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Using Stated Preference Methods to Design Cost-Effective Subsidy Programs to Induce Technology Adoption. An Application to a Stove Program in Southern Chile

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Using Stated Preference Methods to Design Cost-Effective Subsidy Programs to Induce Technology Adoption. An Application to a Stove Program in Southern Chile

Abstract: We study the design of an economic incentive based program –a subsidy- to induce adoption of more efficient technology in a pollution reduction program in southern Chile. Stated preferences methods, contingent valuation (CV), and choice experiment (CE) are used to estimate the probability of adoption and the willingness to share the cost of a new technology by a household. The cost-effectiveness property of different subsidy schemes is explored numerically for different regulatory objectives. Our results suggest that households are willing to participate in voluntary programs and to contribute by paying a share of the cost of adopting more efficient technologies. We find that attributes of the existing and the new technology, beyond the price, are relevant determinant factors of the participation decision and payment. Limited access to credit markets for low income families can be a major barrier for an effective implementation of these types of programs. Variations in the design of the subsidy and on the regulator's objective and constraints can have significant impact on the level and the cost of reduction of aggregate emissions achieved.

Keywords**:** Stated preferences, cost-effectiveness, environmental policy, urban pollution, households, contingent valuation, choice experiments.

1. Introduction

The problem of air pollution in urban areas caused by households burning wood is important in the developing world and also in some regions of developed countries (see, Lewis and Pattayanak 2012, and GACC, 2011, Pattanayak and Pfaff 2009 , WHO 2009 and World Bank 2011). In the case of Chile, there are several cities located to the south of the capital city of Santiago, where air pollution -the main environmental problem- is caused by households' wood combustion to supply energy (see for example Kavouras et. al. 2001, OCDE-CEPAL, 2005, Celis et. al 2004 and 2006).

A representative case of urban pollution problems caused by households burning wood in central-southern Chile is the city of Temuco. In this city of about 350,000 inhabitants around 90% of total emissions of suspended particulate matter is caused by households burning wood. In one of the three monitoring stations in the city it was measured during the year 2012 a total of 92 days with a 24-hours average concentration of suspended fine particulate matter ($PM_{2.5}$) exceeding the Chilean legal limit of 50 $\mu g/m^3$ (http://sinca.mma.gob.cl/). From the total 92 days exceeding the norm 51 correspond to a 24-hour average of more than 110 $\mu g/m^3$ and, again 22 to more than 170 $\mu g/m^3$. To put these figures in context, the Air Quality Guidelines of the World Health Organization (WHO) call for limiting the mean 24-hour average concentration of $PM_{2.5}$ in urban areas to 25 $\mu g/m^3$ (WHO 2005). Further information about the air pollution problem in Temuco can be found, for instance in Díaz-Robles 2008, Sanhueza et. al. 2009, Cereceda-Balic et. al. 2012)

The air pollution problem caused by households burning wood in urban areas is also a major regulatory problem. There are two main aspects of the problem, which make it difficult to solve. First, although individual households' emissions are potentially observable, it is not practical considering that there are tens of thousands of discharge points in medium size cities. This is similar to the nonpoint source pollution problem (see for example, Segerson 1988, Shortle & Horan 2001). Second, there are several sources of uncertainty related to the problem, including weather conditions, individual households preferences for heating, quality of the fuel used.

The regulatory agency in charge can follow different strategies for controlling the problem, like educational programs or proposal of new technical norm for households' wood combustion equipment. Potentially, the most effective tool is the use of economic incentives in order to induce a change in the behavior of the households concerning the quality of wood, and the technology of wood combustion. The use of economic incentives for pollution control has been widely explored in the context of point source pollution problems, where it is feasible to measure and monitor emissions. However, urban pollution caused by individual households is a different, and less explored, problem from the perspective of regulatory design.

A recent review of the literature by Lewis and Pattanayak 2012 shows that even when improved cook stoves have the potential of providing triple dividends (health, environmental quality and climate benefits) their adoption has been slow. The authors report 32 research studies with 11 analyses of improved stove adoptions in Asia, Africa and Latin America. They conclude that even when the use of stove replacement programs is expanding, the literature remain scarce, scattered and with a wide range of quality and therefore, new studies are required to help improving the implementation of stove replacement programs in the future.

In this paper we study, from an empirical perspective, the effect of an economic incentive based program –a subsidy- to induce adoption of a more efficient technology. We focus our analysis on the decision of individual household to participate in a voluntary program and on their willingness to share the cost of adopting the new technology. The data for our econometric calculation and simulations were collected with a survey in the city of Temuco. The area under study is a representative case of urban pollution problems caused by households burning wood in central-southern Chile. Furthermore, we explore, numerically, the cost-effectiveness property of different subsidy schemes under several possible regulatory objectives. Although our work focuses on the case of a stove exchange program, it could be applied to other problems, i.e. pollution caused by car emissions, energy efficiency, etc.

The subsidies we consider are intended to minimize aggregate emissions or total cost of pollution control. Another option would be to consider an efficient subsidy as proposed by Chávez, Stranlund and Gómez 2011. This intervention would need households' specific combustion technology subsidies that internalize the external benefit and cost of the households' wood combustion technology choice. Our focus on subsidies that induce cost-effective pollution control instead of fully efficient intervention is motivated by the difficulties to measure the external benefits from individual households' choices on combustion technology. Moreover, in practical terms, a pollution control policy in an urban area may pursue, instead of economic efficiency, another objective, for example to maximize emissions reduction with a given fixed budget.

