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Private Benefits from Ambient Air Pollution Reduction Policies Evidence from the Household Heating Stove Replacement Program in Chile

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Private Benefits from Ambient Air Pollution Reduction Policies: Evidence from the Household Heating Stove Replacement Program in Chile[1]

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Abstract

We estimate the key private benefits from a program to improve ambient air quality during winter in central Chile by replacing inefficient wood-fired home heating stoves with more efficient pellet stoves. We are interested in the private benefits to households because they represent the additional value of the program and likely drive private adoption. Combining electronic stove surface temperature and air pollution monitoring with household surveys, we estimate the effects of adoption on household fuel expenditures, indoor temperatures, and indoor air pollution concentrations ($PM_{2.5}$). We also explore heterogeneous effects of the program by income group and energy poverty status. Our results suggest that, after controlling for observable characteristics of individuals and dwellings, users of pellet stoves on average enjoy 14% lower indoor $PM_{2.5}$ concentrations compared with those who have traditional stoves. Lower-income and energy-poor households receive much greater than average improvements in indoor air pollution than those with higher-incomes, driving the overall sample estimate and indicating that the program is progressive in this dimension. While those who use more efficient pellet stoves have more stable indoor temperatures than those using traditional stoves, we find no differences in mean temperatures. The improved heating stove has significantly higher operating costs, and we find that these costs are most salient for low-income and energy-poor households.

Keywords: Air pollution; energy transition; environmental policies; household behavior; heating; stoves.

JEL Codes: C21, Q48, Q52, Q55, Q58

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Private Benefits from Ambient Air Pollution Reduction Policies: Evidence from the Household Heating Stove Replacement Program in Chile

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Abstract: We estimate the key private benefits from a program to improve ambient air quality during winter in central Chile by replacing inefficient wood-fired home heating stoves with more efficient pellet stoves. We are interested in the private benefits to households because they represent the additional value of the program and likely drive private adoption. Combining electronic stove surface temperature and air pollution monitoring with household surveys, we estimate the effects of adoption on household fuel expenditures, indoor temperatures, and indoor air pollution concentrations ($PM_{2.5}$). We also explore heterogeneous effects of the program by income group and energy poverty status. Our results suggest that, after controlling for observable characteristics of individuals and dwellings, users of pellet stoves on average enjoy 14% lower indoor $PM_{2.5}$ concentrations compared with those who have traditional stoves. Lower-income and energy-poor households receive much greater than average improvements in indoor air pollution than those with higher-incomes, driving the overall sample estimate and indicating that the program is progressive in this dimension. While those who use more efficient pellet stoves have more stable indoor temperatures than those using traditional stoves, we find no differences in mean temperatures. The improved heating stove has significantly higher operating costs, and we find that these costs are most salient for low-income and energy-poor households.

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Private Benefits from Ambient Air Pollution Reduction Policies: Evidence from the Household Heating Stove Replacement Program in Chile

1. Introduction

Air pollution control policies seek to reduce ambient air pollution levels and generate public benefits, such as reduced premature mortality (Lelieveld et al., 2015), less acid rain (Grennfelt et al., 2020) and lower greenhouse gas emissions (Allen et al., 2018). Therefore, the raison d'être for air pollution policies is to produce shared rather than privately appropriated air quality benefits. This is certainly the case in south and central Chile, which is attempting to improve ambient air quality by reducing small particle emissions from biomass combustion by small residential heating sources.

Reducing small, residential non-point air pollution sources is believed to be critical to reducing excess human mortality from outdoor air pollution. Leilieveld et al. (2015), for example, estimate that outdoor air pollution emissions of fine particles ($PM_{2.5}$) and ground-level ozone (O_3) kill approximately 3.3 million people per year, and about one-third of those deaths are due to biomass burning in residential heating and cooking sources, mainly in Asia, but also in Africa and South America. Biomass stoves are also major sources of black carbon, which is a short-lived but potent greenhouse gas (Bond et al., 2013). On a global scale, curbing outdoor air pollution from inefficient residential biomass stoves is therefore a critical international issue.

Biomass burning for cooking is most common in low-income countries, where such fuels may make up well over 2/3 of primary energy usage. For example, IEA (2020) estimates that three-quarters of the energy used in Sub-Saharan Africa – mainly for cooking - comes from biomass, and without major policy changes an overwhelming majority of people will rely on biomass fuels for the foreseeable future. Households in temperate regions, which generally have higher incomes, also often rely on biomass, though these fuels are mainly used for heating. The 2009 European Union Renewable Energy Directive required member states to derive 20% of their energy from renewable sources by 2020, and offered incentives to convert fossil fuel heating systems to biomass. In a comprehensive review, Miguez et al. (2012) find that the European Union alone had 186 companies producing 995 different biomass stoves and boilers with capacities less than 200 kW (more than 80% from Germany and Austria). Such stoves use a variety of fuels and have technical specifications that affect performance, which can vary air pollution emissions by several orders of magnitude (Johansson et al., 2003).

Reducing outdoor emissions from residential sources can offer not only improvements in ambient air quality, but can also potentially generate private benefits that accrue to households. Examples of such possible benefits include better indoor air quality (Wyss et al. 2016; Ward and Noonan 2008; Noonan et al. 2012), possibly lower fuel costs, if combustion becomes more efficient (Wassie and Adaramola 2021), higher average and more stable room temperatures and better overall performance (Howden-Chapman et al. 2009; Buso et al. 2017).

It is important to consider the private benefits of biomass emission reductions, because households make adoption decisions, and high levels of private benefits have been found to spur regular use of improved biomass stoves (Jeuland and Pattanayak, 2012; Mobarak et al., 2012). Indeed, Boso et al. (2019) find that in Chile reducing indoor air pollution (IAP) is a critical reason households adopt improved biomass stoves.

Access to high quality energy is not equally distributed within or across countries, with the poor tending to use less, lower quality, more polluting fuels for cooking and heating and obtaining fewer services from those fuels. This so-called “energy poverty” is most pronounced when comparing households across countries with very different per capita income levels (Rockefeller

Foundation, Undated; Jeuland et al., 2021), but energy poverty exists everywhere in the world (Bouzarovski and Petrova, 2015; Kelly et al., 2020), with significant within-country variation (Bouzarovski et al., 2012).

In this paper, we present the results of field research to estimate the key private benefits from a program in central Chile to replace inefficient wood-burning home heating stoves with more efficient pellet stoves.[1] Though the goal of the stove replacement program is to improve ambient air quality, which is a critical problem in southern and central Chile (Chávez et al., 2011; Reyes et al., 2015; Schueftan et al., 2016; Gomez et al., 2017; Jaime et al., 2020), we find that the program also reduces indoor air pollution (IAP), measured as the one-hour household-averaged $PM_{2.5}$ concentration, by an average of 14%. Critically, we find that lower-income and energy-poor households receive a substantially greater reduction in IAP than those with higher-incomes, which suggests that such programs can help disadvantaged households.

We also find that households who adopt the technology have more stable indoor temperatures (i.e., lower variance) during the hours when stoves are in use, which may increase comfort (Li et al., 2020), but average indoor temperature is not affected by switching to more efficient heating technologies. Finally, we estimate that adoption of the improved heating stove is more costly for households, increasing fuel costs by an average of about $1.40 per day regardless of income level. As a $1.40 increase is more salient for low-income and energy-poor households, we find that the improved biomass heating technology is not progressive with regard to cost.

The paper proceeds as follows: Section 2 discusses the study area and key literature on adoption and use of improved biomass cooking and heating technologies. We also provide an overview of the key issues related to air pollution and biomass stove replacement in southern and

[1] Please see Figures A1 – A3 for photos of pellet heating stoves distributed in central Chile, as well as the stoves they typically replace.

central Chile. Section 3 presents the details of our field research design. Section 4 discusses the empirical strategy. Section 5 presents the results. Section 6 concludes and discusses the key implications of our findings.

2. Key Literature and the Study Area

In addition to a reduction in unhealthy outdoor air pollution, residential polluters in Chile may receive private benefits from adopting technologies that reduce ambient air pollution. For example, due to more efficient burning, those adopting improved biomass cooking and home heating technologies may use less fuel which reduces costs (Bensch and Peters, 2015; Ludwinski et al., 2011). They may also experience reduced indoor air pollution which may enhance child development (LaFave et al., 2021). On a worldwide basis, IAP is estimated to result in the premature deaths of over 4 million people per year, mainly in lower-income countries (Lim et al., 2012) and recent estimates suggest that willingness to pay to reduce IAP in China, and perhaps other middle income countries, is significant (Ito and Zhang, 2020). Advanced biomass heating stoves, such as pellet stoves, not only offer lower outdoor emissions, because of higher efficiencies (Miguez et al., 2012), they may also reduce IAP, because of lower fuel use and the combustion chamber not having to be opened every time they are refilled with fuel.

Adopting more efficient biomass heating technologies, potentially along with building insulation, may offer higher and more stable indoor temperatures, which is an important aspect of reduced energy poverty in colder regions. Indoor temperatures may be affected using pellet stoves, because they are controlled electronically, offering users more control, to maintain temperatures and reduce variability.

Healy and Clinch (2002) find that two-thirds of those with inadequate access to energy in Ireland have chronic exposure to low ambient indoor temperatures, potentially leading to a physiological condition called “cold strain,” which is linked to energy poverty, illness and even mortality; they find that the homes of half of all the elderly had low indoor temperatures during winter. Milne and Boardman (2000) note that about 30% of the efficiency improvements from a building insulation program in the UK were translated into increased temperatures. In recent studies conducted in Chile, over two-thirds of households did not achieve an average indoor temperature of 21 degrees Celsius (Reyes et al., 2019), and significant portions did not even achieve 15.25 degrees Celsius (often called the lower comfort limit or LCL) for 65% of the winter period, leading to higher self-reported illness and medical expenses (Porras-Salazar et al., 2020). These findings and other literature (e.g., Buso et al., 2017; Fang et al., 2012; Healy and Clinch, 2002) suggest that especially for energy-poor households in colder areas of the world, comfortable indoor temperatures are significant benefits of improved heating and better insulation.

In central Chile, which is the setting for this study, inefficient home heating is a critical driver of poor ambient air quality (Celis et al., 2004, 2006; Chávez et al., 2011; Gómez et al., 2014), and is responsible for as much as 94% of $PM_{2.5}$ emissions in some cities (IQAir, 2021). The top three most polluted cities in Latin America, as measured by average annual $PM_{2.5}$, are in Chile (IQAir, 2021) and the Chilean government estimates that more than 9 million inhabitants (48% of the population) are exposed to poor air quality. Around 3,600 people die in Chile each year from cardiopulmonary diseases associated with chronic exposure to air pollution, the majority in central and southern Chile (Ministry of Environment [MMA], 2014; 2019).

Chile also has significant issues with energy poverty, which Urquiza et al. (2019) argue are primarily related to the quality of energy services rather than access. Using multidimensional indices, they find that 12% - 15% of households in Chile are energy poor, which corresponds with the results of other studies (e.g., Villalobos et al., 2021). The outcome variables we examine in this paper, energy costs and fuel consumption, comfort related to indoor temperatures during winter, as well as IAP, have all been highlighted as key aspects of energy poverty in Chile (e.g., see Schueftan et al., 2016).

The Government of Chile has developed a strategy to reduce air pollution in urban areas caused by households that burn wood for heating. Since 2011, the Ministry of Environment (MMA) has replaced over 51,000 inefficient stoves in more than 30 cities at a cost of more than $85 million (MMA, 2020). This policy is regarded as a central element of national air pollution control plans (DIPRES, 2019).[2] The replacement programs, which are open to all income levels, promote a variety of technologies using several different subsidy schemes. Appendix A provides details on the national stove replacement program and the number of stove replacements by type of technology/fuel between 2011 and 2019.

Despite its policy centrality and scope, there is limited evidence regarding the effects of promoting improved heating stoves in Chile. Key exceptions include Ruiz-Tagle and Schueftan (2021) and Mardones (2021), who examine metrics that are related to the hypotheses we test. Although offering important insights, none of these evaluations analyze the effect of the stove program on the outcomes that are central to our analysis or evaluate the implications of heating stove replacements for energy poverty.

Our study significantly extends the limited existing literature. In the remainder of the paper, we derive causal effects of a stove replacement policy implemented in Talca, which is in central Chile, on fuel costs, IAP, and indoor temperatures. To our knowledge, this study is one of

[2] Policies to reduce air pollution from wood heating stoves in Chile include subsidies for adoption of cleaner and more efficient heating technologies and for retrofitting, enforcement of fuelwood quality standards, and restrictions/bans on burning wood for heating during critical pollution days during winter.

the first causal analyses of the key private benefits heating stove replacements offer those who make the adoption decisions that are critical to air quality in Chile and around the world.

3. Research Design

3.1 Introduction to Research Goals and Implementation of the Stove Program in Talca

The objective of our field research is to estimate the key private benefits generated by a program to replace inefficient wood-burning heating stoves with more efficient pellet stoves. In this section, we describe our population, sampling, assignment of households to treatment, the procedures we follow for the intervention and collection of field data, and our questionnaire.

