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EL EFECTO DE LA POBREZA ENERGÉTICA EN LA REDUCCIÓN DE CONTAMINACIÓN ATMOSFÉRICA POR MATERIAL PARTICULADO 2,5.

TESIS PARA OPTAR AL GRADO DE
MAGÍSTER EN GESTIÓN Y POLÍTICAS PÚBLICAS

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EL EFECTO DE LA POBREZA ENERGÉTICA EN LA REDUCCIÓN DE CONTAMINACIÓN ATMOSFÉRICA POR MATERIAL PARTICULADO 2,5.

La quema de leña residencial es la principal fuente de emisiones de PM2.5 en el centro-sur de Chile. A escala nacional, se observan aproximadamente 4000 muertes prematuras cada año debido a la contaminación del aire. Las políticas de mitigación suelen centrarse en reducir la demanda energética de las viviendas y fomentar el cambio tecnológico hacia fuentes de energía de calefacción más limpias pero más caras. Las condiciones de pobreza energética preexistentes a menudo se pasan por alto al diseñar estas políticas, y los posibles efectos rebote obstaculizan la efectividad y la adopción completa de estas medidas. Esta tesis utiliza el centro-sur de Chile como un estudio de caso para evaluar diferentes escenarios de políticas de mitigación de emisiones de PM2.5 entre 2017-2050, considerando los efectos de rebote relacionados con la pobreza energética. Los resultados muestran que las emisiones de PM2.5 crecen un 16% con el tiempo en un escenario normal. Si se implementan mejoras térmicas y reemplazos de estufas, se reducen las emisiones de PM2.5, un resultado que depende de la escala de la política: una reducción del 8%-9% de las emisiones totales de PM2.5 centro-sur si solo las ciudades actualmente con Planes de Descontaminación Atmosférica son beneficiarios; una reducción del 53% al 55% de las emisiones de PM2.5 si estas políticas incluyen otras ciudades en crecimiento en el área bajo estudio. El efecto rebote de la pobreza energética potencialmente reduce a la mitad la efectividad de estos debido al malestar térmico preexistente y los bajos ingresos familiares. Si no se toman medidas anticipatorias, las condiciones de pobreza energética podrían obstaculizar los objetivos de transición energética en estas ciudades y reducir la eficiencia de las políticas de mitigación para mejorar la calidad del aire.

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TABLA DE CONTENIDO

I. INTRODUCCIÓN

La contaminación atmosférica es uno de los principales desafíos en materia ambiental de Chile, ya que más de la mitad de la población nacional –al menos 10 millones de personas– se encuentran expuestas a concentraciones de Material Particulado 2,5 (MP2,5) y/o Material Particulado 10 (MP10) superiores a la norma vigente y que generan riesgos a su salud (MMA, 2014).

Si bien la contaminación atmosférica ha sido abordado por la política pública hace tres décadas en el caso de la Región Metropolitana, las ciudades del centro-sur de Chile se integran solo durante la última década al diseño de Planes de Descontaminación Atmosférica (PDA) (MMA, 2014). En el caso de estas ciudades, los PDA han reconocido como principal fuente de emisión de material particulado al uso residencial de leña (MMA, 2014). Esto fenómeno posee al menos dos efectos negativos.

En primer lugar, de acuerdo a informes de la Organización Mundial de la Salud, la contaminación atmosférica se relaciona directamente con muertes prematuras asociadas a enfermedades cardiovasculares y respiratorias, que se contabilizan en más de 3 millones de muertes prematuras por año en todo el mundo (Lelieveld, Evans, Fnais, Giannadaki, & Pozzer, 2015) cifra que a nivel nacional se estima en al menos 4 mil muertes prematuras (MMA, 2014).

En segundo lugar, la contaminación atmosférica está compuesta en parte por los llamados Compuestos Climáticos de Vida Corta (CCVC) o aerosoles, entre los que se encuentran el carbono negro que surge a partir de la quema de biomasa o combustibles fósiles (Gioda, 2019; Highwood & Kinnersley, 2006; IPCC, 2013; UNEP & WMO, 2011). Estos CCVC son co-emitidos con los llamados Gases de Efecto Invernadero, por lo que políticas públicas orientadas a mejorar la calidad del aire pueden aportar en mantener el calentamiento global bajo los 1.5ºC para el año 2050 (Brewer, 2019; IPCC, 2013; Yamineva & Liu, 2019).

A pesar de las acciones del Estado en esta materia, las concentraciones de material particulado 10 y 2,5 siguen estando sobre la norma en gran parte de las ciudades del sur de Chile. Por otro lado, las estimaciones de reducción de concentraciones, encontradas en las evaluaciones ex-ante de los PDA, no han tenido el impacto esperado dadas la complejidad en el cambio de hábitos de los usuarios y estructura del mercado de la leña.

Uno de los elementos no considerados dentro de esta política pública es la condición de pobreza energética que posee una proporción importante de los hogares que viven en el sur de Chile. Se entiende que un hogar se encuentra en pobreza energética cuando no tiene acceso equitativo a servicios energéticos de alta calidad (Red de Pobreza Energética, 2019b). En relación a los PDA, la pobreza energética tiene al menos dos resultados no esperados: el efecto rebote de las medidas de aislación térmica, que ocurre cuando la reducción del consumo energético de las medidas implementadas es menor a lo esperado debido a condiciones preexistentes de disconfort térmico (Sorrell & Dimitropoulos, 2008) y el agudizamiento de las condiciones de pobreza energética de tipo económico debido la sustitución de la leña por combustibles de mayor precio (Reyes, Schueftan, Ruiz, & González, 2019).

Frente a esto, se hace necesario estimar el efecto que tiene la pobreza energética como umbral para la transición energética planteada por los PDA. De esta forma, la pregunta de investigación de esta tesis es ¿Cuál es el efecto de la pobreza energética sobre la efectividad de los Planes de Descontaminación Atmosférica de las ciudades del centro y sur de Chile?

La hipótesis de este trabajo es que debido a que una gran proporción de hogares del sur de Chile viven en una condición de pobreza energética la efectividad de las medidas se ve reducida y la resistencia de los hogares al cambio tecnológico es mayor a la esperada. Por tanto, la reducción de concentraciones de material particulado es menor a la esperada por la política pública.

La relevancia de un acercamiento de este tipo radica en que integra aspectos sociales y de comportamiento de los usuarios a una evaluación típicamente realizada en base a supuestos tecnológicos y económicos. Asimismo, permite cuantificar en qué medida la pobreza energética de los hogares es una barrera para la transición energética hacia fuentes más eficientes y menos contaminantes en el sur de Chile. Finalmente, permite evaluar los criterios de focalización de los programas asociados a los PDA en la medida que describe más acertadamente las realidades de los hogares beneficiados.

