

# Energy poverty effects on policy-based PM<sub>2.5</sub> emissions mitigation in southern and central Chile

Rubén Calvo<sup>a,b,c,\*</sup>, Nicolás Álamos<sup>b,c</sup>, Nicolás Huneeus<sup>b,c,d</sup>, Raúl O’Ryan<sup>b,e</sup>

<sup>a</sup> Doctorado en Geografía, Universidad Católica de Chile, Santiago, Chile

<sup>b</sup> Centro de Ciencia del clima y la Resiliencia (CR2), Santiago, Chile

<sup>c</sup> Red de Pobreza Energética, Universidad de Chile, Santiago, Chile

<sup>d</sup> Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile

<sup>e</sup> Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Santiago, Chile

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## ABSTRACT

Residential firewood burning is the main source of PM<sub>2.5</sub> emissions in southern and central Chile. In Chile, approximately 4000 premature deaths are observed each year due to air pollution. Mitigation policies aim to reduce dwellings’ energy demand and foster cleaner but more expensive energy sources. Pre-existing energy poverty conditions are often overlooked in these policies, even though they can negatively affect the adoption of these measures. This article uses southern and central Chile as a case study to assess quantitatively different policy scenarios of PM<sub>2.5</sub> emissions between 2017 and 2050, considering energy poverty-related effects. Results show that PM<sub>2.5</sub> emissions will grow 16% over time under a business as usual scenario. If thermal improvement and stove/heater replacements are implemented, PM<sub>2.5</sub> reductions depend on the scale of the policy: a 5%–6% reduction of total southern and central Chile PM<sub>2.5</sub> emissions if only cities with Atmospheric Decontamination Plans are included; a 54%–56% reduction of PM<sub>2.5</sub> emissions if these policies include other growing cities. Our study shows that the energy poverty effect potentially reduces the effectiveness of these measures in 25%. Consequently, if no anticipatory measures are taken, Chile’s energy transition goals could be hindered and the effectiveness of mitigation policies to improve air quality significantly reduced.

## 1. Introduction

At a global scale, air pollution, especially from particulate matter (PM), is one of the most critical environmental challenges as slightly more than 90% of the world’s urban population lives in areas where pollutant concentrations exceed World Health Organization (WHO) air quality guidelines (WHO, 2016). According to WHO research, outdoor pollution causes at least 3 million premature deaths worldwide each year through increases in cardiovascular and respiratory diseases (Lelieveld et al., 2015; WHO, 2016). In Chile, more than half of the population – at least 10 million people – live in cities where annual PM<sub>2.5</sub> concentrations exceed the national guidelines, causing harmful health conditions and, on average, 4000 annual premature deaths (Ministerio del Medio Ambiente, 2014).

Only in the past decade, most polluted cities located in southern and central Chile in Regions from O’Higgins to Aysen (see Fig. 1) have implemented Atmospheric Decontamination Plans (ADP) to reduce

PM<sub>2.5</sub> concentrations below the national air quality standard (Ministerio del Medio Ambiente, 2014). Despite these efforts, annual PM<sub>2.5</sub> atmospheric concentrations remain above the annual national standard in seven of the ten major southern cities, in particular, due to residential firewood burning for heating and cooking (Ministerio del Medio Ambiente, 2020).

The climate conditions in these cities vary from temperate to polar (Sarricolea et al., 2017), with a high presence of native forests and exotic plantations in the south of Chile (Reyes et al., 2015). The proportion of household-firewood users has been historically very high towards the south of the country where the weather is colder (Fig. 1c), most dwellings have low thermal efficiency, and the prices of cleaner alternatives (i.e., electricity, gas) is relatively higher than wood. In fact, 80% of households in these cities use firewood for heating, cooking, and hot water systems (Urquiza et al., 2019). It is common that families use high humidity firewood (>25% of humidity) due to rainy weather, lack of infrastructure to dry firewood, and an informal production and

\* Corresponding author. Doctorado en Geografía, Universidad Católica de Chile, Santiago, Chile.

E-mail address: [rcalvo@ug.uchile.cl](mailto:rcalvo@ug.uchile.cl) (R. Calvo).

distribution market (Reyes et al., 2019).

Recent literature has stressed the importance of considering energy poverty conditions, i.e., lack of equitable access to high-quality energy services (Urquiza et al., 2019), in technological transition processes to ensure that households improve their access to energy services and also mitigate pollutant emissions and improve air quality conditions (Reyes et al., 2019; Urquiza et al., 2019). In this regard, research has focused on quantifying the impacts of policy measures on air quality conditions taking into account such variables as dwelling thermal retrofitting, energy efficiency measures, and changes in household heating and cooking technologies (He et al., 2002; Kerimray et al., 2017). The part of this literature that refers to technological change in dwellings draws attention to the negative effects of preexisting energy poverty conditions on the effectiveness of policy measures due to rebound effects, that include a pre-rebound effect, and efficiency elasticity, among others (Bone et al., 2010; Galvin, 2015; Jin, 2020; Platten et al., 2020; Streimikiene et al., 2020; Teli et al., 2016).

Energy poverty could produce a pre-rebound effect due to preexisting insufficient energy consumption and dwelling characteristics that lead low-income households to maintain their energy use despite improving the efficiency of their technologies. (Galvin, 2014, 2015;

Galvin and Sunikka-Blank, 2013a, 2016; Greening et al., 2000; Teli et al., 2016; Webber et al., 2015). Low incomes also condition the willingness to change from cheap energy sources (i.e., wet firewood, coal) to more efficient, less polluting, but more expensive energy sources (i.e., gas, electricity, wood pellet). This relates to the economic dimension of energy poverty (Reyes et al., 2019; Schueftan and González, 2013; Urquiza et al., 2019).

Previous scientific literature and technical policy reports for Chile that do not consider an energy poverty effect have projected a PM<sub>2.5</sub> emission reduction of up to 60% in ten years in the central and southern part of the country as a result of ADP implementation, including both subsidized thermal retrofits of dwellings and stove/heater replacement (from firewood to gas, electricity, or wood pellet) (Ambiente Consultores & PRIEN, 2007; CONAMA, 2007; Cortes and Rismanchi, 2020; Creara Consultores, 2013a; GreenLabUC, 2013; Mardones, 2017; Mardones and Sanhueza, 2015; Schueftan and González, 2013). However, none of these previous studies have included an estimate of the energy poverty impacts on the effectiveness of household thermal retrofit and stove/heating replacements.

Preliminary analysis of energy poverty in Chile shows that at least 22.6% of households spend an excessive amount of their household