We conducted our field research in the city of Talca, the capital of the Maule region in central Chile. This city has a population of about 210,000 people, with approximately 50% of households in the city using wood as a source of energy (Jaime et al., 2020). This city has been declared a "saturated area" by the MMA, implying that air pollution is a major policy problem. The stove replacement program in Talca provides around 1,300 replacement subsidies each year and is open to all income levels. Pellet stoves make up approximately 90% of the total subsidy value.[3] The widespread acceptance of this technology is driven by its enhanced caloric power, compared with other cleaner technologies offered by the program.

Each year MMA published application instructions and selection criteria and invited applications via social media. Applicants had to fill out a questionnaire, which included information on (*i*) household members, (*ii*) type of traditional stove[4], (*iii*) dwelling characteristics

[3] At the time of data collection, the program was in the fifth year of a ten-year program. Stove replacement programs in Talca and the nearby town of Maule were promoting pellet stoves as the main technology to replace old wood burning heating stoves. During 2019, 1,322 households received 1,082 subsidies for pellet stoves and 240 for kerosene stoves (https://calefactores.mma.gob.cl/region/9).

[4] Stoves are divided into three categories: 1) one or two chamber; 2) homemade and 3) "salamander" stoves. The salamander stove is a traditional small metal-lined stove with only one main combustion chamber. These stoves are classified as low-efficiency and high-emission stoves. Salamander stoves have similar characteristics to the Franklin stove or the potbelly stove. Please see Appendix A for a photo.

and (*iv*) location, which were then used as selection dimensions. MMA assigned points based on criteria applied to each of these four dimensions. For example, all else being equal, households in more polluted areas received more points, as did those with less efficient baseline stoves and larger household sizes. Subsidies were distributed to those who scored the most points, until the budget was exhausted. Only applications with high scores were accepted for funding, and in this regard successful applicants were like each other. Appendix A details the selection process and offers pictures of stoves and typical houses.

3.2 Population, Sampling and Assignment to treatment

To conduct our field study, we used a list of 3,290 households participating in the stove program in Talca during 2019 and 2020. From this list, 898 households received a pellet stove in 2019, and 2,029 households were applicants for a pellet stove in 2020. During July 2020 we drew a random sample of 169 households that had received the subsidy for a pellet stove in 2019 and had the new technology in place at the time of the study. These households were defined as our treatment group. We also randomly drew a control group, which consisted of 156 households who had applied for a pellet stove subsidy in 2020 and at the time of our data collection in August/September 2020 were still using their traditional stoves.[5] There was little change in selection criteria across the two years, making the treatment and control groups similar based on program selection criteria.

In sum, our treatment households were those who in 2019 received sufficient points when they applied for the program to be selected for a subsidy and by the time of our sample selection and data collection had a pellet stove installed in their homes and no traditional wood stove.

[5] This sample size was chosen to achieve a power of 0.80 and to identify a minimum detectable effect of at least a 14% reduction in indoor $PM_{2.5}$ concentration.

Control households applied for the 2020 round subsidy, met the selection criteria, and were waiting for notification that they were beneficiaries. At the time of the data collection in July/August 2020, these households were still using their traditional stove and did not yet have a pellet stove.[6] The official MMA selection criteria and points by criterion for 2019 and 2020 are provided in Appendix A.

These data were collected during the the COVID-19 pandemic in central Chile. We therefore contacted households and gathered any survey data by mobile phone using mobile phone numbers provided by the local office of the MMA and a local company (QSE), which was responsible for implementing the stove replacement program in Talca. QSE was also trained by the research team to collect the on-site measurement data used in this study. Appendix B provides details about participants in our study distributed across the city of Talca, the timing of the visits, the devices used, and the COVID-19 safety protocols followed.

All randomly sampled households accepted the invitation to participate in the study (i.e., there were no refusals) and all respondents provided written informed consent. COVID-19 protocols recommended by the Ministry of Health and the Ministry of the Environment were strictly followed by QSE to ensure protection of respondents, the research team and QSE staff members. Households agreed to be visited and to follow these protocols.[7]

Though treatment and control households were similar in selection criteria, it is possible that there were differences within individual scoring categories. We therefore test for balance using detailed household information received from the local office of MMA, which included household

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[6] Although we acknowledge that our design based on whether households had a replacement stove involved self-selection, the objective, applicable-to-all 2019 treatment assignment criteria followed by MMA in Talca were such that households were comparable with regard to the selection procedure.

[7] During the 2020 field research, the city of Talca was not in a total lockdown as was the case in other cities in Chile. According to regional authorities, the city of Talca had 1,863 inhabitants infected with COVID-19 on August 13, 2020; by the end of the field work, on September 13, 2020, this number had increased to 2,688 people. This infection rate represented 1.3% of the population in the city.

and dwelling characteristics. As shown in Appendix C, we compare the treatment and control groups based on 13 variables divided across the above categories, which could potentially be related to selection into the treatment (i.e., received a stove in 2019). We find that only household size is associated with assignment to treatment at the 5% significance level, suggesting a very high degree of balance across the treatment and control groups. We nevertheless include household size as a control in all models unless household fixed effects are used.

3.3 The intervention

We visited households twice during the period August 13, 2020, to September 13, 2020. During the first visit, informed consent was obtained, and electronic sensors were installed to measure 1) indoor temperature (ambient and stove surface); 2) outdoor temperature and $PM_{2.5}$ and 3) indoor $PM_{2.5}$. A two-page form like those used in a standard kitchen performance test was given to households to record fuel consumption during the 48-hour measurement period. $PM_{2.5}$ and temperature monitoring devices were installed in the living room, where stoves were placed, as well as outside. To measure stove usage, we employed iButton temperature loggers with a measurement range from 0°C to +125°C (model DS1922T), which recorded stove surface temperatures every hour over a 48-hour period.[8] During the second visit, we removed all measurement equipment and collected the completed fuel log form.

[8] The air quality sensors were assembled using the open-source electronics platform Arduino. It includes a PM sensor model SDS011 Nova Fitness, and a DTH22 temperature-humidity sensor. Both devices are joined to an Arduino Uno microcontroller using a data shield that has a SD memory card and a real time clock. An external battery (10.000 mAh) was included to make this device independent of other sources of energy in the household. The battery runs continuously for 50 hours. The data collected by SUMs were processed using the Platform for Integrated Cookstove Assessment (PICA) developed by the Berkeley Air Monitoring Group.

In sum, during these visits, we measured $PM_{2.5}$ concentrations (inside and outside), number of hours the stove was used based on surface temperature, fuel consumption, and air temperature (inside and outside). We also asked households to write down whether they were using another stove in the same room, which might impact our measurements, and to note whether problems arose during the measurement period.

In addition to the household visits, we conducted a mobile phone (due to COVID-19) survey of respondents. The survey took about 20 minutes and the questionnaire had four sections. The first section collected general information necessary for the study. The second focused on characteristics of the heating stove, fuel consumption (including costs) and use of the heating equipment. The third part of the questionnaire gathered information on dwelling characteristics, including descriptions of building materials, year of construction or renovation and descriptions of windows, walls, and insulation. The last section collected data on characteristics of household members. [9]

4. Empirical Strategy

4.1 Effects on Indoor Air Quality and Temperature

We estimate the effects of using pellet stoves on indoor air quality and temperature using fixed-effects panel data regression models. Because our monitoring devices were started at different times, our panel is unbalanced. Our main specification is as follows:

$$Y_{it} = \alpha ON_{it} + \mu\, PELLET_i\, ON_{it} + X_{it}\beta + g_d + s_p + c_i + \varepsilon_{it} \quad i = 1,\ldots,325;\ t = 1,\ldots,749 \qquad (1)$$

[9] Survey instruments (questionnaires and logging forms) (in both English and Spanish) to collect household level information necessary for the study are available as an online supplement at https://osf.io/4xkma/.

where Y_{it} denotes the outcome variable (i.e., IAP or indoor temperature), i denotes the household, t represents the hour of each measurement, ON_{it} is a dummy variable that denotes whether the stove was operated during the measuring period t, $PELLET_i\,ON_{it}$ is an interaction term denoting whether a pellet stove was operated during the measuring period t, X_{it} is a vector of explanatory variables, including log of outdoor temperature, log of outdoor $PM_{2.5}$ and whether a second stove was used (from self-report annotations). We also control for household size when appropriate. The "outdoor" variables are included as controls to adjust for the ambient environment, which could affect indoor measurements via infiltrations. We include g_d to denote day fix effects (31 days), s_p for period of the day fix effect (4 periods per day: 0.00–6.00; 6.00–12.00; 12:00–18:00; 18:00–24:00), and c_i for households' time-invariant unobserved effects. α, μ, β are parameters to be estimated, and ε_{it} are idiosyncratic errors.

We are primarily interested in the estimates of μ, which capture the average treatment effect of the stove replacement program on the outcome variables. As our study was conducted in the central Chile winter, when all houses require heat, our baseline comparator controls for whether any stove is in operation as measured by our iButtons. We are therefore only interested in μ and not ($\alpha + \mu$). Variable definitions and expected signs of the estimated parameters are presented in Appendix C.

4.2 Effects of the Treatment on the Variance of Indoor Temperature and Fuel Consumption

We analyze the effect of the pellet stoves on the cost of fuels and the variance in indoor temperature during the hours that the stoves were in use. For both outcomes, we estimate cross-sectional models according to the following specification:

$$Z_i = v\,PELLET_i + X_i\,\gamma + \sum_{\{j=1,..,4\}} \theta_j * Di + d + \eta_i\,, \quad i = 1,\ldots,325 \qquad (2)$$

where Z_i is the outcome variable for household *i* , and $PELLET_i$ is a dummy variable equal to one if a household received a pellet stove in 2019, and zero otherwise. X_i is a vector of explanatory variables, including reported or measured hours stoves were used, whether a second stove was used, household size, and whether households had wall and/or ceiling insulation. These variables are included because they affect fuel use, fuel costs and variance in temperatures independent of whether the household used pellet stoves. D_i is a set of dummy variables controlling for week-invariant unobserved effects, v, γ and θ_j are parameters to be estimated, d is the constant term, and η_i are idiosyncratic errors. We are mainly interested in the parameter v, which denotes the average effect of the replacement program, measured as intent to treat, on the outcome variables. Control variable definitions and expected signs are presented in Appendix C.

5. Results[10]

5.1 Descriptive Statistics

Table 1 presents descriptive statistics of outcome variables by treatment status. Descriptive statistics of controls can be found in Appendix C. For the group with traditional stoves (i.e., our control group), the mean $PM_{2.5}$ concentration during our measurement period is higher than for the group with pellet stoves (i.e., our treatment group) (23.69 vs 19.41, $p < 0.01$), but there is no difference in mean temperature (18.41 vs. 18.37). The variance in temperature experienced by traditional stove users is greater than for pellet stoves (3.61 vs 2.56, $p < 0.05$), though the main heating stove is used about 38% of the time by both groups. Second stoves are used 2% and 6% of the time for treatment and control groups, respectively, suggesting that those with traditional

[10] Data, statistical code, and outputs are available as an online supplement at https://osf.io/4xkma/.

stoves are three times more likely to use second stoves. Average fuel consumption costs during the 48-hour measurement period are lower for traditional stove users than for those with pellet stoves (Ch$ 1,786.1 vs Ch$ 4,001.9, $p < 0.01$).[11]

Figure 1 in the upper left corner shows the mean indoor $PM_{2.5}$ concentration during each hour of the day over the whole period of our study for treatment and control households. In both groups, from 00.00 to 12:00 hours, the concentration remains mostly below 20 μg/m^3. During the afternoon hours it is around 20 μg/m^3, and then increases from 17:00 until 23:00 hours, reaching around 40 μg/m^3, which is substantially above the WHO 24-hour guide value of 15 μg/m^3. Average indoor $PM_{2.5}$ concentrations are higher for those with traditional stoves compared with treatment households from 9:00 onward. The bottom left figures in the table are the mean indoor temperature during each hour of the day. We do not find differences in mean temperatures across treatment and control groups. As shown in the figures bottom right, during the hours that the stoves were in use, the variance in temperature for pellet stoves was lower than for traditional stoves. The figures in the upper right of the table suggest that fuel consumption costs during the 48-hour measurement period are, on average, higher for pellet stove users.[12]

5.2 Effects of the Stove Replacement Program on Indoor Air Quality and Temperature

Table 2 presents results of fixed-effects regression models for indoor air pollution and indoor temperature. We identify a statistically significant average reduction of 14% in indoor $PM_{2.5}$ concentration for users of pellet stoves, compared with households operating traditional stoves.

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[11] At the time of our study the exchange rate was US$1 = Ch$790.

