clear that not all of the 38% of households buying gradually or in winter time are 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 also given that 4% of gradual purchasers bought some certified wood, we estimate that 10%-15% of households may be provided with firewood having a moisture level under 25%. 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 having bought some certified firewood (answering quantities from 1% to 100%), and 57% acknowledged knowing what it is. In Figure 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.

Figure 3: Percentage of households that bought different amounts of certified firewood.



With the percentages of purchased certified wood and the total amount of wood confirmed by the corresponding household, one can estimate that 2.7% of the total firewood was from a certified origin. This result is in agreement with previous estimations (SNCL, 2014). However, as seen above, this lack of interest in certified 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 household facilities for storage.

From the above data, we can conclude that the large majority of households knew about the relevance of using dry wood, and actively purchased it in advance and with the best possible conditions in price and dryness. Thus, although the certification program may have contributed to a general consciousness on the advantages of using drier firewood, at present and in the future, the program is very likely to have a 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 significantly help to improve combustion and reduce emissions, and the reason seems to be that the majority of households are aware of the advantages of using dry firewood and already provided with fairly dry firewood. Our understanding is that the assumption of the certification policy that most firewood was highly moist was wrong, and these beliefs, and the publicity given to it, caused the certification program to be received by the public without any credibility. The result would probably have been different had proper measurements and statistics, as yet not performed, shown the public whether the real moisture content of their firewood was or was not worrisome.

3.1.2 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 relating 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 economic status.

The group that purchased firewood in advance is associated with an 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 being aware of the availability of certified firewood, while 43% reported they were not aware. Strikingly, these two groups also present significant differences in house value, firewood consumption and efficient stoves: the group knowing about certification consumes on average 30% more firewood, their house value is 40% higher, and 66% have modern heaters. These results show a poorer performance of the education programs in social sectors with lower economical status, which are in fact the sectors targeted by the programs.

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

	Number of households	Annual firewood consumed (m^3st)	Average house value (million $cl) (1)	Cook stove and salamandra (2)	Improved modern heater (3)
Purchase firewood October to April	1,200	12.3	24	33%	67%
Purchase firewood gradually	743	8.7	14.6	68%	32%
Knows about certificate firewood	1,142	12.1	23.1	34%	66%
Does not know about certificate firewood	849	9.3	16.5	60%	40%

(1) $cl refers to Chilean pesos. Rate of exchange $cl 550 = USD 1

(2) Old steel and iron models of salamandra-type wood-heaters and cook stoves

(3) Modern double chamber air-tight steel stove

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.

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^3st)	Average house value (million $cl) (1)	Average age of equipment (years)
Modern improved combustion stove	1,072	11.5	25.7	7
Traditional steel cook stoves(3)	814	10.5	13.5	12.2
Primitive steel salamandra-type heaters(2)	51	7.5	11.5	11.2

(1) to(3) as in Table 1

Households with modern improved-combustion wood-heaters (55%; 7-year average age) are associated with house values on average 90% higher than those using traditional cook stoves and 123% higher than those with even less developed salamandra-type heaters. These last two types 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, homeowners 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 reached with higher energy consumption.

Table 2 also shows that the program for stove replacement could have limited consequences for air pollution, due to the fact that 55% of homes already have modern equipment. As mentioned in section 3.1.2, even with the subsidy there is a cost to replace older 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 low indoor temperature in households that cannot afford more fuel. In a previous study, 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 for 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 airtight, meaning that users can completely choke the air inlet, a practice that is common in order 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 completely choke the air inlet, 32% that they partially choked it, and a negligible number leave it open. We have found no difference in fuel consumption between completely choked and partially choked groups, suggesting that answers indicating 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 compel manufacturers to redesign air dampers to avoid complete choking. This prospective enforcement for changing 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, and thus manufacturers are compelled to sell only no-air-choked stoves in cities, while regulations for rural areas are not as strict (Bosca NZ, 2014).

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 8,200.

3.1.3 Thermal retrofitting reduction potential

In the studied survey we found high wood-fuel consumption for heating per household, with 11 m^3st/year average, equal to around 16,940 kWh/year. As mentioned in the Methodology, the typologies in the survey were modeled considering the refurbishment as complying 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 reported the study for a prototype social house which resulted in similar consumption of 9,596 kWh/year by retrofitting to comply with the 2007 Norm (Schueftan and González, 2013). These reductions would imply a saving of four to five m^3st 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, 34% on walls, 20% on windows, 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 OCDE standards, namely the ASHRAE 2005. This retrofit level would lower the consumption of the social prototype to 5830 kWh/year and would lead to a savings of 65%, representing a reduction of seven m^3st/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 that have an 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, 2007).

3.1.4 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 18ºC indoors (Schueftan and González, 2013).

Two types of heating devices were considered as options, 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 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 household running conditions (Scott, 2005; CONAMA, 2008). For instance, a Chilean stove was experimentally investigated in Switzerland under different operation conditions. PM emissions ranging from two to 79 g/kg firewood were obtained; the conclusions were 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 Chilean laboratory SERPRAM demonstrated that a cook stove running with plenty of air inlet has 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%). Laboratory values obtained for emissions are similar for cook stoves and wood-stoves; this fact that allows 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 realistic, due to uncontrolled household operational variables (Scott, 2005; CONAMA, 2008). For instance, in 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 a humidity range of 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). Controversy surrounds the reports available in Chile regarding this factor. According to the MMA (2013), a factor of 1.6 should be used. However, this reference cites CONAMA (2008) as a source, and this report addressed Laundhardt's (2002) findings, which 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, a figure that also accords with Kelly et al. (2007). Households that very likely stock dry firewood may be conservatively estimated at 60% for modern stoves, and 40% for the older equipment (section 3.1.2 and Table 1).

Table 3: Emissions of PM2.5 for the sample in Valdivia as a function of thermal retrofit, heating devices and firewood moisture.

	$PM_{2.5}$ emissions (tones/year)					
	Dry firewood (25%)		Semi-humid firewood (25-35%)		Estimated total emissions in the survey	Total emissions with improved stoves and dry wood
# of heaters	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

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 the performance of both methods, i.e. heater renewal and use of dry wood-fuel. Additionally, this reduction would not depend on user behavior. Changing the heating device and using dry certified wood would reduce emissions by 21% even without retrofitting, but this choice maintains a very high energy demand due to 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.

3.2 Energy Poverty

In Table 4, the annual energy requirement for households in Valdivia of different income levels according to official classification (ABC1, C2, C3, D and E) and the expense required are summarized. Since 95% of households use firewood for heating, this option is considered.

The average firewood consumption in the survey was 11 m^3st, but modelling showed that to obtain an indoor temperature of 18ºC, the average consumption would have to be higher, so this amount was used for calculations, according to the definition of fuel poverty. Electricity and gas consumption were obtained for different income groups from official studies, as explained in the methodology.

Table 4: Energy expenses and portion of income needed for average household energy use in Valdivia, for different socio-economic levels. $ stands in for Chilean pesos ($cl)

Income Group	ABC1	C2	C3	D	E
% of households within the income group	6%	15%	27%	37%	15%
Firewood	$ 540,000	$ 400,800	$ 370,200	$ 319,500	$ 298,500
LPG	$ 181,314	$ 214,065	$ 213,333	$ 175,061	$ 164,106
Electricity	$ 351,543	$ 262,337	$ 211,804	$ 182,414	$ 159,881
Total	$ 1,072,857	$ 877,202	$ 795,337	$ 676,975	$ 622,487
Household income	$ 38,543,556	$ 15,136,296	$ 8,066,988	$ 4,440,756	$ 2,024,256
% of income for energy	2.8%	5.8%	9.8%	15.2%	30.7%