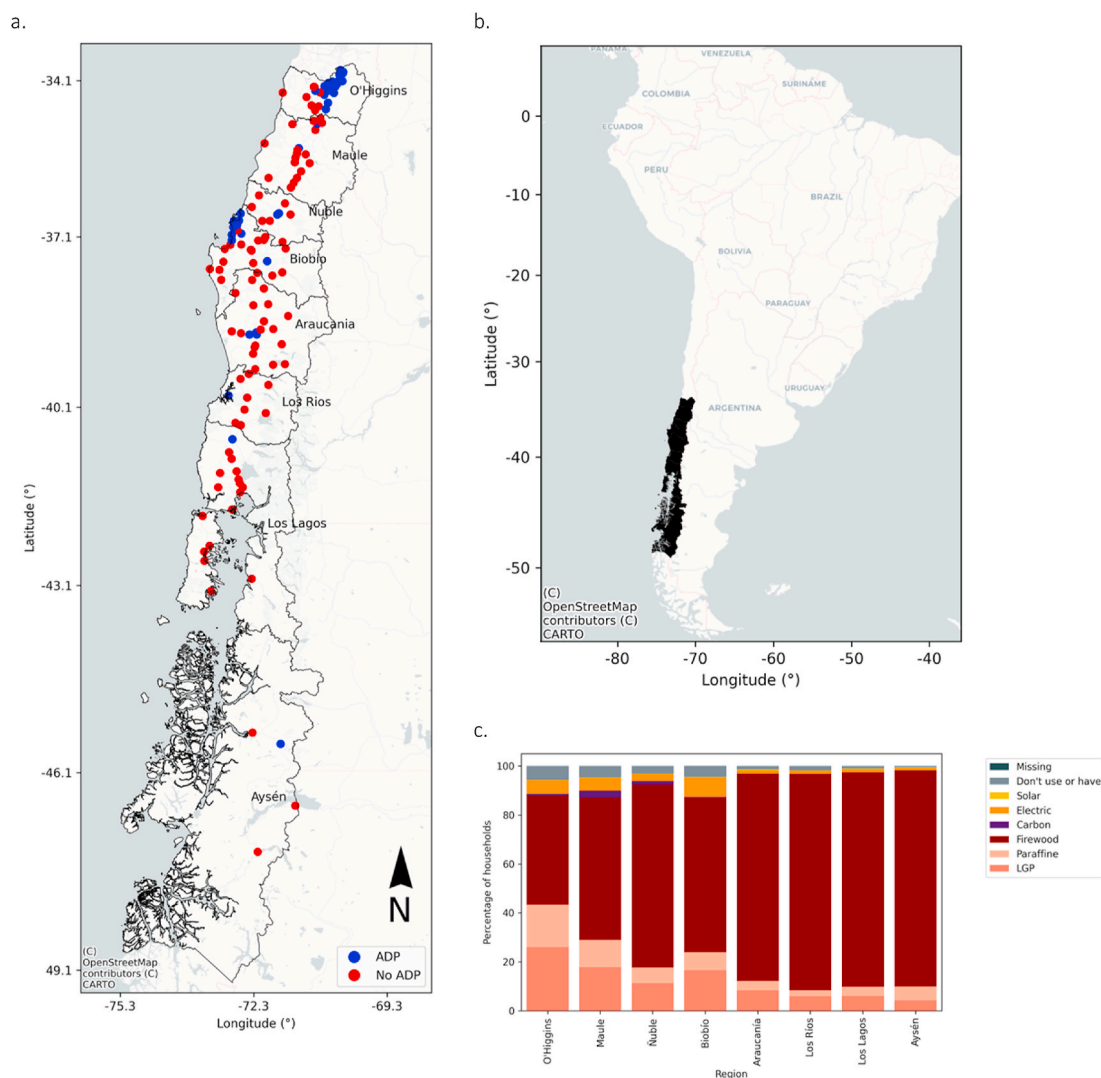


**Fig. 1. Case study description.** a) Southern and central Chile. Cities with (blue dots) or without (red dots) Atmospheric Decontamination Plan (ADP) are noted. The names of each administrative region are also included. b) South America with the black area highlighting the study region (southern and central Chile) illustrated in more detail in Fig. 1a. c) Heating energy sources used by households in southern and central regions Source: (Ministerio de Desarrollo Social, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

income on energy (Red de Pobreza Energética, 2019), and this proportion of households increases up to 60% in some southern cities during the coldest winter months (Reyes et al., 2019). Also, 66% of dwellings at a national scale were built before the implementation of a minimum thermal standard in the year 2000, hence, increasing the energy demand in thermally inefficient dwellings (Urquiza et al., 2019).

In this article, we examine the impact of energy poverty conditions on expected emission trajectories for PM<sub>2.5</sub> emissions for central and southern Chile for the period 2017–2050. In particular, the energy poverty effect is quantified for different policy measures aimed at reducing the use of firewood and PM<sub>2.5</sub> emissions, an issue that is relevant in many countries where the poorer rely heavily on this source of energy for heating and cooking.

The article is structured as follows: Section 2 describes data and methods used to develop the emissions projection model and policy-based scenarios. Section 3 summarizes the main findings and results and discusses its limitations, and Section 4 presents the main conclusions and policy implications.

## 2. Data and methods

This section describes the data and methods used to estimate residential PM<sub>2.5</sub> emissions from firewood under different scenarios between 2017 and 2050 in southern and central Chile. To project the firewood consumption, we use a model based on regional data of population, urbanization and household income projections as main drivers. The parameters of this model are obtained from regression using databases on Chilean households that include firewood consumption as the dependent variable and socioeconomic and demographic characteristics of households as independent variables.

### 2.1. Data

This study uses the most recent datasets on firewood consumption and household socioeconomic characteristics in Chile: the official database for firewood consumption at a national scale produced by the Technological Development Center (CDT from the Spanish Centro de Desarrollo Tecnológico) in 2015 (CDT, 2015) and the Socioeconomic Characterization Survey database from 2015 (CASEN 2015) (Ministerio de Desarrollo Social, 2015). The CDT 2015 database is representative for each one of the sixteen administrative regions with 4115 total cases, and CASEN 2015 is representative of most municipalities of the country with a sample of 83,887 households nationally. Tables 1 and 2 present weighted descriptive statistics of the variables used from the CDT 2015 database, and Tables 3 and 4 from the CASEN 2015 database: firewood users, firewood consumption, household size and proportion of households in each region, rural and urban area.

Although CASEN 2015 has better sampling and a more comprehensive questionnaire, it only includes information on the households' choice to consume firewood (dichotomic) but not the quantity of this consumption. Hence, we use CASEN 2015 to derive the parameters to estimate the probability of choosing firewood as an energy source and CDT 2015 to estimate the parameters needed to project average firewood consumption.

The projection of socioeconomic and demographic drivers for each region between 2017 and 2050 is constructed based on already published databases. The average income for each decile between 2015 and 2050 is projected using the General Equilibrium Model used in O'Ryan et al. (2020). The proportion of urban households for each region is based on the official national population projection between 1992 and 2050, developed by the National Statistics Institute (Instituto Nacional de Estadísticas, 2018, 2019b, 2019a). To estimate the proportion of the population living in each city size category, we use national population projections at the municipality level (Instituto Nacional de Estadísticas, 2018a, 2018b, 2019), as in Chile, the correspondence between spatial boundaries of municipalities and cities is consistent. In the case of major

**Table 1**

Descriptive statistics of Area, Region, and Income on CDT 2015 Database.

| Variable | Categories                    | N of Households  | Percentage  |
|----------|-------------------------------|------------------|-------------|
| Area     | Rural                         | 699,920          | 15.28%      |
|          | Urban                         | 3,880,495        | 84.72%      |
|          | <b>Total (n expanded)</b>     | <b>4,580,415</b> | <b>100%</b> |
| Region   | Northern Chile                | 540,375          | 11.80%      |
|          | Valparaíso                    | 500,305          | 10.92%      |
|          | O'Higgins                     | 254,655          | 5.56%       |
|          | Maule                         | 320,120          | 6.99%       |
|          | Bio-Bio                       | 582,435          | 12.72%      |
|          | Araucanía                     | 293,135          | 6.40%       |
|          | Los Lagos                     | 249,60           | 5.45%       |
|          | Aysén                         | 31,490           | 0.69%       |
|          | Magallanes                    | 46,370           | 1.01%       |
|          | Metropolitana                 | 1,646,820        | 35.95%      |
|          | Los Ríos                      | 115,110          | 2.51%       |
|          | <b>Total (n expanded)</b>     | <b>4,580,415</b> | <b>100%</b> |
| Income   | Less than US\$306             | 527,912          | 11.53%      |
|          | Between US\$306 and US\$459   | 618,140          | 13.50%      |
|          | Between US\$459 and US\$612   | 500,189          | 10.92%      |
|          | Between US\$612 and US\$764   | 926,531          | 20.23%      |
|          | Between US\$764 and US\$917   | 371,362          | 8.11%       |
|          | Between US\$917 and US\$1070  | 136,716          | 2.98%       |
|          | Between US\$1070 and US\$1223 | 469,923          | 10.26%      |
|          | Between US\$1223 and US\$1376 | 305,010          | 6.66%       |
|          | Between US\$1376 and US\$1911 | 181,146          | 3.95%       |
|          | Between US\$1911 and US\$2293 | 201,307          | 4.39%       |
|          | Between US\$2293 and US\$2676 | 122,074          | 2.67%       |
|          | Between US\$2676 and US\$3058 | 28,834           | 0.63%       |
|          | Between US\$2676 and US\$3058 | 68,753           | 1.50%       |
|          | Between US\$3058 and US\$3822 | 36,911           | 0.81%       |
|          | More than US\$3822            | 85,607           | 1.87%       |
|          | <b>Total (n expanded)</b>     | <b>4,580,415</b> | <b>100%</b> |