[12] Prices for fuel are self-reported in the survey. Fuel consumption is based on logs of kitchen fuel type, collected using the logging form. Based on this information, we find that firewood users paid on average Ch$ 106.3 (about US$ 0.14) per kilogram of fuel, with a standard deviation of Ch$ 68.4 (US$ 0.09), which is 0.64 times the mean. Pellet users paid a mean of Ch$ 200.70 (about US$ 0.26) per kilogram (with a standard deviation of Ch$ 19.7 (US$ 0.03) (0.1 times the mean). Energy content per kilogram differs by fuel type.

At the control group mean, this implies that having a pellet stove reduces average indoor $PM_{2.5}$ concentrations by 3.32 μg/m^3, or from a control mean of 23.69 μg/m^3 to 20.37 μg/m^3 We do not find statistically significant differences in indoor air temperature for those using pellet stoves, indicating that on average households do not increase temperatures after receiving improved stoves.

Not surprisingly, we find that due to infiltration outside air pollution and temperature positively affect indoor air pollution and temperature respectively, as does using a second stove. As robustness checks, we run simple OLS models, apply a Mundlak (1978) adjustment to random effects models (Imbens and Wooldridge, 2007) and also use propensity score matching. These results are presented in Appendix F and we show that they are fully consistent with those in Table 2.

5.3 Effects on Variance in Indoor Temperature and Total Fuel Cost

Table 3 shows the cross-section estimates for variance in indoor temperature (Column 1) and fuel costs (Column 2). In addition to the control variables, both models also include a set of week dummy variables, which indicate the week households were visited. These variables allow us to control for special weather conditions and ambient air pollution regulations in place at the time each household was measured over the data collection period. Columns (3) and (4) present models for monthly and annual costs of operating the heating stoves based on data from our household survey.

We find that, compared with using a traditional heating stove, having a pellet stove decreases the variance in temperature during the hours that the stoves are in use and increases the cost of heating homes. Those who have pellet stoves experience almost one standard deviation less variance than those using traditional stoves. However they are estimated to pay an additional Ch$

2,215 (about US$ 2.80) per 48-hour period, which implies that, on average, using pellet stoves for an additional hour costs Ch$ 46 (about US$ 0.06) more than traditional stoves. As expected, households operating stoves for longer periods of time have higher heating costs, and we also find that they have greater temperature variance. We do not find effects of insulation or of having a second stove on temperature variance or fuel cost.

5.4 Distributional Effects of the Improved Stove Program

The replacement program is open to all income levels in areas with high levels of ambient air pollution. To analyze the distributional effects of the stove replacement program, we divide the sample into three income groups: (1) households with total income lower than Ch$ 450,000 (about US$ 577) per month; (2) households with total income between Ch$ 450,001 and Ch$ 900,000 (US$ 577 – US$ $1,154) per month; and (3) households with total income over Ch$ 900,000 (> US$ 1,154) per month.

As an alternative metric for distributional effects, we analyze results based on whether households were experiencing energy poverty. First, we compute the Ten Percent Rule index (TPR) proposed by Boardman (1991), who classifies a household as energy poor if its expenditure on fuels exceeds 10% of net income. Second, we calculate the Minimum Income Standard (MIS) indicator proposed by Moore (2012), which classifies a household as energy poor if it cannot afford energy costs after deducting its minimum living cost. The procedure used to calculate these measures and their underlying assumptions are presented in Appendix D. We find that 68% of the sample is classified as energy poor using the TPR index, and only a slightly lower percentage are energy poor based on the MIS, with energy poverty largely concentrated in our three lower-income categories. These descriptive results are highly consistent with the results of Reyes et al. (2019).

Table 4, Panel A shows the effects of the treatment on indoor air pollution across our four income classifications. We find that using pellet stoves rather than traditional stoves reduces indoor air pollution mainly for the poorest group, with IAP on average falling by 28% for the poorest group ($p<0.01$).[13] It is notable that effects of the treatment on indoor $PM_{2.5}$ concentrations are not statistically significant for other income categories, suggesting that it is the lower-income group that drives our sample-wide finding that using a pellet stove reduces IAP on average by 14%. Panel B shows the estimated parameters for the model of indoor temperature, and we find no evidence of heterogeneous effects. Results using Mundlak's adjustment for each income group are presented in Appendix F and confirm there are significant indoor air pollution effects on the poorest group only.

As shown in Appendix F, our estimates of the progressive effects of the treatment on indoor air pollution are robust to defining households based on energy poverty rather than income category. We find that the treatment reduces indoor air pollution by 15% only for the relatively large subsample of households (total of 193) who experience energy poverty. Consistent with our other panel data model results, we do not find effects on average indoor temperature.[14]

Table 5 presents estimates of the effects of the treatment on fuel costs by income category. Panel A shows the effects for our 48-hour measurement period. Regardless of the income category, we find that pellet stoves increase average fuel costs by approximately Ch$ 2,200 per 48-hour period (Panel A), and between Ch$ 10,000 and Ch$ 17,000 per month (US$ 12.7 - US$ 21.5 per

[13] The larger IAP effects for lower-income households could be due to less efficient baseline technologies. In Appendix E we present regression results supporting the hypothesis that among our 156 control households, those in the low-income category are more likely to have the least efficient traditional stoves, such as salamander, potbelly or Franklin, or homemade stoves.

[14] As shown in Appendix F, using pellet stoves rather than traditional stoves reduces the variance in indoor temperature only for the highest income group, but this finding is marginally significant ($p<0.10$). These results also hold when energy poverty is defined using the TPR index.

month) (Panel B) based on our survey results. These effects are regressive, because these amounts are higher percentages of total estimated income for lower income households.[15]

5.5 Cost-Effectiveness of the Stove Program

We now present back-of-the-envelope calculations to estimate the cost-effectiveness of the stove program related to indoor air quality improvements. Using data from MMA (2014) and our survey results, we compute the fixed and variable costs of replacing 13,000 stoves in Talca by 2025, as planned by the Ministry of Environment. We estimate that the annual program cost per household is US$ 252, with approximately half being fixed costs and the other half variable costs.[16]

The average household enjoys a reduction in $PM_{2.5}$ of 14% (equivalent to 3.3 μg/m^3), implying that the social cost per μg/m^3 reduction based on the one-hour average is about $76 per household per year. As households receive significant subsidies, they actually pay about US$ 42 per year μg/m^3 reduced. Our lowest-income households show a much higher average $PM_{2.5}$ reduction (28%, which is equivalent to 6.6 μg/m^3) and have marginally lower fuel costs than the average household. We therefore, estimate that the average social cost for low-income households is only US$ 38 per year per μg/m^3 reduction and low-income households pay only about US$ 21 per year per μg/m^3 reduced due to the government subsidies they receive. For all income groups, ambient air quality improvements are in addition to IAP benefits.

[15] These findings are robust to parsing the sample based on energy poverty status (Appendix F). We find that all households face similar increases in energy costs when they adopt pellet stoves.

[16] All estimates are at the mean, including our estimated additional pellet stove fuel cost, which we use along with MMA estimates of additional annual maintenance costs (Ch$ 10,0000/stove/year), to calculate the additional variable cost of the pellet stove (Ch$ 100,000/stove/year for overall sample and Ch$ 80,000 for low-income households). Based on Ministry of Environment-provided program information, stoves are assumed to cost Ch$ 950,000 and have twenty-year lifespans, which are discounted at 6% /stove/year. The cost to install is assumed to be Ch$ 25,000/stove and to remove and recycle old stoves costs Ch$ 15,000/stove, with administrative costs/stove of 10% of direct costs.

6. Conclusions and Policy Implications

In this paper, we use field research conducted in central Chile to evaluate the impact of a program to replace traditional wood burning heating stoves with more efficient pellet stove technologies. We find that the program, which is intended to improve ambient air quality, generates important private benefits that may encourage adoption. We identify statistically significant reductions in indoor $PM_{2.5}$ concentrations and find that lower-income households and energy-poor households are the main beneficiaries. These findings suggest that, regarding household air pollution, biomass heating stove replacement programs may be a progressive policy.

We do not identify any treatment effects on average indoor temperature, but we find a statistically significant average effect on the variance in indoor temperature, which has been found in the literature to be a benefit of adopting improved heating or home insulation technologies. These temperature variance benefits do not appear to be progressive, however, as they seem to mainly accrue to higher income households. Regardless of income category or energy poverty status, pellet stoves are more expensive to operate than traditional stoves, and the average effect on fuel costs is similar across income groups, which is a regressive effect. Because the additional costs are economically significant (about US$1.40 per day), the increased costs of adoption could call into question the economic sustainability of the stove replacement program.

Our findings regarding additional fuel costs have important implications for the design and implementation of such stove programs. Programs should consider variable running costs as well as fixed costs, such as cost of the stove and installation, and take steps to promote thick and competitive fuel markets to drive down prices. Attending to pellet supply issues is particularly important at the time of writing, because of serious supply chain problems experienced by the local pellet industry. Ignoring this problem may exacerbate affordability issues, especially for low-income households.

Setting aside such pellet supply issues, which did not appear to be significant at the time we conducted our research, the pellet stove substitution program appears to offer important benefits, especially for low-income and energy-poor households. This is to the extent that households sufficiently value improvements in IAP, as suggested by Boso et al. (2019). This finding could be highlighted by government officials to promote adoption, but officials should be candid about the additional fuel costs – and market dependence - associated with adopting pellet stoves.

Our research can be extended in various ways. We do not know why we observe larger IAP effects on lower-income households, but present preliminary evidence that perhaps it is due to less efficient baseline technologies. This point could be further explored, particularly in light of legislation that allows local authorities to ban homemade "salamander" stoves and makes those households ineligible for stove replacement programs. Delving into differing baseline technologies could be a useful avenue for further investigation. Although we control for the existence of home insulation, we do not examine the effects of complementary programs to improve energy efficiency. Evaluating the synergistic effects of stove replacement and insulation on our outcomes of interest could be very important.

Finally, our study took place during the peak of the COVID-19 pandemic. Thus, an interesting avenue for future research would be to collect post-COVID-19 pandemic data and use estimators that account for the behavior of treated and control households before and after the replacement took place. These approaches could reduce selection problems, providing cleaner estimates of the effects of the treatment on outcomes of interest. Moreover, it is possible that the public health crisis generated systematically different behaviors than found in non-COVID times, which may have magnified or depressed effects of the improved stove program. Comparing our findings on the effects of the stove replacement program during the pandemic with those after the pandemic could help us better understand the effects of COVID-19 on heating behaviors and outcomes. We consider such a post-pandemic evaluation to be an especially fruitful extension of our research.

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Appendices

Appendix A. Details of the Stove Replacement Program

Table A.1

Number of stove replacements carried out by the government in Chile, 2011-2019

Stove Installed/Fuel	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electricity								35	46
Gas				1		188	45	80	15
Kerosene				122	193	1,508	2,204	1,042	2,064
Firewood	438	1,652	2,528	1,742	1,132	1,884	452	473	236
Pellets			421	380	737	1,904	5,375	2,855	10,674
Total	438	1,652	2,949	2,245	2,062	5,484	8,076	4,485	13,035

Source: Own elaboration based on official records. Information was retrieved from https://www.portaltransparencia.cl/

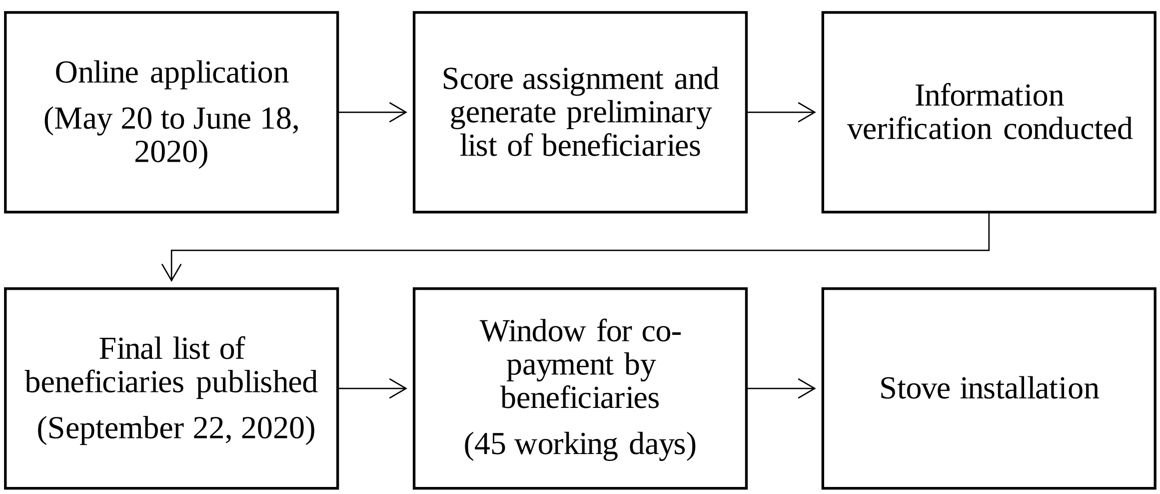

Figure A1. Schematic of the stove replacement program (year 2020)

Note: Own elaboration based on interviews with the Regional Secretary of the Ministry of Environment. This figure depicts the application process of the replacement program for year 2020 in Talca.

