Minimising unwanted interactions between CO_2 and low-carbon energy policies: The case of the Mexican electricity sector

M. A. **Jano-Ito,** D. **Crawford-Brown,** L. J. **de Vries**

C-EENRG Working Papers, 2019-1

October 2019

UNIVERSITY OF CAMBRIDGE

CEENRG
Cambridge Centre for Enviroment, Energy and Natural Resource Governance

Please cite this paper as:

Citation: M. A. Jano-Ito, D. Crawford-Brown, L. J. de Vries. "Minimising unwanted interactions between CO_2 and low-carbon energy policies: The case of the Mexican electricity sector". C-EENRG Working Papers, 2019-1. pp.1-75. Cambridge Centre for Environment, Energy and Natural Resource Governance, University of Cambridge.

The Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG, read 'synergy') was established in 2014 within the Department of Land Economy in order to conduct integrative research on the governance of sustainability transitions, such as the climate-driven transition from a carbon-intensive inefficient energy matrix to a decarbonised and efficient one, or the water/population-driven transformation of food production systems or, still, the broader implications of the transition from the Holocene to the Anthropocene for human knowledge and organisation. C-EENRG approaches interdisciplinary from a problem-driven rather than a discipline-driven perspective, relying on those methodologies and analytical frameworks most useful to understand and address a given problem.

C-EENRG hosts researchers across disciplines, including law, economics, policy, and modelling, and welcomes research on a wide range of environmental topics across the food-energy-water-land nexus.

Marco Aurelio Jano-Ito
Cambridge Centre for Climate Change Mitigation Research (4CMR), Department of Land Economy, University of Cambridge, 19 Silver St, Cambridge CB3 9EP, United Kingdom.

Douglas Crawford-Brown
Cambridge Centre for Climate Change Mitigation Research (4CMR), Department of Land Economy, University of Cambridge, 19 Silver St, Cambridge CB3 9EP, United Kingdom.

Laurens J. de Vries
Energy and Industry Section, Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628 BX, Delft, Netherlands.

Contact:

Marco Aurelio Jano-Ito

Present address: Centro Mario Molina para Estudios Estratégicos sobre Energía y Medio Ambiente (CMM). Prolongación Paseo de los Laureles 458, Despacho 406, Col. Bosques de las Lomas, Cuajimalpa, C.P. 05120, Mexico City, Mexico.

E-mail address: m.janoito@catab.net; mjano@centromariomolina.org

Tel: +52(155)40713743.

Minimising unwanted interactions between CO_2 and low-carbon energy policies: The case of the Mexican electricity sector

Marco Aurelio Jano-Ito, Douglas Crawford-Brown and Laurens J. de Vries

ABSTRACT

Many countries apply a combination of a CO_2 reduction policy with a policy for stimulating renewable energy. However, as these policy instruments have overlapping goals, they interact with each other, not necessarily in a positive way. This paper uses an agent-based model for a case study of the Mexican electricity sector to explore the impacts of a carbon tax and a tradable green certificates (TGC) market on low-carbon transition pathways, focusing on these policies' specific design elements, combinations and interactions. A mechanism aimed at reducing the negative effect of a carbon tax on the TGC price (a sloping penalty function for non-compliance and dynamic quota adjustment in the TGC market) is analysed. The results show that the impact of the combination of the carbon tax with the TGC market depends on the tax level and the penalty values for the TGC market, causing one instrument to dominate over the other. With respect to GHG mitigation goals, if a low carbon tax is applied, a TGC market helps to achieve greater emission reductions. If the carbon tax is high, the addition of a TGC market does not cause significant further emission reductions. The TGC market adjustment mechansims reduce the volatility of TGC prices and the negative interactions between the carbon tax and the TGC market and thereby further facilitates the introduction of low-carbon technologies and the reduction of GHG emissions.

Keywords: Mexico, Electricity sector, Agent-based modelling, Energy and climate policies, Decarbonisation.

1. Introduction

The need to reduce greenhouse gas (GHG) emissions and promote investment in low-carbon energy sources has led countries to implement various types of policy instruments, such as carbon taxes, cap and trade systems, feed-in tariffs, renewable portfolio standards, auctions, premium payments and fiscal incentives [1]. While these efforts represent an important step towards low-carbon electricity sectors, their proper design still represents a significant challenge, especially when multiple policies co-exist [2, 3]. The existing debate on the best policies for decarbonising electricity sectors has focused on individual policies or on the question whether adding a tradable green certificates (TGC) market to, for instance, an emissions trading scheme (ETS) would be useful for achieving further emission reductions [2, 4-6]. However, as highlighted by [7-11], the discussion has largely ignored the interactions and impacts of specific policy design elements which are key factors for determining the success of policies. Furthermore, the study of the issue of their coordination has been more limited [7-9, 11]. This paper tries to fill these gaps by using a novel simulation model to study the impact of specific design elements of climate and energy policies and their coordination. To our best knowledge, similar work has only been conducted on the impact of renewable investment on carbon prices [6] and the design elements of renewable promotion policies [7, 8]. This article also contributes to expanding the study of policy mixes taking the Mexican electricity sector as a case study. The latter could also bring useful insights for other countries that have implemented these policies such as the European Union (EU) [11, 12], California [13], and Australia [14], just to mention some examples.

The research presented here has the objective of analysing the interaction between a TGC market and a carbon tax by using a novel simulation tool that represents their interaction in an out of equilibrium market and agents with bounded rationality. More specifically, the objective is to analyse elements of their design and testing alternative arrangements to enhance their performance through a sloped penalty function and a dynamic quota mechanism for the TGC market. Section 2 of the paper presents the existing literature on the interaction between policies and their modelling; a brief description of the functioning of a TGC market and the proposed adjustment mechanisms, and the electricity sector of Mexico and its policies. Section 3 introduces the methodology used for this work. Section 4 presents the analysed scenarios, Section 5 presents simulation results and their discussion, and Section 6 concludes.

2. **Literature review**

2.1 Interactions between policies for reducing GHG emissions and for promoting low-carbon technologies

Interactions between policies for reducing GHG emissions and promoting low-carbon energy sources have been explored qualitatively and quantitatively (for reviews see [3, 15-17]). [18] and [19] were among the first researchers who studied these interactions from an analytical perspective and since then, different conclusions regarding the appropriateness of their combination have been drawn. [20] argued that the incorporation of a TGC to an established ETS could reduce CO_2 prices and thus promote higher emission power plants. It has also been argued that a cap may already set the emission limits and no further emission reductions could be achieved with a TGC increasing costs as well [16, 20-22]. Contrary to this, [23] stated that the previous conclusions were based on assumptions that do not resemble the reality of markets and policies. In support of this, it has also been argued that a mix of policies could be needed to reduce emissions and increase the use of low-carbon technologies. Their combination could reduce costs to consumers, create a less risky investment environment, and promote non-fossil fuel-based technologies, technological innovation, new job opportunities and regional development [11, 14, 16, 17, 24-29].

The quantitative models of the interactions between energy and climate policies are mainly focused on the EU ETS and the addition of a price-based mechanism (feed-in tariff) or a TGC market. Apart from the quantitative work of [20] and [21], highlighted before, who used a partial equilibrium model, [22] and [27] also used this approach to analyse the interaction between quota mechanisms in the electricity sectors of Germany and the United Kingdom, respectively. Both studies found that there were important interactions between policies but [22] concluded that a TGC market would promote high CO_2 technologies because this market generates a lower carbon price while [27] concluded that an ETS and a TGC market were required to reduce CO_2 emissions and increase the penetration of renewables. With the same modelling approach, [25] derived impact curves for the interaction between a cap and trade system and renewable energy promotion policies on allowance prices and GHG emissions and found that emissions and prices could have been higher without a renewable energy policy.

Focusing on cost manipulation, [30] and [31] found that the existence of an ETS and renewable energy quotas could encourage green energy producers to pad their own costs and try to harm other green energy producers. [32] analysed the EU ETS and a renewable energy quota in the European electricity sector and found that emission allowance prices were more sensitive to changes in electricity demand when the renewable quota was in place. [4] used a linear optimisation model of three regions (Benelux, France and Germany) to assess price and quantity-based mechanisms (both climate and energy). The authors analysed the interactions between a carbon tax and a TGC market, varying the level of the tax and the TGC quota highlighting the interactions between instruments and their impact primarily on the price levels of quota mechanisms [4].

A MARKAL model (linear programming) was used by [33] to study climate and renewable energy mechanisms in the context of the Nordic countries (Sweden, Norway, Finland and Denmark). The authors found that the introduction of a TGC market could reduce electricity and carbon prices in an ETS [33]. Linear programming has also been used by [34] to study the interaction between the EU ETS and the feed-in tariff scheme in Germany and by [35] to study the Baltic Sea region and the interaction between a TGC market and a cap and trade system. [34] found that a feed-in tariff could have negative impacts on ETS prices while [35] concluded that electricity, TGC and CO_2 prices are affected by the respective CO_2 reduction and renewable energy targets highlighting the importance of technologies to provide stability due to a high penetration of renewables.

[29] explored the interaction between an ETS and renewable energy deployment in Germany, highlighting the positive effect of having both policies in reducing a larger amount of CO_2 emissions compared to the standalone cases. The authors pointed out the sensitivity of this interaction to the hourly power system dynamics. [26] discussed the interaction between the EU ETS and a TGC market for the case of Spain based on a long-term oligopolistic capacity expansion model. The authors highlighted the need for both climate and energy policies but also the need to coordinate both policies to avoid negative effects [26]. More recently, [14] explored investment decisions under the political uncertainty of implementing GHG and renewable promotion policies in Australia and concluded that overlapping policies could reduce investment risk by an increased investment in renewable technologies. The modelling of the interaction between policies has also been conducted using computable general equilibrium (CGE) models of entire economies that have stressed the need for the coordination of policies to achieve their targets at the minimum costs (see [36-38]).

While most models used for analysing the combinations of policies rely on optimisation, alternative modelling approaches have also been employed. [13] conducted an experimental game-based simulation to analyse the interaction between carbon and TGC markets in California. The authors found market power issues in both markets and highlighted the complex nature of the interactions and the need to use alternative approaches to model the dynamics of markets, focusing on their specific elements to mitigate possible negative interactions [13].

Agent-base modelling (ABM) is a simulation tool that was used by [28] and [6] to study the interactions between GHG emission reduction and renewable energy support policies. In the case of the former, mechanisms were considered together; the work took the case of the Spanish electricity sector and remarked the need for using both policies for reducing CO_2 emissions and increasing the share of renewable generation but did not consider any dependence among policies [28]. In [6], a relationship was established between subsidised renewable investment and the EU ETS with a dynamic emissions cap. They concluded that the proposed relationship was appropriate to return the level of CO_2 prices to those that would have been achieved without the introduction of renewable policies and to avoid low prices and investment in high emission power plants [6]. Additional research by [8] used ABM to study design elements of renewable energy promotion policies and further took this model in [7] to establish a formal methodology for policy design.

The coexistence of several policy measures creates complex interactions that affect several variables in electricity markets and may lead to positive and/or negative outcomes [1, 9, 17, 39]. While there is, a limited number of modelling efforts that focus on their specific elements and their coordination, more work must be conducted to analyse this. Furthermore, research has primarily studied the impact of renewable policies on CO_2 prices, but the issue of the volatility for certificate prices in a TGC market has not received the same attention [13]. For the latter reasons, this paper examines policy design elements, their interactions and coordination in the context of a TGC market [7, 8, 24].

2.2 Clean energy certificates market with a sloped non-compliance penalty function and dynamic quota adjustment

In a simple annual and single-country TGC market, in which there is no speculation and prices reflect real economic costs, certificate demand (V_t) for year t is given by a quota that is covered by a certain percentage of the total electricity consumption determined by a national government. This demand is inelastic and, if supply is not enough to cover demand, a penalty is imposed on consumers[1] for the demand that is not covered by the certificates (Figure 1). This penalty also becomes the maximum certificate price since rational consumers are not be willing to pay more than the penalty for certificates [40].

The supply of certificates can be represented by short and long-term supply curves. In the case of existing power plants, the short run marginal certificate cost (SRMCC) is given by the difference between marginal cost of renewable energy production and the spot electricity price. In the case that the marginal cost is lower than the electricity price, the certificate price could be zero or set to a minimum price. For new investment in green generation, the long run marginal certificate cost (LRMCC) results from the difference between the long run marginal cost of production (LRMC) and the expected electricity price. The intersection between the LRMCC and demand corresponds to the certificate price, P_t for compliance year t. The LRMC is the LCOE and represents the minimum cost that utilities are expected to receive for new investment [40].

[1] Refers to electricity distribution companies or other consumers who have the obligation to acquire a certain percentage of their electricity from renewable energy sources [18].

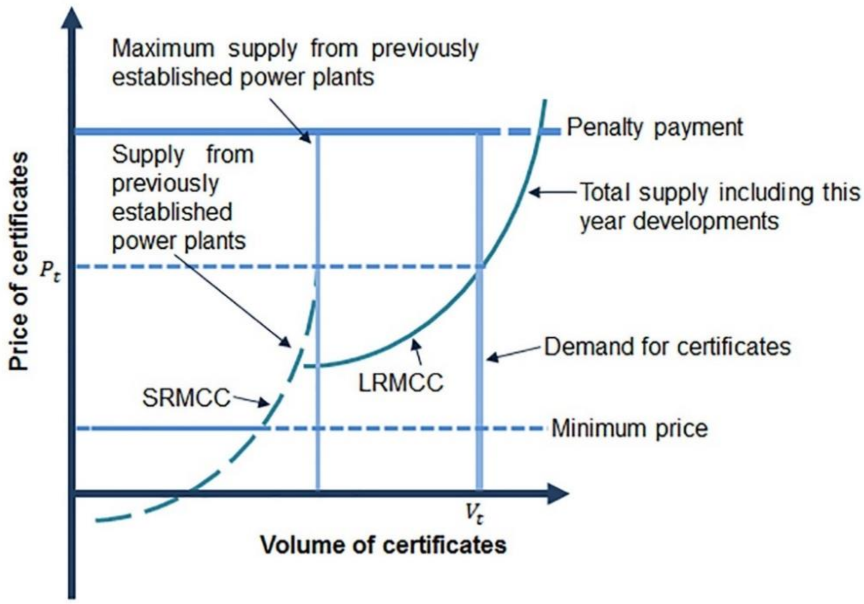

Figure 1. Representation of a tradable green certificates market.[2]

The energy production fluctuations that renewable energy technologies present may have an important impact on the stability of certificate market prices. Moreover, the fulfilment of the established quotas and shortages in certificates could aggravate this issue [40]. To cope with the resulting price volatility, banking has been suggested. Certificates should not have an expiration date, so a deficit can be covered with banked certificates from previous years [40, 41]. While banking may reduce volatility by adding elasticity to the annual demand function of certificates, it also has the disadvantage that it could allow strategic behaviour by certificate sellers. This situation could result in an incentive for sellers to withhold certificates, sending wrong price signals [42, 43]. Different approaches have been taken to cope with this problem by adjusting the penalty level and its dynamic nature. For instance, it could be adjusted depending on electricity prices or the emissions factor of the highest emitting thermal power plant [13, 42]. However, a mechanism that introduces a sloped penalty function together with adjustable low-carbon generation quotas which depend on the excess and shortage of previous year certificates could be another effective solution to avoid certificate banking issues [44].

