Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Residential black carbon emission scenarios under Atmospheric Decontamination Plan for Valdivia, Chile

**Jean Paul PINAUD-MENDOZA**
Universidad Austral de Chile
**Claudio BRAVO-LINARES**
Universidad Austral de Chile
**Paola DIAZ-NAVARRETE**
Universidad Católica de Temuco
**Oscar PERALTA**
oscar@atmosfera.unam.mx

Universidad Nacional Autónoma de México

**Research Article**

**Keywords:** Black Carbon, Residential Emissions, Scenario Analysis, Atmospheric Decontamination Plan

**Posted Date:** November 10th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-11256351/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

**Additional Declarations:** No competing interests reported.

# Residential black carbon emission scenarios under Atmospheric Decontamination Plan for Valdivia, Chile

Jean Paul PINAUD-MENDOZA [a,b]; Claudio BRAVO-LINARES [c.]; Paola DIAZ-NAVARRETE [d]; Oscar PERALTA[e,f*]

[a] *Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile. Valdivia, Chile.*

[b] *Secretaría Regional Ministerial del Medio Ambiente, Región de La Araucanía; jpinaud@mma.gob.cl. Valdivia, Chile. ORCID: 0000-0001-6399-9681*

[c] *Instituto de Ciencias Químicas, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile; cbravo@uach.cl. ORCID: 0000-0002-1118-2300*

[d] *Departamento de Ciencias Veterinarias y Salud Pública, Facultad de Recursos Naturales, Universidad Católica de Temuco. Temuco, Chile; paola.diaz@uct.cl. Chile. ORCID: 0000-0003-0512-7695*

[e] *Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Nacional Autónoma de México (UNAM); oscar@atmosfera.unam.mx. Ciudad de México, México. ORCID: 0000-0001-8644-1314*

[f] *Instituto Nacional de Ecología y Cambio Climático, oscar.peralta@inecc.gob.mx. Ciudad de México, México. ORCID: 0000-0001-8644-1314*

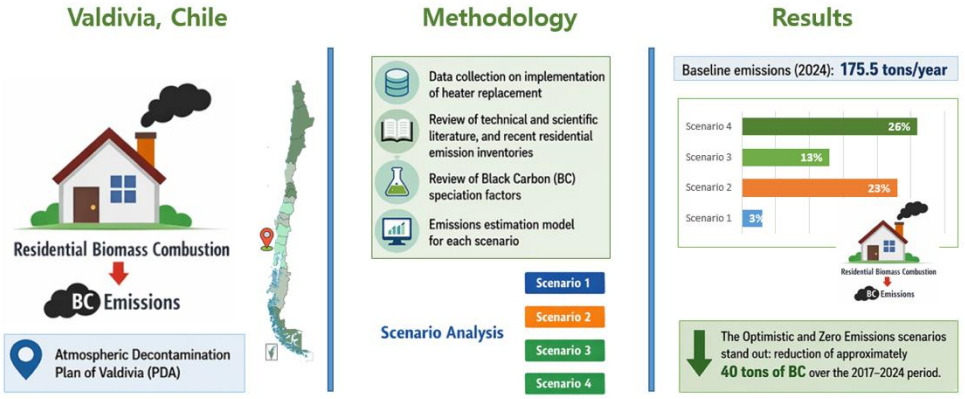
**Corresponding author*: Oscar Peralta (*oscar@atmosfera.unam.mx*)

Black Carbon from Residential Source in Valdivia

## HIGHLIGHTS

- Scenario analysis shows up to 24% reduction in Black Carbon emissions from residential sources.
- Current implementation achieves only 6–14% reduction, revealing a gap with mitigation potential.
- Residential heater replacement is effective but insufficient alone to meet national targets.

## GRAPHICAL ABSTRACT




## ABSTRACT

Publicly available information was compiled on activity levels and the degree of implementation of the heating-system replacement measure under the Atmospheric Decontamination Plan for Valdivia (PDA). Based on the level of implementation of this measure, four black carbon (BC) emission assessment scenarios were defined: Current Scenario, Optimistic Scenario, Conservative Scenario, and a Challenging or

Zero-Emission Scenario. A review of technical and scientific literature was conducted to define the emission estimation model, along with methodological aspects from recent atmospheric emission inventories of the residential sector in the municipality. Additionally, BC speciation factors were reviewed to determine which factors to use in the emission estimation model for each scenario.

The main results indicate that all scenarios reduce BC emissions compared to the baseline. The Optimistic and Zero-Emission scenarios stand out, showing reductions of approximately 40 tons of BC over the period 2017–2024. By 2024, emissions are estimated at 138 and 134 tons/year, respectively, corresponding to reductions of 23% and 26% compared to the baseline of 175.5 tons/year. It is concluded that residential measures under the PDA significantly reduce BC emissions and represent an important step toward meeting national climate change commitments.

**Keywords**: Black Carbon; Residential Emissions; Scenario Analysis; Atmospheric Decontamination Plan

## 1. Introduction

Black Carbon (BC), also known as soot, is a component of particulate matter generated during the combustion of carbon-based fuels, particularly under incomplete combustion conditions of fossil fuels, biomass, and other sources (Bond et al., 2013; Pino-Cortés et al., 2020a). BC has gained significant attention due to its climatic relevance, as it strongly absorbs solar radiation and contributes to global warming. It is considered a short-lived climate forcer at the global scale, influencing cloud formation, accelerating glacier melt, and reducing snow albedo (Gallardo et al., 2020). Its radiative forcing is estimated to range between approximately 0.1 and 1 W $m^{-2}$ (Wang, 2015; Gustafsson and Ramanathan, 2016; Gallardo et al., 2020), with upper-bound values comparable in magnitude to those of carbon dioxide ($CO_2$).