Figure A2. Pellet stove offered by the program (left) and salamander stove (right). Source: MMA.

Figure A3. Firewood stove before the replacement in Talca. Source: with the consent of an anonymous beneficiary.

Figure A4. Pellet stove already installed in Talca. Source: with the consent of an anonymous beneficiary.

Figure A5. House chosen for stove replacement program in Talca. Source: with the consent of an anonymous beneficiary.

Table A.2

Evaluation Criteria used by the Ministry of Environment to select beneficiaries for the stove replacement program in Talca during 2019.

Dimension	**Sub-dimension**	**Detail**	**Scores**		**Max. score**
Family	Risk of illness	Num. people older than 60 OR younger than 5.	3 or more 1 or 2 none	15 pts. 10 pts. 0 pts.	15 pts.
	Num. Persons	Num. people per household	4 or more 2 or 3 1	15 pts. 10 pts. 0 pts.	15 pts.
Type of stove	Type of stove	Higher score for less efficient technology	1 Homemade and salamander stove 2 Cookstove 3 Single chamber 4 Double chamber	40 pts. 30 pts. 20 pts. 10 pts.	40 pts.
Housing	Housing construction	Year of construction	After 2007 Between 2000 and 2007 Before 2000	10 pts. 5 pts. 0 pts.	10 pts
	Thermal insulation	Household obtained the subsidy from MINVU	Beneficiary Not Beneficiary	20 pts. 0 pts.	20 pts.

Source: Own elaboration based on information from Ministry of Environment https://calefactores.mma.gob.cl/region/9.

Table A.3

Evaluation Criteria used by the Ministry of Environment to select beneficiaries for the stove replacement program in Talca during 2020.

Dimension	**Sub-dimension**	**Detail**	**Scores**		**Max. score**
Family	Risk of illness	Num. people older than 60 OR younger than 5.	3 or more 1 or 2 none	7 pts. 4 pts. 0 pts.	7 pts.
	Num. Persons	Num. people per household	5 or more 3 or 4 2	8 pts. 4 pts. 1 pts.	8 pts.
Type of stove	Type of stove	Higher scores for less efficient technology	1 Single chamber 2 Double chamber	40 pts. 10 pts.	40 pts.
Territory	Location	Higher score for zones more contaminated	Zone 1 Zone 2 Zone 3 and 4	10 pts. 5 pts. 2 pts.	10 pts
Housing	Housing construction	Year of construction	After 2007 Between 2000 and 2007 Before 2000	35 pts. 10 pts. 5 pts.	35 pts
	Thermal insulation	Household obtained the subsidy from MINVU	Beneficiary Not Beneficiary	25 pts. 0 pts.	

Source: Own elaboration based on information from Ministry of Environment https://calefactores.mma.gob.cl/region/9.

Appendix B. Details of Our Field Research

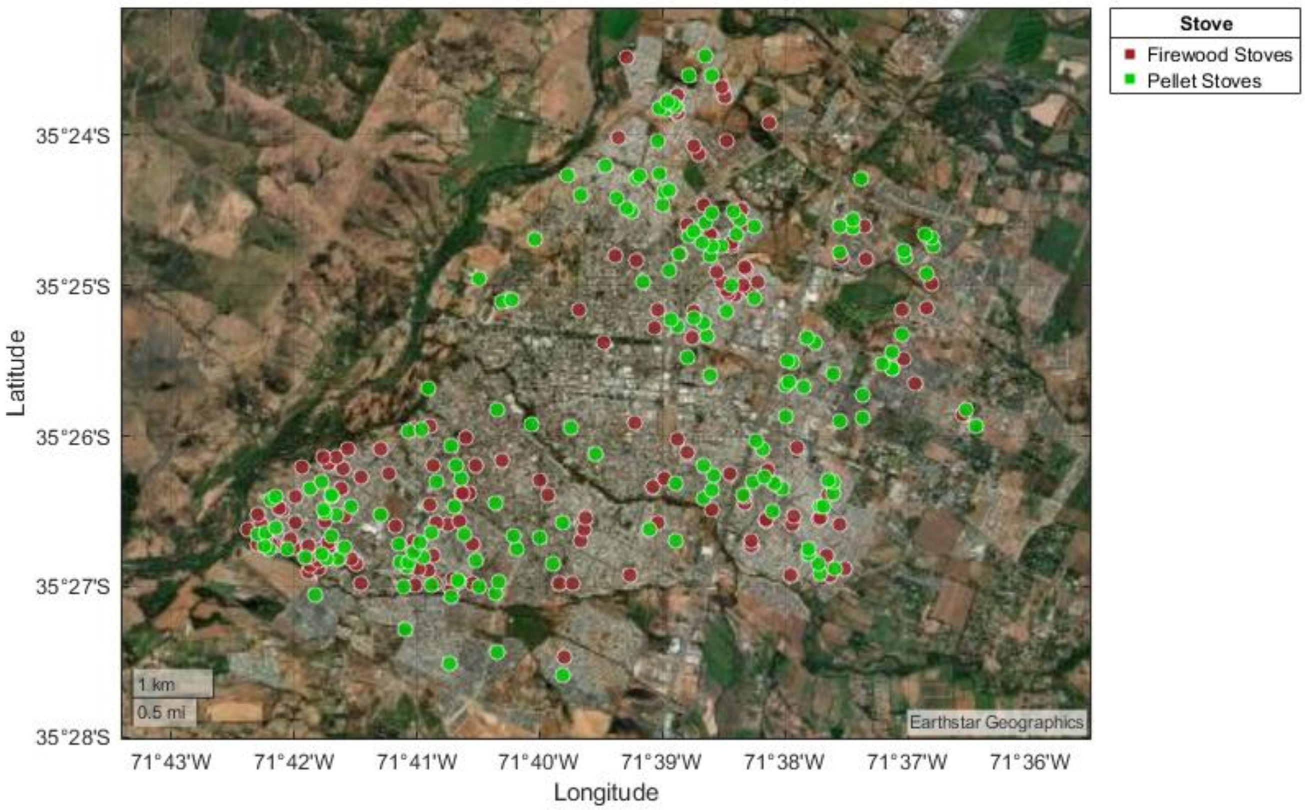

Figure B1. Participants in the study distributed across the city of Talca, Chile. (brown = households with firewood stoves (control). Green = households with pellet stoves (treatment))

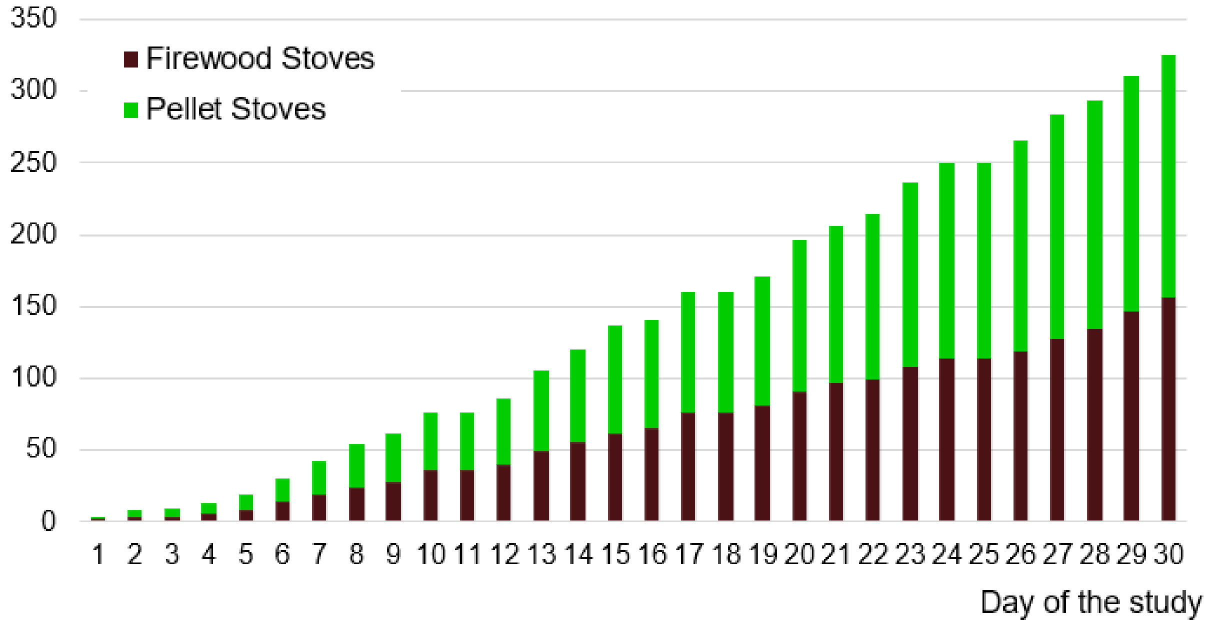

Figure B2. Measurement carried out in Talca between 13th of August and 13th of September of 2020. Cumulative number of households visited.

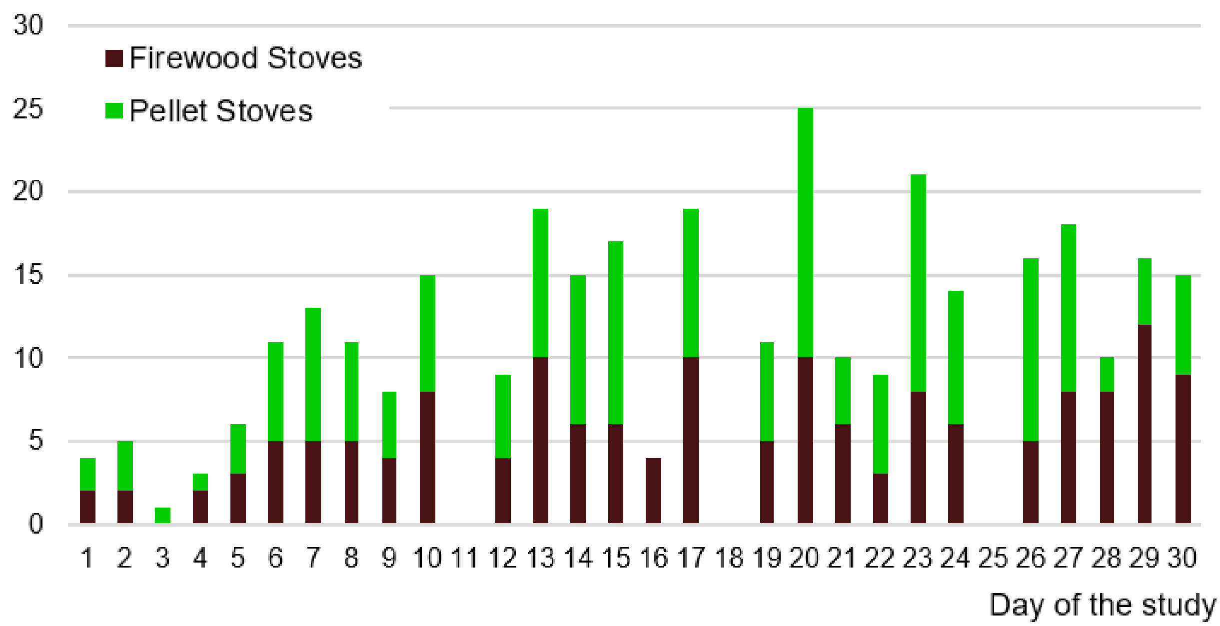

Figure B3. Measurement carried out in Talca during 13th of August and 13th of September of 2020. Number of households visited per day.

Figure B4. Prototype of the air quality sensors assembled for this study.

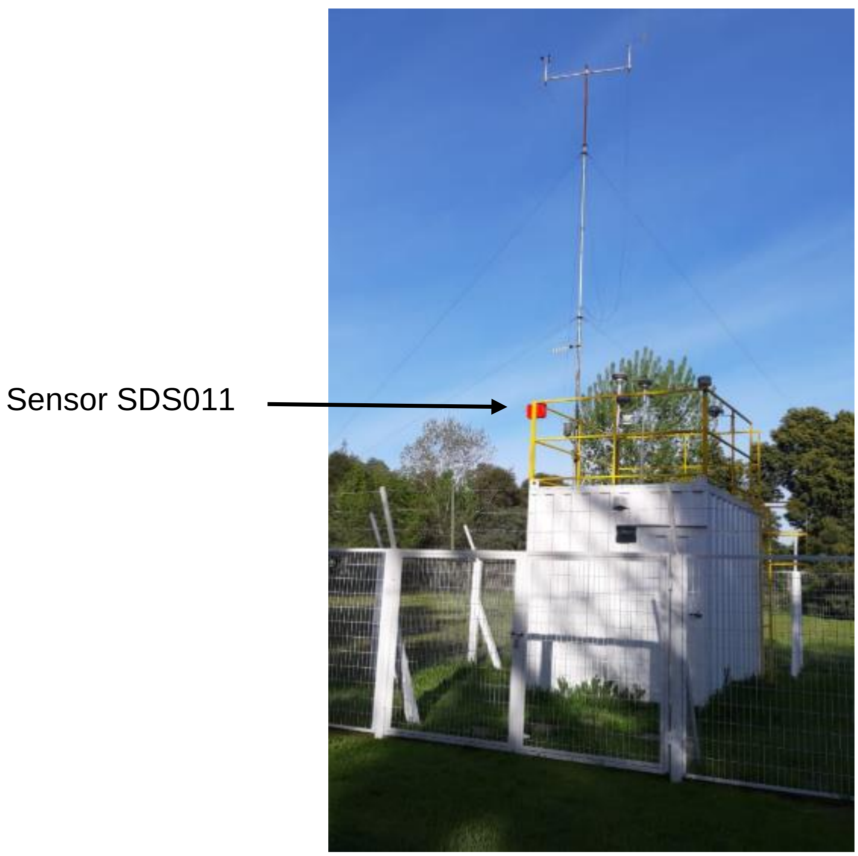

Figure B5. Comparison between our SDS11 PM2.5 sensor and the reference Air Quality Sensor

Figure B6. Stove use monitors (SUMS) are small devices that are placed on stoves to record surface temperature

Figure B7. Electronic devices used in fieldwork.

