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The firewood dilemma: Human health in a broader context of well-being in Chile

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ABSTRACT

The mitigation of climate change requires developing alternatives to fossil fuels, while simultaneously looking for ways to increase the resilience of our socioecological systems especially those reliant on ecosystem goods and services. Forest biomass is receiving increased attention as a source of renewable fuel; yet at the same time, increased use of wood fuels raises health concerns about the adverse effects of pollution and as a possible contributor to deforestation and forest degradation. For these reasons, where people use wood fuel, policies are designed to shift people away from wood fuel and using forest biomass and up the energy ladder, typically toward fossil fuels. Using a case study from Chile, where air pollution from residential firewood combustion has become a serious issue, we show that while such policies might reduce pollution in the short term, they are unlikely to improve either human well-being or the sustainability of resource use in the long term. Instead of policies designed to reduce or eliminate wood fuel use, by examining the interlinked energy and resource subsystems and socioeconomic context within which wood fuel is used, we argue that a combination of policy interventions targeting the adoption of energy-saving technologies, while still maintaining wood fuel as a primary energy source, would yield higher economic, social, and environmental benefits.

Introduction

Wood fuels[2] are an important source of energy in the world: approximately 2.8 billion people rely them, especially in developing countries (Food and Agriculture Organization of the United Nations, FAO, 2010; Bonjour et al., 2013), and it makes up 9% of the world primary energy matrix (International Energy Agency, IEA, 2014). Over half of global timber harvests (52%) are used for fuel (FAO, 2015). Asia, Africa, and Latin America are the main wood fuel consumers, with 42%, 32%, and 17% of the total volume, respectively (FAO, 2010). The associated impacts of wood fuel use depend on what kind of biomass is used, who uses it and how, and the impact of the level and kind of extraction activities on the forest ecosystem.

In Africa and Asia, where wood fuels have been mainly studied, woody biomass is used in low efficiency cook stoves or as open fires, which can be also observed in some areas of Latin America. However, in the most developed countries of South America (Uruguay, Argentina, and Chile), wood fuels are used for cooking and heating in rural areas and for heating in urban ones, using higher efficiency equipment (Costa and Delgado, 2001; Reyes, 2013), and there is extensive use of natural gas or liquefied petroleum gas (LPG) for cooking, especially in urban areas.[3] In North America and Europe, the use of forest biomass is growing, where the wood fuel comes in the form of pellets, mainly produced from forest wastes (Goh et al., 2013), and used for both residential heating and power generation.

There is a divergence in wood fuel policies, with those promoting its use as potentially more sustainable energy sources than fossil fuels, as in Europe and North America (Lundmark and Mansikkasalo, 2009; Sikkema et al., 2011). In other regions, wood fuel consumption is producing significant health issues due to indoor air pollution[4] and ambient particulate matter pollution (Lim et al., 2012). Health problems related to indoor air pollution from solid fuels in sub-Saharan Africa and South

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[2] All types of biofuels derived directly or indirectly from woody biomass (FAO, 2004).

[3] In contrast to Africa and Asia, wood fuels in Latin America are also widely used by industry as well (steel factories, ceramic factories, food and beverage manufacturing plants, dairies, sawmills, forest industries, etc.), commercial and retail firms (restaurants, bakeries, hotels, etc.), and public institutions (hospitals, schools, municipalities, etc.) (Baker et al., 2014; Ministerio de Minas y Energía de Brasil, 2009; Reyes, 2013).
[4] The smoke produced by burning forest biomass and other materials in unventilated places is an important driver of respiratory diseases, cataracts, and cardiovascular problems, among others (Srogi, 2007; Fullerton et al., 2008; Pénard-Morand et al., 2010). Indoor air pollution accounted for 3.5 million deaths and 108 million disability-adjusted life years in 2010 (Lim et al., 2012). This has given rise to many research and development initiatives oriented to promote new cooking stoves, the use of cleaner fuels, etc. (Kanagawa and Nakata, 2007; Ruiz-Mercado et al., 2011).

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Asia account for between 4% and 6% of the total DALYs,[5] while in Chile they only represent 0.75% (30,000 DALYs).[6] Yet, in Southern Chile, wood fuel consumption is the main driver of ambient particulate matter pollution, being the responsible for the emission of more than 80% of the total PM2.5 (Ministerio de Medio Ambiente, 2013) with a significant impact in public health (Secretaría de Medio Ambiente Región de Los Ríos, 2014).

Moreover, there has been a long debate on the role that wood fuels play in deforestation and forest degradation, starting in the 1970s with the publication of "the other energy crisis" (Eckholm, 1977). Although the incidence of wood fuel production on deforestation remains a controversial topic (Bensel, 2008; Bhatt and Sachan, 2004), it is accepted that overharvesting of wood for fuel contributes to forest degradation (Ahrends et al., 2010; FAO, 2010). Nevertheless, the balance between supply and demand, and the potential overharvesting, significantly varies among countries and regions (Bailis et al., 2015), where some Asian and African countries have the highest rates of non-renewable biomass consumption (Bailis et al., 2015).

Much of the analysis and concerns around the social and environmental impacts of wood fuel consumption has drawn on the experiences of places like India, China, and sub-Saharan Africa, where poverty, high population density, and other factors create a complex scenario for the consumption of wood fuels. Chile (and other regions in Latin America), by contrast, present a different socioeconomic setting, where (a) there are higher levels of income and development, (b) extraction of forest biomass takes place with different forms of forest governance and for personal and commercial use, and (c) wood fuel is used mainly for heating rather than cooking.

This different context offers the opportunity to examine the "wood fuel issue" from a novel perspective, where wood fuel use is quite high (28%) being the second most important primary energy source after petroleum (CNE, 2014). At the same time, Chile is one of the Latin American countries with a negative rate of deforestation (FAO, 2012), and while wood fuel production has been raised as a cause of forest degradation in some areas, there is evidence that cattle grazing is the main driver behind this process (Zamorano et al., 2014). In this setting then, the wood fuel issue in Chile may not necessarily be to shift users "up" the energy ladder; instead, it is to evaluate wood fuel policies against a broader set of measures reflecting the environmental and social impacts of these policies not only human health, but also on human well-being and resource sustainability.

The Chilean context

In the last four decades, Chile has experienced rapid development resulting in a significant improvement of the socioeconomic condition of its population. According to the World Bank (2014), Chile now has comparable levels of per capita income (US$21,000/year) and life expectancy (80 years) to developed countries, and it has seen reductions in poverty and corruption, indicators that have characterized it as a successful development case (Ramirez and Silva, 2008; Rehner et al., 2014). Yet at the same time Chile is one of the countries with the highest per capita wood fuel consumption worldwide (Bailis et al., 2015), although there is strong regional variation, influenced by differences in resource availability and climate. Industrial wood fuel consumption is more concentrated in central Chile (between Valparaiso and Biobío regions), where the economic activity is more intense, while the residential consumption is concentrated in southern Chile, due to colder climatic conditions (Fig. 1). The average wood fuel consumption in the urban residential sector of central Chile is 1 m^3/hh/year, as opposed to 18 m^3/hh/year in Patagonia[7] (Reyes, 2013).

Wood fuel consumption is strongly rooted in the Chilean tradition and culture due to the abundance of forest biomass, the relative scarcity and high cost of fossil fuels, and the cold and rainy winters (Burschel et al., 2003). The wood fuel market is also very important from a socioeconomic standpoint, employing 60,000 people in the supply chain and related services (maintenance of heaters, exhaust systems and chimneys, input supply, and others) (Burschel et al., 2003). The firewood market represents an important income source for thousands of small and medium landowners, especially during winter or periods of economic recession, when agricultural activity is lower.

In this document, we analyze the case of Valdivia City in Southern Chile to show the social and environmental impacts of policies designed to limit or eliminate the use of wood fuel and alternative policies. Valdivia is the largest city in the region and is representative of other southern cities in terms of both demographics and the socioenvironmental characteristics related to the firewood consumption. In addition, several studies have been carried out in Valdivia in the last two decades, providing the data necessary to perform a more comprehensive analysis of this topic.