A 'cliff' policy, with completely inelastic demand, leads to the maximum certificate price (P_1) if the supply of certificates (v_1) is not sufficient to meet demand (V_t), or to a price of zero (P_2) if supply of certificates (v_2) exceeds V_t. Instead, in our model we apply a downward sloping demand function, as shown in Figure 2. This idea is taken from the design of capacity markets [45] and proposed by [44] for the Solar Renewable Energy Certificates market (SREC) in the United States

[2] Taken from [40].

(US). With the introduced function, the prices P'_1 and P'_2 for supply v_1 and v_2 are closer to price P_t, reducing the price volatility that could result from year to year quota changes and the possibility of not meeting these quotas because of renewable resource variability.

The sloped certificate demand function is defined between the quota range $(1+\gamma)V_t$ and $(1-\gamma)V_t$, with γ representing a percentage that sets the lower and upper limits of the sloped function. In the case of the adjustable low-carbon generation quotas, depending on the excess or shortage of certificates S_{t-1} in the previous year $t-1$, the quota in year t, V_t is adjusted by adding (excess of certificates) or subtracting (shortage of certificates) a percentage α of S_{t-1} to the originally established quota $\widehat{V_t}$ [44]. It is important to remark that in this work, the quota was only adjusted for an excess of certificates, i.e. certificates were not subtracted.

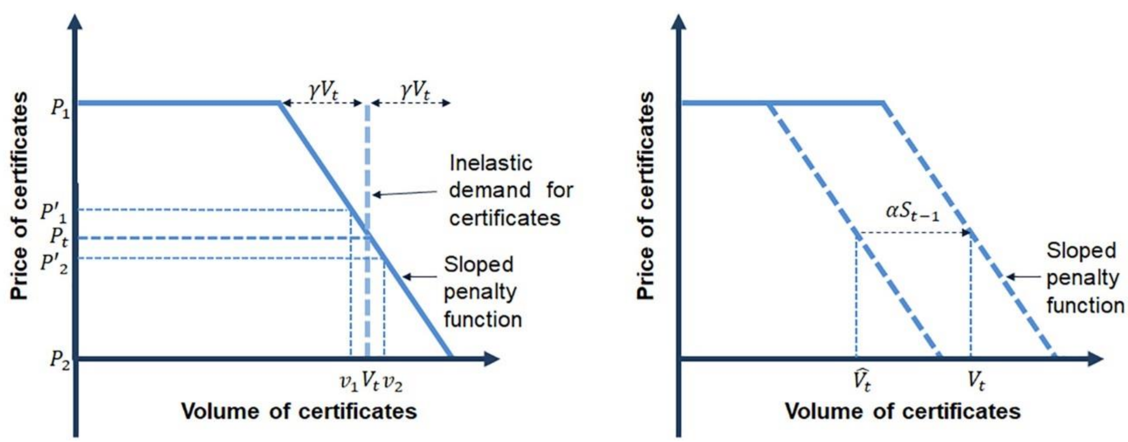

Figure 2. Representation of the sloped penalty function (left) and quota adjustment (right).[3]

The mathematical formulation of the latter is described by the following conditions [44].

$$
\begin{aligned}
P_t &= CP_t && v_t < (1-\gamma)V_t \\
P_t &= CP_t - \frac{CP_t}{2\gamma V_t}(v_t - (1-\gamma)V_t) && (1-\gamma)V_t \leq v_t < (1+\gamma)V_t \\
P_t &= 0 && (1+\gamma)V_t \leq v_t
\end{aligned}
\quad (1)
$$

[3] Constructed from [44].

The set of equations (1) represent the sloped penalty function, in which penalty price P_t is equal to the maximum penalty value CP_t (this value remains constant through the simulation in this work) when v_t is below the limit of the sloped function $(1-\gamma)V_t$ and zero when above the upper limit $(1+\gamma)V_t$. The quota adjustment in this mechanism is represented by equation 2.

$$V_t = \widehat{V}_t + \alpha S_{t-1} \tag{2}$$

The implementation of a GHG emission reduction mechanism increases the volatility of green certificate prices and produces low certificate prices because of increased investment in low-carbon sources (both because of a movement in supply v_t).

2.3 Energy and climate change policies in the Mexican electricity sector

Mexico intends to reduce national GHG emissions by 30% in 2020 with respect to 2000 levels and by 50% in 2050 [46]. In its Nationally Determined Contributions (NDCs), the government redefined its targets with an unconditional reduction commitment of 22% of GHG emissions by 2030, with reference to the baseline [47]. Additionally, the country set a target of generating 35% of total electricity production from low-carbon sources in 2024, increasing this to 40% in 2035 and to 50% in 2050 [48].

Mexico liberalised its electricity sector in 2013, allowing the participation of new actors. It also introduced instruments for promoting low-carbon technologies and reducing CO_2 emissions [49-51].[4] The Mexican government stablished a carbon tax of 39.8 Mexican pesos per ton of carbon (around 0.82 US Dollars per ton of CO_2 (t_{CO2}))[5] [55]. In addition, a tradable green energy certificates (TGC) market was introduced. This mechanism started in 2018 and electricity market participants are required to comply with clean energy generation obligations. Producers can buy electricity from other low-carbon electricity producers, generate their own low-carbon electricity or buy certificates (valid for 5 years). The Ministry of Energy (Secretaría de Energía, SENER) sets the obligations for a 3-year period (this period can be shortened) and participants are allowed to deviate up to 25% of their targets for 2 years with a penalty of an additional 5% per year. For 2018, the required quota was set to be 5% of total electricity use, while the requirements for 2019 – 2022 are 5.8%, 7.4%, 10.9% and

[4] For a broader discussion of the Mexican energy sector and the reform see [52], [53] and [54].
[5] It has to be highlighted that the regulation does not specifically define the price in terms of CO_2 and only refers to carbon. Per ton of carbon, the price would be around 3.5 US Dollars. Translated to CO_2, the price would be 0.82 US Dollars per ton of CO_2, which was considered for the calculations.

13.9%, respectively [56]. In case of not meeting their obligations, producers are penalised with fees between 30 and 250 US Dollars per MWh. The penalty is determined considering various factors including the amount of certfiticates not covered by the supplier, the economic situation of suppliers and the motivations for not complying with the required quota [57, 58].

3. **Methodology**

Agent-based modelling (ABM) is the approach adopted in this paper because of its ability to represent real decision-making processes [59]. Moreover, the use of ABM in electricity markets has proven its power in simulating electricity market configurations with accurate results that resemble reality, as shown in [60-62].

3.1 Description of the ABM for the electricity sector in Mexico

Our model of the long-term evolution[6] of the electricity sector of Mexico is based on an open source model which was modified and adjusted to the system under study. The model we used was EMLab-Generation, developed by the Energy and Industry Section of the Delft University of Technology (Technische Universiteit Delft, TU Delft).[7] This model was selected because of its applications (CO_2 emission reduction policies and renewable subsidised investment), which are relevant to the Mexican case, and because of its maturity and comprehensiveness including the modelling of capacity markets and specific renewable energy policy design elements [7, 8, 63-67]. The following sections present a general description of the adapted model and the supplementary materials further develop the specific implementation of the model.

3.1.1 *Fuel prices and electricity demand*

The evolution of fuel prices was simulated by using a geometric Brownian motion (GBM) with drift algorithm with the values of the drift and the variance parameters determined from the planning scenarios developed by [68] and the historical volatility of fuel prices, respectively.[8] The initial prices

[6] The simulations cover the period from 2013 to 2050.
[7] Source code can be downloaded from: https://github.com/emlab/emlab-generation.
[8] Fuel prices follow a log-normal distribution.

were taken from [69], and as in [70] and [71], the values were aimed at portraying the long-term trends and volatility of fuels, and not the short-term features.

In the case of demand, the load duration curve (LDC) for the Mexican system was used and was discretised in 14 segments starting with the maximum demand of 38,138 MW which corresponded to 2013 (Figure 3) [72-74]. As in [75], a triangular distribution was assumed for yearly changes of demand. The parameters for the distribution were set to 1% for the minimum growth, 5% for the maximum growth and 3% for the average growth. They were based on historical values of maximum demand (from 2003 to 2012) [72, 74].

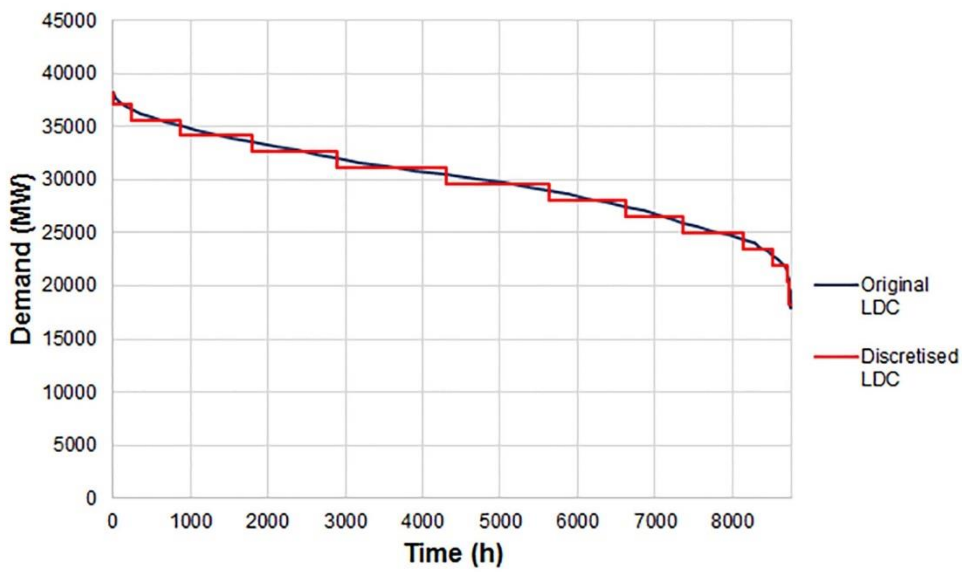

Figure 3. Load duration curve of the National Interconnected System (SIN).

3.1.2 Energy technologies

The model incorporated different technologies including solar photovoltaic (PV) systems and supercritical pulverised coal combustion with and without CO_2 capture. In total, 12 technologies were included. Table A2 summarises the technical and economic information used in the model, which was obtained from [68] and [75]. Geothermal energy was assumed to provide baseload power while hydropower was assumed to serve during peak load times, based on the characteristics of the Mexican sector [76, 77]. As shown in Table A3 of the supplementary materials, the capacities for new power plants were also increased as in [75] because of computational reasons. An important aspect of the model is the age of power plants, which was based on [78] and [79] and was also coupled with the expansion and retirement plans presented by [72].

3.1.3 *Agents*

The simulations for the electricity sector of Mexico included 12 agents replicating eight private companies currently operating as independent power producers, CFE, PEMEX and two additional private companies that represent large industrial users, which are already participating in electricity generation. It is possible that a larger number of companies could enter the market, but it was decided to consider the companies that occupy an important part of the sector today. The main characteristics of these companies were introduced into the model to differentiate them and in Table A4 of the supplementary materials this information is presented.

3.1.4 *Electricity generation investment behaviour*

The electricity market in the model[9] clears for every discretised segment of the LDC [67]. Once the market is cleared, the agents decide whether to invest in new technologies or not. The agents' investment decision-making process is based on imperfect information and agents create a simple estimation of the future supply conditions in the market. This is accomplished by first considering the existing power plants in the system and the demand in current year t, and then estimating the future condition of the supply during the considered period of time which corresponds to $t + th$, where th is the reference year of the time horizon [67].

For this work, the investment decision rule was based on [42] and [80], in which the profitability of a project was calculated by the difference between the expected annual average electricity price and the levelised cost of electricity (LCOE). This was done to facilitate the incorporation of renewable resource potentials through cost curves into the investment algorithm. The calculation of the LCOE is represented by equation 3.

$$LCOE_h = \frac{\sum_{t=0}^{t_c} \frac{I_h/(1+t_c)}{(1+wacc)^t} + \sum_{t=t_{c+1}}^{t_c+t_d} \frac{\sum_{s=1}^{Ts} \left(F_{s,h,t+th}\right) Rh_{s,h,t+th} + FOM_{h,t}}{(1+wacc)^t}}{\sum_{t=t_{c+1}}^{t_c+t_d} \frac{PP_{h,t+th}}{(1+wacc)^t}} \tag{3}$$

In (3), I_h is the investment cost for technology h, t_c is the construction time of the power plant, t_d is the depreciation time, s is a segment of the load duration curve, Ts is the total number of segments considered for the load duration curve, $F_{s,h,t+th}$ is the variable cost of the operation of the plant (estimated future fuel prices) for segment s of the load duration curve and technology h, $FOM_{h,t}$ is the fixed variable cost for technology h, $Rh_{s,h,t+th}$ are the estimated future running hours

[9] The model also includes a carbon market and the possibility to include a carbon tax.

of the power plant for segment s of the load duaration curve and technology h, $PP_{h,t}$ is the power plant expected production of electricity for technology h and time t, and $wacc$ is the weighted average cost of capital. The $wacc$ was estimated for public and private companies as 10.0%[10] and 6.5% respectively.

3.1.5 Quantification of renewable energy costs for investment decisions

An important aspect in the modelling of possible energy futures is related to the local availability of energy resources and their incremental costs as the number of potential sites decrease [82]. The costs of renewable technologies were incorporated, as in [83], to limit the development of renewable energy plants to their technical and economic potentials. In the model, agents evaluated the costs of renewable energy technologies with these curves and incorporated them in their investment decision rule. The methodology [84] that was used to determine these curves is presented in the supplementary materials and they were only applied for new technologies and the remaining resources.

3.1.6 Clean energy certificates market

A clean energy certificates market was added to the original EMLab-Generation model based on the version that was developed by [85] for the study of a capacity market. This market was designed to follow the theoretical description presented in the Literature Review. It was cleared on an annual basis, after the electricity market was cleared, and was assumed to start in 2018. In this model, only power plants constructed after 2014 were considered and as in [28], every agent calculated a fundamental value[11] for their power plants and bid the higher value between the fundamental value and the difference between the SRMCC and the electricity price. The government played the role of the only buyer of certificates and subject to meeting the quota as well. In case that the quota was not met, the certificate price was set at the penalty level (either a fixed value or modified by the sloped function). The market was cleared by matching supply and demand for certificates. Once the certificate price and volume were defined, this information was used by generators to evaluate investment alternatives and the quota for the following year was adjusted (either a fixed value or a dynamic quota).

---

[10] The Ministry of Finance (Secretaría de Hacienda y Crédito Público, SHCP) determined the value as 10% [81].

[11] As defined by [86], the fundamental value is a perceived certificate value from an agent that is based on an evaluation of the costs of a new project. In the case of this work, agents do not estimate future prices and the fundamental value is based on the market prices at a specific time of the simulation.

4. Scenarios

Two sets of scenarios, in addition to a Base Case Scenario, were defined in order to first analyse the policies separately and their interaction (set 1, Table 1), and subsequently analyse the effect of the TGC market adjustment mechanisms together with a carbon tax (set 2, Table 2).

The Base Case Scenario considers the expansion of the system without any climate or low-carbon energy policy and uses the adaptation of the model to the Mexican case. Fuel prices and demand were considered as stochastic (shown in the supplementary materials) and the same trajectories for these variables were used for the policy scenarios to have comparable results [75, 64]. Monte Carlo simulations were used and every scenario including the Base Case was run 120 times with a High-Performance Cluster (HPC) located at the Centre for Atmospheric Sciences at the National Autonomous University of Mexico (UNAM).[12]

Table 1. Policy scenarios and assumptions for scenario set 1.