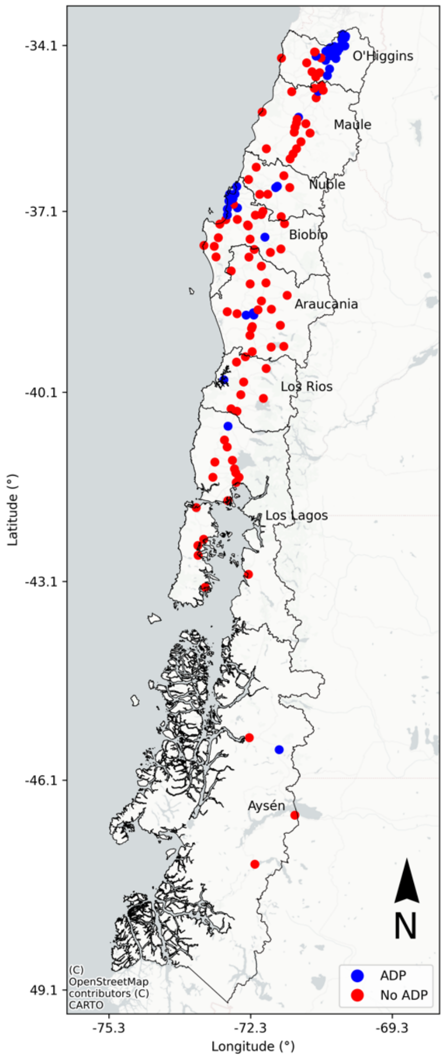
La metodología utilizada se basa en modelos econométricos que permiten estimar la cantidad de leña y emisiones de material particulado a nivel regional. Asimismo, en base a revisión de literatura científica se estima la magnitud del efecto rebote y de sustitución de combustible. Luego, se diseñan un conjunto de escenarios de política pública para proyectar en el tiempo la reducción de concentraciones de material particulado y el efecto de la pobreza energética en las medidas de los PDA.

A continuación se reproduce el texto del artículo titulado “Energy poverty effect on policy-based PM2.5 emissions mitigation in southern cities of Chile” enviado para evaluación a la revista Energy Policy y que presenta la metodología y resultados de esta tesis. La sección 2 presenta una dbreve descripción del caso de estudio, para luego en la sección 3 presentar la metodología utilizada. En la sección 4 se describen los resultados y finalmente se conluye con los principales hallazgos del trabajo e implicancias para la política pública.

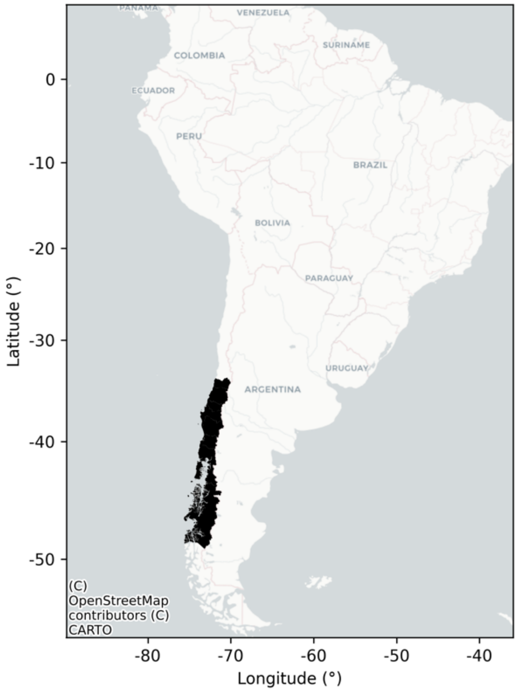
II. MARCO DE REFERENCIA

According to Census data from 2017, Chile's total population is roughly 17.5 million, with almost 90% residing in urban areas, and around 36% (6.3 million) in cities and settlements of center-south Chile (34° to 49° south, Figure 1a) (Instituto Nacional de Estadísticas, 2018a).

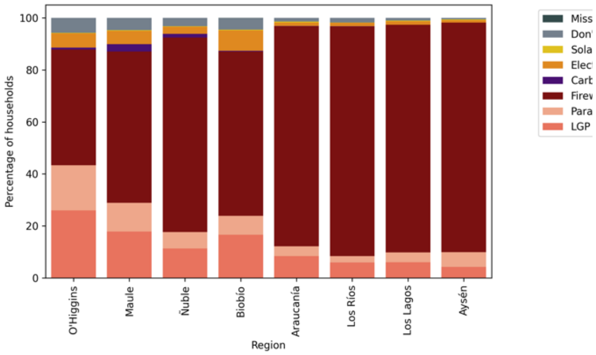
The climate in the center-south regions varies from temperate to polar (Sarricolea et al., 2017) and is characterized by a high presence of native forests and exotic plantations (Reyes et al., 2015). As shown by Figure 1c, the proportion of firewood household users becomes extremely relevant as we move towards the south. As a result of cold weather, the low thermal efficiency of most dwellings, and high prices of cleaner alternatives (i.e., electricity, gas), 80% of households in these southern cities use firewood for heating, cooking, and hot water systems (Urquiza et al., 2019). Most of the time, families use high humidity (>25%) firewood due to rainy weather, lack of infrastructure to dry the firewood, and informal production and distribution market (Reyes et al., 2019).



b. Center-southern Chile. Cities with (blue dots) or without (red dots) Atmospheric Decontamination Plan (ADP) are included. Names of each political region are also included.



a. South America with political division. The black area highlights the study region (center-southern Chile) illustrated in more detail in figure 1B.



c. Heating energy sources used by households in center southern regions. Source: (Ministerio de Desarrollo Social, 2017)

Figure 1. Case study description

III. MARCO METODOLÓGICO

This section presents the methodologies used to estimate residential PM2.5 emissions (section 3.1), based on emission factors, and to project future emissions considering the main drivers (section 3.2), different scenarios (section 3.3), and the energy poverty rebound effect (section 3.4).

1.1 PM 2.5 emissions

Residential PM2.5 emissions (RE) are computed based on firewood consumption and the corresponding emission factor as follows:

$$RE_{i,j} = TCF_{i,j} * EF_i \quad (1)$$

where $TCF_{i,j}$ is the total firewood consumption factor for each year j from the period 2017-2050 and each of the 16 administrative regions (i) in Chile (Figure 1b) and EF_i is the emission factor for each administrative region. Present emissions are taken from Álamos et al. (n.d.), where residential emissions are estimated for the period 2015-2017 based on multiple datasets (Corporación de Desarrollo Tecnológico, 2015; Instituto Forestal, 2019; Instituto Nacional de Estadísticas, 2018a; Ministerio de Desarrollo Social, 2015) and are distributed in space at a 1x1 km resolution. To assure continuity and consistency of emissions throughout time, estimated emissions in this article for the year 2017 are scaled to fit the corresponding emissions showed in Álamos et al. (n.d.).

In the absence of any reliable information on the potential evolution of emission factors of firewood heating technology and as a first-order approximation, constant emission factors are considered for the entire period 2017-2050, and therefore all variations (temporal and spatial) are solely driven by changes in the firewood consumption.

1.1.1 Firewood consumption datasets

Data on the quantity of firewood consumption in Chile is very scarce since only one national-wide survey has been conducted with special focus on this issue by the Technological Development Center in 2015 and financed by the Energy Ministry (Corporación de Desarrollo Tecnológico, 2015). Other relevant data at the national scale are the 2006 and 2013 Socioeconomic Characterization Survey, implemented by the Social Development Ministry, where firewood consumption was addressed in a large-sized questionnaire (Ministerio de Desarrollo Social, 2006, 2013).

Official estimations and projections of firewood consumption used in Chile to evaluate residential energy policies and national climate change mitigation plans are based on a top-down approach (MAPS Chile, 2014). In these estimations, it is assumed that household energy consumption varies according to GDP growth and also that sufficient thermal comfort is achieved when annual household income reaches up to US30.000-US$35.000, similar to what is observed in developed countries (Centro de Energia, 2019; MAPS Chile, 2014).

In this article, we use a bottom-up approach using data on firewood consumption and household socioeconomic characteristics found in the Technological Development Center database from 2015, the official source for firewood consumption at a national scale (CDT, 2015) and Socioeconomic Characterization Survey from 2015 (CASEN 2015) (Ministerio de Desarrollo Social, 2015) to complement data for household socioeconomic characteristics. An important advantage of this approach is that firewood consumption is estimated using household data. This allows better characterizing firewood use practices in the context of high energy poverty differentiating the use by socioeconomic conditions since these uses are different from estimates under ideal conditions (Galvin, 2015; Rojo et al., 2017; Urquiza et al., 2019).