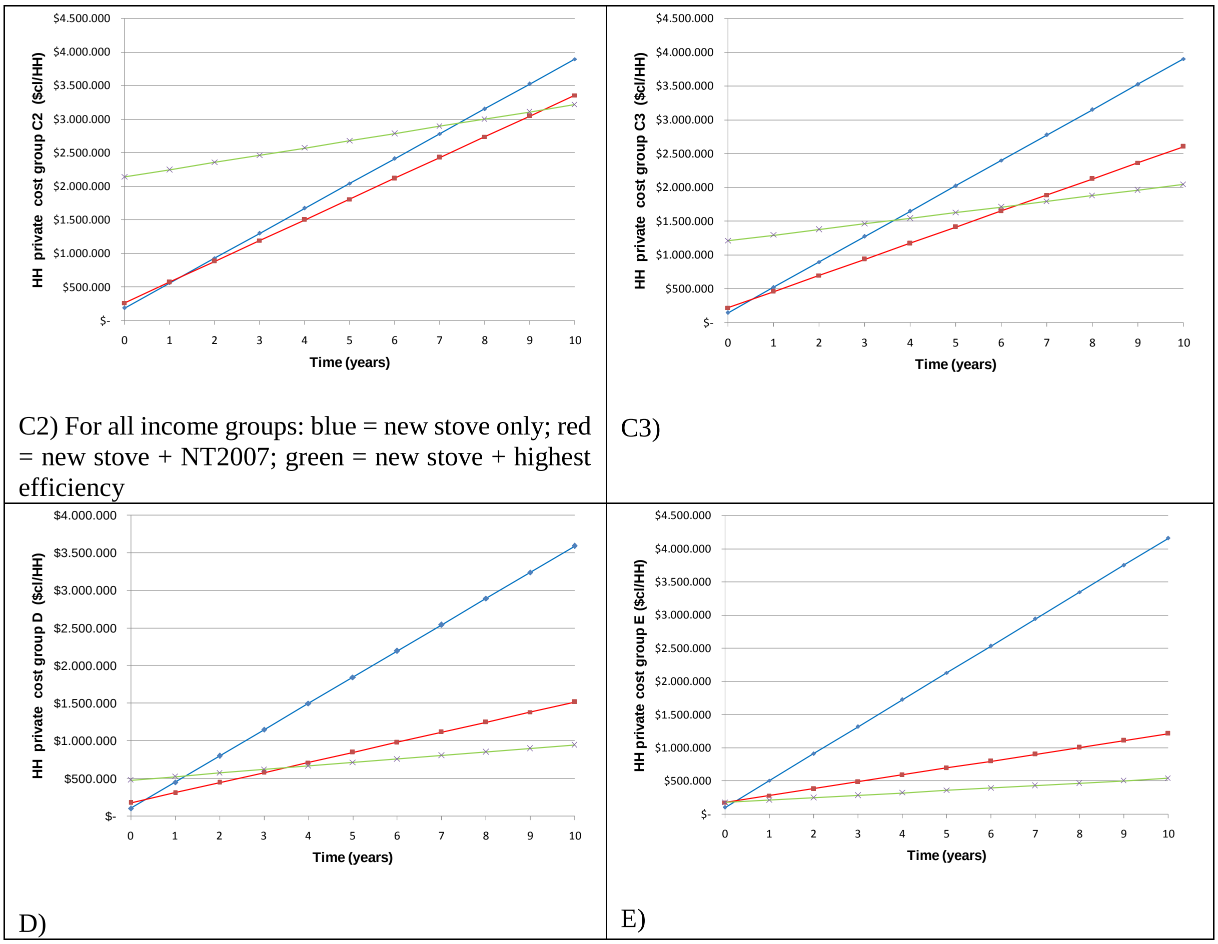
Results show high levels of energy poverty, with 52% of households spending more than 10% of their income in energy and another 27% very near the limit, spending 9.8%. This fact will be relevant in the analysis below, for deciding on energy strategies affecting private household spending in firewood.

3.3 Private and public cost

We have studied the private cost for households and the public cost for the various efficiency improvements. Private cost initially includes retrofit and stove replacement costs and yearly increases due to healthcare cost (only for C2 and C3 incomes) and fuelwood purchase. In Figure 4 private costs are depicted for the four income levels studied.

As explained in section 2.2.4, the total cost of reforms and the benefits on wood fuel saved, and on healthcare, depends strongly on household income. The variations are due to: i) different costs for retrofitting larger or smaller houses, and thus different coverage of improvement subsidies; ii) various levels of rebound effect, e.g., lower incomes reportedly have colder indoor rooms; iii) different efficiency improvements because of larger number of older types of equipment in lower income households; iv) income groups C2 and C share 20% and 10% of healthcare costs in the public system, respectively, while groups D and E are fully covered by the public system.

Figure 4: Private cost for households (HH) for income groups C2, C3, D and E.



C2) For all income groups: blue = new stove only; red = new stove + NT2007; green = new stove + highest efficiency

C3)

D)

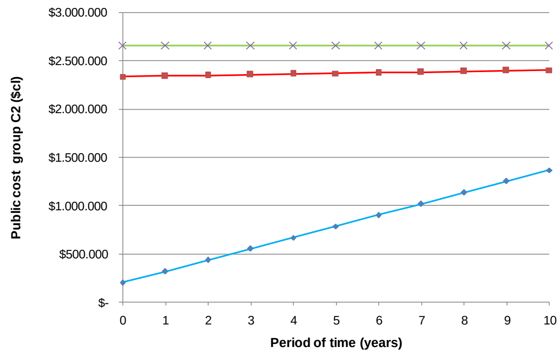
E)

In Figure 4, the total cost for households as a function of time is depicted for the four income groups considered and for the three levels of efficiency improvement. The option that only replaces wood fuel stoves (blue line, diamonds) have the lowest initial cost for all incomes; however, due to higher operating costs, the option including retrofitting to the NT2007 level (squares) become more cost effective just in the first year. For income groups E and D, the government subsidy for retrofitting covers most initial costs, which makes the highest efficiency option EE most cost effective in less than one year for incomes E and in 3.5 years for income group D. Subsidies for retrofitting at level EE do not cover the whole initial cost for dwellings in income groups C2 and C3, and then initial costs for households are higher. For income group C2, it requires 7.5 years for the level EE to be more cost effective than replacing only stoves, and 9.5 years than retrofitting to the lower level NT2007; the same periods of time are 3.5 and 6.5 years for income group C3, respectively.

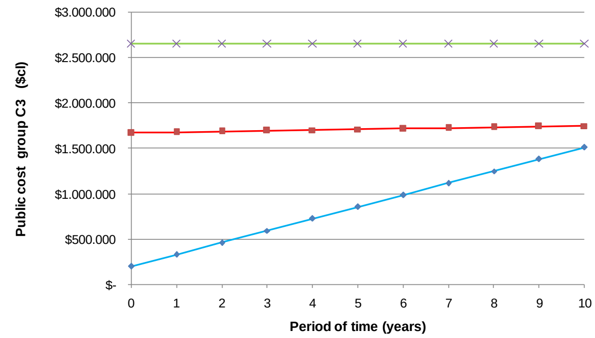
Due to government subsidies, initial retrofit and stove costs are small in the NT2007 and the replacement of stoves. The EE efficiency option has larger initial cost, but after a number of years, for all incomes, it becomes the best-value option. This option is most effective after nine years for C2, after six years for C3, after three years for D, and after less than one year for E incomes. Very large savings in fuel wood purchase in the retrofitted options lead to relative decreases in total private costs. For all incomes, and from the first year, the NT2007 option is more convenient than replacing only stoves. We will see below that replacing only stoves is not a sustainable alternative for private households, as the cost of fuel wood actually increases to achieve 18ºC indoors; hence, fuel poverty will increase as well.

In Figure 5, public cost of retrofit and health care are shown. Public costs for EE efficiency option does not depend on time for all income groups (horizontal lines in Figure 5). This is a consequence of very low emissions resulting from the EE option, leading to no health costs due to PM emissions. For the NT2007 retrofit level there is a small slope as this level almost reaches the ideal reduction in emissions. A different picture is found when replacing only stoves. The initial cost is obviously low, however, the reduction in efficiency is not enough to reach safe PM levels, and thus a residual cost for health increases for all incomes.

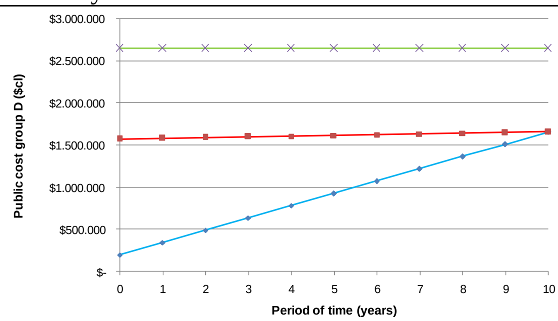
Figure 5: Public cost for income groups C2, C3, D and E.