We use stated preferences methods -Contingent Valuation (CV) and Choice Experiments (CE)- to study the probability of adoption of a new technology of wood combustion by a household and the type of technology they would acquire. Most of environmental valuation studies using stated preferences have focused on cost-benefit analysis of environmental policies (see Bateman et al. 1999, Kanninen 2007). Because these studies use stated preferences methods to evaluate the benefit (or cost) of a policy intervention, their main objective is an efficient and reliable estimation of the willingness to pay (WTP or willingness to accept, WTA) for a change in the environmental quality. Our goal in this paper is somewhat different because we are interested in using the stated preference techniques to design a subsidy program to provide proper incentives for adoption of new technologies of wood combustion. From that perspective we are not only interested in the WTP but also in the set of attributes of the technology and attributes of individuals that would affect the probability of adoption. Urban households differ in attributes and preferences (heterogeneous) and they may react differently to the same economic incentive (subsidy) and technological stimulus (attributes of a new technology). Identifying how households' characteristics and technology attributes affect their decisions, as for instance their propensity to participate in a program or the specific technology to be adopted, can contribute to the appropriate design of a subsidy program to achieve environmental goals and efficiency objectives.

The design of the subsidy program in our case involve not only the price of the new technology (and implicitly the subsidy), but also characteristics of different types of households. This information will allow us to simulate people`s responses to the attributes design of the program and will inform policy makers about the optimal design according to different goals and restrictions. For instance, the government might be interested in finding a design to maximize the number of replacements given a limited budget, or to maximize the impact of the program on air pollution, each objective may have a different optimal design.

Different econometric techniques have been used for studying the effects and the determinants of adoption of programs oriented to replace stoves and substitute fuels, see for a systematic review Lewis and Pattanayak 2012. As pointed out in this review, the literature on adoption is scattered. In particular, we are not aware of any study that used econometric results of stated preferences in order to design the subsidy structure and also to improve the cost-effectiveness of the subsidy program.

Our research efforts have produced four main results. The first result is that households are not only willing to participate in voluntary programs, but also to contribute by paying for more efficient technologies. This suggests that a cost-effective design of an incentive-based program should consider sharing the costs of acquisition of new technologies between the public and private households.

Our second result is that attributes of the existing and the new technology, beyond the price, are relevant determinant factors of the participation decision and payment. The third result is that the imperfection of credit markets that restrict access to credit for low income families can be a major barrier for effective implementation of these types of programs. A consequence of these results is that the design of a cost-effective program should consider, beyond the subsidy, at least two aspects: the heterogeneous preferences of families; and the need of access to credit for the poor.

The fourth result is that the specific design of the subsidy affects the individual decision to participate and contribute to the payment for more efficient technology. Variation in the design of the subsidy and on the objectives of the regulator can have significant impact on the level of reduction of aggregate emissions achieved. The numerical analysis also shed light on possible targeting strategies of subsidies on households' types, which greatly vary depending upon the regulatory objective.

The rest of the paper is organized as follows. In section 2 we discuss an empirical model of participation in a voluntary stove program and estimate the determinant factors of individual participation as well as households' willingness to pay for the new technology. Section 3 contains the analysis of a cost-effective subsidy program for urban pollution control considering different regulatory objectives and alternative designs of the subsidy scheme. We conclude in section 4.

2. An Empirical Model of Participation and Estimation of Willingness to Pay for Efficient Wood Combustion Stoves

In this section we present the methods used in the empirical analysis. First, we describe in general the methods used to study the determinants of the adoption decision and the private contribution to the adoption of new wood combustion technology. Second, we describe the data used and the estimation results.

2.1 Methods

The objective of the empirical model is twofold. First, to describe the adoption curve, that represents the probability of adoption of the new technology for different subsidies, given the attributes of the technology and household's characteristics. Second, to estimate the mean WTP of different classes of households. Both aspects contribute to the understanding and the design of cost-effective programs of technology change regarding the goals defined by policy makers.

Given the lack of market data we rely on Stated Preference (SP) approaches, Contingent Valuation and Choice Experiment, which are more flexible to accommodate introduction of new products in the market and to evaluate or manipulate the combination of attributes of the technological alternatives. The methodological choice has a caveat, which is the hypothetical nature of the questions and the lack of a binding constraint that might bias the estimation of the adoption curve and the mean WTP.

Contingent Valuation (CV) has become one of the most commonly used methodologies to value nonmarket goods in the economic literature, see, for instance, Bateman et. al.1999, Carson et. al.. 2003, Champ et. al. 2003. Choice experiments (CE) have been profusely used in marketing and transportation, see, for instance, Louviere et al 2000; Hensher et al. 2005. In a CV study researchers directly ask individuals about their willingness to pay (WTP) for a particular good of policy interest. CE is a type of conjoint analysis in which people have to declare their preference by choosing one alternative over a set of experimentally designed alternatives (Scarpa, 2008).

The number of applications using CV and CE in environmental economics has grown significantly in the last decade, but there are only few articles devoted to the use of these techniques for the design and implementation of actual environmental policies, see, for instance, Casey et. al. 2006, Fischer et.al. 2008, Lewis and Pattanayak 2012, Laurans et. al. 2013, and the references therein.

