Lessons Learned from Chile's Wood-Burning Heaters Replacement Program

Short title: Lessons from Wood-Burning Heaters Replacement Program

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Word count: 5,756.

Abstract

The wood burning is one of the main causes of air pollution by $PM_{2.5}$, having serious consequences on the health of the population. For this reason, governments should play an active role in implementing policies that encourage the reduction of this pollutant. This case study analyzes the Chilean government's Heater Replacement Program, a policy that seeks to reduce the number of wood-burning heaters in exchange for providing more efficient heating systems that do not emit pollutants.

The reader will learn about the history of this program and the challenges it has faced through the analysis of three central pillars: 1) The amount of the subsidy, 2) The characteristics considered for targeting, and 3) The choice of heating systems to be delivered. The discussion focuses on the search for an efficient environmental program without affecting its effectiveness in achieving its purpose, a challenge that is not easy considering the geographical and social differences in the country, and the political aspects that may affect the program. The study concludes by analyzing the effectiveness of the public policy to reduce $PM_{2.5}$ pollution in one of the main cities of Chile, showing that in three years the program managed to reduce pollution by 20%.

It is hoped that the lessons learned from the program and its pending challenges will serve as an input for the reader to question other public policies in order to improve them, thus reducing air pollution by $PM_{2.5}$ and reducing its consequences on the health of the population.

Introduction

During wood combustion, a number of harmful pollutants are released into the environment, such as carbon monoxide (CO), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and particulate matter below 10 micrometers (PM_{10}) and 2.5 micrometers ($PM_{2.5}$) [1]. Small-scale wood combustion, caused mainly by households and small and medium industry, is responsible for the emission of a large amount of particulate matter into the atmosphere [2-3]. Globally, the contribution of biomass burning for domestic use, such as wood, to the emission of $PM_{2.5}$ is about 20% [4].

The above is worrisome considering that air pollution is the leading global environmental risk factor [5]. World Health Organization estimates indicate that about 7 million deaths, mainly from non-communicable diseases, are attributable to the joint effects of ambient and household air pollution [6]. One of the causes of these deaths is decreased respiratory capacity due to constant exposure to $PM_{2.5}$ [7]. For example, Guarnieri et al. [8] found evidence of a relationship between smoke caused by biomass combustion and chronic obstructive pulmonary disease. Other conditions that have been associated with $PM_{2.5}$ exposure include brain tumor formation in children [9], atopic dermatitis [10-11] and Alzheimer's disease [12].

According to the ranking of the most polluted countries in the world by $PM_{2.5}$ prepared by IQAir [13], the first place among OECD member countries is occupied by Chile with the 40th place in the world ranking. This does not imply that the problem of $PM_{2.5}$ pollution is relevant only in emerging or developing countries. If the monthly pollution peaks of specific cities are analyzed, the ranking is led by Polistena (Italy), Sahiwal (Pakistan) and Weaverville (United States).

Given all of the above, governments must play an active role in reducing the level of air pollutants in cities. This task is not easy. There are multiple environmental policy alternatives, such as emission taxes, tradable emission rights, emission reduction subsidies, mandates for the adoption of specific technologies, among others [14], so the choice of the appropriate tool must be analyzed in detail. Some examples of poorly implemented policies are the subsidy for the installation of drip irrigation in India [15], which generated price speculation by supplier companies, and the fraud committed by companies in China by irregularly applying for and obtaining subsidies that incentivized the development of hybrid and electric vehicles [16].

Chile does not escape from the problem generated by air pollution by $PM_{2.5}$. The country's geographic layout causes the environmental situation to differ considerably among its cities. Its mountain ranges produce valleys that make it difficult to ventilate the towns, which, added to low temperatures in winter, generates an alarming level of $PM_{2.5}$ pollution in the southern part of the country. Of the 53 Chilean cities analyzed by IQAir [13] in July 2021, ten of them exceeded the WHO standard by more than 10 times, eleven exceeded it by between 7 and 10 times, and thirteen were between 5 and 7 times above the standard. Studies related to pollution in Chilean cities are not new in the literature, one of the most emblematic cases being the situation of the Puchuncaví-Ventanas industrial cordon [17-19].

Although environmental prevention and decontamination plans have existed in Chile since 1995, they have not been updated for 17 years [20]. This implied that in 2013 a decree was published that institutionalizes the Prevention and/or Atmospheric Decontamination Plans (PADP). This study analyzes one of the flagship policies of the PADP, the Heater Replacement Program (HRP). Broadly speaking, this policy offers various efficient heating systems to households in exchange for them turning in their wood-burning heaters to the government. Analyzing the problems faced by the HRP and the solutions provided by the government is relevant as a lesson learned for the implementation of environmental public policies.

Case description

The Heater Replacement Program (HRP) is a public policy of the Chilean government that seeks to reduce the number of wood-burning heaters and stoves in households through a service that includes the purchase and installation of a heating system with low or zero emission of pollutants, and the removal and subsequent destruction of the wood-burning appliance, which is illustrated in Figure 1. In order to access the service, the household must apply to the call of its territorial region, selecting the type of heating system it wishes to receive. Currently, the government offers pellet, kerosene and air conditioning heating systems. Figure 2 shows some beneficiaries with the heaters received by the program. The service delivered has a bipartite financing, an amount contributed by the beneficiary, if selected, and a government subsidy, which is referred to as a "co-payment" throughout the study.

[Figure 1]

[Figure 2]

The purpose of the HRP is "To reduce the emissions of pollutants produced by the wood combustion for heating, in the cities of the center and south of the country that have a Decontamination Plan in force or in the process of elaboration" [22]. The determination of the purpose of this public policy is not due to improvisation, but to a detailed analysis of the sources of $PM_{2.5}$ emissions in each territory of the country. Table 1 shows the total tons of $PM_{2.5}$ emissions and the participation of each emission source by region[1]. In the Metropolitan Region, where the country's capital is located, the main source of $PM_{2.5}$ pollution is the transportation sector, a source that shares first place with wood combustion in the Valparaíso region. From the O'Higgins region to the south (35% of the country's population), the combustion of wood in homes is the main source of $PM_{2.5}$ pollution, which is why the HRP has focused on this part of the country.

