

ECONOMICS

Evaluation of a CO₂ Tax in Chile: Emissions Reduction or Design Problems?

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In 2014, Chile introduced a tax reform on carbon dioxide (CO₂) emissions that began to be collected in 2017; the reform is restricted to large industrial and power generation sources with thermal power greater than 50 megawatts (MW). Therefore, this study evaluates each industrial source's option to reduce its taxes by switching to cleaner fuels (investing in new combustion equipment, such as boilers and dual burners). The results show that a tax of US\$5 per ton of CO₂ for industrial sources of more than 50 MW of thermal power is wholly ineffective in reducing emissions. If a carbon tax is applied to all independent sources of power, only a few industrial sources are predicted to change their current fuel, mainly changing coal to biomass. The conclusion is that the carbon tax serves to raise tax revenues rather than reduce emissions.

En la reciente reforma tributaria de 2014 Chile introdujo un impuesto a las emisiones de CO₂, el cual comenzó a ser cobrado en 2017 y está restringido a las grandes fuentes industriales y de generación eléctrica con potencia térmica mayor a 50 MW. Este estudio evalúa la opción de cada una de las fuentes industriales para reducir su carga tributaria al cambiarse a combustibles más limpios invirtiendo en nuevos equipos de combustión, tales como calderas y quemadores duales. Los resultados reflejan que un impuesto de US\$5 por tonelada de CO₂ para fuentes industriales con potencia térmica mayor a 50 MW es completamente inefectivo para reducir las emisiones. Si un impuesto es aplicado a todas las fuentes, independiente de su potencia, solo unas pocas fuentes industriales cambiarían su combustible actual, principalmente de carbón a biomasa. Se concluye que el impuesto sirve para recaudar recursos más que para reducir las emisiones.

The Kyoto Protocol is an international agreement submitted by the Convention of the United Nations to reduce the emissions of greenhouse gases. The protocol entered into force on February 16, 2005, after being ratified by 55 of the 181 UN member countries, including Chile; its objective was to reduce 5 percent of the countries' emissions between 2008 and 2012. At the UN Climate Change Conference in Paris (COP21) in December 2015, 195 countries signed a new climate change agreement. Specifically, Chile committed to reducing its emissions intensity by 30 percent by 2030 from its 2007 level.

The countries that emit higher quantities of CO₂ include China, the United States, India, Russia, and Japan, which produce 55 percent of CO₂ emissions (OECD 2012). The human action source that most contributes to CO₂ emissions is the use of fossil fuels. Globally, the three main economic sectors that generate CO₂ emissions are the power generation and heat production sector (energy), the transport sector, and the industrial sector. CO₂ is mainly emitted to the environment by the energy and industrial sectors by means of boilers and furnaces.

In Chile, energy consumption is mainly based on petroleum, which represents 54.8 percent of the total secondary consumption.¹ The second most used energy source is electricity, which represents 19.9 percent

¹ Secondary energy refers to the products that result from transforming or processing natural energy resources (primary energy) or, in certain cases, from another energy source already delineated.

of final consumption; next is biomass, with 18.1 percent of consumption, and natural gas with a 5.4 percent of consumption (Ministry of Energy, 2015). The industrial sector uses 23.2 percent of the total energy consumption of the country, which corresponds to 1406.8 trillion BTUs.

Although Chile is not a major CO₂ emitter on the planet, with 0.23 percent of total emissions, the country's amount of emissions is growing rapidly.² Furthermore, the electricity sector contributes 42 percent of total emissions (Mardones and Muñoz 2017). These antecedents may explain the tax reform proposed in 2014 that incorporates a tax on CO₂ emissions. This tax began to be collected in 2017 and includes a charge for CO₂ emissions generated by establishments whose stationary sources (boilers or turbines) individually or collectively total greater than or equal to 50 megawatts (MW) of thermal power. Each source will pay US\$5 per ton of CO₂ emitted; however, stationary sources whose primary energy source is biomass will be excluded from the charge.