Contingent Valuation

We use a dichotomous choice model for our CV model. In our application, people were offered a general description of the replacement technology, with an associated price and a possible range of subsidies to finance the new technology. Given the final price offered (after subsidy) people have to decide whether or not they would be willing to participate in the replacement program. An important component of our program is that people have to give up their old equipment which would be destroyed in order to assure a reduction in air pollution.

Households in the city of Temuco are very familiar with wood combustion equipments. In average the families were using their current equipments for about nine years. In our survey the marketing mixed always include price, thermal efficiency and/or heated area (m^2). In the last few years, this marketing mix has included emissions or some measure of ecological performance due to increasing awareness of outdoor and indoor pollution. Therefore, the attributes are well known and relevant in the market place and we should verify how relevant they are in relative terms.

In order to define the reduction in emissions and wood consumption due to the replacement we characterized the current technology used in the households. For this purpose a set of standard attribute levels based on the current technology was created. Consequently, different households faced different reductions in wood consumption and emissions, depending of the technology they used. This individual calculation of the effects of the replacement was possible, because the new technology was identically defined for all the households (in the CV), and we could compare it with the current technology declared in a previous section of the survey.

The survey was divided in four sections. The first section was devoted to the presentation of the interviewer, the type of survey, its main attributes and to recruit the household to be interviewed. The second section gathered information about the current technology used for wood combustion in the household. This information included the age of the technology, costs of using the stove, amount of wood consumed, etc. Additionally the second section contained some questions about the perception of the underlying air pollution problem. This perception included the level of importance of the problem for the interviewee , the responsibility in its solution assigned to the households and to the government, and willingness to take actions individually to solve the problem, among others. The third section contained the properly contingent valuation questions and the choice experiments. Finally, in the last fourth section we gathered socio-demographic information and included debriefing questions to evaluate the responses´ quality.

The survey design followed several steps. In the first step, the survey was designed using information provided by various members of the group in charge of the implementation of technology change programs for wood combustion equipments working at the Chilean Ministry of the Environment. In the second step, we evaluated the first version of the survey using students from a local university. Later on, in the third step, we applied 50 pilot surveys in order to evaluate the wording, extension and other survey design issues. After some corrections based on the result of the pilot surveys, in the fourth step, the final version of the survey was applied (505 observations).

The sampling strategy was done in two consecutive stages. First, the blocks to be visited in the city were randomly selected from a list of income stratified neighborhoods. Second, we randomly chose a house (with evidence of having a stove) in the selected blocks.

Traditionally, CV applications have used a single-bound (SB) or double-bound (DB) format. In the former, people are offered only one value whereas, in the latter, they are given two valuation questions, each proposing different prices. For our study, we use the One-and-One-Half-Bound (OOHB) approach suggested by Cooper et al. 2002 which consists of a survey design in which a respondent is given two prices up front and told that, "although the exact final price of the item is not known for sure, it is known that it lies within the range bounded by these two prices". We used this design because it has been shown that it reduces statistical inconsistencies founded in the DB format without losing statistical efficiency as in the SB model (Carson et. al. 1992; Altf and DeShazo 1994; Bateman et. al. 2009).

Some information was given to the households as framing to the main question of the CV. This included general information of the replacement program to be implemented by the government, including the price (without subsidy) of the new equipments and a general description of the new technology. Moreover, some ranges for the individual impact of the replacement on the wood consumption, and emission were provided on base of the information previously gathered about the wood combustion technology used in the household. After that, the following valuation question was asked, where $\$B^{-}$ and $\$B^{+}$ denote the lower and upper bound for the BID, or final price (defined as the difference between the price of the new equipment and the subsidy) respectively:

"So far we do not know the exact subsidy for this technology and therefore we do not know the exact final price you have to pay, but we do know that this amount is in the range of ($\$B^{-}$, $\$B^{+}$). Considering all the expenses related to your daily living, would you be willing to pay $\$ B^{+}$ (or $\$B^{-}$) for this equipment"

One of the two final prices ($\$B^{-}$, $\$B^{+}$) was randomly selected, and the respondent was asked whether he or she would be willing to pay this amount. The other final price was asked, only if doing so would be consistent with the stated BID range. For instance if the lower of the two final prices ($\$B^{-}$) was initially selected and the answer is "yes" then the higher BID, $\$B^{+}$, is offered; but if the answer is "no" to the lower BID, there is no follow-up question, because that would exceed the stated BID range. The interview then proceeded to the debriefing questions (Cooper et. al. 2002).

If the individual was also willing to pay the higher BID, then we deduced that his/her maximum WTP is in the interval (B^{+},∞). On the contrary, if the lower price was accepted but the higher final price is refused then the WTP should be on the interval $(\$B^{-},\$B^{+})$. Finally, if a person rejected paying the lower BID, his/her WTP is in the interval $(0, B^{-})$. Similar intervals for the WTP can be obtained from the surveys that start with an upper bound; for instance $(0,B^{-})$ corresponds to two consecutive negative answers, (B^{+},∞) for a first positive answer, and $(\$B^{-},\$B^{+})$ for a negative answer followed by a positive answer.