The firewood issue in Valdivia

In Valdivia City, the wood fuel consumption (mainly firewood) averages 211,000 m^3/year (Reyes and Frene, 2006). It is consumed in 84% of households, basically for heating, with an average of 8.3 m^3/hh/year (Reyes and Frene, 2006), and even at the highest socioeconomic decile (average income larger than US$70,000/hh/year), 62% of households consume firewood for heating. Wood fuel consumption is not necessarily driven by poverty but also by traditions, availability, comfort, and other factors (Reyes and Frene, 2006) as has been reported in other countries (Hiemstravan der Horst and Hovorka, 2008). One consequence has been ambient particulate matter pollution. From 2008, when the Air Monitoring Program started to be implemented in Valdivia, PM10 and PM2.5 concentrations have frequently overcame the Chilean air quality standards for both particles[8] (Ministerio de Medio Ambiente, 2015). In 2014, Valdivia was declared a PM10 Saturated Zone, requiring the development of an Environmental Decontamination Plan that includes several measures to reduce air pollution. One of the measures that has been proposed is the replacement of wood fuel by LPG or other oil derivatives. However, international experience shows that the replacement of traditional fuels by oil derivatives, normally through prohibitions or/and subsidies, has not been very effective (Gangopadhyay et al., 2005; Hosier and Kipondya, 1993; Pitt, 1985). The fuel switching process is not linear, but instead much more complex, where other factors influence behavior and use, especially where different energy sources are simultaneously used to satisfy the family needs (Hiemstravan der Horst and Hovorka, 2008). It is this question we address in the remainder of this study: what are the costs and benefits of wood fuel-based systems versus the proposed alternatives, and which offers the most long-term sustainable environmental and social benefits, with a focus on the well-being of Valdivian residents?

Methods

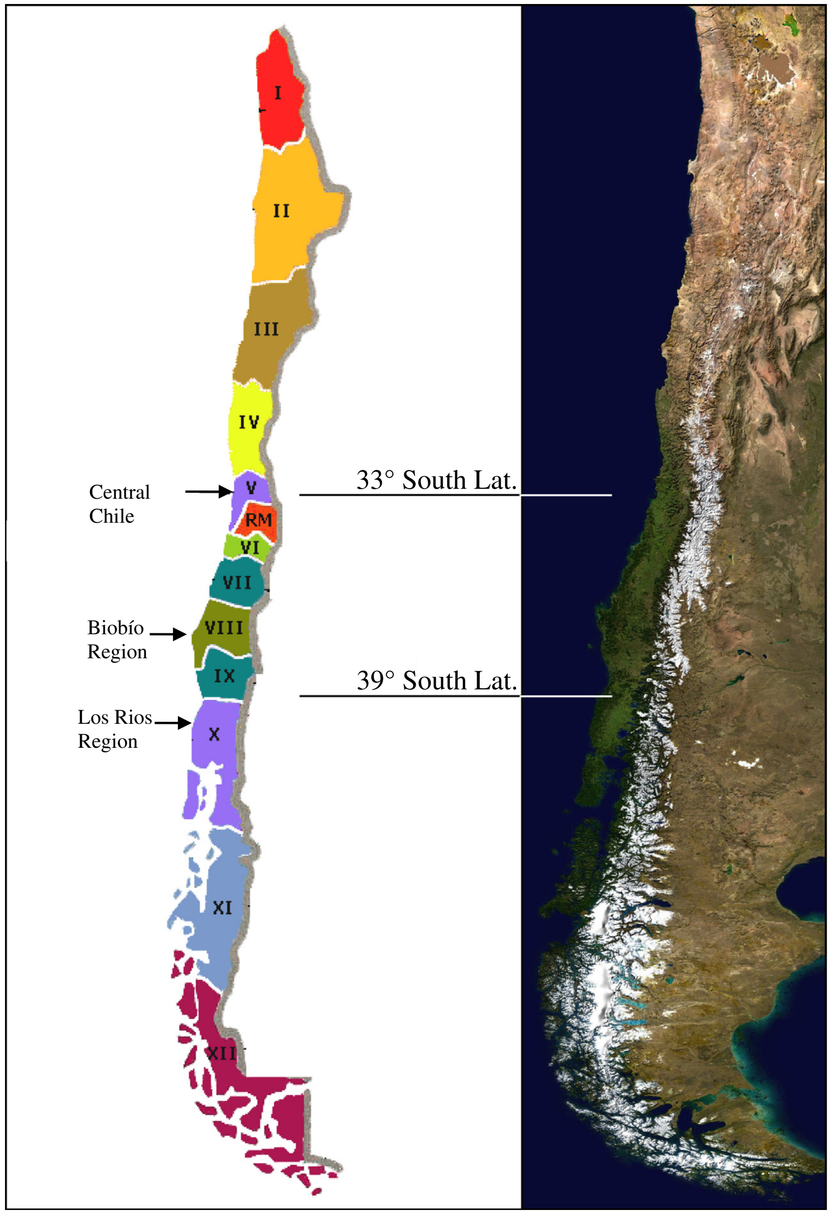
We answer these questions by carrying out a comprehensive analysis of the residential heating system (RHS) of Valdivia, including both environmental and social dimensions (Fig. 2), to assess the implications of switching fuel sources along with the alternative of continuing wood

[5] Disability-adjusted years of life—this factor reflects the quantity of years lost due to ill-health, disability, or early death (Murray, 1994) and is a common metric used in public health to better capture the broader health impacts beyond just mortality.

[6] It includes 1,500 deaths and 28,500 disability-adjusted life years (Institute for Health Metric and Evaluation, 2013).

[7] Solid cubic meter. 1 m^3 solid = 1.5625 m^3 bulk (stacked firewood with air between spaces).

[8] That is, 150 and 50 μg /m^3, 24-h average, for PM10 and PM2.5, respectively (Ministerio de Medio Ambiente, 2013). Data show that PM2.5 is dominant in the total PM10 (Ministerio de Medio Ambiente, 2015).



Source: own development based on Wikipedia images. In 2007, Los Rios Region was created in the northern section of Los Lagos Region.

Fig. 1. Map of Chile. Source: own development based on Wikipedia images. In 2007, Los Rios Region was created in the northern section of Los Lagos Region.

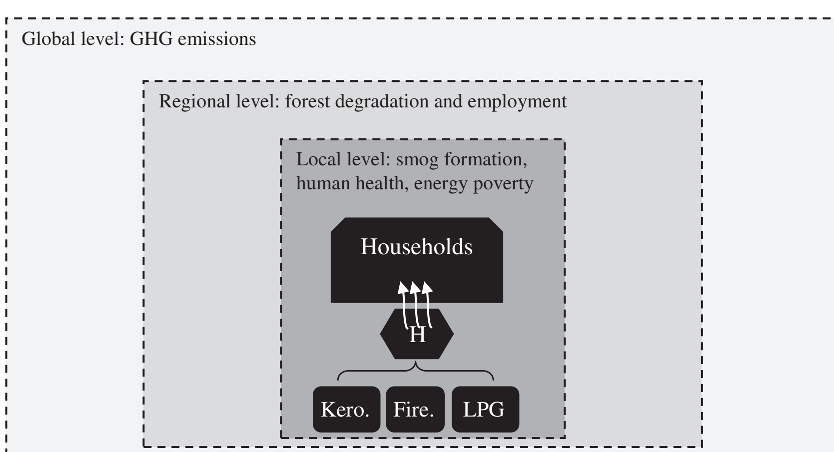


Fig. 2. Analytical model.

fuel use. We use a Life Cycle Assessment (LCA) to analyze the global and local environmental impacts of the RHS of Valdivia, comparing different kinds of energy sources and technologies (the types of heaters) used in the City. We complement the LCA with a social analysis, evaluating the RHS in terms of public health, energy poverty, and employment. We examine changes in the status quo assuming that any proposed changes would shift consumption away from wood fuel use but not completely replace it (as changes in behavior and policy in this context can be expected to be incremental). Therefore, no assumptions are made about major changes in capital investment or infrastructure required or the adoption of new technologies that are not already in use (albeit in a limited manner). We conclude with some policy proposals to better achieve environmental and social objectives, improving not just human health but human well-being and environmental conditions.