According to preliminary data from the Environment Superintendent,³ this tax would affect approximately 150 stationary emission sources;⁴ of this total, 93 would correspond to thermoelectric and the others to stationary sources related to the cement, paper, pulp, metallurgical, and food industries. Although this preliminary list of emission sources was generated, there was no ex ante evaluation to model the behavior of industrial sources under this new regulation; this situation is addressed in this study.

A tax on CO₂ emissions could affect the industrial source's behavior when choosing both the type of fuel to be used and the combustion technologies. Assessment of the applied tax is relevant for estimating the economic impact on the affected industrial sources, the degree of substitution of fuels, and the regulatory effectiveness of the environmental policy in Chile. The proposed methodology will allow for estimation of the effects of extending this policy to all industrial sources (independent of MW of thermal power). In addition, this environmental policy is of interest to other Latin American countries, because Chile is the second country in the region (after Mexico) to introduce this carbon tax, and the amount of the tax will be five times higher than the Mexican carbon tax.

The objective of this study is to assess the environmental effectiveness of a CO₂ tax on industrial sources and to focus on technological and fuel changes motivated by the tax. For this, the fuel consumption of industrial sources in Chile is estimated from the Annual National Industrial Survey (ENIA) developed by the National Institute of Statistics (INE 2014), which allows for the individual estimation of CO₂ emissions. This study then evaluates different options associated with a possible fuel change that enables each industrial source to conduct an economic analysis to find the best alternative to the CO₂ emissions tax.

The results of this study could be useful for other Latin American countries that intend to introduce this type of environmental tax in the future, because it would define the tax rates necessary to achieve specific environmental objectives.

International Experience with Taxes on CO₂

One of the measures being taken worldwide to stop global warming is the introduction of carbon taxes, which burden CO₂ emissions. However, this idea is not new; in the nineteenth century, the economist Arthur Pigou (1920) proposed taxes to reduce pollution.

The fundamental principle of a system of taxes on CO₂ emissions is the internalization of negative externalities, which would lead to the adoption of cleaner technologies in the production of goods and services.

Between 1991 and 1996, Denmark, Finland, the Netherlands, Norway, and Sweden began to apply CO₂ taxes. Agnolucci (2004) reviewed the studies that evaluated the effect of this tax and concluded that taxes on their own or as a part of packages of measures have helped reduce CO₂ emissions, as the economic theory predicts. However, the taxes' individual contributions are uncertain. Agnolucci also notes that in practice, there has been no cost-effective policy, because tax rates are very heterogeneous given the different agreements and subsidies generated between emission sources.

A more recent study (World Bank 2014) noted that this type of tax is already implemented in Australia, Denmark, Finland, France, Iceland, Ireland, Japan, Mexico, Norway, Sweden, Switzerland, and the United Kingdom. The study also noted that South Africa, Brazil, Chile, South Korea, and the US state of Oregon will

² "Emisiones de CO₂ (kt)," Banco Mundial, <http://datos.bancomundial.org/indicador/EN.ATM.CO2E.KT/countries>.

³ Environment Superintendent is a decentralized public service that runs, organizes, and coordinates action plans for environmental decontamination, environmental standards, and all other instruments. This agency also establishes criteria for environmental regulations.

⁴ However, the ENIA survey and the methodology developed in this study estimate that 436 industrial sources will be affected.

soon implement the tax. The lowest tax is US\$1 per ton of CO₂, implemented in Mexico, and the highest tax is US\$ 168 per ton of CO₂, implemented in Sweden.

According to the same World Bank (2014) study, in certain countries, the CO₂ tax increased preexisting energy taxes (e.g., Sweden), whereas tax levels remained unchanged in other countries (e.g., Denmark, Finland) because it reduced the tax burden of energy taxes or income tax. Moreover, with the introduction of emissions trading in the European Union (EU Emission Trading Scheme), certain tax exemptions have been generated to avoid double payment for the emissions, which affects the enterprises' competitiveness.