[Table 1]

Although it is a national policy for eight regions of the country (between O'Higgins and Aysén), it may differ between territories without specific guidelines. The main differentiating elements are: 1) the co-payment made by the HRP, 2) the weightings of the postulation variables, and 3) the

[1] Emissions from forest and residential fires were excluded as they were considered anomalous.

heating systems available for replacement. While it is true that this flexibility allows the HRP to adjust to the reality of each region, it can also cause inconveniences if the determinations of the authorities of each territory deviate from the purpose of the program. For this reason, it is necessary to analyze each of these elements and illustrate the drawbacks they may cause. The questions that will motivate the discussion of the study are:

How to determine the amount of the co-payment?

How to assign the weightings of the application variables?

How to decide on the heating systems to be delivered?

How to determine the amount of the co-payment?

The amount of co-payment the HRP makes determines the number of heaters it can deliver. With a given budget, the higher the subsidy, the lower the number of replacements it can deliver. Table 2 illustrates the co-payments made by the HRP in its last application by region. It can be seen that the lowest co-payment is made in the Los Lagos region for the air conditioning system. The regions of La Araucanía and Aysén stand out for offering co-payments higher than 95% in all types of heating.

[Table 2]

The international experience most similar to the Chilean program is the wood stove exchange program in British Columbia, Canada. In this program the co-payment made by the provincial government is close to 30% [26], one of the most efficient programs of this type if compared to similar policies in the United States where the federal government contributes close to 50% of the cost of the equipment [27]. These figures demonstrate that the HRP co-payment is one of the highest in the world for programs of this type. This characteristic is due to the fact that, at the origin of the program, it was designed as a no-cost policy for beneficiaries (100% co-payment), which was modified to increase the efficiency of the subsidy.

Currently, the co-payment of the HRP is defined without a determined criterion, often influenced by a political decision because part of the financing comes from the regional government [22]. This generates that the subsidy delivered by the HRP differs from its purpose, becoming a social subsidy instead of an environmental one. The direct consequence of this change of purpose is a lower impact of the policy to reduce $PM_{2.5}$ pollution due to the lower number of replacements made with the same budget.

For the HRP to be efficient and maintain its environmental purpose, it is relevant to consider the households' willingness to pay for heating systems. This concept is related to the valuation of individuals and is defined as the highest amount that the user would be willing to finance for acquiring a good. To maximize the efficiency of the program without undermining its effectiveness, it is necessary to implement a co-payment high enough so that the cost to the beneficiary is equal to his willingness to pay. In response to this concern, the government has

gradually decreased the co-payment to the rates shown in Table 2. Table 3 shows the "efficient"[2] co-payments according to estimates by the Ministry of the Environment by socioeconomic level. It can be seen that for all heating systems the co-payment shown in Table 2 is higher than the "efficient" co-payment, with the exception of three regions for the air conditioning system (Ñuble, Biobío and Los Lagos). These results show that there is still a margin for action to maximize the efficiency of the program, but far from the 30% co-payment of the British Columbia program.

[Table 3]

Is it impossible to reach the 30% HRP co-payment due to the national reality? While it is a great challenge, there are policies to further decrease the HRP co-payment. To achieve this, it is necessary for the government to implement policies that seek to increase the willingness to pay for different heating systems. One type of policy with a relatively low cost is the provision of information to subsidy applicants.

The decree that governs the PADP dictates that the National Consumer Service (SERNAC for its Spanish acronym) must publish a monthly bulletin with the suppliers of wood and pellets in the regions where the policy applies. Providing information on prices and locations where to buy pellets affects the willingness to pay for pellet heating systems. To explain this relationship, let's illustrate with the following situation:

> A person values a pellet stove low because the fuel is sold in 18-kilogram bags and the user does not own a vehicle, so it requires a lot of effort to carry the fuel. Reading the monthly SERNAC bulletins, it is reported that many stores sell the pellet at home, so that the purchase of fuel is no longer an impediment to the purchase of the stove, increasing their valuation of it (and, therefore, their willingness to pay).

It should be noted that the provision of information can increase or decrease the willingness to pay for goods. SERNAC's monthly bulletin also publishes information on suppliers of dry wood, which decreases the willingness to pay to replace heating systems (since the individual knows where to buy less polluting wood). So why does the government publish information on wood given this effect? It does so because it knows that not all individuals will be able or willing to change their heating systems, so it prefers to provide information so that people who continue to use wood stoves pollute as little as possible (since the combustion of dry wood produces less $PM_{2.5}$ emissions than wet wood).

Another information policy carried out by the government within the framework of the HRP is to expose the characteristics of the heating systems it offers in each application. An opportunity for improvement in this policy is to inform the government of the cost of the acquisition and

[2] An "efficient" copayment is defined as a copayment rate that implies that the cost to the beneficiary is equal to his willingness to pay.

installation of the heating systems, since currently the applicant is only informed of the amount that must be contributed to acquire the device (in the case that the subsidy is awarded)[3].

Discussion questions:

What other information policies could be implemented in the country to increase the willingness to pay for heaters with lower emissions of $PM_{2.5}$?

How could companies and foundations contribute to the financing of the HRP?

Would a state lending policy be more efficient than providing subsidies?

How to assign the weightings of the application variables?

Since public policies have a limited budget and cannot be delivered to all inhabitants, they must be as efficient as possible without losing their effectiveness in achieving their purpose. One way to ensure effectiveness is to target the policy. If the purpose of the HRP is to reduce $PM_{2.5}$ pollution, it is not the same to give the subsidy to a family that uses the stove one hour a day as it is to give it to another family that uses the appliance for eight hours a day.