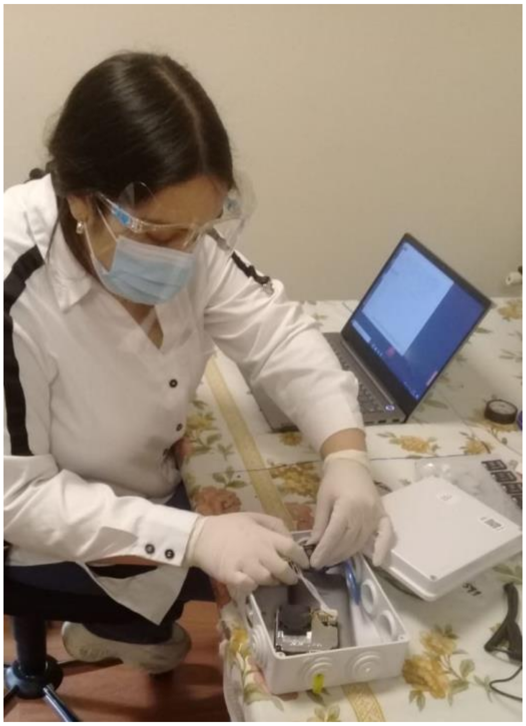

Figure B8. Collecting information from electronic devices

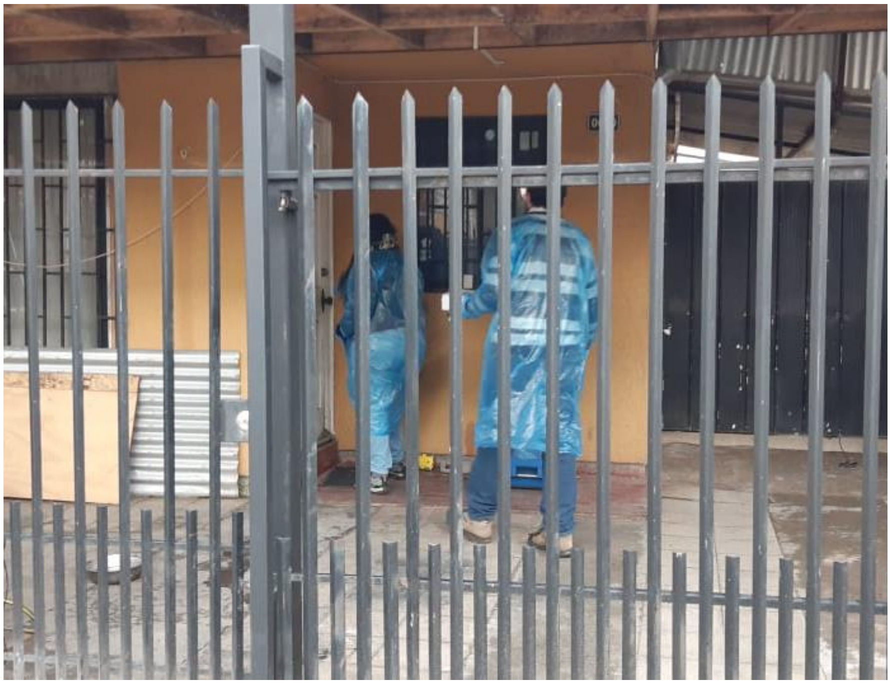

Figure B9. Visiting households using personal protective equipment against Covid-19.

Appendix C. Control Variable Definitions, Descriptive Statistics and Balancing Tests

Table C1. Fixed-effects Model Control Variable Definitions and Expected Signs

	Expected sign and motivation	
Variable	Indoor air pollution	Indoor temperature
ON: Dummy variable to indicate the use of a pellet stove or firewood stove on each measurement period.	(+) The emissions are generated when the stoves are used.	(+) The purpose of using stoves is to increase indoor the temperature.
PELLET*ON: Dummy variable to indicate that pellet stove is used during the measurement period.	(-) Installing a pellet stove and using it should reduce indoor air pollution.	(+) Users can control the heat from pellet stoves; however, it may involve a higher cost.
SECONDSTOVEON: Dummy variable to indicate that another stove is used during the measurement period.	Effect is likely to depend on the technology used as second stove.	(+) The use of any stove increases the indoor temperature.
LOG_PM_OUT: Log of concentration of PM2.5 measured outside the dwelling.	(+) Pollution in the outdoor ambient air infiltrates to inside the dwellings with lack of proper thermal insulation.	
LOG_TEMP_OUT: Log of temperature measured outside the dwelling.		Lower outdoor temperature motivates to increase indoor temperature only if stove is used.

Source: Authors

Table C2. Cross Section Model Control Variable Definitions and Expected Signs

	Expected sign and motivation	
Variable	Variance of indoor temperature	Cost of fuel
PELLET: Dummy variable indicating a pellet stove.	(-) Pellet stoves control the combustion, releasing heat evenly.	(+) Pellet is a high efficiency fuel. Its production is more complex than firewood.
HOURSON_MEASURED: Number of hours per day that stove was used over 48-hour measurement period.	(null) There is no prior reason for an association.	(+) Any extra hour of use increases de expenditure in fuel.
HOURSON_REPORTED: Number of hours per day that stove is used according to the survey.		(+) Any extra hour of use increases de expenditure in fuel.
SECONDSTOVE_MEASURED: Dummy variable to indicate another stove is used at least during one hour of measurement.	Variance depends on the type of technology used as second stove.	(-) Decrease in the use of the main stove (firewood or pellet).
SECONDSTOVE_REPORTED: Dummy variable to indicate that household reported in survey that they use another stove.		(-) Decrease in the use of the main stove (firewood or pellet).
INSULATION: Dummy to indicate that the dwelling has thermal insulation.[17]	(-) The insulation decreases heat loss from the dwelling.	(-) Insulation decreases the heating demand.
NFAMILY: Number of family members	(null) There is no prior reason for an association.	(+) Bigger families may demand heating services for more time

Source: Authors

The baseline survey collected information on socioeconomic and dwelling characteristics, which were expected to be crucial for identifying the effects of the stove replacement program on the outcomes of interest. We perform tests of differences in means of the covariates across treatment and control groups (i.e., balance tests) to evaluate whether the sampling approximated a randomized process. Table C.3 presents the results of this analysis. For 13 of the 12 variables examined, we do not find evidence at the 5% significance level that treatment and control groups exhibit differences in means. The only exception is household size, which we include as a control in our models.

[17] In this study we consider that a dwelling has thermal insulation if the household reported it directly in the survey, or if the household reported having a subsidy for thermal insulation from the Ministry of Housing and Urban Planning (MINVU), or if a dwelling built after 2007 was compliant with energy efficiency standards.

Table C3. Balance Test and Descriptive Statistics for Households and Dwelling Characteristics

Variable	N	(1) Control Mean/SE	N	(2) Treatment Mean/SE	t-test Difference (1)-(2)
Household characteristics:					
Number of family members (persons)	156	3.846	169	4.219	-0.373**
		(0.121)		(0.108)	
Age of household head (years)	155	49.665	165	51.830	-2.166
		(1.004)		(1.046)	
Formal schooling of household head (years)	155	12.665	165	13.170	-0.505
		(0.300)		(0.269)	
Any person younger than 5 years old (1 if yes, 0 if no)	156	0.410	169	0.527	-0.116
		(0.051)		(0.063)	
Any person older than 60 years old (1 if yes, 0 if no)	156	0.583	169	0.704	-0.121
		(0.065)		(0.063)	
Any person facing respiratory issues (1 if yes, 0 if no)	155	0.406	166	0.380	0.027
		(0.058)		(0.049)	
Income lower than Ch$ 300.000 (1 if yes, 0 if no)	156	0.346	169	0.385	-0.038
		(0.038)		(0.038)	
Dwelling characteristics:					
Dwelling size (Area in m^2)	156	73.776	169	80.734	-6.958*
		(2.227)		(2.828)	
Dwelling type (1 if Single dwelling, 0 Otherwise)	155	0.168	165	0.248	-0.081*
		(0.030)		(0.034)	
Construction Before 2000 (1 if yes, 0 if no)	156	0.583	169	0.533	0.051
		(0.040)		(0.038)	
Construction Between 2000 and 2007 (1 if yes, 0 if no)	156	0.205	169	0.266	-0.061
		(0.032)		(0.034)	
Construction after 2007 (1 if yes, 0 if no)	156	0.192	169	0.189	0.003
		(0.032)		(0.030)	
High insulation by subsidy, private investment or construction after 2007 (1 if yes, 0 if no)	156	0.327	169	0.320	0.007
		(0.038)		(0.036)	

Note: The value displayed for t-tests are the differences in the means across the groups. * $p < .10$, ** $p < .05$ and *** $p < .01$.

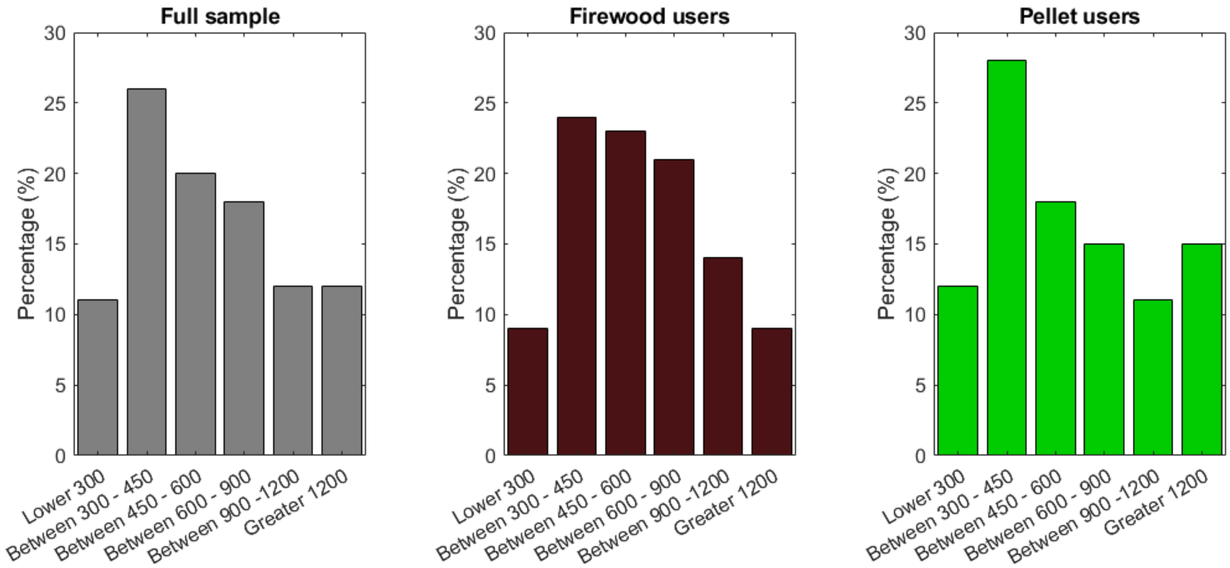

Figure C1. Income distribution in the sample and subsamples.

