PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE
ESCUELA DE INGENIERÍA

CO_2 TAX DESIGN AND TRAJECTORY ANALYSIS IN POWER SYSTEM EXPANSION PLANNING

ANDRÉS JOAQUÍN PEREIRA MASSARDO

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the degree of
Master of Science in Engineering

Advisor:
ENZO SAUMA SANTIS

Santiago de Chile, July 2019

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"If we do not do the impossible, we shall be faced with the unthinkable"

-Murray Bookchin

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ABSTRACT

Nowadays, Climate Change is one of the main global concerns. Worldwide efforts to fight this problem have been compromised in 2015's UNFCCC Paris Agreement which set a series of goals for its parties in order to prevent a 1.5°C rise in global temperature. To achieve those goals, greenhouse gas (GHG) emissions must be limited and one way to do so is by pricing emissions with market-based policies such as carbon taxes. This work examines the design and application of a flexible carbon tax in a ten-year expansion-planning model of the Chilean energy system. The problem is solved by modeling a bi-level problem where the upper level minimizes the carbon tax and the lower level solves the expansion planning problem as a mixed integer optimization problem. A weighted sum bisection method is proposed to obtain the optimal tax, however, for investigation purposes different taxes from US\$5/tonCO_2 to US\$40/tonCO_2 are analyzed for the case scenarios. The trajectory of the tax is analyzed by studying the costs, investments, economic dispatch and emissions in single and two-stages tax schemes. Conclusions point out that under the absence of political economy constraints, the most cost effective solution is to have a minimum tax in the first stage and an optimal tax in the second. Incorporating this result while ignoring unaccounted benefits of modifying the trajectory of application of the tax may lead to an inadequate tax scheme.

Keywords: Carbon tax;Climate Change; power system economics; power system expansion; tax flexibility.

RESUMEN

El cambio climático es una de las principales preocupaciones a nivel mundial. El acuerdo de París impulsado por la UNFCCC el año 2015 comprometió metas concretas entre los países para evitar un aumento de ms de 1,5°C. Dentro de esas metas está la disminución de emisiones de gases de efecto de invernadero, la cual se puede realizar mediante políticas de mercado tales como un impuesto al carbono. En esta tesis se estudia el diseño y aplicación de un impuesto a las emisiones de CO_2 en un modelo de expansión del sistema eléctrico chileno para un plazo de diez años. El problema se resuelve mediante un modelo de dos niveles donde en el nivel superior se minimiza el impuesto al carbono y en el inferior se resuelve la expansión como un problema de programación entera mixta. Un método de bisección de sumas ponderadas (WSBM por su sigla en inglés) se propone para obtener el impuesto óptimo, no obstante, se inspeccionan distintos niveles de impuesto entre US\$5/tonCO_2 a US\$40/tonCO_2 por motivo de la investigación. Se analiza la trayectoria del impuesto analizando los costos, inversiones, despacho y emisiones en esquemas de una y dos etapas. Las conclusiones apuntan a que bajo la ausencia de restricciones de economía política, la solución más costo efectiva es tener un impuesto mínimo a las emisiones en la primera etapa y uno óptimo en la segunda. Se señala además que tomar en cuenta este resultado ignorando los beneficios de la modificación de la trayectoria del impuesto podría llevar a la implementación de un esquema de impuesto al carbono que no es el adecuado.

Palabras Claves: Impuesto al carbono; Cambio Climático, economía de sistemas eléctricos; expansión de sistemas de potencia; flexibilidad de impuestos.

1. INTRODUCTION

1.1. Motivation

The relation between mankind and its environment is a fundamental issue to consider specially for disciplines like engineering where most of its activity is related to some level of exploitation of nature's resources. This exploitation can take many shapes and, as centuries of industrial revolution have taught us, it can have serious consequences for the environment. It has become evident that the human race left an indelible print over the planet ecosistems in several levels. One of the most relevant environmental effects to account for is the Climate Change. Since the beginning of the industrial revolution, anthropogenic green house gases (GHG) emissions have risen to unsuspected levels. This phenomenon was not a major concern until a few decades ago, when the first voices alarming about this subject started to became notorious (Le Treut et al., 2007).

Around the decade of the 1980's research started to point towards a consensus around the effects that emissions of GHG could have in the environment (Le Treut et al., 2007). In nature, GHG like SO_X, NO_X, CH_4 , F-gases and most notoriously, CO_2, have a crucial role in keeping the temperature of the earth on an adequate level to mantain life as we know it. However, the last centuries of intensive burning of fossil fuels have affected the natural equilibrium of the GHG which has been steadily rising earth's average temperature (Le Treut et al., 2007). The effects of the increase in global temperature can be catastrophic if emissions keep the business as usual predictions. The melting of the ice caps would produce the rise of the sea levels. Local climate will be affected producing the increment of extreme weather conditions. The biodiversity will be affected and it is expected that and important amount of species will be extinct due to this new climate conditions (Urban, 2015). This and many other negative consequences will happen if the temperature rises above 1.5°C (IPCC, 2018) and are exclusively to blame on human action. This is why there is an ethical imperative to take action globally to attack this issue.

One of the main problems of fighting the global warming phenomenon is that individual action is useless if others do not also take part. There are incentives not to take action against global warming if others do not do so. This is, amongst other reasons, because emitting GHG is cheaper than using cleaner technologies, thus producing a competitive disadvantage for those who concern about the effects of Climate Change. Therefore, the need of a world-wide agreement with the participation of every nation is needed to address this problem. In this context, the first international reunions began to search for a global agreement regarding Climate Change.

In 1988 the first Intergovernmental Panel on Climate Change (IPCC) established as the first multinational action to begin addressing the global warming issue. This lead the United Nations to create a Framework Convention on Climate Change (UNFCCC), which periodically organize several international conventions around the subject of global warming. One of the first and most notorious agreements that this joint work made possible was the Kioto Protocol adopted in 1997 (UNFCCC, 2018). This agreement, despite the fact that it had major faults that made it very ineffective to fight the rise of carbon emissions (Pollitt, 2015), set the precedent for the posterior global action against global warming by being the first international treaty on GHG emissions. Many years and lots of political debate had to pass until a more tangible worldwide agreement was met to fight global warming: the Paris Agreement of 2015 (UNFCCC, 2015). Amongst many compromises, it set the task of limiting the rise of global temperature only to a maximum of 1.5°C and nations made individual pledges to help achieve this goal. Despite the fact that still there are problems as the untraceability of the accomplishment of this goals or the absence of ways to enforce every country to fulfill their pledges, it was a major advance that set a clear course of action. Research has shown that despite all of the mentioned worldwide efforts, it is very unlikely to stop global warming before surpassing the 1.5°C goal (Kriegler et al., 2018; Millar et al., 2017; Nordhaus, 2018; Rogelj et al., 2018). Nonetheless, endeavors should try to get as near of it as it is possible.

In this context, Chile as a party member of the UNFCCC made part of this agreement and also took several compromises. Regarding the carbon emissions mitigation action, Chile agreed the following goal (Ministry of the Environment, 2015):

a) Commitment to reduce its CO_2 emissions per gross domestic product (GDP) unit by 30% below their 2007 levels by 2030.
b) Reduction of its CO_2 emission per GDP unit by 2030 until it reaches a 35% to 45% reduction with respect to the 2007 levels (Subject to the grant of international monetary funds).

As can be seen, Chile must commit to emit less than 70% of the base line GHG emissions per GDP unit nationally. That is why the country must take serious actions to reach its compromises as emissions keep rising. The main emission source of the country is the energy sector as can be seen in figure 1.1 (Ministry of the Environment, 2018).

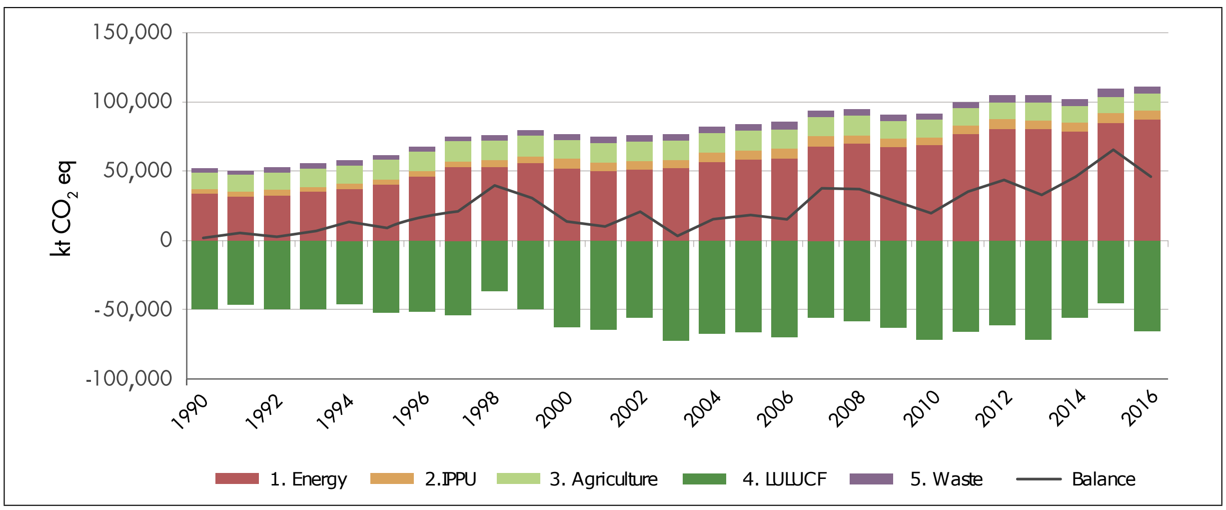

Figure 1.1. Chile's National GHG inventory: balance of GHG (kt CO_2eq) by sector, 1990 - 2016 series. Adapted from (Ministry of the Environment, 2018, p.33). IPPU stands for industrial processes and product use; LULUFC stands for land use, land-use change and forestry.

In year 2016, the Energy Industry sector was responsible of emitting 36.16 $MTCO_2$eq which corresponds to 41.5% of the country's total emissions (Ministry of the Environment, 2018). Also, to year 2017 coal consisted in almost 39% of the total generation in Chile (National Energy Comission, 2017). As this technology is a heavy emitter of GHG, Chile has a lot of potential to lower its emissions by limiting this coal generation.

How will Chile achieve this goal is not clear. The government has proposed for the energy sector a mitigation plan (Energy Ministry, 2017a), which consists in different packages of measures to implement in different energy areas. The lack of specificity regarding those measures is important and despite the proposal of several actions, it is not clear how most of them will be implemented and whether they will be successful to meet the emissions goals compromised by Chile.

Carbon pricing is fundamental for climate-change policy (Stern, 2006). In this sense, Chile was the first South-American country in implementing a carbon tax (Benavides et al., 2015) which consisted on a \$5/tonCO_2[1] tax applied to stationary sources greater than 50 MWt (Ministry of the Environment, 2018). This tax has many limitations and it is very distant from an economically efficient tax because it is not applied to the variable costs of the generators. However, it is the first approach to the problem and could be considered as a step forward. The Chilean power system consists of a mixture of renewable energy, mainly hydroelectric, and fossil fueled based power plants such as coal, gas and diesel plants. Applying a policy which would put an adequate price their carbon emissions would help to achieve the countries goals.

Certainly, a carbon tax will be helpful for mitigating the countries GHG emissions. However, many questions arise on when to apply the tax, in what way and how high the tax should be. This is one of the aspects that motivates this work as there are no evident answers to those questions. At the same time, it is the author's desire of the author to make this work so it can be a useful contribution to anyone analyzing an eventual modification of the carbon tax legislation in Chile. Being able to carry out investigation that can have an application in the future and a real positive impact in society is quite comforting and motivating.

[1] In this thesis \$ stands for United States Dollars

1.2. Literature review

1.2.1. Carbon pricing: taxes v/s tradable emission permits

Since the beginning of the Industrial Revolution, carbon emissions have rocketed and it is forecasted that this trend will be catastrophic if no action is taken. Reducing carbon emissions is one of the main methods to fight global warming and the central challenge is to do it in an efficient and effective way. Carbon taxes and tradable emission permits (cap and trade schemes) can be implemented to control emissions in a market-based manner, depending on whether the regulator prefers a price- or a quantity-based instrument.

Both instruments have advantages and disadvantages from a policy application point of view, as it is reported in several research works that compare both methods (Goulder and Schein, 2013; Weitzman, 1974). Weitzman (1974) proved that there is no theoretical difference between them, but their application in the real world implies certain distinctions. Goulder and Schein (2013) make a comprehensive review of the differences, advantages, and disadvantages regarding both approaches (and a hybrid of both). They showed that the evaluation of both policies strongly depends on what issues are considered more relevant for the implementation. For example, carbon taxes can be more useful to avoid price volatility or to minimize administrative costs while a cap and trade (C&T) scheme is more flexible to cope with new information and is able to fix the total amount of emissions. No policy dominates the other in all aspects, so the correct implementation will depend on which of those issues are considered more important for the policy maker. An hybrid method can be a good alternative as it mixes some of the positive attributes of both.

Regarding the application of these two approaches in power systems, He et al. (2012) make a comparison of different carbon taxes and C&T schemes applied to an expansion planning problem on a power system. The effectiveness for reaching certain emission levels and the economic efficiency of C&T and carbon taxes (related to the impacts on expansion planning decisions of generation firms) are compared for different cases of C&T, uniform and non-uniform taxes. They found that a uniform tax is more inefficient than a non-uniform tax, as the latter can reduce unnecessary costs due to the flexible application of the tax.

In the same vein, Barragán-Beaud et al. (2018) performed an economic and political analysis of the application of C&T and carbon tax to the Mexican power system, studying the effects over different emission goals and caps. They showed that there is no straight-forward economic comparison amongst the different cases and that, depending on the different scenarios chosen, either a C&T or a carbon tax dominates the other in terms of some, but not all, of the economic criteria analyzed (cost-effectiveness, distributional effects, and dynamic efficiency). The authors also show that the policy scenario and the emission goal chosen are important variables to embrace.