To access the HRP benefit, households must apply to the regional calls for applications. In this process they are asked to complete a questionnaire to assign them an application score[4]. The four variables considered for the selection of beneficiaries are:

- **Family group:** The three main sub-variables (although in some application they may vary) are: 1) the number of members of the family group, 2) the number of members under 5 years of age or over 60 years of age, and 3) whether the family group has a member with a disability and/or chronic cardiorespiratory disease.

- **Wood-burning appliances:** Type of wood-burning appliance to be replaced (salamander, heater with tempering device, wood stove, among others). The more emissions and the worse the efficiency of the device, the higher the score.

- **Housing insulation:** Type of thermal insulation that the house has. To determine this, the year of construction of the house or if the applicant has conditioned his home thanks to the Housing Thermal Conditioning Subsidy (HTCS).

- **Territorial zone:** Determines whether the household is located within a given zone with critical pollution episodes. Not all regions include this variable.

[3] An example of an application is the Ministry of the Environment [28].

[4] An example of an application questionnaire with its respective scores can be found in the appendix.

A first necessary exercise to ensure a correct targeting is to analyze whether the variables to be considered allow achieving the purpose.

The variables "Wood-burning appliances" and "Territorial area" are appropriate since they have a direct impact on the emission and mitigation of $PM_{2.5}$. The first indicator prioritizes the replacement of the most polluting appliances, while the second indicator prioritizes replacement in the most critical areas in relation to $PM_{2.5}$ pollution.

The relevance of the variable "Housing insulation" is more debatable: Why does a change in housing construction decrease $PM_{2.5}$ emissions? At first sight, there is no direct relationship, but it is necessary to contextualize the thermal insulation of dwellings in Chile to analyze an indirect effect.

Until 2007, little or no thermal insulation of homes was required by law. Since 2008, regulations focused on the thermal conditioning of homes were implemented, mainly in relation to the walls of the dwelling and the maximum glazed area [29]. Subsequently, changes have been made in the regulations that seek better thermal efficiency of new constructions. Thermal conditioning of homes allows heating to be maintained for longer inside the home, which means that heating systems can be used for less time (thus reducing $PM_{2.5}$ emissions). For this and other reasons, the government implemented, within the framework of the PADP, the Housing Thermal Conditioning Subsidy (HTCS) for homes built up to 2007.

The above description implies that the HRP and HTCS are policies with a similar purpose, and for this reason they should not be used together. For targeting to promote the effectiveness of the policy, the HRP should prioritize the replacement of heaters in homes without thermal insulation, since they are the ones that use heating systems for the longest time.

Despite this criticism, there is an argument that justifies considering HTCS within the targeting. One advantage of wood-burning appliances over other heating alternatives is the number of square meters it heats. If a household replaces its wood heater with another system with less power (e.g., air conditioning) it is likely to suffer a heat deficit if the house is not thermally insulated, so there is a possibility that it will return to its previous heating system (wood) to supplement or eliminate the system obtained by the HRP. So, by ensuring that the house is thermally insulated, the HRP is ensuring the efficiency of the resources expended, which has an impact on efficiency. In other words, it is better to replace a heater in a thermally conditioned home because, although its impact on $PM_{2.5}$ emissions is less than that of an uninsulated home, it ensures that the appliance delivered is used and resources are not wasted.

The fourth variable considered in the application is the "Family group". The relationship with the emission of $PM_{2.5}$ is not direct. It could be considered that households with more members use more heating and, therefore, pollute more, but it is a forced indirect relationship. The number of members is relevant only because of its relationship with the size of the household. A household of 50 square meters requires a certain amount of heating use, regardless of whether the dwelling

is inhabited by three or five people. The other sub-variables of the indicator[5] do not have an effect on $PM_{2.5}$ emissions, but are rather part of a health policy given the effects that $PM_{2.5}$ has on at-risk populations. It is important to remember, as explained in the previous section, that the HRP is affected by political aspects due to the nature of its funding.

Table 4 illustrates the weights that each variable had in 2018 by region. It is observed that the variable "Family group" had a high weight in almost all regions, highlighting the 50% weighting in La Araucanía. While in 2018 only two regions used the variable "Territorial area", between 2018 and 2022 five regions used the variable.

[Table 4]

After all that has been discussed, what should be the optimal allocation of weightings?

Undoubtedly, the highest weighting should be given to "Wood-burning appliances" and "Territorial area". This last variable is important to be used by regions with larger areas in order to prioritize according to the environmental reality of each year. The next highest weighting should be given to "Housing insulation", to assign the lowest weighting to "Family group". Table 5 shows the weightings used in the last application by region. It can be seen that, unlike the co-payment, the regions have homogenized the weightings. "Family group" decreased its importance in line with what was recommended by González et al. [22], although this group recommended that the weighting of the variable should not exceed 10%. The variable "Housing insulation" is consolidated with a weighting of 40%, equal to the sum of the variables "Wood-burning appliances" and "Territorial area".

[Table 5]

Discussion questions:

Are there other postulation variables that can be considered to ensure the effectiveness of the HRP?

Is the homogenization of the weightings of the variables correct, or should they differ by region given the reality of each territory?

The Chilean government focuses the HRP with a voluntary application system. Wouldn't a system of automatic selection of beneficiaries through administrative data be more effective? What problems could this type of system have?

[5] The number of members under 5 years of age or over 60 years of age, and if the family group has a disabled member and/or a member with chronic cardiorespiratory disease.

How to decide on the heating systems to be delivered?

When a state subsidy is monetary, the discussion consists of determining the amount to be given to each beneficiary. On the other hand, when the subsidy is given in goods, the type and quality of the product that is given becomes relevant. A poor choice of good implies that the expected purpose will not be fulfilled and, therefore, a waste of public resources.