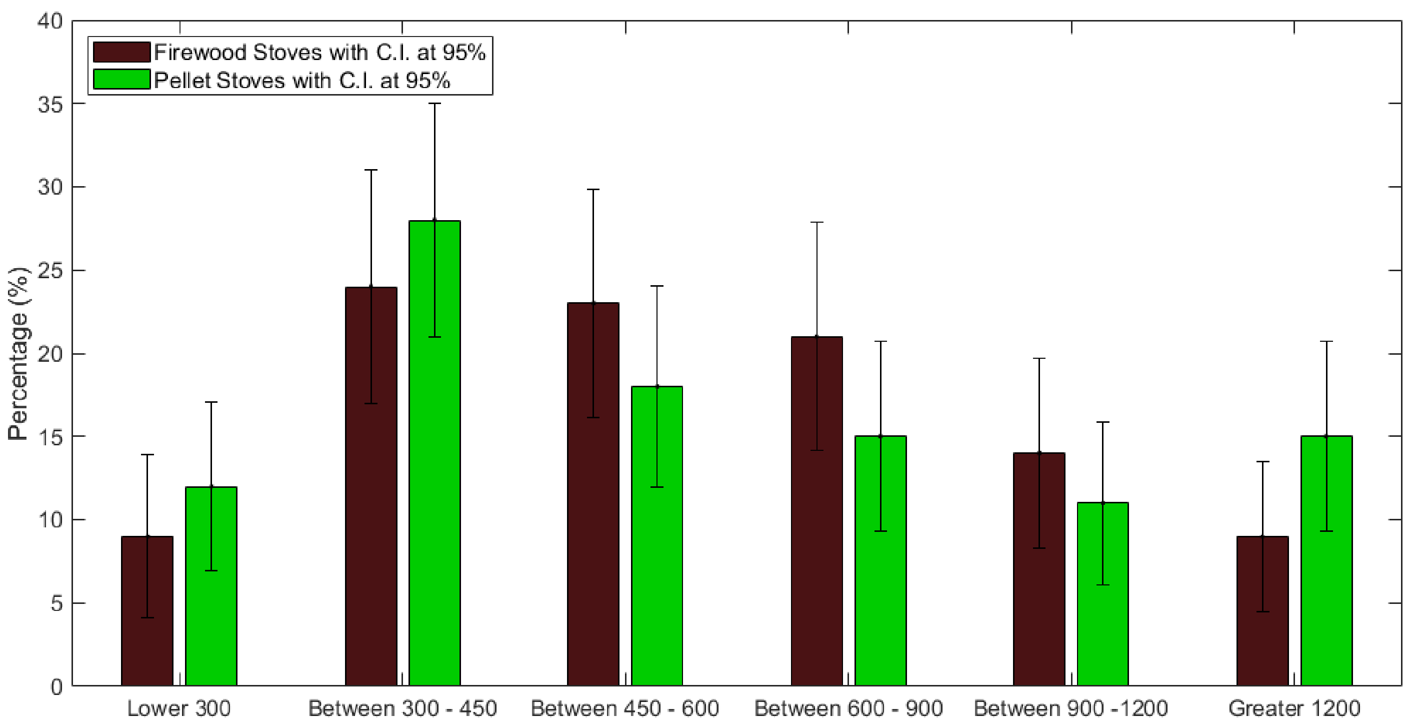

Figure C2. Comparison of income distribution among households with Firewood stoves and households with Pellet stoves. Levels in 1,000 Chilean pesos.

Appendix D. Energy Poverty analysis

1. Ten Percent Rule of Income (TPR) calculations

Assumptions

- We took the upper limit from each level of income. For instance, for the income level 0-300K group, 300K was selected as income since is closer to the minimum wage in Chile.
- We consider expenditure in heating reported in our survey for the month of July 2020 (firewood or pellet) + Electricity bill + LPG bill.
- For the electricity bill, we take an average of 34,392.1 CLP per month. This value comes from the National Energy Commission that reported a total amount of electricity distributed in the city of Talca during July 2019 was 17,789,577 kWh and the total amount of billing regulated customers, Residential BT1 Tariff in Talca was 94584 clients. Data for July 2020 is not available yet[18]. Then we divide 17,789,577 kWh over 94,584 clients, obtaining 188.08 kWh per client during July 2019 on average. From our survey, we know that households spent more time at home during 2020 than 2019. We found than on average they use their stove 3.6 hours more than the previous year (3.6/24 = 15% more). A recent report also found than in winter 2020 the residential sector spent 15-20% more on electricity than in 2019[19]. We take 17% as the increase in a household's electricity bill due to the pandemic. Then: 188.08 * 1.17 = 220.1 kWh per client, in average, for July 2020. We consider the price of electricity according to the BT1 Tariff for Talca from CGE[20]. For July 2020, the tariff is divided into 1046.9 CLP for management, 20.8 CLP/kWh for distribution and 130.7 CLP/kWh for consumption. P = 1046.9 + 151.5 Q (Q in kWh). For a household consuming 220.1 kWh, the bill is equivalent to: 1,046.9+151.5 *(220.1) = 34,392.1 CLP per month for the electricity bill.
- We consider the average annual demand of LGP equivalent to 1,812 kWh per household, that is the sum for cooking and warm water for showering and cleaning (CDT, 2019). We take only 1 month; we assume 151 kWh per month for year 2018. From our survey, we know that households report than they spend more time at home and more people are working from home or home schooling than before. Households report that 1.3 persons on average are working from home. The average household size is 4 persons. Based on this it we can assume that other energy consumption also increases. We take the same percentage of 17% used for electricity. Therefore, we consider 151 kWh *1.17 = 176.7 kWh per July 2020 for GLP consumption on average. For price, we take 18,132 CLP per

[18] Data from National Energy Commission http://datos.energiaabierta.cl/dataviews/257030/facturacion-clientes-regulados/

[19] Reports that support this idea are: Revista EI https://www.revistaei.cl/2020/07/29/las-tres-causas-del-alza-de-las-tarifas-electricas-segun-la-asociacion-de-empresas-del-sector/; Documentos OLADE http://biblioteca.olade.org/opac-tmpl/Documentos/old0452.pdf Revista Ingeniería de Sistemas http://www.dii.uchile.cl/~ris/RIS2020/p5_impactos_covid19_consumo_electrico.pdf

[20] Reports from CGE https://www.cge.cl/wp-content/uploads/2020/07/Tarifas-de-Suministro-CGE-Julio-2020.pdf

15 kg for July 2020[21] and a calorific value of 12,8 kWh per Kg[22] We obtain a monthly average demand of GAS with a cost of: (176.7 kWh) / (12.8 kWh / Kg)* (18,132 CLP/15 kg) = 16,687.1 CLP per month.

2. Minimum Income Standard (MIS) calculations

According to Moore (2012), "*households are deemed to be in fuel poverty if, after deducting their actual housing costs, they have insufficient residual net income to meet their total required fuel costs after all other minimum living costs (as defined by the MIS) have been met*". "*a household is in MIS based fuel poverty if Fuel costs > Net household income – housing costs – minimum living costs (MIS)."* We rewrite this equation as:
Net household income – Fuel costs – housing costs – minimum living costs (MIS) < 0."

Assumptions:

- Net household income: we took the upper limit from income level group. For instance, for level 0-300K, 300K was selected as income since is closer to the minimum wage in Chile.
- Fuel Cost: as before, we consider expenditure in heating reported in our survey for the month of July 2020 (firewood or pellet) + Electricity bill + LPG bill.
- For housing costs: We took for each quantile, the amount of expenditure reported by INE[23]
- Minimum living costs: We consider the Minimum wage in Chile of 326,500 CLP.

Energy poverty analysis

Our computed measure of energy poverty based on the TPR index is displayed in the upper section of Figure D1. In this index we show the percentage of income spent on energy services for groups defined by income level for all the households in our sample. We find that the lower the income level, the higher the TPR index. However, we also identify households facing higher energy costs (more than 10%) at the upper side of the income distribution with incomes of over 900,000 CLP (US$ 1,154) per month. According to the TPR index, we find that 68% of the total sample is classified as energy poor and these households are located above the red line of the TPR threshold in this figure.

We also extend our analysis based on the MSI index. It is displayed at the bottom of Figure D1. This figure suggests that energy poverty is correlated with income distribution. Using this index we identify as energy poor households only at income levels lower than 600,000 CLP (US$ 769) per month. According to the MSI index, we find that 58% of the total sample is classified as energy poor and these households are located below the zero-red line MSI threshold in Figure D1.

[21] Price for LPG http://datos.energiaabierta.cl/dataviews/242618/precios-nacionales-de-gas-licuado-petroleo/
[22] Calorific value considered from:
https://energia.gob.cl/sites/default/files/documentos/informe_final_caracterizacion_residencial_2018.pdf
[23] According to INE reports https://www.ine.cl/docs/default-source/encuesta-de-presupuestos-familiares/publicaciones-y-anuarios/viii-epf---(julio-2016---junio-2017)/informe-de-principales-resultados-viii-epf.pdf?sfvrsn=d5bd824f_2

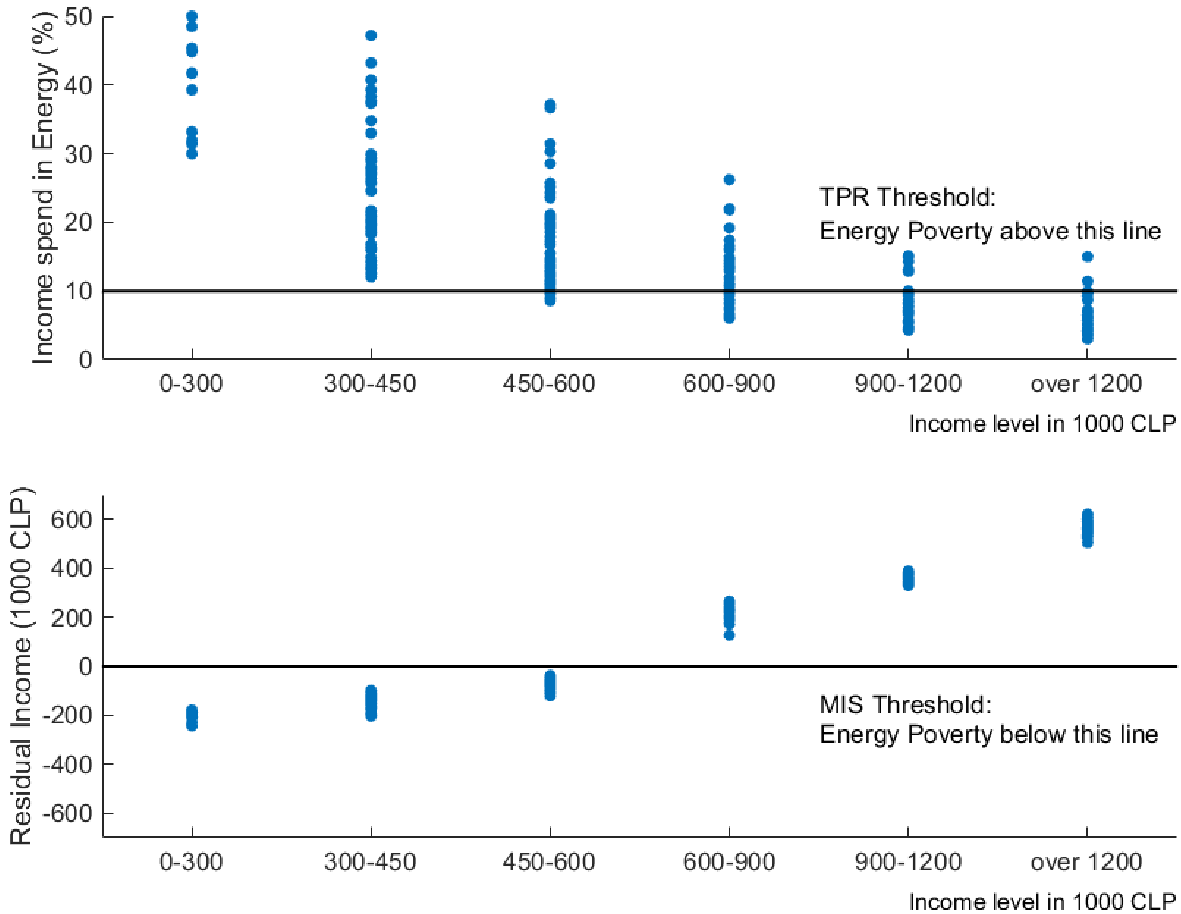

Figure D1. Households Experiencing Energy Poverty

Note: In the upper panel, energy poverty is measured using the TPR method, represented by dots above the red 10% threshold line. In the lower panel, energy poverty measured using the MIS method is represented by the dots below the zero line.

Appendix E. Relationship Between Income Category and Baseline Stove Type

Model 1 (binary logit model)

$StoveType_i = \beta_1 * Income_i + \beta_o + \varepsilon_i$

The dummy variable $StoveType_i$ takes the value of 1 if a control household has a high-efficiency firewood technology (wood burning stove with 1 chamber or 2 chambers). It takes the value of 0 if the household has a lower-efficiency firewood technology, such as a salamander stove, potbelly or Franklin stove, or homemade stove. $Income_i$ is a proxy for the income of the household, considering the lower level of the income group for household *i* in the control group (*i* =1,…,156).

Model 2 (binary logit model)

$StoveType_i = \beta_1 * MiddleIncome_i + \beta_2 * HighIncome_i + \beta_o + \varepsilon_i$

Same as Model 1, but in this case $LowIncome_i$, $MiddleIncome_i$, and $HighIncome_i$ are dummy variables indicating the income level of each household *i* in the control group (*i* =1,…,156). (*LowIncome* is the base category).