1.1.2 Firewood consumption model

To estimate future residential firewood consumption, a regional scale model was developed for the period 2017-2050. This is a bottom-up model that projects future firewood consumption using sociodemographics and household variables as the main drivers. The selection of these variables is based on previous literature findings, where the most important household variables are income, household size, and its presence on urban or rural settlements (Bustos & Ferrada, 2017; Schueftan & González, 2013; Van Der Kroon et al., 2013).

The main equation of the model is:

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

where TFC is Total firewood consumption, AHFC is the *Average household firewood consumption*, QH is the *Quantity of households*, SRF is the *Saturation Rate of firewood users* corresponding to the proportion of firewood users in each region, and CF are corrections factor to the model. Total firewood consumptions are computed for each year j from the period 2017-2050 and each one of the 16 regions (i) in Chile.

Average household Firewood Consumption is estimated by the following equation derived from the Ordinary Least Square regression on CDT 2015 database.

$$AHFC_{i,j} = \alpha + \sum_{i=i}^{14} \beta_{1,i} \cdot cat\_income_{i,j} + \beta_2 \cdot urban_{i,)j} \qquad (3)$$

where AHFC is the *Average household firewood consumption*, *cat_income* is the proportion of households in one of the 14 levels of income (as shown in Table 1), and *urban* is the proportion of the population living in urban areas. The coefficients $\alpha, \beta_{1,} \beta_2$ are parameters estimated by an Ordinary Least Squares Regression analysis using CDT 2015 database. These parameters describe the statistical relationship between firewood consumption and household income and its presence in an urban settlement.

Table 1 Income household categories used in AHFC equation

Monthly Income categories in CLP Pesos	**USD equivalences (2015 annual average)**
Less than CLP$200.000	Less than US$306
Between CLP$200.000 and CLP$300.000	Between US$306 and US$459
Between CLP$300.000 and CLP$400.000	Between US$459 and US$612
Between CLP$400.000 and CLP$500.000	Between US$612 and US$764
Between CLP$500.000 and CLP$600.000	Between US$764 and US$917
Between CLP$600.000 and CLP$700.000	Between US$917 and US$1070
Between CLP$700.000 and CLP$800.000	Between US$1070 and US$1223
Between CLP$800.000 and CLP$900.000	Between US$1223 and US$1376
Between CLP$1.000.001 and CLP$1.250.000	Between US$1376 and US$1911
Between CLP$1.250.001 and CLP$1.500.000	Between US$1911 and US$2293
Between CLP$1.500.001 and CLP$1.750.000	Between US$2293 and US$2676
Between CLP$1.750.001 and CLP$2.000.000	Between US$2676 and US$3058
Between CLP$2.000.001 and CLP$2.500.000	Between US$3058 and US$3822
More than CLP$2.500.001	More than US$3822

The Quantity of households in the 2017-2050 period is projected by the equation:

$$QH_{i,j} = \frac{TP_{i,j}}{HS_{i,j}} \qquad (4)$$

where TP is the *Total population* for region i on year j, and HS is the *Average household size* in region i on year j.

The proportion of firewood users (or *Saturation rate of firewood users;* SRF) is derived from the logistic regression on CASEN 2015 database.

$$SRF_{i,j} = \alpha + \beta_{1,j} \cdot income_{i,j} + \beta_{2,j} \cdot urban_{i,j} + \beta_{3,j} \cdot HS_{i,j} + \sum_{i=1}^{5} \beta_{4,j} \ \cdot CS_{i,j} \qquad (5)$$

where *income* is the average household total income, *urban* is the proportion of the population living in urban areas, and CS is the proportion of households living in each five categories of city sizes (small, medium-small, medium, large, metropolis). The parameters $\alpha, \beta_{1,}\ \beta_2, \beta_{3,}\ \beta_4$ describe the statistical relationship between these variables and firewood consumption and are estimated by the Logistic Regression analysis using CASEN 2015 database for each region (Ministerio de Desarrollo Social, 2015).

A Correction Factor (CF) is applied to equation (1) to avoid possible biases on the average consumption and saturation rate (Figure 2), based on the following:

i. An improved thermal efficiency standard is assumed for new dwellings at a national scale, as it is already used in cities with currents ADP and is probably to be implemented in other cities. This seeks to reduce the annual firewood consumption based on this new thermal standard according to the dwelling's previous characteristics.
ii. According to government commitments, the current pace of firewood stove replacement will be maintained in cities currently with ADP (ending on average in 2027). Hence, reducing the number of firewood users in the same magnitude as the government stoves replacement program to cleaner alternatives (i.e., gas, electricity, or wood pellets).
iii. As cities grow, apartment buildings become more present and, hence, removing the possibility of using a firewood stove. In the absence of a more precise land-use model and city growth model, this estimate maintains observed trends of new building construction in the 1992-2017 period.

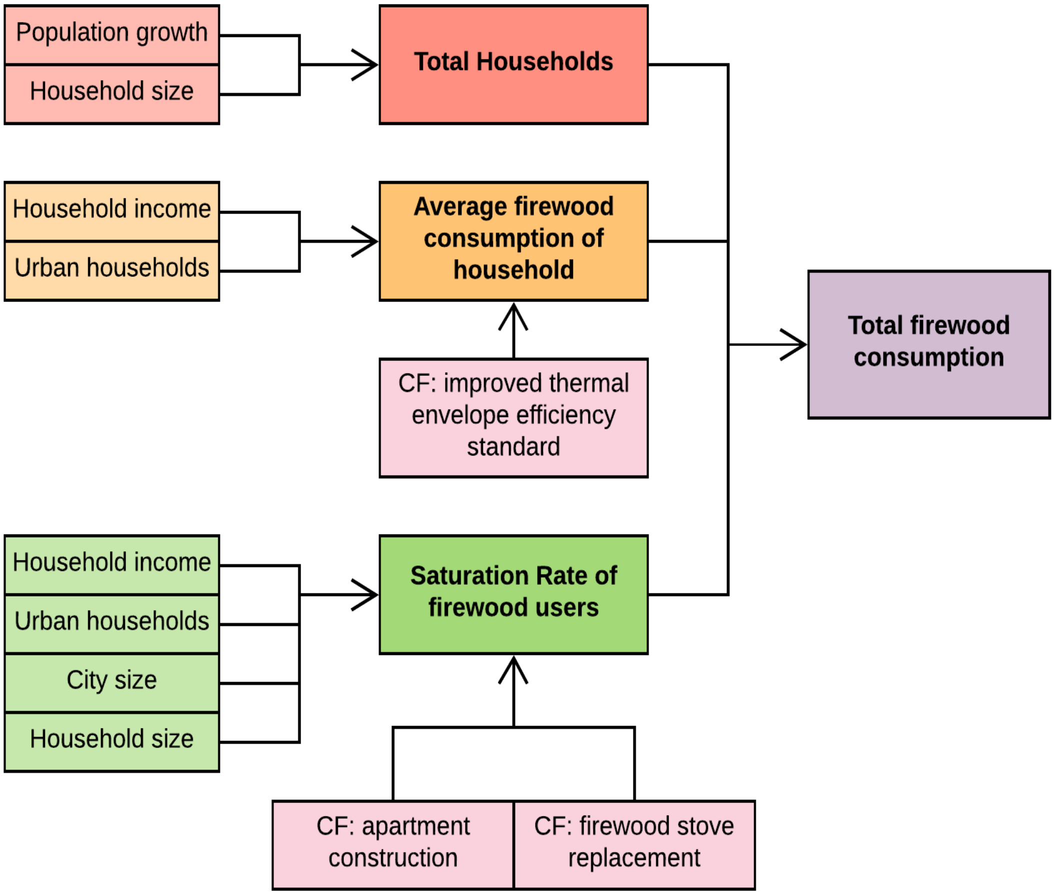


Figure 2. Schematical representation of the firewood consumption model.