Key in framing the analysis is framing the boundary of the systems to be analyzed. Here, we defined three levels of analysis: local, regional, and global. The local scale corresponds to the city of Valdivia, where the energy is used and the emissions produced by the residential heating system create localized impacts. At that level, smog formation, human health, and energy poverty are therefore analyzed. Los Rios Region represents the regional scale, where the wood fuels consumed in Valdivia are produced and traded as part of the regional economy. Here, the impact of the Valdivia wood fuel market on employment and native forests are analyzed. Finally, as emissions also contribute to greenhouse gases (GHG), we undertake an analysis at the global scale to capture the full range of emissions from these activities throughout the process of extracting, refining, and transporting of fuels to consider their impact on global warming (Fig. 2).

Study area

Valdivia City is the capital of Los Ríos Region (39°48′50″S–73°14′45″ W) in the south of Chile, which has 154,000 inhabitants (Instituto Nacional de Estadísticas, 2012). Los Ríos Region is characterized by an oceanic climate (Cfb), similar to New Zealand, the United Kingdom, the states of Washington and Oregon in the United States, the Province of British Columbia in Canada, among others (Peel et al., 2007). Rainfall averages 1,800 mm per year, with a mean temperature of 12.9 °C (Castillo, 2001). These conditions result in a high-energy demand for heating.

Valdivia City has 40,000 households (INE, 2012), of which 84% use firewood, 29% LPG, and 9% kerosene as the main heating sources (Reyes and Frene, 2006). These percentages sum to greater than 100%, as almost one third of households use a combination of these three fuels, although firewood prevails. Kerosene is more common in low-income households, while LPG is used in medium and high-income households (Reyes and Frene, 2006). LPG and kerosene are the most usual complement or replacement for firewood.

According to the U.S. Environmental Protection Agency (EPA, 1996), the wood stoves used in Valdivia can be classified as either "conventional" (45% efficiency) or "non-catalytic" (60% efficiency) ones, with conventional stoves accounting for 56% and non-catalytic stoves 44% of the total stoves (Ambiente Consultores, 2007; Reyes and Frene, 2006; Ulloa et al., 2011). The most common conventional wood stoves are the "cocina chilota"[9] (cooking stoves mainly used for heating) and the "salamandra", while the most common non-catalytic wood stove is the "slow combustion stove"[10] (estufa de combustión lenta), which has a small secondary combustion chamber as a complement of the main one (Ambiente Consultores, 2007; Ulloa et al., 2011).

[9] http://www.flickr.com/photos/lpbb/5204262659/.

[10] http://www.bosca.cl/#!chimeneas-calefactores/c1h3h.

LPG heaters[11] (convective and radiant) and kerosene heaters[12] (with a wick) are also used by the residential sector. Both systems are more efficient as they are able to transform almost all the primary energy into heat, although they also produce indoor pollution because of the absence of gas discharge ducts (Dirección de Investigaciones Científicas y Tecnológicas de la Universidad Católica de Chile, DICTUC, 2011). For both LPG and kerosene heaters, an efficiency of 100% was assumed[13] in order to perform later comparisons. In the case of wood fuels, it was assumed that all energy is used for heating.

Environmental and social impacts

Environmental impacts

The functional unit for the Life Cycle Assessment (LCA) was defined as "megajoule (MJ) of effective heating" (total heat produced from fuels minus the heat lost through discharge ducts). It was used to analyze environmental impacts at the local level for smog formation and at the global level for the GHG emissions. The global analysis included all those processes related to the fuel supply, including the final consumption, and the LCA considered four different energy sources and technologies used to heat homes: a conventional wood stove, a non-catalytic wood stove, a kerosene heater, and an LPG heater.

In the case of wood stoves, the process starts with firewood being harvested in forests. This stage involves the use of gasoline to operate the chainsaw used to cut trees and chop the timber. In the transportation stage, diesel trucks are used to transport firewood from the countryside to the city, where it is finally burned to produce heat. Data required to characterize this supply chain were taken from Medel (2008).

In the case of kerosene and LPG heaters, the process starts with oil extraction from oil wells. After that, oil is carried out in vessels toward the Chilean refineries, which are located in central Chile. Oil vessels use heavy oil[14] to operate. At the refineries, oil is then turned into kerosene and LPG. Later, diesel tank trucks transport them to Valdivia, where they are consumed. Each fuel used in the supply process has different provenances that determine the distance traveled by vessels. These provenances were provided by the Comision Nacional de Energía de Chile (CNE, 2012), and the distances were estimated by using Google Earth.

All emissions related to oil extraction and refining of the gasoline, diesel, and heavy oil used in transports were considered in the analysis, based on units of fuel produced (Lewis, 1997). The production, maintenance, and final disposal (landfill or recycling) of wood stoves and heaters were not considered, since the assessment is focused on the emission flows. The same criterion applies for the construction, maintenance, and dismantling of refineries, oil vessels, and tank trucks, as well as the exploration and drilling of oil wells.

The assessed environmental impacts were atmospheric emissions associated with GHG and smog formation. The first is assessed as the contribution to global emissions, while the second one is analyzed locally (Valdivia). Global warming is measured in terms of CO_2 equivalent (CO_2e), considering CO_2, NOx, N_2O, CO, CH_4, VOCs, and HAPs. Usually, CO_2 coming from biomass combustion is accounted as carbon neutral in LCA assessments, especially when it is sustainably produced. However, some researchers point out that CO_2 should be always accounted (Rabl et al., 2007; Johnson, 2009). In order to address this aspect, and taking into account the uncertain origin of the forest biomass used in Valdivia, we performed the LCA considering both alternatives.

[11] http://www.albintrotter.cl/prontus_trotter_productos/site/artic/20090518/pags/20090518164637.html.

[12] http://fensa.cl/tienda/product/99_estufa-kerosene-mod1120-gm#descripcion.

[13] Unvented heaters are typically rated at a 99–100% efficiency. Most combustion energy is recovered by water condensing on room surfaces. Equipment assumed to be properly calibrated with an ideal fuel/air mixture.

[14] Oil fraction got from hydrocracking. It is the heaviest fuel obtained by distillation process at atmospheric pressure.

Table 1
Primary energy consumption for residential heating in Valdivia.

Energy source	House holds	Average cons. (tonnes/household/year)	Total cons. (tonnes/year)	Total cons. (million MJ/year)[a]	Effective cons. (million MJ/year)[b]
Firewood	36,960	4.00	147,840	2,217	1,153
LPG	12,760	0.42	5,308	245	245
Kerosene	3,960	0.44	1,738	77	77
Total				2,539	1,475

Source: own elaboration based on EPA (1996), Reyes and Frene (2006), INFOR (2009), and Natural Resources Canada (2010).
[a] Energy density: 15.0, 46.1, and 44.5 MJ/kg for firewood, LPG, and kerosene, respectively.
[b] Considering an average efficiency of 52% for wood stoves, and 100% for LPG, and kerosene heaters.

Particulate matter was not taken into account in the analysis, despite black carbon and organic carbon are linked to global warming (and cooling) (MacCarty et al., 2008), because many uncertainties remain concerning the way as these particles really impact on climate (Cappa et al., 2012; Bond et al., 2013).

Smog formation was measured in terms of C_2H_4 equivalent (C_2H_4e), and all its different components: particulate material (it was only considered PM10, since the emission factors used for this calculations do not consider PM2.5), carbon monoxide (CO), volatile organic compounds (VOCs), and hydrocarbon aromatic polycyclic (HAPs). The non-consideration of PM2.5 is one of the main limitations of this study because PM10 is not a good indicator of wood smoke, although monitoring data show that PM2.5 prevails in the total PM10 in the Southern Chilean cities (Sanhueza et al., 2009; Ministerio de Medio Ambiente, 2013; Secretaría de Medio Ambiente Región de Los Ríos, 2014).

We also carried out a regional analysis, looking at the environmental impact of wood fuel production. Although several authors have linked firewood production to forest degradation and deforestation (Carmona et al., 2010; Echeverría et al., 2007; Echeverria et al., 2008; Marín et al., 2011), there are few formal studies that have actually assessed the impact on native forests in Los Rios Region. In order to assess this potential impact, we utilize research conducted in the past 10 years to define general trends.