1.2.2. Carbon tax trajectories

The quantification of an optimal carbon price is a fundamental task to incorporate the social cost of CO_2 emissions. However, it is also important to investigate the path of the implementation of the tax over time. It is not necessarily obvious nor optimum to apply a carbon tax evenly from the beginning, especially when there are economical, technical, and political variables to consider.

There is not much consensus around this topic, as there are different analyses of carbon tax trajectories depending on the different research scopes. On the one hand, there are analyses based on stock of fossil fuels and of externalities (Farzin and Tahvonen, 1996; Ulph and Ulph, 1994). For instance, Ulph and Ulph (1994) propose an analysis of the path of a carbon tax depending on the stock of the externality (CO_2) and the level of depletion of the externality source (fossil fuels). They studied the interaction of two sets of dynamic factors, concluding that there can be no general presumption about the direction of movement of a carbon tax over time. Nevertheless, they showed that, for some representative cases of pollution problems, a carbon tax should be rising when the initial stock of pollutant is small and then be falling towards the end of the resource's reserves.

A similar analysis was done by Farzin and Tahvonen (1996) leading to the conclusion that carbon tax will have different paths over time depending on the pollution stock over time and initial conditions. If pollution stock is decaying over time, the path is either decreasing or having an inverted U shape. If the stock does not decay over time, the tax increases monotonically. However, depending on the initial conditions, the tax can be constant or have a U shape in this case.

More recently, Van Der Ploeg and Withagen (2014) proposed a Ramsey growth model of the global economy to analyze the effects of carbon pricing. They identify the conditions under which the optimal carbon tax rises or decreases depending on four different regimes that occur depending on the sizes of the initial stock of oil and the initial stock of capital.

On the other hand, there are some analyses based on the impacts of carbon tax and C&T approaches on investments and/or research and development (Greaker and Pade, 2009). For instance, some arguments for a higher initial tax to improve technological research and development is examined by Greaker and Pade (2009). According to their simulations, they concluded that a higher initial tax may be desirable because of its positive effects over research and development, but only when there are intertemporal knowledge spillovers or weak patent protection.

In addition, the whole area of Climate Models makes various approaches to tax trajectories with different and sometimes divergent results. Integrated assessment models are generally utilized to depict the future and, amongst other purposes, propose a carbon price that would eventually avoid a catastrophic outcome, therefore addressing indirectly matters of trajectory of the tax. One of the most relevant reviews of these climate models was performed by Stern (2006), who argues that immediate and radical actions must be taken to prevent the catastrophic damage that global warming poses. A main conclusion of his Review is that " the benefits of strong, early action considerably outweigh the costs" (Stern, 2006, p. 193). The rationale of this is that "early action to stabilize GHG stock at a relatively low level will avoid the risk and cost of bigger cuts later. The longer the action is delayed, the harder it will become" (Stern, 2006, p. 193). A recent Nobel Prize winner, William Nordhaus, is critical to Sterns view (Nordhaus, 2007), especially regarding the parameters of discount of the carbon emission externalities. He criticizes Sterns calculations and argues that a more moderate and market-based discount rate leads to a typical increasing-ramp shaped carbon tax over time.

Regarding prediction models and policy application, the definition of parameters, such as the discount rate, can be quite discretional and, therefore, transcend the purely technical area towards a more philosophical discussion. Pindyck (2017) criticizes these climate models, pointing out crucial flaws such as incorrect damage functions, climate sensitivity, poor tail risk incorporation and arbitrary parameters that become determinant of the results.

In synthesis, there is not a clear way to set a path for a carbon tax. Depending on the way of analyzing and solving the problem, results for the trajectory of a tax can take various shapes. It is important to highlight that there are assumptions over initial parameters, as well as discretional decisions, which can radically change the output of predictions, as pointed out by Pindyck (2017) and Nordhaus (2007). Nonetheless, accelerating emission mitigation when possible is recognized as desirable in most cases since the main objective of carbon pricing is limiting emissions. The action of accelerate emission mitigation becomes especially useful when global carbon emissions rise every year and the world's destiny is running against the clock.

Despite the fact that there is no conclusive evidence on how to shape a carbon tax, its trajectory is still an important part of the policy implementation. There is no doubt that the emissions saved in the present have a value, but the relevant question is how much that value is and how can policy makers effectively incorporate it. An analysis of the path of a carbon tax in a horizon of 10-20 years (which is the typical horizon of a power system capacity expansion plan) has not been addressed extensively, as far as it is known to the author. Most of the related research is done in longer-horizon terms (e.g., climate models), taking the analysis of economic variables in a longer time span. Then, one question that arises is how can an optimal path in a 10-year period can be defined when most global warming goals aim to specific emission levels in a determined future year (e.g., reach a fraction of some base case emissions by year

2030). Accordingly, it is interesting to study what effects and incentives can trigger a country to accelerate the application of a carbon tax.

1.2.3. Considerations on flexible taxes

A flexible tax allows the regulator to modify its trajectory over time, accelerating or delaying its implementation in order to take into consideration, for instance, political economy aspects or changes in the system parameters. This is very important in practice because, sometimes, the theoretical optimal tax may be infeasible, or at least problematic, to implement in the real world (Pearce, 2006). Political constraints, market failures, policy failures, institutional deficiencies or excessive transaction costs can affect the implementation of the tax, not allowing to meet the Pareto optimal solution (Jenkins, 2014). In those cases, it may be better for the regulator to accept a more feasible, second best solution (Lipsey and Lancaster, 1956).

In this context, the implementation of a more flexible tax (specifically accelerating its implementation) would allow dealing in a better way with the uncertainties and irreversibilities associated to the highly capital-intensive investments in power systems. A more aggressive initial carbon tax may be a better signal for investors as they make their decisions based on expected economic policies, but considering a risk averse perspective (Jackson and Orr, 2019). Thus, early fixing the carbon tax in a value close to the optimal final tax level would reduce the policy uncertainty about the future.

On the other hand, accelerating a tax implementation can have collateral positive outcomes such as health co-benefits (Baranzini et al., 2017) or encouragement of more research and development under certain conditions (Greaker and Pade, 2009). Therefore, a carbon tax can have a positive effect on social welfare that may not be explicitly considered as a variable in the calculation of the optimal (power-system least cost) tax trajectory.

In addition, a carbon tax can be influenced by international policies. Worldwide pressure and compromises are forcing nations to take serious action to cut greenhouse gas emissions. The implementation of a carbon tax can be done to address an internationally compromised cap of emissions, as it could be the one proposed by the UNFCCC (2015) Paris Agreement. Most of the parties commitments are set as specific-year goals in emission reductions, in contrast to path-dependent commitments. However, as mentioned before there is no doubt that emissions saved in early stages still have a value. Accelerating tax implementation can also be seen as a good way to be certain that the emission goals will be met. This is indeed very important, considering that there was still a significant emissions gap in year 2018 (UNEP, 2018), as well as a many doubts regarding the technical and political feasibility of the 1.5°C goal (Kriegler et al., 2018; Millar et al., 2017; Rogelj et al., 2018). Furthermore, early actions can trigger even further motivation amongst other nations (Baranzini et al., 2017).

1.2.4. Power system capacity expansion planning considering tax regulation

Power system expansion planning has become a more complex process with the high penetration of variable renewable energy (RE) generation. The variability of RE sources implies that short-term uncertainties have an important impact on long-term capacity expansion decisions. Consequently, sophisticated power-systems expansion models must be developed to adequately capture the interactions between short-term and long-term uncertainty. Ignoring detailed information about the market operation (short term) and planning (long term) of the power systems may significantly distort the anticipated impacts of regulatory policies, as several authors have pointed it out (Munoz et al., 2013; Vajjhala et al., 2008).

Research about carbon tax regulation in power systems has been addressed with different focuses and solution methods (Hashim et al., 2005; Munoz et al., 2013; Olsen et al., 2018; Park and Baldick, 2015,0; Shao and Jewell, 2010; Srivastava et al., 2000; Wei et al., 2014). Distinctive differences over the problem formulation are noted regarding the analysis horizon, the treatment of uncertainty, and other model assumptions.

Several works have analyzed the planning and operational behavior of power systems when incorporating a carbon tax in the short run. For instance, Park and Baldick (2015) analyzed the effects of considering a carbon tax and renewable portfolio standard (RPS) on a (short-term) stochastic generation capacity expansion planning. They formulate a two-stage stochastic integer program for solving a one-year expansion plan by employing some decomposition techniques. Uncertainty on load and wind is depicted by independent and identically distributed random samples generated via a Gaussian copula method. Transmission constraints are not included in the model. They found that a purely deterministic treatment of the problem can lead to misleading expected costs and important differences with respect to the actual solution, compared with the stochastic version of the model where uncertainty is included in the model formulation. By varying carbon tax from \$0/tonCO_2 to \$30/tonCO_2, they show that most of the resulting emission abatement comes from changes in the economic dispatch, without significantly altering the generation capacity mix. They also pointed out the existence of an inflexion point in the cost behavior (which, in their case, is between \$13.5/tonCO_2 and \$15/tonCO_2), which corresponds to the transition point from coal to combined cycle gas turbines (CCGT).

Shao and Jewell (2010) incorporated a CO_2 pricing scheme in an AC optimal power flow model. They study the influence of different CO_2 emission prices over economic dispatch and operations. They compare the economic dispatch results when ignoring transmission constraints and when considering the AC optimal power flow. Some of their findings show that certain CO_2 tax levels produce significant changes in the merit order of the economic dispatch and that those changes are higher when ignoring transmission constraints, compared to the case of the full AC power flow problem. They conclude that including transmission constraints is fundamental for analyzing CO_2 pricing, especially on power systems with significant network congestion. This same conclusion is highlighted by Munoz et al. (2013) regarding the need of accurate modelling of transmission constraints, but for the case of renewable portfolio standards. Applying single and multi-stage modelling of a power system, they show how simplified approaches that ignore transmission constraints can yield distorted investment results.

Alternatively, Wei et al. (2014) proposed a method to determine a different tax for each generator, depending on the emission goals. This is done by balancing CO_2 emissions with the benefit surplus of the power sector. The optimization problem is formulated as a bi-level model, representing a Stackelberg game between the government agency and generation companies.

The particularity of this approach is that there is not a uniform tax for every generator, but an optimal tax to minimize emissions applied differently to every generator.

Olsen et al. (2018) describe a different approach for solving the power system operation problem with carbon taxes by using a Weighted Sum Bisection Method (WSBM) to determine the lowest CO_2 tax rate that can reduce emissions in a power system under a defined target in the short run. Uncertainty is considered through different scenarios of wind penetration, coal plant retirement, gas prices, and gas supply limitations on unit commitment solutions. They propose a bi-level model that can reach certain emission goals while looking for a system-wide minimum tax to achieve those emission goals.

Regarding long-term expansion planning models that study carbon emission mitigation, there is a vast body of literature. Srivastava et al. (2000) proposed a capacity expansion model where a carbon emission limit is included as a constraint while Quiroga et al. (2019) and Hashim et al. (2005) show the effects of minimizing CO_2 emissions in the capacity expansion planning.

Time span importance is highlighted by Park and Baldick (2016).They added a multi-year treatment to the model proposed by Park and Baldick (2015) to formulate the long-term generation expansion problem. They use a reduced scenario tree to incorporate intertemporal stochastic parameters. Their results lead to the conclusion that short-term (one-year) expansion planning models do not allow an accurate representation of the optimal generation capacity expansion decisions.

Regarding modeling and solutions methods for solving the capacity expansion planning problem, there is a large amount of literature (Hobbs, 1995; Nasiri and Huang, 2008; Pozo et al., 2013b). The mixed integer linear programing (MILP) optimization approach has proven to be effective in modeling these type of problems (Liu et al., 2011). Moreover, several authors have shown that results are more accurate and realistic when the capacity expansion planning is formulated with a joint consideration of long-term generation and transmission expansion decisions (Pozo et al., 2013a). In agreement with this, the expansion planning model proposed in this work is formulated as a MILP model that jointly consider generation and transmission capacity expansion investment decisions.

1.3. Hypothesis

The hypothesis of this work points to the fact that minimizing cost in the expansion planning of a power system while having a CO_2 emission mitigation goal as an objective, ignoring other extra effects of the tax trajectory, may lead to a result that assumes greater flexibility than the system's real capacity. The hypothesis is formulated as follows: Assuming full flexibility when formulating an expansion plan of a power system (as it is done by the National Energy Commission) when taking action in CO_2 emission mitigation leads to the result that there is no value in early emission savings. However, if that flexibility is reduced, early emission saving can have a social value.

1.4. Objectives

The main objective of this thesis is to study the design of an optimal tax for a power system in the long run. The formulation of the tax must consider not only its optimal value but also the way it is applied over time. This general approach is applied to a study case of the Chilean National Energy system. The specific objectives therefore are to:

(i) design a method to obtain an optimal carbon tax for a power system via an optimization model of an expansion planning problem.

(ii) examine the effect of the trajectory of the tax, level of the tax and uncertainty of determinate parameters over the variables of an expansion planning system.

(iii) discuss about the implications of considering a tax calculated through cost minimization approach that ignores practical variables such as political economy constraints or unaccounted benefits of accelerating a tax scheme.

1.5. Contributions

The main contributions of this work are:

(i) A methodology to determine the least-cost tax in a power system that keeps CO_2 emissions within certain level, which is based on the formulation of a bi-level model that considers the carbon tax minimization in the upper level and both the joint generation and transmission investments and the economic dispatch in the lower level.

(ii) The implementation of the proposed methodology to a specific case study, which is the analysis of the Chilean National Electric System, providing a guideline on how a least-cost carbon tax can be applied on the power sector.