Few scientific studies have evaluated the economic taxation of CO₂ to determine its effectiveness. Larsen and Nessbakken (1997) evaluated the effect of a CO₂ tax on oil consumption; established in Norway, the study uses partial equilibrium models for different economic sectors. The results show that the CO₂ tax had an impact on reducing emissions.

Bjorner and Jensen (2002) used firm-level data to assess the effect of a package of voluntary agreements, environmental taxes, and subsidies in Denmark. With one of the different estimated models, they concluded that the effect of taxes in 1997 reduced energy consumption by 10 percent but subsidies did not generate impacts.

Morley (2012) used a dynamic panel methodology with data from different EU countries; the results suggest that the recent introduction of environmental taxes has a negative and significant effect on per capita greenhouse-gas emissions.

However, Lin and Li (2011), using the difference method in different samples, showed that a CO₂ tax has a very heterogeneous effect between countries. According to their estimations, the applied tax has generated a significant reduction in per capita CO₂ emissions solely in Finland.

Gerbelová and colleagues (2014), applying a dynamic simulation model, examined the effects on the electrical system in Portugal under the CO₂ emissions tax in the European trading system. Other studies, such as Symons, Proops, and Gay (1994), have focused on the impacts on fuel prices, manufactured goods prices, consumption, and distribution in the United Kingdom. Wissema and Dellink (2007) determined, using a computable general equilibrium model, that CO₂ emissions in Ireland could be reduced by 25.8 percent with a tax of €10–€15 euros per ton emitted. The researchers also concluded that an emissions tax is more effective than an energy tax.

In the case of Chile, Gallardo and Mardones (2013) identified the economic sectors that face the greatest trade-offs among growth, equality, and environmental protection (including the highest direct and indirect CO₂ emissions). Vera and Sauma (2015) compare the effects on reducing CO₂ emissions with a carbon tax and energy efficiency measures in the energy sector. Muñoz and Mardones (2016) used an environmental extension of the Leontief price model to simulate the economic and environmental effects of a carbon tax to mitigate impacts from Chilean agricultural and livestock sectors on climate change. Finally, Mardones and Muñoz (2017) show that a much higher tax rate than the Chilean carbon tax on energy sector is needed (US\$ 130 per ton) to reduce emissions to the required levels by COP21.

Methodology

Information Sources

For Chile, it is possible to obtain industrial data on employment, raw material and energy consumption, and physical production from the Annual National Industrial Survey (ENIA). For this study, variables including identification information, the International Standard Industrial Classification (ISIC) economic activity code, region, fuel consumption, fuel measurement units, fuel expenditure, and working days (Table A2 in Appendix) were used. In particular, we used the 2011 survey because it was the latest available at the time of the study's termination (at the beginning of 2015).

To estimate the energy used by each industrial source, we used the data from ENIA on the quantity of each consumed fuel, as well as the fuel density and heating values obtained from the National Energy Balance from the Ministry of Energy and the US Environmental Protection Agency (EPA 2009). However, the ENIA survey does not directly identify which industry sources have thermal power greater than 50 MW; this can be inferred only indirectly by annual fuel consumption. Therefore, the following descriptive analysis presents the behavior of all industrial sources (independent of MW of thermal power) that are included in the ENIA survey (3,223 industrial sources).

The following industry sectors consume high quantities of coal: the metallurgical industry, with 66 percent of total fuel consumption (129,712 million tons per year); the nonmetallic minerals industry, with 20 percent of total consumption (39,307 million tons year); and the food industry, with 13 percent of total consumption (25,549 million tons per year).

The largest industry sector that mainly consumes fuel oil and diesel is the food industry, with 53 percent of the total (650 million tons per year); this is followed by the paper industry, with 22 percent (270 million tons per year), and the nonmetallic minerals industry, with 5 percent (61 million tons per year).

The industry sector that consumes the most gasoline is the food industry, with 40 percent of the total coal consumption (7,429 tons per year); this is followed by the metal-mechanical industry, with 12 percent (2,229 tons year), and the metal products industry, with 10 percent (1,857 tons per year).