When applying for the HRP, the household must select which heating system to obtain from a limited list of options offered by the government, which may differ from call to call. Given the objective of the HRP, one might consider choosing the heating systems that most reduce pollution given a budget. Table 6 illustrates the appliances that have been available for replacement and the cost per gram of reduced $PM_{2.5}$ compared to a non-certified wood-burning appliance. Based on these costs, the government should prefer liquefied gas and certified wood-burning heaters. The disadvantage of choosing this criterion is that it does not ensure that the beneficiary will actually use the appliance, which is necessary to fulfill the purpose of the project.

[Table 6]

Table 7 shows the monthly fuel cost for each type of heater, considering a daily use of eight hours. It can be seen that the cost of liquefied gas is 5.6 times higher than the cost of kerosene, the second most expensive fuel. If the beneficiary does not have this information when applying for the liquefied gas system, it is likely that after a few months of use the beneficiary will stop using the heater due to its high monthly cost. In the long term, this implies a waste of resources on the part of the government, since these heaters that become unusable cannot be recovered.

[Table 7]

The decision to provide certified wood stoves to replace non-certified wood-burning heaters is controversial. While it is true that the replacement means a 50% reduction of $PM_{2.5}$ released into the atmosphere, this level is still high enough to cause harm to the population[6]. Despite this, Table 8 shows that the HRP delivered, between 2015 and 2020, 2,759 certified wood stoves. The possible reasons for this determination are the low price of the fuel and the existing cultural resistance in some regions to decrease their consumption of wood. Due to the political determination to which the HRP is exposed, in the region of La Araucanía in 2020 a call was made to replace 15% of the certified wood heaters delivered in the region, a fact that means a waste of resources because the heaters are unusable.

[Table 8]

The above arguments may explain the HRP's determination to focus mainly on pellet and kerosene heaters, and in recent years on air conditioning systems. This does not imply that these appliances are free from criticism.

[6] In these cities, the WHO standard is exceeded by more than 10 times.

The monthly cost is not the only factor to consider related to fuel, but also its availability. Fuel shortages may mean that the beneficiary returns to a more polluting heating system or misuse the device received (for example, placing garbage inside the heaters). In Chile, two of the fuels necessary for the operation of the appliances offered, dry wood and pellets, have been in short supply. For example, in August 2022 there was a pellet stock crisis in five of the eight regions due to the shortage of the raw material to produce the fuel. For this reason, ensuring the pellet stock for heating must be part of the HRP to achieve its purpose.

The split inverter air conditioning system is the newest type of heater that has been strongly incorporated into the HRP since 2020, which is illustrated in Figure 3. The main features of this device are the zero emission of pollutants into the atmosphere, favoring energy savings by self-regulating the speed of its compressor, and having the dual mode to heat or cool homes as required. Although it is a great alternative to achieve the purpose of the HRP, it must be considered that it needs certain technical requirements to be installed.

A 12,000 BTU air conditioner has a power rating of 1.3 kW. If we consider that households also have other appliances connected to the electrical grid, it is possible that the installation of an air conditioner may require the household to request an increase in the power contracted with the local power distribution company. Although this service can be requested quickly, sometimes it is necessary to change the connection of the electrical line to the house, which involves a major modification. Another drawback is that houses built more than twenty years ago do not have the minimum technical conditions currently required by the authority for electrical installations, so the installation of energy-intensive equipment, such as an air conditioning system, can have serious consequences for household members. For this reason, the HRP could include within the installation services a review and modification, if necessary, of the home's electrical system, although the impact this would have on the program's budget must be considered.

[Figure 3]

Discussion questions:

What heating systems should the HRP offer?

Is it efficient to leave the choice of heater up to the applicant?

Are there other types of heaters that can contribute to achieving the purpose of the program efficiently?

Analysis of the effectiveness of the HRP

Once all the characteristics of the HRP have been exposed, it is necessary to study the effectiveness of the program to achieve its purpose, i.e., to reduce $PM_{2.5}$ emissions. For this

analysis, one of the emblematic cases of the program will be used as an example, the conurbation of the cities of Temuco and Padre Las Casas (Temuco-PLC) in the region of La Araucanía.

According to the last census conducted in the country (2017), in Temuco and Padre Las Casas there are 97,737 and 16,033 homes respectively. According to a survey conducted by the Ministry of Environment [33], in 2017 82% and 70% of households in Temuco and Padre Las Casas, respectively, had at least one wood stove. Considering the homes reported in the census, this means that there are 91,367 homes with wood-burning stoves in the Temuco-PLC conurbation as of 2017. A later version of the survey conducted in 2020 indicated that 61% and 47% of households in Temuco and Padre Las Casas had at least one wood stove, which means a decrease in wood stoves of 25.61% and 32.86%, respectively. This implies, according to the census data, that there should still be 67,155 houses with at least one wood stove (a reduction of 24,212 stoves). Considering that, according to the ministry, 10,659 stove replacements were carried out until 2020 under the HRP, it is estimated that 13,553 wood stoves were discarded on the households' own initiative.

Figure 4 shows the average pollution per month in the conurbation. As can be seen, $PM_{2.5}$ pollution rises substantially between April and September, which is consistent with the coldest months and, therefore, with the intensive use of wood heating. Considering only these months, Figure 5 shows the average pollution per hour of the day. The highest level of daily pollution occurs at night (between 5 pm and 3 am). This is related to households leaving the wood stove on at night until the fuel is completely consumed. There is also a small increase in the hours around 9 a.m., which is the time when people are at home before going to their daily work.

[Figure 4]

[Figure 5]

Figure 6 breaks down the average pollution per hour and per year[7] to analyze the existing differences resulting from the HRP. At first glance, there is a considerable difference between 2017 and the years 2019-2022. First, let's analyze whether the HRP had the expected impact on $PM_{2.5}$ pollution. For that, it will be assumed that pollution should have decreased, between 2017 and 2020, in the same proportion as the reduction of wood-burning heaters[8]. Figure 7 shows the hourly pollution estimate if the HRP was effective. The gray line "2020e" is the own estimate and the orange line "2020" is the effective pollution for the year. As can be seen, the estimate is quite close to the actual pollution recorded, although with differences in the nighttime hours. The average effective pollution reduction between 2017 and 2020 was 20.27%, 29.86% lower than estimated.