Social impacts

The social impacts considered in the analysis were public health, energy poverty, and employment. The first two were assessed at a local scale, while the third one was analyzed regionally. Public health was evaluated in terms of the DALY (disability-adjusted life years) factor (Murray, 1994), developed by the World Bank and the World Health Organization. This considers the number of years lost due to poor health, disability, or early death (World Health Organization, WHO, 2014).

DALY factors were obtained from GABI 6 software database[15] and the Eco-indicator 99 methodology (damage oriented method), which is an LCA weighing method developed by Pre Consultants and published by the Institute of Environmental Science, Leiden University (Goedkoop and Spriensma, 2001). The Egalitarian perspective included in the model was selected because it takes into account the effect of all substances that are suspected to be carcinogenic in the long term (Hofstetter, 1998). This methodology estimates the quantity of years lost due to poor health, disability, or early death, from a modeled exposure to different compounds (Ministry of Housing, Spatial Planning and the Environment of Netherland, 2000). This implies that estimations have a high uncertainty, so results from this section cannot be compared to other studies unless they have used the same methodology.

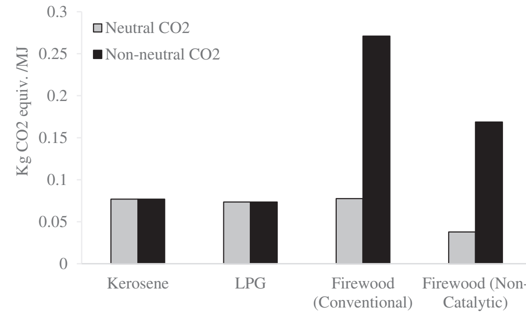


Fig. 3. Global warming potential by type of heater (global level).

Energy poverty[16] was estimated by comparing energy expenditures of Valdivian Households, with the regional income deciles. Energy expenditure considered an average expenditure for heating (based on firewood, kerosene, or LPG),[17] and a minimum expenditure in LPG[18] (cooking and heating water) and electricity (essential appliances and lighting) (Sovacool, 2012), while the income deciles were obtained from the Ministerio de Desarrollo Social de Chile (2011).

We estimate the impact of the firewood market on employment by taking into account all components of the firewood supply chain: producers, transporters, wholesalers, retailers, and related services (input suppliers and service providers). This estimation was performed based on previous works (Burschel et al., 2003; INE, 2007; Medel, 2008; Olivares et al., 2009; Reyes and Frene, 2006).

Results and discussion

Characterization of the residential heating system of Valdivia

Due to climatic characteristics, the residential heating system of Valdivia works during 8 months (April–November)[19] (Reyes and Frene, 2006), consuming 2.5 billion MJ/year (Table 1). This equals to an average primary energy consumption of 63,000 MJ/hh/year, which is very high in comparison to other similar temperate regions in the World. In the south of New Zealand, for example, households consume 14,000 MJ/hh/year, while households in the states of Oregon and Washington consume 28,000 MJ/hh/year, and 48,000 MJ/hh/year in the Province of British Columbia (U.S. Energy Information Administration, EIA, 2009; Isaacs et al., 2010; Natural Resource Canada, 2011). Schueftan and González (2013) estimate that Valdivian consumption could be even higher, reaching 75,000 MJ/hh/year.

This high primary energy consumption is due to the low efficiency of the residential heating system due to several factors: (a) the high water content of the firewood consumed, (b) the low efficiency wood stoves, and (c) the poor thermal insulation of dwellings.

The reason for this high consumption is that 42% of the energy obtained from the combustion process is lost, first, evaporating water, and later, leaking through walls, ceiling, doors, windows, and the

[15] DALYs per kilogram of polluters (from GABI 6): CO_2: 2.1 × 10^{-7}; CO: 7.3 × 10^{-7}; NOx: 8.9 × 10^{-5}; SO_2: 5.5 × 10^{-5}; CH_4: 1.3 × 10^{-8}; PM10: 3.8 × 10^{-4}; N_2O: 6.9 × 10^{-5}; benzene: 4.7 × 10^{-7}; toluene: 1.4 × 10^{-6}; *o*-xylene: 2.2 × 10−6; and other compounds emitted by fuels.

[16] Energy poverty is a multi-dimensional concept that includes elements of access, affordability, quality, reliability, etc. The way as this concept is used in this document considers only the balance between average income and an estimation of energy expenditure. Energy poverty is defined as a state in which families cannot adequately meet all their energy needs. Boardman (1991) proposed that when energy expense overcomes 10% of the family income there is energy poverty. Above this threshold energy spending was considered undue.

[17] This estimation assumes that an average heating consumption permits to maintain homes above 18–21 °C, temperature recommended by the World Health Organization to avoid respiratory diseases and other disorders, especially in children and elder (WHO, 1987).

[18] An LPG consumption of 15 kg per month (US$432/yr) and an electricity bill of 20,000 Chilean pesos per month (US$480/yr) were considered.

[19] Beyond this period, people turn off their heaters (Reyes and Frene, 2006). While this fact does not have consequences for this analysis, because it is based on annual averages, if estimations about heating expenses were made monthly, the energy poverty levels in the city would get worse during the 8-month heating period.

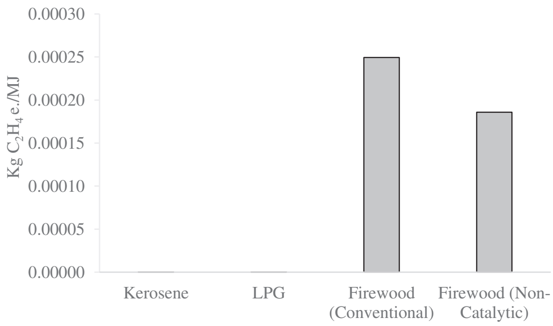


Fig. 4. Smog formation impact by type of energy source (local level).

emission discharge duct. Schueftan and González (2013) estimate that the energy consumption for heating would drop by 62% if dwellings would meet higher standards of thermal insulation. In order to reach this standard, they calculate that an investment of US$3,800 dollars per dwelling is needed.

Environmental impacts

Details concerning the inventory of inputs and emissions of the Life Cycle Assessment are found in Appendix A.

Global warming

The residential heating system of Valdivia annually releases into the atmosphere 94,500 tonnes of CO_2e, when CO_2 is considered carbon neutral (2.2 tonnes CO_2e/hh/year), and 285,000 tonnes of CO_2e when carbon dioxide is not neutral (7.1 tonnes CO_2e/hh/year). This estimate is based on the energy that is effectively used for heating (last column of Table 1), which is the functional unit of this analysis. In all cases, the stage that contributes the most to increases in CO_2 equivalent emissions is the final consumption (more than fuel extraction, transport, and other processes combined).

By comparing the global warming impact of different heaters, with CO_2 neutral, the non-catalytic wood stove has the best performance, with an average of 1.34 tonnes of CO_2e/hh/year (Table 2). Although firewood is assumed CO_2 neutral, the low efficiency of the conventional wood stove implies CO_2 equivalent emissions very similar to those produced by kerosene and LPG heaters. This is because firewood combustion produces high emissions of methane, carbon monoxide, and nitrous oxide (Fig. 3). When biomass is not accounted as carbon neutral, kerosene and LPG heaters have the best performance. The efficiency of wood stoves is a key aspect to reduce CO_2e emissions.

Another factor that increases CO_2 emissions of wood stoves, although less relevant in the total balance, is the low efficiency of firewood transport. While 1 MJ of kerosene requires 0.0194 MJ for maritime transport and 0.0208 MJ for land transport to reach Valdivia, 1 MJ of firewood requires 0.0239 MJ (land transport). Thus, firewood transport consumes the 59% of the energy used in the total transport of kerosene, although it is produced from a distance of only 100 km around Valdivia. This is because of the nature of forest biomass, which contains less energy per unit of weight and volume, and the inefficiency of the vehicles used to transport the wood fuel.