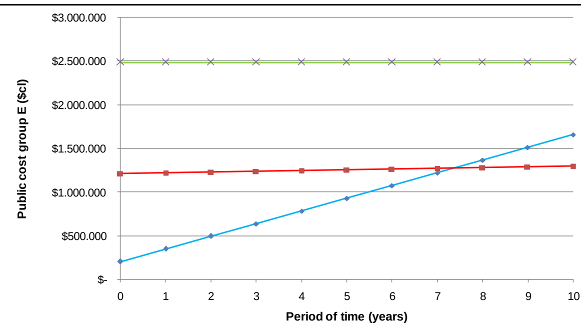
C2) For all income groups: blue = new stove only; red = new stove + NT2007; green = new stove + highest efficiency



C3)



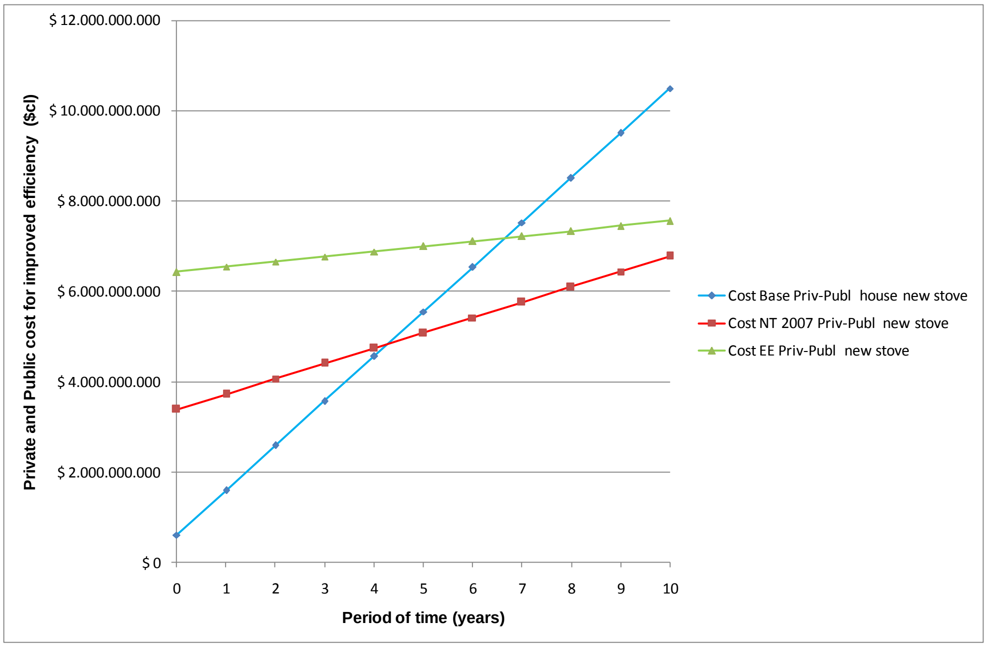
D)



E)

In the two previous figures we showed private and public total costs separately to stress their striking differences, which mark the economical convenience (or lack thereof) of every program for either private or public sectors. Based on these group costs we could calculate the total cost for the sample of 1,937 houses in Valdivia, depicted in Figure 6.

Figure 6: Total private and public cost for efficiency improvements in the sample of 1,937 households using fuel wood in Valdivia.



Even though the retrofit options NT2007 and EE have higher initial costs, after four years NT2007 becomes the lowest cost, and after 6.5 years EE becomes a lower cost than changing stoves only.

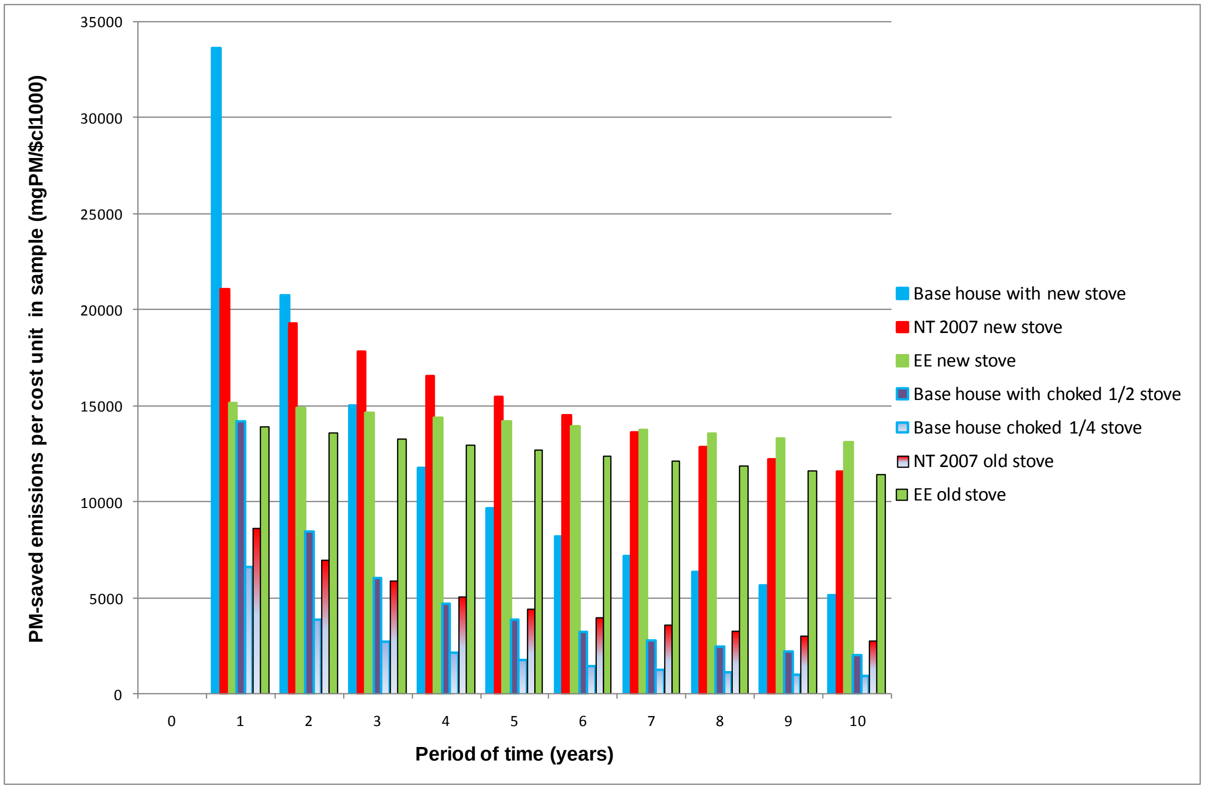
3.4 Reduced Emissions

Figure 7 depicts the amount of PM emissions (in mgPM2.5) reduced yearly per $cl 1000 of total public and private costs in retrofitting, fuel and healthcare for the sample in Valdivia. The three options of efficiency improvement shown in Figure 7 are: 1) the base house with new stove, 2) the NT2007 retrofit level, and 3) the highest efficiency retrofit EE level. In addition, we have included the option of retaining old stoves in retrofitted houses, and two different levels of choking, which lead to emission reductions of one-half and one-quarter of what is found with the new stove running without choking. These two levels of choking that we considered involve partial air choking.

Quantitatively, the maximum reduction from old to new stoves is 6.5 gPM/kg firewood burnt. Therefore, reducing by half means the reduction is 3.25 gPM/kg wood, and reducing by a quarter means the reduction is 1.6 gPM/kg wood; hence, this results in the new stove partially choked to emissions 9.8 gPM/kg firewood if the reduction is half and emissions of 11.3 if the reduction is a quarter.

Note that both scenarios for new stoves are below 13 gPM/kg wood, which is the value for old stoves. We cannot go beyond this value as the comparison is done on old and new stoves for "real-life" measurements. It is possible that choking could make new stoves emit much greater than 13gPM/kg firewood, but this could happen to old ones as well. Methodologically, we perform the comparison of scenarios on the same basis. If data were available on detailed effects of choking, we could have included more scenarios for new and old ones. In any case, note that the scenarios are very possible and give a fair idea of what it would be the situation in which the advantages of new stoves are diluted by choking practices.

Figure 7: PM emissions saved per $cl 1,000 of total cost (public and private) in retrofitting, fuel and healthcare.