(iii) An analysis showing that early emission savings due to the acceleration of a tax scheme may be socially beneficial, if they are valued in an appropriate way.

2. METHODOLOGY

2.1. Proposed Model

In this work, it is proposed a methodology to design the minimum carbon tax needed to reach a specific CO_2 emission goal in an electrical power system. However, differently than Olsen et al. (2018) that also proposes a minimum calculation approach, the carbon tax is allowed flexibility over time. Specifically, this flexibility in the carbon tax scheme, and its effects on the power system, is examined by analyzing the model outcomes when applying a two-stage flexible tax. In particular, the effect of the trajectory of the tax over time is studied by analyzing how an accelerated tax implementation can be socially beneficial and how this can be economically justified.

It is worth to mention that the model assumes that the power market is perfectly competitive and thus, cost minimization leads to the same outcome as social welfare maximization. The rationale of this common assumption is that market power is adequately mitigated by the corresponding authorities. Although this is a common assumption in power system economics literature, some authors have argue the evidence of market power in electricity markets (Varas and Rudnick, 2014).

The problem is formulated as a bi-level mixed integer linear programming (MILP) optimization model. The first level consists of the minimization of the carbon tax level subject to a constraint guaranteeing that total CO_2 emissions are below the final-year emission goal and the solution of the capacity expansion planning problem (lower level). The lower level corresponds to a traditional power system capacity expansion planning model. In this context, this bi-level MILP model seeks for minimizing the carbon tax and the total costs of the power system.

The problem's mathematical formulation is depicted as follows:

2.1.1. Model

As mentioned before, the optimization problem is divided in an upper and a lower level. The upper level consists on the minimization of the carbon tax subject to the emission goal constraint. The emissions are determined by the power generation defined in the lower level, where the operation and expansion plan is solved subject to several transmission and generation constraints [1].

Upper Level problem

$$\min p_{CO_2}^t \tag{2.1}$$

$$E^{\text{Total}} \leq E^{Goal} \tag{2.2}$$

$$E^{Total} = \sum_{g\in G}\sum_{b\in B}\sum_{h\in H}\sum_{d\in D} p_{g,t_n,d,h,b}^{gen} E_{g,b}^{gen}; t_n \in T \tag{2.3}$$

Lower level problem:

$$C^{Pinst} = \sum_{b\in B}\sum_{t\in T}\sum_{g\in G} C_g^{Tech} F_t^{Disct} \sum_{\tau\in(0,t)} p_{g,\tau,b}^{inst} \tag{2.4}$$

$$C^{Xinst} = \sum_{n\in N}\sum_{t\in T} C_n^{Cand} F_t^{Disct} \sum_{\tau\in(0,t)} x_{n,\tau}^{inst} \tag{2.5}$$

$$C^{Pgen} = \sum_{g\in G}\sum_{b\in B}\sum_{t\in T}\sum_{h\in H}\sum_{d\in D} p_{g,t,d,h,b}^{gen} C_g^{MW} \tag{2.6}$$

$$C^{Pnons} = \sum_{b\in B}\sum_{t\in T}\sum_{h\in H}\sum_{d\in D} p_{t,d,h,b}^{nons} C^{nons} \tag{2.7}$$

$$C^{PCO2} = \sum_{g\in G}\sum_{b\in B}\sum_{t\in T}\sum_{h\in H}\sum_{d\in D} p_{g,t,d,h,b}^{gen} E_{g,b}^{gen} p_{CO_2}^t \tag{2.8}$$

$$min\left\{C^{Pinst} + C^{Xinst} + C^{Pgen} + C^{Pnons} + C^{PCO_2}\right\} \tag{2.9}$$

[1]For detail on the model's nomenclature refer to appendix A

Constraints:

$$\sum_{t\in T} x_{n,t}^{inst} \ \leq \ 1 \ \forall n \in N \tag{2.10}$$

$$-\pi \leq \ 2\theta_{t,d,h,b} \ \leq \pi \,; \forall t \in T, \forall d \in D, \forall h \in H, \forall b \in B \tag{2.11}$$

$$f_{c,t,d,h}^{\text{exist}} = S_c(\theta_{t,d,h,b_o} - \theta_{t,d,h,b_i});$$

$$\forall c \in C, \forall t \in T, \forall d \in D, \forall h \in H, \forall b_o \in B_o^c, \forall b_i \in B_i^c \tag{2.12}$$

$$-M(1 - \sum_{\tau\in(0,t)} x_{n,\tau}^{inst}) \leq f_{n_i,t,d,h}^{\text{cand}} - S_n\left(\theta_{t,d,h,b_o} - \theta_{t,d,h,b_i}\right)$$

$$\leq M\ (1 - \sum_{\tau\in(0,t)} x_{n,\tau}^{inst});$$

$$\forall n \in N, \forall t \in T, \forall d \in D, \forall h \in H, \forall b_o \in B_o^n, \forall b_i \in B_i^n \tag{2.13}$$

$$-F_{d,c}^{\text{Max-c}} \leq f_{c,t,d,h}^{\text{exist}} \leq F_{d,c}^{\text{Max-c}} \forall c \in C, \forall t \in T, \forall d \in D, \forall h \in H \tag{2.14}$$

$$-F_{d,n}^{\text{Max-n}} \ \leq \ f_{n,t,d,h}^{\text{cand}} \sum_{\tau\in(0,t)} x_{n,\tau}^{inst} \ \leq \ F_{d,n}^{\text{Max-n}}\,;$$

$$\forall n \in N\ , \forall t \in T\ , \forall d \in D\ , \forall h \in H \tag{2.15}$$

$$\sum_{t\in T} p_{g,t,b}^{inst} \ \leq \ P_{g,b}^{Max}\,; \ \forall g \in G\ , \forall b \in B \tag{2.16}$$

$$\sum_{b\in B} p_{g,t,b}^{inst} \leq \ P_{max}^{inst}; \ \forall g \in G\ , \forall t \in T \tag{2.17}$$

$$p_{g,t,d,h,b}^{gen} \leq \left(P_{g,b}^{\text{exist}} + \sum_{\tau\in(0,t)} p_{g,\tau,b}^{inst}\right) Cf_{h,d,g,b};$$

$$\forall g \in G, \forall t \in T, \forall d \in D, \forall h \in H, \forall b \in B \tag{2.18}$$

$$\sum_{h\in H}\sum_{d\in D} p_{g,t,d,h,b}^{gen} \leq \left(P_{g,b}^{\text{exist}} + \sum_{\tau\in(0,t)} p_{g,\tau,b}^{inst}\right) H^d Cf_g^{\text{A}};$$

$$\forall g \in G\ , \forall t \in T\ , \forall b \in B \tag{2.19}$$

$$D_{b,h,t,d} = \sum_{n_i\in N_i^b} f_{c_i,t,d,h}^{\text{exist}} + \sum_{c_i\in C_i^b} f_{n_i,t,d,h}^{\text{cand}}$$

$$- \sum_{n_o\in N_o^b} f_{c_o,t,d,h}^{\text{exist}} - \sum_{c_o\in C_o^b} f_{n_o,t,d,h}^{\text{cand}} + p_{g,t,d,h,b}^{gen} + p_{t,d,h,b}^{nons};$$

$$\forall g \in G\ , \forall t \in T\ , \forall d \in D\ , \forall h \in H\ , \forall b \in B \tag{2.20}$$

$$\alpha_{g,t,d,h,b} \leq \Big(\sum_{\tau \in (0,t)} p^{inst}_{g,\tau,b} \Big) + P^{\text{exist}}_{g,b} - p^{gen}_{g,t,d,h,b};$$

$$\forall g \in G^D\ , \forall t \in T\ , \forall d \in D\ , \forall h \in H\ , \forall b \in B \tag{2.21}$$

$$\alpha_{g,t,d,h,b} \leq \Big(\sum_{\tau \in (0,t)} p^{inst}_{g,\tau,b} + P^{\text{exist}}_{g,b} \Big) Rp^{up}_{g,b};$$

$$\forall g \in G^D\ , \forall t \in T\ , \forall d \in D\ , \forall h \in H\ , \forall b \in B \tag{2.22}$$

$$D_{b,h,t,d}\, D^{\alpha} \leq \sum_{b \in Z} \sum_{g \in G^D} \alpha_{g,t,d,h,b};\ \forall t \in T\ , \forall d \in D\ , \forall h \in H \tag{2.23}$$

$$-\Big(\sum_{\tau \in (0,t)} p^{inst}_{g,\tau,b} + P^{\text{exist}}_{g,b} \Big) Rp^{up}_{g,b} \leq p^{gen}_{g,t,d,h-1,b} - p^{gen}_{g,t,d,h,b}$$

$$\leq \Big(\sum_{\tau \in (0,t)} p^{inst}_{g,\tau,b} + P^{\text{exist}}_{g,b} \Big) Rp^{\text{down}}_{g,b};$$

$$\forall g \in G\ , \forall t \in T\ , \forall d \in D\ , \forall h \in H\ , \forall b \in B \tag{2.24}$$

Every equation can be understand as follows: The upper level is centered on the minimization of the carbon tax ($p^t_{CO_2}$) (2.1) subject to the emissions goal (2.2). Total emissions (2.3) are indirectly dependent of the different costs of the system. The lower level corresponds to the expansion planning problem (2.4)-(2.25). Total costs depend on the installed power (2.4), installed circuits (2.5), generated power (2.6), non-supplied power (2.7) and carbon tax collection(2.8). Costs (2.4)-(2.8) are minimized in the lower level objective function (2.10). Transmission constraints are depicted between (2.10)-(2.15). These are new lines investment (2.10), lines phase angle limit constraints (2.11)-(2.13) and max power flow (2.14)-(2.15). On the other hand, generation economic dispatch (2.16)-(2.24) is constituted by maximum generation building capacity (2.16), maximum annual generation building capacity (2.17), maximum generation for capacity factor (2.18), maximum annual generation for capacity factor (2.19), demand balance (2.20), reserve energy (2.21)-(2.23) constraints; and ramp up and down constraints (2.24).

2.1.2. Solution Method

The lower-level optimization is solved using a classic MILP solver (e.g., Branch and Bound method) while the upper level is solved by a weighted sum bisection method (WSBM, see appendix B for more detail) as proposed by Olsen et al. (2018). For the analysis of the two-stage carbon tax studied in Section 3.2.2 , the optimal solution is obtained by the WSBM while fixing the first-stage tax and iterating over the second-stage tax. Accordingly, different first-stage taxes are examined and, for each one of them, several tax schemes are analyzed in the lower level. This allows the obtainment of the optimal carbon tax, as well as the least-cost outcome of the transmission and generation expansion-planning problem (i.e., new generation capacity installed, new transmission capacity installed, generation levels, power flows, and non-supplied energy, among other variables).

3. CASE STUDY

3.1. Case Study

The proposed model is used to analyze the effects of implementing a flexible carbon tax in the case of the Chilean National Electric System (NES). The Chilean electricity market possesses several characteristics that make it a noteworthy case of study. Firstly, it has a particular technology mix, characterized by the balanced presence of hydro, thermal, and renewable energy (RE) generation. Despite that, Chile has almost no production of fossil fuels (i.e., all fossil fuel used to generate energy is imported). This also contrasts with Chiles great RE potential, which suggests that there will exist a significant transition from thermal generation to RE generation in the near future (Energy Ministry, 2017b). Secondly, Chile has been a pioneer in power market design innovations. It was the first country in deregulating the power market during the 1980s and a regional leader in electricity market regulations (Guzowski and Recalde, 2010; Pollitt, 2004; Rainieri, 2006). Also, Chile was the first South-American country in implementing a carbon tax (Benavides et al., 2015). Finally, the Chilean topography makes it an interesting case study from the power transmission expansion planning point of view. As the Chilean system is roughly radial and considerably long, transmission constraints are extremely relevant for solving the capacity expansion problem. The Chilean NES covers over 90% of the country's power demand with a total installed power capacity of 22,580 MW and an annual generation of 74,647 GWh in year 2017 (National Energy Comission, 2017). Currently power capacity is 30% based on hydro, 21% coal, 20% natural gas, 13% diesel, 8% solar, 6% wind, 2% biomass, and 0.2% geothermal (National Energy Comission, 2017). The system is modeled with 155 existing transmission lines and 9 candidate lines, linking 46 buses where up to 10 different generation technologies are located (appendix C shows the diagram of the transmission lines and appendix D presents information about generation technologies). Power demand and generation capacity factors for non-dispatchable RE technologies are hourly modeled, at every bus and in every period of the 10-year horizon (starting in year 2020 through 2029), considering two representative days (accounting for summer and winter, respectively). Network data are taken from the long-term national strategic energy plan (Energy Ministry, 2017b) and the information provided by the (National Electrical Coordinator, 2018).

As mentioned before, Chile has already implemented a carbon tax of \$5/tonCO_2, which affects the operation of the NES. However, this tax does not modify variable costs at the time of the economic dispatch. For modelling purposes, this condition will be ignored and the optimization problem will consider that the tax does affect the variable costs.

For the experiments the total emission goal is defined as reaching 70% of the base case emissions during the last period (year 2029). This goal was fixed in accordance to the Paris agreement pledge of reaching 70% of the base case (2007) scenario to year 2030. As can be seen, the goal chosen is an approximation because of two main reasons. The first is that the exact value of the tax is not the main scope of this research as attention is put mainly over the effect of the different tax schemes more than over the actual value. The second is due to the fact that the modelling simplifications difficult the formulation of a base case scenario for year 2007.

Four different experiments were designed, and implemented in the model proposed in the previous section, to study the effects of implementing a flexible carbon tax. This experiments are presented as follows:

(i) Fixed tax case (FT case): It considers a uniform tax, which keeps the same level during the entire planning horizon.