**Table 2**

Descriptive statistics of firewood consumption on CDT 2015 Database.

| Variable                                                                  | Mean | Std  | P25 | P50 | P75 | N sample | N expanded |
|---------------------------------------------------------------------------|------|------|-----|-----|-----|----------|------------|
| Firewood consumption in stere meters (m <sup>3</sup> of stacked firewood) | 2.56 | 4.85 | 0   | 0   | 3.5 | 4115     | 4,580,415  |

**Table 3**

Descriptive statistics of firewood users and city size on CASEN 2015 Database.

| Variable       | Categories                                       | N of Households  | Percentage  |
|----------------|--------------------------------------------------|------------------|-------------|
| Firewood users | Non-firewood consumers                           | 3,815,387        | 69.94%      |
|                | Firewood consumers                               | 1,639,527        | 30.06%      |
|                | <b>Total (N expanded)</b>                        | <b>5,454,914</b> | <b>100%</b> |
| City Size      | Rural (<5000 inhabitants)                        | 1,060,425        | 19.4%       |
|                | Small (≥ 5000 and <20,000 inhabitants)           | 718,787          | 13.2%       |
|                | Medium (≥ 20,000 and <50,000 inhabitants)        | 1,463,234        | 26.8%       |
|                | Medium large (≥ 50,000 and <100,000 inhabitants) | 1,351,506        | 24.8%       |
|                | Large (>200,000 inhabitants)                     | 860,505          | 15.8%       |
|                | <b>Total (N expanded)</b>                        | <b>5,454,914</b> | <b>100%</b> |

cities with multiple municipalities, the total population was aggregated.

### 2.2. PM<sub>2.5</sub> emissions estimations

In order to obtain PM<sub>2.5</sub> emissions from the residential sector between 2017 and 2050, it is necessary to estimate the total firewood

**Table 4**

Descriptive statistics of income and household size on CASEN 2015 Database.

| Variable                 | Mean      | Std       | P25     | P50     | P75       | N sample | N expanded |
|--------------------------|-----------|-----------|---------|---------|-----------|----------|------------|
| Income (US\$)            | \$1,312,9 | \$1,723,8 | \$489,1 | \$865,1 | \$1,518,3 | 83,887   | 5,454,914  |
| Household size (persons) | 3.21      | 1.61      | 1       | 3       | 15        | 83,887   | 5,454,914  |

consumption and use an emission factor to convert this consumption into an emitted mass of PM<sub>2.5</sub>. To calculate total firewood consumption for each year, we develop a regional estimation based on three elements: the quantity of households (QH), the proportion of households that use firewood (Proportion of Firewood Users, PFU), and their average firewood consumption (AHFC).

We use emissions factors (constants for all the period) from the National Inventory of Anthropogenic Emissions (INEMA) developed by Álamos et al. (2021a,b) for the year 2017. This is a recently produced PM<sub>2.5</sub> inventory for 2015–2017 based on multiple datasets that correct previous inventories, providing more accurate estimates of firewood consumption emissions based on firewood species and humidity as well as stove efficiency (Álamos et al., 2021; Álamos et al., 2021). To ensure consistency with INEMA estimations, we use INEMA's 2017 PM<sub>2.5</sub> emissions as the starting point of our projections and then apply percentage variations of firewood consumption derived from our model to obtain annual PM<sub>2.5</sub> estimates for each year between 2018 and 2050.

Also, as the focus of this paper is on southern and central Chilean cities, which exhibit higher PM<sub>2.5</sub> concentration, we distribute the total regional emissions in each city and rural settlement based on its population according to projections by the National Statistics Institute (Instituto Nacional de Estadísticas, 2019b, 2019a). All estimations are for the southern and central cities of Chile (see Fig. 1).

### 2.2.1. PM<sub>2.5</sub> emission computation

Residential PM<sub>2.5</sub> emissions per year  $i$  and region  $j$  ( $RE_{i,j}$ ) are computed based on total firewood consumption for each year  $i$  and region  $j$  ( $TFC_{i,j}$ ) and the corresponding emission factor per region  $j$  ( $EF_j$ ) as follows:

$$RE_{i,j} = TFC_{i,j} \cdot EF_j \quad (1)$$

Where  $TFC_{i,j}$  the total firewood consumption for each year  $i$  for the period 2017–2050 in each of the 16 administrative regions in Chile ( $j$ ) (Fig. 1b). As mentioned above, we use INEMA's 2017 PM<sub>2.5</sub> emissions as a starting point with a constant emission factor, and therefore all temporal variations in emissions are solely driven by changes in the firewood consumption.

To compute the Total Firewood Consumption for each year and each region, we use the following equation:

$$TFC_{i,j} = PFU_{i,j} \cdot AHFC_{i,j} \cdot QH_{i,j} \cdot CF_{i,j} \quad (2)$$

Where  $TFC_{i,j}$  is Total firewood consumption for each year  $i$  in each region  $j$ .  $PFU_{i,j}$  is the proportion of firewood users,  $AHFC_{i,j}$  is the Average household firewood consumption,  $QH_{i,j}$  is the Quantity of households, and  $CF$  is a correction factor for the model. Each of these variables is estimated per year  $i$  and for the sixteen administrative regions  $j$ .

The proportion of firewood users in each region and year (PFU) is computed using equation (3), which is driven by the mean household income, mean household size, proportion of households in each category of city size (rural, small, medium). The selection of these variables is based on previous literature findings that establish the variables with the most explanatory potential are income, household size, and presence in urban or rural settlements (Bustos and Ferrada, 2017; Schueftan and González, 2013; Van Der Kroon et al., 2013). The equation is the following:

$$PFU_{i,j} = \alpha_j + \beta_{1,j} \cdot \overline{income}_{i,j} + \beta_{2,j} \cdot \overline{HS}_{i,j} + \sum_{i=1}^3 \beta_{3,j} \cdot \overline{CS}_{i,j} \quad (3)$$

Where for each year  $i$  and each region  $j$ ,  $income_{i,j}$  is the mean household income,  $HS_{i,j}$  is the mean household size and  $CS_{i,j}$  is the proportion of households within each of the three categories of city sizes (rural, small, medium). These variables are projected for each year  $i$  and region  $j$  for the period 2017–2050 using previously published databases as stated in subsection 2.1. The alpha and beta parameters used are estimated based on a set of logit regression models using CASEN 2015 database for each region  $j$  (explained in detail in the next section).

The Average Household Firewood Consumption per year  $i$  and region  $j$ ,  $AHFC_{i,j}$ , is computed using equation (4). The selection of the explanatory variables is based on the same criteria as the previous equation but is restricted by the comprehensiveness of the CDT 2015 database. In this database the income variable is categorical and does not include household size.

$$AHFC_{i,j} = \gamma + \sum_{k=1}^{14} \theta_k \cdot cat\_income_{i,j} + \theta_2 \cdot rural_{i,j} + \theta_3 \cdot region_i \quad (4)$$

For each region  $j$  in each year  $i$ ,  $AHFC_{i,j}$  is the Average household firewood consumption,  $cat\_income_{i,j}$  is the proportion of households in each income category,  $rural_{i,j}$  is the proportion of households located in rural areas, and  $region_i$  is the constant associated with each region. These variables are also projected for the period 2017–2050. The gamma and theta parameters are estimated by a linear regression model using the CDT 2015 database (also explained in detail in the next section).