Valdivian households release an average of 35.8 kg CO_2e/m^2/year[20] (carbon neutral estimation), of which 32.8 kg CO_2e/m^2/year come from the final consumption as such, and 3 kg CO_2e/m^2/year from the fuel supply chain (extraction and transport). When CO_2 is not neutral, this value increases to 118.5 kg CO_2e/m^2/year. In order to satisfy heating needs, British households release an average of 35 kg CO_2e/m^2/year (Monahan and Powell, 2011), Norwegian ones between 20 and 50 kg CO_2e/m^2/year (Thyholt and Hestnes, 2008), and New Zealand ones between 15 and 36 kg CO_2e/m^2/year (Camilleri, 2000). In all these countries, residential heating systems are based on fossil fuels so CO_2 emissions are not considered neutral.

[20] Considering an average dwelling size of 60 m^2.

Table 2
Global warming by process and type of heater.

Global warming potential (kg CO_2e./MJ)		Kerosene	LPG	Firewood[a]	
				Conventional	Non-catalytic
Local level	Consumption	684.0×10^{-4}	625.0×10^{-4}	745.0×10^{-4}	355×10^{-4}
Global level	Extraction	39.4×10^{-4}	43.1×10^{-4}		
	Maritime transport	10.3×10^{-4}	11.2×10^{-4}		
	Refining	24.2×10^{-4}	38.6×10^{-4}		
	Land transport	10.9×10^{-4}	16.6×10^{-4}	25.4×10^{-4}	19.1×10^{-4}
	Logging			2.6×10^{-4}	1.9×10^{-4}
	Timber bucking			3.2×10^{-4}	2.4×10^{-4}
	Subtotal global	84.8×10^{-4}	110.0×10^{-4}	31.2×10^{-4}	23.4×10^{-4}
Total		769.0×10^{-4}	735.0×10^{-4}	776.0×10^{-4}	378.0×10^{-4}

[a] Estimate based on carbon neutrality.

Smog formation

The residential heating system of Valdivia releases 255 tonnes per year of C_2H_4 (ethylene) equivalent (only considering local level), which basically come from firewood consumption (Fig. 4). This equals to an average of 5.8 kg of C_2H_4e/hh/year. Conventional wood stoves produce 34% more C_2H_4 equivalent emissions than non-catalytic ones; 13,500 times more than kerosene heaters and 131,000 times more than LPG heaters. That is a huge difference in favor of LPG and kerosene heaters (Table 3).

In general terms, households using conventional wood stoves are releasing into atmosphere an average of 57 kg/hh/year of PM10, 427 kg/hh/year of carbon monoxide, 84 kg/hh/year of volatile organic compounds (VOCs), and 1.4 kg/hh/year of polycyclic aromatic hydrocarbons (PAHs). Non-catalytic wood stoves produce three times less PM10 than conventional ones, and approximately the half of the carbon monoxide, VOCs, and PAHs. By contrast, LPG heaters only emit an average of 0.11 kg/hh/year of PM10, 1.2 kg/hh/year of carbon monoxide, and practically zero VOCs and PAHs.

Forest degradation and deforestation

There is limited evidence on fuel wood production and fuel wood markets beyond ongoing PhD research in the region[21] that suggests that firewood production is not a cause of deforestation but a consequence of agriculture and livestock expansion. This is consistent with what Zamorano et al. (2014) found, where firewood was a by-product of a growing dairy, meat, and cereal production. Therefore, even if the firewood market of Valdivia did not exist, that timber would be burnt on the fields, as it still occurs in some farms when clearing takes place. The absence of a cause–effect relationship between firewood production and deforestation has been also observed in other countries (Bensel, 2008; Bhatt and Sachan, 2004).

Reyes (2004) found that farmers use native forests as a savings account, which is used when other production components fail to generate sufficient income. Therefore, the interannual pressure on native forests varies according to markets' fluctuations: labor market, agricultural market, etc. (Bluffstone, 1995; Amacher et al., 1996; Shively, 2001; Godoy et al., 2005). This in the past has created a pattern of harvesting periods alternating with resting periods, and in the absence of

[21] Reyes, R. Drivers of firewood production for sale in Los Rios Region. PhD thesis. University of British Columbia.

Table 3
Smog formation by process and type of heater.

Smog formation potential (Kg C_2H_4 e./MJ)		Kerosene	LPG	Firewood	
				Conventional	Non-catalytic
Local level	Consumption	0.184×10^{-7}	0.019×10^{-7}	$2{,}490 \times 10^{-7}$	$1{,}860 \times 10^{-7}$

other agents of disturbance, these resting periods allow forests to recover.

It is the case that under certain conditions of isolation and poverty (few off-farm income opportunities, low opportunity cost of labor, and large families), firewood production can produce a real and permanent degradation of forests. However, given the other factors influencing firewood extraction, and the fact that farmers have an economic incentive in maintaining forests, the effect of the firewood market on forest degradation could be treated as carbon neutral and correspondingly without an effect on CO_2 emissions.

Social impacts

Energy poverty

The current residential heating system of Valdivia has an annual cost of 40 million dollars, considering an average firewood price of US$78/m^3, and LPG and kerosene prices of US$2.5/kg and US$1.5/L, respectively (500 Chilean pesos per U.S. dollar). The unitary costs, in terms of primary energy, are US$0.0108/MJ for firewood, US$0.0421/MJ for kerosene, and US$0.0542/MJ for LPG, which implies a significant advantage of firewood in comparison to kerosene and LPG (4–5 times cheaper).

During the last several years, national authorities have proposed to address air pollution problems through the replacement of firewood by kerosene, LPG, and other fossil fuels.[22] If this proposal were successful, annual expenditures on residential heating would increase from the current 40 million dollars to more than 100 million, even considering an efficiency of 100% for LPG and kerosene heaters. On a household basis, this would increase the average heating cost from the current US$623/hh/year (based on firewood only) to US$1,411/hh/year (kerosene) or US$1,817/hh/year (LPG).

This measure would increase the energy poverty levels in the city, while there is a net export of wealth from Valdivia to oil producing countries. Considering an average expenditure in heating of US$623/hh/year (based on firewood), and a minimum of US$912/hh/year for other uses (lighting, cooking, appliances, etc.), 60% of Valdivian households are already classified as energy poor, as they cannot cover the total energy bill with the 10% of their incomes (Fig. 5). If heating were based on kerosene or LPG, this situation would affect 80% of the households. This could get even worse due to the consumption seasonality (Moore, 2012).

Currently, many families use several strategies to reduce their total energy cost. These include the use of low-quality firewood (low density and high humidity), the collection of timber and forest wastes inside and around the City, and obtaining low-cost firewood from relatives living in the countryside among others. These actions lessen the cost for securing energy in Valdivia. Nevertheless, similar actions could not be undertaken if the heating system were based on kerosene or LPG since these fuels are not locally produced.

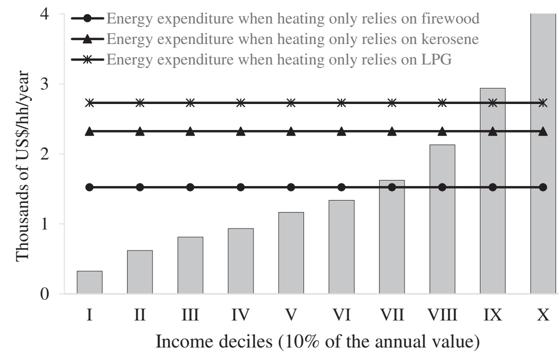


Fig. 5. Energy poverty levels in Valdivia City. Note: *y*-axis represents the total spending on energy in thousands of US dollar per year per household, considering heating and others (lighting, hot water, cooking, appliances, etc.). Bars (*x*-axis) correspond to 10% of the annual income deciles (thousands of dollar per year per household). Source: Own elaboration based on Ministerio de Desarrollo Social de Chile (2011), Reyes and Frene (2006), and Boardmand (1991).

Human health

Considering an average human weight of 70 kg, a life expectancy of 70 years, and a heating system only based on conventional wood stoves (45% of efficiency), Valdivia would have a total burden of disease due to ambient particulate matter pollution from wood fuel of 72,000 DALYs. This equals to 0.47 DALYs/person. Otherwise, if the heating system were based on non-catalytic wood stoves (60% of efficiency), the total burden of disease would decrease to 0.17 DALYs/person, and for the case of LPG and kerosene heaters to 0.013 DALYs/person. This estimation does not include indoor air pollution, where LPG and kerosene heaters (without discharge ducts) would have a higher health impact (Ruiz et al., 2010; Carteret et al., 2013), especially in terms of PM2.5 and carbon monoxide (Prockop and Chichkova, 2007). This is a significant limitation of this study.