All possible answers can be summarized in three groups: (NO/NO), (YES/NO), and (YES/YES). Note that the answer (NO/YES) results in the same interval estimation for the WTP as the

(YES/NO) answer, and it is therefore considered in the same group. We denote the corresponding response probabilities as π^N, π^{YN}, and π^{YY}. If C_i is the true WTP then the probabilities associated with each possible answer are:

$$\pi_i^N = \pi_i^{NN} = prob\left(C_i \leq B_i^-\right) = G\left(B_i^-;\theta\right) \tag{1}$$

$$\pi_i^{YN} = \pi_i^{NY} = prob\left(B_i^- \leq C_i \leq B_i^+\right) = G\left(B_i^+;\theta\right) - G\left(B_i^-;\theta\right) \tag{2}$$

$$\pi_i^{YY} = \pi_i^Y = prob\left(C_i \geq B_i^+\right) = 1 - G\left(B_i^+;\theta\right) \tag{3}$$

where $G\left(B_i, \theta\right)$ is the distribution function of the WTP and θ the parameters to be estimated. Let d^N be a dichotomous variable taking the value 1 if the answer is (NO/NO) and 0 otherwise. d^{YN} is a dichotomous variable taking the value 1 if the answer is (YES/NO) and 0 otherwise. And, finally, d^Y is a dichotomous variable equal to 1 if the answer is (YES/YES) and 0 otherwise. Using these variables, the likelihood function is:

$$\ln L^{OOHB}(\theta) = \sum_{i=1}^{N} \left\{ d_i^Y \ln\left[1 - G\left(B_i^+;\theta\right)\right] + d_i^{YN} \ln\left[G\left(B_i^+;\theta\right) - G\left(B_i^-;\theta\right)\right] + d_i^N \ln\left[G\left(B_i^-;\theta\right)\right] \right\} \tag{4}$$

Maximizing this function with respect to the parameter vector θ, we obtain an estimation of the set of parameters θ based on the maximum likelihood principle. The associated welfare measures are the mean and median of the WTP distribution calculated with the parameters. These measures are well known in the literature and, therefore, we do not develop them here (see Hanemann, 1984, 1989).

The parametric estimation requires the assumption of a distribution function $G\left(B_i, \theta\right)$ and an argument for this function. In our application we use the traditional linear indirect utility function suggested by Hanemann 1984 and a logit distribution function, therefore, the probability of a positive answer to the WTP question is given by $G(B_i, \theta) = e^{x'\theta}(1 + e^{x'\theta})^{-1}$, with *x* as a set of explanatory variables.

The BID levels are implicitly defined by the subsidies and must be below the price of the new technology (Ch$350,000, around US$700). The amounts of the subsidies offered were randomly selected from five possible fixed values. The resulting BID used in the survey were Ch$70.000 (around US$140) , Ch$140.000 (around US$280), Ch$210.000 (around US$420), Ch$280.000 (around US$560) and Ch$320.000 (around US$640).

We used a sequential optimal design procedure (Nyquist 1992) to reach an efficient estimation of the mean (median) WTP, that is, we collected a subsample of the data, estimated the mean WTP and recalculated the optimal number of observations in each of the bids. We repeated this procedure five times until we reached a robust estimation of the mean (median) value of the WTP.

Choice experiment

In the CE part of the survey individuals were asked to decide either keeping the current technology or moving to one of two new equipments. The alternative equipments were defined by different combinations of four attributes relevant for consumers, (Mansfield et al., 2006; Johnson et. al. 2000). The attributes of the new equipments used in the CE were BID, reduction in operations costs, reduction of emissions and the heating capacity of the new stove. The reduction values were obviously intended as result of the adoption of the improved technology.

For each of the four attributes we used three levels in the design with a total of 81 possible combinations (full factorial). For instance, the three levels used for the BID were Ch$ 150,000 (around US$300), Ch$ 210,000 (around US$420) and Ch$ 280,000 (around US$560). Using optimal design strategies (Kuhfled 2010 and Hensher et al. 2005) we selected a main effect fractional factorial design with 27 combinations.

Like in the CV part, we assumed that people will choose the alternative that provides the highest utility level and use a Lancasterian random utility model (Lancaster, 1966). Since people faced several decision occasions we have a panel that allows us to estimate a conditional logit or mixed logit model.

The econometric estimation of this model follows the traditional conditional logit model or its extension, the mixed logit model (Train, 1998; 2003). The utility function for individual *n* in each decision occasion t, given that she/he chose the alternative j, is given by

$$U_{njt} = \beta' x_{njt} + \varepsilon_{njt}, \qquad (5)$$

in which x_{njt} is a vector of attributes of alternative j, β is a vector of coefficients to be estimated and ε_{njt} is a random component independent of β. The probability that individual *n* chooses alternative *j* in decision occasion t is $L_{njt} = e^{\beta' x_{njt}} / (\sum_i e^{\beta' x_{nit}})^{-1}$, which is the traditional conditional logit model. The joint probability that individual *n* chooses the sequence of alternatives $y_{n\mathbf{j}} = \left\langle y_{nj_1 1}, \ldots, y_{nj_T T} \right\rangle$ is

$$\mathbf{L}_{n\mathbf{j}}(\beta) = L_{ny_{nj1}1} * \ldots * L_{ny_{njT}T} = \prod_{t=1}^{T} L_{ny_{njt}t} = \prod_{t=1}^{T} \prod_{j}^{J} \left(\frac{e^{\beta_n' x_{njt}}}{\sum_i e^{\beta_n' x_{nit}}} \right)^{y_{njt}}, \qquad (6)$$

where y_{njt} takes the value 1 if the alternative j was chosen and 0 otherwise.

2.2 Data and Estimation Results

Table 1 presents a list of variables included in the estimation of the CV models. It contains also the variables used in the CE methodology. BID, is the amount of money people would have to pay if they want to change the current wood combustion technology for the new equipment.