[Figure 6]

[7] A sample of years was selected for simplification.

[8] The decrease in wood-burning appliances was 25.61% in Temuco and 32.86% in PLC, according to a survey by the Ministry of the Environment [33].

[Figure 7]

Why did the pollution not decrease as expected? One possible answer is that the HRP ensures that the beneficiary acquires a new heating system and the old one is destroyed, but does not ensure its correct use over time. In 2020 there was a pellet stock crisis, which meant that the availability of this fuel was restricted. In this situation, it could have happened that some families used other types of organic materials to heat their pellet appliances, for example, wood. To test this hypothesis, Figure 8 shows the effective and estimated pollution for August 2020, the month in which the crisis occurred. It is observed that the effective pollution in 2020 was even higher than that of 2017 in most of the nighttime hours[9], which could cause the observed average of the 2020 effective pollution in Figure 7 to be higher than the estimate.

[Figure 8]

These results have three implications: 1) indeed most of the $PM_{2.5}$ pollution is due to residential use of wood, 2) the reduction in pollution observed since 2017 can be attributed to the decrease in residential wood use, and 3) ensuring fuel availability of delivered heating system fuel is critical to reducing air pollution.

Figure 6 shows no significant difference in pollution between 2019 and 2022. The only significant difference occurs at off-peak times, which can be attributed to a remnant of remote work due to the pandemic. Before delivering a foregone conclusion, it is necessary to consider the following aspect. Heating use depends on the temperature of the home. If 2022 was colder than 2019, it is not surprising that households used heaters more intensively. To test this theory, a heater usage rate was created, which is obtained by multiplying the pollutant emission exposed in Figure 6 by the average temperature of each schedule in its respective year. Figure 9 shows that this indicator shows a significant decrease in pollution during peak hours of use and an increase in midday use (which is explained by the existing remote work in 2022). This result allows us to affirm that the HRP was effective in reducing pollution between 2019 and 2022, provided that it is weighted by the temperature of the year.

[Figure 9]

Conclusion

Atmospheric pollution by $PM_{2.5}$ has serious consequences on people's health, with residential wood combustion being one of the main culprits. To combat this problem, the Chilean government has implemented the Heater Replacement Program (HRP), a policy that seeks to reduce the number of wood-burning heaters in exchange for providing more efficient heating systems that do not emit pollutants.

[9] According to data from Ministry of Environment [34], the average temperature at night time was similar between 2017 and 2020.

This case study analyzes the main problem areas of this program. First, it is observed that the subsidy, or co-payment, provided by the government for this policy is one of the highest in the world, so it is recommended that the subsidy be adjusted to the willingness to pay of the beneficiaries, in addition to implementing information policies to increase the appreciation of households for the replacement of their wood heaters. The second area describes the variables considered by the program to target the beneficiaries, concluding that the greatest weight should be given to the factors that promote a greater reduction in the emission of $PM_{2.5}$. The third aspect is related to the heating systems that the government provides for the replacement, obtaining as main lesson that the choice of the device must consider all the problems that households may be affected by using the device, since this is the only way to effectively reduce pollution in the cities.

Once all the characteristics of a public policy have been described, it is necessary to analyze whether it has been effective in achieving its purpose, in this case, to reduce $PM_{2.5}$ pollution. It can be seen that the policy managed to reduce pollution in one of Chile's main cities by 20.27% in three years. Although this is a promising result, it must be considered that the effect is 29.86% lower than expected. The study attributes this difference to the lack of fuel stock of the main heating system provided by the government. This fact is a demonstration that when implementing a public policy of this type it is not enough to deliver the devices, it is necessary to ensure that the beneficiaries can use their devices correctly over time.

Public policies should not be static; they should be transformed over time based on the lessons learned from their implementation, but always bearing in mind their purpose. This case study aimed to expose the characteristics that the critical analysis of an environmental policy should have, as well as to illustrate a case from which other policies in Chile and the world can learn.

Case study questions

1. What other information policies could be implemented in the country to increase the willingness to pay for heaters with lower emissions of $PM_{2.5}$?
2. How could companies and foundations contribute to the financing of the HRP?
3. Would a state lending policy be more efficient than providing subsidies?
4. Are there other postulation variables that can be considered to ensure the effectiveness of the HRP?
5. Is the homogenization of the weightings of the variables correct, or should they differ by region given the reality of each territory?
6. The Chilean government focuses the HRP with a voluntary application system. Wouldn't a system of automatic selection of beneficiaries through administrative data be more effective? What problems could this type of system have?
7. What heating systems should the HRP offer?
8. Is it efficient to leave the choice of heater up to the applicant?
9. Are there other types of heaters that can contribute to achieving the purpose of the program efficiently?

Author contributions

F.O.: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Visualization; Writing – original draft; Writing – review & editing.

E.S.: Investigation; Resources; Writing – original draft.

G.A.: Investigation; Resources; Writing – original draft.

V.M.: Investigation; Resources; Writing – original draft.

Acknowledgments

We thank the DUOC UC Foundation for their support, especially Adriana Abarca for her collaboration and support during the research.

Competing Interests

The authors have declared that no competing interests exist.

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Figure legends

Figure 1, 2, 3, 4, 5 and 6: Without legend.

Figure 7: The gray line "2020e" is the estimate of expected pollution given the reduction of wood stove by 28.9% between 2017 and 2020.

Figure 8: The graph considers only the month of August of each year. The gray line "2020e" is the estimate of expected pollution given the reduction of wood stoves by 28.9% between 2017 and 2020.

Figure 9: The "heater usage rate" indicator is obtained by multiplying pollution by temperature.

Figures

Figure 1: Truck collecting wood heaters removed by the HRP.

Source: Picture of Government [21].