In addition, as a constituent of particulate matter (PM), BC directly affects air quality and has significant local health impacts. Exposure has been associated with respiratory diseases, impaired lung function, and increased mortality rates (Lim et al., 2012; Chen et al., 2020; Pino-Cortés et al., 2020b). These effects are not only

related to particle size but also to its toxicity, which is largely driven by its chemical composition, particularly the presence of polycyclic aromatic hydrocarbons (PAHs) in its organic fraction (Bravo et al., 2016; Bravo et al., 2017; Mudge et al., 2017).

The main sources of BC emissions to the atmosphere include wildfires, volcanic eruptions, fossil fuel and biomass combustion for energy, and industrial activities. It is estimated that nearly two-thirds of global BC emissions originate from anthropogenic sources, with diesel vehicle transport, residential heating, and cooking with biomass identified as the dominant contributors (Wang, 2015). Some studies indicate that biomass burning is the largest global source of BC emissions, encompassing both residential biomass use (heating and cooking) and open burning, including wildfires, grassland burning, and agricultural waste combustion (Wang et al., 2015; Garland et al., 2017). BC is primarily composed of elemental carbon (Chow et al., 2018) and is predominantly found in fine particulate matter fractions equal to or smaller than $PM_{2.5}$ (Gatari and Boman, 2003; Díaz, 2016).

In Chile, air pollution is recognized as a major environmental challenge and one of the leading public health concerns (MMA, 2014). According to the Ministry of the Environment, approximately ten million people are exposed to annual average $PM_{2.5}$ concentrations exceeding the annual national standard of 20 μg $m^{-3}$, resulting in around 4,000 premature deaths each year (MMA, 2016). This issue is particularly critical in the south-central region of the country, where residential biomass combustion (firewood use) is the primary source of air pollution and a major contributor to BC emissions (Chow et al., 2010; Wang et al., 2015).

The city of Valdivia, located in southern Chile, is also affected by this problem. Since 2017, it has implemented an Atmospheric Decontamination Plan (PDA), established under Supreme Decree No. 25 of 2016 issued by the Ministry of the Environment (DS No. 25/2016, MMA). This plan primarily focuses on improving residential heating conditions through the promotion of heating system replacement, enhancement of housing thermal efficiency, and regulation of emissions from residential and industrial sources. It also includes public education and community engagement measures, with a planned implementation period of ten years.

In 2020, Chile updated its Nationally Determined Contributions (NDCs) under the Paris Agreement, committing to reducing total BC emissions by at least 25% by 2030 relative to 2016 levels (NDC, 2020). Atmospheric Decontamination Plans are recognized as key instruments for mitigating $PM_{2.5}$ and BC emissions. Therefore, it is essential to accurately quantify emission reduction potentials using standardized and replicable methodologies, particularly considering emissions from residential biomass combustion due to their significant contribution to these pollutants.

In this context, the objective of this study is to evaluate annual BC emission levels through scenario analysis associated with the implementation of residential measures under the Atmospheric Decontamination Plan of Valdivia, with a particular focus on the heating system replacement program implemented by environmental authorities.

## 2. Materials and methods

### *2.1 Description of the study area*

The geographical area considered in this study corresponds to the commune of Valdivia (Fig. 1), with a primary focus on its urban area. This spatial definition is since the main measures of the Atmospheric Decontamination Plan evaluated in this study are concentrated within this zone.