1.2 Projection of drivers

To project the emissions, based on the drivers of this model, we use the following data sources and methods:

- **Household income** between 2015-2050 is projected under a Business as Usual scenario with average GDP growth of 4% using the General Equilibrium Model used in O'Ryan et al. (2020). Decile income percentage variation obtained from this model is applied to the CASEN 2015 household sample to obtain an income distribution for each year and are then regrouped according to the 14 levels of income from the CDT 2015.

- To estimate the **quantity of households,** we use national population projections (Instituto Nacional de Estadísticas, 2018, 2019b), and the average household size is determined using the Mitigation Action Plans and Scenarios initiative (MAPS) model where GDP growth is its main driver (MAPS, 2014).
- To estimate the **proportion of urban households,** we use the official national population projection between 1992-2050, developed by the National Statistics Institute (Instituto Nacional de Estadísticas, 2018a, 2018b, 2019)
- To estimate **city-size,** we use national population projections at the communal level (Instituto Nacional de Estadísticas, 2018a, 2018b, 2019), as in Chile, the correspondence between spatial boundaries of communes and cities is consistent. In the case of major cities, the total population of conurbation communes was aggregated.

1.3 Future emission scenarios

Seven different scenarios were implemented using our model only in urban areas of center-southern regions as they are suffering from higher concentrations and are subject to ADP policies (see figure 1b). First, in a Business as Usual (hereafter BAU) scenario, the pace of present stove 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 are made to incorporate new technologies and energy sources in the residential sector. The BAU scenario also assumes an improvement of average thermal standard as newer dwellings are constructed based on ADP thermal retrofit standards.

Three policy-based scenarios are generated focusing on: thermal retrofits of dwellings hereafter referred to as Dwelling Energy Efficiency (DEE) scenario, wood pellets stoves replacement referred to as Energy Transition to Wood Pellets (ETWP) scenario and electric heating in the

Energy Transition to Electricity (hereafter ETE) scenario. Each one of these scenarios is applied initially only to cities currently (CC) with an ADP. Then, two Integrated Policy scenarios (IP) are estimated where thermal retrofits are complemented both for wood pellets and electric heating devices.

In the DEE scenario, air quality measures are implemented focusing on the thermal retrofit of older dwellings (construction year prior to the year 2000). The goal of this policy is to improve the thermal efficiency of ~17,000 older houses annually to an ADP thermal standard, meaning on average a 33.7% reduction in energy demand in improved dwellings (Ambiente Consultores & PRIEN, 2007; Creara Consultores, 2013a, 2013b; GreenLabUC, 2013).

The Energy Transition to Wood Pellets scenario focuses on government subsidies to firewood stove replacement over 2017-2050, a more extensive period than present ADP stove replacement programs, which end on average in 2027. The annual stove replacement subsidies increase to ~13.000, a more ambitious goal than the current ADP. In this scenario, Wood Pellets are preferred over gas or electric heating devices because of the importance of forest resources to local economies, and it is the second-best alternative (compared to firewood) from a cost-effective point of view at the household level (Schueftan & González, 2013).

Energy Transition to Electricity assumes the same conditions and implementation pace of EWTP scenario, but firewood stoves are replaced with electric heating devices with high energy efficiency (e.g., inverter technology) instead of using wood pellets. This scenario also assumes a reduction in KWh prices as a result of a special bidding process, where generation companies could offer a reduced price exclusively to heating consumption. This program is a novel addition to ADP in Chile and is implemented by Energy Ministry and Distribution companies; a 20% reduction in electricity prices is expected (Comisión Nacional de Energía, 2020).

Finally, two Integrated Policy scenarios (IP) are estimated, where both thermal retrofit and stove replacement programs are implemented – both for Wood Pellet (IP-ETWP) and Electricity heating devices (IP-ETE). Hence these scenarios assume a reduced energy demand of beneficiary households and a higher energy efficiency of the technology used.

Additionally, these Integrated Policy scenarios are estimated under two different conditions each. First, a Current-Cities (CC) scale condition, where only cities currently under an ADP policy are beneficiaries of these public programs. Second, a Regional-scale condition (R), where policy measures are extended to every city in the center-south regions. This regional-scale application would increase thermal retrofits from ~17,000 annual subsidies in cities with ADP to ~22.000 dwellings between ~2027-2050. Stove replacement subsidies also increased at a regional scale, from ~13.000 to ~35.000 subsidies in the same period.

Table 2 Summary of measures under policy-based scenarios.

Measures	**BAU**	**DEE**	**ETWP**	**ETE**	**IP-ETWP-CC**	**IP-ETWP-R**	**IP-ETE-CC**	**IP-ETE-R**
Thermal retrofits	ADP	ADP and ~17.000 annually in 2025-2050 period.	ADP	ADP	ADP and ~17.000 annually in 2025-2050 period.	ADP and ~22.000 annually in 2025-2050 period.	ADP and ~17.000 annually in 2025-2050 period.	ADP and ~22.000 annually in 2025-2050 period.
Stove replacements	ADP	ADP	ADP and ~13.000 annually in 2025-2050 period.	ADP and ~13.000 annually in 2025-2050 period.	ADP and ~13.000 wood pellet stoves annually in 2025-2050 period.	ADP and ~35.000 wood pellet stoves annually in 2025-2050 period.	ADP and ~13.000 electric heating annually in 2025-2050 period.	ADP and ~35.000 electric heating annually in 2025-2050 period.
Scale of policy	Current-Cities	Current-Cities	Current-Cities	Current-Cities	Current-Cities	Regional	Current-Cities	Regional

1.4 Energy poverty rebound effect

Energy poverty relates to the lack of access to high-quality and affordable energy services, reducing the chances of households' human and economic development (Urquiza et al., 2019). According to the authors, essential energy services (i.e., cooking, sanitation, lighting, diverse electric appliances, and dwelling heating) must meet four criteria: adequacy, reliability, safety, and low indoor pollution (Urquiza et al., 2019). An energy-poor household suffers from diverse adverse effects on persons' wellbeing: thermal discomfort and low indoor temperatures that pose a risk to its inhabitant's health, lack of access to modern electrical appliances, economic and academic inequality (Lu, 2020; Thomson et al., 2017).

Thermal retrofit measures are not 100% effective in energy-poor households, and energy consumption reductions are lower than expected (Calì et al., 2016; Galvin, 2015; Galvin & Sunikka-Blank, 2013b, 2016; Sierra et al., 2018; Teli et al., 2016). Due to pre-existing thermal discomfort, thermal retrofits allow energy-poor households to achieve minimum indoor temperatures at the expense of not reduce their energy consumption as estimated under ideal conditions.