Between 2008 and 2014, the 24-h average PM10 and PM2.5 concentrations in Valdivia were 50.7 and 36.4 μg/m^3, respectively (Ministerio de Medio Ambiente, 2015). In this period, the Chilean PM10 and PM2.5 air quality standards[23] were overcame an average of 16 and 83 times (Fig. 6). The data base shows that 2010 was the worse year in terms of PM2.5, with 122 days above the standard. That year was also the worse in terms of ARIs (acute respiratory infections), with 1,113 cases (Secretaría de Medio Ambiente Región de Los Ríos, 2014). The public health system is paying the cost of this situation. According to Gómez-Lobo et al (2006), the social benefit of reducing the concentration of fine particulate material (PM2.5) by 1 μg fluctuates between US$8 and US$34.5/person. This equals to between 1.2 and 5.2 million dollar per year for the Valdivian population.

Nevertheless, it is important to note that the absence of an adequate heating is also related to health issues. According to WHO (1987), indoor temperature should be above 18–21 °C to maintain a healthy life. The combination of low temperatures and high relative humidity, as it is the case in Southern Chile, can be even more dangerous for people's health than the air pollution produced by firewood (Fisher et al., 2007; Howden-Chapman et al., 2009) when the pollution level remains below a reasonable threshold. Thus, a higher energy poverty level is also linked to human health problems, creating a dilemma for Chilean authorities: reducing air pollution without increasing the heating cost.

Employment

Firewood production and commercialization play a very important role, both in rural and urban areas, by creating hundreds of jobs (Burschel et al., 2003). Fig. 7 shows a normal firewood supply chain in southern Chile, where it is possible to observe all players involved in

[22] http://www.revistaei.cl/2014/07/07/gas-podria-representar-mas-del-30-de-la-electricidad-y-reemplazar-la-lena/.

[23] The Chilean standard for both particles points out a maximum of 150 and 50 μg/m^3.

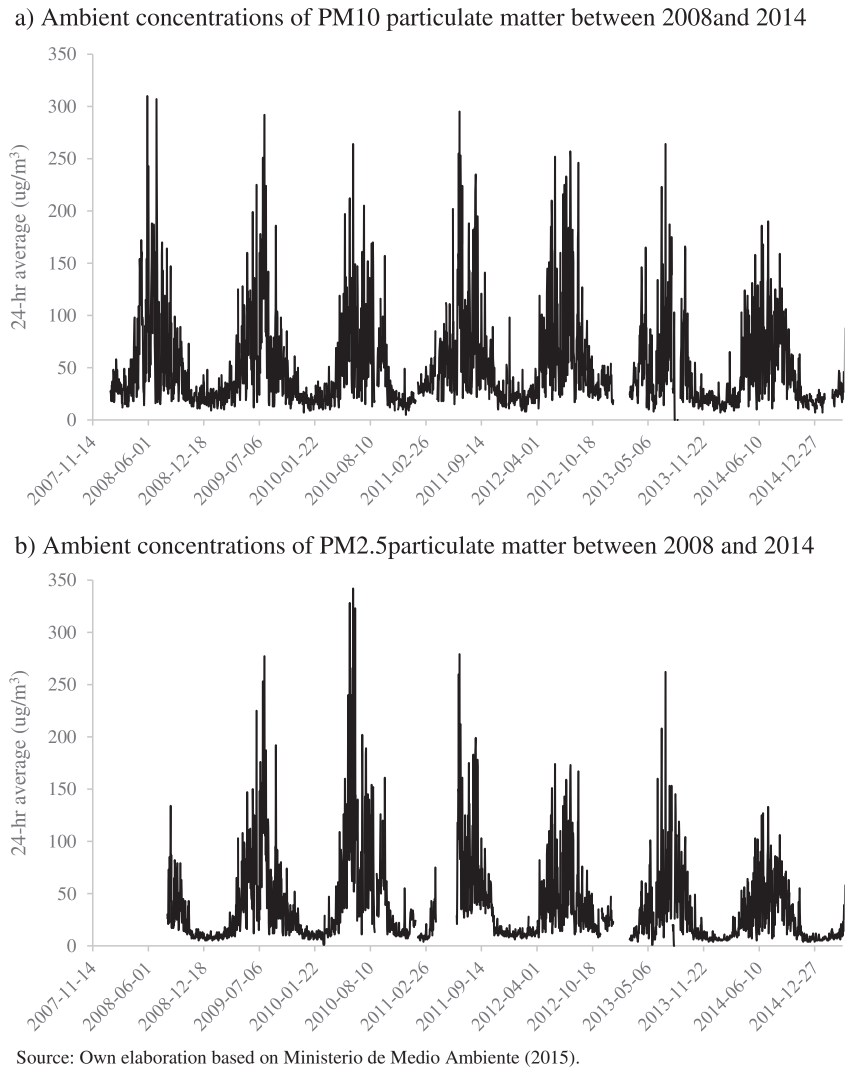


Fig. 6. Particulate matter emissions between 2008 and 2014. Source: Own elaboration based on Ministerio de Medio Ambiente (2015).

the process. According to the last Agricultural and Forestry Census (INE, 2007), there are 2,050 firewood producers in Los Ríos Region, who normally hire people for logging and wood chopping, where half of them would supply the Valdivia's firewood market.

However, it is difficult to know how many traders (transporters, wholesalers, and retailers) are involved in the firewood supply chain of Valdivia as most of them work illegally. However, using the average income of firewood traders (Olivares et al., 2009), it is possible to estimate that approximately 60 wholesalers and retailers, and 150 transporters participate in the supply chain. Transporters, in turn, hire two workers for the loading and unloading of trucks. Another 180 people are involved in the chopping and storage of firewood at homes, while one hundred works around the installation and maintenance of wood stoves and the cleaning of discharge ducts.[24]

A conservative estimation therefore indicates that the use of firewood in Valdivia would be producing around 1,000 fulltime jobs, many of them informal ones, which is relatively high considering that the industrial forest sector, one of the mainstays of the regional economy, produces at a regional level about 9,000 jobs in logging, secondary industry, primary industry, and related services (INFOR, 2010), while the dairy and livestock industries produce about 6,000 (Fantuzzi, 2012).

[24] Estimate based on municipal records and local experts.

Table 4 shows a summary of the main aspects involved in the firewood dilemma.

Conclusions and policy implications

Our results show that alternative fuel sources (LPG and kerosene) do result in lower ambient particulate matter pollution (although they produce a higher indoor air pollution), while non-catalytic wood stoves have approximately half the GHG emissions of the other sources when forest biomass is carbon neutral. Yet only comparing the environmental performance in terms of air pollution and GHG emissions does not provide a more comprehensive assessment of the full effects on human well-being. Proposed firewood substitutes would significantly increase the heating cost and would contribute to higher energy poverty levels in the city, especially when a long-term trend in fossil fuel prices is considered, and this, in turn, would have a negative effect on indoor environmental conditions and peoples' health. There would also be negative economic impacts from reduced demand for firewood, leading to less employment and lower prices for farmers. This may then reduce the incentives for farmers to maintain forest and therefore could lead to increased degradation and deforestation as alternative land uses become more attractive.

Expanding the perspective to consider the broader range of benefits and costs around the use of wood fuel then reframes the choices facing

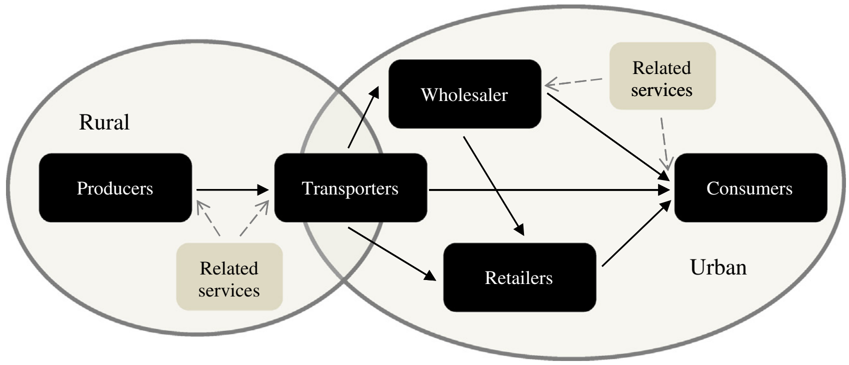


Fig. 7. Firewood supply chain and related services (input suppliers and service providers). Source: own elaboration based on Reyes (2000).