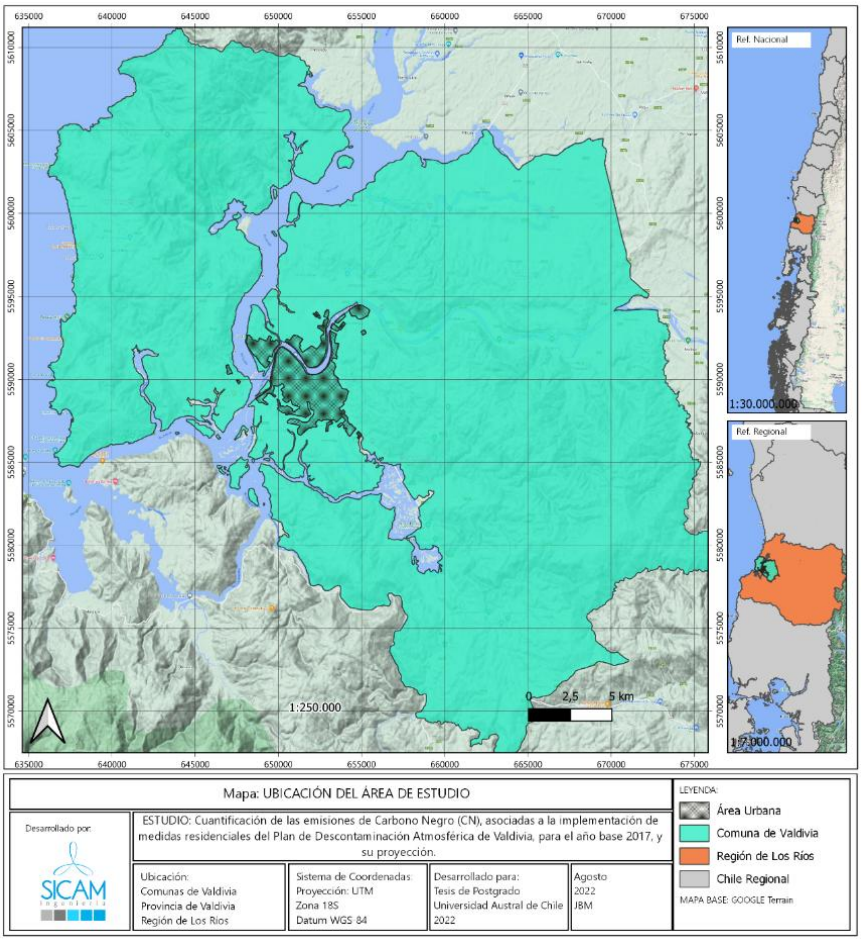



Fig. 1. Location map of the study area, Valdivia commune

The commune has a population of 166,080 inhabitants, of which 93.2% reside in urban areas, and a total of 61,192 households (INE Census, 2017). More than 90% of these households rely on firewood-based biomass for heating during the autumn and winter months (SICAM, 2015; SISTAM, 2019). This widespread use of biomass significantly impacts local air quality, leading to frequent exceedances of the national standard for $PM_{2.5}$ (50 μg $m^{-3}$, 24-hour average), as shown in Fig. 2.

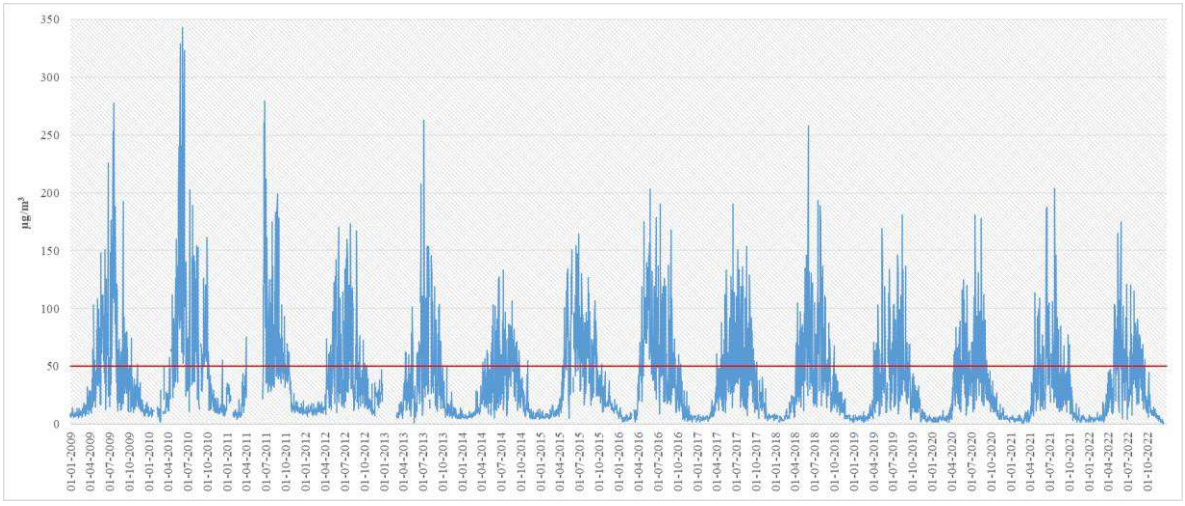



Fig. 2. Time series of daily $PM_{2.5}$ concentrations, 2009–2022, Valdivia air quality monitoring station (data obtained from the National Air Quality Information System, SINCA)

*2.2 Mission estimation model*

For the estimation of BC emissions, the calculation model was defined based on a review of reports and scientific literature (Chow et al., 2010; USEPA, 2012; Mingjiang et al., 2014), as well as technical manuals and Black carbon emission inventories (CEC, 2015; EEA, 2019; Minister of Environment and Climate Change of Canada, 2021).

The selected model establishes a relationship between atmospheric $PM_{2.5}$ emissions and the Black Carbon speciation factor (SF).

$$E\,BC = (NA \times EF\,PM_{2,5}) \times SF\,BC/PM_{2,5} \qquad \text{Equation 1}$$

where *E* BC corresponds to Black Carbon emissions, $EF\ PM_{2.5}$ represents $PM_{2.5}$ emission factor, and $SF\ (BC/PM_{2.5})$ corresponds to the Black Carbon speciation factor in $PM_{2.5}$.

The selected model establishes a relationship between atmospheric $PM_{2.5}$ emissions and the Black Carbon speciation factor (SF):

$$E\,BC = E\,PM_{2,5} \times SF\,BC/PM_{2.5} \qquad \text{Equation 2}$$

where $E\ PM_{2.5}$ represents $PM_{2.5}$ emissions, and $SF\ BC/PM_{2.5)}$ corresponds to the Black Carbon speciation factor in $PM_{2.5}$.

### *2.3 Baseline and Black Carbon (BC) Emission Estimation*

#### *2.3.1 Definition of the $PM_{2.5}$ Emission Baseline*

The definition of $PM_{2.5}$ emissions from residential sources for the BC emission baseline was carried out through the analysis of three atmospheric emission inventories developed for the commune of Valdivia (Table 1). The inventory developed by *Servicios Integrales de Calidad Ambiental (SICAM Ingeniería)*, with a 2017 base year, was selected, as it applies a bottom-up methodology for estimating activity levels and incorporates emission factors representative of national conditions. This approach allows for a higher level of detail and lower uncertainty in the quantified emission values, as recommended in the literature (Greenlab, 2016; Carmona et al., 2016; MMA, 2019).