The effectiveness of this kind of measures is uncertain as diverse studies have shown that expected energy savings are reduced by 10%-50% due to pre-existing insufficient energy consumption, dwelling characteristics, and household income (Galvin, 2014, 2015; Galvin & Sunikka-Blank, 2013a, 2016; Greening et al., 2000; Teli et al., 2016; Webber et al., 2015) associated with the energy poverty context (Urquiza et al., 2019). Hence, expected energy demand reduction from thermal retrofit scenarios in this article is estimated considering both 100% (full) and 60% (partial) effectiveness to address energy poverty pre-existing conditions in low-income context (Galvin, 2014; Galvin & Sunikka-Blank, 2013a, 2016; Teli et al., 2016; Webber et al., 2015).

The second probable impact of energy poverty is related to the household's budget restrictions due to cleaner but more expensive energy sources. The economic dimension of energy poverty has been a frequent topic in this literature (Moore, 2012; Thomson et al., 2017; Urquiza et al., 2019), and there is a wide range of definitions and indices to measure economic energy poverty. One of the most used methodologies is called the 10% rule indicator and classifies a household as energy-poor when its total 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). To include the economic energy poverty effect, we estimate equivalent energy expenditure using wood pellets and electricity from average firewood household consumption. If this projected expenditure exceeds 5% of household disposable income (Bhatia & Angelou, 2014, 2015; Boardman, 1991, 2014), we assume that households would reject the technological change. Stove replacement policy is estimated both for partial adoption using this assumption and for a complete adoption scenario (without rebound effect).

As electric heating devices have different energy efficiency standard, the rebound effect was estimated using a high-efficiency appliance (3.5 Coefficient of Performance 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. However, these estimations do not consider the potential losses of performance in extremely cold conditions, as is common in southern Chile (Ruhnau et al., 2019; Sarricolea et al., 2017), causing an increase in the energy consumption required to achieve previous thermal comfort. In addition, the wood pellets stove market in southern Chile is not so diversified as the technology is relatively standard in terms of efficiency (0.8 Coefficient of Performance).

IV. ANÁLISIS DE RESULTADOS

This section presents expected emissions from firewood burning in households of south center Chile considering a business as usual scenario, the seven policy-based scenarios discussed in the previous section, and the impact of a potential energy poverty rebound effect.

1.5 Policy-based scenarios at current cities scale

Under a Business as Usual scenario, total PM2.5 emissions from firewood burning in households in the south-central cities increase 16% from 125 Kt in 2017 to 145 Kt in 2050, driven by an 8% increase in the number of households that consume firewood (see Figure 3a and 3b). This trend varies geographically, as in some cities the quantity of firewood consumers increases only by 3% between 2017-2050 (especially in Biobío Region), up to 12% in cities of Los Lagos Region, and a maximum of 21% growth on PM2.5 emissions in O'Higgins Region's central city.

PM2.5 emissions are influenced by the total quantity of households and the proportion of these households that choose firewood as its primary energy source (Saturation Rate). Current ADP stove replacement program goals reduce firewood users between 2017-2025, but if no additional policy efforts are implemented after this period, total firewood consumers increase over time (see figure 3b).

Under a Dwelling Energy Efficiency scenario at the current-cities scale (DEE-CC), the number of firewood consumers follows the same BAU scenario trend as no technological change is fostered. In this scenario, total PM2.5 emissions increase up to 139Kt in 2050, showing a 10% increase compared to the base year (see figure 3a). Nonetheless, thermal retrofit measures reduce the firewood consumption on average by 34% in beneficed households, hence the 10% increment of emissions projected under this scenario is caused mainly by large cities without current ADP measures (e.g., cities in Los Lagos Region).

Under the DEE scenario, the main driver of emissions reduction is the change in Average Household Firewood Consumption due to better thermal insulation. The resulting reduction of the base heating energy demand of improved dwellings ranges from 12% to 62% depending on pre-existing conditions and house typology (Corporación de Desarrollo Tecnológico, 2010; Creara Consultores, 2013; GreenLabUC, 2013). Average household firewood consumption drops from 5.9 m^3 to 4.3 m^3 on average in the central south region, where in some cases, this reduction is greater in absolute magnitude – ie. Aysén City reduces consumption from 17.5 m^3 to 13.6 m^3 between 2017 and 2050.

For the EWTP-CC scenario, the percentage of firewood users is reduced at a very fast pace between 2025-2050 in cities with ADP, consequently, PM2.5 emissions are strongly affected by this change; total PM2.5 emissions are reduced by 6% from 125 Kt in 2017 to 117 Kt in 2050. This reduction is much more significant in Coyhaique (Aysén Region), where the projected decline is 54% compared to its 2017 level, and in the urban centers of O'Higgins, the expected reduction is up to 16%.

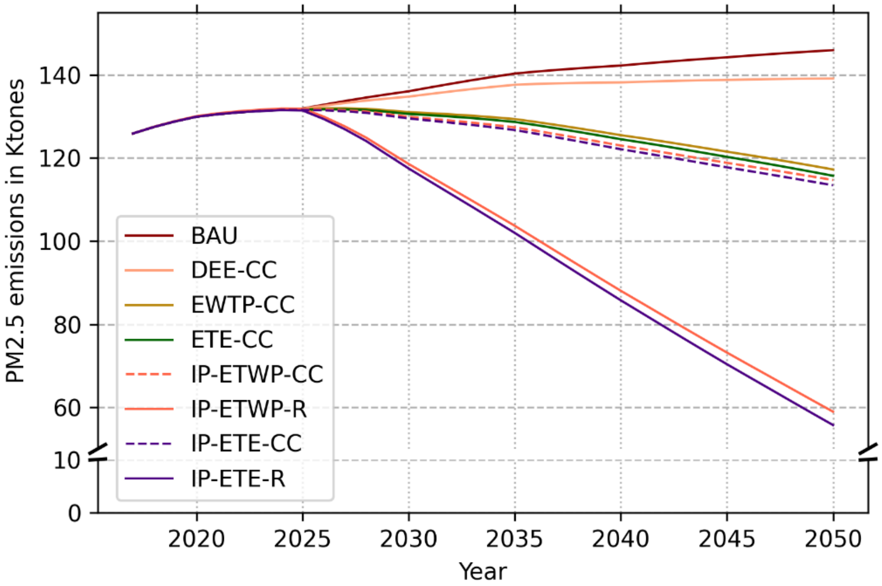
The main driver of these reductions is the drop in the Firewood Saturation Rate (proportion of households consuming firewood) of between 1-5% annually, resulting in extensive technological change and the removal of a major fraction of firewood stoves (see figure 3b). In central-south cities, the Saturation Rate of firewood stoves decreases from 61.9% of households in 2017 to 25.1% in 2050. In Aysén and Araucanía Region, this indicator falls from 88.1% to 15.7% and 80.9% to 27.8% in the same period, respectively.

When the public subsidies are focused on electric heating devices (ETE scenario), the expected reduction of firewood users is the same under the ETWP scenario since the same number of subsidies were considered. However, PM2.5 emissions are different since under the ETWP scenario PM2.5 particles are still emitted as a result of combustion. As a result, under the ETE scenario emissions levels fall from 125 Kt in 2017 to 115 Kt in 2050, a slightly larger reduction (2%) than ETWP.