The Quantity of households in the 2017–2050 period is projected using equation (5):

$$QH_{i,j} = \frac{TP_{i,j}}{HS_{i,j}} \quad (5)$$

Where  $TP_{i,j}$  is the total population and  $HS_{i,j}$  is the average household size, per year  $i$  and region  $j$ . To compute the quantity of households, we use national population projections (Instituto Nacional de Estadísticas, 2018, 2019b). The average household size is determined using the Mitigation Action Plans and Scenarios initiative (MAPS) model in which GDP growth is its main driver (MAPS, 2014).

A Correction Factor (CF) is applied to equation (2) to avoid possible biases on the average consumption and the proportion of firewood users based on the following:

- An improved thermal efficiency standard is assumed for new dwellings at a national scale as it is already used in cities with current ADP and is probably to be implemented in other cities. Hence, the average firewood consumption decreases as the proportion of newer and more efficient dwellings increase. An average of 33.7% reduction in energy demand has been documented in dwellings under the new standard (Ambiente Consultores & PRIEN, 2007; Creara Consultores, 2013a, 2013b; GreenLabUC, 2013), consequently we use this parameter to estimate the energy demand reduction for newer dwellings.
- According to government commitments, the current pace of firewood stove/heater replacement will be maintained in cities currently with ADP (ending in 2027). Hence, we reduce the number of firewood users in the same magnitude and regional distribution as the government's stove-replacement program commitment, achieving a total of 141,300 beneficiaries between 2017 and 2027.
- As cities grow, apartment buildings become more common, which necessarily reduces the possibility of using firewood. In the

absence of a more precise land-use and city growth model, we estimate the proportion of newer dwellings that will be apartments maintaining the observed linear trend of building construction in the 1992–2017 period.

### 2.2.2. Econometric estimation of firewood consumption parameters

In this section we present the models used to estimate the parameters required to determine firewood consumption in equations (3) and (4), based on household level data.

The statistical parameters needed to estimate the proportion of firewood users (alpha and beta in equation (3)) were derived using a set of logit regression models – one for each region in southern and central Chile – with firewood use (FU) as a dependent variable (value 1 if households choose to use firewood and value 0 if not) and household income for each household  $h$  in each region  $j$ , household size, and a categorical variable with the city size (CS) where the household is located (rural, small, medium) as independent variables. CASEN 2015 household's database is used following equation (6).

$$FU_{hj} = \alpha_j + \beta_{1j} \cdot income_{hj} + \beta_{2j} \cdot HS_{hj} + \sum_{k=1}^3 \beta_{3kj} \cdot CS_{hj} + \epsilon_j \quad (6)$$

The parameters used to determine firewood consumption per household (lambda and theta) were estimated using an ordinary least squares regression model. The available information from CDT 2015 only allowed estimating country level parameters in this case. The quantity of firewood consumption (FC) of each household is the dependent variable and a set of categorical variables are the independent variables. These are: household income using the 15 categories defined by CDT 2015 database (*cat\_income*), the administrative region where household is located (*region*) and *rural* as a dummy variable (0 means urban household and 1 rural household). This ordinary least squares regression is estimated using CDT 2015 household's database following equation (7).

$$FC_h = \gamma + \sum_{k=1}^{14} \theta_1 \cdot cat\_income_h + \theta_2 \cdot rural_h + \theta_3 \cdot region_h + \epsilon \quad (7)$$

### 2.3. Policy based PM2.5 emissions scenarios

Five different scenarios were implemented using our model in cities in the southern and central regions of Chile (see Table 5). First, in a Business as Usual (BAU) scenario, the pace of present stove/heater replacement and thermal retrofit programs within ADP is maintained until its end in ~2027 in cities currently benefited by these policies. This baseline scenario assumes that firewood consumption grows according to population, urbanization, and income in the period 2017–2050, and no additional efforts besides those committed to in the ADPs are made to incorporate new technologies and energy sources in the residential sector. The BAU scenario also assumes an improvement in average thermal standards as newer dwellings are built based on ADP thermal retrofit standards.

Two Integrated Policy scenarios are computed with thermal retrofit and stove/heater replacement programs financed entirely by a government subsidy similar to the current ADP programs. In the first one, firewood stoves are replaced exclusively by wood pellet stoves which are currently increasing their presence in Chilean households. In the second, electric heating devices (air conditioners) are chosen to replace firewood stoves. In both of these scenarios, thermal retrofit of older dwellings is implemented. The premise is that thermal retrofit combined with stove/heater replacement reduces PM2.5 emissions due to both reduced energy demand and higher energy efficiency. Based on the fact that many

households are already using gas or electric appliances for cooking and water heating,<sup>1</sup> an important assumption is that the use of firewood stoves for these uses is replaced by some other alternative financed by the households.

These Integrated Policy scenarios are computed under two different conditions. First, a Current-Cities condition, where only cities which currently have an ADP are benefited. Second, a Regional condition, where policy measures are extended to every city in the southern and central regions. This regional-scale application would increase thermal retrofits from 17,000 annual subsidies if only the current cities are included to 22,000 dwellings between 2027 and 2050 if this is extended to a regional scale. Stove/heater replacement (wood pellet or electric) subsidies would also increase at a regional scale, from 13,000 to 35,000 annual subsidies in the same period.

To estimate the reduction in energy demand caused by thermal retrofits, we use previous technical reports, which estimate an average 34% reduction in energy demand in each improved dwelling (Ambiente Consultores & PRIEN, 2007; Creara Consultores, 2013a, 2013b; GreenLabUC, 2013). This reduction varies based on the year of dwelling construction and if it is an isolated, semi-isolated or a paired house (Ambiente Consultores & PRIEN, 2007; Creara Consultores, 2013a, 2013b; GreenLabUC, 2013).

The stove/heater replacement program is based on government subsidies that finance complete replacement with a higher efficiency stove/heater (gas, electric or wood pellet). In this scenario, as in the current stove replacement programs, the firewood stove is removed from the home and a new higher efficiency stove/heater is installed. This would mean that PM2.5 emissions are completely avoided in the case of electric heating and significantly lower in the case of wood pellet stoves due to improved efficiency and significantly lower emission factors (CONAMA, 2007).

### 2.4. Energy poverty effects

Energy poverty relates to the lack of access to high-quality and affordable energy services, reducing the chances of household human and economic development (Urquiza et al., 2019). In this study we focus on two energy poverty effects, and we apply them simultaneously in our estimates. First, the energy savings from thermal retrofits are not as high as expected because energy poor household are commonly not consuming the energy necessary to achieve thermal comfort (Galvin and Sunikka-Blank, 2016). Hence, thermal retrofit measures are not 100% effective in reducing energy consumption because energy-poor households were likely previously under consuming, and will not reduce their energy consumption as expected (Cali et al., 2016; Galvin, 2015; Galvin and Sunikka-Blank, 2013b, 2016; Sierra et al., 2018; Teli et al., 2016). This effect has been called pre-rebound effect by recent literature (Galvin and Sunikka-Blank, 2016).

The second effect of energy poverty, which we will call household rejection, is related to the household's unwillingness to change to cleaner but more expensive energy sources, due to the increase in monthly energy bills. One of the most widely used methodologies to quantify this kind of economic energy poverty is called the 10% rule indicator and classifies a household as energy poor when its total monthly energy expenditure in all energy services (i.e., heating, cooking, electric appliances, among others) is more than 10% of its total disposable income (Boardman, 1991, 2014).

Recent literature has found that the effectiveness of thermal retrofits is reduced between 10% and 50% due to pre-existing insufficient energy consumption, dwelling characteristics, and household income (Galvin, 2014, 2015; Galvin and Sunikka-Blank, 2013a, 2016; Greening et al., 2000; Teli et al., 2016; Webber et al., 2015) associated with energy

<sup>1</sup> According to CASEN 2015, 80% of households in center and south Chile already use gas for cooking, and 75% use electricity or gas for heating water.