Table 1. Atmospheric $PM_{2.5}$ emission inventories for the commune of Valdivia

| **Base Year** | **Residential Source $PM_{2.5}$ Emissions (tons/year)** | **Reference** |
|---|---|---|
| 2013 | 3,145 | SICAM Ingeniería, 2015[1] |
| 2013 | 7,171 | AGIES - MMA, 2015[2] |
| 2017 | 4,699 | SISTAM Ingeniería, 2019[3] |

(1) Servicios Integrales de Calidad Ambiental (SICAM Ingeniería)
(2) Ministry of the Environment – General Analysis of Economic and Social Impacts (AGIES)
(3) Sistemas Ambientales e Ingeniería (SISTAM Ingeniería)

#### *2.3.2 Speciation factor (SF)*

According to major global BC emission inventories, two key methodological assumptions must be considered when estimating BC emissions. First, BC is predominantly emitted within the $PM_{2.5}$ fraction, and second, only $PM_{2.5}$ emissions resulting from combustion processes contain significant amounts of BC (Minister of Environment and Climate Change Canada, 2022).

Based on the previously defined inputs, including the BC emission estimation model and residential $PM_{2.5}$ emission levels, a BC speciation factor in $PM_{2.5}$ (SF

199 ($BC/PM_{2.5}$)) was determined. To this end, a comprehensive literature review was
200 conducted, including scientific articles, technical manuals, and emission inventories
201 in which BC emissions are quantified. The use of a speciation factor was preferred
202 over an emission factor, as it represents a fraction of $PM_{2.5}$ emissions and better
203 reflects local conditions, including appliance types, activity levels, and usage
204 patterns. Table 2 presents the range of speciation factors identified in the literature.

205 Table 2. Speciation Factors, SF ($BC/PM_{2.5}$)

| **$BC/PM_{2.5}$ Speciation Source** | **SF($BC/PM_{2.5}$)** | **Reference** |
|---|---|---|
| Residential Wood Combustion | 0.096 | Chow et al, 2010 |
| Pellet Heater | 0.15 | EMEP/EEA, 2013<br>MMA, 2019 |
| Wood Stove | 0.1 | EMEP/EEA, 2013<br>MMA, 2019 |
| Wood Stove | 0.056 | US EPA, 2023 |
| Residential Wood Combustion | 0.250 | Pino-Cortes et al, 2020a |
| Pellet Heater – Conventional and Certified Wood Stove | 0.056 | US EPA, 2023<br>Environment and Climate Change Canada (ECCC), 2021- 2022 |

206

207 To standardize a methodology consistent with BC emission estimation
208 approaches used in international inventories that consider residential combustion
209 sources, a speciation factor of SF ($BC/PM_{2.5}$) = 0.056 was selected. This value has
210 been applied in emission inventories developed by the Ministry of Environment and
211 Climate Change Canada and is also recommended by the United States
212 Environmental Protection Agency (US EPA) for pellet heaters and wood-burning
213 stoves.

214 *2.4 Black carbon emission scenarios*

215 Scenario definition was based on information obtained through a formal request
216 submitted via the Transparency Portal to the Ministry of the Environment (MMA)
217 (Folio AW002T0006199; Annex 1). The dataset describes the level of
218 implementation of residential heater replacement measures under the Valdivia
219 Atmospheric Decontamination Plan (PDA) (Table 3). These data were used to
220 project scenarios based on annual implementation rates and the remaining units

required to meet the target of 26,000 replacements over an eight-year period, relative to a baseline stock of 44,125 heating devices reported for 2016 in the commune of Valdivia (Supreme Decree No. 25/2016, MMA).

Table 3. Annual Implementation Level of the Heating Replacement Program

| Year | Number of annual replacements |
|---|---|
| 2017 | 265 |
| 2018 | 476 |
| 2019 | 424 |
| 2020 | 744 |
| 2021 | 689 |
| Average rate | 520 |

The scenarios defined for evaluation are presented in Table 4. These scenarios assume constant equipment replacement rates from 2022 onwards, based on the calculated and projected rates corresponding to each scenario.

**Scenario 1** projects the current annual implementation rate of the measure, assuming an average of 520 replacements per year.

**Scenario 2** projects the required annual replacement rate to achieve full implementation of the measure, assuming 7,801 replacements per year.

**Scenario 3** represents the average annual rate between Scenarios 1 and 2, corresponding to 4,161 replacements per year.

**Scenario 4** projects the required annual replacement rate to achieve full implementation of the measure exclusively through air conditioning (A/C) systems, also assuming 7,801 replacements per year.

Table 4. Defined Scenarios for Evaluating BC emissions

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| Year | Replacements | | | |
| 2017 | 265 | 265 | 265 | 265 |
| 2018 | 476 | 476 | 476 | 476 |
| 2019 | 424 | 424 | 424 | 424 |
| 2020 | 744 | 744 | 744 | 744 |

| | | | | |
|---|---|---|---|---|
| 2021 | 689 | 689 | 689 | 689 |
| 2022 | 520 | 7801 | 4161 | 7801 |
| 2023 | 520 | 7801 | 4161 | 7801 |
| 2024 | 520 | 7801 | 4161 | 7801 |
| 2025 | 0 | 0 | 0 | 0 |
| 2026 | 0 | 0 | 0 | 0 |
| 2027 | 0 | 0 | 0 | 0 |

### *2.5 Black carbon emission estimation*

To estimate emissions under the proposed scenarios, the model presented in Equation 2 was applied. This model, developed for this study, is based on the following assumptions:

1. The heating replacement program considers only the replacement of systems using pellet as fuel. This assumption reflects the dominance of this technology within the program, accounting for nearly 80% of installed systems.
2. Activity levels (fuel consumption) are assumed to remain constant, as the analysis considers the potential reduction in fuel consumption associated with thermal improvement measures. This is supported by the program's eligibility criteria, which require either thermal subsidies or housing built after 2007, when thermal standards were incorporated into the Chilean General Urban and Construction Ordinance (OGUC).
3. Emission reductions from replaced systems assume the removal of conventional double-chamber wood stoves (with damper), with an activity level of 10.1 $m^3$ $year^{-1}$ and a wood density of 555 kg $m^{-3}$ (SICAM, 2015). This technology was selected as it represents the most common heating system in households, according to the emission inventory for Valdivia (base year 2013).
4. Scenario 4 also assumes the exclusive removal of double-chamber wood stoves (with damper), based on their prevalence in the residential sector, as indicated in the same emission inventory (SICAM, 2015).

5. To ensure the use of representative pellet consumption data and considering the bottom-up methodology applied as well as anomalies in consumption during the 2020 sanitary contingency, a constant average annual pellet consumption of 1,707 kg year$^{-1}$ (based on 2019 data) was adopted. This value was obtained from information provided by the Ministry of the Environment (request ID AW002T0006199).

To evaluate annual reductions in BC emissions, Equation 3 was applied, which quantifies the net emission change relative to the previous year, using 2017 as the baseline:

$$E\ BC = E\ BC\ (baseline) - E\ BC\ (wood) + E\ BC\ (pellet) \quad \text{Equation 3}$$

*Where:*

*E BC (baseline)* corresponds to black carbon emissions from the year preceding the evaluated year in each projection.

*E BC (wood)* represents to black carbon emissions corresponding to the number of wood-burning appliances removed.

*E BC (pellet)* represents to black carbon emissions corresponding to the number of pellet-based appliances installed.

*2.6 Uncertainties*

The uncertainties associated with BC emission estimates assess the robustness of the proposed scenarios and identify the variability of main sources in the emission model. BC emissions were estimated as a function of $PM_{2.5}$ emissions and a BC/$PM_{2.5}$ speciation factor, so uncertainty propagation was applied to the variables included in Equation 2. The total uncertainty of BC emissions was estimated using error propagation associated with PM2.5 emissions and speciation factors (Lumbreras et al, 2015; EEA/EMEP, 2023).

$$\left(\frac{\sigma_{EBC}}{E_{BC}}\right)^2 = \left(\frac{\sigma_{PM2.5}}{E_{PM2.5}}\right)^2 + \left(\frac{\sigma_{SF}}{SF}\right)^2$$

Where:

$\sigma_{EBC}$: uncertainty in BC emissions

$\sigma_{PM2.5}$ : uncertainty in $PM_{2.5}$ emissions

$\sigma_{SF}$: uncertainty associated with the BC/$PM_{2.5}$ speciation factor

The uncertainty ranges were assigned to the model parameters based on literature variability and inventory assumptions were the following:

$PM_{2.5}$ residential emissions: ±20–30%

BC/$PM_{2.5}$ speciation factor: ±30–50%

Fuel consumption/activity data: ±15–25%

Heating replacement implementation rates: ±10–20%

## 3. Results and discussion

The results of the scenario analysis provide a comprehensive assessment of the potential reduction in BC emissions associated with the implementation of residential measures under the Atmospheric Decontamination Plan in Valdivia. The evaluation considers different implementation pathways, reflecting both current progress and more ambitious mitigation efforts. Fig. 3 illustrates the temporal evolution of BC emission reductions for each scenario, highlighting differences in mitigation performance depending on the rate and extent of heating system replacement. These results allow for a comparative analysis of the effectiveness of each scenario, as well as the identification of gaps between current implementation levels and the reductions required to meet national mitigation targets.