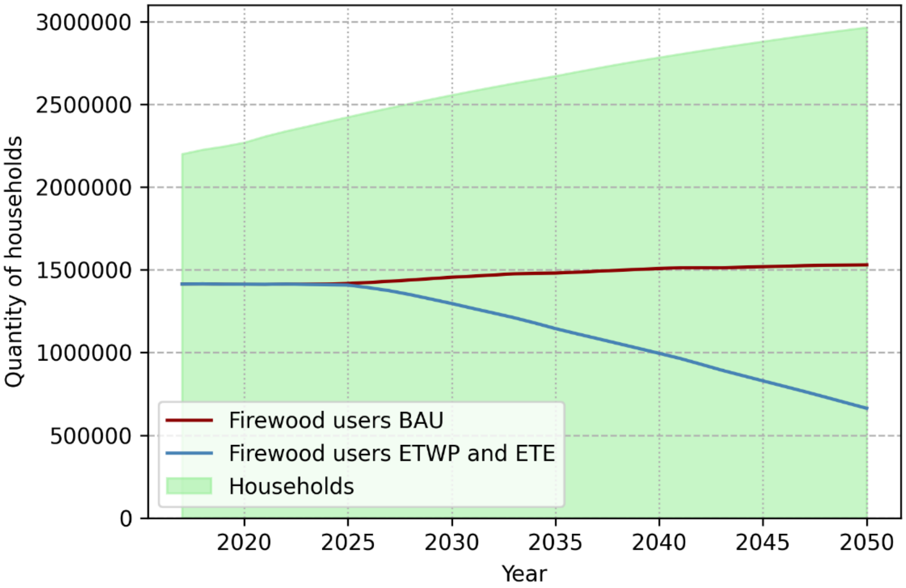
Under the IP-ETWP scenario, where both thermal retrofits and stove replacements to Wood Pellets are implemented, the average household consumption of beneficiaries and Saturation rate of firewood is reduced according to DEE and EWTP trends commented above. If these measures are applied only in cities currently under ADP (IP-ETWP-CC scenario), PM2.5 emissions in the central-south urban areas decrease by 8% compared to 2017 from 125 Kt in 2017 to 114 Kt in 2050. Although this reduction varies across regions, in cities with ADP, PM2.5 emissions reductions are on average 33% and, while in cities where this scenario is not applied emissions increase by an average of 17%.

Assuming an IP-ETWP at a Regional scale (expanding policy to all cities in center-south Chile), PM2.5 emissions are reduced by 53% in the south center, from 125 Kt to 58 Kt. Major reductions are projected, especially in Los Ríos and Los Lagos Region, where total emissions are reduced by over 77% compared to 2017 (see figure 3c). This major reduction is caused by the synergies between an energy demand reduction of improved dwellings under the DEE Regional-scale and fast firewood stove replacement under the EWTP Regional-scale scenario.

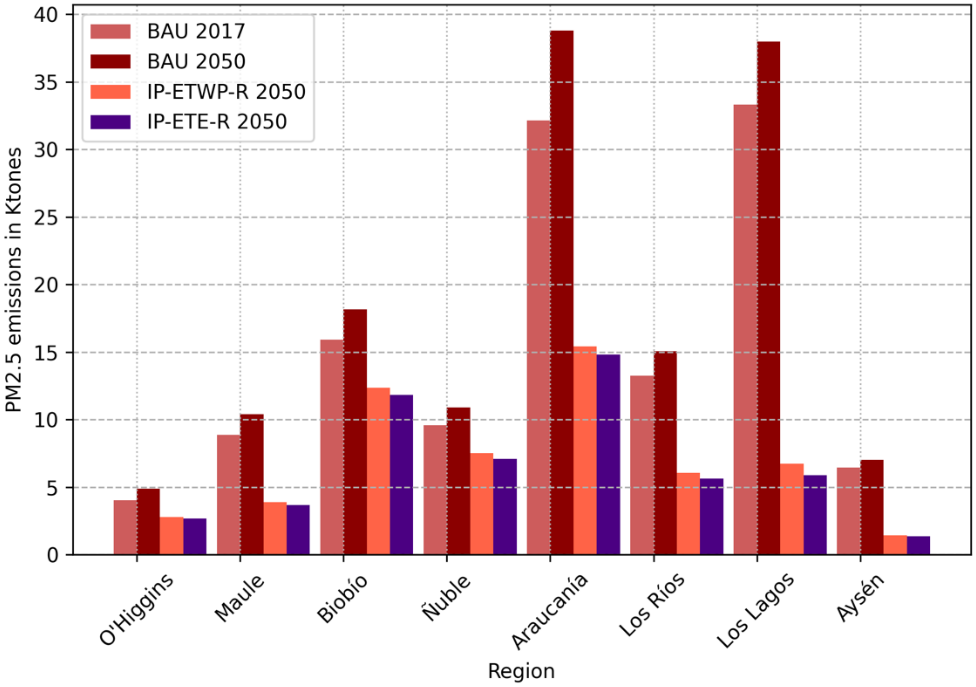
Similar results are observed when implementing energy transition to electricity instead of wood pellet devices. Under IP-ETE scenario only in cities currently under ADP, a 9% reduction in PM2.5 emissions are projected, but if this policy expands to all other cities in the center-south area, a 55% reduction on PM2.5 emissions is achieved, from 125 Kt to 55 Kt in 2050 (see figure 3a).



a. PM2.5 emissions trajectories under policy-based scenarios (2017-2050). Y-axis has been adapted to facilitate the reading of the trajectories.



b. Total quantity of households and quantity of firewood users under BAU and stove replacements (ETWP and ETE) 2017-2050



c. PM2.5 emissions under policy-based scenarios by region, 2017 and 2050 comparison.

Figure 3. Emissions trajectories and firewood users under policy-based scenarios.

1.6 Energy poverty rebound effect on policy-based scenarios

The PM2.5 emission reductions commented above assume 100% effectiveness of thermal improvements and complete adoption of stove replacement programs. However, as discussed in section 3.3, energy poverty pre-existing conditions are expected to produce less effective results, also known as rebound effect. To quantify this impact, we present PM2.5 reductions estimated under partial adoption and incomplete effectiveness of the measures due to a double rebound effect: the loss of effectiveness of thermal insulation to reduce firewood consumption due to pre-existing thermal discomfort and the economic restrictions for an energy transition due to the use of more expensive fuels (wood pellet and electricity).

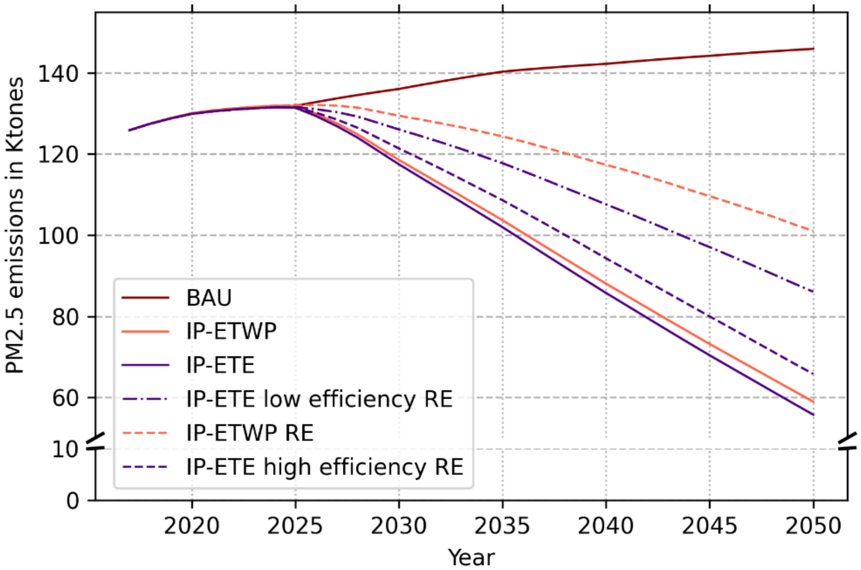
Figure 4a shows the expected reductions of PM2.5 emissions considering the two rebound effects on the Integrated Policy (IP) scenarios, both for wood pellet and electricity stoves replacement. The IP scenario focused on wood pellets would cause a 53% reduction of PM2.5 emissions if a full implementation is achieved, however under the partial adoption scenario only a 19.7% reduction is projected. This large difference is due to the fact that between 2017-2050 in at least 30% of the households, the projected operational cost of wood pellet stoves is greater than 5% of household incomes, causing the rejection of the new technology.