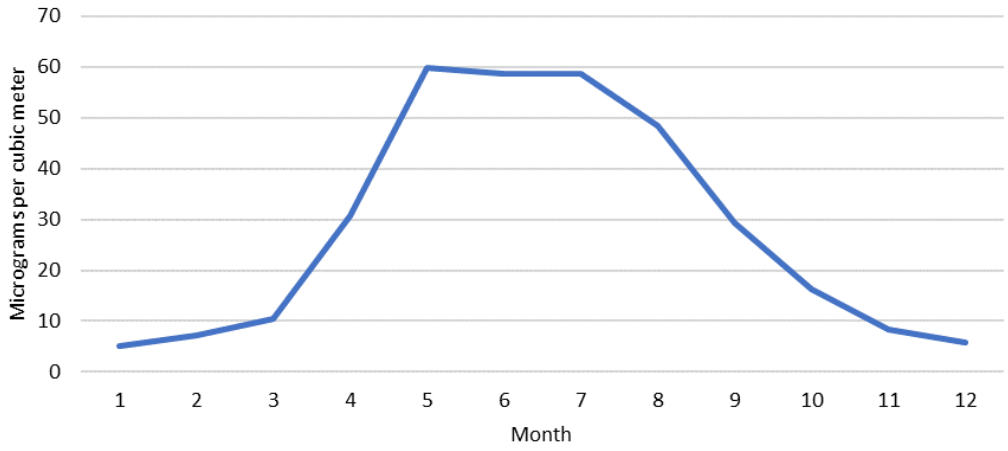
Figure 2: HRP beneficiaries with their pellet heaters.

Source: Picture of Government [21].

Figure 3: Household receiving installation of an air conditioner by the HRP.

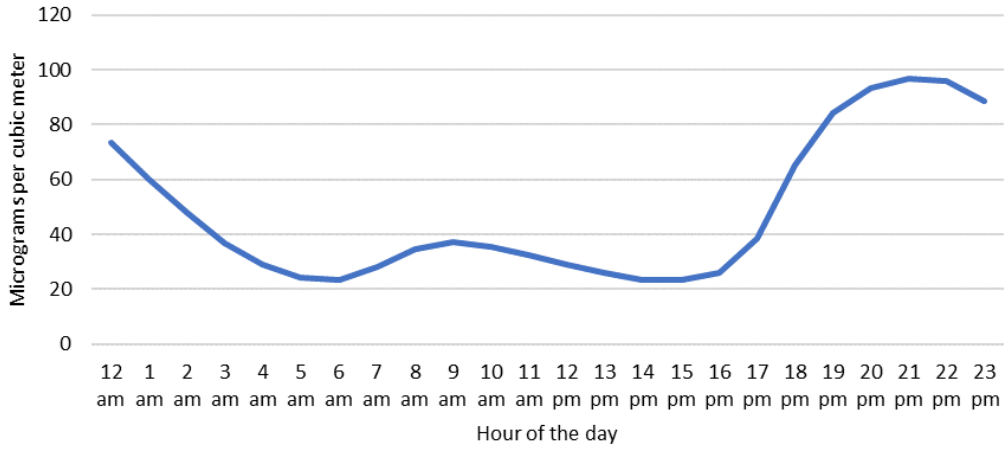
Source: Picture of local media [32].

Figure 4: Average monthly $PM_{2.5}$ contamination in the Temuco-PLC conurbation



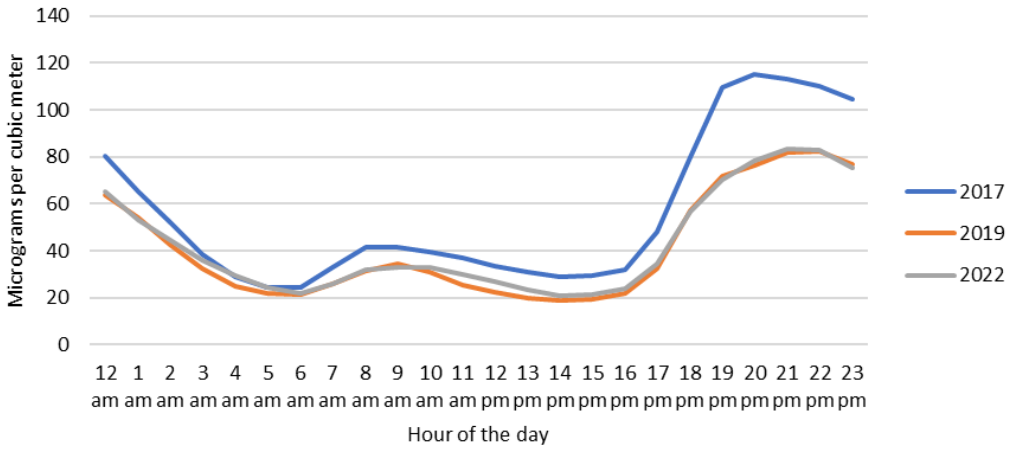
Source: Own elaboration based on data from Ministry of the Environment [34].

Figure 5: Average $PM_{2.5}$ pollution per hour of the day in the Temuco-PLC conurbation



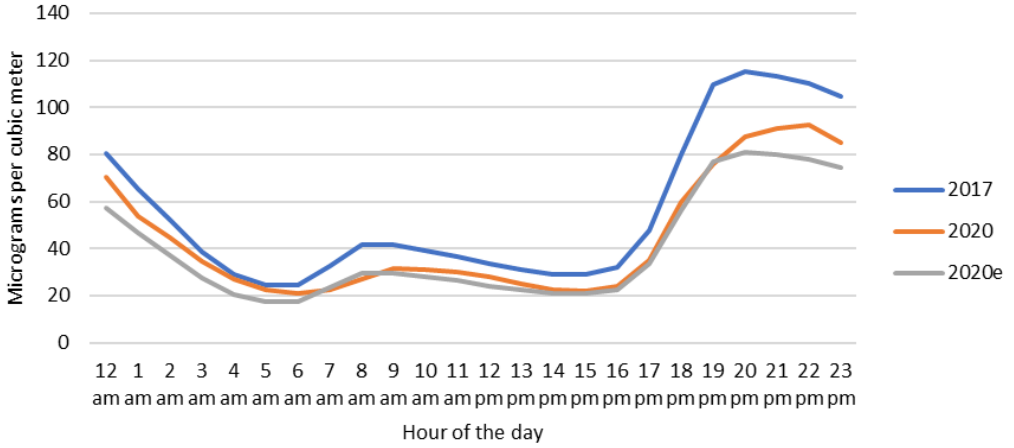
Source: Own elaboration based on data from Ministry of the Environment [34].