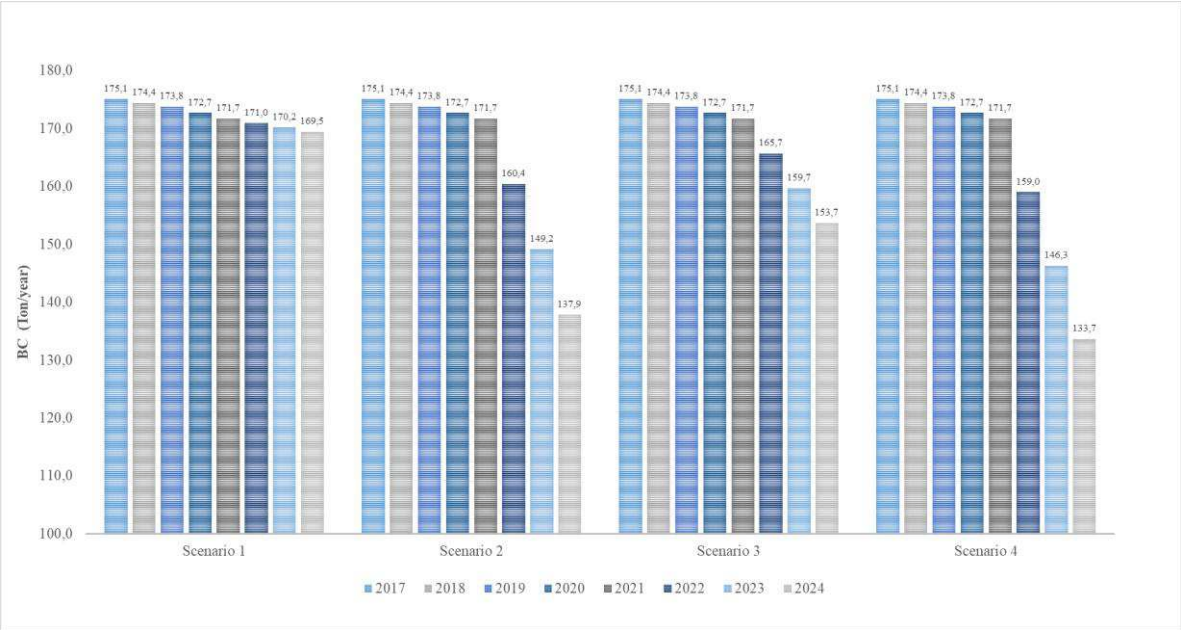



Figure 3. Black carbon emission levels across the evaluated scenarios

Overall, all evaluated scenarios show a consistent reduction in BC emissions associated with the progressive implementation of the heating replacement program. The most significant decreases are observed in Scenarios 2, 3, and 4, with reductions ranging between approximately 20 and 40 tons of BC over the period 2017–2024. Beyond this period, emission levels stabilize, reflecting the absence of additional replacements.

Scenarios 2 and 4 achieve the largest reductions, with decreases of approximately 40 tons of BC between 2017 and 2024, reaching emission levels of 138 and 134 tons/year, respectively, by 2024. These results highlight the strong mitigation potential of accelerated implementation pathways. In relative terms, Scenario 4 achieves a 26.2% reduction in BC emissions from the residential sector (Table 5), exceeding the national target of 25% established in Chile's Nationally Determined Contributions (NDCs) for 2030. However, the results also indicate that, even under ambitious implementation conditions, meeting the heater replacement rate defined in the PDA—as represented by Scenario 2—may still be insufficient for residential measures alone to fully achieve national mitigation targets. This

underscores the need for complementary strategies targeting additional emission sources, as well as for strengthening policy implementation.

Table V. Percentage reductions across the evaluated scenarios

| Year | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|---|---|---|
| Scenario 1 | 0.2 | 0.6 | 1.0 | 1.6 | 2.2 | 2.6 | 3.0 | 3.5 |
| Scenario 2 | 0.2 | 0.6 | 1.4 | 1.6 | 2.2 | 8.7 | 15.8 | 23.3 |
| Sscenario 3 | 0.2 | 0.6 | 1.4 | 1.6 | 2.2 | 5.7 | 9.3 | 13.1 |
| Sscenario 4 | 0.2 | 0.6 | 1.4 | 1.6 | 2.2 | 9.5 | 17.2 | 26.2 |

It is worth noting that in the study “Black Carbon Mitigation in the Update of Chile’s Nationally Determined Contribution” (Gallardo et al., 2020), BC emissions from the residential sector were estimated using BC emission factors (EF), primarily to maintain consistency with the methodological framework reported by the Ministry of the Environment (MMA, 2018), adopting the same EF proposed by Akagi et al. (2011). However, Gallardo et al. (2020) also state that BC emissions are generally derived from $PM_{2.5}$ emissions, if a fraction of $PM_{2.5}$ corresponds to BC. This approach supports the use of a speciation factor (SF) instead of a BC emission factor, particularly considering that $PM_{2.5}$ emissions are estimated using emission factors representative of national conditions. Therefore, the use of $SF_(BC/PM_{2.5})$ provides sufficient methodological consistency for this study.

## 4. Conclusions

Among the evaluated scenarios, only the scenario based on the replacement of heating systems with air conditioning (AC) technologies (Scenario 4) achieves a reduction equal to or exceeding the 25% target committed at the national level under Chile’s Nationally Determined Contributions (NDCs) for BC mitigation. This finding underscores the need to strengthen and accelerate the implementation of measures under the Atmospheric Decontamination Plan (PDA) in the commune of Valdivia, as well as across other communes nationwide. In contrast, scenarios reflecting current

implementation rates (1 and 3) show significantly lower reductions (3.5% and 13.1%), revealing a clear gap between technical mitigation potential and real-world execution of Atmospheric Decontamination Plan in Valdivia.

The replacement of residential heating systems, particularly with pellet-based technologies, represents an effective mitigation measure and contributes to national climate commitments. However, this strategy alone is insufficient to meet international targets and should be complemented by additional actions, including stronger economic incentives, enhanced enforcement, broader adoption of cleaner technologies, and improvements in the thermal efficiency of housing.

Further methodological refinement is recommended, particularly regarding the use of static speciation factors and the incorporation of uncertainties related to fuel consumption and technological variability. Strengthening the linkage between air quality policies and health outcomes would also help highlight important co-benefits, such as reductions in respiratory diseases and premature mortality. Overall, while residential measures under the PDA have contributed to BC emission reductions during the 2017–2027 period, achieving sustained and substantial improvements will require enhanced implementation, expanded policy scope, and continuous evaluation of their effectiveness.

## Author contributions

**JPPM**: conceptualization, methodology, formal analysis, writing (original draft) and project administration. **JPPM, OP, CBL, PDN**: methodology, writing (review and editing), validation. **JPPM, CBL**: conceptualization, supervision and resources. All authors have read and agreed to the published version of the paper.

## Acknowledgments

Authors acknowledge the support of the Master's Scholarship for Public Officials (No. 2020-79200036).) provided by ANID, Chile.

## Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. J.P. Pinaud-Mendoza acknowledges support

from the ANID Master's Scholarship for Public Officials (Grant No. 2020-79200036), Chile.

## Data Availability Statement

All data generated or analyzed during this study are included in this published article.

## Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable

## References

AGIES – MMA (2015), Análisis General del Impacto Económico y Social del Anteproyecto de Plan de Descontaminación de Valdivia por MP10 y MP2.5.

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., & Crounse, J. D. (2011). and Physics Emission factors for open and domestic biomass burning for use in atmospheric models. 4039–4072. https://doi.org/10.5194/acp-11-4039-2011

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., Deangelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research Atmospheres, 118(11), 5380–5552. https://doi.org/10.1002/jgrd.50171./ 10.1002/jgrd.50171

Bravo-Linares, C., Ovando-Fuentealba, L., Orellana-Donoso, S., Villenas-Fernández, K., Hernández-Millán, M., Mudge, S. M., Pinaud-Mendoza, J. P., & Loyola-Sepulveda, R. (2016). Source Apportionment of PAHs in Airborne Particulates (PM 2,5) in Southern Chile. Polycyclic Aromatic Compounds, 37(2–3), 189–202. https://doi.org/10.1080/10406638.2016.1238400

Bravo-Linares C, Ovando-Fuentealba L, Orellana-Donoso S, Gatica S, Klerman F, Mudge SM, Gallardo W, Pinaud JP, Loyola-Sepulveda R. Source identification, apportionment and toxicity of indoor and outdoor PM2.5

airborne particulates in a region characterised by wood burning. Environ Sci Process Impacts. (2016b) May 18;18(5):575-89. https://doi.org/10.1039/c6em00148c.

Luis Gabriel Carmona Aparicio, Mauricio Alexander Rincón Pérez, Andrés Mauricio Castillo Robles, Boris René Galvis Remolina, Hugo Enrique Sáenz Pulido, Rodrigo Alberto Manrique Forero, Jorge Eduardo Pachón Quinche. Conciliación de inventarios top-down y bottom-up de emisiones de fuentes móviles en Bogotá, Colombia. (2016). vol.20, n.49, pp.59-74. ISSN 0123-921X. https://doi.org/10.14483/udistrital.jour.tecnura.2016.3.a04

CEC. 2015. North American Black Carbon Emissions Estimation Guidelines: Recommended Methods for Estimating Black Carbon Emissions. Montreal, Canada: Commission for Environmental Cooperation. 89 pp

Chen, X. C., Cao, J. J., Ward, T. J., Tian, L. W., Ning, Z., Gali, N. K., Aquilina, N. J., Yim, S. H. L., Qu, L., & Ho, K. F. (2020). Characteristics and toxicological effects of commuter exposure to black carbon and metal components of fine particles (PM2.5) in Hong Kong. Science of The Total Environment, 742, 140501. https://doi.org/10.1016/j.scitotenv.2020.140501

Chow Judith C, Watson John G, Green Mark C, Wang Xiaoliang, Chen L.-W. Antony, Trimble Dana L. Cropper Paul M, Kohl Steven D &. Gronstal Steven B (2018) Separation of brown carbon from black carbon for IMPROVE and Chemical Speciation Network PM2.5 samples, Journal of the Air & Waste Management Association, 68:5, 494-510, DOI: 10.1080/10962247.2018.1426653

Chow, J. C., Watson, J. G., Lowenthal, D. H., AnTony, L., Motallebi, N., Chow, J. C., Watson, J. G., Lowenthal, D. H., AnTony, L., Chow, J. C., Watson, J. G., Lowenthal, D. H., & Chen, L. A. (2010). Black and Organic Carbon Emission Inventories : Review and Application to California Black and Organic Carbon Emission Inventories : Review and Application to California. 2247. https://doi.org/10.3155/1047-3289.60.4.497

DECRETO SUPREMO N°25 (2016). DSN°25/2016, Establece Plan de Descontaminación Atmosférica para la comuna de Valdivia. Ministerio del Medio Ambiente.

Díaz Hernández, Carlos Guadalupe. Estudio del Carbono Negro (Black Carbon) contenido en partículas suspendidas en ambientes urbanos (2016). Tesis para obtener el grado de Maestria en Ciencia y Tecnologia Ambiental. Centro de Investigación en Materiales Avanzados, S.C, Mexico.

Environmental Protection Agency (US EPA) (2012). Report to Congress on Black Carbon.

Environmental Protection Agency (US EPA). (2023). 2020 National Emissions Inventory Technical Support Document: Fuel Combustion – Residential Heating -Wood

European Environmental Agency (EEA/EMEP). (2019). EMEP/EEA air pollutant emission inventory guidebook 2019. Vol.13.

European Environmental Agency (EEA/EMEP). (2023). EMEP/EEA air pollutant emission inventory guidebook 2023. Appendix A5: Uncertainties.

Gatari, M. J., y Boman, J. (2003). Black carbon and total carbon measurements at urban and rural sites in Kenya, East Africa. Atmospheric Environment, 37, 1149–1154.

Gallardo, L., Basoa, K., Tolvett, S., Osses, M., Huneeus, N., Bustos, S., Barraza, J., Ogaz, G. (editores) (2020), Mitigación de carbono negro en la actualización de la Contribución Nacionalmente Determinada de Chile: Informe extendido y anexos. Centro de Ciencia del Clima y la Resiliencia para el Ministerio del Medio Ambiente a través de Programa de las Naciones Unidas para el Medio Ambiente (PNUMA) y la iniciativa Supporting National Action and Planning on Short-Lived Climate Pollutants (SNAP), 116 pp. Disponible en: http://www.cr2.cl/carbononegro/mitigacion

Garland, C., Delapena, S., Prasad, R., Orange, C. L., Alexander, D., & Johnson, M. (2017). Black carbon cookstove emissions: A field assessment of 19 stove / fuel combinations. Atmospheric Environment, 169, 140–149. https://doi.org/10.1016/j.atmosenv.2017.08.040

Greenlab DICTUC (2016), Manual para el Desarrollo de Inventarios. 1–163.