Chilean authorities. The real firewood dilemma is to consider how the negative impacts, such as those associated with air pollution, can be mitigated while enhancing the positive aspects (reduced GHG emissions, contribution to local economies, etc.) of wood fuel and forest biomass use. Indeed, when framed in this way, it points toward considering ways in which the overall heating system itself can be improved, whether it is through improving efficiencies such as addressing individual heating systems and associated technologies, improving distribution systems, or the functioning of wood fuel markets, which can also strengthen local economies and yield environmental benefits. Like many European countries, where wood fuels have become a very important energy source, Chile has the opportunity to take advantage of the high availability of forest resources (native forests and forest plantations) to develop its own path in terms of energy supply and local development, but this will require approaching the issue from a more holistic perspective rather than only focusing on one aspect—human health—and one solution.

At the same time, it is important to realize that in the medium-term air pollution will remain as a significant issue for Valdivia and other southern cities of Chile due to the complexity of the system and the difficulty in changing human behavior, associated with any of these proposed policy interventions. Indeed, in order to address air pollution without increasing the heating cost and energy poverty levels (the firewood dilemma currently facing authorities), there are several steps that could be taken to improve the efficiency of the residential heating system and reduce emissions without necessarily promoting fossil fuel use.

The first of these is independent of energy sources. Investments in improving the energy efficiency of the buildings would reduce energy use and the associated costs, regardless of energy source. According to Fissore and Colonelli (2013), based on field data, the current primary energy consumption for heating could drop by 50% after performing some investments in thermal insulation of dwellings, reaching the average energy consumption for heating of other temperate regions (EIA, 2009; Isaacs et al., 2010; Natural Resources Canada, 2011). Nevertheless, this efficiency gain may not be completely achieved because of the potential for a rebound effect in the primary energy consumption. Hens (2010) and Sorrell et al (2009) point out that a rebound effect of about 30% could be expected after a dwelling refurbishment. Still, taking that into account, considering a dwelling retrofit program applied to all Valdivian households could reduce the primary energy consumption for heating to 37,000 MJ/hh/year and avoid the emission of at least 33,000 tonnes of CO_2 equivalent, 800 tonnes of PM10, 6,000 tonnes of carbon monoxide, 1,200 tonnes of VOCs, and 20 tonnes of HAPs, with a positive impact in indoor temperature and relative humidity, energy poverty, and people well-being (Howden-Chapman et al., 2007).

A one-time measure like that would cost about US$150 million (Fissore and Colonelli, 2013; Schueftan and González, 2013), with annual savings of about US$14 million due to a lower firewood consumption, and a non-determined amount related to the public health system because of a lower air pollution. Such an investment could be targeted, as some Valdivian families can afford the costs of the thermal insulation of their homes; therefore, one opportunity might be to use matching investments or subsidizing loans. Long-term and low-interest-rate loans could be attractive enough for families, as their costs would then be covered by savings in heating, while public funding should be oriented to families in the lower-income deciles.

Second, the replacement of inefficient wood stoves by more efficient ones (based on firewood or even wood-pellets) would further reduce heating costs and emissions, avoiding the burden of higher heating costs associated with fossil fuel energy sources. Considering that 56%

Table 4
Summary of the main aspects considered in the analysis.

Scope	Impact	Description
Environment	Global warming	The heating system based on non-catalytic wood stoves (60% efficiency) emits 50% less CO_2e than kerosene/LPG heaters, when forest biomass is considered carbon neutral. Otherwise, wood stoves have higher emissions, being technology a key aspect to improve its performance (energy efficiency).
	Smog formation	Wood stoves are producing thousands of times more emissions than LPG and kerosene heaters. Therefore, in terms of smog formation and other pollutants, firewood is much more problematic than LPG and kerosene.
	Forest degradation and deforestation	While there is native forest degradation and deforestation taking place around Valdivia, other factors linked to agriculture and livestock expansion, and overgrazing (destruction of natural regeneration due to grazing) are more direct contributor, and there is no clear relationship (positive or negative) on overall degradation or deforestation with the firewood market.
Society	Energy poverty	60% of Valdivian households are already in a condition of energy poverty. In order to relieve this situation, families tend to reduce the heating cost by using several strategies (collecting forest wastes, buying low-quality firewood, etc.). If firewood were replaced by LPG or kerosene, the current heating cost and energy poverty levels would significantly increase.
	Human health	Firewood combustion augments the concentration of particulate material and other toxic compounds, increasing the cases of acute respiratory infections and other problems. However, the absence of an adequate heating is also related to significant human health issues. Therefore, the heating cost is a key factor that should be considered in the analysis.
	Employment	The firewood market in Valdivia City creates approximately 1,000 permanent jobs in production, trade, and related services, in the city and in outside rural areas. This employment is very important when it is compared with other productive sectors, like forestry or livestock, especially for lower-income families.

of wood stoves are conventional ones, a significant reduction in air pollution could be achieved by implementing a replacement of wood stoves program, as it has been reported in other places (Li et al., 2011; Ward et al., 2009). Nevertheless, this process should be carefully implemented because the adoption of new technologies has shown being a challenging process (Allen et al., 2009; Bailis et al., 2007; Hanna et al., 2012; Ruiz-Mercado et al., 2011).

These measures would gradually reduce air pollution in Valdivia. In the long term, given the impacts of air pollution on human health, strategies may switch to consider measures that increase the performance of forest biomass fuels through the use of pellets and other technologies that minimize emissions and development of more efficient delivery systems to reduce emissions, while simultaneously looking for opportunities to create more value for local biomass sources. This offers the most long-term sustainable benefits to the local residents.

More broadly, the Chilean case offers the opportunity to analyze a similar problem facing millions of people around the world, where the growing problems in the production and supply of fossil fuels force us to think of different solutions in how we source and use energy. Our energy systems for the most part have been built upon the supply of inexpensive and widely available fossil fuels; it is in this context that wood fuels—especially for firewood—have traditionally been considered more for subsistence use and as an indicator of low levels of development. Instead of thinking of an "energy ladder" moving away from firewood, however, we could think of the broader contributions forest biomass-based energy systems can make, especially as we expect the costs of these fossil fuels (whether measured in financial or environmental terms) to continue to grow. Through this lens, countries with a high availability of forest resources, strategies, and policies might consider developing a new "biomass ladder" that could involve the development of technologies and the systems in which we source and use that biomass that can contribute significantly to meeting not just energy needs but human well-being as well.

Acknowledgments

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Appendix A. Inventory of inputs and emissions

Inventory of inputs

Stage 1 Logging and chopping timber. Medel (2008) estimates that, on average, a fully loaded chainsaw (0.72 L of gasoline) produces 3.62 m^3 of 1-m-long logs.[25] This is equal to 0.2 L of gasoline per cubic meter of timber (0.00002766 L of gasoline per MJ of timber). Chopping timber (turning 1-m logs in 33 cm pieces; ready for consumption) requires 0.25 L of gasoline per cubic meter (0.00003458 L of gasoline per MJ of firewood) (Medel, 2008).

Stage 2 Transportation. In Chile, almost 100% of oil is imported. Thus, both for kerosene and LPG two transports were considered: between oil producing countries and the Chilean refineries (in the central zone), and between the Chilean refineries and Valdivia city. Due to firewood is locally produced only one transport was considered, between local forests and Valdivia city (Table A.1).

Table A.1
Distances and energy consumption.