The highest-consuming liquefied petroleum gas (LPG) industry sectors are the food industry, with 39 percent (41,509 tons per year), followed by the chemical industry, with 16 percent (17,029 tons per year), and the paper industry, with 14 percent (14,901 tons per year).

Natural gas is primarily consumed in the chemical industry, with a consumption of 34 percent (175,174 tons per year); this is followed by the food industry, with 19 percent (98,892 tons per year), and the paper industry, with 19 percent (98,892 tons per year).

The largest biomass consumer in the industry sector is the paper industry, with 64 percent (726,980 million tons per year); this is followed by the wood industry, with 22 percent (249,900 million tons per year), and the food industry, with 14 percent (159,027 million tons per year).

Estimation of CO₂ Emissions

The following fossil-fuel sources were considered in order to evaluate the effect of applying a CO₂ tax on industrial sources; coal, diesel oil, fuel oil, natural gas, and biomass. Other fuels, such as gasoline and kerosene, are not primarily used in the production processes of industries, whereas LPG is mainly used for room and office heating. For those industrial sources that consume more than one fuel, they were divided into a source for each fuel (coal, biomass, petroleum No. 6, petroleum No. 2, and natural gas); thus, the research has information from 3,223 sources. In the baseline scenario, all these sources emit a total of 5,198,826 tons of CO₂.

To evaluate a potential change of fuel in case of a CO₂ tax, it is necessary to know the quantity of fuel required for each industrial source to generate the same quantity of energy (BTU). If the payable tax amount under the original fuel for an industrial source is greater than the sum of the annualized cost of technology investments and the increase of spending associated with the new fuel, the industrial source should then reduce its emissions.

To estimate the quantities of CO₂ emitted by each industrial source, the consumed quantities of energy must be multiplied by the factors of CO₂ emissions according to the type of fuel. These data are obtained from "IPCC Guidelines 2006 for the National Greenhouse Gases Inventories" (**Table 1**).

It is important to note that the CO₂ emission factor for biomass is zero because trees capture CO₂ from the atmosphere during growth; then, in the process of burning the same quantity of wood, the CO₂ captured during the growth phase is released. Although this course has been questioned because the recapture of vegetation may vary from years to centuries, it is valid to assume zero emissions in this study because the tax in Chile excludes emission sources that use biomass as fuel.

Technology Options

Of the industrial sources to be analyzed, 303 consume solid fuels (225 consume biomass and 78 consume coal), 2,114 consume liquid fuels (1,403 consume petroleum No. 2 and 711 consume petroleum No. 6), and 806 consume natural gas.

Table 1: CO₂ emission factors per fuels.

Fuel	Factor	Unit (MMBTU = 10⁶ BTU)
Petroleum	77.2	Kg CO ₂ / MMBTU
Coal	97.6	Kg CO ₂ / MMBTU
Gasoline	72.2	Kg CO ₂ / MMBTU
LPG	65.8	Kg CO ₂ / MMBTU
Natural gas	58.8	Kg CO ₂ / MMBTU
Biomass	0.0	Kg CO ₂ / MMBTU

Source: IPCC 2006.

Table 2: Technological requirements.

Current fuel	Fuel to be evaluated	Technology
Liquid	Solid	Boiler change
Liquid	Gas	Burner change
Solid	Liquid	Boiler change
Solid	Gas	Boiler change
Gas	Liquid	Burner change
Gas	Solid	Boiler change

Source: Own elaboration from Mechanical Engineering Department, University of Concepción.

The technological requirements that are necessary to change the fuel currently used in the production processes from industrial sources are presented in **Table 2**. Sources that consume liquid fuels will need to change to dual burners, which operate on gas and petroleum. Conversely, the solid fuel sources that want to use liquid or gaseous fuels will require a complete change of equipment, because the fuel supply to the boiler and in the area in which the fuel is burned differs.