Scenario	Assumptions
Low carbon tax (LowCT)	The initial CO_2 price is assumed to grow by 0.85 US Dollars/t_{CO2} annually in order to reach a price of 32 US Dollars/t_{CO2} by 2050.
High carbon tax (HighCT)	The initial CO_2 price is assumed to grow by 4.36 US Dollars/t_{CO2} annually in order to reach a price of 162 US Dollars/t_{CO2} by 2050.
Low certificates market penalty value (LowCMP)	The value of the penalty was considered as 30 US Dollars/MWh.
High certificates market penalty value (HighCMP)	The value of the penalty was considered as 250 US Dollars/MWh.
Combination of low carbon tax and low certificates market penalty value (LowCTLowCMP)	The LowCT scenario was combined with the LowCMP scenario.
Combination of low carbon tax and high certificates market penalty value (LowCTHighCMP)	The LowCT scenario was combined with the HighCMP scenario.
Combination of high carbon tax and low certificates market penalty value (HighCTLowCMP)	The HighCT scenario was combined with the LowCMP scenario.
Combination of high carbon tax and high certificates market penalty value (HighCTHighCMP)	The HighCT scenario was combined with the HighCMP scenario.

[12] The HPC is formed by nodes with Intel Xeon X5472 processors with 8 cores per node.

The assumptions for CO_2 prices were taken from [87] and [88]. The initial carbon tax was fixed at 0.82 US Dollars per ton of CO_2 (t_{CO2}) and was increased every year, following different trajectories as specified in Table 1[13]. In the case of the clean energy certificates market, as presented in section 2.3, the penalty scheme for the case of Mexico includes a range between 30 and 250 US Dollars per MWh. Since the establishment of the penalty depends on the specific situation of every supplier, the high and low values mentioned earlier were considered as fixed for all agents and part of the scenarios. The initial value of the quota corresponded to 5% of total energy consumption and assumed to grow by 7.5% per year so that in 2050, the requirement was set as 50.0%.

For the sloped penalty function and the dynamic quota adjustment scenarios, the scenario with the high certificates market penalty value (HighCMP) was taken, and different values were tested based on [44]. In order to analyse the effect of the sloped penalty function and the dynamic quota adjustment policy with a carbon tax, set 2 of policy scenarios included two additional scenarios in which the HighγLowα scenario (Table 2) was combined with the LowCT and HighCT scenarios.

Table 2. Policy scenarios and assumptions for scenario set 2.

Scenario	Assumptions
Low γ value (Lowγ)	The value for γ was set as 0.1 while α was fixed as 0.
High γ value (Highγ)	The value for γ was set as 0.5 while α was fixed as 0.
Combination of high γ value and low α value (HighγLowα)	The value for γ was set as 0.5 while α was fixed as 0.1.
Combination of high γ value and high α value (HighγHighα)	The value for γ was set as 0.5 while α was fixed as 0.5.
Combination of low carbon tax and high γ value and low α value (LowCTHighγLowα)	The LowCT scenario was combined with the HighγLowα scenario.
Combination of low carbon tax and high γ value and low α value (HighCTHighγLowα)	The HighCT scenario was combined with the HighγLowα scenario.

It must be highlighted that the following sections present the most relevant simulation results. The supplementary materials contain additional results.

[13] The Base Case scenario considered a constant carbon tax of 0.82 US Dollars per t_{CO2}. This is the value presented in section 2.3 of this paper.

5. Simulation results and discussion

5.1 Base case

The shape of the cost-supply curves played a fundamental role giving cost advantages to natural gas combined cycles (NGCC) and pulverised coal SC (super critical), as investment in renewable technologies decreased (because of increasing costs). Figure 4 presents the average installed capacity and generation between the period under study.

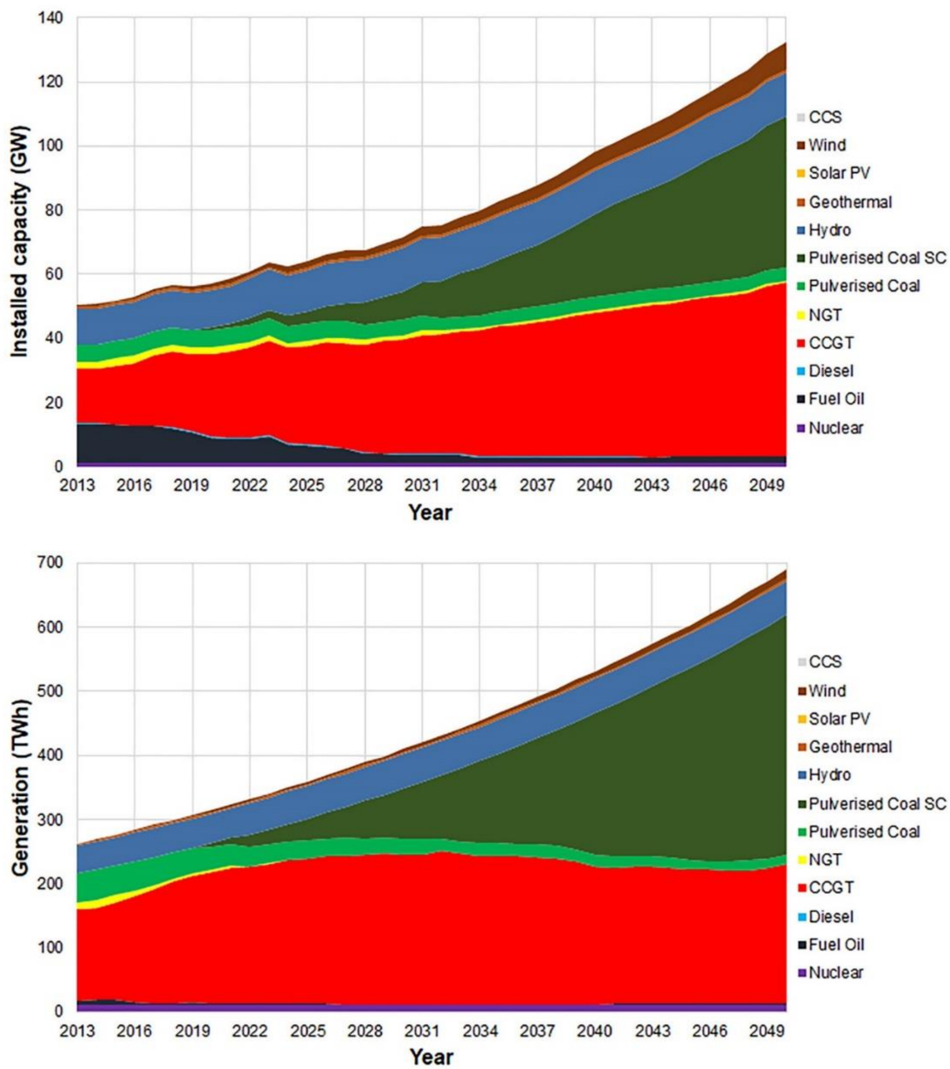

Figure 4. Evolution of installed capacity (top) and generation (bottom) for the Base Case.

[89] provides a study of the decarbonisation of the Mexican economy in which different approaches including economy wide models (EPPA, GCAM, IMAGE, POLES and TIAM-ECN)[14] were used. We compared our model results with the baseline scenario results of [89]. Table 3 presents a summary of the generation shares of the electricity technologies by 2050 estimated in this work and the ranges obtained in the previously mentioned models.

Table 3. Energy mix shares (%) from the ABM and other models.

Model	ABM in this work	Other models
Natural gas	31.6	27.0 – 74.0
Coal	56.0	10.0 – 50.0
Fuel oil	0.2	1.0 – 28.0
Renewables	10.4	8.0 – 43.0

Figure 5 presents the CO_2 emission trajectories in the electricity sector. The estimated emissions for 2013 in the model were 128.3 million t_{CO2} with a carbon intensity of 0.488 t_{CO2} per MWh. The model estimated average CO_2 emission values of 187.1 million t_{CO2} for 2030 and 402.9 million t_{CO2} for 2050 (Figure 5). Mexico's Nationally Determined Contributions (NDCs) quantified the baseline with 127.0 million t_{CO2e}[15] in 2013 and 202 million t_{CO2e} in 2030. The goal for 2030 is to emit 139 million t_{CO2e}, representing a decrease of 31.1% [90, 91]. The determined values for the modelling exercise were similar to the established values in the NDCs.

[14] [89] presents a description of these models and their information sources.

[15] The model used in this work estimated CO_2 emissions, while the government estimations include CH_4 and N_2O emissions. The last two compounds only represent 1.4% of total GHG emissions (2010 data) and for this reason, further comparisons in this work were performed considering government goals as CO_2 emissions.

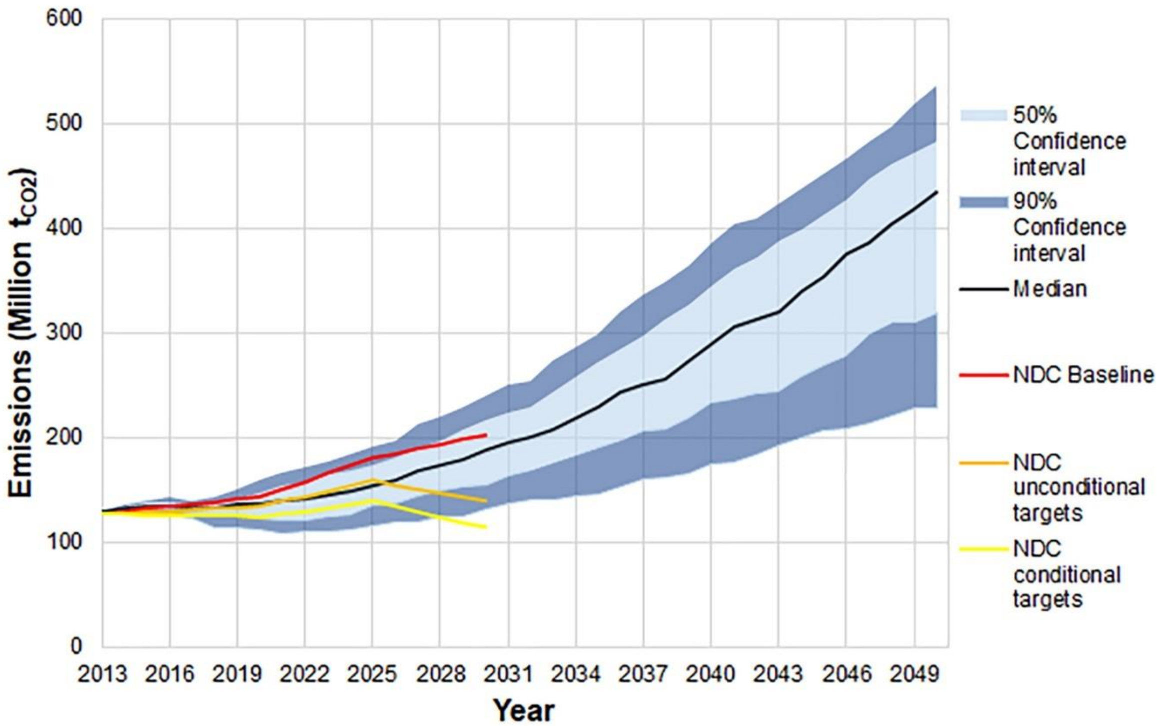

Figure 5. Evolution of CO_2 emissions in the power sector.[16]

Figure 6 presents the evolution of yearly average electricity prices. The initial increase in prices was driven by the continuation of the use of fuel oil with a rapid decrease caused by a substitution from fuel oil to natural gas.[17] In comparison to data from the Mexican government and the International Energy Agency (IEA), the industrial prices of electricity remained constant between 2013 and 2014, but presented a decrease of 32.8% between 2014 and 2015 and 16.9% for the initial months of 2016 compared to 2015 [92, 93]. In the model, average prices were relatively stable during the first years (with an initial increase of 10.5% and a decrease of 3.6%) with a reduction of 14.9% for 2016.

[16] The dark blue envelope illustrates the 90% confidence interval while the light blue envelope the 50% confidence interval. The dark blue line represents the median values.

[17] As presented in [53], the energy policy of the country was to promote fuel oil and investment in natural gas burning technologies was delayed. The recent structural changes of the natural gas markets in North America, have been accelerating the transition towards the use of this fuel.

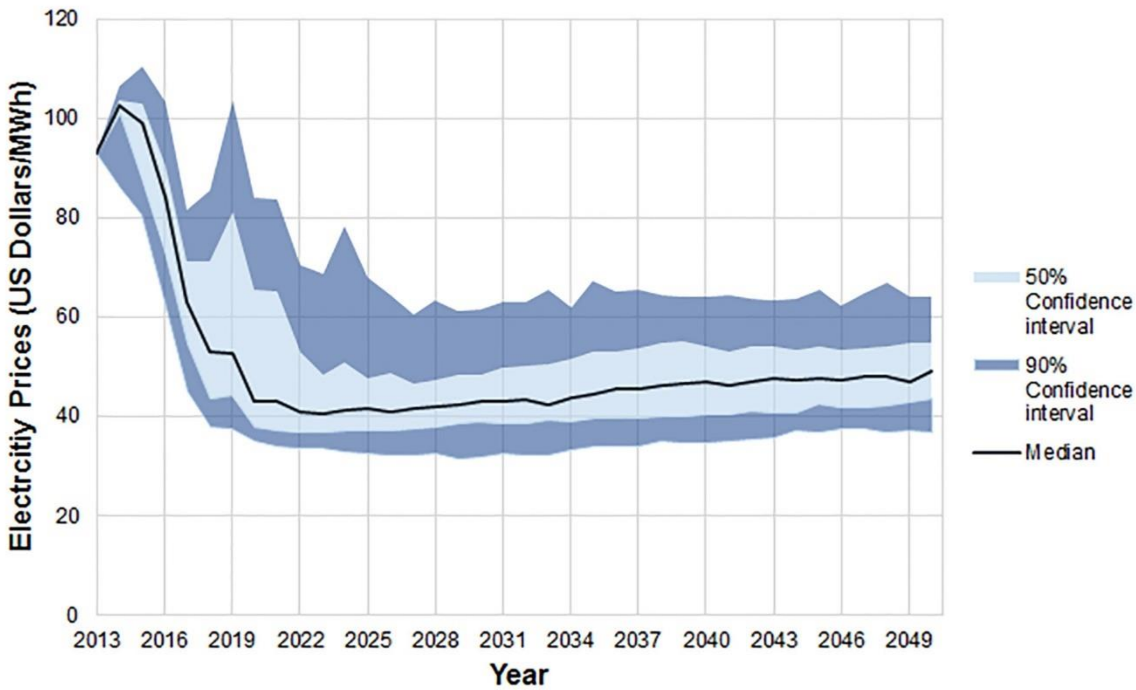

Figure 6. Development of wholesale electricity prices.[18]

5.2 The impact of the carbon tax and the TGC market

The implementation of CO_2 price trajectories alone (without the TGC market) resulted in average CO_2 emissions as low as 115.3 million t_{CO2} for 2030; and 173.9 million t_{CO2} by 2050 for the high carbon tax (HighCT) scenario. In comparison to Mexico's NDCs, that defines a reduction goal of 63 million t_{CO2} by 2030, the HighCT scenario achieved the required reductions. Nevertheless, a lower price trajectory (LowCT) or the implementation of a TGC market alone could also bring emission reductions. When the instruments were combined (carbon tax and TGC market penalty values), the scenarios that brought the highest emission reductions were those that used a high carbon tax (HighCTHighCMP and HighCTLowCMP scenarios). As observed in Figure 7, the latter mentioned scenarios also show that the high level of the carbon tax reduced the benefits of introducing the TGC market and did not lead the system to further significant emission reductions. These results were also obtained by [16, 20, 21] who concluded that it would be expected that higher taxes would induce emission reductions until no abatement options remain, regardless of whether there is a TGC market. In contrast to the latter, a lower level tax in combination with a TGC market (LowCTHighCMP

[18] The dark blue envelope illustrates the 90% confidence interval while the light blue envelope the 50% confidence interval. The dark blue line represents the median values.

scenario) created the opposite effect, increasing emission reductions by approximately 50 million t_{CO2} in 2050 in comparison to the case when only a low carbon tax was considered (LowCT scenario).