(ii) Two-stage tax case (TST case): It considers that there is a tax level for the first five periods (years) and a different tax level for the remaining five periods. The first five periods are denominated as the first stage (periods 1 to 5) and the other five (periods 6 to 10) are considered as the second stage. This experiment seeks for studying the economic flexibility and responsiveness of the system. The main idea of considering this case is to analyze the value of allowing flexibility in adjusting the optimal carbon tax level after there is more certainty about new power generation and transmission investments, as well as about long-term demand levels in the power system. This experiment also allows us to study the power system capability to suddenly lower emissions by analyzing, for instance, the effect of being unrestricted (or establishing a low tax level) during the first stage and very restrictive in the second stage, suffering the consequent repercussions of this action in the second-stage emissions.

(iii) Case of two-stage tax with CO_2 savings compensation (TST-SC case): This experiment is similar to the TST case, but adding an ex-post monetary compensation for the additional CO_2 emission savings with respect to the optimal solution in the TST case. In other words, it contrasts the TST optimal case from the previous experiment with TST cases that have a higher first stage tax than the optimal TST case thus presenting a lower amount of emissions (saved emissions). This saved emissions are valued in different levels and then compared in order to determine the best solution for the goal and the given saved emissions value.

(iv) Case of two-stage tax with low reservoir hydro availability (TST-LH case): This experiment is similar to the TST case, but it considers that the capacity factor for reservoir hydro power plants is 35%. The rationale for considering this case is that the first three cases are optimized considering the traditional Chilean assumption of a capacity factor for reservoir hydro power plants equal to 65% (National Energy Comission, 2018). However, the effects of Climate Change in the Chilean power system have shown consistent and continuous droughts during the last ten years, leading to an empirical average capacity factor of approximately 35% in the last 5 years(National Energy Comission, 2018).

3.2. Case study results

In this section are presented the results obtained with the four experiments described in the previous section. In the FT case, detailed information is presented about the simulation results with respect to generation capacity expansion, transmission capacity expansion, power system operation (economic dispatch), CO_2 emissions, total costs, and sensitivity analyses. For the rest of the cases, only some results are provide that are interesting from a comparison viewpoint.

Also for comparison purposes, results are shown for different levels of tax from \$5/tonCO_2 to \$40/tonCO_2 regardless of the WSBM optimal solution.

3.2.1. Fixed tax case (FT case)

The optimal level of CO_2 tax when considering the FT case and a goal of 70% of the emissions predicted by the base scenario for 2029 is \$25/tonCO_2. However, since the goal is based on atmospheric science and political considerations, the socially optimal tax level will actually depend on the amount of emissions desired by the policy maker in each given case. Accordingly, the numerical result for the optimal tax is meaningless, and for that reason, different tax levels were analyzed to check the outcomes of varied policies. As mentioned before, for comparison purposes, results are shown for different levels of tax from \$5/tonCO_2 to \$40/tonCO_2, regardless of the WSBM optimal solution.

3.2.1.1. Generation capacity expansion

The resulting generation capacity expansion is mostly based on renewables, dominated by solar power, as can be seen in Figure 3.1 . Roughly speaking, the higher the tax is, the larger the penetration of wind, dam hydro, combined cycle gas turbine (CCGT), and solar is. However, the total amount of solar power installed does not significantly change compared to the current tax case (\$5/tonCO_2) because the best locations for solar power development are already used. The variability of the resource and the transmission constraints make further solar power inclusion a non-cost-effective solution. At the same time, wind power investment proportionally varies more than other technologies when the tax is larger accounting for a large proportion of the extra renewable generation investments. As it is observed in Figure 1, it is economically efficient to install a large amount of renewable energy capacity. As well, investments in CCGT show a notorious increment for a tax larger than \$25/tonCO_2. This situation coincides with the change in the merit order of the economic dispatch, between CCGT and coal generation. This change in the merit order is addressed in details in the economic dispatch analysis section. Finally, it must be noted that generation expansion by technology was intentionally limited to 500 MW for a more realistic depiction of the system's capacity expansion.

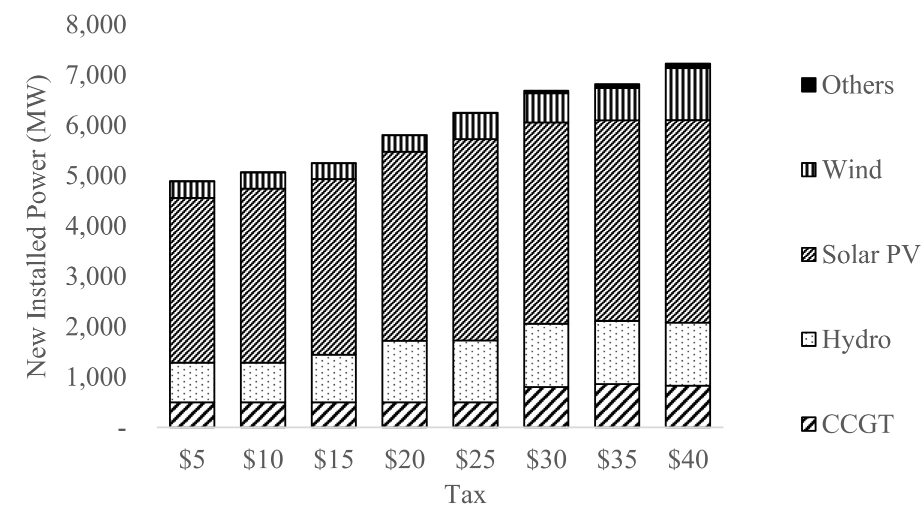

Figure 3.1. Total (in 2020-2029) new installed power capacity by technology and CO_2 tax (in MW)

3.2.1.2. Transmission capacity expansion

In the Chilean case, the application of a larger CO_2 tax affects the transmission expansion plan by accelerating the investment decisions, but not changing the lines constructed, as described in Table 3.1. This implies that the decisions are not as irreversible as they would be if the lines constructed varied for different tax levels. Lines L0, L1, and L2 are located in the northern region of the system, where most of the solar and wind power capacity is installed. This explains why lines are needed earlier as the tax gets larger, due to the larger amount of new RE built. Some congestion was present in the existing lines in the northern region, prior to the incorporation of new lines, so line construction is also justified in these terms. Nonetheless, the system still presents some congestion after the installation of the new lines because the model does not consider more candidate lines available to be built in the northern region. As it will be described later, this congestion partially explains why, even with the new lines, there is expensive diesel generation in certain buses.

Table 3.1. Installation year of built transmission lines for different CO_2 taxes (Taxes in \$/Ton of CO_2).

Tax	$5	$10	$15	$20	$25	$30	$35	$40
L0	2023	2022	2022	2020	2020	2020	2020	2020
L1	2020	2020	2020	2020	2020	2020	2020	2020
L2	2022	2022	2021	2020	2020	2020	2020	2020
L3	-	-	-	-	-	-	-	-
L4	-	-	-	-	-	-	-	-
L5	-	-	-	-	-	-	-	-
L6	-	-	-	-	-	-	-	-
L7	-	-	-	-	-	-	-	-
L8	2028	2025	2025	2024	2024	2024	2024	2024
L9	-	-	-	-	-	-	-	-

3.2.1.3. Power economic dispatch

Figure 3.2 shows the total energy generated from every technology in the last period of the planning horizon, separating summer and winter representative days. The impact of the CO_2 tax on the economic dispatch is notorious. The main change is the progressive variation from coal to CCGT generation, as the tax increases. Accordingly, coal-based generation proportionally loses predominance for large taxes, and eventually disappears. Diesel and gas turbines (other than CCGT) are almost not dispatched (except for diesel in certain periods and buses, due to the transmission congestion in the system).

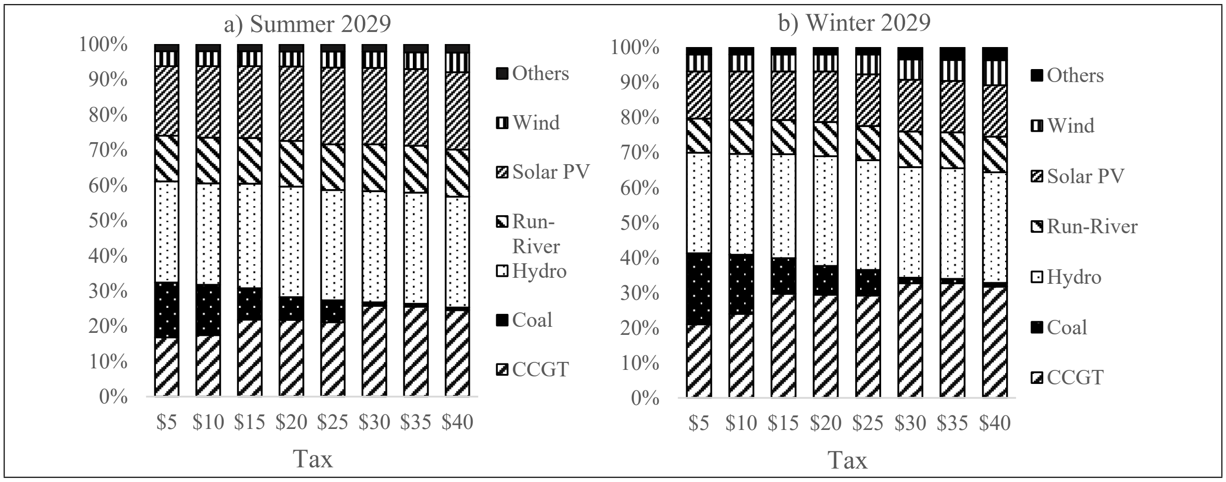

Figure 3.2. Proportion (in %) of power dispatched by technology in 2029 for different CO_2 taxes and season: a) Summer 2029, b) Winter 2029.

The by-technology daily dispatch for different taxes is depicted in Figures 3.3a, 3.3b, and 3.3c, where it is evident that solar power absence at night is compensated mainly by CCGT generation. For higher taxes the participation of coal generation, which is mostly dispatched at night, becomes lower. This is evident when comparing Figure 3a (\$5/tonCO_2 tax), where coal-based generation is similar to CCGT, with Figure 3.3c (\$40/tonCO_2 tax), where coal-based generation is negligible. It is important to remark that the model ignores CCGT and coal start-up and shut-down costs, so the operational cost of the system is underestimated regarding this issue. Wind and solar power generation profiles are relatively smooth because representative days corresponds to the average day in the season. It is also important to mention that the proposed model does not account for the opportunity cost of water (i.e., hydro generation is modeled through an average capacity factor).

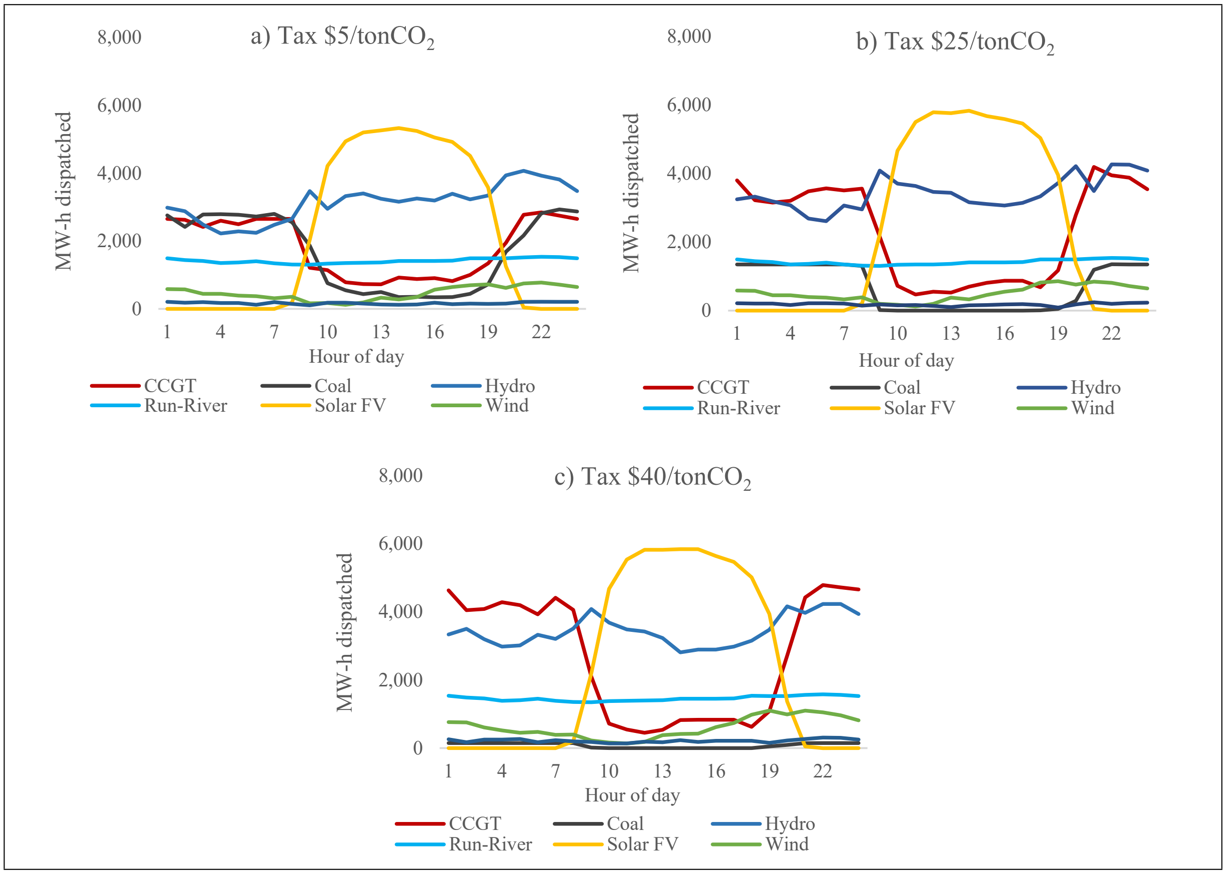

Figure 3.3. Hourly-dispatched power for year 2029-summer, for tax levels of a) \$5/tonCO_2, b) \$25/tonCO_2, and c) \$40/tonCO_2.