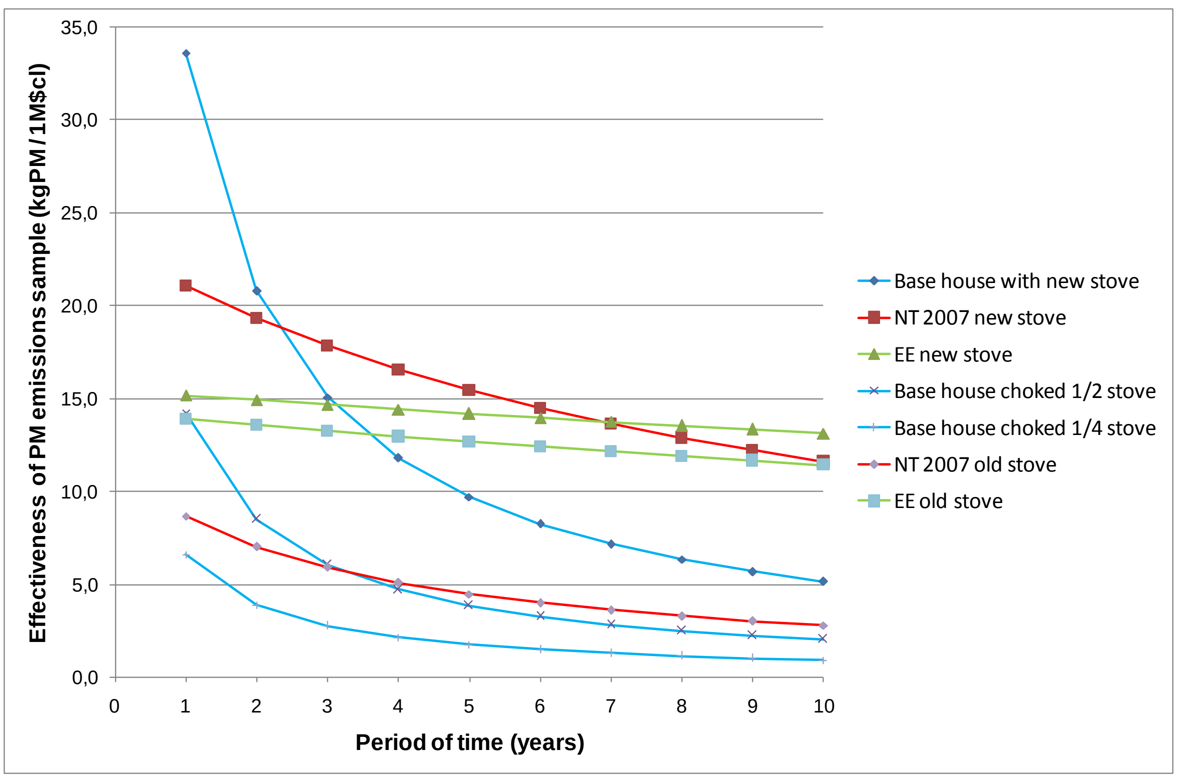


In the first year, option 1) with a new stove and no choking presents the largest PM saved per $cl1,000 spent. As seen above in the cost analysis, this is due to the very low cost of replacing stoves. However, already in the second year option 2 results in similar PM reductions, and beyond three years option 3 (the one with highest initial cost) also results in a larger PM saved. It is interesting to note that keeping old stoves in retrofitting options leads to larger PM savings per cost unit than scenarios in which choking practices were in use. For instance, beyond the third year, NT2007 with old existing stoves have the same PM reduction than those having a new stove but one partially choked. When the retrofit is done to the highest level EE, PM reductions are very large due to house insulation; then, reductions do not depend much upon the choice of stove. This is reflected in Figure 7 in the comparative results of PM-saved for EE with new stoves or with existing old ones. Note that the intermediate efficiency option NT2007 is very sensitive to the stove chosen.

3.5 Effectiveness of PM saved

To see in greater detail the differences in costs among the previous options, we also calculated the effectiveness cost of PM saved, in units of kgPM saved yearly per 1 million Chilean pesos (kgPM / 1M$cl), and shown in Figure 8. In this figure, the higher the value of kgPM / 1M$cl the higher the performance results. Therefore, crossing points between the different lines are of interest in analyzing the convenience of each option.

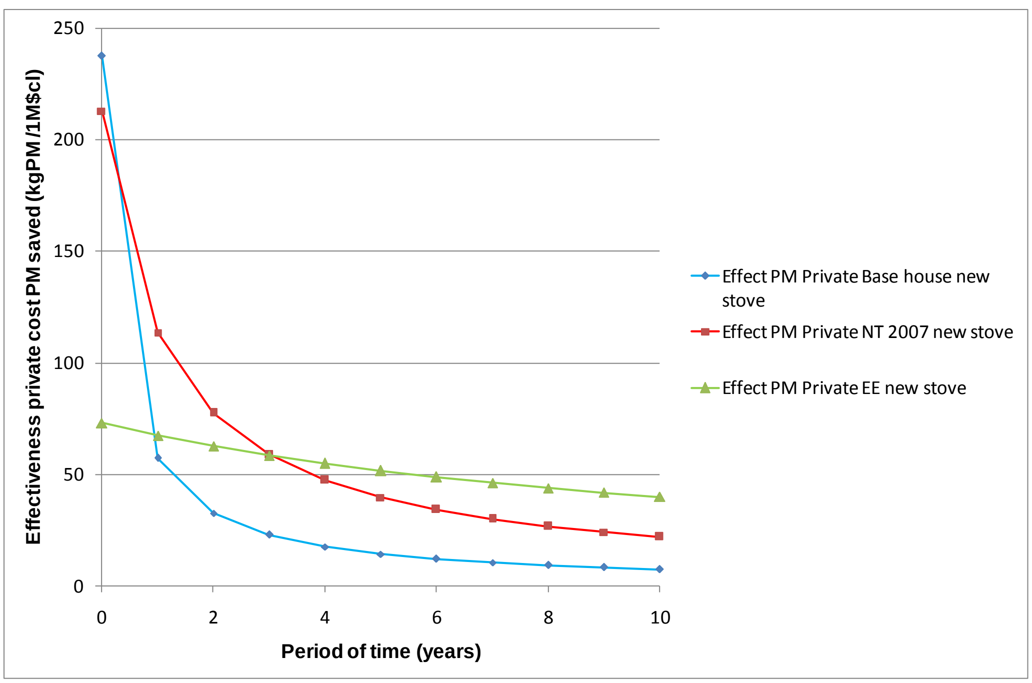
Figure 8: Effectiveness cost (public and private) of PM emissions saved.



In Figure 8, blue, red and green lines represent the three efficiency options. The scenarios with lower emission reductions result in lower effectiveness values. Thus, the area between lines represents the possible intermediate values. For instance, in NT2007, if the operation of the new stove leads to higher emissions than accepted values but still lesser than the old stove, the corresponding graphic line should lay between the red lines in Figure 8. Note that options with higher retrofit efficiency present smaller areas between scenarios of "good" and "bad" stoves. The fact that EE has almost no area between new and old stoves strongly suggests that EE is not affected by user practice. This is due to large reductions in space heating needs when dwellings are provided with high efficiency thermal envelopes. Beyond the seventh year the option with highest retrofit efficiency is the most effective, including a new stove; it is also very interesting that beyond the 10^{th} year the EE option is the most effective even when old stoves were not replaced (crossing points between NT2007 and EE in Figure 8).

Results for the effectiveness of the private household spending, i.e. considering private spending in improvements, health insurance and yearly provision of fuel wood are presented in Figure 9.

Figure 9: Effectiveness cost in kg of PM emissions saved per million $cl cost afforded by households, based on the sample of 1,937 houses studied in Valdivia.

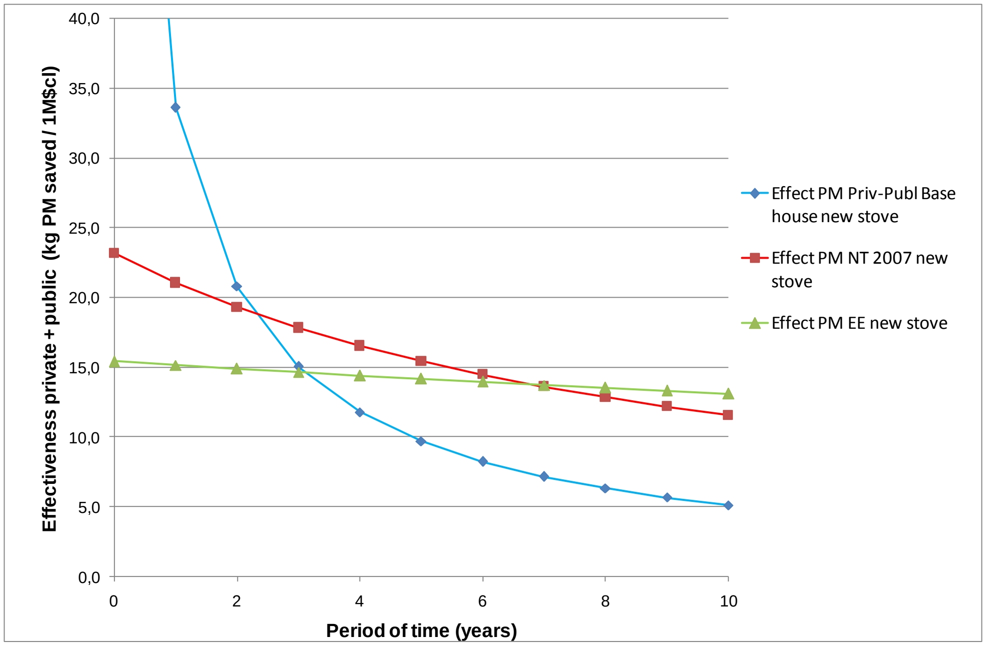


When the program starts, the effectiveness of PM saved is slightly higher for the option with stove only renovation; however, it is interesting to see the intersections of the graphics for each efficiency level. In only a few months, the effectiveness of the option of the NT2007 retrofit becomes the highest. After only one year, the effectiveness of EE retrofit becomes higher than the base stove-only replacing, and beyond three years the highest EE efficiency option leads to the highest amount of PM saved per unit of private cost.