Table E.1. Estimates for the Baseline Stove Type

VARIABLES	(1) *StoveType*	(2) *StoveType*
Income	0.00212***	
	(0.000640)	
MiddleIncome		1.061***
		(0.383)
HighIncome		2.020***
		(0.600)
Constant	-0.540	-0.0741
	(0.394)	(0.272)
Observations	156	156

Note: Own elaboration. Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The results indicate that a higher income increases the probability of a household owning a better firewood technology. In other words, having an efficient firewood technology is positively correlated with having higher income.

Appendix F. Additional Estimates and Robustness Checks

Table F1. Panel data Mundlak's estimates for indoor air pollution and indoor temperature

VARIABLES	(1) log_PM2.5Indoor	(2) log_TIndoor
ON	0.0861**	0.125***
	(0.0346)	(0.00867)
PELLET*ON	-0.126***	-0.00264
	(0.0458)	(0.0121)
SECONDSTOVEON	0.0530*	0.0349***
	(0.0312)	(0.0114)
LOG_PM_OUT	0.641***	0.00816***
	(0.0193)	(0.00253)
LOG_TEMP_OUT	0.202***	0.0744***
	(0.0288)	(0.00860)
NFAMILY	0.00408	-0.00280
	(0.0131)	(0.00420)
Mean_ON	-0.0245	0.124***
	(0.0839)	(0.0264)
Mean_PELLET*ON	-0.155*	0.00725
	(0.0849)	(0.0309)
Mean_SECONDSTOVEON	0.193	0.0312
	(0.128)	(0.0738)
Mean_LOG_PM_OUT	-0.0410	-0.00789
	(0.0632)	(0.0160)
Mean_LOG_TEMP_OUT	-0.242	0.0853
	(0.204)	(0.0552)
Constant	0.800*	2.452***
	(0.456)	(0.130)
Observations	14,484	14,713
Number of ID	302	307
Household FE	YES	YES
Period FE	YES	YES

Note: Own elaboration. Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table F2. Cross-sectional OLS for indoor air pollution and indoor temperature

VARIABLES	(1) logPM2.5i	(2) logTi
PELLET	-0.141***	-0.00295
	(0.0386)	(0.0147)
log_PMo	0.663***	
	(0.0178)	
log_To		0.0910***
		(0.0132)
Constant	0.655***	2.630***
	(0.0760)	(0.0677)
Observations	14,484	15,711
R-squared	0.501	0.242
Day FE	YES	YES
Period FE	YES	YES

Note: Own elaboration. Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table F3. Panel data Mundlak's estimates for indoor air pollution and indoor temperature with a dummy variable for households facing Energy Poverty

VARIABLES	(1) log_PMi	(2) log_PMi	(3) log_Ti	(4) log_Ti
ON	0.0861**	0.0861**	0.125***	0.125***
	(0.0346)	(0.0346)	(0.00867)	(0.00867)
PELLET*ON	-0.126***	-0.126***	-0.00264	-0.00264
	(0.0458)	(0.0458)	(0.0121)	(0.0121)
SECONDSTOVEON	0.0528*	0.0528*	0.0350***	0.0350***
	(0.0313)	(0.0313)	(0.0114)	(0.0114)
LOG_PM_OUT	0.641***	0.641***	0.00815***	0.00815***
	(0.0193)	(0.0193)	(0.00253)	(0.00253)
LOG_TEMP_OUT:	0.202***	0.202***	0.0745***	0.0745***
	(0.0288)	(0.0288)	(0.00860)	(0.00859)
EnergyPoverty_TPR	0.0991**		-0.0142	
	(0.0436)		(0.0137)	
EnergyPoverty_MIS		0.0982**		-0.0164
		(0.0410)		(0.0135)
Mean_ON	-0.0324	-0.0335	0.125***	0.126***
	(0.0819)	(0.0817)	(0.0264)	(0.0262)
Mean_PELLET*ON	-0.151*	-0.140*	0.00596	0.00413
	(0.0847)	(0.0845)	(0.0305)	(0.0307)
Mean_SECONDSTOVEON	0.188	0.205*	0.0324	0.0300
	(0.128)	(0.125)	(0.0729)	(0.0726)
Mean_LOG_PM_OUT	-0.0514	-0.0531	-0.00621	-0.00543
	(0.0610)	(0.0618)	(0.0157)	(0.0156)
Mean_LOG_TEMP_OUT:	-0.222	-0.230	0.0800	0.0816
	(0.202)	(0.202)	(0.0543)	(0.0541)
Constant	0.758*	0.796*	2.454***	2.447***
	(0.453)	(0.453)	(0.130)	(0.130)
Observations	14,484	14,484	14,713	14,713
Number of ID	302	302	307	307
Household FE	YES	YES	YES	YES
Period FE	YES	YES	YES	YES

Note: Own elaboration. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table F4. Panel data Mundlak's estimates for indoor air pollution and indoor temperature with dummy variables for income distribution (total household income and income per capita)

VARIABLES	(1) log_PM2.5Indoor	(2) log_TIndoor	(3) log_PM2.5Indoor	(4) log_TIndoor
ON	0.0861**	0.125***	0.0861**	0.125***
	(0.0346)	(0.00867)	(0.0346)	(0.00866)
PELLET*ON	-0.126***	-0.00263	-0.126***	-0.00263
	(0.0458)	(0.0121)	(0.0458)	(0.0121)
SECONDSTOVEON	0.0529*	0.0349***	0.0529*	0.0350***
	(0.0312)	(0.0114)	(0.0313)	(0.0114)
LOG_PM_OUT	0.641***	0.00817***	0.641***	0.00815***
	(0.0193)	(0.00253)	(0.0193)	(0.00253)
LOG_TEMP_OUT:	0.202***	0.0745***	0.202***	0.0744***
	(0.0288)	(0.00860)		
Income = Low	0.112**	-0.0352**		
	(0.0557)	(0.0174)		
Income = Middle	0.0928*	-0.00119		
	(0.0541)	(0.0176)		
Income = High	-	-		
IncomePerCap = Low			0.123**	-0.0420***
			(0.0532)	(0.0157)
IncomePerCap = Middle			0.0363	-0.0349**
			(0.0466)	(0.0154)
IncomePerCap = High			-	-
mean_ON	-0.0254	0.122***	-0.0180	0.122***
	(0.0819)	(0.0264)	(0.0827)	(0.0260)
mean_PELLETON	-0.136	0.00358	-0.166*	0.00812
	(0.0847)	(0.0306)	(0.0860)	(0.0302)
mean_OtherStoveON	0.154	0.0305	0.217*	0.0293
	(0.129)	(0.0719)	(0.125)	(0.0725)
mean_log_PMo	-0.0472	-0.00543	-0.0483	-0.00468
	(0.0614)	(0.0153)	(0.0614)	(0.0156)
mean_log_To	-0.225	0.0840	-0.247	0.0840
	(0.201)	(0.0538)	(0.201)	(0.0534)
Constant	0.745	2.446***	0.825*	2.455***
	(0.453)	(0.128)	(0.454)	(0.126)
Observations	14,484	14,713	14,484	14,713
Number of ID	302	307	302	307
Household FE	YES	YES	YES	YES
Period FE	YES	YES	YES	YES

Note: Own elaboration. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table F5. Cross section estimates for the variance of indoor temperature for three different subsamples based on income level

VARIABLES	(1) Variance Temp. Lower Income	(2) Variance Temp. Middle Income	(3) Variance Temp. High Income
PELLET	-0.259	-0.911	-1.755*
	(0.598)	(0.857)	(1.047)
NFAMILY	0.468	-0.472	-0.272
	(0.357)	(0.320)	(0.205)
INSULATION	-0.117	0.349	0.140
	(0.804)	(0.952)	(0.666)
HOURSON_MEASURED	0.0753**	0.0168	0.0551*
	(0.0342)	(0.0283)	(0.0279)
SECONDSTOVE_MEASURED	-0.0757	0.301	-1.055
	(0.897)	(1.088)	(1.289)
Constant	-0.146	6.494***	4.041**
	(1.188)	(2.282)	(1.907)
Observations	106	110	70
R-squared	0.194	0.083	0.211
Week FE	YES	YES	YES

Note: Own elaboration. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1
Lower Income: income lower than Ch$ 450,000 (about US$ 577) per month; Middle Income: income between Ch$ 450,001 and Ch$ 900,000 (US$ 577 – US$ $1,154) per month; High Income: income over Ch$ 900,000 (>US$ 1,154) per month.

Table F6. Fixed effects estimation of panel data for households facing Energy Poverty

VARIABLES	(1) logPM2.5i TPR = 1	(2) logPM2.5i TPR = 0	(3) logTi TPR = 1	(4) logTi TPR = 0
ON	0.130***	0.0276	0.133***	0.0961***
	(0.0420)	(0.0603)	(0.0105)	(0.0120)
PELLET ON	-0.150***	-0.135	0.00182	-0.00425
	(0.0547)	(0.0845)	(0.0152)	(0.0174)
OtherStoveON	0.0875*	0.0704	0.0207	0.0486***
	(0.0446)	(0.0439)	(0.0132)	(0.0182)
log_PMo	0.685***	0.597***		
	(0.0189)	(0.0233)		
log_To			0.0762***	0.0616***
			(0.0128)	(0.0119)
Constant	0.422*	0.245	2.792***	2.801***
	(0.225)	(0.340)	(0.0885)	(0.0955)
Observations	10,061	4,423	11,068	4,643
R-squared	0.522	0.483	0.488	0.469
Number of ID	211	91	225	94
Household FE	YES	YES	YES	YES
Day FE	YES	YES	YES	YES
Period FE	YES	YES	YES	YES

Note: Own elaboration. Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Model 1 considers the subsample of households facing energy poverty according to the TPR index (TPR=1) for PM2.5 and Model 2 considers the rest of households (TPR=0) for PM2.5. Model 3 considers the subsample of households facing energy poverty according to the TPR index (TPR=1) for indoor Temperature, and Model 4 considers the rest of the households (TPR=0) for indoor Temperature.

Table F7. Cross section estimates for indoor temperature variance for households facing Energy Poverty

VARIABLES	(1) VarTi ON TPR=1	(2) VarTi ON TPR=0
PELLET	-0.613	-1.257*
	(0.537)	(0.689)
NFAMILY	0.213	-0.254
	(0.270)	(0.170)
INSULATION	0.191	-0.102
	(0.597)	(0.679)
HOURSON_MEASURED	0.0569**	0.0352
	(0.0229)	(0.0237)
SECONDSTOVE_MEASURED	0.169	-0.280
	(0.800)	(0.849)
2.Week	0.960	-0.727
	(1.309)	(0.825)
3.Week	-0.882	-1.298*
	(0.708)	(0.731)
4.Week	-1.628***	-0.617
	(0.581)	(0.956)
5.Week	-0.339	-1.519
	(0.810)	(1.128)
Constant	1.834	4.400***
	(1.238)	(1.252)
Observations	192	94
R-squared	0.082	0.144

Note: Own elaboration. Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table F8. Cross section estimates for the cost of fuel for households facing energy poverty

PANEL A	*Energy Poverty by TPR*	
	(1) TPR = 1	(2) TPR = 0
VARIABLES	Cost48h	Cost48h
PELLET	1,906***	2,828***
	(279.3)	(332.7)
NFAMILY	18.75	104.2
	(102.9)	(134.9)
INSULATION	482.1	174.0
	(310.0)	(349.8)
HOURSON_MEASURED	75.56***	50.63***
	(14.06)	(13.97)
SECONDSTOVE_MEASURED	575.1	170.8
	(492.1)	(484.0)
Constant	382.0	-265.2
	(525.6)	(727.9)
Observations	211	114
R-squared	0.331	0.514
Week FE	YES	YES
PANEL B	*Energy Poverty by TPR*	
	(1) TPR = 1	(2) TPR = 0
VARIABLES	Cost 1 month	Cost 1 month
PELLET	12,016***	15,462***
	(2,992)	(4,109)
NFAMILY	871.9	1,220
	(1,099)	(1,123)
INSULATION	-4,986*	621.5
	(2,787)	(3,994)
HOURSON_REPORTED	1,592***	1,524***
	(358.5)	(510.8)
SECONDSTOVE_REPORTED	3,565	-1,787
	(3,396)	(3,957)
Constant	10,180*	5,565
	(5,358)	(9,754)
Observations	204	109
R-squared	0.166	0.172
PANEL C	*Energy Poverty by TPR*	
	(1) TPR = 1	(2) TPR = 0
VARIABLES	Cost 1 year	Cost Cost 1 year
PELLET	24,768**	21,143
	(10,061)	(18,701)
NFAMILY	6,079	9,343
	(3,740)	(6,092)
INSULATION	-20,028**	10,654
	(9,682)	(18,242)
HOURSON_REPORTED	5,265***	3,037
	(1,323)	(2,658)
SECONDSTOVE_REPORTED	6,738	30,321
	(11,881)	(21,896)
Constant	67,794***	83,076*
	(18,744)	(48,005)
Observations	205	109
R-squared	0.133	0.066

Note: Own elaboration. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table F9. Fixed Effects Estimation for Indoor Air Pollution and Indoor Temperature for selected households by propensity score matching