Distances and consumptions	Firewood	Crude oil	LPG	Gasoline	Diesel
Average distance from oil producing countries (km)[a]		6,576	3,246	9,426	11,953
Energy intensity of oil vessels (MJ/ton km)[b]		0.0867	0.0867	0.0867	0.0867
Average distance refinery—Valdivia (km)		600	600	600	600
Average distance local forests—Valdivia (km)[a]	97.5				
Fuel efficiency of trucks (km/L)[c]	4.5	2.8	2.8	2.8	2.8

[a] Weighted average of oil imports between 2007 and 2011 (CNE, 2012), and Medel (2008) in the case of firewood.
[b] Oil vessels with a weight of 150,000 tonnes were considered (DWT) (Natural Resources Canada, 2010). It was assumed that vessels carrying LPG have a similar weight and energy consumption than those carrying liquid fuels.
[c] For kerosene and LPG, new trucks with a capacity of 30,000 L were considered. For firewood, old trucks with a capacity of 20 m^3 of firewood (12.8 m^3 solid) were considered. The information about firewood truck efficiency was obtained from firewood traders (average between loaded and unloaded trucks).

According to CNE (2012), between 2007 and 2011, 100% of the kerosene, 43% of the LPG, 81% of the gasoline and 44% of the diesel consumed in Chile was nationally refined. While oil travels an average distance of 6,576 km, LPG (mostly from Argentina), gasoline (Puerto Rico, Canada, and others), and diesel (Puerto Rico, South Korea, and others) travel an average distance of 3,246, 9,426, and 11,953 km, respectively.

According to Table A.1, the oil vessel energy consumption is 0.0867 MJ per tonnes-kilometer. This equals to 0.00040, 0.00019, 0.00059, and 0.00075 L of heavy fuel per MJ of crude oil, LPG, gasoline, and diesel transported to the Chilean coasts, respectively. Considering that a share of these fuels are produced locally from crude oil, the final fuel consumption is equivalent to 0.00040, 0.00028, 0.00044, and

Table A.2
Emissions from extraction and refining of crude oil.

Emissions	Extraction		Refining	
	Kerosene (kg/MJ)	LPG (kg/MJ)	Kerosene (kg/MJ)	LPG (kg/MJ)
CO_2	3.223E−03	3.533E−03	2.200E−03	3.500E−03
CO	1.391E−06	1.525E−06	4.800E−07	7.800E−07
NOx	9.055E−06	9.925E−06	5.500E−06	8.900E−06
SO_2	5.270E−10	5.780E−10	4.430E−05	6.090E−05
CH_4	1.399E−05	1.534E−05	1.900E−07	2.800E−07
PM	0.000E+00	0.000E+00	5.100E−07	8.300E−07

Source: emission factors taken from Lewis (1997).

Table A.3
Emissions related to logging and wood chopping.

Gases	Logging		Wood chopping	
	Conventional (kg/MJ)	Non-catalytic (kg/MJ)	Conventional (kg/MJ)	Non-catalytic (kg/MJ)
CO_2	1.319E−04	9.889E−05	1.651E−04	1.239E−04
CO	4.756E−05	3.567E−05	5.978E−05	4.484E−05
NOx	1.273E−06	9.545E−07	1.598E−06	1.199E−06
SO_2	2.052E−07	1.539E−07	2.521E−07	1.891E−07
CH_4	2.802E−08	2.102E−08	3.406E−08	2.554E−08
TOC	2.300E−06	1.725E−06	2.890E−06	2.168E−06
PM	1.98148E−09	1.48611E−09	2.40824E−09	1.80618E−09

Source: emission factors from EPA (1996).

[25] Solid cubic meter; 1 m^3 solid = 1.5625 m^3 bulk (stacked firewood with air between spaces).

Table A.4
Emissions related to transport.

Gases	Oil vessels			Tank trucks		
	Kerosene (kg/MJ)	LPG (kg/MJ)	Kerosene (kg/MJ)	LPG (kg/MJ)	Firewood (kg/MJ)	
					Conventional	Non-catalytic
CO_2	1.013E−03	1.102E−03	1.063E−03	1.627E−03	2.484E−03	1.863E−03
CO	2.225E−08	2.420E−08	2.959E−08	4.528E−08	6.912E−08	5.184E−08
NOX	1.589E−07	1.729E−07	2.378E−07	3.639E−07	5.555E−07	4.166E−07
SO_2	8.849E−07	2.489E−07	8.849E−07	1.354E−06	2.067E−06	1.550E−06
CH_4	2.960E−07	3.066E−07	2.652E−07	4.058E−07	6.195E−07	4.646E−07
PM	9.646E−09	3.477E−09	9.646E−09	1.476E−08	2.253E−08	1.690E−08
N_2O	2.416E−08	2.628E−08	2.746E−08	4.201E−08	6.413E−08	4.810E−08

Source: Emission factors from EPA (1996).

0.00059 L of heavy fuel per MJ of kerosene, LPG, gasoline, and diesel, respectively.

In the case of the land transportation, 430 L of diesel are required to travel 1,200 km round trip between refineries and Valdivia city. This amounts to 0.00040 and 0.00056 L of diesel per MJ of kerosene and LPG, respectively. On the other hand, 43 L of diesel are required to travel 194 km (round trip) and deliver 12.8 m^3 of firewood, which equals to 0.00046 L of diesel per MJ of firewood transported.

Inventory of emissions

Stage 1 Extraction and refining of crude oil. The emissions factors were taken from Lewis (1997) assuming a simple refinery. These emissions result from the combustion and venting of gases related to the refining and production of 1 MJ of fuel (Table A.2).

Stage 2 Logging and chopping timber. Related emissions are presented in Table A.3. Emission factors for both types of wood stoves were taken from EPA (1996). Emissions related to extraction, refining, and transportation of gasoline (chainsaw) were included. It is important to note that conventional stoves produce higher emissions per MJ of firewood combusted, due to their lower efficiency (EPA, 1996).

Stage 3 Maritime and land transports. Related emissions are displayed in Table A.4. Extraction, refining, and transport, both from the consumption of heavy fuel in oil vessels and diesel in tank trucks, are also included.

Stage 4 Consumption. Related emissions are presented in Table A.5, where CO_2 emissions coming from forest biomass were considered zero (emissions related to transport were taken into account in the previous stage. Thus, what is considered neutral in this stage is only the carbon dioxide produced during combustion). Yet, a similar estimate was done when forest biomass is not considered carbon neutral, but it is not presented in this table.

Table A.5
Emissions related to fuel consumption.

Gases	Combustion			
	Kerosene (kg/MJ)	LPG (kg/MJ)	Firewood[a] (kg/MJ)	
			Conventional	Non-catalytic
CO_2	6.602E−02	5.873E−02	0.000E + 00	0.000E + 00
CO	1.535E−05	3.524E−05	1.275E−02	5.832E−03
NOx	5.528E−05	6.108E−05	1.546E−04	1.160E−04
SO_2	1.744E−05	8.457E−08	2.209E−05	1.657E−05
CH_4	5.466E−06	9.397E−07	1.657E−03	6.627E−04
PM	1.228E−06	3.289E−06	1.690E−03	6.047E−04
N_2O	1.535E−07	4.229E−06	1.657E−05	1.243E−05
TOC	7.656E−06	4.699E−06	2.927E−03	4.970E−04
Benzene	6.572E−10		1.070E−04	8.027E−05
Toluene	1.904E−08		4.031E−05	3.024E−05
o-Xylene	3.347E−10		1.116E−05	8.366E−06
Cadmium	1.222E−09		1.215E−09	8.284E−10
Chromium	2.595E−09		5.522E−11	4.142E−11
Manganese	9.213E−09		9.388E−09	5.799E−09
Nickel	2.595E−07		7.731E−10	8.284E−10
Ethane			8.118E−05	6.088E−05
Ethylene			2.480E−04	1.860E−04
Acetylene			6.207E−05	4.655E−05
Propane			1.977E−05	1.483E−05
Propene			6.870E−05	5.152E−05
i-Butane			1.546E−06	1.160E−06
n-Butane			3.093E−06	2.319E−06
Butenes			6.583E−05	4.937E−05
Pentenes			3.402E−05	2.551E−05
Furan			1.889E−05	1.417E−05
Methylethylketone			1.602E−05	1.201E−05
2-Methyl furan			3.623E−05	2.717E−05
2,5-Dimethyl furan			8.946E−06	6.710E−06
Furfural			2.684E−05	2.013E−05

Source: emission factors taken from EPA (1996).
[a] CO_2 emissions were considered zero.

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