In Figure 10 we have plotted the effectiveness cost of PM saved, including the total private and public cost, in which we have included public spending in subsidies for retrofits and stoves and the cost of health care in public hospitals for PM-related diseases.

The intersection of the various graphs is most interesting. Due to higher costs needed for retrofits NT2007 and EE at the starting date, the option for replacing stoves only has higher initial cost effectiveness; however, beyond two and three years lower fuel wood consumption in retrofitted NT2007 and EE houses leads to higher effectiveness, respectively. After seven years we found that the option of EE is most effective, followed by NT 2007. The option of business as usual leads to no savings in PM emissions, and thus it would be represented by zero kgPM, as shown in Fig. 10.

Figure 10: total private and public cost effectiveness PM emissions saved per million $cl, for the sample of 1,937 houses studied in Valdivia.



An important consideration regarding health and house improvements is in order. When retrofit reforms would be done and stoves would be replaced, PM emissions would drop sharply, and hence related health costs would drop as well. As explained in section 2.2.5, a reduction of 22 μg/m^3 $PM_{2.5}$ emissions (annual average) is required to achieve PM levels that comply with regulations. For the sample of 1,937 houses that use firewood in Valdivia, Table 1 depicts the emission reduction for the various options of retrofitting. The option of stove-only replacement leads to annual emissions higher than the maximum of 15 μg/m^3 recommended, while the options with either NT 2007 or EE and new stoves satisfied the requirement. Therefore, the options with higher efficiency would not incur for public PM-related health costs after the retrofits, while the option with stove-only replacement would still carry a burden related to 7 ug/m^3 of excess annual emissions.

Table 5: Wood fuel saved and PM emission reductions for Valdivia based on different levels of improvements in surveyed dwellings.

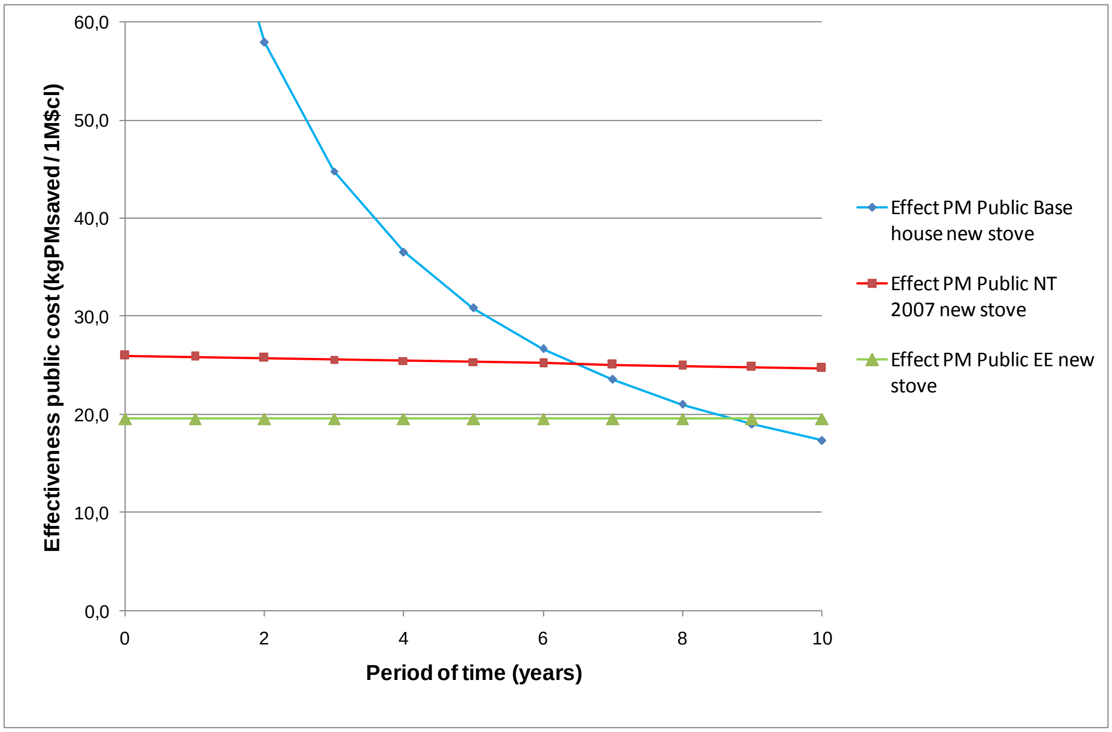
	Wood fuel saved m3st/year	PM2.5 from wood fuel after efficiency reductions μg/m^3	PM2.5 baseline traffic and other μg/m^3	PM2.5 new annual after improvements μg/m^3	Further reductions needed to accomplish max. yearly 15μg/m^3
Only replacing for new stove	-52,300 [1)]	13	9	22	7
NT 2007 and new stove	171,000	6.4	9	15.4	0.4
EE and new stove	358,000	1	9	10	0

1) Negative value means there is no saving but greater wood fuel consumption than at present.

Table 5 shows another interesting characteristic connected to the options for improvements. We are considering all options allowing indoor temperatures of 18ºC. If stoves only were improved, emissions would become much lower; however, wood fuel consumption would rise due to the rebound effect. The present wood fuel consumption estimated for all households in Valdivia is around 460,000 m^{3}st (ca. 170,000 tons); therefore, the reductions in consumption obtained with retrofitting options are substantial, as well as the emissions.

Figure 11 shows the cost effectiveness of public spending to reduce $PM_{2.5}$ emissions in the sample. The small slope in the graph for NT 2007 and the zero slope for the EE option are due to the lower PM-related public healthcare spending after PM reductions (see Table 5), while the significant increase in effective public cost for the stove-only replacement option is a consequence of the remaining $PM_{2.5}$ above the maximum recommended level. Even with immediate low implementation cost, the replacement of stoves without retrofitting would become less effective in 6.5 or 8.5 years, in comparison with NT 2007 or EE options, respectively.

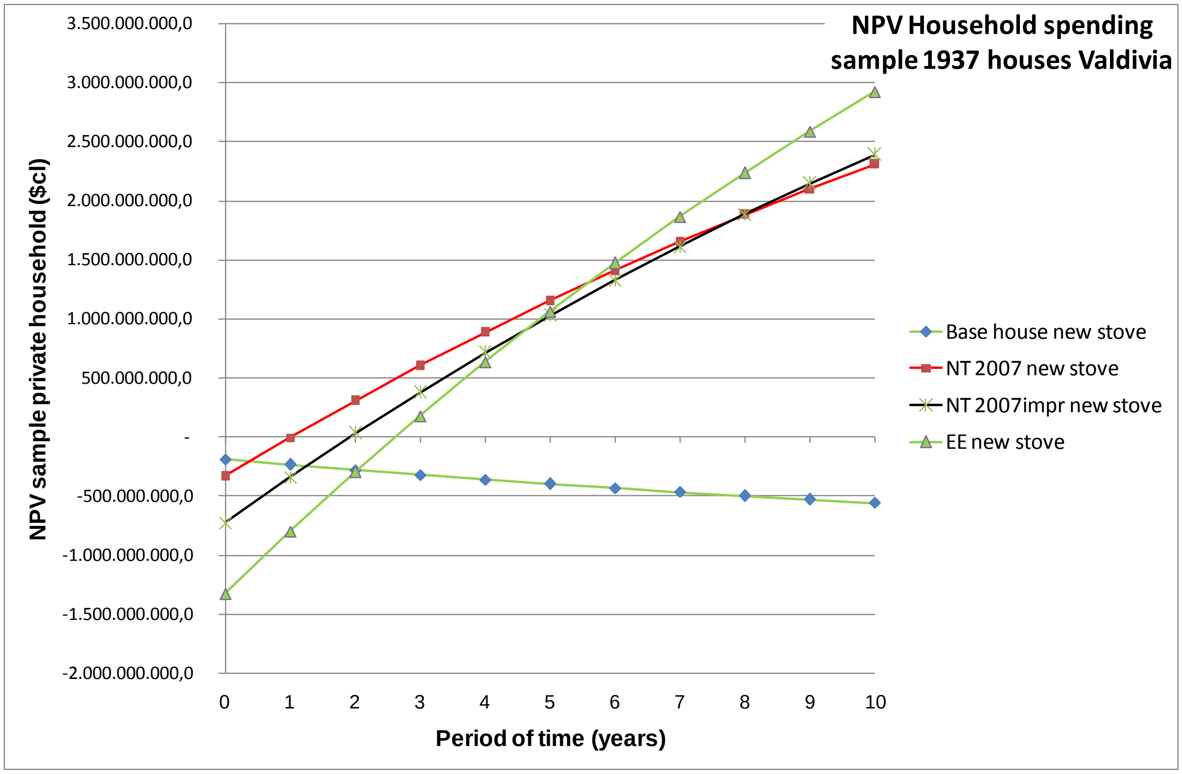
Figure 11: Effectiveness of public investment to save PM2.5 emissions for three levels of efficiency improvements in the 1,937 houses surveyed.