Estimation for Contingent Valuation

In the Table 2 the results for the contingent valuation model are given. It can be noted that a reduction of Ch$ 100,000 (around US$200) in the cost of the equipment increases the probability of adoption by 27%, while an equivalent rise on income increases the adoption probability only by 2%. The average willingness to pay is close to Ch$ 160,000 (around US$320), requiring a subsidy of 55% of the price. These results are robust to different statistic specifications, suggesting that in a subsidy program it is important to promote adoption of the new technology.

We also explored the effect of credit options offered to families, including 12 and 24 installments. In this case, a monthly payment was offered to each person. The results in Table 3 show that controlling for the price and characteristics of the replacement technology the willingness to participate in the program under the 24 months credit option was much lower than the willingness to participate under the 12 months options, being the latter higher than the no credit option.

Due to these responses, the average monthly WTP is Ch$ 23,291 (around $47) and Ch$ 3,670 (around US$7) for the 12 and 24 months options, with a total cost of Ch$279,000 (around US$560) for the 12 payments option and Ch$88,080 (around US$180) for the 24 payments case. Based on the WTP of Ch$160,000 (around US$320) for the no-credit model, these results imply a 9.8% discount rate for the 12 months and a negative discount rate for the 24 months model. Finally, we estimated a random effects logit model considering the three questions together, i.e. payment in one, 12 and 24 installments. The dependent variable was the Yes/No answer to the each of the valuation questions and the explanatory variables include the BID that was calculated as the present value of each payment alternative using a market average interest rate. The results are similar to previous models and the dummy variables are positive and significant for the 12 months alternative while negative and significant for the 24 month alternative, confirming the previous hypothesis about preferences for a 12 months credit period (See Table 4).[1]

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[1] Even when this result seems strange and it is not consistent with hyperbolic discounting and decreasing discount rate, it is consistent with future bias and increasing discounting over time (e.g. Anderhub et al., 2001; Sutter et al., 2010, Takeuchi 2011 and Dohmen et al. 2012).

Estimation for Choice experiment

We estimated an unlabeled model with only one set of parameters, where the status quo was defined as keeping the current technology. We consider a first model with several explanatory variables (Model E.E.1) and a second parsimonious model that includes only the statistically significant variables (Model E.E.2). Results are shown in Table 5. As expected, the greater the duration, the lower the probability of adoption. Older people are less likely to change their technology, but the use of other sources of fuel, larger family size, higher education and a positive expectation of future financial situation increase the probability of adoption.

3. Designing a Cost-Effective Subsidy Program for Urban Pollution Control

3.1 Methodology

In this section we give a formal description of the basic models considered in order to use the results from the stated preference methods in the cost-effective design of subsidy programs.

From the previous econometric results the most important issues for simulations and optimal design of the subsidy program are the following: the data base containing characteristics of households and stoves, and the functions estimating the probability of accepting a subsidy for a stove. The probability functions depend, among other variables, on the characteristics of the households and the characteristics of the wood combustion equipment being subsidized.

The base of the design strategy is a classification of the households from the data set according to the key characteristics determining the probabilities above mentioned. The finest classification was based on the following set of characteristics: income, expected time of use of old wood burner, Cost for the total amount of wood consumed, conditions of the old stove, age, size of the household, education, expected own future financial situation, a dummy variable for the case that the used burners has two combustion chambers, the total amount of wood consumed and the kind of burner in use (the old burners are classified in four types).

By considering the combinations of all the previously described characteristics, the households can be divided in 58 classes. Nevertheless, in the simulations we shall work with fewer classes defined on base of just some of the characteristics to classify the households. For each class an expansion factor can be calculated that relates the size of the class with the total number of households in the data base. Using the expansion factors it is possible to explore based on the results of the simulations the impact of a subsidy program for the whole set of households in the city of Temuco.

We use classes of families instead of specific family characteristics due to practical purposes. The subsidy offered cannot be differentiated at the family level (first degree price discrimination) but only on a general basis. This procedure also allows us to understand the key elements to be considered in the program to select a limited number of subsidy options, based on the program objectives.

In this paper we consider two different structures for the design of the subsidy program. In the first case the regulator selected one specific wood burner to be subsidized, and let the amount of subsidy depend on the characteristics of the households. In the second case, there are several stoves that are subsidized, i.e. the households can select the new stove from a given set, and the amount of subsidy differs for each stove depending only on its technical characteristics.

Subsidy based on the characteristics of the household

Let us denote by T the number of household types, by $N = (N_1, \dots, N_T)$ the vector of expansion factors for each class and by $Z_t = (Z_1, \dots, Z_K)$ the vector of characteristics of the household type $t = 1, \dots, T$. Based on the contingent valuation experiment we can calculated the probability $P_t^{CV}(Z_t, P - S_t)$ that a household of type t agrees to change its old stove for a new one on the basis of a subsidy S_t. In the calculation of this probability there is a fixed new stove to be subsidized (known by the household). We assume that the price P of the new stove is the only characteristic relevant for the probability of acceptance. In fact, if a household of type t accepts the offer of replacing the wood burner, it will have to pay the difference $(P - S_t)$ between the price of the new stove and the offered subsidy. For each t the function $P_t^{CV}(Z_t, P - S_t)$ increases with S_t.