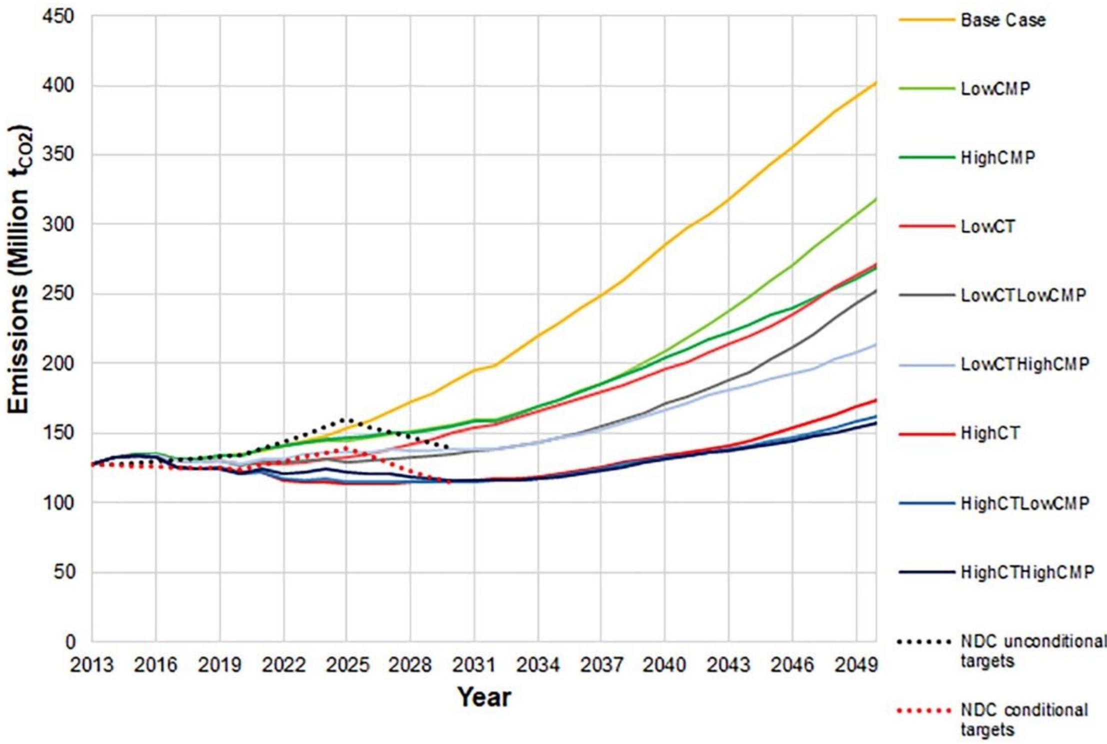

Figure 7. CO_2 emission trajectories for scenario set 1.

These emission trends were caused by the technological alternatives in the fuel mix. The introduction of a carbon tax mainly triggered a substitution of fuel oil fired power plants by natural gas combined cycles (NGCC) and a later introduction of wind power plants. A high penalty (HighCMP Scenario) resulted in more investment in low-carbon generation sources while the low penalty (LowCMP Scenario) fundamentally served as a subsidy of 30 US Dollars per MWh, highly promoting wind energy.

The combination of policy instruments caused a higher share of low-carbon technologies, also of high-cost alternatives (solar PV and coal CCS), in comparison to single policy instruments. These results were also obtained by [4] and Figure 8 presents the average generation share (in percentage) of low-carbon technologies (nuclear included) in the evolution of the sector.

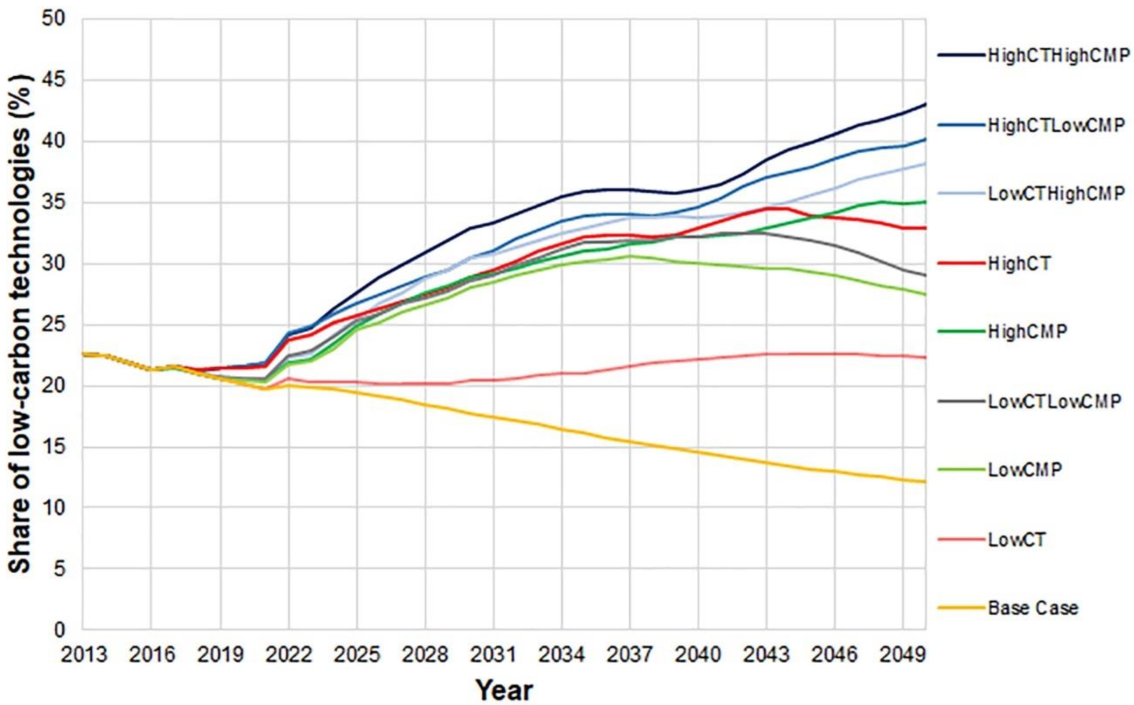

Figure 8. Technology generation shares for the simulation period for scenario set 1 (fixed demand for TGC).

Figure 9 presents the evolution of certificate prices in the scenarios with a high penalty level alone and in combination with a low and high carbon tax (HighCMP, LowCTHighCMP and HighCTHighCMP). The results for the scenario with a low penalty level (LowCMP) are not included in Figure 9 because the penalty value was reached during the entire simulation period for this case serving as a constant subsidy for wind.

A high penalty (HighCMP scenario) led to increased TGC price volatility because of the initial failure in achieving the low-carbon energy quota and the later increased investment in low-carbon technologies (especially wind) that rapidly increased their participation and led to a certificate price collapse, also found in the work of [43], [94] and [95]. This volatile behaviour was aggravated by the existence of a CO_2 price, which additionally promoted investment in low-carbon energy sources and decreased certificate prices. The increased investment in intermittent wind energy, together with the gradual decommissioning of several power plants by 2030, increased the level and volatility of electricity prices highlighting the need for more controllable generation as discussed by [96]. The latter issue directly affected the certificate prices that drastically decreased around 2025. Despite of the increased investment in wind during this period, it was not enough to comply with the TGC quotas increasing TGC prices during the last decade of the simulation. The amount of wind was limited by the cost-supply curve and its potential. When this potential was reached, agents stopped investing in wind. The TGC equilibrium price was not enough to promote the required quantities of more expensive technologies (solar PV for example), so agents mainly invested in other technologies such as coal. The drastic increase demonstrated the features of a market design with a vertical demand, i.e. even a small shortage in certificate supply increased the certificate price to the penalty levels.

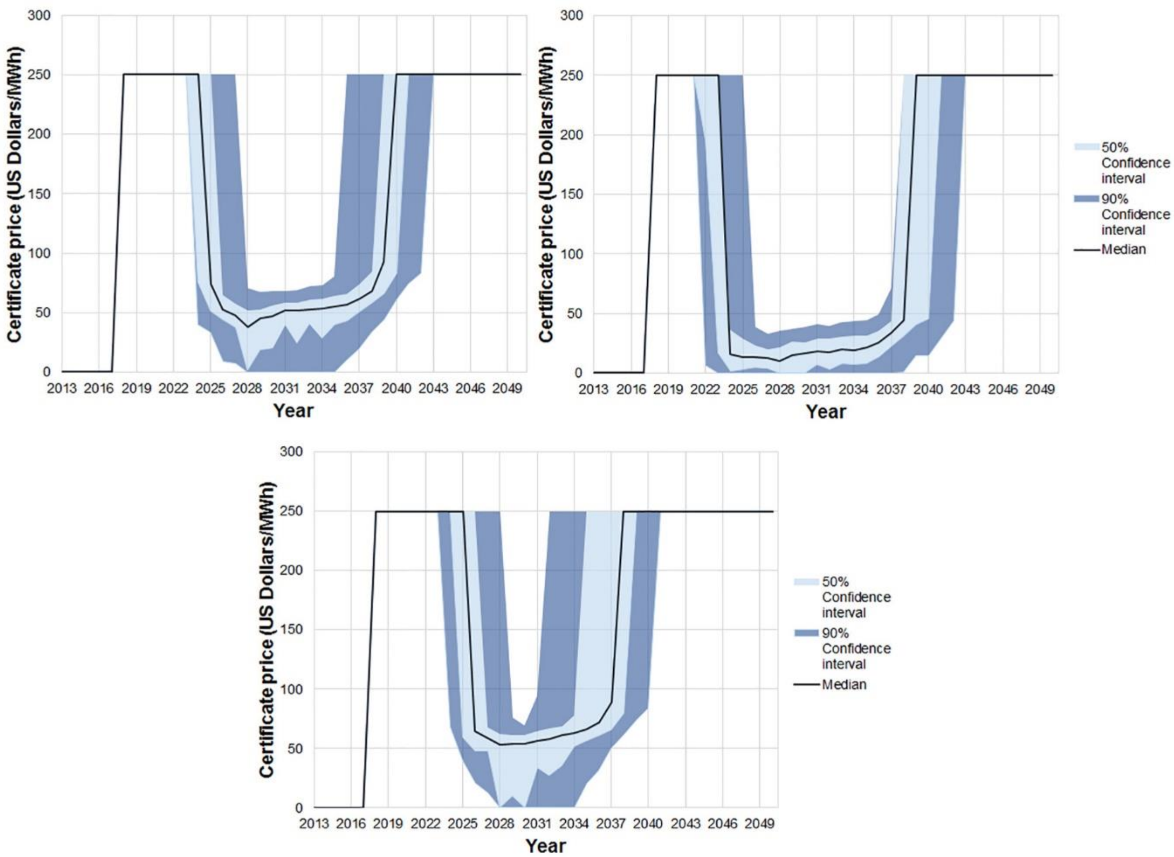

Figure 9. Certificate prices for the HighCMP (bottom), HighCTHighCMP (top right) and LowCTHighCMP (top left) scenarios.[19]

It is important to mention that the experience in other countries illustrates the similarity between actual trends and the ones presented in Figure 9. The historical trends documented by [94] and [95] provided data for the spot market prices of several states in the United States, emphasising the effects of shortages and oversupply on certificate prices, showing periods when prices nearly reached the penalties but also very low prices. The data considered in the ABM used for the Mexican

[19] The dark blue envelope illustrates the 90% confidence interval while the light blue envelope the 50% confidence interval. The dark blue line represents the median values.

electricity sector did not take into consideration the existence of self-supply private generators who could also participate in the market in addition to the long-term auctions that commit generation projects in the future. These sources could lower the initial price but the uncertainty in the possibility of delays in the construction of the committed generation projects may also result in higher prices [97].

5.3 The impact of a sloping demand function and a dynamic quota

The results from section 5.2 confirmed several concerns regarding the design of a TGC market and its interaction with a CO_2 emission reduction policy. This section presents a modification to the TGC market, introducing a sloping TGC penalty curve and a dynamic quota adjustment mechanism (scenario set 2).

Figure 10 presents the effect of different values of the parameters of a sloped certificate penalty function and the dynamic adjustment of the quota on certificate prices. The modification of the certificate demand is presented in the top two graphs of Figure 10. In comparison to the scenario with a high carbon tax and a high TGC penalty (HighCTHighCMP) in Figure 9, certificate prices were more stable and followed a smoother decrease and increase as the slope of the demand function was reduced (increase in the value of γ), since there was a wider range of penalty values that avoided the drastic drops and increases in prices. It was also observed that the possibility of having prices of zero decreased. Even a small change in the slope of the demand (low value of γ) brought benefits. The mean of certificate prices decreased slightly with a reduction in the slope of the demand function. The standard deviation of prices was also reduced.

The incorporation of a dynamic quota (shown in the bottom graphs of Figure 10) had a major impact on the price levels of the certificates. The mean certificate price increased from 132 US Dollars per MWh in the scenario with a lower slope of the demand function (Highγ) to 168 US Dollars per MWh in the scenario that added a low value of the dynamic quota adjustment parameter (HighγLowα) and 187 US Dollars per MWh in the scenario with a high value of the dynamic quota adjustment parameter (HighγHighα). The increase in the previously mentioned parameter (α) which took a larger number of unused certificates to be added to the certificate quota of the following year, increased prices as expected. A higher value of this parameter can increase the level of the certificate price so that it acts as a constant subsidy. The volatility in prices remained the same as in the scenario without the dynamic quota adjustment (Highγ), evidencing the importance of the sloped function in controlling volatility.