3.6 Net Present Value for the different policies

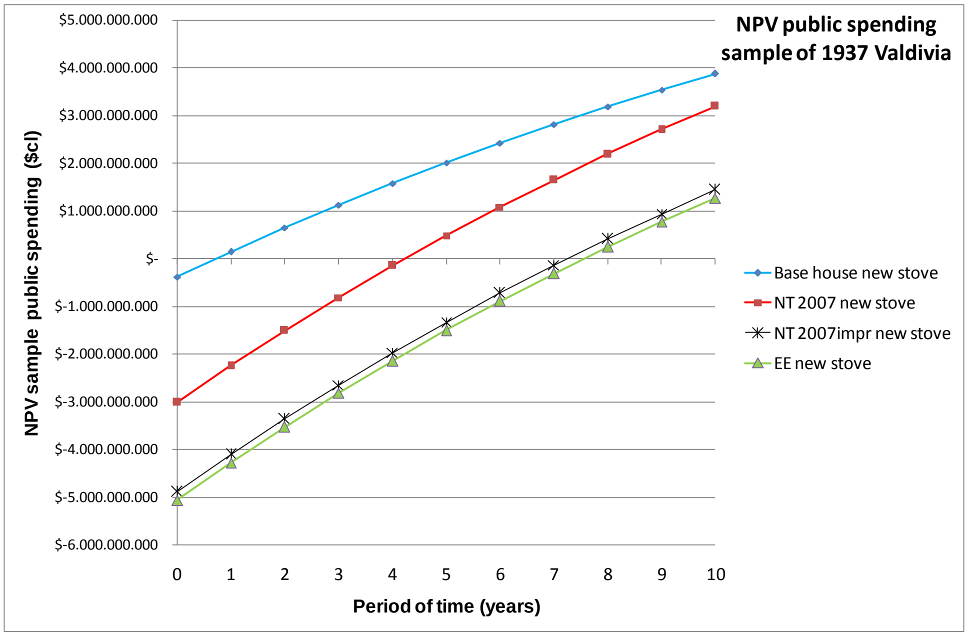
Figure 12 shows the net present value in each year (the sum total of benefits minus total costs divided by the discount factor) for household spending. The option that changes stoves only has the highest value at the beginning of the program; however, it soon declines due to the fact that more firewood is needed to achieve comfort conditions (18ºC indoors). In only six and eighteen months the options NT2007 and NT2007 improved, showing higher NPVs. In approximately five years the best efficiency option EE begins to have the highest NPVs for private spending. The graph reflects a play between private spending in retrofits (moderated by government subsidies), firewood costs and health insurance. The option that changes stoves only has a negative slope due to the fact that more firewood than at present is needed to achieve the comfort condition of 18ºC (rebound effect). NPV for private spending is only a little sensitive to PM emissions, because most households in the sample rely on public healthcare.

Figure 12: Net present value (NPV) of private household spending to improve the efficiency for the sample of 1,937 houses in Valdivia



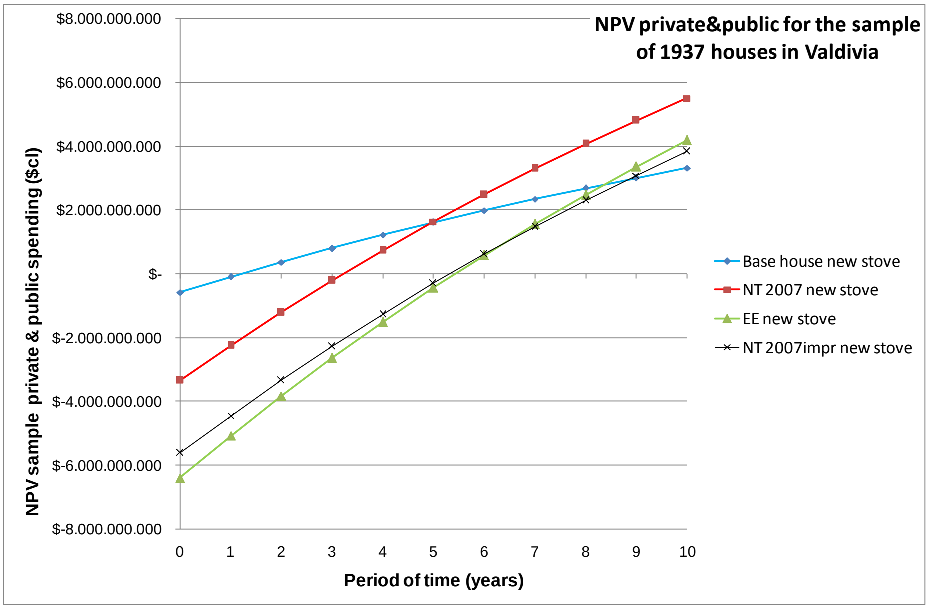
In Figure 13, NPV for public spending in retrofit and health is shown. Public subsidies for retrofit and replacing stoves were considered, as were costs of health that are saved when dwelling improvements are performed at the beginning of the program. Health costs were calculated based on cost per µg/m3 PM reduction, given previously by Gómez-Lobo et al. (2006). Most health costs are public for the income levels found in the sample, all are covered by the public FONASA system in Chile; thus, NPV for public spending depends strongly on PM emissions. Levels D and E do not pay for health costs, and C2 and C3 share 20% and 10% respectively. Accordingly, these percentages were differentiated in the private and public costs. NPV for public spending shows a completely different picture for households in Fig. 12. Public spending does not account for firewood consumed, and hence the option that changes stoves only, which is the worst for private spending, appears to be the best for public NPV up to year 15, beyond which NT2007 option results in higher NPVs. The options of highest efficiency, EE and NT2007 improved, reduce emissions to a level that would require no health costs, and their small difference in NPVs is due to the small difference in retrofit costs for the public sector.

Figure 13: Net present value (NPV) of public spending to improve the efficiency for the sample of 1,937 houses in Valdivia



We added up the private and public NPVs, and the result is depicted in Figure 14. The option of changing stoves only has the highest total NPV during the first five-year period of the program, while option NT2007 will result in highest NPV after five years, and after eight and a half years, options NT2007 improved and EE will have higher NPVs than changing stoves only. In any case, the option of changing stoves only is not convenient for households (see Figure 12), as they pay for the firewood consumed. The efficiency option EE becomes the highest NPV after a period of 22 years (not shown in Fig. 14).

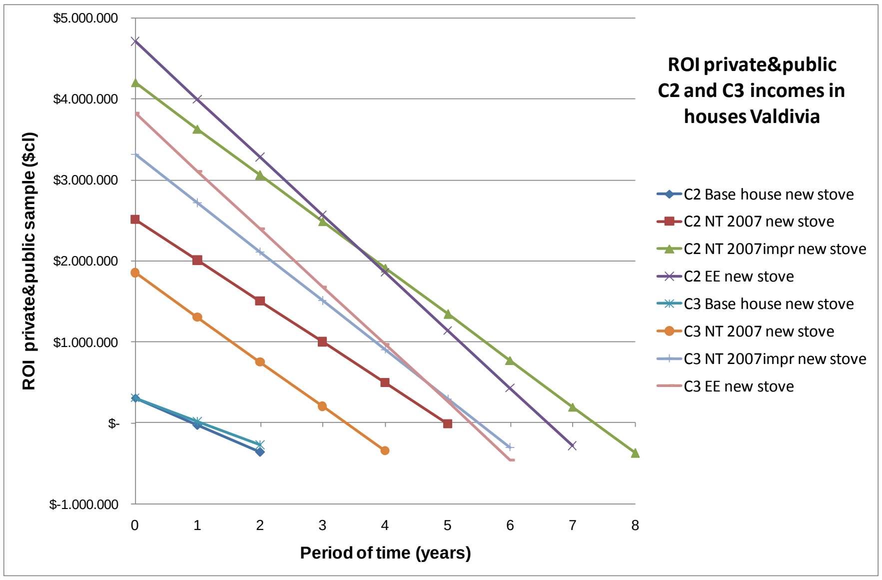
Figure 14: Net present value (NPV) of private and public spending to improve the efficiency for the sample of 1,937 houses in Valdivia