The decision variables of the regulator in order to design a subsidy within our design are the components of the vector $S = (S_1, \dots, S_T)$. Each of the variables S_t should be selected into the box constraint $0 \leq S_t \leq P$, $t = 1, \dots, T$.

For any feasible selection of the vector of subsidies S the expected number of households accepting the offer ("**E**xpected **R**eplacements") can be calculated as follows:

$$ER_1(S) = \sum_{t=1}^{T} N_t P_t^{CV}(Z_t, P - S_t) \tag{7}$$

A second important quantity that can be easily calculated for each selection of subsidies S is the total "**E**xpected **C**ost" of the subsidy program, i.e

$$EC_1(S) = \sum_{t=1}^{T} N_t P_t^{CV}(Z_t, P - S_t)S_t \tag{8}$$

Finally the regulator is also interested on the impact of the subsidy program on the reduction of PM10 emissions. Let us denote R_t the yearly reduction of emissions (kgs. of PM10) that results from the replacement of a wood burner from a household of type t. This reduction is well defined, since for all households of the same type the old burners are identical and the yearly wood consumption is taken as the average in the group. The "**E**xpected **I**mpact" of a feasible set of subsidies S can now be calculated as follows:

$$EI_1(S) = \sum_{t=1}^{T} N_t P_t^{CV}(Z_t, P - S_t)R_t \tag{9}$$

As a referee correctly pointed out, there is a second order effect of the replacements that can eventually diminish the reduction of emissions. In fact, some households could burn more wood on the new stoves. However, due to the big differences in the emission factors between the old and new stoves, this increment in the amount of wood burn should still result in a reduction of emissions. It has to be mentioned that the better efficiency of the new equipments might also cause a reduction of the total wood burn for the households.

We have no data to compare the wood consumption using old and new stoves, since the new equipments are not yet used in Chile. Studies addressing the exact effect of a stove replacement under household conditions of use (not measurements in laboratories) are quite specific (see for instance Wilton et. al. 2006, Bergauff et. al.2009, Noonan et. al.2011, Ward et. al.2013) and can hardly be adapted to our situation. Since the second order effect due to the increase of wood consumption should anyway be less significant than the equipment replacement we considered the average values and assumed that the wood consumption in average remains the same.

Subsidy based on the stove characteristics

Let us now suppose that the regulator has selected Q different burners to be subsidized. For each of the new burners there is a vector of characteristics Y_k, $k = 1, \dots, Q$. Since the price is the key characteristic of the burners, it is considered separately of the vector Y_k and denoted by P_k $k = 1, \dots, Q$.

As a result of the choice experiment we can estimate for each type of household $t = 1, \dots, T$ the vector $P_t^{CE} = (P_{(t,1)}^{CE}(Z_t, Y_1, P_1 - U_1), \dots, P_{(t,Q)}^{CE}(Z_t, Y_Q, P_Q - U_Q))$, where each component $P_{(t,k)}^{CE}(Z_t, Y_k, k - U_k)$ denotes the probability that a household of type t accepts a subsidy U_k (paying the difference $P_k - U_k$) for exchange its old burner to a new stove of characteristics Y_k. In this model, the household has to decide among $Q + 1$ alternatives that includes the status quo, i.e. not to accept the offered subsidies and keep the old wood burner. The probability that a household of type t choices the "status quo" is given by

$$P_{(t,0)}^{CE} = 1 - \sum_{k=1}^{Q} P_{(t,k)}^{CE}(Z_t, Y_k, P_k - U_k) \qquad (10)$$

The decision variables for the regulator is now the vector $U = (U_1, \dots, U_Q)$, where each level of subsidy U_k must satisfy the box constraint
$0 \leq U_k \leq P_k$.

Our first attempt to estimate the expected number of replacements was the following formula

$$\widetilde{ER}_2(U) = \sum_{t=1}^{T} N_t \sum_{k=1}^{Q} P_{(t,k)}^{CE}(Z_t, Y_k, P_k - U_k) \qquad (11)$$

However, we observed that the probability of accepting one (anyone, not a particular one) of the offered subsidies using the above formula was extremely high. Consequently the expected number of replacements was also too big. This can be related to a common finding in the literature of choice experiment with an status quo alternative (Scarpa 2008; Hanley et.al. 1998; Haijer et al. 2001). In some applications people tend to have a bias against the status quo (or in favor depending of the problem). While there are several explanations for this, we think that this overestimation, at least in our case, will tend to bias upward the probability of adoption, especially comparing that the CV data provided a much lower probability of adoption.

There are several econometric approaches to account for the Status Quo bias, for instance Nested logit model, conditional logit with alternative specific constant for the SQ, changes in the codification of the attributes, among others (Breffle and Rowe, 2002). However, our interest is not only to avoid status quo potential bias, but also to represent the two step process of actual implementation of stove exchange programs in southern Chile. Therefore, we model the decision making process in two stages. In a first step the household decide about the subsidy program on base of the amount to be paid for the subsidized stoves. This decision is calculated using the probabilities of the CV application. In the second step the household should select one of the subsidized stoves looking to the attributes of the alternatives, or decide the status quo option. This second decision step is modeled on base of the CE results.

The previously described methodology seems to be related to the nested approach; however, this is not exactly the case. On the one hand, the alternatives in the choice set are not perfectly known by the respondent of the survey in the first step. On the other hand, even individual household that rejected to participate in the CV step, were also confronted to the decision in the CE step. Accordingly to this procedure for survey implementation, the econometric estimation of CV and CE was performed separately.