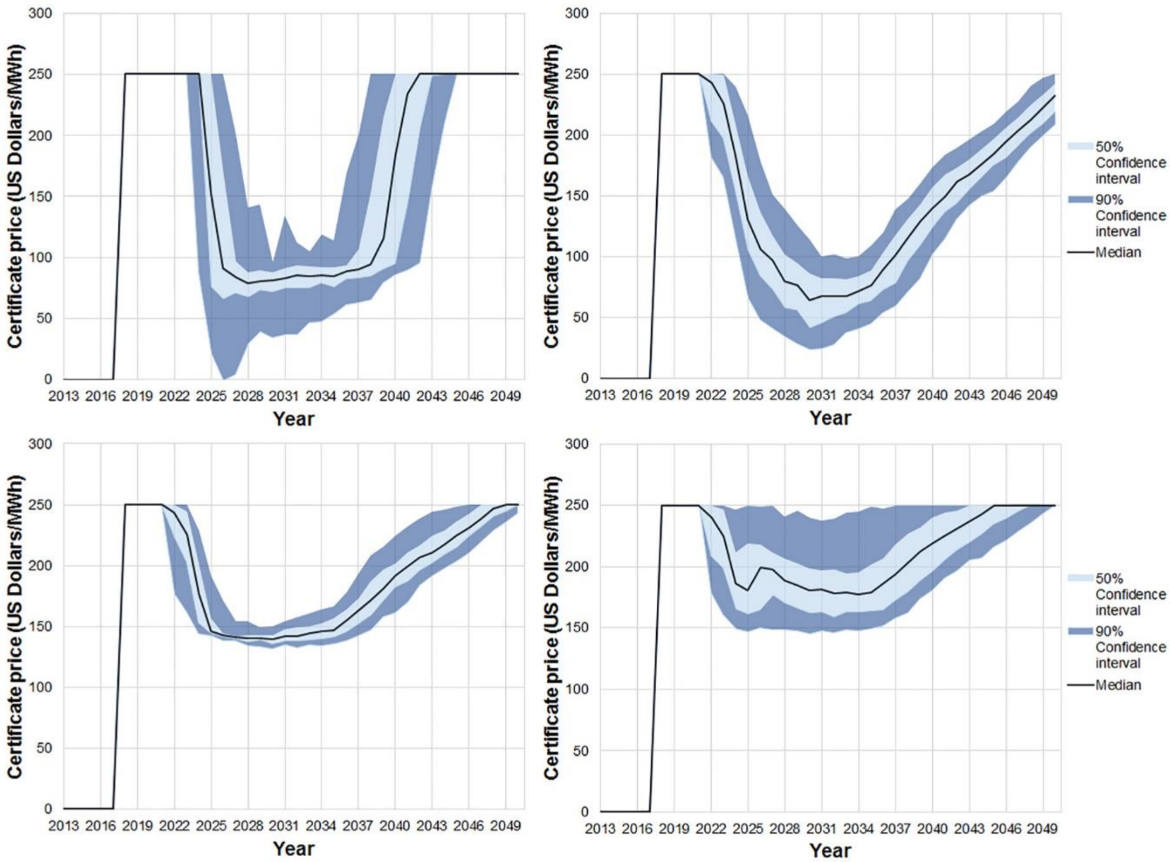

Figure 10. Certificate prices for the Low$\boldsymbol{\gamma}$ (top left), High$\boldsymbol{\gamma}$ (top right), High$\boldsymbol{\gamma}$Low$\boldsymbol{\alpha}$ (bottom left) and High$\boldsymbol{\gamma}$High$\boldsymbol{\alpha}$ (bottom right) scenarios.[20]

When the low and high levels of the carbon tax were combined with the highest reduction in the slope of the demand function and a low level of the dynamic quota adjustment (scenarios LowCTHighγLowα and HighCTHighγLowα), the same results as those presented in the bottom left graph of Figure 10 for the certificate prices were obtained. The latter shows that the effect of a carbon tax was eclipsed, eliminating the negative impact created by the CO_2 emission reduction policy on TGC prices. Even though certificate prices were not affected; in terms of technologies, there were some changes. These results were compared to the scenario with a high value of the TGC penalty (HighCMP) of section 5.2. There were differences in the numbers of wind, hydro, NGCC and pulverised coal SC power plants that were built, with slight changes for geothermal and solar PV and more visible differences in the adoption of coal CCS which required lower certificate prices. The most significant trend was observed for the scenario with a high carbon tax, a high level of reduction in the demand slope and a low level of the quota adjustment (HighCTHighγLowα). In this

[20] The dark blue envelope illustrates the 90% confidence interval while the light blue envelope the 50% confidence interval. The dark blue line represents the median values.

scenario, NGCC adoption was approximately 10 GW to 15 GW higher than the other scenarios by the end of the simulation caused by the carbon tax and the fuel substitution between natural gas and coal, as mentioned in section 5.2.

The low-carbon shares (Figure 11) showed the positive effect of including a sloped demand function and the dynamic quota. For the scenarios that combined the carbon tax levels and the TGC market, there were further increases in the penetration of low-carbon sources. In the case of the scenario with a high carbon tax, a high level of reduction in the demand slope and a low level of the quota adjustment (HighCTHighγLowα), the low-carbon targets set by the Mexican government were almost met, with 40.3% in 2035 and 48.9% in 2050. For the 2024 goal of 35.0% generation from low-carbon sources, the model estimated a low-carbon share of 26.4%.

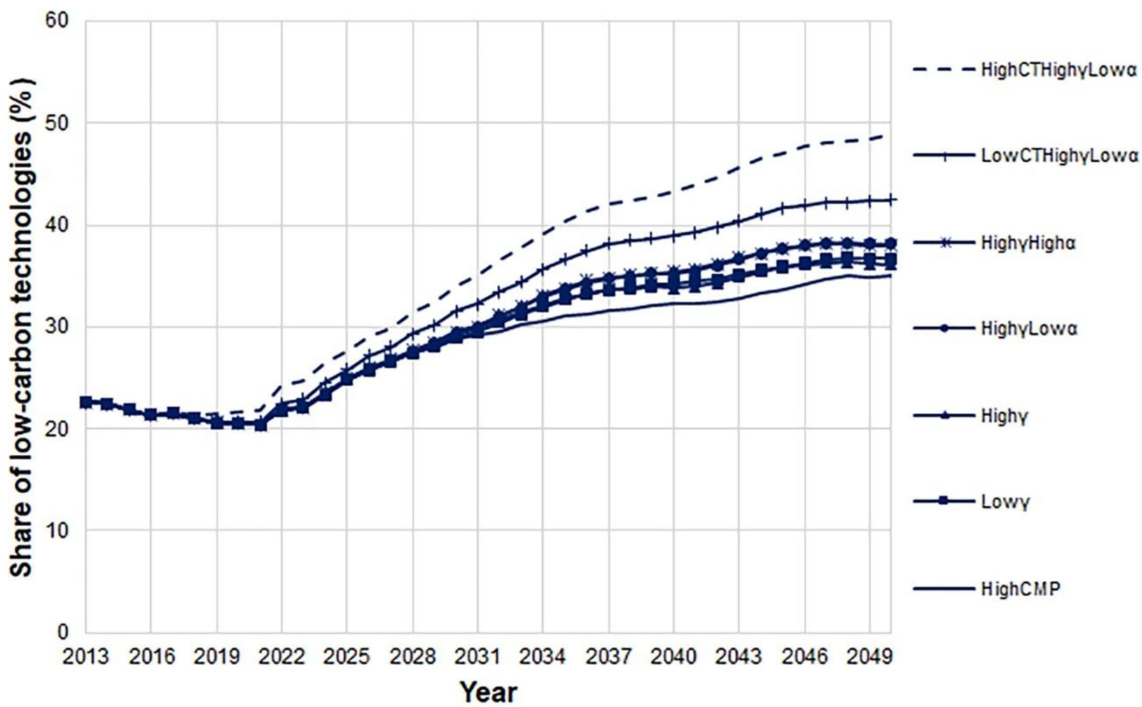

Figure 11. Technology generation shares for the simulation period for scenario set 2.

Figure 12 presents the CO_2 emission trajectories for these scenarios. The results indicate that in order to have an increase in emission reductions, it is necessary to design a mechanism specifically for this purpose. In this case, a higher level of the carbon tax would be beneficial.

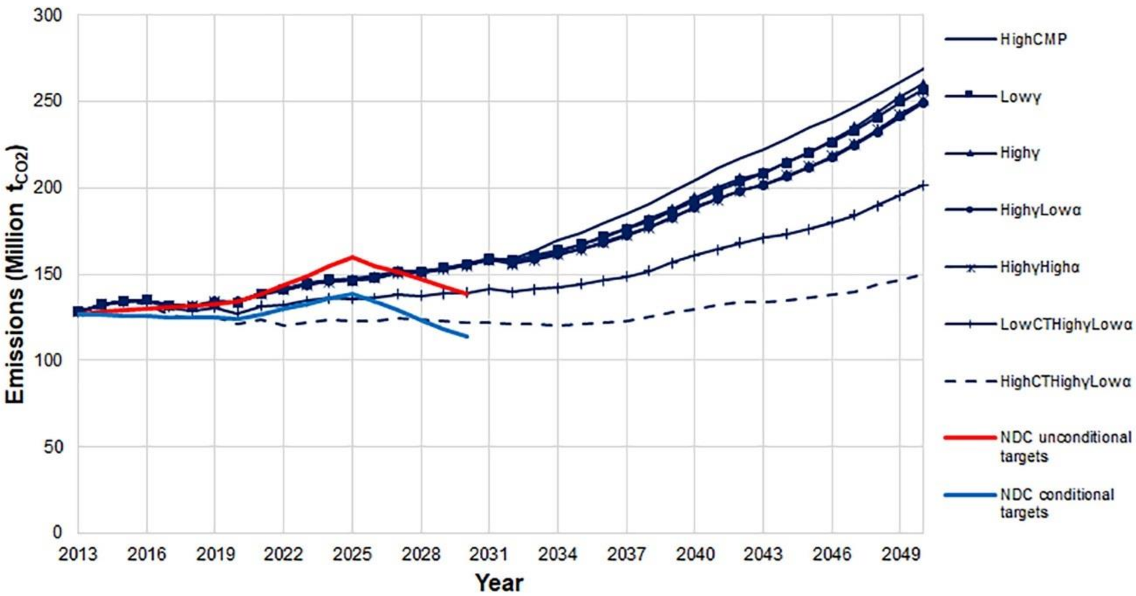

Figure 12. CO_2 emission trajectories for scenario set 2.

5.4 Sensitivity to TGC quotas

As presented in the supplementary materials, the calculated resource potential is similar to renewable energy assessments performed by public and private institutions [58]. However, it is important to mention that in the scenario runs of section 5.2; the estimation of wind resources was a limiting factor. For this reason, additional simulations were ran considering a lower quota that grew by 3.7% every year (almost half the value of the simulations presented above) starting with 5% in 2018. The considered scenarios for the low TGC quota were the HighCMP (high TGC penalty), LowCTHighCMP (low carbon tax and high TGC penalty) and HighCTHighCMP (high carbon tax and high TGC penalty) scenarios of the original simulations. Figure 13 shows the TGC price behaviour for a lower TGC quota. In this case, the TGC market reaches an equilibrium because the simulation runs were not constrained by the wind resource potential limitations. These results can be comparable to those presented in Figure 9, in the sense that the introduction of a carbon tax increased the volatility of TGC prices and lowered their value as the level of the carbon tax was increased.

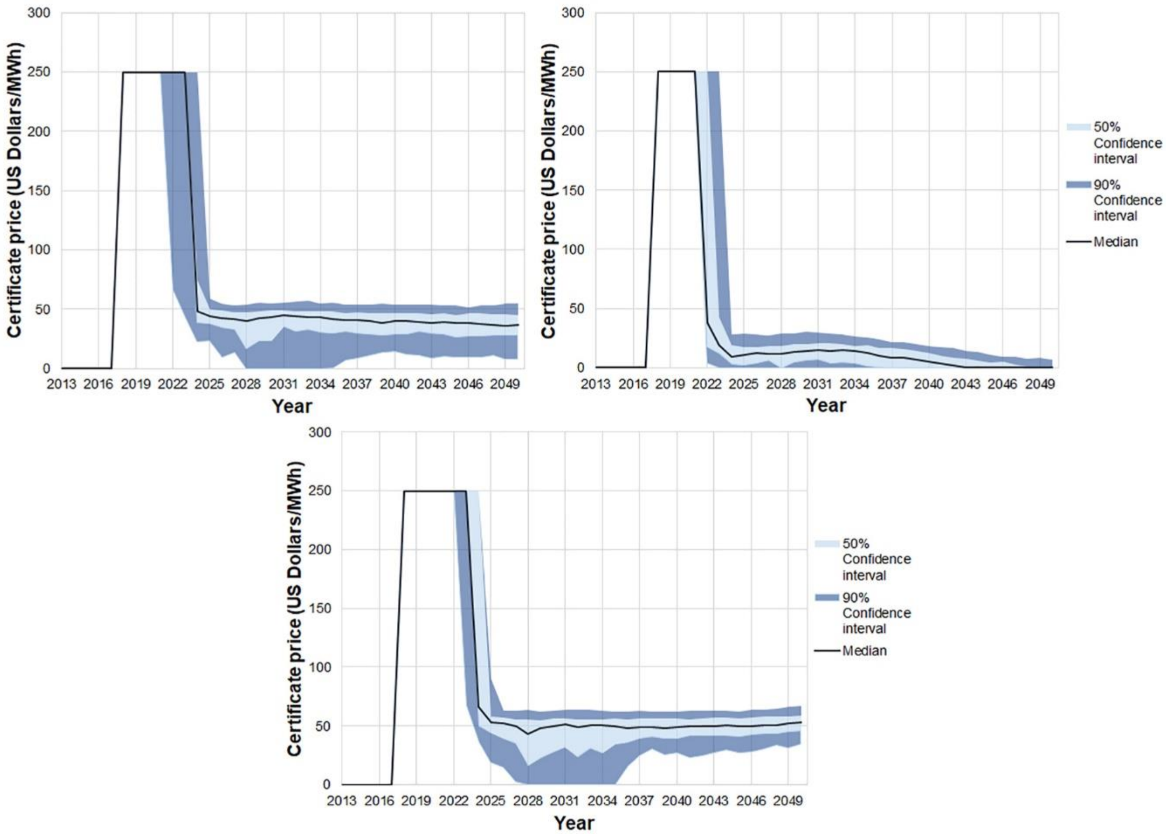

Figure 13. Certificate prices for the HighCMP (bottom), HighCTHighCMP (top right) and LowCTHighCMP (top left) scenarios considering a lower TGC quota.[21]

The sloped certificate penalty function and the dynamic adjustment mechanisms presented in section 5.3 were tested using a lower quota as well. In this case (Figure 14), adding the quota adjustment mechanism (HighγHighα and HighγLowα scenarios) had an impact on TGC price values and trajectories which were similar to those analysed in Figure 10 of section 5.3. This similarity in results was also observed when a low and high value of the carbon tax was considered (scenarios LowCTHighγLowα and HighCTHighγLowα, not shown here because were the same as the bottom right graph of Figure 14) further supporting the importance of the adjusting mechanisms for the TGC market.

[21] The dark blue envelope illustrates the 90% confidence interval while the light blue envelope the 50% confidence interval. The dark blue line represents the median values.