VARIABLES	(1) logPM2.5i	(2) logTi
ON	0.102**	0.115***
	(0.0416)	(0.00890)
PELLETON	-0.167***	-0.00985
	(0.0543)	(0.0133)
OtherStoveON	0.130***	0.0346**
	(0.0426)	(0.0154)
log_PMo	0.664***	
	(0.0183)	
log_To		0.0626***
		(0.00782)
Constant	0.259	2.738***
	(0.298)	(0.0699)
Observations	8,996	9,726
R-squared	0.529	0.548
Number of ID	187	196
Household FE	YES	YES
Day FE	YES	YES
Period FE	YES	YES

Note: Own elaboration. Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Tables

Table 1. Measurements across Treatment and Control sub-samples

Variable	N	(1) Control Mean/SE	N	(2) Treatment Mean/SE	*t*-test Difference (1)-(2)
Hourly measurements:					
Indoor PM2.5 concentration (μg/m^3)	7576	23.688	7933	19.407	4.282***
		(0.479)		(0.309)	
Outdoor PM2.5 concentration (μg/m^3)	7297	24.427	8043	24.951	-0.524
		(0.395)		(0.371)	
Indoor Temperature (°C)	7625	18.414	8088	18.371	0.042
		(0.040)		(0.035)	
Outdoor Temperature (°C)	8185	10.372	8785	10.245	0.127**
		(0.046)		(0.042)	
Indoor Relative Humidity (%)	7576	57.239	7886	56.833	0.406***
		(0.116)		(0.099)	
Outdoor Relative Humidity (%)	7297	73.510	8036	74.357	-0.847***
		(0.178)		(0.167)	
Stove use ON (% time)	8185	0.384	8785	0.386	-0.002
		(0.005)		(0.005)	
Other stove ON (% time)	8185	0.065	8785	0.022	0.043***
		(0.003)		(0.002)	
Aggregated measurements:					
Use of stove in 48 h (hours)	156	18.760	169	18.740	0.020
		(1.175)		(0.867)	
Cost of fuel per 48 h (10^3 CLP)	156	1.786	169	4.002	-2.216***
		(0.155)		(0.175)	
Variance Indoor Temp. in 48 h	154	5.403	165	5.025	0.378
		(0.442)		(0.403)	
Variance Indoor Temp. only if ON = 1	129	3.610	157	2.560	1.049**
		(0.395)		(0.195)	

Note: The value displayed for t-tests are the differences in the means across the groups. * $p < 0.10$, ** $p < 0.05$ and *** $p < 0.01$.

Table 2. Fixed Effects Estimation for Indoor Air Pollution and Indoor Temperature

Variable	(1) Log PM indoor	(2) Log Temp indoor
ON	0.0970***	0.123***
	(0.0351)	(0.00855)
PELLET * ON	-0.135***	0.00234
	(0.0461)	(0.0129)
Other Stove ON	0.0712**	0.0303***
	(0.0320)	(0.0110)
Log outdoor PM	0.662***	
	(0.0153)	
Log outdoor Temperature		0.0718***
		(0.00968)
Constant	0.245	2.786***
	(0.264)	(0.0631)
Observations	14,484	15,711
R-squared	0.507	0.474
Number of ID	302	319
Household FE	YES	YES
Day FE	YES	YES
Period FE	YES	YES

Note: Robust standard errors in parentheses. * $p < .10$, ** $p < .05$ and *** $p < .01$. The baseline comparator is adjusted for whether any of the main stoves is in operation as measured by our iButtons. We are therefore only interested in μ from PELLET*ON and not ($\alpha + \mu$), that is adding α from ON.

Table 3. Cross-Sectional Estimates for the Variance of Indoor Temperature and Fuel Cost

Variable	(1) Var Ti ON	(2) Cost 48h	(3) Cost 1 month	(4) Cost 1 year
Pellet	-0.882**	2,215***	13,382***	22,521**
	(0.428)	(221.2)	(2,359)	(9,206)
Number of family members (persons)	-0.0393	43.67	956.3	7,742**
	(0.176)	(82.13)	(797.4)	(3,189)
High insulation (1 if yes, 0 if no)	0.0268	352.5	-2,859	-7,777
	(0.454)	(238.2)	(2,252)	(9,231)
Use of main stove (measured)	0.0503***	66.69***		
	(0.0170)	(10.33)		
Use of second stove (measured)	0.0122	372.8		
	(0.593)	(357.5)		
Use of main stove (survey reported)			1,497***	4,622***
			(292.2)	(1,269)
Use of second stove (survey reported)			1,154	14,761
			(2,506)	(10,640)
Constant	3.049***	191.8	9,615**	69,733***
	(0.881)	(434.5)	(4,636)	(18,675)
Observations	286	325	313	314
R-squared	0.075	0.376	0.158	0.099
Week Fixed Effect	YES	YES	NO	NO

Note: Robust standard errors in parentheses * $p < .10$, ** $p < .05$ and *** $p < .01$. Model 1 and Model 2 consider the information from our 48 hour visits. Model 3 and Model 4 are based on information from our household survey.

Table 4. Fixed Effects Estimation for Indoor Air Pollution and Indoor Temperature by Income Category

PANEL A Variable	(1) Log indoor PM *Lower Income*	(2) Log indoor PM *Middle Income*	(3) Log indoor PM *High Income*
ON	0.259***	0.0196	-0.0602
	(0.0635)	(0.0466)	(0.0565)
PELLET * ON	-0.283***	-0.0373	-0.0135
	(0.0817)	(0.0711)	(0.0732)
Other Stove ON	0.0997	0.0183	0.170**
	(0.0729)	(0.0320)	(0.0842)
Log outdoor PM	0.680***	0.684***	0.578***
	(0.0267)	(0.0234)	(0.0276)
Constant	0.576**	0.0449	0.387**
	(0.290)	(0.257)	(0.164)
Observations	5,159	5,790	3,535
R-squared	0.515	0.542	0.474
Number of ID	106	122	74
Household FE	YES	YES	YES
Day FE	YES	YES	YES
Period FE	YES	YES	YES
PANEL B Variable	**(1) Log indoor Temp. *Lower Income***	**(2) Log indoor Temp. *Middle Income***	**(3) Log indoor Temp. *High Income***
ON	0.110***	0.144***	0.0941***
	(0.0117)	(0.0147)	(0.0115)
PELLET * ON	0.0343*	-0.0151	0.00349
	(0.0191)	(0.0222)	(0.0156)
Other Stove ON	0.0272	0.0147	0.0633*
	(0.0167)	(0.0150)	(0.0326)
Log outdoor Temp.	0.0638***	0.0922***	0.0543***
	(0.00986)	(0.0208)	(0.0115)
Constant	2.710***	2.498***	2.739***
	(0.0937)	(0.0601)	(0.0411)
Observations	5,674	6,248	3,789
R-squared	0.529	0.470	0.491
Number of ID	114	128	77
Household FE	YES	YES	YES
Day FE	YES	YES	YES
Period FE	YES	YES	YES

Note: Robust standard errors in parentheses. * $p < .10$, ** $p < .05$ and *** $p < .01$. Lower Income: income lower than Ch$ 450,000 (about US$ 577) per month; Middle Income: income between Ch$ 450,001 and Ch$ 900,000 (US$ 577 – US$ $1,154) per month; High Income: income over Ch$ 900,000 (>US$ 1,154) per month.

Table 5. Cross-Sectional Estimates for Fuel Cost by Income Level

PANEL A Variable	(1) Cost 48 hours *Lower Income*	(2) Cost 48 hours *Middle Income*	(3) Cost 48 hours *High Income*
Pellet	2,228***	1,909***	2,728***
	(385.6)	(295.1)	(403.3)
Num. family members (persons)	-52.47	144.3	133.1
	(118.0)	(135.3)	(181.3)
High insulation (1 if yes, 0 if no)	305.7	1,141***	-343.4
	(424.9)	(374.4)	(404.8)
Use of main stove (measured)	96.23***	57.43***	52.34***
	(24.06)	(9.668)	(17.32)
Use of second stove (measured)	556.6	577.8	-537.7
	(657.9)	(496.6)	(651.2)
Constant	247.3	-319.0	61.50
	(728.6)	(571.5)	(975.3)
Observations	119	128	78
R-squared	0.368	0.432	0.507

PANEL B Variable	(1) Cost 1 month *Lower Income*	(2) Cost 1 month *Middle Income*	(3) Cost 1 month *High Income*
Pellet	16,994***	10,029***	15,714***
	(3,370)	(3,461)	(5,736)
Num. family members (persons)	-714.4	2,309**	825.5
	(1,196)	(1,133)	(1,571)
High insulation (1 if yes, 0 if no)	1,330	-9,595***	-73.11
	(2,947)	(3,289)	(5,339)
Use of main stove (reported)	1,159***	1,373***	1,331**
	(419.8)	(442.1)	(656.4)
Use of second stove (reported)	819.0	3,516	-3,978
	(3,671)	(3,917)	(5,581)
Constant	12,259**	10,293	15,605
	(6,149)	(6,564)	(13,970)
Observations	116	122	75
R-squared	0.199	0.200	0.125

Note: Robust standard errors in parentheses. * $p < .10$, ** $p < .05$ and *** $p < .01$. Lower Income: income lower than Ch$ 450,000 (about US$ 577) per month; Middle Income: income between Ch$ 450,001 and Ch$ 900,000 (US$ 577 – US$ $1,154) per month; High Income: income over Ch$ 900,000 (>US$ 1,154) per month.

Figures

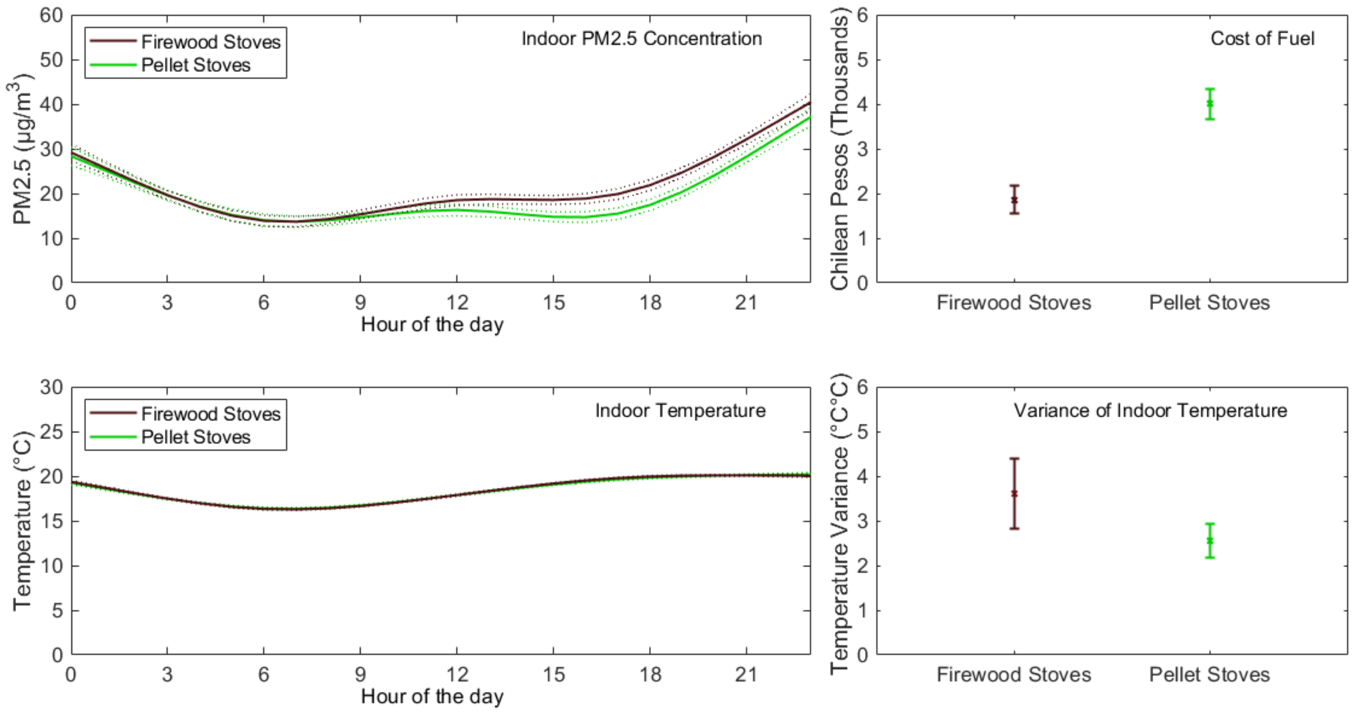

Figure 1. Air quality, fuel cost, and comfort

Note: Upper left corner: Splines for 1 hour mean of indoor $PM_{2.5}$ during the whole day and 95% confidence intervals by treatment and control. Bottom left corner: Splines for 1 hour mean of indoor temperature during the whole day and 95% confidence intervals by treatment and control. Upper right corner: Mean for cost of fuel for each group. Bottom right corner: Variance of the indoor temperature for the hours that the stoves were in use during the study.