3.2.1.4. Reductions on CO_2 emissions

Figure 3.4 shows the annual evolution of CO_2 emissions for different tax levels. As expected, CO_2 emissions are reduced with a larger tax; however, there are some leaps on the emission level from a tax level to another due to the changes in the merit order of the economic dispatch. In particular, there is an abrupt change from a tax level of \$26/tonCO_2 to \$27/tonCO_2, which is a consequence of the inflexion point where the variable cost of an important amount of CCGT generation become lower than the coal variable cost. These results are in agreement with those observed in the literature (Park and Baldick, 2015; Shao and Jewell, 2010). For a CO_2 tax larger than \$30/tonCO_2, the capability to reduce system emissions is restricted by other constraints, such as technology availability and network congestion.

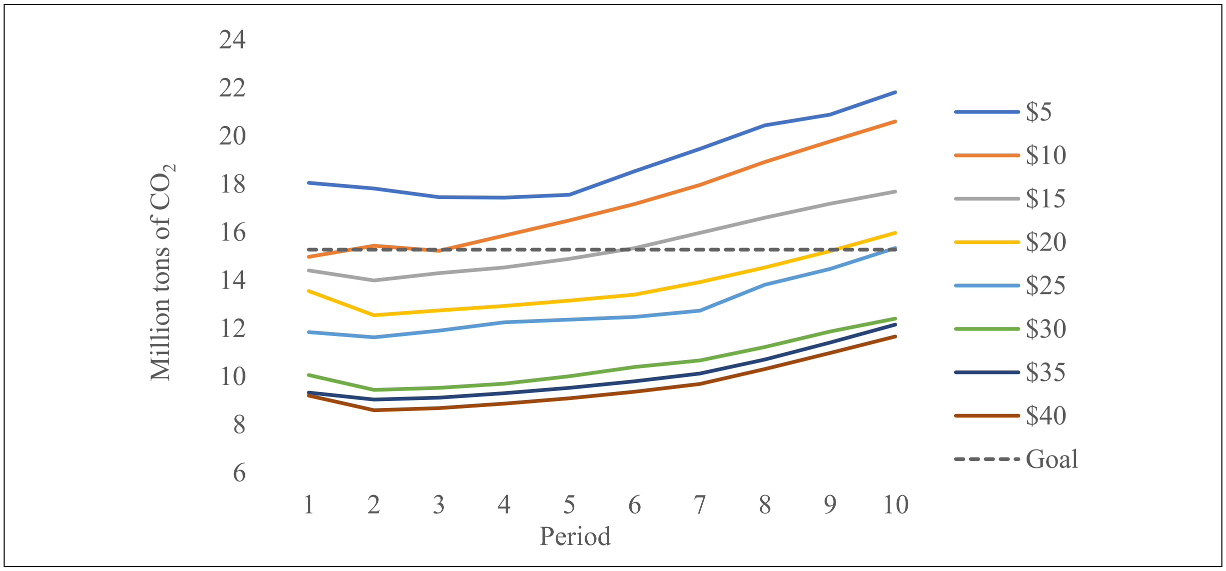

Figure 3.4. Annual CO_2 emissions for different taxes, Fixed tax case

The optimal tax determined by the proposed model depends on the amount of emissions desired from the policy maker. Nonetheless, it is important to remark that there is a change in the merit order of the economic dispatch in the surroundings of the goals optimum, which creates significant emissions abatement. It is useful to know this inflection point because it allows a rough foreseeing of the most significant reduction in CO_2 emissions that can be obtained with a specific tax level. This can be done by analyzing the emission factors and the variable costs of both CCGT and coal generators. Nevertheless, it is important to keep in mind that there are also other variables, such as the availability of new generation and transmission capacity, which also influence CO_2 emissions.

3.2.1.5. Total costs

As expected, total costs increase as the tax level gets higher. There is a significant increase in cost when tax changes from \$25/tonCO_2 to \$30/tonCO_2, which coincides with the leap in emissions between those tax levels. The tax collection gets larger for a larger tax, except for \$30/tonCO_2, where the change in the merit order of the dispatch (i.e., CCGT for coal) and the emission reductions explain the lower tax collection. As CCGT generators have larger variable costs, but emit less, than coal generators, total cost rises in the case of having \$30/tonCO_2, but tax collection gets lower. Total Costs (T.C.), Generation Investment Costs (G.I.), Circuit Investment Costs (C.I.), Tax Collection Costs (T.), and the difference between T.C. and T. (T.C.-T.) are presented in Table 3.2.

Table 3.2. Total system costs for different tax level (in millions of \$). Tax levels in \$/Ton of CO_2

Tax	\$5	\$10	\$15	\$20	\$25	\$30	\$35	40
Total Costs (T.C.)	11,381	11,976	12,524	12,999	13,448	13,822	14,160	14,485
Generation Investment (G.I.)	2,449	2,809	2,932	3,495	3,799	4,077	4,182	4,477
Circuit investment (C.I.)	45.5	53.2	56.2	66.5	66.5	66.5	66.5	66.5
Tax Collection (T.)	629	1,132	1,539	1,834	2,129	2,090	2,322	2,548
T.C.–T.	10,752	10,844	10,986	11,165	11,319	11,732	11,839	11,937

3.2.1.6. Sensitivity analysis: Fixed Tax

Sensitivity analyses are done to study the effect of considering some of the uncertainty in the RE investment costs and in demand levels. In particular, a combination of four different situations are studied, which corresponds to a combination of long-term demand levels and generation technology costs. Additionally, an analysis over the goal stringency is done, checking for the effect of an increment of 25% and a decrement of 25% and 50% over the emission cap.

Regarding the long-term energy demand level, it is assumed that this can be steady or high. The level of demand in the long run is considered to be unknown at the moment of establishing the CO_2 tax. This is justified due to the long-term demand uncertainty produced by the unknown success rate of energy efficiency programs and electric vehicles penetration, as well as other factors affecting energy demand such as the economic activity and growth. A higher demand implies higher emissions and therefore there will be a direct effect on the level of the tax for a determinate goal.

Regarding the RE (solar-PV and wind power) technology investment costs, it is assumed that this can be steady or low. These costs are also considered unknown when establishing the CO_2 tax level. The rationale of considering this uncertainty is the fact that RE have shown an important dynamism regarding their investment cost, especially for solar power (Creutzig et al., 2017; Energy Ministry, 2017b; Irena, 2016). Accordingly, it is important to assess the effect of a further investment cost drop in the future. RE investments cost can affect the final tax results as a lower cost may imply a bigger amount of new zero-emission power plants in the system and consequently the tax needed to reach a goal could be affected.

As expected, sensitivity analysis results show that a higher demand level leads to higher CO_2 emissions, as it is seen in Table 3.3. To reach the final goal, a slightly higher tax level would be needed. For the goal chosen in this case study, it coincides with the inflection point between coal and CCGT technologies mentioned before, so that a \$27tonCO_2 tax is enough to reach de goal. Depending on the tax level, the generation investment cost for different taxes barely changes in the high demand case (3.4% is the maximum for a tax of \$15/tonCO_2). The same occurs with the transmission investment level, where the variation is small and, in some cases, inexistent. In the case of reduced RE costs, effects on decreasing emissions are not significant, as power dispatch does not vary. The investment cost level is evidently lower in this case, but the amount of new power capacity added to the system is the same for almost all taxes. For that reason, emissions do not change with the RE cost scenarios. Only with the \$20/tonCO_2 tax, emissions are affected -1.9%, due to a 3.8% additionally installed RE power. This suggests that investments in RE are not cost constrained, which means that a lower RE cost does not necessarily lead to a higher investment level. When both scenarios (i.e., low RE cost and high demand) are combined, there is no significant difference with the case of only considering high demand, for the same reasons that the outcomes in the purely low-RE -cost scenario are not significantly different than in the original case. This analysis can be extended to all the other cases (i.e., TST, TST-SC, and TST-LH cases).

Table 3.3. Percentage difference in costs (in %) between the original case and High Demand (HD) and low RE cost (LRC) cases. Taxes in \$/Ton of CO_2

Tax	$5		$10		$15		$20		$25		$30		$35		$40	
Case	HDR	LRC	HDR	LRC	HDR	LRC	HDR	LRC	HDR	LRC	HDR	LRC	HDR	LRC	HDR	LRC
Total Costs.	3.3	-0.4	3.3	-0.4	3.3	-0.4	3.3	-0.5	3.3	-0.5	3.3	-0.5	3.3	-0.5	3.3	-0.6
Tax Collection	3.6	-0.2	4.0	0.0	3.6	0.0	3.6	-2.1	4.9	0.0	4.3	-0.6	4.3	0.0	4.4	0.0
Emissions	3.4	-0.2	3.8	0.0	3.3	0.0	3.5	-1.9	4.7	0.0	4.2	-0.5	4.2	0.0	4.3	0.0
G.C.E†	2.3	0.1	2.1	0.0	3.4	0.0	2.3	3.5	1.7	0.0	1.4	0.8	2.8	0.0	2.8	0.0
G.C.E so-lar & wind	2.1	0.2	1.9	0.0	2.3	0.0	2.5	6.0	1.6	0.0	1.4	1.4	3.0	0.0	2.1	0.0
G.C.E. Renewables	2.5	0.2	2.2	0.0	3.6	0.0	2.5	3.8	1.8	0.0	1.6	1.1	2.9	0.0	2.1	0.0

† G.C.E. stands for Generation Capacity Expansion

For the sensibility analysis over the emission goal, the problem was solved for different caps of emissions both higher and lower than the previous emission goal. Three new different goals are proposed: One that is 25% higher than the original goal (Goal L) and two other 25% (Goal M) and 50% (Goal H) lower than the 70% base case scenario goal. Therefore, goals of 87.5%, 52.5% and 35% of the 2029 base case emissions were tested. Results are shown in 3.5.

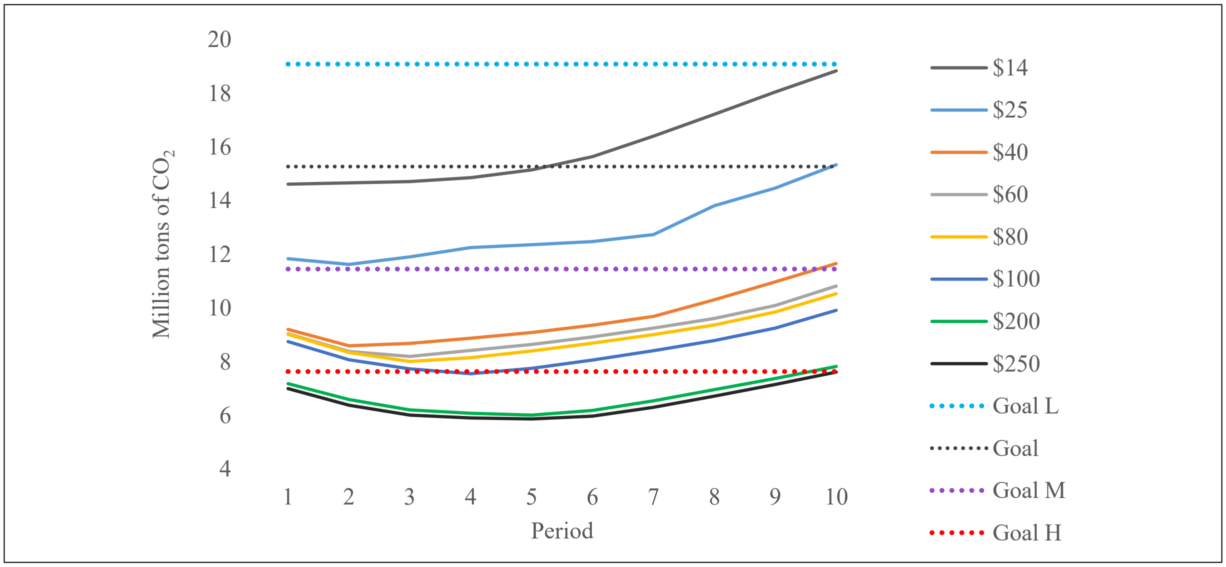

Figure 3.5. Annual CO_2 emissions for different taxes and goals, FT sensitivity analysis

First, for the case of the looser goal(Goal L) of 87.5% of the base case scenario, the results show that the optimal tax obtained is approximately of \$14/tonCO_2. As the tax is lower than the optimal \$25/tonCO_2, investment in renewables are lower and there is more dispatch of carbon intensive technologies as coal.

For the 52.5% Goal (Goal M) the optimal tax is \$40/tonCO_2. For this tax as it was shown in the FT analysis, emissions are avoided mainly by new investments and the avoidance of coal dispatch.

For the more stringent goal, results show that it is more difficult to reach higher levels of emission abatement. The optimal tax must be incremented up to \$250/tonCO_2. However, it can be seen that the \$200/tonCO_2 presents emissions quite similar to those of the \$250/tonCO_2 tax. This means that the marginal emissions mitigation for high taxes is very low. This could be explained by the fact that the model is reaching its maximum abatement potential. As the tax gets higher the model presents important increments in the renewable power investment, with full use of the new PV capacity (The model is restricted to the construction of a maximum of

500 MW per technology every) and more than 3000 MW of wind power. Economic dispatch shows that there is an important shedding of solar power during the day and also there is congestion in the transmission lines due to the new power investments, despite the new lines that are constructed.This shows that the system is reaching its maximum mitigation potential at least with the model parameters.

In conclusion this sensitivity analysis points to the fact that the model is relatively sensitive to the goal stringency depending on the magnitude of the goal variation. Attention must be pointed to the fact that the tax's capacity to mitigate is not linear and can be limited by physical parameters.

