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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.