The final improved formula for the expected number of replacements takes the following form:

$$ER_2(U) = \sum_{t=1}^{T} N_t P_t^{CV}(Z_t, \min_{k=1,\dots,Q}\{P_k - U_k\}) \sum_{k=1}^{Q} P_{(t,k)}^{CE}(Z_t, Y_k, P_k - U_k) \qquad (12)$$

Since the function $P_t^{CV}(Z_t, r)$ decreases with the last argument r it holds the relationship

$$P_t^{CV}\left(Z_t, \min_{k=1,\dots,Q}\{P_k - U_k\}\right) = \max_{k=1,\dots,Q}\{P_t^{CV}(Z_t, P_k - U_k)\} \qquad (13)$$

Consequently the first step of our model, related to the use of the CV results in (12), recover all the households that could be interested in the subsidy program, even those motivated by only one of the prices of the new stoves. Following the same line of reasoning, the expected cost for a set of subsidies U can be calculated as follows.

$$EC_2(U) = \sum_{t=1}^{T} N_t P_t^{CV}(Z_t, \min_{k=1,\dots,Q}\{P_k - U_k\}) \sum_{k=1}^{Q} P_{(t,k)}^{CE}(Z_t, Y_k, P_k - U_k)\, U_k \qquad (14)$$

Finally the expected impact is given by the expression

$$EI_2(U) = \sum_{t=1}^{T} N_t P_t^{CV}(Z_t, \min_{k=1,\dots,Q}\{P_k - U_k\}) \sum_{k=1}^{Q} P_{(t,k)}^{CE}(Z_t, Y_k, P_k - U_k)\, R_{(t,k)} \quad (15)$$

Here the parameters $R_{(t,k)}$ represent the reduction in emissions resulting from replacing an old burner in a household of type t with a new stove of type k.

3.2. Cost-effective subsidies.

We use the results of the contingent valuation study to explore the effects that different characteristics of a subsidy could have in both, the probability of adoption and the cost of implementing a hypothetical stove replacement program. For this exercise, we fix the characteristics of the stove that will be used as replacement, offering a single equipment to the household participating in the stove replacement program. In this program, the regulator needs to design a subsidy for the households depending on the observable characteristics that are expected to influence their technology adoption, according to our statistical model. We consider in our simulations a classification of the households in only 9 types. This is obviously a coarser classification than the one in 58 types, and it was constructed considering the combinations of some of the observable characteristics. Among the observable characteristics we consider the self-reported level of income, the size of the house and if the household has a slow combustion stove. The characteristics of these 9 groups and their share in the sample are presented in Table 6.

We first analyze an unconstrained problem where the regulator maximizes the number of new technology adoptions without any constraint. Under this scenario the subsidy covers 100% of the cost of the new equipment. We use these results as a benchmark for the next four cases. In case 1, we consider a regulator that is interested on maximizing the number of stove replacements, but constraining its subsidy budget to 50% of the base scenario. In the case 2, we assume that the regulator is interested on maximizing the impact of pollution reduction, also constraining the subsidy budget to 50% of the base scenario. In the case 3, we consider a regulator that wants to minimize the expected expenditure in subsidies with the goal of reaching a number of replacements equal to 50% of the base case. Finally, in case 4 we consider a regulator that is interested on minimizing the budget required to reach a 50% reduction in emissions. These cases are summarized in Table 7.

The results of the optimal subsidy determined for the 9 household types under the different regulatory objectives are presented in Table 8.   We can observe that the results of the program will depend on the type of objective that the regulator has. For example, even when the regulator has a budget constraint of 50% an optimal design of the subsidy could allow him to reach 75% of replacement or 85% of emission reductions, depending on the regulator objective. Additionally, a correct design of the subsidy could allow the regulator to obtain 50% of replacements using only a 24% of the budget. Finally, he could obtain a 50% of emission reductions using only a 16% of the original budget. These results suggest that a correct design of the subsidy is crucial to obtain the goals that the regulator has in a cost-effective way. This is only possible by analyzing the consumers preferences for technology adoption and household characteristics.

The optimal subsidy determined for each household type under the four different optimization problems are presented in Figure 1. We can observe that there are important differences in the focalization of the subsidy to the different household depending on the goal of the regulator. When the goal is to maximize the number of replacements with a low budget, the subsidy is reduced in a relatively homogeneous way among household types. Nevertheless, given that some household types have a higher probability of adoption, the expected number of replacements can be increased by slightly increasing the subsidy to households with a smaller probability of adoption, such as low income and those that do not own a slow combustion stove. Something similar happens in case 3, where the regulator wants to reach a 50% replacement at minimum cost. The only difference with the previous case is that fewer replacements are needed and therefore the required subsidy is lower. The situation changes dramatically when the regulator is interested on reduction of pollution level. In this case, the regulator should focus the subsidy on households with lower quality stoves (no slow combustion). This is the case in scenarios 2 and 4 where the pollution reduction is involved. In these cases, an optimal subsidy involves fully subsidizing these types of households and to have a lower subsidy for families with newer combustion technologies. These differences in the optimal subsidies are explained by the fact that families with newer combustion technologies are more inclined to participate in stove replacement programs, but the replacement will have a smaller impact on emission reductions.