3.2.2. Two-stage tax case (TST case)

In this case, a CO_2 tax level is established at the first period, but it can be changed at period 6 (remaining at that level until period 10). The optimal outcome of the proposed model in the TST case suggests a scheme where there is a low tax level during the first stage (first five periods) and a significantly higher tax level during the second stage (periods 6 to 10) in order to meet the emission goal. This occurs mainly because there is no economic incentive in the model for having a higher tax level in the first stage (and the model shows itself a lack of inertia, which could eventually imply a need for larger tax levels at the first stage).

In terms of the optimal generation and transmission capacity expansion plan, the model has no construction time lag constraints and investments are decided annually, as in the FT case. However, in this case, investors can perfectly foresee the future tax level and will have certainty that there will be a higher tax in the second stage. This information leads towards larger investment levels from the very beginning, having more generation capacity available at the start of the second stage. For illustrative purposes, results obtained in the TST case for the situation of having a tax scheme of \$5/tonCO_2 in the first stage and \$25/tonCO_2 in the second stage are shown in Figure 3.6.

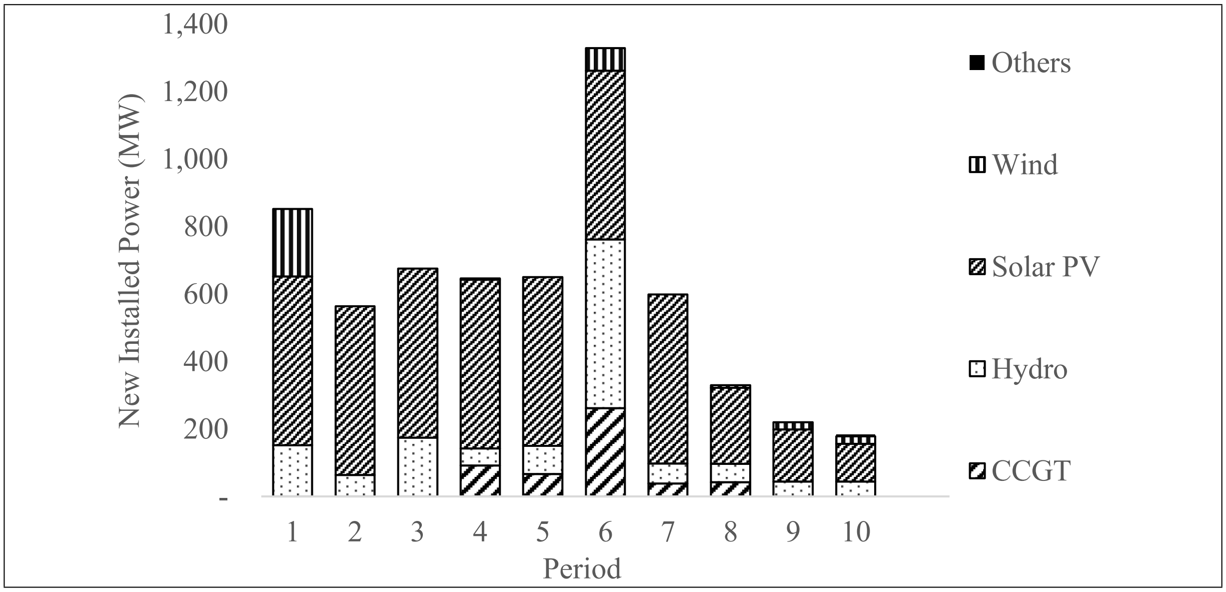

Figure 3.6. Annual power capacity added to the system (in MW) for a \$5/tonCO_2 -\$25/tonCO_2 tax scheme

In the TST case, generation capacity added in the second stage is slightly lower (<2%) than the one installed during those periods in the FT case. This is explained by the anticipatory optimization of the model when being certain about a tax level rise in the second stage. If investors were uncertain about the second stage tax, the investment gap would be higher as the entry of new power would probably be delayed until there is certitude about the tax levels.

Naturally, when the focus is only put on the final-period goal, the two-stage tax scheme is a more cost-effective way of reducing CO_2 emissions than the fixed-tax scheme. This is possible in this situation because this particular system is able to rapidly change its emissions in period 6 by adding new RE power and using the excess of CCGT power that is present in the system. For these reasons (and in the lack of additional incentives to accelerate the implementation of a larger tax level), it is optimal to establish a low CO_2 tax level in the first stage and a higher CO_2 tax level (high enough to meet CO_2 emission goal) in the second stage. This is evident in Figure 3.7, where CO_2 emissions are only significantly reduced in the second stage, as a consequence of the larger tax level imposed. The FT and TST case emissions are almost coupled in the second stage mainly thanks to the foreseeing capacity of investors that produce the entrance of new power in period 6. If there was uncertainty about the second stage tax, there would be a decoupling between the emissions of both cases due to a deficit of low carbon generators caused by delayed investments.

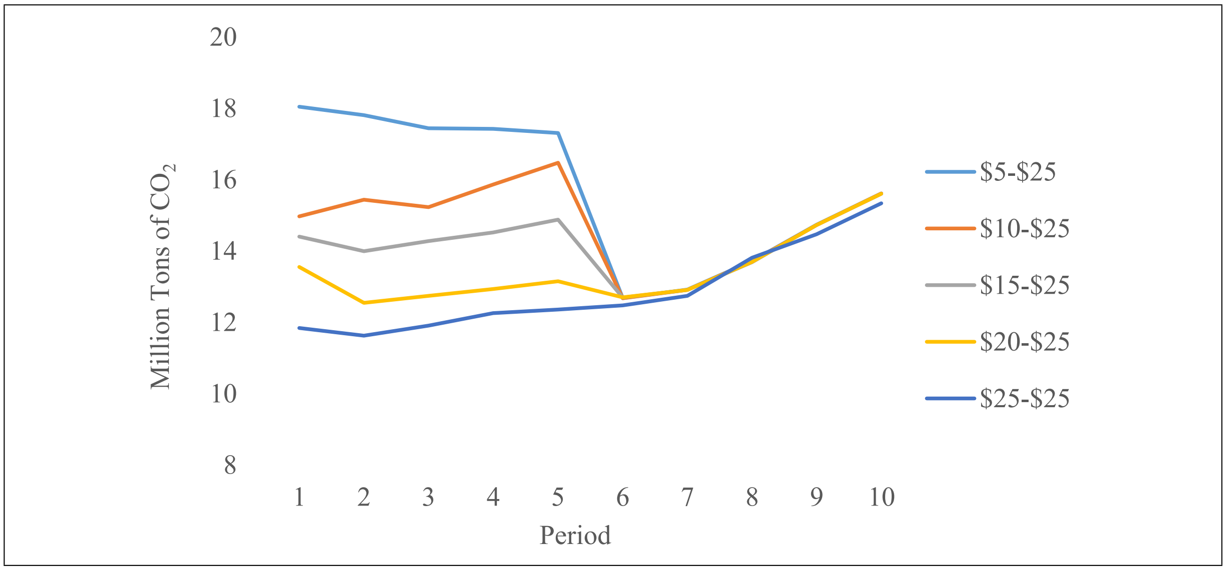

Figure 3.7. CO_2 emissions for different first-stage tax levels

Total Costs (T.C.), Generation Investment Costs (G.I.), Circuit Investment Costs (C.I.), Tax Collection Costs (T.), and the difference between T.C. and T. (T.C.-T.) are depicted for different two-stage tax schemes in Table 3.4, for the optimal (least-cost) solution of the model. The capacity added per technology for a fixed tax level of \$25/tonCO_2 and for a two-stage \$5/tonCO_2-\$25/tonCO_2 tax is shown in Table 3.5 for comparison purposes.

Table 3.4. Total Costs for different first-stage taxes in (in millions of \$). Taxes in \$/ton of CO_2

Tax	$5-$25	$10-$25	$15-$25	$20-$25
Total Costs (T.C.)	12,245	12,589	12,904	13,133
Generation Investment (G.I.)	2,980	3,221	3,283	3,502
Circuit investment (C.I)	51	53	56	67
Tax Collection (T.)	1,260	1,540	1,792	1,983
T.C.–T.	10,985	11,050	11,112	11,151

Table 3.5. Capacity added per technology (in MW) for fixed tax of \$25/tonCO_2 and for a \$5/tonCO_2-\$25/tonCO_2 tax scheme

Tax	\$5-\$25	\$ 25
Biomass	0	0
CCGT	500	500
Coal	0	0
Diesel	6	6
Gas	0	0
Geothermal	0	0
Dam Hydro	1,224	1,227
Run-of-river	0	0
Solar PV	3,992	3,995
Wind	323	522
Total	6,045	6,249

3.2.2.1. Sensitivity analysis: TST

An analysis to the goal stringency was done to test if the results of the TST were consistent for different emission goals. The same goals analyzed for the sensitivity analysis of the FT tax were chosen: a 87.5% (Goal L $\sim$ \$14/tonCO_2), 52.5% (Goal M $\sim$ \$40/tonCO_2) and a 35% (Goal H$\sim$\$250/tonCO_2) of the 2029 base case scenario emissions.

Results show that changing the goal affects the model's output in the same way that the TST case. The same behaviour as the TST case analyzed before can be seen for this different goals where the first stage tax emissions adjust to the second stage final period goal (The same tax obtained in the FT sensitivity analysis). Figures 3.8, 3.9 and 3.10 evidence that in the model, for lower and higher taxes, it is possible to adjust to the emission goal with a minimum first stage tax and an optimal second stage tax.

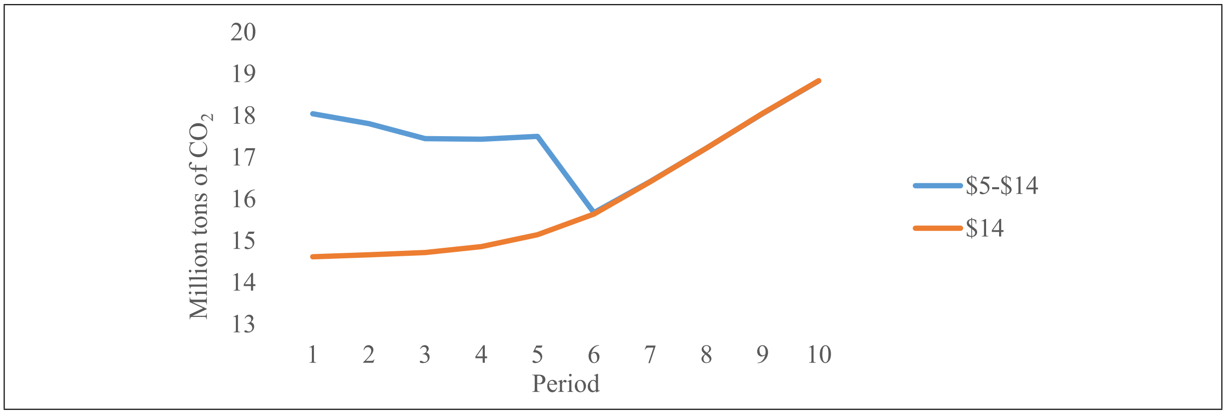

Figure 3.8. CO_2 emissions for TST of \$14/tonCO_2

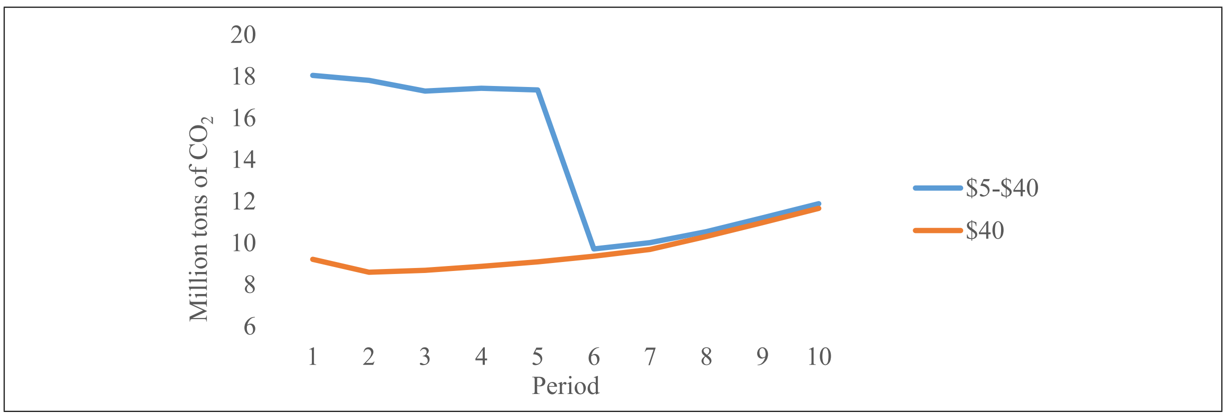

Figure 3.9. CO_2 emissions for TST of \$40/tonCO_2

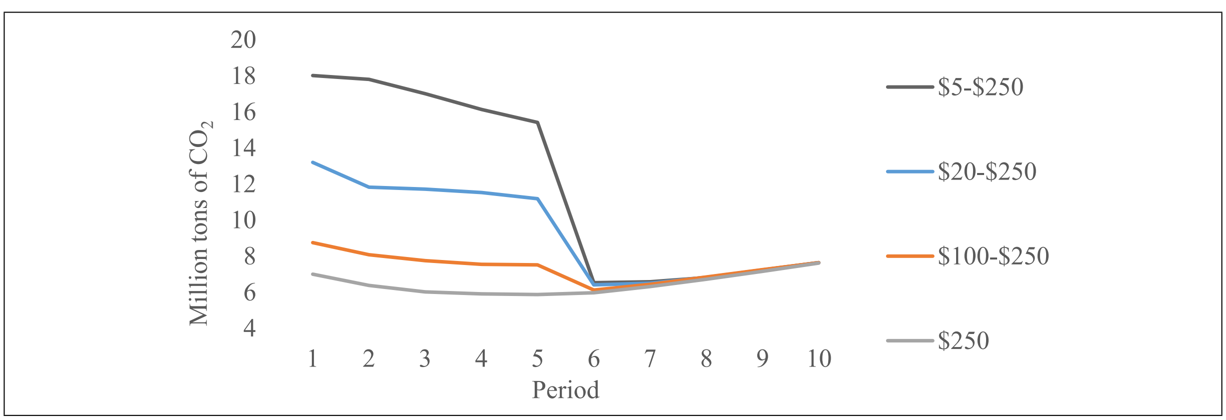

Figure 3.10. CO_2 emissions for TST of \$250/tonCO_2

3.2.3. Case of two-stage tax with CO_2 savings compensation (TST-SC case)

In this case, an exogenously determined value is assigned to emissions savings with respect to a base scenario, which is considered as the optimal solution in the TST case (i.e., without payments for extra emission savings). Results show that the optimal tax level for the first stage is equal to the value paid for abated emissions. Figure 3.11 shows, for values assigned to abated emissions from \$5/tonCO_2 to \$45/tonCO_2, that the optimal tax level is equal to the value exogenously assigned to the CO_2 emissions. In other words, it is desirable to have the same tax level as the market value of CO_2 emissions. This makes economic sense as the system will decide to abate emissions until the marginal abatement cost equals the marginal market reward for doing such emission savings.