**Table 5**

Summary of measures under policy-based scenarios.

| Measures                         | Business as Usual (BAU)              | Restricted Wood Pellet                                            | Extensive Wood Pellet                                             | Restricted Electric                                             | Extensive Electric                                              |
|----------------------------------|--------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| <b>Thermal retrofits</b>         | 17,000 dwellings annually until 2027 | BAU and 17,000 dwellings annually between 2025 and 2050.          | BAU and 22,000 dwellings annually between 2025 and 2050.          | BAU and 17,000 dwellings annually between 2025 and 2050.        | BAU and 22,000 dwellings annually between 2025 and 2050.        |
| <b>Stove/heater replacements</b> | 15,000 stoves annually until 2027    | BAU and 13,000 wood pellet stoves annually between 2025 and 2050. | BAU and 35,000 wood pellet stoves annually between 2025 and 2050. | BAU and 13,000 electric heating annually between 2025 and 2050. | BAU and 35,000 electric heating annually between 2025 and 2050. |
| <b>Scale of policy</b>           | Current ADP <sup>a</sup> Cities      | Current ADP Cities                                                | Regional                                                          | Current ADP Cities                                              | Regional                                                        |

BAU: Business as Usual.

**Restricted Wood Pellet:** thermal retrofits and wood pellet stove replacements at current scale.**Extensive Wood Pellet:** thermal retrofits and wood pellet stove replacements at regional scale.**Restricted Electric:** thermal retrofits and electric stove replacements at current scale.**Extensive Electric:** thermal retrofits and electric stove replacements at regional scale.<sup>a</sup> ADP: Atmospheric Decontamination Plan.

poverty conditions. To include this pre-rebound effect in the scenarios presented in Table 7, the expected energy demand reduction from thermal retrofit scenarios in this article is computed considering both full and partial (40% loss of potential reduction) effectiveness to address energy poverty pre-existing conditions in low-income contexts (Galvin, 2014; Galvin and Sunikka-Blank, 2013a, 2016; Teli et al., 2016; Webber et al., 2015).

To include the household rejection effect, we estimate equivalent energy expenditure using wood pellets and electricity based on firewood household consumption estimates. Following Bhatia and Angelou (2014, 2015) and Boardman (1991, 2014) if the projected monthly expenditure exceeds 5% of household disposable income we assume that households would reject the technology change. The stove/heater replacement scenarios are estimated both for partial adoption using this assumption and for a complete adoption scenario (without rejection effect).

To compute equivalent energy expenditure, we transform the projected firewood consumption to KWh and compute the necessary wood pellet and electricity consumption to meet the same energy demand. For this it is assumed that wood pellet stoves have a 0.8 Performance Coefficient, meaning that for each unit of wood pellet only 80% of its potential is converted to heat (CONAMA, 2007). Also, the relation between wood pellet and firewood prices is assumed to maintain the present ratio, given high uncertainties and contradictory trends.

In the case of electric heating, the two energy poverty effects were computed for both a high-efficiency appliance (3.5 Coefficient of

Performance or 350% efficiency according to Chilean energy efficiency certification) and a low-efficiency air conditioner (2.2 Coefficient of Performance) in order to obtain the range of possible outcomes according to policy budgets. With respect to electricity prices, this scenario assumes a reduction in KWh prices as a result of a special bidding process, where generation companies could offer a reduced price exclusively for heating. This program is a novel addition to ADP in Chile and is implemented by the Energy Ministry and Distribution companies. As a result, a 20% reduction in electricity prices is expected (Comisión Nacional de Energía, 2020).

### 3. Results and discussion

This section presents the results from parameter estimation used in this article and the projected emissions from firewood burning in households of southern and central Chile considering a BAU scenario, the four policy-based scenarios discussed in the previous section, and the impact of a potential energy poverty effect.

#### 3.1. Parameters to compute firewood consumption

Table 6 shows the odds-ratio derived from the logit regression model (equation (6)) for each of the southern and central regions. An odds-ratio greater than 1 means that an increment in the independent variable increases the probability to choose firewood as an energy source. If the odds-ratio is less than 1, an increment in the independent variable

**Table 6**

Odds-ratio of logit regression models for each region in southern and central Chile using the CASEN 2015 database.

|                                              | Region                                |                           |                           |                         |                         |                      |                         |
|----------------------------------------------|---------------------------------------|---------------------------|---------------------------|-------------------------|-------------------------|----------------------|-------------------------|
|                                              | O'Higgins                             | Maule                     | Bio-Bio                   | Araucanía               | Los Lagos               | Aysén                | Los Ríos                |
| <b>Income (<math>\beta_1</math>)</b>         | −0.0109***<br>(0.000942) <sup>a</sup> | −0.00380***<br>(0.000855) | −0.00630***<br>(0.000611) | −0.0201***<br>(0.00130) | −0.0557***<br>(0.00191) | −0.0117<br>(0.006)   | −0.0132***<br>(0.00264) |
| <b>Household size (<math>\beta_2</math>)</b> | 0.208***<br>(0.00297)                 | 0.184***<br>(0.00289)     | 0.194***<br>(0.00222)     | 0.173***<br>(0.00439)   | 0.315***<br>(0.00602)   | 0.219***<br>(0.0204) | 0.150***<br>(0.00865)   |
| <b>City Size (<math>\beta_3</math>)</b>      |                                       |                           |                           |                         |                         |                      |                         |
| Rural <sup>b</sup>                           | 2.146***<br>(0.0120)                  | 1.725***<br>(0.0104)      | 1.921***<br>(0.00923)     | 1.648***<br>(0.0143)    | 1.949***<br>(0.0231)    | 2.141***<br>(0.117)  | 1.809***<br>(0.0286)    |
| Small City <sup>b</sup>                      | 1.260***<br>(0.0132)                  | 0.837***<br>(0.0121)      | 0.983***<br>(0.00820)     | 0.726***<br>(0.0140)    | 0.527***<br>(0.0196)    | 0.948***<br>(0.0745) | 0.877***<br>(0.0357)    |
| Medium city <sup>b</sup>                     | 1.124***<br>(0.0181)                  | 0.549***<br>(0.0116)      | 0.615***<br>(0.00739)     | 0<br>(.)                | 0<br>(.)                | 0<br>(.)             | 0<br>(.)                |
| <b>Constant (<math>\alpha</math>)</b>        | −1.947***<br>(0.0156)                 | −0.999***<br>(0.0132)     | −0.435***<br>(0.00895)    | 0.894***<br>(0.0172)    | 1.639***<br>(0.0243)    | 1.984***<br>(0.0786) | 1.396***<br>(0.0353)    |
| <b>n (sample)</b>                            | 6900                                  | 5600                      | 11,039                    | 6944                    | 6106                    | 1149                 | 3295                    |
| <b>N (expanded)</b>                          | 270,234                               | 325,129                   | 614,588                   | 298,466                 | 270,083                 | 34,340               | 112,253                 |
| <b>Pseudo R-square</b>                       | 0.117                                 | 0.085                     | 0.080                     | 0.074                   | 0.091                   | 0.055                | 0.087                   |

\*p &lt; 0.05 \*\*p &lt; 0.01 \*\*\*p &lt; 0.001.

<sup>a</sup> Standard errors in parentheses.<sup>b</sup> Rural: less than 5000 inhabitants. Small city: more than 5000 and equal to or fewer than 20,000 inhabitants. Medium city: more than 20,000 inhabitants.