3.3. Cost-effective subsidy in the presence of multiple replacement alternatives.

The results from the choice experiment survey allow us to explore offering household two replacement options with different technology. Different households' preferences and characteristics might imply different replacement choices. The regulator needs to take into account the household preferences and the impact of the possible replacements on emission reductions given his management goals. For example, the regulator might be interested on maximizing the number of replacements, maximizing the impact of replacement on emission reductions, or minimizing the expenditure needed to reach an environmental goal. The regulator might design the optimal subsidy to reach these goals with different replacement alternatives.

In this section we present the results from four alternative subsidy programs, each of them with two stove replacement alternatives offered to each family. We consider four new stove types as the choice set for the regulator, based on the information observed in the stove market in Chile. The technical characteristics of these stoves are presented in Table 9. The regulator first decides a combination of two replacement stoves to include in the program and then he decides on the optimal subsidy for each stove, depending on his management objective, according to Table 7. The families then decide which stove to choose, if any, according to its welfare maximization alternative for which we use the conceptual framework presented before in the choice experiment exercise.

We consider four possible replacement sets offered to the families. The first case offers stoves 1 and 2. These are the two most expensive alternatives. One of them is expensive because it is an imported stove and the second because it has higher heating capacity. The second replacement case offers stoves 3 and 4. These stoves have a lower price with similar emission impact, but with stove 4 having higher heating capacity. In the third case, the regulator offers stove 1 and 3. In this case there are important differences in terms of price and emission levels but both stoves have the same heating capacity. In the fourth case, the regulator offers stoves 2 and 4, which are similar in terms of heating capacity but with stove 2 having a higher price and emission level.

Table 10 shows the effects of designing an optimal subsidy in the different subsidy programs and depending on the management goal. For the base scenario the numbers of replacements, expenditure and emission reductions are shown. For all the other scenarios, the percentage of the base scenario is presented. The base scenario shows what would be the results of offering the different alternatives with a 100% of subsidy. We can observe differences in the number of replacements and the associated cost and emission reductions. This is because families have different choices depending on the alternatives being offered. In scenario 1, the regulator intends to maximize the number of replacement with an optimal subsidy and a budget constraint equal to 50% of the base case. We observe that with an optimal subsidy the regulator is able to achieve between an 82% and an 87% of replacements and a reduction in emission between 76% and 82% of those under an unconstrained subsidy program.

A similar analysis is presented for scenarios 2, 3 and 4. In scenario 2, the regulator might achieve up to an 87% of replacement and 82% of emission reductions with 50% of the budget when he offers stoves 1 and 3. If the regulator is limited in the number of replacements, as in scenario 3, he could achieve up to 52% of emission reductions with 60% of replacements compared to the unconstrained situation. Finally, if the regulator needs to achieve an emission reduction goal of 50% compared to the unconstrained case, he could do it with only 22% of the original budget, if he designs the subsidy properly.

Finally, in tables 11 and12 we present the proportion of the price covered by the optimal subsidy and the cost per unit of Kg of emission reduced. In Table 11 we observe that for most of the programs considered it is optimal to provide a relatively high subsidy to only one of the two offered stoves. This is due to the fact that households have different characteristics and might be inclined toward different alternatives. When one of the alternatives is clearly superior for the regulator either because the cost of the equipment is lower or because it has characteristics such that a lower subsidy is required to induce the adoption in most households, the regulator only needs to offer a subsidy for one of them. Table 12 shows that the most efficient programs, in terms of cost per unit of emission reduction, are found when the regulator designs a subsidy to minimize the cost of adopting the policy or program subject to a fixed goal on the number of replacements or the emission reductions. In these efficient programs stoves 3 and 4 were offered, but 53% of the price of the stove 4 is subsidized, i.e. Program 2 and Scenarios 3 and 4 in Table 12.

4. Conclusions

We have explored the use of stated preferences methods (contingent valuation and choice experiments) to estimate household preferences and willingness to participate in a stove exchange program to reduce air pollution from wood combustion in southern Chile. We conducted a survey and estimated the probability adoption function as the probability that a household is willing to participate in the exchange program depending on household characteristics, the technology currently being used, the technology being offered and the subsidy level.

We use the estimated adoption probability function to simulate the cost-efficiency property of different subsidy schemes, depending on household types. The household types are based on their observable characteristics. This allows to set differentiated subsidies and give the regulator and idea of where should he focus the stove exchange program, depending on the goal of the stove replacement program.

There are four main results. First, households are not only willing to participate in voluntary stove adoption programs, but they are also willing to contribute to the program by paying a share of the cost of adopting more efficient technologies. This suggests further that a cost-effective design of an incentive-based program should consider partial subsidies, sharing the costs of the adoption of stove replacement programs between the government and private households.

Second, attributes of the existing and the new technology, beyond the price, are relevant determinants of the likelihood of the participation in the program and the amount the household is willing to pay. Third, the credit restrictions of low income families can be a major barrier for an effective implementation of this type of programs. Consequently, the design of a cost-effective program should consider, beyond the subsidy, heterogeneous preferences, and access to credit for the poor.

Fourth, the specific design of the subsidy and the regulatory goal, in terms of in which household characteristics the program should focus and if the goal is replacement level or expected reduction in pollution, will importantly affect the individual decision to participate and contribute to the payment for more efficient technology. Specifically, our results suggest that when the regulatory objective is to maximize emissions reduction it is optimum to allocate a given fixed budget on fully subsidizing the oldest wood combustion stoves. The numerical analysis also shed light on possible targeting strategies of subsidies on households' types, which greatly vary depending upon the regulatory objective.

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