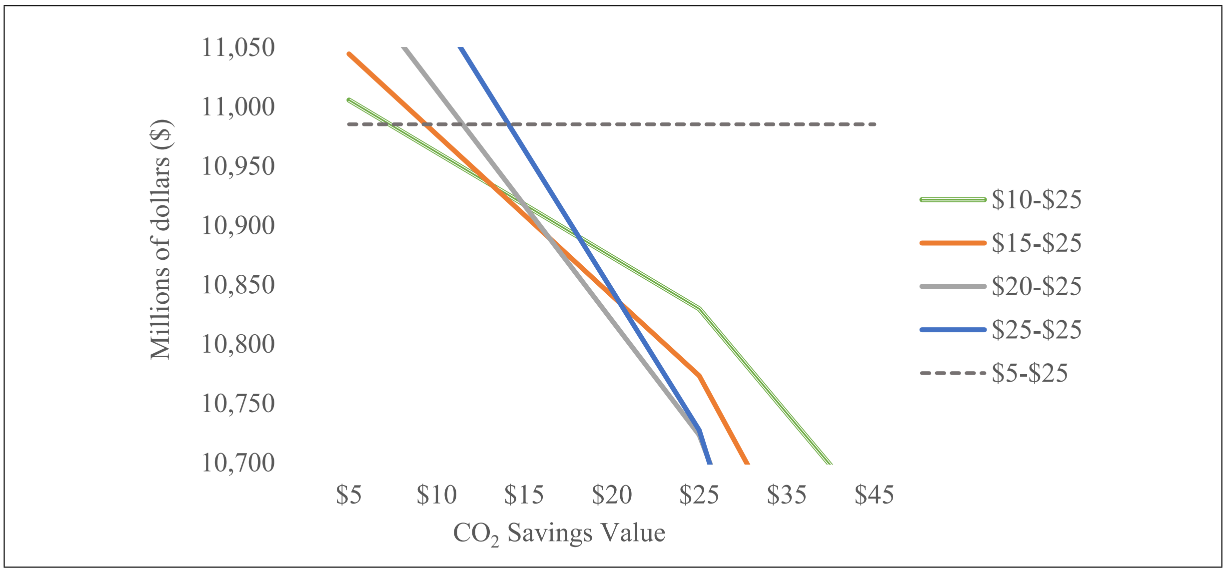

Figure 3.11. Total cost of the system for different taxes and CO_2 external value.

The two-stage tax with compensation is an interesting way of quantifying the effects of accelerating the carbon tax implementation. As previously explained, the results of the two-stage tax with no compensation show that there are no economic incentives to save emissions early. Accordingly, a higher tax level in the first stage would be convenient only if there was a monetary compensation for that saved emissions caused by the tax anticipation, like an external carbon market to trade those saved emissions, for example. The optimal tax level for the first stage when there is a compensation scheme is equal to that external price of carbon. This suggests that having an international carbon market would make appealing to save emissions in an anticipatory manner. Otherwise, if there was no value assigned to early action, a low tax level in the first stage, followed by a higher tax level in the second stage, should be established in order to meet the final-period goal. Another interpretation of this result is that the monetary compensation given for the emissions saved accounts for the total cost of the tax anticipation, providing a helpful quantification of the cost of accelerating the tax.

3.2.4. Case of two-stage tax with low reservoir hydro availability (TST-LH case)

Since the Chilean power system has a relatively high percentage of hydropower capacity, which is close to 27% of total installed power (National Energy Comission, 2017), results (in terms of emissions and costs) are significantly affected by the hydro availability. This experiment is similar to the two-stage tax case, but it considers that the capacity factor for reservoir hydro power plants is 35%. This case is motivated because the previous cases are optimized considering the traditional Chilean assumption of a capacity factor for reservoir hydro power plants of 65% (National Energy Comission, 2017). However, as mentioned before, the effects of Climate Change in the Chilean power system have shown consistent and continuous droughts during the last ten years, leading to an empirical average capacity factor of 35% (UC Global Change Center, 2014). In this case, the proposed model is optimized for a fixed tax and for a two-stage tax for comparison purposes. Figure 3.12 shows the CO_2 emissions for different levels of the fixed tax, where a \$45/tonCO_2 tax is needed to reach similar emission levels as in the original case optimal tax (\$25/tonCO_2). At the same time, significant differences are also observed in costs and power capacity additions in the hydro constrained case. In the two-stage tax case, the results are similar to the ones described in the previous case, where tax is set at a low level in the first stage and at the same value as in the fixed-tax case in the second stage.

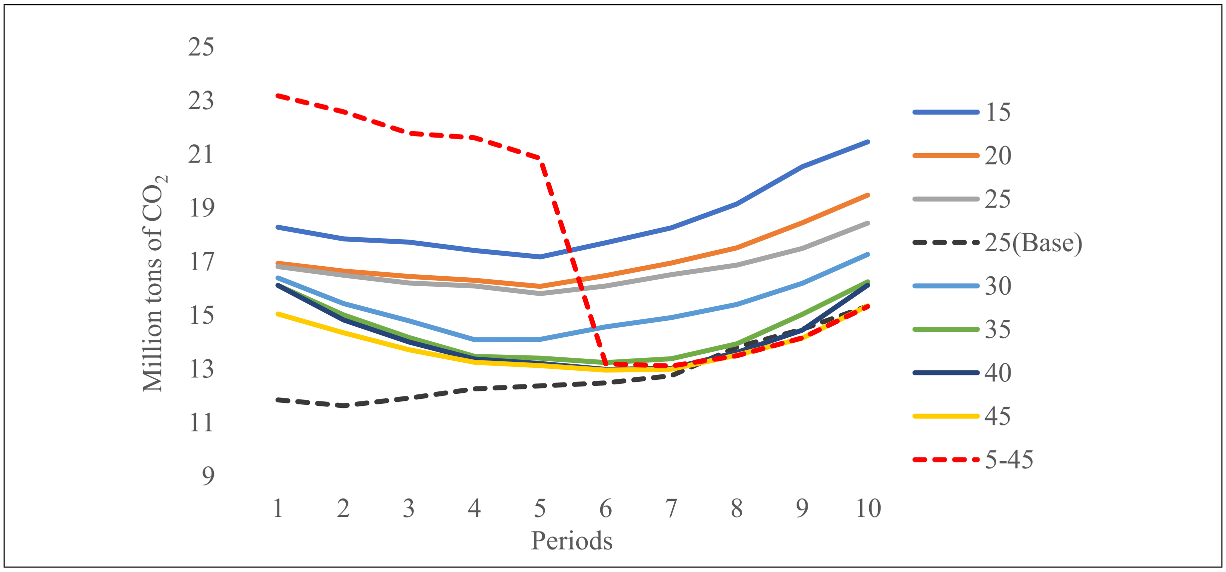

Figure 3.12. Annual CO_2 emissions for different taxes($) in the TST-LH case

The new capacity factor for hydro generation and the higher tax level affects the investment decisions in generation and transmission expansion. For both fixed- and flexible-tax schemes, the optimal generation expansion plan leads to a higher penetration of wind and CCGT power capacity. As expected, there is no investment in new dam hydro in this case, however, the total power capacity added to the system is over 9,000 MW (in contrast of the near 6,000 MW of additional capacity in the optimal solution of the TST case of \$5/tonCO_2 and \$25/tonCO_2 tax). Transmission expansion also varies in this case. Now, an additional new line is constructed (L4) in order to transport solar power from the northern to the southern region of the network (to compensate the lack of hydro power in the southern region). Moreover, the timing of the investment also varies for other lines (L0 and L2). Table 3.6 shows a summary of the costs and capacity expansions resulting in different cases and tax schemes where base stands for the full hydro capacity case (65% capacity factor) in every tax scheme.

Table 3.6. Cost comparison for different tax levels of the base and the hydro-constrained cases. Taxes in \$/Ton of CO_2

Tax	\$5		\$25		\$5-\$25		\$45		\$5-\$45	
Case	Base	Hydro	Base	Hydro	Base	Hydro	Base	Hydro	Base	Hydro
Total Costs (\$MM).	11,381	14,381	13,448	16,977	12,245	15,415	14,801	18,979	12,824	16,184
Tax Collection (\$MM)	629	767	2,129	2,800	1,260	1,570	2,826	4,217	1,565	2,063
Emissions (MM ton of CO_2)	189	229	129	167	158	197	95	138	140	179
Installed Power (MW)	4,887	6,192	6,249	8,204	6,045	8,142	7,452	9,083	7,332	9,045
Installed solar & wind (MW)	4,887	6,192	6,249	8,204	6,045	8,142	7,452	9,083	7,332	9,045
Installed Renewables (MW)	4,381	5,686	5,743	7,658	5,539	7,596	6,544	8,322	6,407	8,256
N° of new circuits	4	4	4	4	4	4	4	5	4	5

Economic dispatch is also affected by the smaller hydro availability and the consequent larger penetration of RE and CCGT power. Because of the higher tax levels in this case, coal and diesel power plants are almost never dispatched (only dispatched in some places due to network congestion issues). In this case, total cost may be underestimated even more than in the original case, because the proposed optimization model does not include a full unit commitment formulation (ignoring, for instance, start-up and shut-down costs of thermal units). The further addition of solar power capacity in the \$45/tonCO_2 tax case forces the system to replace near 5,000 MWh of solar power during the afternoon in less than 3 hours. This is an important technical aspect to consider, given that solar power generation supplies more than 50% of the demand during some hours in this case.

The results when the low hydro availability case incorporates a reward for the extra (anticipatory) CO_2 emission abatement are analogous to the results presented in subsection 3.2.3. The CO_2 tax during the first stage must be equal to the external carbon value in order to minimize total costs.

This case analysis shows that the optimal CO_2 tax, especially in the Chilean case, is very sensitive to the hydro power availability. In the Chilean system case, the CO_2 tax level required to reach the same CO_2 emission goal than in the case assuming high hydro availability is almost double.

4. DISCUSSION AND CONCLUSIONS

As it is expected, a CO_2 tax reduces the CO_2 emissions of power systems. In the Chilean system case, the optimal level of CO_2 tax when considering a fixed-tax case and a goal of 70% of the emissions predicted by the base scenario for 2029 is \$25/tonCO_2. However, since the goal is based on atmospheric science and political considerations, the socially optimal tax level will actually depend on the amount of emissions desired by the policy maker in each given case. Accordingly, the numerical result for the optimal tax is meaningless, and for that reason, different tax levels were analyzed to check the outcomes of varied policies. Results depend on the characteristics of every system analyzed and its available generation and transmission infrastructure as well as demand and other parameters. It must be mentioned that as the sensitivity analysis of the FT showed, the effectiveness of the tax as the goal gets more stringent is lower, fact that suggests that the tax as a tool for reaching a certain goal has a limited action for extreme emission abatement. This must be considered when choosing a tax as a policy for a final year emission goal. Nonetheless, by looking at the model outcomes in the FT case and in TST-LH case, it is possible to make an approximation of the possible ranges of CO_2 taxes for a 70% base case emission goal. Therefore, one could roughly say that a CO_2 tax for a 70% base line goal in the Chilean system will probably be around \$25/tonCO_2 to \$45/tonCO_2 depending on the parameters considered.

The results obtained are robust to variations in demand and RE investment cost levels. The scenarios of low RE costs and high demand yield to similar results (in terms of capacity expansion and costs) than in the original-scenarios (base) case. This suggests that the results are robust against changes in the technology cost and the level of demand. RE, especially solar power, is the systems first choice for expanding the system, which is coherent with the current literature (Creutzig et al., 2017; Energy Ministry, 2017b; Irena, 2016). From a CO_2 emissions point of view, CCGT power is the best complement for RE in order to reduce emissions while keeping an adequate system security level.

The formulation of the problem, as shown in the literature review, is quite important for the results. Ignoring detailed information about the market operation (short term) and planning (long term) of the power systems may significantly distort the anticipated impacts of regulatory policies, as several authors have pointed it out (Munoz et al., 2013; Vajjhala et al., 2008). The model proposed in this work considers these detailed formulation. On the other hand, the proposed model also makes some simplifications, like ignoring the exercise of market power. However, ignoring market power in the Chilean power system is coherent with the current literature showing the increasing competitiveness of the Chilean power market (Bustos-Salvagno et al., 2017). Also, the model does not account for the unit commitment problem (because of the high resolution times), overlooking the start and stop costs and associated emissions and inefficiencies. Ergo, actual emissions and cost might be underestimated.