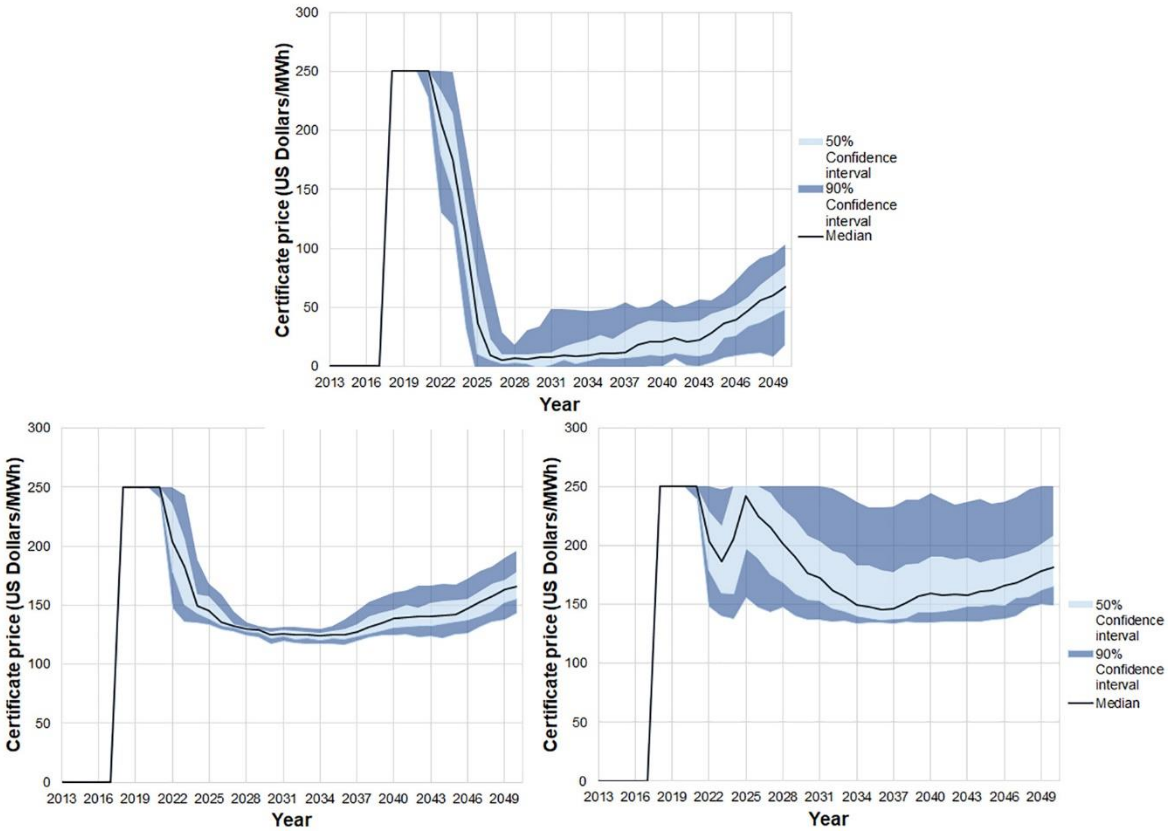

Figure 14. Certificate prices for the High$\boldsymbol{\gamma}$ (top right), High$\boldsymbol{\gamma}$Low$\boldsymbol{\alpha}$ (bottom left) and High$\boldsymbol{\gamma}$High$\boldsymbol{\alpha}$ (bottom right) scenarios considering a lower TGC quota.[22]

5.5 Limitations of the model

One of the main aspects that the implemented TGC market did not consider was certificate banking. The consideration of this aspect for future research could be important in order to improve the representation of the TGC market in Mexico since limited banking is allowed. The trajectory of certificate and electricity prices described here should be considered carefully and only as an indication of their dynamic behaviour, as warned by [6], since other alternatives could help increasing security of supply in the system (particularly the medium-term and long-term energy auctions and capacity markets). Furthermore, the government could relax certificate market rules in order to provide better prices for consumers as documented by [98]. With this regard, TGC prices

[22] The dark blue envelope illustrates the 90% confidence interval while the light blue envelope the 50% confidence interval. The dark blue line represents the median values.

often hit the price cap because of ambitious policy goals relative to the cost-supply curves and potentials estimated for renewable energy sources.

6. Conclusions

The interactions between the low-carbon energy and CO_2 emission reduction policies and its design elements create a complex environment within electricity systems that could lead to undesirable impacts. This work shows that one policy tends to dominate over the other, depending on the level of the carbon tax and the penalty values in the TGC market. With respect to CO_2 emissions, the combination of a high TGC penalty and a high carbon tax did not cause significant additional emission reductions in comparison to only a high value tax and no TGC market. For this reason, a properly defined carbon tax or a well-functioning carbon market should be enough to achieve emission reductions. However, in case of a lower carbon tax, the combination could increase emission reductions. This is the situation in Mexico and a TGC market could aid with achieving emission reductions while carbon-pricing mechanisms mature.

The research showed the competition that exists between the most cost-efficient technologies and the importance of the penalty level in promoting the more expensive low-carbon technologies. Wind energy and hydropower were the main technologies that appeared in the results, but the estimation of natural resources indicated that there is still an unused potential for solar energy (PV) and geothermal.

A sloping penalty function and dynamic quota adjustment mechanism reduced the volatility of certificate prices and had a positive effect on price stability, especially when a TGC market was combined with a carbon tax. The mechanisms helped to introduce a larger amount of low-carbon technologies, promote coal CCS technology and further reduce emissions. The mechanism could maintain a higher certificate price making higher cost technologies attractive for investors.

Mexico is currently implementing a TGC market and is creating an ETS. However, the incorporation of an ETS to existing low-carbon promotion policies is being pursued in other regions and may cover several jurisdictions [99]. From this work, a high and stable carbon price could bring significant CO_2 emission reductions. However, it is suggested that to promote innovative low-carbon technologies, which still require economic support (for instance CCS technology), a high penalty should be introduced in TGC markets as opposed to the current scheme. This value should be coordinated with the levels of the carbon tax or an ETS so that their benefits are optimised. With this regard, the use of a sloped penalty function and dynamic quota adjustment mechanism would help the government to define the required quotas and reduce the volatility in certificate prices, further promoting investment in low-carbon sources and decoupling the negative interactions between instruments.

ACKNOWLEDGEMENTS

M.A.J.-I. gratefully acknowledges the financial support of the National Council for Science and Technology (CONACYT) (Grant number: 359077) and the Mario Molina Center for Strategic Studies in Energy and the Environment (CMM) in Mexico for his PhD scholarship; and St. Catharine's College (University of Cambridge) for the travel grant. The authors acknowledge Dr. Jorge Zavala-Hidalgo for granting access and support to the HPC at the Centre for Atmospheric Sciences of the National Autonomous University of Mexico (UNAM). Two anonymous reviewers are also acknowledged together with Luisa Sierra for proofreading and comments, Dr. Pablo Salas for providing useful suggestions for improving the manuscript and Dr. Pradyumna Bhagwat for his support, comments and discussions during the early stages of this work.

BIBLIOGRAPHY

[1] Rogge KS, Kern F, Howlett M. Conceptual and empirical advances in analyzing policy mixes for energy transitions. Energ Res Soc Sci. 2017; 33: 1 – 10.

[2] Batlle C, Pérez-Arriaga IJ, Zambrano-Barragán P. Regulatory design for RES-E support mechanisms: Learning curves, market structure and burden sharing. Cambridge: MIT Center for Energy and Environmental Policy Research; 2011. CEEPR WP 2011-011.

[3] Pérez de Arce M, Sauma E, Contreras J. Renewable energy policy performance in reducing CO_2 emissions. Energ Econ. 2016; 54: 272 – 280.

[4] De Jonghe C, Delarue E, Belmans R, D'haeseleer W. Interactions between measures for the support of electricity from renewable energy sources and CO_2 mitigation. Energ Policy. 2009; 37 (11): 4743 – 4752.

[5] Fischer C, Preonas L. Combining policies for renewable energy. Is the whole less than the sum of its pats? Washington: Resources for the Future; 2010.

[6] Richstein JC, Chappin EJL, De Vries LJ. Adjusting the CO_2 cap to subsidised RES generation: Can CO_2 prices be decoupled from renewable policy? Appl Energ. 2015; 15: 693 – 702.

[7] Iychettira K, Hakvoort RA, Linares P. Towards a comprehensive policy for electricity from renewable energy: An approach for policy design. Energ Policy. 2017; 106: 169 – 182.

[8] Iychettira K, Hakvoort RA, Linares P, De Jeu R. Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare. Appl Energ. 2017; 187: 228 – 242.

[9] Del Río P, Cerdá E. The missing link: The influence of instruments and design features on the interactions between climate and renewable electricity policies. Energ Res Soc Sci. 2017; 33: 49 – 58.

[10] Del Río P, Mir-Artigues P. Combinations of support instruments for renewable electricity in Europe: A review. Renew Sust Energ Rev. 2014; 40: 287 – 295.

[11] Del Río P. Why does the combination of the European Union Emissions Trading Scheme and a renewable energy target make economic sense? Renew Sust Energ Rev. 2017; 74: 824 – 834.

[12] Duscha V, Del Río P. An economic analysis of the interactions between renewable support and other climate and energy policies. Energ Environ. 2017; 28 (1-2): 11 – 33.

[13] Thurber MC, Davis TL, Wolak FA. Simulating the interaction of a renewable portfolio standard with electricity and carbon markets. Electricity Journal. 2015; 28 (4): 51 – 65.

[14] Shahnazari M, McHugh A, Maybee, B, Whale, J. Overlapping carbon pricing and renewable support schemes under political uncertainty: Global lessons from an Australian study. Appl Energ. 2017; 200: 237 – 248.

[15] Spyridaki N-A, Flamos A. A paper Trail of evaluation approaches to energy and climate policy interactions. Renew Sust Energ Rev. 2014; 40: 1090 – 1107.

[16] Del Río-González P, Klessmann C, Winkel T, Gephart M. Interactions between EU GHG and renewable energy policies – how can they be coordinated? Brussels: Intelligent Energy Europe Programme of the European Union; 2013.

[17] Del Río-González P. The interaction between emissions trading and renewable electricity support schemes. An overview of the literature. Mitig Adapt Strat Gl. 2007; 12 (8): 1363 – 1390.

[18] Morthorst PE. A green certificate market combined with a liberalised power market. Energ Policy. 2003; 31: 1393 – 1402.

[19] Jensen SG, Skytte K. Simultaneous attainment of energy goals by means of green certificates and emission permits. Energ Policy. 2003; 31: 63 – 71.

[20] Böhringer C, Rosendahl KE. Green promotes the dirtiest: on the interactions between black and green quotas in energy markets. J Regul Econ. 2010; 37 (3): 316 – 325.

[21] Böhringer C, Behrens M. Interactions of emission caps and renewable electricity support schemes. J Regul Econ. 2015; 48 (1): 74 – 96.

[22] Böhringer C, Rosendahl KE. Green serves the dirtiest. On the interaction between black and green quotas. Oslo: Statistics Norway, Research Department; 2009. Discussion papers 581.

[23] Lehmann P, Gawel E. Why should support schemes for renewable electricity complement the EU emissions trading scheme? Energ Policy. 2013; 52: 597 – 607.

[24] Del Río-González P. On evaluating success in complex policy mixes: the case of renewable energy support schemes. Policy Sci. 2014; 47 (3): 267 – 287.

[25] Delarue E, Van den Bergh K. Carbon mitigation in the electric power sector under cap-and-trade and renewable policies. Energ Policy. 2016; 92: 34 – 44.

[26] Linares P, Santos FJ, Ventosa M. Coordination of carbon reduction and renewable energy support policies. Clim Policy. 2008; 8 (4): 377 – 394.

[27] Nelson HT. Planning implications from the interactions between renewable energy programs and carbon regulation. J Environ Plann Man. 2008; 51 (4): 581 – 596.

[28] Fagiani R, Richstein J, Hakvoort R, De Vries L. The dynamic impact of carbon reduction and renewable support policies on the electricity sector. Util Policy. 2014; 28: 28 – 41.

[29] Weigt H, Elleman D, Delarue E. CO_2 abatement from renewables in the German electricity sector: Does a CO_2 price help? Energ Econ. 2013; 40: S149 – S158.

[30] Currier KM. Cost reduction incentives in electricity markets with overlapping regulations. Electricity Journal. 2016; 29: 1 – 6.

[31] Currier KM. Incentives for cost reduction and cost padding in electricity markets with overlapping “green” regulations. Util Policy. 2016; 38: 72 – 75.

[32] Flues F, Löschel A, Lutz BJ, Schenker O. Designing an EU energy and climate policy portfolio for 2030: Implications of overlapping regulation under different levels of electricity demand. Energ Policy. 2014; 75: 91 – 99.

[33] Unger T, Ahlgren EO. Impacts of a common green certificate market on electricity and CO_2-emission markets in the Nordic countries. Energ Policy. 2005; 33 (16): 2152 – 2163.

[34] Fais B, Blesl M, Fahl U, Voß A. Analysing the interaction between emission trading and renewable electricity support in TIMES. Clim Policy. 2015; 15 (3): 355 – 373.

[35] Hindsberger M, Nybroe MH, Ravn HF, Schmidt R. Co-existence of electricity, TEP, and TGC markets in the Baltic Sea Region. Energ Policy. 2003; 31 (1): 85 – 96.

[36] Kalkuhl M, Edenhofer O, Lessmann K. Renewable energy subsidies: Second-best policy or fatal aberration for mitigation. Res Ener Econ. 2013; 35: 217 – 234.

[37] Dai H, Xie Y, Liu J, Masui T. Aligning renewable energy targets with carbon emissions trading to achieve China’s INDCs: A general equilibrium assessment. Renew Sust Energ Rev. 2018; 82: 4121 – 4131.

[38] Mittal S, Dai H, Fujimori S, Masui T. Bridging greenhouse gas emissions and renewable energy deployment target: Comparative assessment of China and India. Appl Energ. 2016; 166: 301 – 313.

[39] Diekmann J. EU Emissions Trading: The need for cap adjustment in response to external shocks and unexpected developments? Berlin: German Federal Environment Agency; 2013.

[40] Morthorst PE. The development of a green certificate market. Energ Policy. 2000; 28 (15): 1085 – 1094.

[41] Amundsen ES, Baldursson FM, Mortensen JB. Price volatility and banking in green certificate markets. Environ Resour Econ. 2006; 35 (4): 259 – 287.

[42] Ford A, Vogstad K, Flynn H. Simulating price patterns for tradable green certificates to promote electricity generation from wind. Energ Policy. 2007; 35 (1): 91 – 111.

[43] Schaeffer GJ, Sonnemans J. The influence of banking and borrowing under different penalty regimes in tradable green certificate markets – results from an experimental laboratory experiment. Energ Environ. 2000; 11 (4): 407 – 422.

[44] Khazaei J, Coulon M, Powell WB. ADAPT: A price-stabilizing compliance policy for renewable energy certificates: The case of SREC markets. Oper Res. 2017; 65 (6): 1429 – 1445.

[45] Hobbs BF, Inon JG, Hu M, Stoft SE, Bhavaraju M. A dynamic analysis of a demand curve-based capacity market proposal: The PJM reliability pricing model. IEEE Trans Power Syst. 2006; 22 (1): 3 – 14.

[46] CICC. Estrategia Nacional de Cambio Climático. Visión 10-20-40. Mexico City: Comisión Intersecretarial de Cambio Climático (CICC); 2013.

[47] UNFCCC. 2015. Intended Nationally Determined Contribution. Government of Mexico. Available from: http://www4.unfccc.int/submissions/INDC/Published%20Documents/Mexico/1/MEXICO%20INDC%2003.30.2015.pdf [Accessed 28 June 2016].

[48] DOF. Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética. Mexico City: Diario Oficial de la Federación (DOF); 2013.

[49] DOF. Ley de la Industria Eléctrica. Mexico City: Diario Oficial de la Federación (DOF); 2014.

[50] SENER. Industria eléctrica. 2014. Available from: http://www.energia.gob.mx/webSener/leyes_Secundarias/Ind_elect.html [Accessed 14 August 2014].

[51] Presidencia de la República. Reforma Energética. 2016. Available from: http://www.presidencia.gob.mx/reformaenergetica/#!leyes-secundarias [Accessed 11 May 2016].

[52] Ibarra-Yunez A. Energy reform in Mexico: Imperfect unbundling in the electricity sector Util Policy. 2015; 35: 19 – 27.