However, the ENIA survey does not specify the technical characteristics of the combustion equipment of the sources; in particular, it does not include thermal powers in MW (PotMW) that are relevant to determining the equipment cost. Then, and based on the Industrial Emissions Inventory from Metropolitan Concepción (UDT-PROTERM 2011), it was possible to obtain a sample from industrial sources that included information on fuel consumption and boiler power; this information was used to estimate functions to simulate the boiler power for each industrial source that was included in the ENIA survey (see Table A1 in Appendix). The estimated functions, the standard errors of the coefficients, and R² are as follows:

$$PotMW_{Biomass} = 0.0000881 + 5.58 * Biomass\ Consumption(Kg) R^2 = 0.61 \quad (1)$$

(0.0000677) (1.70)

$$PotMW_{Coal} = 0.0014727 * Coal\ consumption(Kg) R^2 = 0.66 \quad (2)$$

(0.0002488)

$$PotMW_{petroleum/gas} = 0.0036547 * Petroleum\ or\ gas\ consumption(m^3) R^2 = 0.70 \quad (3)$$

(0.0004095)

The Economic Costs of Technological Options

To perform a comparative analysis of different alternatives for the industrial sources once a CO₂ tax on emissions is applied, it is necessary to know the data regarding the energy consumed by the different sources and the power in MW of each piece of combustion equipment, the quantity of technological equipment used in each source,⁵ the value of the new combustion equipment, the fuel prices per power unit, and the number of tons of CO₂ emitted from the fuel being evaluated.

The fuel prices were obtained from the ENIA survey as the average value per MMBTU (one million BTU) paid by sources in each region of Chile. In the regions without fuel price information, the average price of the nearest regions is reported. **Table 3** contains price information for each type of fuel.

Because alternative fuel switching is associated with a change in boilers or burners, it is necessary to formulate an annualized cost function for each of the source's options for change. It was possible to know the price of burners and boilers that are required for fuel change from combustion equipment quotes. Then, the annualized investment cost of this equipment was related to the MW thermal power to estimate the statistical functions that allow the extrapolation of the annualized cost for all industrial sources available in the ENIA data.⁶

⁵ This information is not available in the ENIA; therefore, the quantity of the equipment (boilers) is obtained from the power (MW) estimated, considering that a large kettle should have a maximum power of 50 MW. The quantity of the equipment is simply the closest to the value produced by dividing the power consumption by the equipment's per unit power production.

⁶ High R² in certain regressions can explain why there were few observations to estimate cost functions (17 observations for oil/gas, 16 observations for coal, and 33 observations for biomass); few companies reported the prices of their boilers.

Table 3: Fuel price US\$/MMBTU for 2011.

Region	Petroleum No. 2	Petroleum No. 6	Natural gas	Biomass	Coal
Arica-Parinacota	23.6	15.8	18.7	4.5	7.0
Tarapacá	29.0	19.4	20.4	4.5	7.0
Antofagasta	25.7	17.2	16.2	4.8	1.8
Atacama	26.0	17.4	14.4	4.6	3.5
Coquimbo	26.7	17.9	17.6	3.4	3.5
Valparaíso	27.4	18.3	15.3	4.8	1.5
O'Higgins	26.6	17.8	13.8	4.2	3.5
Maule	26.1	17.5	14.9	2.8	5.0
Bío Bío	26.3	17.6	16.5	3.3	5.2
Araucanía	27.2	18.2	16.5	2.8	1.0
Los Lagos	27.6	18.5	14.2	3.4	4.4
Aysén	29.4	19.7	13.7	2.2	11.9
Magallanes	25.6	17.1	16.6	2.2	11.9
Metropolitana	26.6	17.8	14.6	5.0	3.8
Los Ríos	25.6	17.2	17.1	2.7	1.3

Source: Own elaboration from ENIA 2011.

$$CT\ Boiler_{pet/gas} = 236886 + 1421722 * PotMW + 65381 * PotMW^2 \quad R^2 = 1.00 \quad (4)$$

(48935) (69719) (910)

$$CT\ Burner_{pet/gas} = 199077 + 131720 * PotMW \quad R^2 = 0.91 \quad (5)$$

(43860) (9844)

$$CT\ Boiler_{coal} = (513041 * PotMW^2 - 631 * PotMW^3 + 0.2 * PotMW^4) * 0.86 \quad (6)$$