3.7 Return of investment (ROI)

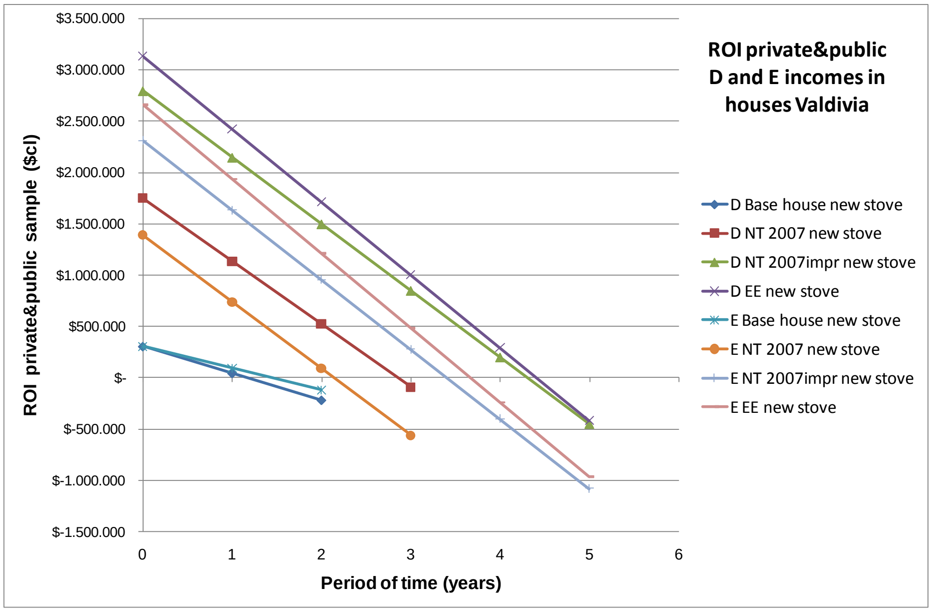
We have calculated ROI for total public and private spending, and then obtained the ROI for the sample. In Figures 15 and 16 the ROI values for the total private and public investment is depicted for the four income levels analyzed.

Figure 15: ROI for different efficiency options and income levels C2 and C3.



The time for recovering the investment is slightly shorter in incomes D and E, due to a combination of lower value of retrofits and higher benefits in PM saved. For all income groups the return is shorter for the NT 2007 option (five and three years for C2 and C3; three and two years for D and E, respectively). In any case, the differences with higher efficiency options EE and NT2007I are not substantial. Note that options EE and NT2007I led to similar results, but EE has slightly better economic performance. Here again we see why the option NT2007I is similar but less convenient than EE, which on the other hand allows for much greater reductions in fuel consumed and emissions.

Figure 16. ROI for different efficiency options and income levels D and E.



The same arguments we had above for NPVs are valid here for ROI values shown in Figures 15 and 16: private and public ROI are very different. If only private ROI is considered, there is no time to return the initial investment when stoves only are replaced without retrofitting. This is due to greater spending in fuel wood to achieve comfort levels with only new stoves (see Figure 12).

With the results for each income level, the ROI value for the sample of 1,937 houses in Valdivia can be obtained for each of the efficiency options, as shown in Figure 17.

Figure 17: ROI for different efficiency options for the sample of 1,937 homes using firewood in Valdivia.

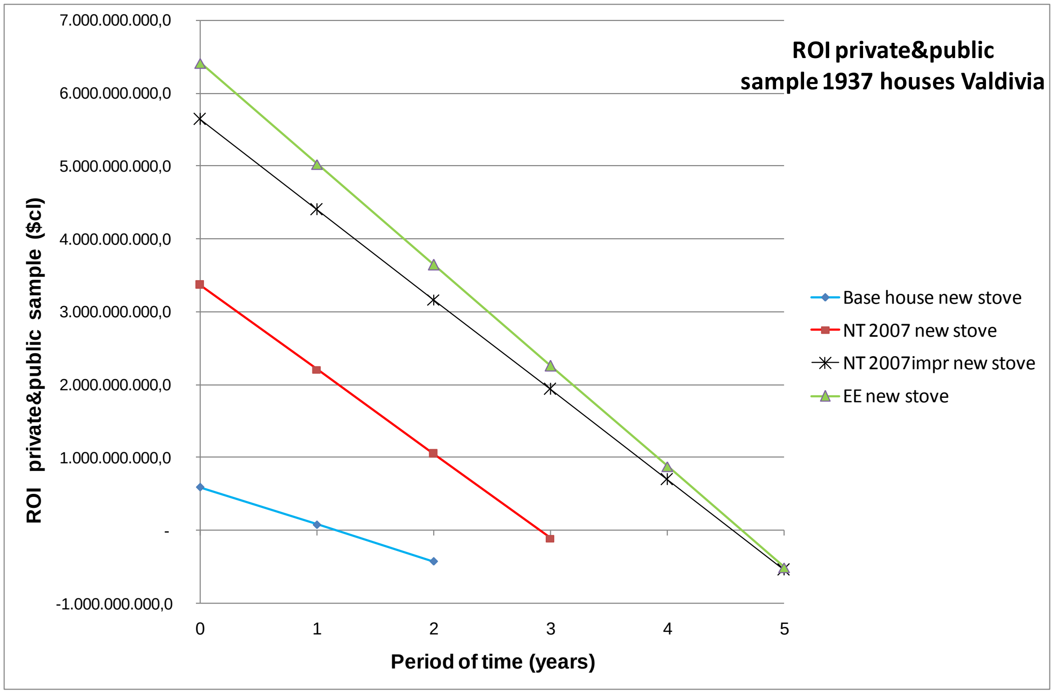


Figure 17 shows that if the efficiency of the sample of 1,937 homes would be improved, the combined private and public spending would be returned in less than four and a half years for all efficiency options. The option changing stoves only has the shortest return period (about one year), followed by NT2007 (less than three years) and the highest efficiency options in four and a half years. As discussed above, even though changing only the stove clearly led to the shorter period of return, this option presents several unsolved problems: a) private households would spend more on firewood and so fuel poverty would increase; b) it does not solve indoor winter low temperature, high humidity and undesirable air infiltrations into the dwelling; and c) as we have shown in previous works (Schueftan and González, 2015a), replacing stoves only does not guarantee that emissions will lower as theoretically predicted, due to the strong influence of user practice of choking on emissions. Clearly, changing only the stove is not recommended, especially so in lower income groups D and E.

4. Conclusions and policy implications

We have investigated technical and economical aspects of the characteristics of the use of fuel wood in households of south-central Chile. A sample of 2,025 households in Valdivia was analyzed as a case study. High consumption of firewood was found, correlated with low efficiency in the envelope of buildings. Different techniques and materials to retrofit existing houses to comply with current regulations and to achieve even better standards were studied. It was found that retrofits have high potential to lower fuel consumption and thus reduce air pollution. In addition, emissions of particulate matter (PM) from wood stoves through their chimneys are very high.

Presently, there are government programs that subsidize retrofits and stove replacement. We have thus studied different options for stoves and considered emissions as measured in real-life operation, which differ from ideal laboratory measurements. These ideal data are based on laboratory studies on the equipments, and are usually declared by manufacturers as stove performance. Real-life values for efficiency are lower than declared and emissions can be as much as four times higher than declared. Nevertheless, real-life operation does not include a malpractice consisting in choking air inlet to let wood burning slower, which is very common in the operation of stoves in Chile. Here, wood stoves in the market have the possibility to choke the air inlet, which is discourages in the manufacturers' stove manuals but still possible in home operation. This mode is much used because wood can burn for a longer time; however, this practice increases PM emissions dramatically due to bad combustion.

In the economic analysis we have considered the cost of retrofits and the savings on firewood in the operation of retrofitted houses with new stoves. The percentage of improvement costs that the subsidies cover depends on income level, as houses in higher incomes are larger and require more spending to retrofit. Also, the savings in firewood depend on income groups, due to a different composition of old stoves and cooking wood stoves found across incomes. Therefore, many of the technical solutions and economical implications are income sensitive; care was taken to consider these differences. In addition, energy consumed, emissions and the economic analysis were performed based on a basic comfort standard of 18ºC. Present average household indoor temperatures in winter are less than that, and a rebound effect was included that also depends on income groups, as their base present average temperature is not the same, ranging from 15ºC for E incomes to 18ºC in C2.

In the economic analysis we have calculated the total cost for private and public sectors, which include the initial investment as well as the yearly, spent on fuel wood and healthcare. From the private household point of view, the options with retrofit led to a much lower cost, as the savings on fuel wood spent are larger, and subsidies reduce the cost of retrofits. From the public sector, the savings are in healthcare services and the main investment is in the subsidies; thus, the option replacing stoves only appears to have the lowest cost for the public sector.