Regarding the tax trajectory and flexibility, and assuming a final-period emission goal, the results show that the most cost-effective tax scheme is a two-stage tax with a low level in the first stage and a larger optimal tax level in the second stage. However, early actions can be justified depending on how relevant the policy maker considers the positive economic and not economic outcomes of a higher first stage tax. A useful tool for that decision-making process is the reward for extra emissions savings, which allows quantifying how much will accelerating the tax cost. If the influence of irreversibility is high on investors, then a flexible tax may not be the best option because it can lead to lower investments and higher emissions. The same logic applies to problems such as political opposition to new generation projects. This has lately been an important issue in Chile (Maillet, 2018) and elsewhere (Pasqualetti, 2011a,0; Reusswig et al., 2016) for RE and non-RE projects. If the risks of political opposition to projects is high, it may be better to accelerate the implementation of the tax in order to incentivize early investments that may otherwise take longer to build or to give time to the construction of new projects in case there is impossibility of completing others.

Finally, focusing on a final-period goal may not be the best way of facing the global warming problem, if emissions saved early have an important value when preventing the disaster of

Climate Change. As mentioned before, a final cap optimization may be blind to other constraints and positive externalities that affect the trajectory of the tax. When this is the case, a better way to achieve the desired results may be to have a final emission goal complemented with a total emission goal. In that sense, final emissions and emission trajectory could be driven by both constraints, having a more thorough inclusion of the real cost of carbon emissions.

In synthesis, this work has been helpful on giving an insight on how carbon pricing policy should be designed. It has shown that simplified yet thorough modelling of the power systems is absolutely necessary in the obtainment of an optimal carbon tax. However, this fact must not overlook other fundamental issues where cost minimization solutions may be half-blind. One of this issues is the trajectory of the tax under uncertainty which has shown to be of great importance and must be taken into notice by policy makers. A different trajectory can have effects over the systems outputs as well as the market and other related agents. On the other hand, intimately connected with the trajectory is the fact that there are other variables affecting the problem such as the political economy constraints or the unaccounted benefits of carbon taxing. A merely cost minimization approach will be deficient in estimating the real increase on social welfare due to those effects, underestimating the real influence that the carbon pricing policy might have. Taking into consideration this three aspects will help in the design of a more effective and efficient carbon tax that, in the imminence of climate change catastrophe, can make a great deal of difference for society.

As a final consideration, it is also expected that this work may be useful in the near future to anyone studying carbon tax policy. The combination of technical and economic aspects that are included in this investigation try to give a meaningful contribution to this matter, especially in the case of the Chilean power system analyzed.

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APPENDIX

A. NOMENCLATURE

Sets and Indexes

T: Set of periods (years), indexed by t.

G Set of generation technologies, indexed by g.

B: Set of buses, indexed by b.

H: Set of hours in a day, indexed by h.

D: Set of representative days, indexed by d.

N: Set of candidate lines, indexed by n.

C: Set of existing lines, indexed by c.

Sc: Set of existing lines' susceptances, indexed by c.

Sn: Set of candidate lines' susceptances, indexed by n.

G^D: Set of dispatchable generation technologies.

B_o^c: Set of buses where existing line c starts.

B_o^n: Set of buses where candidate line n starts.

B_i^c: Set of buses where existing line c ends.

B_i^n: Set of buses where candidate line n ends.

N_i^b: Set of candidate lines that end in the bus b.

C_i^b: Set of existing lines that end in the bus b.

N_o^b: Set of candidate lines that start in the bus b.

C_o^b : Set of existing lines that start in the bus b.

Variables

$p^{t}_{CO_2}$: Carbon tax in period t (\$/tonCO_2).

$p^{inst}_{g,t,b}$: Installed power for technology g in period t, bus b (MW).

$x^{inst}_{n,t}$: Binary, 1 if line n is installed in period t, 0 if not.

$p^{gen}_{g,t,d,h,b}$: Power generated by technology g, in period t, day d, hour h and bus b (MWh).

$f^{\text{exist}}_{c,t,d,h}$: Flow in existing line c, period t,day d, hour h (MWh).

$f^{\text{cand}}_{n,t,d,h}$: Flow in candidate line n, period t, day d, hour h (MWh).

$\theta_{t,d,h,b}$: Phase angle in period t, day d, hour h, bus b (rad).

$\alpha_{g,t,d,h,b}$: Reserve power of generation technology $g \in G^D$, period t, day d, hour h, and bus b (MWh).

$p^{nons}_{t,d,h,b}$: Non-supplied power in period t, day d, hour h and bus b (MWh).

Parameters

C^{Tech}_{g}: Construction cost for technology g (\$/MW).

C^{MW}_{g}: Generation cost for technology g (\$/MWh).

F^{Disct}_{t} Discount factor in period t.

C^{Cand}_{n}: Cost of the candidate line n (\$).

C^{nons}: Cost of non-supplied energy (\$/MWh).

$P^{Max}_{g,b}$: Maximum building capacity for technology g in bus b (MW).

S_c: Susceptance of existing line c (uS).

S_n: Susceptance of candidate line n (uS).

H^d: Number of hours a day.

Cf_g^{A}: Annual capacity factor per technology g.

$Cf_{h,d,g,b}$: Capacity factor of non-dispatchable technologies g in hour h, day d, and bus b.

$F_{d,c}^{\text{Max-c}}$: Maximum flow on existing line c on day d (MW).

$F_{d,n}^{\text{Max-n}}$: Maximum flow on candidate line n on day d (MW).

$P_{g,b}^{\text{exist}}$: Installed power of existing generators g in bus b (MW).

D^{α}: Demand back-up percentage.

$Rp_{g,b}^{up}$: Ramp up rate for generator technology g in bus b.

$Rp_{g,b}^{\text{down}}$: Ramp down rate for generator technology g, bus b.

$D_{b,h,t,d}$: Power demand for bus b, hour h, period t, day d (MWh).

P_{max}^{inst}: Maximum buildable power for a technology in one period (MW).

$E_{g,b}^{gen}$: Emission factor for technology g in bus b (tonCO_2/MWh).

M: Large auxiliary number.

B. WEIGHTED SUM BISECTION METHOD

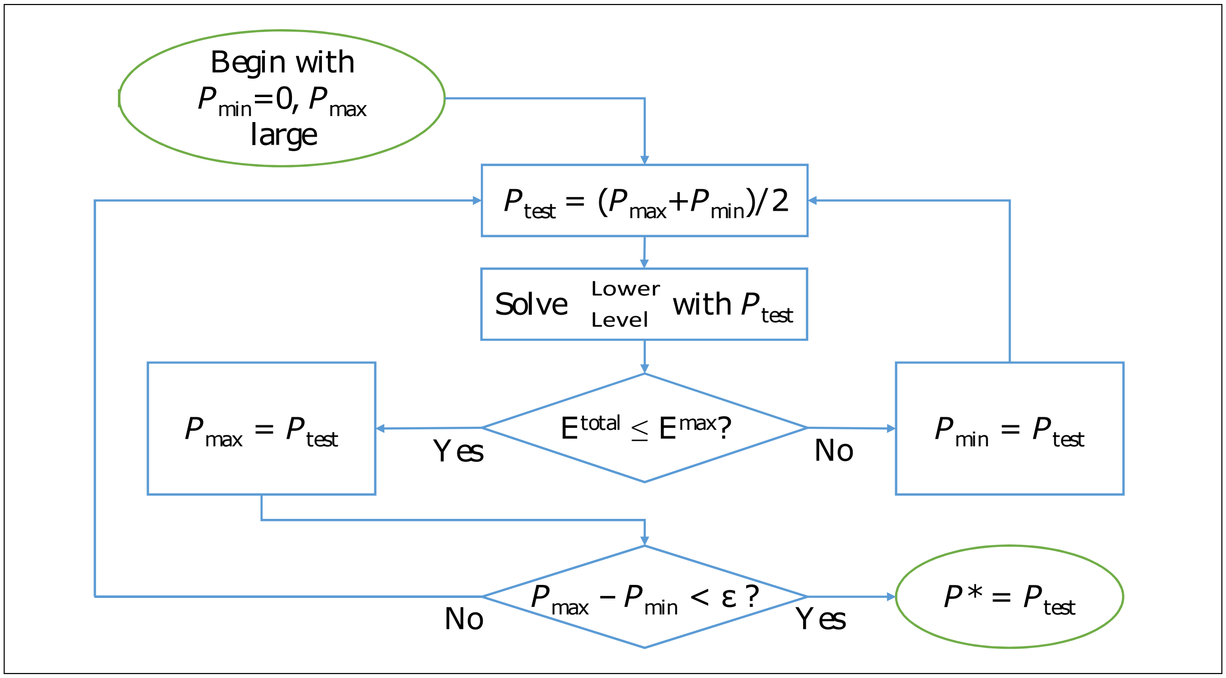

Figure B.1. Flowchart of the Weighted Sum Bisection Method to calculate minimum tax. Adapted from (Olsen et al., 2018).

The weighted sum bisection method applied to find a minimum tax consists on an iterative guessing of the minimum carbon tax (Olsen et al., 2018). In this case, P represents the carbon price, Pmin the minimum carbon tax possible and Pmax the maximum tax possible. The optimal solution will be a value between both. The algoritm solves the lower level (expansion planning problem) for a Ptest (candidate to be optimal tax) and will iterate until the difference between Pmin and Pmax is smaller than an ϵ value chosen.

C. TRANSMISSION MODEL DIAGRAM

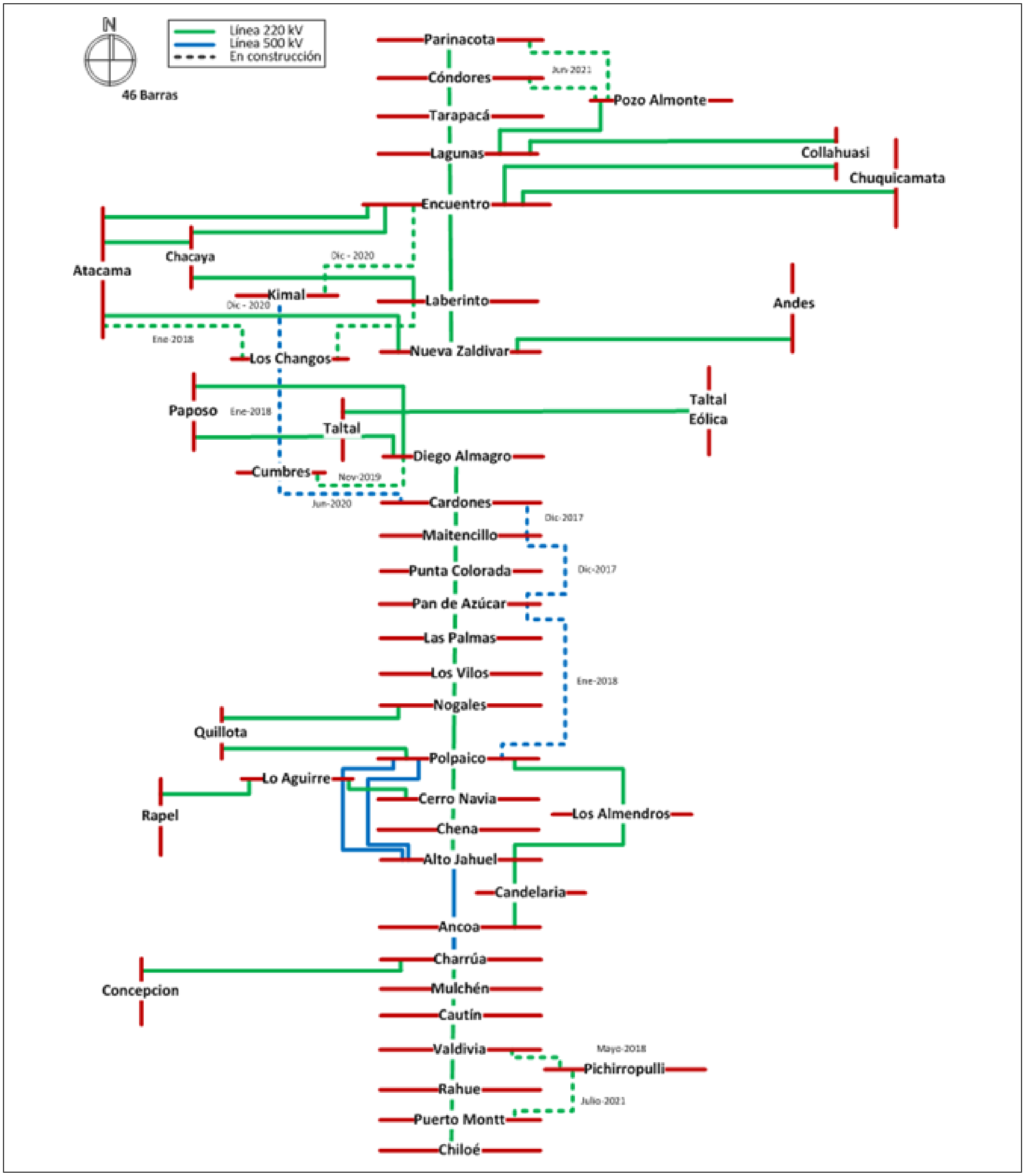

Figure C.1. Transmission system diagram modeled in the study case. Adapted from (Energy Ministry, 2017b).

D. GENERATION TECHNOLOGIES

Table D.1. Generation technologies data

Technology	Capacity Factor	Capital Cost [$/MW]
Biomass	0.83	3,100,000
Combine Cycle Gas Turbines	0.87	1,150,000
Coal	0.85	3,000,000
Diesel	0.92	900,000
Gas Turbines	0.92	800,000
Geothermal	0.9	7,800,000
Dam Hydro	0.65	2,200,000
Run-of-River Hydro	0.46 †	3,650,000
Solar Photovoltaic	0.30 †	970,000
Wind	0.28 †	1,365,000

† Run of river, solar and Wind capacity factors represent averages of the hourly capacity utilized.