(46054) (75) (0.25)

$$+ (1 - 0.86) * 112000000 * PotMW \quad R^2 = 1.00$$

(7693338)

$$CT\ Boiler_{biomass} = 20200000 * PotMW \quad R^2 = 1.00 \quad (7)$$

(4937990)

These functions correspond to the annualized investment in boilers and burners; however, they do not cover the additional costs of installation, which correspond to 20 percent of the cost of the boiler (Escobar 2013).

Because the CO₂ tax paid by industrial sources will depend on the tons of CO₂ emitted per year, it is necessary to know the annual cost of the fuels used and the annualized price of the boilers and burners to economically value the best option to address this tax. An equipment life of twenty years was considered to obtain the equivalent annual cost of the technological equipment; this horizon is used in industrial boiler projects that are admitted to the Environmental Assessment in Chile.⁷

⁷ The Environmental Assessment Service (<http://www.sea.gob.cl>) is a public agency whose main function is to set environmental assessment of projects as provided for in current legislation in Chile, to promote and facilitate public participation in the evaluation of projects.

Comparison of Alternatives Based on Cost Indicators

To address the existence of a CO₂ tax, it was considered that each source could maintain its fuel consumption and could switch to any of the other types of fuels. Thus, a comparison table was created in which the current scenario was present with no investment in technological equipment but considers the cost of the tax for annual tons of CO₂ emitted by the fuel used. Furthermore, four additional scenarios for each fuel were generated; they reflected the annualized cost of the acquisition of technological equipment to create a change of fuel, the installation cost of such equipment, the annual differential fuel cost to maintain the fuel energy equivalence, and the cost per ton of CO₂ emissions through the use of the new fuel.

The analysis of the quantity of industrial sources that could decide to change their use of fuel were first restricted according to the availability of certain fuels. Thus, in the case of biomass availability, this number was limited to the regions of Arica-Parinacota, Tarapacá, Antofagasta, and Atacama, according to information from the Ministry of Agriculture.⁸ At the same time, natural gas was also limited because not all regions have pipeline capacity that enables the supply of this fuel (information from the National Energy Commission).⁹

Then, total costs were compared for each of the alternatives that could opt for industrial sources. Moreover, different adjustment costs were applied to simulate the initial equilibrium because certain sources, in the absence of taxes, equally chose to switch fuel.¹⁰ These sources were estimated, and adjustment costs were added that allow for replication of the base situation.

Finally, an analysis of scenarios was performed; it considers different error rates in estimating the potential adjustment costs by undercutting the estimation of costs associated with changes in the combustion equipment in the sources.

For a better understanding of the methodology used in Table A3 (Appendix), twenty-five industrial sources (identified by ID) are shown as examples. This table is a sample of the total industrial sources included in the analysis. This table includes fuel consumption, energy used (BTU), boiler power (MW), number of boilers, original CO₂ emissions, and the annualized cost indicator (US\$) for each alternative for fuel change under the same energy requirement. Finally, from the lower cost indicator chosen, each fuel source is selected to determine the final emissions and CO₂ tax collections.

Results and Analysis

A total of 3,223 industrial sources that consume different fuels and emit approximately 5.2 million tons of CO₂ in the baseline scenario was evaluated. When the study solely considers sources of thermal generation greater than 50 MW, the quantity is reduced to 436 sources that emit a total of 3.3 million tons of CO₂, which corresponds to 63 percent of the total.

In the case of a US\$5 tax per ton of CO₂ emitted, no industrial source finds it economically attractive to switch from its current fuel; therefore, it is concluded that no reduction in CO₂ emissions would be observed, and tax collection would correspond to \$ 16.3 million.¹¹ This result is robust to different errors in estimating the costs of adjustment in fuel switching (to a maximum of 25 percent of the adjustment cost).