We have calculated the net present value (NPV) of the various efficiency options throughout a 10-year time period. For private households, the option that improves efficiency with new stoves but keeps the house without retrofit led to a decreasing NPV, resulting in more fuel poverty, and is thus unsustainable. All retrofitting options increase NPV. In the beginning, the option NT2007 has a higher NPV but after five years the highest efficiency EE leads to a higher NPV. NPVs calculated with total spending, private plus public, are increasing with time. In the first five years the option that changes only for new stoves has higher NPVs, but after five years NT2007 becomes the largest NPV.

It is to note that retrofit has a higher public NPV than only replacing stoves when the time horizon is at least 15 years, which shows this is a long-term policy. Besides, as there is no detailed information on levels of choking used in households and the effect this has on emissions, for this comparison we used the best case for choking as it has been previously explained. If there were information available on the actual use of stoves in choking conditions the NPV for the stove replacing program would be much lower. The study presented above is for a sample of households and shows the impact by income level, illustrating the relative impact on private and public NPV. When both, private and public spending are considered, NPVs for the retrofit options become higher than only changing stoves in just five years and eight and a half years for NT2007 and EE efficiency levels.

The return of the initial investment (ROI) in improvements was also studied. For the sample in Valdivia, a range of one to four and a half years time period for return was found, corresponding to changing stoves only or for the highest efficiency options, respectively.

We have calculated an effectiveness to save PM emissions, defined as the total cost for each year divided by the weight of PM saved yearly (units $cl/kgPM-saved). For the sample in Valdivia, and considering all total private and public cost, between the second and third year the retrofit options are more effective than changing stoves only, and after the sixth year the EE option is the most effective of all, i.e., the cost is smallest for each kg of PM saved.

A sensitivity analysis was performed assuming different levels of choking that would raise emissions in new stoves. We have considered choking to a level that the reduction of emissions from old stoves would be, whether it be one-half or one-quarter of that which is achieved with new stoves. The effectiveness of the retrofit options show less variation when emissions rise, while for the option of changed stoves only, the effectiveness is very sensitive in raising emissions due to choking. The highest efficiency option EE does not show sensitivity to stove replacement in the effectiveness parameter. This reflects the fact that option EE leads to very low fuel wood consumption.

Furthermore, it was found that 52% of the population spends more than 15% of their income on energy consumption at the household level, which places them within an energy poverty situation. An additional 27% has an expenditure that is near 10% of their income; only 21% do not risk energy poverty.

It is worth noting that stove replacement moderately improves thermal performance but does not lead to an important reduction in firewood consumption, so that we can conclude stove replacement does not solve the problem of energy poverty that affects most of Valdivia’s population. On the other hand, even if the rebound effect is considered, indoor temperatures would not reach the recommended levels, affecting health that is not only strained by high levels of air pollution, but also by low indoor temperatures.

In addition, the low-emission stoves that are considered in the subsidy are not found in the market yet. It is important that the new equipment does not allow complete closure of the air inlet as it occurs nowadays, because reducing the air in the combustion process makes firewood last longer but this action can produce an increase in emissions of up to 10 times more than with the air inlet open.

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 the cities of south-central Chile. The environment, housing, energy and health authorities are strongly focusing firstly on enforcing firewood certification, and secondly on stove replacement. However, these two strategies strongly depend on household behavior.

The objective of the policies is the reduction of firewood consumption per household to achieve the following goals: 1) improvement in human health and wellbeing, 2) improvement in equity in the reduction of energy poverty 2) improvement in sustainability with the use of firewood as fuel for heating, and 3) effectiveness and positive NPV of government subsidies and programs.

The public cost for the different programs was studied in this work and presented above. The effectiveness of the program applied will be measured according to the reduction of $PM_{2.5}$ concentrations, reduction of firewood consumption per household and increase in indoor temperatures. The methodology to obtain this data is from existing monitoring stations, direct t° measurement in households and the application of surveys to compare results with previous data.

Different options and combinations of programs have relative merits that have been assessed in this study and are useful for policy makers. The policy matrix presented in figure 18 shows the tradeoffs in the policies.

Figure 18: Policy matrix for different program options and their effect in achieving policy objectives.

		Effectiveness			Social Cost		Program Structure	Equity	Total
		Reduction PM2.5 concentration	Reduction of firewood per HH	Increase in indoor tº	Implementation	Health			
Energy Efficiency	Subsidies according to income level	1	1	1	3	1	2	1	10
	Credit with payback from savings	2	2	1	2	2	2	1	12
	Education and technical assistance	2	2	2	1	2	1	2	12
	Stricter thermal regulation for new constructions	2	2	2	1	2	1	3	13
Firewood	Subsidy to dry firewood	2	2	2	2	2	2	2	14
Heating Devices	Regulation for air inlet	1	3	3	1	2	1	3	14

Since the retrofit option which has shown the greatest reductions in air pollution and energy poverty (EE efficiency level), has a complexity of implementation and requires the participation of different ministries as housing, health, environment and energy; then a combination of policies and phases of implementation must be considered. There are also budget issues that have to be considered, since replacing stoves has a lower implementation cost than the retrofit, although the retrofit option has shown the best long-term results.

The policy options matrix shows the effect of different policies on the goals that have to be achieved, with green showing the most positive effect, yellow the intermediate and red the lower effect or the barrier or problem that appears when considering a specific policy. This information allows the definition of a policy mix design and the implementation steps.

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 [available] in the market. It is urgent to have reliable empirical data on user 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 neighborhood residents, and coordinate requirements and suggestions. This is a way to encourage social participation in the process of improving energy efficiency, as well as communitarian and associative initiatives in neighborhoods.

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 acknowledged as an effective means to both reduce consumption of wood fuel and to avoid indoor pollution from incoming outdoor smoke.

d) It is urgent to investigate the effects of air-choked equipment on PM emissions and to have industrial and commercial concerns jointly address it. This will lower chimney smoke significantly but, given current the low thermal efficiency of 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 changing to better stoves and house retrofits cannot be separate initiatives from changing practices in the use of stoves. A further step would be to ban devices that allow complete air choking.

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 on 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 improve their current practice regarding 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 that disregard social housing plans.

h) The limitations on eligible income levels for the thermal insulation subsidy should be more lenient so as to include assistance for mid-level income social sectors. It is more likely that medium-income sectors would 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 does the number of subsidies have to increase, but so does their correct execution. Surveys of households after the retrofit show improvements in condensation, mold reduction, and lifetime of materials, but other problems such as infiltrations and thermal bridges were not solved with the thermal refurbishment (MINVU, 2013). The same study also shows that sometimes the subsidy is used for other improvements in the dwellings that are unrelated to 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. Prioritization of items in retrofits could ensure users are receiving an intervention that will be efficient in reducing their energy consumption.

k) In public housing the building extensions made by the owners are not considered in the subsidy; thus, only the original part of the structure 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) Research and implementation of incentives should be implemented for mid- to high-income sectors to self-finance thermal refurbishments, for instance, subsidizing state and private technical offices so that they may assist all households to determine efficiency improvements.

m) Currently, householders are not informed about the benefits of thermal retrofitting, but have shown they appreciate it after they receive the subsidy. Surveys after the retrofit have shown that users are willing to invest in thermal improvements of the dwelling after they have seen the results; furthermore, 55% of this group do in fact perceive health improvements (MINVU, 2013).

n) Results showed that retrofit programs are the best option to achieve the objective, but as it is a more complex option, levels and phases of implementation should be considered in planning.

o) Raising the price of firewood has been proposed by some studies, but this would sharply increase fuel poverty, as currently the average annual energy bill in Valdivia accounts for around four minimum monthly wages. In countries that have a similar energetic situation in the residential sector, as in New Zealand, this move has been proven to increase inequality in the access to energy, fuel poverty and health problems due to low indoor temperatures (Howden-Chapman et al., 2012). Besides, a higher price of firewood would lead to an increase in air choking of heating devices in order to make fuel last longer, but with the undesirable consequences that have been previously explained.

p) Promotion of soft loans to buy firewood before the winter season to allow householders to stock firewood during the summer months.

q) Householders with no income capacity to afford replacing old cook stoves should be provided with alternative cooking and water heating devices; this initiative goes beyond simply providing a new space heater, as they would continue opting out of the program as it presently exists.

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 our study, the two current main strategies will only have limited potential for improving air quality: i) acceptance of certified firewood is very low; and ii) stove replacement has only a low impact if wood-heaters with an option of air-choking are still provided. Further acknowledgement of household realities and further public-private interaction could speed the process needed to successfully combine the three strategies studied.

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