**Table 7**  
Ordinary least squares regressions results using CDT 2015 database.

| Explanatory variables                  | Firewood consumption (FU) |
|----------------------------------------|---------------------------|
| <i>Cat. income</i>                     |                           |
| Less than US\$306 (01)                 | 0                         |
| (Omitted category used to comparison)  | (.)                       |
| Between US\$306 and US\$459            | 1.135*                    |
|                                        | (0.444) <sup>a</sup>      |
| Between US\$459 and US\$612            | 1.031                     |
|                                        | (0.637)                   |
| Between US\$612 and US\$764            | 1.433***                  |
|                                        | (0.301)                   |
| Between US\$764 and US\$917            | 0.986*                    |
|                                        | (0.460)                   |
| Between US\$917 and US\$1070           | 0.824                     |
|                                        | (0.579)                   |
| Between US\$1070 and US\$1223          | 1.758***                  |
|                                        | (0.416)                   |
| Between US\$1223 and US\$1376          | 3.112***                  |
|                                        | (0.673)                   |
| Between US\$1376 and US\$1911          | 2.929***                  |
|                                        | (0.774)                   |
| Between US\$1911 and US\$2293          | 2.876***                  |
|                                        | (0.555)                   |
| Between US\$2293 and US\$2676          | 3.233***                  |
|                                        | (0.582)                   |
| Between US\$2676 and US\$3058          | 4.130***                  |
|                                        | (0.911)                   |
| Between US\$2676 and US\$3058          | 3.964***                  |
|                                        | (0.921)                   |
| Between US\$3058 and US\$3822          | 2.041**                   |
|                                        | (0.626)                   |
| More than US\$3822                     | 2.059**                   |
|                                        | (0.655)                   |
| <i>Rural</i>                           |                           |
| Urban                                  | 0                         |
| (Omitted category used for comparison) | (.)                       |
| Rural (02)                             | 0.286                     |
|                                        | (0.248)                   |
| <i>Region</i>                          |                           |
| O'Higgins region (03)                  | 0                         |
| (Omitted category used for comparison) | (.)                       |
| Maule region                           | -0.0370                   |
|                                        | (0.199)                   |
| Bio-Bio region                         | 1.860***                  |
|                                        | (0.246)                   |
| Araucanía region                       | 3.946***                  |
|                                        | (0.369)                   |
| Los Lagos region                       | 9.277***                  |
|                                        | (0.390)                   |
| Aysén region                           | 14.03***                  |
|                                        | (0.526)                   |
| Los Ríos region                        | 10.45***                  |
|                                        | (0.396)                   |
| Constant ( $\gamma$ )                  | 1.945***                  |
|                                        | (0.299)                   |
| n (sample)                             | 2220                      |
| N (expanded)                           | 1,581,193                 |
| R-square                               | 0.505                     |

\* $p < 0.05$  \*\* $p < 0.01$  \*\*\* $p < 0.001$ .

<sup>a</sup> Standard errors in parentheses.

decreases the chances of choosing firewood as the main energy source.

Table 6 show that the probability of choosing firewood as an energy source decrease in higher income and larger households, as the related parameter is negative and statistically significant. Conversely, the chances to consume firewood increase if the household is located in a rural settlement and decrease in small and medium cities in most of the regions. All the parameters ( $\alpha$ ,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ) are statistically significant with a p-value less than 0.01.

Table 7 show the lambda and theta parameters estimated by the linear regression model (equation (7)) most of which are statistically significant. In this case they represent the linear statistical relationship

between the magnitude of firewood consumption and the explanatory variables (rurality, region and income). Based on the statistical significance of most parameters it can be concluded that the average firewood consumption increases in southern regions of Chile (Aysén, Los Lagos, Los Ríos, see Fig. 1), which is expected due to lower temperatures in southern Chile. Also, the magnitude of firewood consumption is higher in middle income households reaching up to 4 stere meters (cubic meter of stacked firewood) more than the households in the lowest income category. In the highest income households, this quantity corresponds to 2 stere meters but is still larger than poorer households.

When the theta parameter is not statistically significant, as in the rural case, Maule Region, and some categories of income, we assume that there is no statistical difference in this condition related to the base category used for comparison (see Table 7). Hence, the parameter is not used in the estimation.

### 3.2. Policy-based scenarios

In this section, the Business as Usual scenario is presented, together with the four policy based scenarios summarized in Table 7. From Fig. 2a, it can be observed that in a Business as Usual scenario, total PM2.5 emissions from firewood burning in households in southern and central cities increase 16% from 129 Kt in 2017 to 149 Kt in 2050, driven by a 7% increase in the number of households that consume firewood (see Fig. 2a and b). These trends vary geographically. From Fig. 2c, PM2.5 emissions increase over 20% in O'Higgins and Araucanía regions but less than 10% in Aysén. In some cities the quantity of firewood consumers increases only by 3% between 2017 and 2050 (especially in Biobío Region), up to 12% in cities of Los Lagos Region (not shown in graph).

PM2.5 emission trends are driven by the total quantity of households and the proportion of these households that choose firewood as its primary energy source. Current ADP stove/heater replacement goals reduce firewood users between 2017 and 2025, but if no additional policy efforts are implemented after this period, total firewood consumers increase over time (see Fig. 2b).

In the scenario with wood pellet replacement at current scale (i.e., Restricted Wood Pellet), the percentage of firewood users is reduced at a fast pace between 2025 and 2050, and consequently, PM2.5 emissions are strongly affected by this change. From Fig. 2a, PM2.5 emissions in the central and southern urban areas (with active ADP) decrease by 5%, from 129 Kt in 2017 to 122 Kt in 2050.

As shown in Fig. 2c the degree of reduction of emissions varies geographically. It is much more significant in Aysén, where the projected decline in 2050 is 43% (the triangle in Fig. 2c) compared to its 2017 level, and in the urban centers of O'Higgins 16% (the triangle in Fig. 2c). In comparison, in cities where this scenario is not applied (i.e., no ADP in place), emissions increase by an average of 16% in the same period.

The main driver of these reductions is the decrease in the proportion of firewood users of between 1 and 5% annually from the replacement of firewood stoves with wood pellet or electric sources. As a result, in central and southern cities, the proportion of firewood users decreases from 63% of households in 2017 to 23% in 2050. In cities of Aysén and Araucanía Region, this indicator falls from 88.1% to 15.7% and 80.9%–27.8% in the same period, respectively.

From Fig. 2a, under the scenario where these measures expand to a Regional scale, i.e. to all cities in central and southern Chile (the Extensive Wood Pellet scenario), PM2.5 emissions are reduced by 54%, from 129 Kt in 2017 to 59 Kt in 2050. Major reductions are projected, especially in Los Ríos and Los Lagos Regions, where total emissions are reduced up to 80% in 2050 compared to 2017 (see Fig. 2c). This major reduction is caused by the synergies between an energy demand reduction of improved dwellings and rapid firewood stove replacement.

In the case of the Restricted Electric scenario, emission reductions are similar to the restricted wood pellet scenario. This is because under