Gustafsson, Ö., & Ramanathan, V. (2016). Convergence on climate warming by black carbon aerosols. Proceedings of the National Academy of Sciences of the United States of America, 113(16), 4243–4245. https://doi.org/10.1073/pnas.1603570113

Lim, S. S., Vos, T., Flaxman, A. D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H. R., Andrews, K. G., Aryee, M., Atkinson, C., Bacchus, L. J., Bahalim, A. N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M. L., Blore, J. D., … Ezzati, M. (2012). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. The Lancet, 380(9859), 2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8

Lumbreras, J., Andrés, J. M. de, Pérez, J., Borge, R., Paz, D. de la, & Rodríguez, M. E. (2015). A methodology to estimate uncertainty for emission projections through sensitivity analysis. *Journal of the Air & Waste Management Association*, *65*(4), 384–394. https://doi.org/10.1080/10962247.2014.996268

Mingjiang Ni, Jianxin Huang, Shengyong Lu, Xiaodong Li, Jianhua Yan, Kefa Cen. A review on black carbon emissions, worldwide and in China. Chemosphere, Volume 107 (2014). Pages 83-93, ISSN 0045-6535. https://doi.org/10.1016/j.chemosphere.2014.02.052

Minister of Environment and Climate Change. (2021). CANADA'S BLACK CARBON INVENTORY REPORT 2013 – 2019.

Minister of Environment and Climate Change. (2022). CANADA'S BLACK CARBON INVENTORY REPORT 2013 – 2020.

Ministerio del Medio Ambiente, MMA. (2014). Planes de Descontaminación Atmosférica. Estrategia 2014-2018. Gobierno de Chile, Santiago., 1–10. http://airechile.mma.gob.cl/download/Plan-Descontaminacion-Atmosferica-2014-2018.pdf

Ministerio del Medio Ambiente, MMA. (2016). Gobierno de Chile. Guía de Calidad del Aire y Educación Ambiental.https://mma.gob.cl/wp-content/uploads/2018/08/Guia-para-Docentes-Sobre-Calidad-del-Aire-003.pdf

Ministerio del Medio Ambiente, MMA. (2018). Gobierno de Chile. Tercer Informe Bienal de Actualización de Chile sobre Cambio Climático [en línea]: https://mma.gob.cl/wp-content/uploads/2018/12/3rd-BURChile-SPanish.pdf, 2018

Ministerio del Medio Ambiente, MMA. (2019) Manual para el Desarrollo de Inventarios de Emisiones Atmosféricas. http://catalogador.mma.gob.cl/sinia/SINIA/Manual_inventarios.pdf

Mudge, S. M., Bravo-Linares, C., Ovando-Fuentealba, L., & Pinaud-Mendoza, J. P. (2017). A comparison between three unmixing models for source apportionment of PM2.5 using alkanes in air from Southern Chile. Environmental Forensics. https://doi.org/10.1080/15275922.2017.1340366

NDC (2020). Para el Acuerdo Climático. Contribución Determinada a Nivel Nacional de Chile Gobierno de Chile. Actualización 2020.

Pino-Cortés, E., Carrasco, S., Díaz-Robles, L. A., Cubillos, F., & Cereceda-Balic, F. (2020a). Black and organic carbon fractions in fine particulate matter by sectors in the South Hemisphere emissions for decision-making on climate change and health effects. Environmental Science and Pollution Research, 27(30), 38344–38352. https://doi.org/10.1007/s11356-020-10164-w

Pino-Cortés, E., Díaz-Robles, L.A., Campos, V. et al. Effect of socioeconomic status on the relationship between short-term exposure to PM2.5 and cardiorespiratory mortality and morbidity in a megacity: the case of Santiago de Chile. Air Qual Atmos Health 13, 509–517 (2020b). https://doi.org/10.1007/s11869-020-00818-6

SICAM – MMA (2015). Resumen Ejecutivo Inventario de Emisiones Atmosféricas y Modelacion de Contaminates de la comuna de Valdivia, año base 2013

SISTAM – MMA (2019). Inventario de Emisiones de Contaminantes Atmosféricos, desde la región del Libertador Bernardo O´higgins hasta la región de Los Lagos.

Wang, M., Xu, B., Kaspari, S. D., Gleixner, G., Schwab, V. F., Zhao, H., Wang, H., & Yao, P. (2015). Century-long record of black carbon in an ice core from the Eastern Pamirs: Estimated contributions from biomass burning. Atmospheric Environment, 115, 79–88. https://doi.org/10.1016/j.atmosenv.2015.05.034

Wang, R. (2015). Global emission inventory and atmospheric transport of black carbon: evaluation of the associated exposure. https://doi.org/10.1007/978-3-662-46479-3

Intergovernmental Panel on Climate Change — *2019 Refinement to the 2006 IPCC Guidelines, Chapter 3: Uncertainties*

European Environment Agency — uncertainty scoring for emission inventories.

Krecl et al. (2022) — BC inventory uncertainty framework using data quality ranking. Ya está directamente relacionado con tu PDF.

Lumbreras et al. (2015) — uncertainty bands in emission scenarios using ±20% sensitivity ranges.

Climate & Clean Air Coalition BC inventory guidance — recomienda IC95% para incertidumbre.