If the application of a tax of US\$ 10 per ton of CO₂ emitted is evaluated, one industry source that uses petroleum No. 6 would change to biomass. The quantity of tons of CO₂ emitted would be 3,191,685, which implies a reduction of 2 percent of the total tonnage currently emitted by thermal power sources over 50 MW. The reduction in tax revenues associated with the fuel change is reflected by the same percentage. The result is not robust at different levels of errors in adjustment costs, particularly for errors greater than 5 percent in the adjustment costs in which no source would change to biomass.

These results reflect the ineffectiveness of this CO₂ tax, as currently proposed in the tax reform of 2014, to reduce industrial emissions. Thus, it is necessary to evaluate other, more restrictive settings to determine whether a tax actually can help reduce industrial emissions in Chile. Therefore, an evaluation of the application of the tax to all industrial sources regardless of their installed thermal power is proposed. That is, a tax is proposed on the industrial use of fuels that emit CO₂; the amount of the tax is US\$5 per ton of CO₂. **Table 4** shows the results after raising awareness of different error scenarios in estimating the adjustment costs.

⁸ Cifes Archivos, http://cifes.gob.cl/archivos/1_Karin-von-Osten.pdf.

⁹ "Hidrocarburos," Comisión Nacional de Energía, <http://www.cne.cl/estadisticas/energia/hidrocarburos>.

¹⁰ The adjustment cost is simply the difference between the annual cost of using the current fuel in connection with the annual cost of using the simulated fuel with lower cost. Because the fuel currently used was not the same as the lowest cost in all cases, it was assumed that any adjustment costs prevented the use of the fuel with minimal cost. Initial equilibrium is achieved when the estimated annual cost for each fuel and the adjustment costs allow for the simulation that each source chooses the same currently used fuel.

¹¹ This value is obtained by multiplying the 3.3 million tons of CO₂ emitted by the tax value of US\$5 per ton of CO₂.

Table 4: Simulation of applying a CO₂ tax of US\$5 per ton emitted.

Variable	Percentage of error in adjustment costs					
	0%	5%	10%	15%	20%	25%
Tax collection (in US\$ millions)	25.13	25.13	25.13	25.13	25.13	25.13
Reduction of tax collection	3.31%	3.31%	3.31%	3.31%	3.31%	3.31%
Tons of CO ₂ baseline situation	5,198,826	5,198,826	5,198,826	5,198,826	5,198,826	5,198,826
Tons of CO ₂ carbon tax situation	5,026,701	5,026,701	5,026,701	5,026,701	5,026,701	5,026,701
Reduction of tons of CO ₂	3.31%	3.31%	3.31%	3.31%	3.31%	3.31%
Number of changes	22	22	22	22	22	22
% change biomass sources	9.78%	9.78%	9.78%	9.78%	9.78%	9.78%
% change coal sources	-28.21%	-28.21%	-28.81%	-28.81%	-28.81%	-28.81%
% change petroleum No. 6 sources	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
% change petroleum No. 2 sources	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
% change natural gas sources	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Power range (in MW)	1–26 MW	1–26 MW	1–26 MW	1–26 MW	1–26 MW	1–26 MW

Industrial sources that are willing to make a fuel change under a \$5 tax scenario are heterogeneous, with thermal power from 1 MW to 26 MW, whereas large thermal power sources (over 50 MW) would not change their fuel. Of the sources currently using coal, 28.8 percent would change to biomass; however, sources that use fuel that pollutes less than coal would decide not to make changes in their fuel because of their relatively low emissions and payable tax amount. The following industries would adopt a new fuel: food (50 percent), plastics (20 percent), leather (20 percent), metal products (5 percent), and other (5 percent). In all simulated scenarios, tax collections would be \$25.1 million and the reduction of emissions, 3.3 percent.

Although it may seem counterintuitive that including a larger group of small sources increases the effectiveness of the tax, this result is logical because smaller firms have lower investment costs for a change of fuel. In contrast, investment costs are significantly higher for the largest sources and do not generate sufficient incentives to switch to cleaner fuels if taxes are low. Furthermore, because emission factors by fuel type are not affected, this result could be generalized to other Latin American countries with similar technological fuel change options to reduce emissions. However, the results could vary if other relative fuel prices exist or if the relative prices change of technologies related to changing boilers.