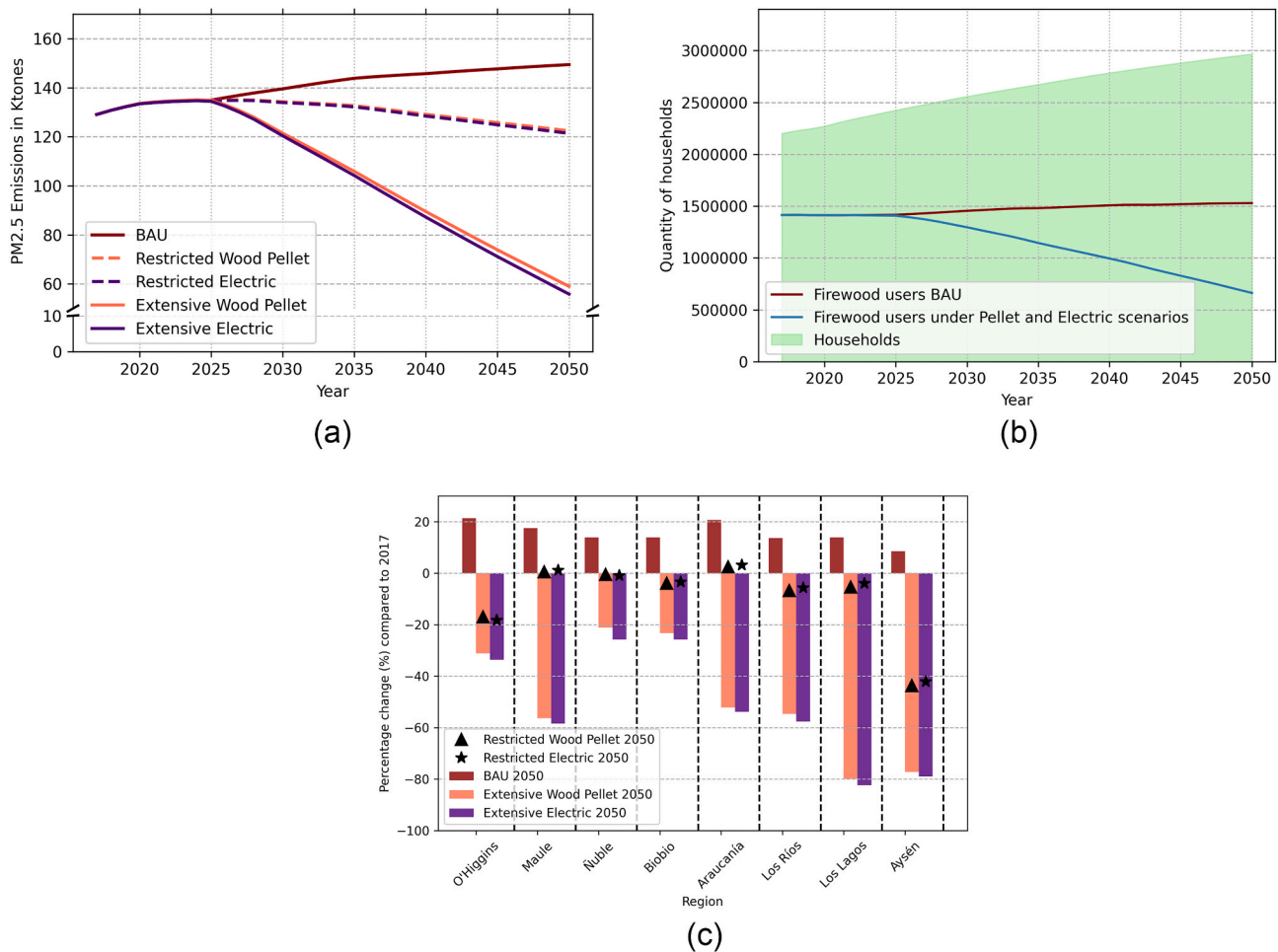


**Fig. 2. Regional emission trajectories and firewood users under policy-based scenarios.** a) PM<sub>2.5</sub> emissions trajectories under policy-based scenarios (2017–2050). Note that the Y-axis has been compressed to facilitate reading. b) Total quantity of households and quantity of firewood users under BAU and Regional IP scenarios (Pellet and Electric) 2017–2050. c) Percentage change between 2017 and 2050 in Business as Usual, Wood Pellet and Electric scenarios.

both scenarios the number of firewood users that switch to the new technology is the same (the same number of subsidies are handed out), and emissions from wood pellet heaters are relatively low, reaching only 2 kt in 2050. Under this scenario as a result, emission levels fall from 129 Kt in 2017 to 121 Kt in 2050, a slightly larger reduction (1%) than the Restricted Wood Pellet scenario.

When this measure is implemented in all cities of southern and central Chile (i.e., Extensive Electric scenario), the expected reduction is much higher. In fact, under the Restricted Electric scenario a 6% reduction in PM<sub>2.5</sub> emissions is projected, but when this policy expands to all other cities in the center and southern areas, a 56% reduction in PM<sub>2.5</sub> emissions is achieved, reducing emissions from 129 Kt in 2017 to 55 Kt in 2050 (Fig. 2a).

These results suggest that a significant reduction of PM<sub>2.5</sub> emissions would be obtained only under an extensive regional application of the wood pellet and electric scenarios.

### 3.3. Energy poverty effects on policy-based scenarios

The PM<sub>2.5</sub> emission reductions commented above assume 100% effectiveness of thermal improvements and complete adoption of stove/heater replacement programs. However, as discussed in Section 2.4, preexisting energy poverty conditions are expected to negatively impact the effectiveness of policies, due to both the pre-rebound effect and household rejection. To quantify this, we present PM<sub>2.5</sub> reductions computed under partial adoption and incomplete effectiveness of the

measures due to this double energy poverty effect.

Fig. 3a shows the expected reductions of PM<sub>2.5</sub> emissions considering the two energy poverty effects on the policy-based scenarios, where thermal retrofits of older dwellings are combined with wood pellet and electric stove/heater replacement. The scenario using wood pellets would cause a 53% reduction of PM<sub>2.5</sub> emissions if full implementation (i.e., no energy poverty effect) is considered, however under the partial adoption scenario (i.e., with energy poverty effect) a 37% reduction is projected. This 16% difference in the emission reduction is a measure of the energy poverty effect. This large difference is because the projected monthly costs of using wood pellet stoves is greater than 5% of household incomes in 15% of the households in 2017 and 9.5% in 2050. We assume this would cause the rejection of the new technology by these households.

Under the Extensive Electric scenario with high efficiency air conditioners full implementation results in a 55% emissions reduction. When partial implementation is considered, this reduction only reaches 47%, an energy poverty effect of 8%, because the rejection of the new technology would be relatively low: 10% of household would have excessive expenditure in 2017 decreasing to 4.1% in 2050. Due to the efficiency of the appliances, the monthly energy bill would be relatively low and acceptable to most households. However, if new air conditioners have a low efficiency, their operational costs would be significant, triggering a higher rejection rate. Consequently, partial implementation would result in an emission decrease of only 31% compared to the base year, an energy poverty effect of 24%. In this case,

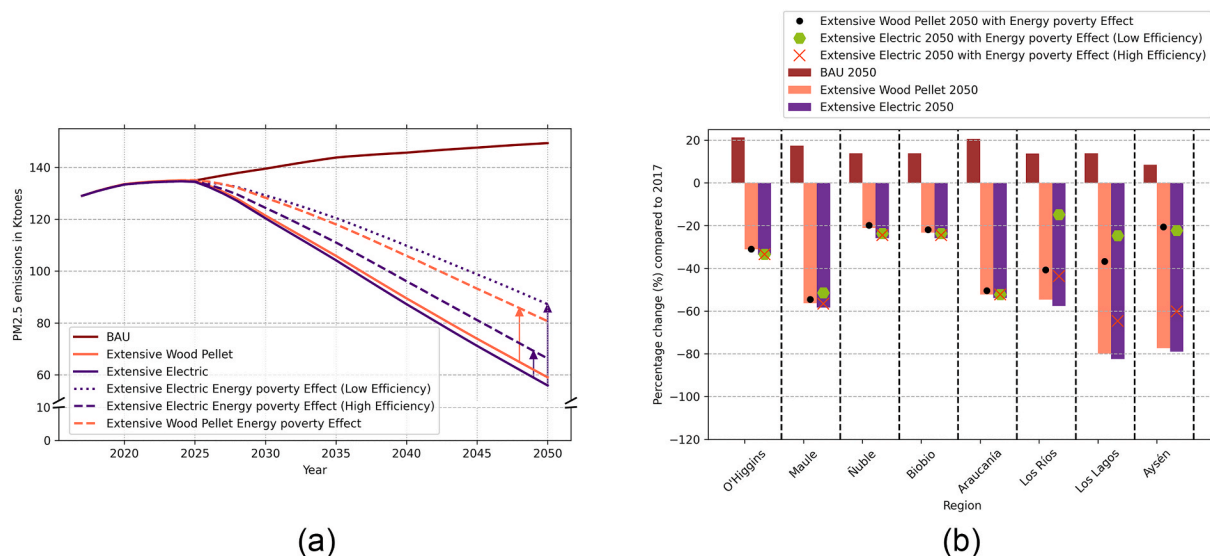


**Fig. 3. Regional emission trajectories and firewood users under policy-based scenarios.** a) PM2.5 emissions trajectories under BAU and policy scenarios with energy poverty effect (2017–2050). Note that the Y-axis has been compressed to facilitate the reading of the trajectories. b) Percentage change on PM2.5 emissions between 2017 and 2050 in Business as Usual, Wood Pellet and Electric scenarios with and without energy poverty effect by region.

the proportion of households with energy expenditures above 5% of their income varies from 24% in 2017 to 17% in 2050.