Under the IP-ETE scenario at a regional scale, the replacement of firewood stoves for electric heating devices under full implementation results in a major emissions reduction of 55%. However, when a rebound effect is considered this reduction only reaches 47%, because electricity is an expensive energy source compared to firewood. In this case, the proportion of households with energy operational costs larger than 5% of its income, and thus not switching technology, is 16% in 2017 and decreases to 6.9% in 2050. However, if a low-efficiency appliance is used, the rebound effect causes that emissions would decrease only 31% compared to the base year. In this case, the proportion of households with excessive energy expenditure range from 33% in 2017 to 25% in 2050.

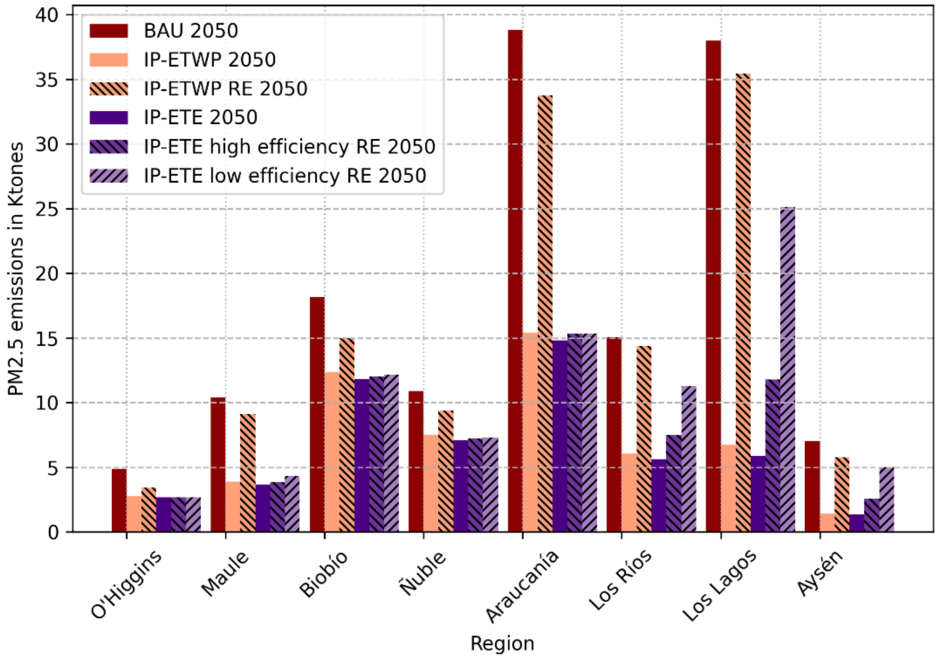
The combined impact of these two rebound effects is different across cities. In urban areas where current firewood technology used is inefficient and/or energy demand is lower than in other southern cities (for example, O'Higgins, Maule, Biobío, Ñuble,) wood pellets is a cost-effective and convenient alternative for households, hence causing a rebound effect of between 2% and 7%. However, in regions such as Araucanía, Los Lagos, Aysén, and Los Ríos the rebound effect of wood pellet is greater, with 27%, 63%, 62%, and 54% loss of potential reduction respectively (see figure 4b and 4c). As commented above, this is due to the higher energy expenditure by households when switching to wood pellets, which would produce greater resistance to change or return to firewood as an energy source for heating.

In the case of electricity, when using a high-efficiency appliance, the rebound effect is lower in O'Higgins, Maule, Biobío, Ñuble, and Araucanía region, with less than 1% of potential reduction loss due to household budget restriction. However, if low-efficiency appliances are used, the rebound effect is greater than when wood pellets are used. In this case, Araucanía, Los Lagos, Los Rios, and Aysén Region have a 63%, 66%, 52%, and 60% loss of potential emissions reduction, respectively, relative to the ideal scenario that does not consider the rebound effect.

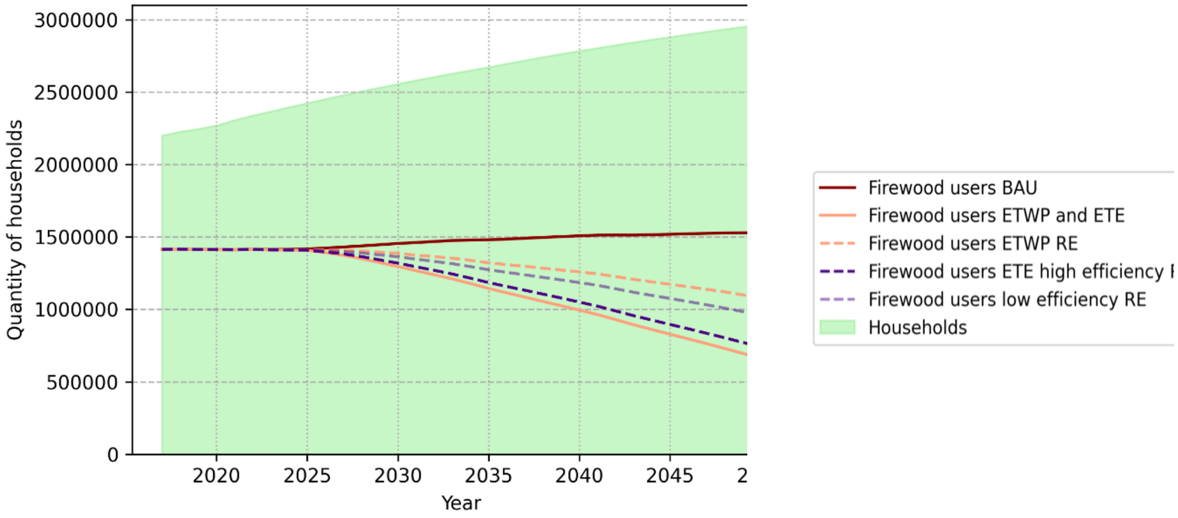
In all these cases, stove replacement represents the major source of the total rebound effect, while thermal retrofits of dwellings produce approximately 30% of this effect. Hence, while stove replacements reduce PM2.5 emissions at a faster pace and in a greater proportion, it is also a riskier alternative as it puts more pressure on the already low family budget.



a. PM2.5 emissions trajectories under BAU and Integrated Policy scenarios with rebound effect (RE) (2017-2050). Y-axis have been adapted to facilitate the reading of the trajectories.



b. PM2.5 emissions trajectories under BAU and Integrated Policy scenarios with rebound effect (RE) by region (2017 and 2050).



b. Total quantity of households and quantity of firewood users under BAU and stove replacements (ETWP and ETE) with Rebound Effect (RE) 2017-2050

Figure 4. Emissions trajectories and firewood users under policy-based scenarios considering energy poverty rebound effect.

Conclusions and policy implications

This article evaluates the impact of policy measures on reducing PM2.5 emissions and quantifies the potential impact of energy poverty conditions on the effectiveness of these measures.

Specifically, using an econometric model, we estimate PM2.5 emissions from the residential sector under different policy scenarios between 2017-2050 in Chile's southern cities, considering a rebound effect due to a partial impact of both thermal retrofit and stove replacement.