Figure 6: Average annual pollution per year by $PM_{2.5}$



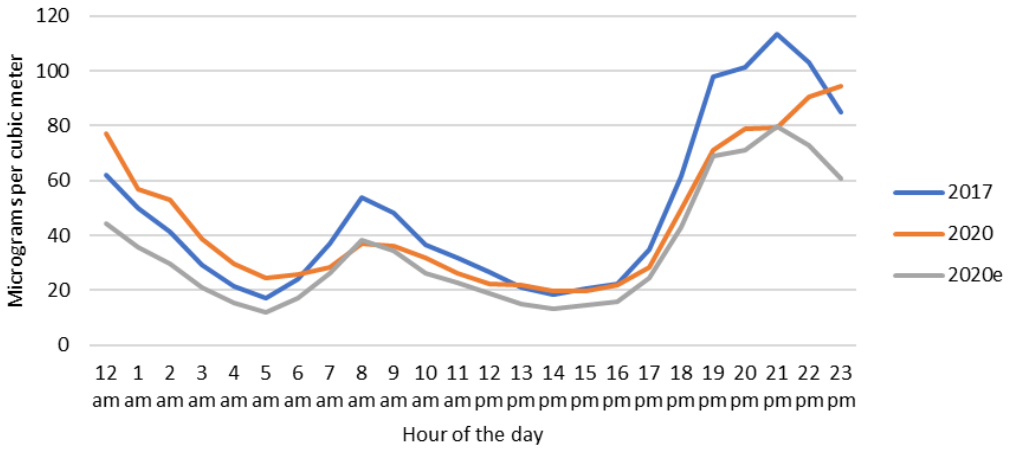
Source: Own elaboration based on data from Ministry of the Environment [34].

Figure 7: Estimated average $PM_{2.5}$ pollution in 2020



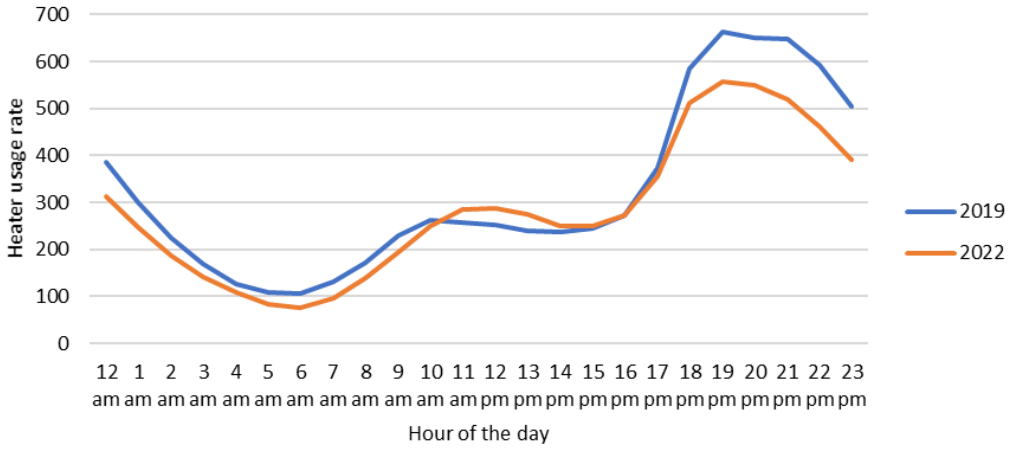
Source: Own elaboration based on data from Ministry of the Environment [34].

Figure 8: Estimated average $PM_{2.5}$ pollution in August 2020



Source: Own elaboration based on data from Ministry of the Environment [34].

Figure 9: Effective $PM_{2.5}$ pollution indicator in the Temuco-PLC conurbation



Source: Own elaboration based on data from Ministry of the Environment [34].

Tables

Table 1: Emissions of $PM_{2.5}$[†]

Region	Emissions of $PM_{2.5}$ (Tn)	Industry	Transportation	Wood Combustion	Agricultural Burning
Valparaíso	5,571.4	18.5%	40.3%	41.1%	0.1%
Metropolitana	9,626.0	21.4%	58.6%	19.8%	0.3%
O'Higgins	5,395.1	30.6%	8.0%	60.8%	0.6%
Maule	9,604.4	12.0%	3.6%	81.5%	2.9%
Ñuble	4,741.7	2.6%	7.5%	70.4%	19.4%
Biobío	13,300.8	4.6%	10.4%	81.7%	3.3%
La Araucanía	23,813.7	1.4%	2.5%	81.5%	14.6%
Los Ríos	9,518.5	0.8%	1.8%	96.0%	1.4%
Los Lagos	17,241.0	9.1%	2.9%	87.2%	0.8%
Aysén	3,018.3	0.5%	2.1%	97.2%	0.2%
Magallanes	1,506.2	9.1%	6.8%	84.0%	0.0%

Source: Own elaboration based on data from Ministry of the Environment [23].

Table 2: HRP co-payment by region and heating type[‡]

Region	Kerosene	Pellet	Air conditioning
O'Higgins	89.5%	87.4%	87.1%
Maule	93.7%	82.3%	82.3%
Ñuble	93.7%	84.9%	75.8%
Biobío	86.3%	83.6%	79.0%
La Araucanía	97.9%	97.5%	96.8%
Los Ríos	89.5%	87.4%	83.9%
Los Lagos	96.8%	83.6%	74.2%
Aysén	96.8%	96.2%	95.2%

Source: Own elaboration based on data from Ministry of the Environment [24] and Ministry of Finance [25].