Applying a tax of US\$10 per ton of CO₂ emitted does not generate major changes in fuel switching decisions on industrial sources (**Table 5**). Adjustment costs remain for twenty-two sources that changed from coal to biomass for all other scenarios; CO₂ emissions regarding the base situation are reduced by 3.3 percent, and tax collections could reach \$50.3 million.

According to unreported additional estimations, a tax of \$13.73 per ton of CO₂ applied to all industrial sources could meet the goal of reducing industrial CO₂ emissions by 20 percent. However, this result is very sensitive to errors in estimating the adjustment costs. If adjustment costs achieve 25 percent, the tax required to meet the target would rise to \$51.47 per ton of CO₂. Thus, the required tax is consistent with those applied in the United Kingdom (\$16), Australia (\$22), British Columbia and Ireland (\$28), Denmark (\$31), and Finland (\$48).

Conclusion

In analyzing the effects on Chile of the tax reform, which includes a tax of US\$5 per ton of CO₂ emitted for thermal generating sources over 50 MW, we conclude that no industrial source will decide to opt for cleaner fuels; the quantity of CO₂ tons actually emitted remains the same.

By analyzing more restrictive settings, it can be concluded that a tax of \$5 to \$10 per ton of the CO₂ emitted by all industrial, independent sources of thermal power boilers does not generate major changes in the use of fuels. The reduction in emissions is 3.3 percent (172,125 tons of CO₂) in nearly all the simulated scenarios, which is why industrial sources would find it more expensive to change their production systems to consume a lower contaminant fuel than to pay the tax.

Table 5: Simulation of CO₂ tax applied to US\$ 10 per ton emitted.

Variable	Percentage of error in adjustment costs					
	0%	5%	10%	15%	20%	25%
Tax collection (in US\$ millions)	49.58	50.27	50.27	50.27	50.27	50.27
Reduction of tax collection	4.62%	3.31%	3.31%	3.31%	3.31%	3.31%
Tons of CO ₂ baseline situation	5,198,826	5,198,826	5,198,826	5,198,826	5,198,826	5,198,826
Tons of CO ₂ carbon tax situation	4,958,443	5,026,701	5,026,701	5,026,701	5,026,701	5,026,701
Reduction of tons of CO ₂	4.62%	3.31%	3.31%	3.31%	3.31%	3.31%
Number of changes	24	22	22	22	22	22
% change biomass sources	10.67%	9.78%	9.78%	9.78%	9.78%	9.78%
% change coal sources	-28.21%	-28.21%	-28.21%	-28.21%	-28.21%	-28.21%
% change petroleum N°6 sources	-0.28%	0.00%	0.00%	0.00%	0.00%	0.00%
% change petroleum N°2 sources	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
% change natural gas sources	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Power range (in MW)	1–50 MW	1–26 MW	1–26 MW	1–26 MW	1–26 MW	1–26 MW

Therefore, the application of a \$5 tax would increase tax revenue for the country rather than promote a change to cleaner fuels. This result is consistent with the ineffectiveness of the CO₂ tax estimated by Lin and Li (2011). However, this study establishes that a higher tax (between \$ 13.7 and \$51.5) could be more effective.

Additional File

The additional file for this article can be found as follows:

- **Appendix.** Tables A1–A3. DOI: <https://doi.org/10.25222/larr.33.s1>

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Belén Flores graduated with a degree in industrial engineering from University of Concepción (Chile) in 2015.

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How to cite this article: Mardones, C and Flores, B. Evaluation of a CO₂ Tax in Chile: Emissions Reduction or Design Problems? *Latin American Research Review*. 2017; 52(3), pp. 334–343. DOI: <https://doi.org/10.25222/larr.33>

Submitted: 03 March 2015

Accepted: 20 January 2016

Published: 22 September 2017

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