Under a Business as Usual scenario PM2.5 emissions increase 16% between 2017-2050 in all center-southern area of Chile. This is surprising since the current Atmospheric Decontamination Plans, ending formally approximately in 2027, project a significant reduction of PM2.5 emissions to below the national air quality standard. However, this increase is the result of the increment in the number of households and income, especially in cities without ADP or after ADP formally ends.

Policy-based scenarios that do not consider a rebound effect project a significant reduction in PM2.5 emissions. First, a 33% average reduction is projected in cities currently under an Atmospheric Decontamination Plan when thermal retrofits of older dwellings and stoves replacements are implemented (IP-ETPW-CC and IP-ETE-CC). However, as there are still large cities not included in this policy, overall only an 8% reduction is observed in PM2.5 emissions considering all center-southern Chile. If these cities are included in these policies, a significant 53% and 55% reduction in emissions is estimated associated with IP-ETPW-R and IP-ETE-R, respectively.

These estimates consider full adoption by households of technological changes encouraged by the proposed policy. However, uncertainties derived from pre-existing energy poverty conditions may preclude full adoption and cause rebound effects. In fact, the expected 53% reduction under an integrated policy scenario changing to wood pellet stoves is significantly reduced to only 20% as many low-income households choose not to change due to income restrictions. The 55% reduction of integrated policy using electric heating devices is reduced to 47% when high-efficiency devices are used and to 31% when low-efficiency electric heating is preferred. Consequently, the rebound effect has a very significant impact on expected emission reductions, particularly in the case of wood pellets.

Based on these results, a first policy recommendation is that it is necessary to apply mitigation policies to the entire center-south of Chile and not only to cities with ADP avoiding that cities not included in current ADPs become polluted areas in the near future due to increasing population and income.

A second policy recommendation is that the risk of rebound effect should be reduced to ensure adequate emissions reductions. Stove replacement programs have a larger impact in reducing PM2.5 emissions. However, they are risky because many low-income households may not adopt this technology due to the costs of using them. The thermal retrofit scenarios developed have less impact on emissions reduction compared to stove replacement measures, however, they are less risky, and the rebound effect is estimated to be less significant.

These results consider only two of the multiple factors that can reduce the effectiveness of policy measures. Future research should include other relevant phenomenon related 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.

Additionally, it is relevant to ensure that both policies be taken together since there are important synergies, in particular reducing heating energy demand and lower expenditures in energy. Also, scientific literature has documented many additional co-benefits related to thermal comfort, dwelling quality, and local economic development would be obtained.

Finally, if the energy transition fails to integrate energy poverty conditions in its design and implementation, it could worsen households' wellbeing. If technological change is implemented with no anticipatory or mitigating measures, these households will confront a difficult context of higher heating costs in low-efficiency dwellings. To ensure the effectiveness of emission control measures and avoid possible rebound effects related to energy poverty conditions, anticipatory actions should be taken. Improving the national standard of thermal insulation of homes is necessary to reduce energy demand and increase thermal comfort, reducing the possibilities of rebound effect due to pre-existing thermal discomfort conditions. Dissemination of energy efficiency practices and knowledge to users together with financial subsidies are two anticipatory measures required to avoid household budget restrictions in the energy transition process. Finally, better data about pre-existing energy poverty conditions in Chilean homes will allow policymakers to better quantify the potential rebound effect and complement the design of current air quality policies.

V. CONCLUSIONES

Esta investigación tuvo como objetivo estimar el efecto de las condiciones de pobreza energética presentes en las ciudades del sur de Chile en la efectividad de las medidas de calidad del aire. Para esto se implementó una metodología basada en un modelo estadístico que permite estimar la tendencia del consumo de leña entre los años 2017-2050 bajo distintos escenarios de política pública y el impacto de condiciones preexistentes de pobreza energética en la población.

En términos generales, se identifica un aumento de la cantidad de viviendas dentro del período de estudio, acorde a la tendencia de crecimiento de población y disminución de personas promedio por vivienda dentro de las regiones de estudio. En un escenario *business as usual* si bien se identifica una disminución del porcentaje de usuarios de leña en todas las regiones – asociada a las tendencias de aumento de los ingresos, crecimiento de las ciudades y de las viviendas en altura –

la cantidad total de consumidores aumenta durante el período estudiado y de esta forma, aumenta también el consumo total de leña. Estos resultados expresan la tendencia actual proyectada bajo un escenario *business as usual*, en el que entre 2017 y 2050 el consumo total de leña aumenta un 16%.

Bajo un escenario de Eficiencia Energética de Viviendas (DEE), se observa una disminución entre 12% y 62% del consumo promedio por vivienda, debido a la menor demanda energética de las viviendas y variando según región. Por otro lado, bajo un escenario de transición energética al pellet de madera (EWTP) se observa una disminución rápida de la cantidad de usuarios de leña y, por tanto, la reducción del consumo total de leña es de un 6% entre los años 2017 al 2050, lo que puede resultar atractivo en relación con las metas de reducción de concentraciones. Sin embargo, es necesario considerar que este escenario no implica la eliminación total de las emisiones de material particulado, debido a que el pellet genera emisiones, aunque considerablemente en menor medida que la leña.

El efecto de la pobreza energética es distinto en estos escenarios. Por un lado, bajo el escenario DEE el efecto de la pobreza energética se asocia a una situación inicial de disconfort térmico y la reducción del consumo de energía es menor a la esperada debido a que los hogares podrán mantener su nivel de consumo para mejorar la situación de confort térmico al interior de la vivienda. Por otro lado, bajo los escenarios EWTP y ETE, el efecto rebote se debe a las restricciones presupuestarias que poseen los hogares frente al cambio a un combustible como el pellet o la electricidad, que implicaría un gasto mayor para calefacción.

Otro hallazgo relevante de esta investigación es la necesidad de ampliar los Planes de Descontaminación Atmosférica a ciudades en crecimiento en el centro-sur de Chile, con el objetivo de evitar que en el futuro se conviertan en zonas saturadas por concentraciones de material particulado.

Dados estos hallazgos, se recomienda que la política pública de calidad del aire busque integrar estos fenómenos en el diseño e implementación de los PDA, con tal de asegurar el cumplimiento de metas socialmente relevantes como disminuir la contaminación atmosférica. En el caso del efecto rebote debido a confort térmico, una medida anticipatoria para abordar el efecto de la pobreza energética es la actualización de los estándares térmicos de las viviendas para generar mejores condiciones de base en el parque habitacional, de este modo, reducir la cantidad de hogares que actualmente experimentan bajas temperaturas al interior de sus viviendas. Por otro lado, respecto al cambio de fuente energética la política pública posee instrumentos para aminorar el impacto de este cambio en los presupuestos familiares, tales como la reducción de tarifas de electricidad en ciudades con altas concentraciones de material particulado, el subsidio de cuentas energéticas en hogares vulnerables, promover prácticas de eficiencia energética en las comunidades, incentivar la autogeneración de energía, entre otras medidas.

En términos globales, esta investigación ha relevado el efecto de las condiciones de pobreza energética en las medidas de control de calidad del aire en las ciudades del centro y sur de Chile. Incoporar las condiciones de pobreza energética en el diseño e implementación de las medidas de reducción de emisiones podrá reducir las riesgos de incumplimiento en las metas de estas políticas y aumentar su efectividad. Por otro lado, tener en cuenta este fenómeno permitirá una mejor sinergia entre los objetivos de reducción de concentraciones de material particulado con otros objetivos igualmente relevantes, tales como aumentar las condiciones de bienestar térmico y ambiental de los hogares del centro y sur de Chile y acelerar el proceso de transformación de la matriz energética residencial hacia fuentes más limpias y eficientes.

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