[†] Only the regions of central and southern Chile are listed (in order from north to south).

[‡] The calculations have taken into account the contribution of households in the latest applications and the cost of equipment according to the latest offers accepted by the government.

Table 3: Efficient HRP co-payment by socioeconomic status and heating type[§]

Socioeconomic status	Kerosene	Pellet	Air conditioning
C1	87.6%	76.6%	80.7%
C2	87.1%	76.7%	81.7%
C3	86.1%	77.1%	82.7%
D-E	87.4%	80.3%	85.6%

Source: Own elaboration based on data from In-Data [26] and Ministry of Finance [25].

Table 4: Average weightings of the application variables in 2018

Region	Family group	Wood-burning appliances	Housing insulation	Territorial area
O'Higgins	30%	40%	30%	0%
Maule	35%	35%	30%	0%
Ñuble	40%	30%	30%	0%
Biobío	40%	30%	30%	0%
La Araucanía	50%	17.5%	17.5%	15%
Los Ríos	35%	35%	30%	0%
Los Lagos	27.5%	22.5%	35%	15%
Aysén	45%	20%	35%	0%

Source: Own elaboration based on data from Ministry of the Environment [24].

Table 5: Weightings of the postulation variables in the last call (2021 or 2022)

Region	Family group	Wood-burning appliances	Housing insulation	Territorial area
O'Higgins	20%	30%	40%	10%
Maule	20%	40%	40%	0%
Ñuble	20%	40%	40%	0%
Biobío	20%	30%	40%	10%
La Araucanía	20%	30%	40%	10%
Los Ríos	20%	40%	40%	0%
Los Lagos	20%	40%	40%	0%
Aysén	20%	30%	40%	10%

Source: Own elaboration based on data from Ministry of the Environment [24].

[§] For the calculations, the cost of the equipment was considered according to the latest tenders accepted by the government. The monthly income per household for each socioeconomic status (SES) is: C1: $2,207, C2: $1,511, C3: $999, D: $624, E: $360 (exchange rate: 900 Chilean pesos/U.S. dollar).

Table 6: Monthly emissions of $PM_{2.5}$ by type of heater[¶]

Type of heater	Monthly $PM_{2.5}$ emission (grams)	Cost of appliance purchase (US$)	Cost per gram of $PM_{2.5}$ reduced (US$)
Non-certified wood stove	4,614	-	-
Certified wood stove	2,176	$269.4	$0.11
Pellet	165	$702.43	$0.16
Air conditioning	0	$605.5	$0.13
Kerosene	29	$1082.98	$0.24
Liquefied gas	0	$364.25	$0.08

Source: Own elaboration based on Ministry of Environment [30] and Energy Sustainability Agency [31].

Table 7: Monthly expenditure by type of heater[††]

Type of heater	Monthly expense (US$)
Certified wood stove	$20.36
Pellet	$34.38
Air conditioning	$36.04
Kerosene	$51.43
Liquefied gas	$289.29

Source: Own elaboration based on Energy Sustainability Agency [31].

Table 8: Heaters delivered by the HRP

Type of heater	2015	2016	2017	2018[‡‡]	2019	2020	2021	2022[§§]
Certified wood stove	68	1,884	452	278	74	3	0	0
Liquefied gas	0	188	46	23	21	0	0	0
Kerosene	193	1,461	1,840	989	2,275	2,476	1,907	23
Pellet	737	1,904	4,053	4,297	14,746	20,045	9,340	510
Air conditioning	0	0	0	20	67	913	2.836	752
Total	998	5,437	6,391	5,607	17,183	23,437	14,083	1,285

Source: Own elaboration based on data from Ministry of the Environment [24].

[¶] Costs are expressed in U.S. dollars (exchange rate: 900 Chilean pesos/U.S. dollar).

[††] Costs are expressed in U.S. dollars (exchange rate: 900 Chilean pesos/U.S. dollar).

[‡‡] The first call published in Ministry of Environment [24] is from June 2018, so this year's information may be partial.

[§§] Preliminary information as of October 2022.

Appendix

Criteria	Sub-criteria	Assignment of Scores	Scores		Maximum score
Family Group (20 points)	Members of the family group	Number of people under 5 years old or over 60 years old	3 or more	5 pts.	5
			1 a 2	3 pts.	
			None	0 pts.	
	Number of people in the family group	Number of members	4 or more	5 pts.	5
			2 a 3	3 pts.	
			1	0 pts.	
	Risk groups	Family groups with members with disabilities and/or chronic cardiorespiratory diseases	Has	10 pts.	10
			Does not have	0 pts.	
Wood-burning appliances (30 points)	Type of appliance	Appliance installed	Spellbinders, salamander, single plate stove or single chamber heater	30 pts.	30
			Heater with tempering device (double chamber)	20 pts.	
			Wood stove	10 pts.	
Territorial area (10 points)	Residing in the Critical Event Management (CEE) territorial zone year 2020	Higher score for applicants residing in areas affected by restriction during the CEE year 2020	Lives inside the restriction zone	10 pts.	10
			Lives outside the restriction zone	0 pts.	
Housing insulation (40 points)	Thermal insulation	Homes with thermal insulation	House with SERVIU thermal conditioning, from 2018 onwards, or with building permit from 2018 onwards	40 pts.	40
			Housing with thermal conditioning by SERVIU, in the period 2015 to 2017, or with building permit between 2016 and 2017	20 pts.	
			Housing with thermal conditioning by SERVIU from 2008 to 2014	15 pts.	
			Housing with building permit between 2007 and 2015	10 pts.	
			Housing without thermal insulation	0 pts.	
Total					100

Source: Translation from Ministry of Environment [27].