The combined impact of these two energy poverty effects is different across regions. In urban areas where current firewood technology used is inefficient and/or energy demand is lower than in other southern cities (for example, O'Higgins, Maule, Biobío, Ñuble, and Araucanía), the use of wood pellets is a cost-effective and convenient alternative for households, resulting in an energy poverty effect of less than 2%. However, in regions such as Los Lagos, Aysén, and Los Ríos, with higher energy expenditure by households due to lower average temperatures, the expected energy poverty effect of using wood pellets would be greater, 43%, 56%, and 13%, respectively (see Fig. 3b).

In the case of electricity, when using a high-efficiency appliance, the energy poverty effect is relatively low – less than 3% – in O'Higgins, Maule, Biobío, Ñuble, and Araucanía regions. On the other hand, if low-efficiency appliances are used, this effect is greater and would reach 55%, 39%, and 54% in Los Lagos, Los Ríos, and Aysén Regions, respectively.

In all these cases, the household rejection effect has the largest impact on emission reductions, while thermal retrofits of dwellings are lower albeit important (around 30%). Hence, while stove/heater replacement reduces PM2.5 emissions at a faster pace and in a greater proportion, it is also a riskier alternative as it puts more pressure on the already low family budget.

### 3.4. Discussion

The results presented here highlight the relevance of including energy poverty conditions in air quality policies based on technological change of household's energy use. Although restricted, the approach used in this article to include energy poverty could improve *ex ante* evaluation of air quality and energy transition policies options in countries with data restrictions, as is the case of Chile and most developing countries. The concept of energy poverty used here is restricted to high energy expenditure (household rejection) and pre-existing thermal discomfort (pre-rebound effect), so other relevant aspects of this phenomenon are not included. For example, the affordability of modern appliances to cook food and heat water, the perception of thermal discomfort, and the quality of electric services are relevant factors to foster change in the context of air quality policies but also for decarbonization pathways.

The scenarios developed here consider energy for heating because central and southern Chile have temperate to cold climate conditions. However, cooling may become an issue in parts of the country since anthropogenic climate change is expected to increase the average temperature in central Chile between  $\sim 1.2$  °C (RCP2.6) and  $\sim 3.5$  °C (RCP8.5) during the XXI century (Bozkurt et al., 2018). This increment in average temperature could reduce energy demand for heating but increase energy requirements for cooling in parts of the country not accustomed to higher temperatures, and possibly reduce PM2.5 emissions from residential firewood use. However, this change would probably not occur in a short-time period as prices of air conditioners are relatively expensive for household incomes (Calvo et al., 2021) and sociocultural structures takes longer time to change. Nonetheless, air conditioners present a better alternative compared to wood pellets stoves in the long-term perspective for technological change in some parts of central Chile, as they could be used both for heating and cooling needs.

From a methodological perspective, the PM2.5 emissions estimations presented have uncertainties related to incomplete information on the determinants of PM2.5 emissions factors such as humidity of firewood, trees species used, operational use of wood stoves, among others mentioned by Álamos et al. (2021a,b). Because there is insufficient information to project changes in emission factors, we assume that they are constant over time, hence, not including possible autonomous improvement of firewood technology that reduces PM2.5 emissions. This could result in an over-estimation of PM2.5 emissions under a Business as Usual scenario. However, since firewood stoves have a use time of approximately 20 years the most likely scenario is that households would choose to change to other energy sources (gas, electricity, wood pellet) rather than improve their firewood stove in the long term.

Also, autonomous technological change to cleaner energy sources (wood-pellet, electricity) is included under our Business as Usual scenario as a result of income increasing over time. However, the income increment projected in this scenario is not high enough to reduce the quantity of firewood users in a significant magnitude. For this reason, government policies are the main source of technological change based on subsidies to improve energy efficiency of dwellings and stoves/heater replacement. The magnitude of the subsidies required in both the restrictive and extensive wood pellet and electricity scenarios are of the similar magnitude to the current Atmospheric Decontamination Plans (ADP) already implement in a year-to-year basis.

#### 4. Conclusions and policy implications

This study presents an assessment of the impact of policy measures on reducing PM<sub>2.5</sub> emissions in Chile and quantifies the potential impact of energy poverty conditions on the effectiveness of these measures in the 2017–2050 period. It also explores how extending policies to reduce PM<sub>2.5</sub> emissions to more cities in southern and central Chile could further reduce these emissions. Specifically, using scenarios based on econometrically estimated parameters, we quantify PM<sub>2.5</sub> emissions under different policies between 2017 and 2050 considering two probable energy poverty effects: pre-rebound effect due to pre-existing energy under consumption and household rejection of new heaters due to higher monthly costs on mitigation policies (thermal retrofit and stove replacement).

The current Atmospheric Decontamination Plans (ADPs), that are implemented up to 2027, have projected a significant reduction of PM<sub>2.5</sub> emissions for that year in the cities included, to below the national air quality standard. However, the results of the BAU scenario show that increased firewood use after 2027 in these cities together with increases in emissions in many medium and large cities not considered in ADP's, will produce an overall 16% increase in PM<sub>2.5</sub> emissions in 2050. This signals the need to incorporate more effective and large-scale policies to reduce emissions and related health impacts.

Under policy-based scenarios, if energy poverty effects are not considered, the restricted wood pellet and electricity scenarios for cities currently under ADPs would allow a decrease in 5% and 6% respectively in total emissions in 2050. This result can be improved on significantly if other medium to large cities are included in the ADP program (our extended scenario): In this case a significant 53%–55% reduction in emissions is projected for 2050, respectively.

However, these reductions are significantly affected if the pre-existing energy poverty conditions result in a pre-rebound effect and household rejection effect. In fact, the 53% reduction under the extended wood pellet stoves is reduced to 37%. This is because many low-income households would not reduce firewood use due to pre-existing energy under consumption, and others would choose not to change given the increased cost involved in comparison to firewood. In the same way, the 55% reduction of an extended electric scenario is reduced to 47% when high-efficiency devices are used and to 31% when low-efficiency electric heating is preferred. Consequently, the energy poverty effect has a significant impact on expected emission reductions, particularly in the case of wood pellets and low efficiency air conditioners.

Indeed, if energy transition policies fail to integrate energy poverty conditions in their design and implementation, it could worsen many households' wellbeing. If technology change to cleaner but more expensive energy sources is implemented with no anticipatory or mitigating measures, these households will confront a difficult context of higher heating costs in low-efficiency dwellings. The results show that in 2050 between 4% and 17% of households would increase their heating energy expenditure above the 5% threshold and increase the risk of technological rejection.

To ensure the effectiveness of emission control measures and avoid possible pre-rebound effects related to energy poverty conditions, complementary actions should be taken such as: Improving the national standard of thermal insulation of new homes that would reduce energy demand and increase thermal comfort, reducing the possibilities of the pre-rebound effect due to pre-existing thermal discomfort conditions. Dissemination of energy efficiency practices and knowledge to users together with financial subsidies are two other complementary measures required to reduce the effects of household budget restrictions on the energy transition process, and particularly to reduce technology rejection. Finally, better data about pre-existing energy poverty conditions in Chilean homes will allow policymakers to better quantify the potential pre-rebound effect and household rejection and complement the design of current air quality policies.

Future research could include other possible causes for household rejection, for example the assumption that all households that change to other energy source have the required appliances to cook and heat water. Also, another relevant phenomenon to be analyzed relates to the perception of heat and the thermal comfort achieved from different energy sources, that could be another reason for households to reject technological change when electric or wood pellet stoves are considered.

#### Author contribution statement

Rubén Calvo: conceptualization, methodology, investigation, writing - original draft, review & editing. Nicolás Álamos: conceptualization, methodology, investigation, writing - original draft, review & editing. Nicolás Huneus: conceptualization, methodology, investigation, writing - original draft, review & editing and funding acquisition. Raúl O'Ryan: conceptualization, methodology, investigation, writing - original draft, review & editing.

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#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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