[53] Jano-Ito MA, Crawford-Brown D. Socio-technical analysis of the electricity sector of Mexico: Its historical evolution and implications for a transition towards low-carbon development. Renew Sust Energ Rev. 2016; 55: 567 – 590.

[54] Alpizar-Castro I, Rodríguez-Monroy C. Review of Mexico's energy reform in 2013: Background, analysis of the reform and reactions. Renew Sust Energ Rev. 2016; 58: 725 – 736.

[55] DOF. Ley del Impuesto Oficial sobre Producción y Servicios. Mexico City: Diario Oficial de la Federación (DOF); 2013.

[56] SENER. 2017. Certificados de energías limpias. Available from: https://www.gob.mx/cre/acciones-y-programas/certificados-de-energias-limpias-51673 [Accessed 15 June 2018].

[57] DOF. Lineamientos que establecen los criterios para el otorgamiento de Certificados de Energías Limpias y los requisitos para su adquisición. Mexico City: Diario Oficial de la Federación (DOF); 2014.

[58] IRENA Renewable Energy Policy Brief. Mexico. Abu Dhabi: International Renewable Energy Agency (IRENA); 2015.

[59] Bale CSE, Varga L, Foxon TJ. Energy and complexity: New ways forward. Appl Energy. 2015; 138: 150 – 150.

[60] Bunn DW, Oliveira FS. Agent-based simulation – An application to the New Electricity Trading Arrangements of England and Wales. IEEE Trans Evol Comput. 2001; 5 (5): 493 – 503.

[61] Newbery D. The robustness of agent-based models of electricity wholesale markets. Cambridge: Electricity Policy Research Group (EPRG), University of Cambridge; 2012. Working paper 1213.

[62] Young D, Poletti S, Browne O. Can agent-based models forecast spot prices in electricity markets? Evidence from the New Zealand electricity market. Energ Econ. 2014; 45: 419 – 434.

[63] Bhagwat PC, Iychettira K, De Vries LJ. Cross-border effects of capacity mechanisms. In: 11th International Conference on the European Energy Market (EEM); 2014 May 28 – 30; Krakow, Poland; 2014. pp. 1 – 5.

[64] Bhagwat PC, Richstein J, Chappin E, De Vries L. The effectiveness of a strategic reserve in the presence of a high portfolio share of renewable energy sources. Util Policy. 2016; 39: 13 – 28.

[65] Bhagwat, PC, Richstein J, Chappin E, Iychettira K, De Vries L. (2017) Cross-border effects of capacity mechanisms in interconnected power systems. Util Policy. 2017; 46: 33 – 47.

[66] Bhagwat, PC, Marcheselli A, Richstein J, Chappin E, De Vries L. (2017) An analysis of a forward capacity market with long-term contracts. Energ Policy. 2017; 111: 255 – 267.

[67] De Vries LJ, Chappin EJL, Richstein JC. EMLab-Generation. An experimentation environment for electricity policy analysis. Version 1.0, February 2013. Delft: Delft Technische Universiteit Delft (TU Delft); 2013.

[68] CFE. Costos y parámetros de referencia para la formulación de proyectos de inversión en el sector eléctrico 2013. Mexico City: Comisión Federal de Electricidad (CFE); 2013.

[69] Jano-Ito MA, Crawford-Brown D. Investment decisions considering economic, environmental and social factors: An actors' perspective for the electricity sector of Mexico. Energ. 2017; 121: 92 – 106.

[70] Yang M, Blyth W. Modeling investment risks and uncertainties with real options approach. Paris: International Energy Agency (IEA); 2007. Paper Number LTO/2007/WP01.

[71] Yang M, Blyth W, Bradley R, Bunn D, Clarke C, Wilson T. Evaluating the power investment options with uncertainty in climate policy. Energ Econ. 2008; 30 (4): 1933 – 1950.

[72] CFE. Programa de obras e inversiones del sector eléctrico 2014 – 2028. Mexico City: Comisión Federal de Electricidad (CFE); 2014.

[73] CFE. Curvas de duración de carga mensual y anual 2013, Sistema Interconectado Nacional. Mexico City: Comisión Federal de Electricidad (CFE); 2014.

[74] SENER. Prospectiva del Sector Eléctrico 2014 – 2028. Mexico City: Secretaría de Energía (SENER); 2014.

[75] Richstein JC, Chappin EJL, De Vries, LJ. Cross-border electricity market effects due to price caps in an emission trading system: An agent-based approach. Energ Policy. 2014; 71: 139 – 158.

[76] CMM. A low-carbon growth. A potential path for Mexico. Mexico City: Centro Mario Molina para Estudios Estratégicos sobre Energía y Medio Ambiente (CMM); 2008.

[77] Hartley P, Martínez-Chombo E. Electricity demand and supply in Mexico. Houston: Rice University, Baker Institute, Center for Energy Studies; 2003.

[78] CFE. Centrales Generadoras. 2013. Available from: http://www.cfe.gob.mx/ConoceCFE/1_AcercadeCFE/Estadisticas/_layouts/mobile/view.aspx?List=147f7738-221c-48e1-9abe-a20d67dbaa92&View=ca721019-c0d6-4786-b8a6-3766c7b2ad57 [Accessed 7 July 2014].

[79] CFE. Catálogo de centrales generadores 2013. Mexico City: Comisión Federal de Electricidad (CFE). IFAI folio: 1816400235414; 2014.

[80] Gillenwater M, Lu X, Fischlein M. Additionality of investments in the U.S. voluntary green power market. Renew Energ. 2014; 63: 452 – 457.

[81] SHCP. Tasa social de descuento (TSD). 2014. Available from: http://www.gob.mx/shcp/documentos/tasa-social-de-descuento-tsd [Accessed 5 July 2016].

[82] Mercure JF. FTT:Power: A global model of the power sector with induced technological change and natural resource depletion. Energ Policy. 2012: 48: 799 – 811.

[83] Held A. Modelling the future development of renewable energy technologies in the European electricity sector using agent-based simulation. Karlsruhe: University of Karlsruhe, PhD Thesis; 2011.

[84] Mercure JF, Salas P. An assessment of global energy resource economic potentials. Energ. 2012; 46 (1): 322 – 336.

[85] Iychettira K. Orchestrating investment in an evolving power sector: An analysis of capacity markets. Delft: Technische Universiteit Delft (TU Delft), MSc Thesis; 2013.

[86] Vogstad K. A system dynamics analysis of the Nordic electricity market: The transition from fossil fuelled toward a renewable supply within a liberalised electricity market. Trodheim: Norges Teknisk-Naturvitenskapelige Universitet (NTNU), PhD. Thesis; 2005.

[87] Octaviano C, Paltsev S, Gurgel CA. Climate change policy in Brazil and Mexico: Results from the MIT EPPA model. Energ Econ. 2016; 56: 600 – 614.

[88] Van der Zwaan BCC, Calvin KV, Clarke LE. Climate mitigation in Latin America: Implications for energy and land use: Preface to the special section on the findings of the CLIMACAP-LAMP project. Energ Econ. 2016; 56: 495 – 498.

[89] Veysey J, Octaviano C, Calvin K, Herreras-Martínez S, Kitous A, McFarland J, Van der Zwaan B. Pathways to Mexico's climate change mitigation targets: A multi-model analysis. Energ Econ. 2016; 56: 587 – 599.

[90] Lacy R. Compromisos de mitigación y adaptación ante el cambio climático 2020 – 2030. Instrumentación. In: México – Unión Europea. Hacia un acuerdo global sobre cambio climático; 2015 June 17; Mexico City, Mexico; 2015.

[91] Öko-Institut e.V. Designing an emissions trading system in Mexico: Options for setting an emissions cap. Mexico: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

[92] IEA. Energy prices and taxes. Quarterly statistics, first quarter 2016. Paris: International Energy Agency (IEA); 2016.

[93] SENER. Programa de desarrollo del Sistema Eléctrico Nacional (PRODESEN) 2016 - 2030. Mexico City: Secretaría de Energía (SENER); 2016.

[94] Heeter J, Barbose G, Bird L, Weaver S, Flores-Espino F, Kuskova-Burns K, Wiser R. A survey of state-level cost and benefit estimates of renewable portfolio standards. Denver and Berkeley: National Renewable Energy Laboratory (NREL) and Lawrence Berkeley National Laboratory (LBNL); Technical report NREL/TP-6A20-61042, LBNL-6589E; 2014.

[95] Coulon M, Khazaei J, Powell WB. SMART-REC: A stochastic model of the New Jersey solar renewable energy certificate market. J Environ Econ Manag. 2015; 73: 13 – 31.

[96] Pollitt M, Anaya K. Can current electricity markets cope with high shares of renewables? A comparison of approaches in Germany, the UK and the State of New York. Cambridge: Energy Policy Research Group (EPRG), University of Cambridge. Working Paper 1519; 2015.

[97] Reforma. Advierten presión a ley energética. 2016. Available from: http://www.reforma.com/aplicacioneslibre/preacceso/articulo/default.aspx?id=707374&urlredirect=http://www.reforma.com/aplicaciones/articulo/default.aspx?id=707374 [Accessed 16 May 2016].

[98] Reforma. Evitarían escasez de energías limpias. 2016. Available from: http://www.reforma.com/aplicacioneslibre/articulo/default.aspx?id=808040&md5=14ff97f6b86c8915717445940f603acf&ta=0dfdbac11765226904c16cb9ad1b2efe&po=4 [Accessed 1 June 2016].

[99] SEMARNAT. Líderes de las Américas se comprometen a cooperación regonal en torno a fijación de precios al carbono. 2017. Available from: https://www.gob.mx/semarnat/prensa/lideres-de-las-americas-se-comprometen-a-cooperacion-regional-en-torno-a-fijacion-de-precios-al-carbono [Accessed 15 January 2018].

SUPPLEMENTARY MATERIALS

Renewable cost-supply curves

Renewable resource cost-supply curves were calculated using the work and assumptions of [1-4]. The following subsections present a description of the methodology and data assumptions used to define the curves. In this case, as an additional feature, and in order to emphasise the regional nature of resources, cost-supply curves for the northern and southern interconnected systems were estimated and are presented as well.

Wind energy

The potential and cost-supply curve for wind was defined using the approach from [1, 2]. While renewable energy sources may provide almost unlimited energy, the quality of the resource depends on the characteristics of the location of the power plants. This fact is acknowledged by the methodology originally derived by [1] and focuses on the land use characteristics and quality of the resources. In this case, wind speed data (annual average and at 50 m) was taken from [5] for 1° by 1° geographical coordinate grids. The initial calculation of the geographical potential involved the use of land use data, which was taken from [6]. This database provided land use information for 0.08333° grids. The land use data in these grids was translated to percentage coverage and to 1° grids. The classification of land used types was adjusted to the classification defined by [1].[23] The land use data corresponded to the year 2000, which was used to have consistency with the data source (NASA) of the wind speed information. In [1], the first step is the calculation of the usable land and the equation used for this purpose is:

$$UA_{g,a} = f_a A_{g,a} \tag{A.1}$$

In the previous equation, $UA_{g,a}$ indicates the usable land of type a for grid g, f_a the feasibility factor and $A_{g,a}$ the area for every grid and land use type. The calculation of the feasibility factor included the consideration of the elevation of the grid. The elevation data was obtained from [7]. The usable area calculated using equation A.1 was 117,321 km^2. This value was approximately half the value of suitable land area estimated by the government, which is 233,750 km^2 [8]. It is important to mention that the government defines the potential of renewable resources in terms

[23] In [1], bio-reserve areas were defined as remote rangeland settlements in [6]; agricultural areas as villages and croplands; urban areas as urban and mixed settlements; shrubland and grassland as residential rangeland and woodlands; extensive grassland and desert as populated rangeland, inhabited treeless and barren lands and woodlands.

of possible, probable and proven [9].[24] For probable resources, the government estimated that 10% of the usable land would be adequate for wind power generation and because of this, this factor was used in the calculation of the available area in this paper (11,732 km^2). The 10% also corresponds to the definition of [10] for real available resources where the suitable land area for onshore wind is multiplied by a factor between 0.5% and 20% depending on the type of land and for low, medium and high estimates ($AF_{g,a}$, in equation A.2). The technical potential $E_{g,a}$ is calculated by the following equation.

$$E_{g,a} = UA_{g,a} AF_{g,a} \eta_{av} \eta_{ar} Pd\, flh_g \tag{A.2}$$

In equation A.2, η_{av} is the availability of the wind turbines, η_{ar} the efficiency of the turbine arrangement, Pd the power density and flh_g the full-load hours. The calculation of the full-load hours for each grid was conducted using the equation for the capacity factor presented by [11] using the average annual wind speed in the cells. The wind speed data was adjusted to an average hub height of 80 m using the roughness factors and the equation proposed by [12] and used by [1], where V_H is the speed at height H, V_{50} the wind speed at 50 m and z_0, the roughness factor.

$$V_H = V_{50} \left(\frac{ln\left(\frac{H}{z_0}\right)}{ln\left(\frac{50}{z_0}\right)} \right) \tag{A.3}$$

The obtained values for capacity factors were around 20%, and as in [1], a value of 4 MW per m^2 was assumed for the power density while η_{av} and η_{ar} were set to 0.95 and 0.90, respectively. The calculation of costs (LCOE)[25] per grid g and land type a, was performed using the following equation.

$$LCOE_{h,g,a} = \frac{\sum_{t=0}^{t_c} \frac{I_h/(1+t_c)}{(1+wacc)^t} + \sum_{t=t_{c+1}}^{t_c+t_d} \frac{FOM_{h,t}+CL}{(1+wacc)^t}}{\sum_{t=t_{c+1}}^{t_c+t_d} \frac{E_{g,a}}{(1+wacc)^t}} \tag{A.4}$$

[24] The government defines possible resources as the theoretical potential; probable resources as those that have been subject of studies but do not incorporate economic or technical considerations; and proven resources as those that are supported by engineering and economic studies [9].

[25] 2013 US Dollars.

Equation A.4, is the same as equation 3, but in $LCOE_{h,g,a}$, h refers to renewable energy sources only and the variable cost is assumed to be zero. In this equation CL is the cost of renting land. The technical and economic information was the same as presented in section 3.1.2 and the renting cost of land was set to 125 US Dollars per hectare [13, 14]. In the case of fixed investment costs, they were adjusted on the basis of the scale of the wind project cost using the equation proposed by [1] where the reference costs corresponded to 1,538 US Dollars per kW and 100 MW of installed capacity using a power factor of -0.3. Equation A.4, was used by considering the $wacc$ of the public companies and the private ones which were discussed in section 3.1.4. The total estimated potential for wind energy was 46,928 MW of installed capacity and 70 TWh per year. Estimates of wind energy potential for other sources in the literature, suggest a potential of more than 50,000 MW, including the government estimate of 71,000 MW for possible resources [8, 15]. The following graph (Figure A1) presents the cost-supply curve estimated from the previously described methodology for the Mexican system and containing the curves for the northern and southern interconnected systems. The graph presents the cumulative energy potential and costs arranged in an ascending order for the public companies (the shape in the case of the private companies was the same, but with slightly lower costs as a consequence of the $wacc$).

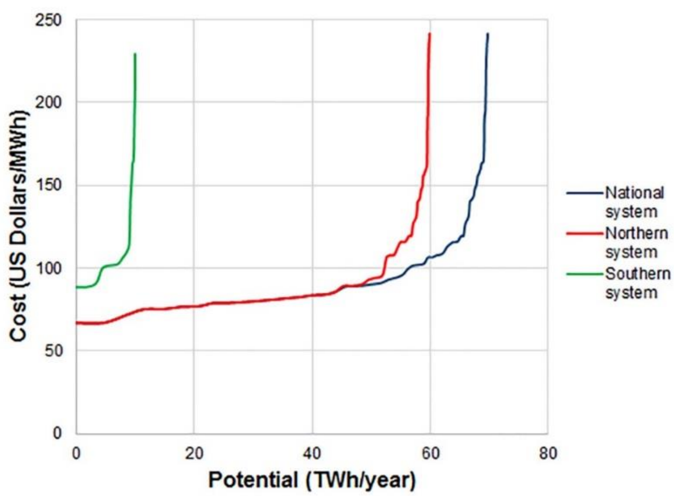

Figure A1. Cost-supply curves for wind power in Mexico.

Solar photovoltaic energy

The procedure to calculate the potential for solar photovoltaic energy was similar to the methodology described in the previous section for wind. In this case, the potential calculation only considered centralised generation systems connected to the grid. The data for horizontal radiation was taken from [5], whereas the data for land use was the same as in the case of wind. Equations A.1 and A.4 were used while in the case of the energy estimation, equation A.5 was employed to calculate the technical potential, which in this case is a function of the usable land, $UA_{g,a}$, the available resource factor, $AF_{g,a}$, the conversion efficiency, η_m, and the performance ratio of the photovoltaic module, pr [1]:

$$E_{g,a} = UA_{g,a}\, AF_{g,a} \eta_m\, pr$$

(A.5)

The assumed values for η_m and pr were 0.105 and 0.75, respectively as suggested by [1]. As in the case of wind energy, the suitable area was adjusted using the factors proposed by [10].[26] The reference cost and capacity was also taken from Table A2. The estimated potential for centralised solar PV systems was 248 TWh per year. It has to be noted that this value assumed that the entire suitable area was covered with solar panels. This value is within estimates from the government that go from 66 TWh per year to 6,500 TWh per year [8, 16]. This value may by highly optimistic, but it was used for the model since there are no other estimates for probable resources conducted by the government. Figure A2 presents the cost-supply curve for the public companies and solar PV energy in Mexico.

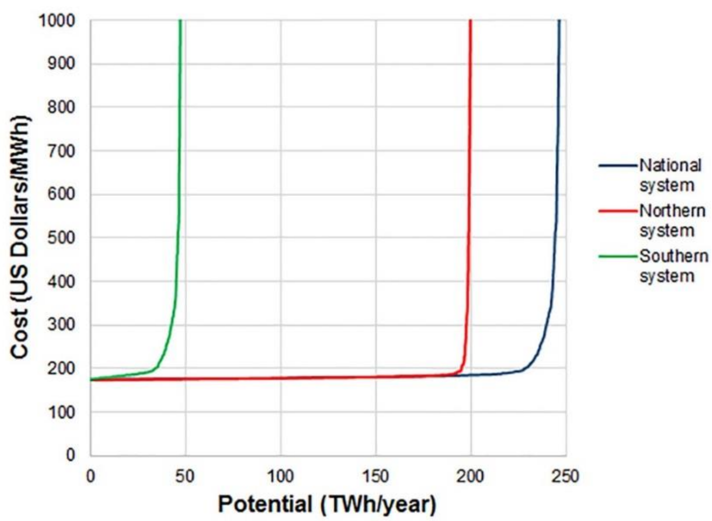

Figure A2. Cost-supply curve for solar PV energy in Mexico.

Geothermal energy

The cost-supply curves for geothermal energy were determined using the existing potential estimates from the government for possible hydrothermal resources and was combined with the

[26] Medium estimate: 0.5% for agricultural land, 1% for savannah and tundra, and 5% for extensive grassland and desert.

technical and economic data from Table A2. In this case, the cost function (equation A.4) did not include the cost for renting land but the costs for drilling and operation of the geothermal field were added. The probable geothermal resources taken from the most recent government estimates were 5,730 MW of installed capacity and 45.2 TWh per year of generation [17]. The following graph (Figure A3) presents the cost-supply curve for geothermal energy and the public companies.

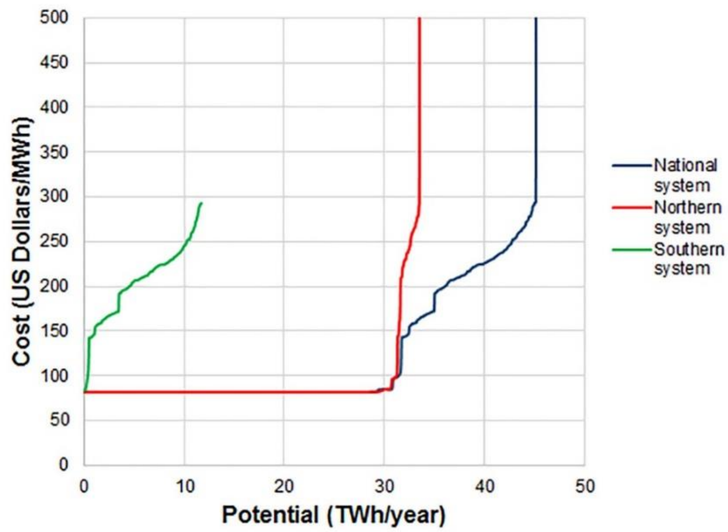

Figure A3. Cost-supply curve for geothermal energy in Mexico.

Hydropower

For the case of the potential of hydro energy resources, the same procedure as for geothermal energy potential was applied. As highlighted by [4], the cost of using water resources highly varies depending on their location. In the calculation of the cost-supply curves, the potentials for mini and large hydropower projects were combined. The estimated total potentials for hydropower, as estimated by the government were 9,243 MW of installed capacity and 39 TWh per year [17]. Figure A4 presents the cost-supply curve for this natural resource and the public companies.

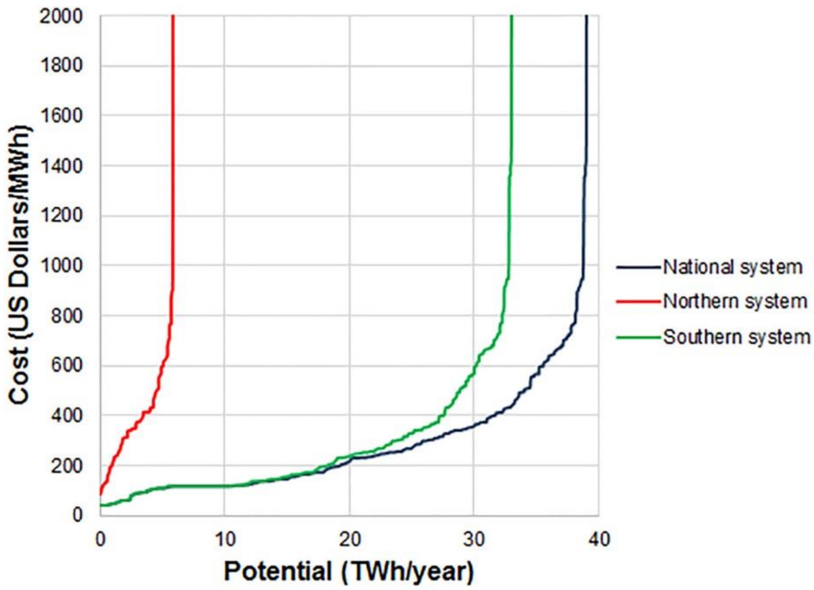

Figure A4. Cost-supply curve for hydropower in Mexico.

Determination of cost-supply curve functions

As presented in 3.1.5, the results from the geographical analysis were used to adjust the resource distribution equations, using least-squares non-linear fits. Equations A.6 and A.7 present the LCOE for technology h (only of the renewable energy sources) as a function of the usage of renewable energy resources N_{Ren}, the total energy potential, TP, the scaling factor, SF, and the cost off set, C_0. In equation A.7, $inverf$ is the inverse error function. Table A1 presents the obtained parameters for equations A.6 and A.7 for public and private actors.

$$LCOE_h = \frac{-SF}{ln\left(\frac{N_{Ren}}{TP}\right)} + C_0 \tag{A.6}$$

$$LCOE_h = \sqrt{2}SF\ inverf\left(\frac{N_{Ren}}{TP}\right) + C_0 \tag{A.7}$$

Table A1. Parameters for cost-supply curves.

	Public companies			Private companies		
Resource	TP (TWh)	SF (US Dollars/ MWh)	C_0 (US Dollars/ MWh)	TP (TWh)	SF (US Dollars/ MWh)	C_0 (US Dollars/M Wh)
Wind (National interconnected system)	77.973	11.512	67.286	81.072	10.251	58.661
Solar PV (National interconnected system)	243.527	8.951	173.099	243.705	7.772	143.082
Geothermal (National interconnected system)	31.179 12.716	0.020 130.043	81.589 105.639	31.179 13.165	0.017 116.329	75.432 96.049
Hydro (National interconnected system)	58.661	129.934	43.917	44.680	101.704	34.425

For wind energy, Figure A5 presents the obtained cost-supply curves for public companies and the fitted curves. The fitting follows the resource classification proposed by [4] for wind with a hierarchical resource distribution. While the work of [4] included uncertainty in resource estimations, this work considered deterministic curves, in order to simplify the calculations in the model and because the agents in the model perform deterministic calculations of the LCOE. The hierarchical distribution of resources is characterised by the dispersed nature and a defined ordering of this resource. It is important to highlight that from the analysed grids, the main zones that had a higher potential were those located in the northern part of the country, near the Gulf of Mexico, and on the opposite site, next to the Pacific Ocean. Additionally, the state of Veracruz and the Yucatán Peninsula were other sites that showed high potential. In the special case of the state of Oaxaca in southern Mexico, where important wind resources have already been exploited, did not appear in the calculations. The reason for the latter is based on the high regional aggregation of the data, which used averages of 32 km by 32 km grid cells and not point data, ignoring the spatial variability of wind speed, which takes place in small spatial scales [18]. However, the main sites that have been highlighted with wind potential appeared in the calculations and were considered adequate, given the regional resolution of the ABM model.

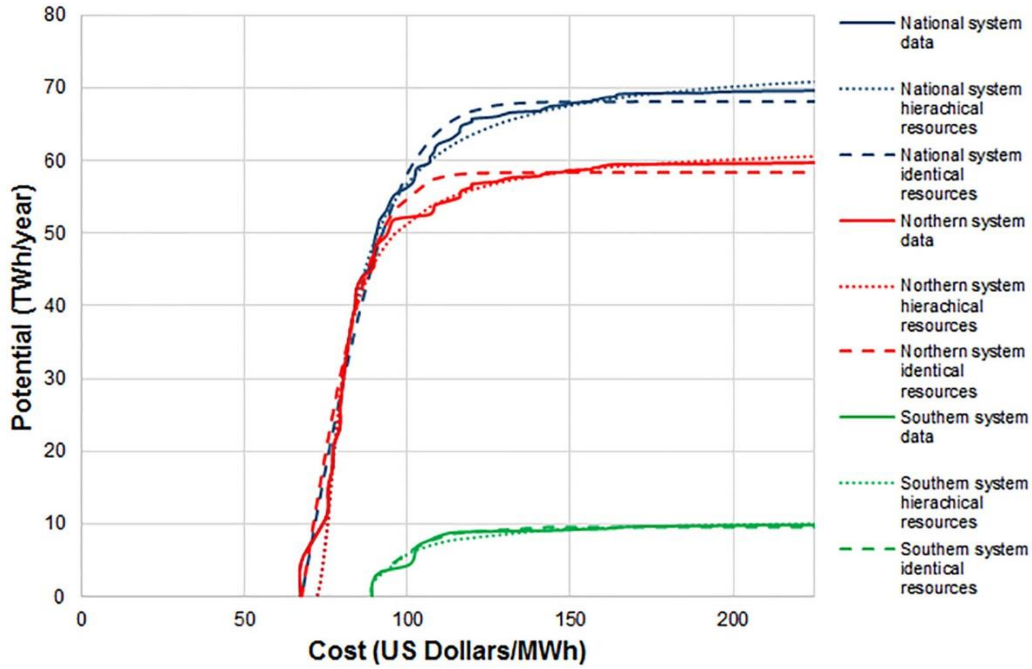

Figure A5. Original and fitted cost-supply curves for wind energy.

The case of solar PV presented in Figure A6 in general followed the classification of [8], with a nearly identical resource distribution. However, in the case of solar resources in the southern system, the adjusted curve had a better fit for a hierarchical type of resource distribution. The quantification of resource potentials as shown in the previous sections is dependent on land use characteristics and the resources existing in that location. In the northern system, which is dominated by arid zones with high solar radiation, costs remain constant as the resources are used until approximately 200 TWh per year when there is a drastic change. The southern system presented a different trend based on the variable characteristics of land and radiation that increase costs as the places with the better potentials are occupied.

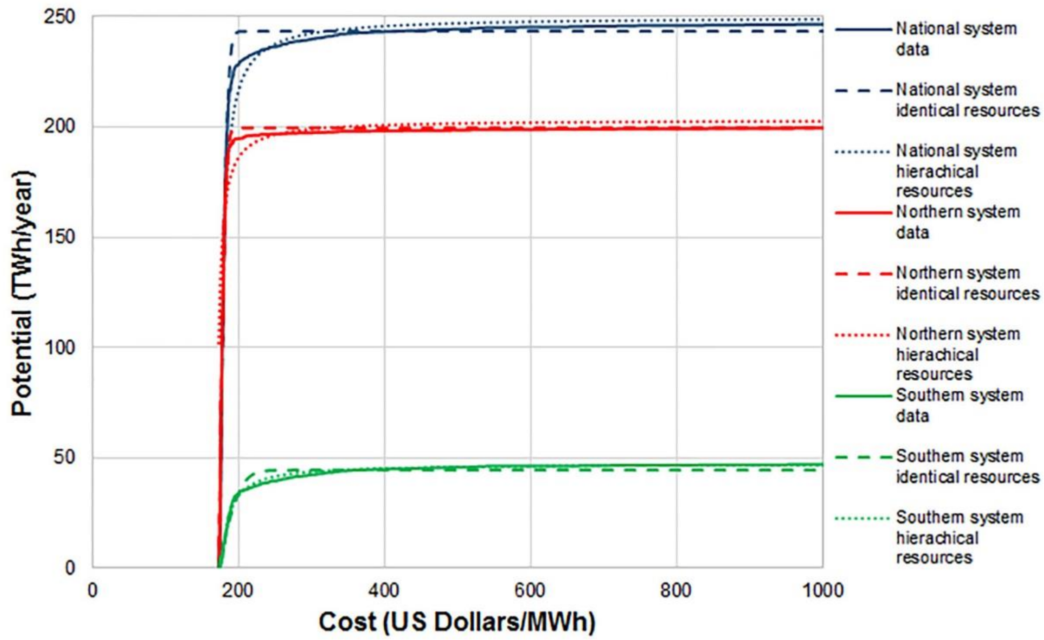

Figure A6. Original and fitted cost-supply curves for solar PV.

The adjusted cost-supply curves for geothermal energy considered two separate curves and distributions for the national and northern systems as observed in Figure A7. The central zone of Mexico presents an important volcanic activity concentrating high temperature hydrothermal resources [19]. In accordance to this, the adjusted data followed the classification from [8] in which high temperature resources are assumed to behave as a hierarchical distribution, whereas low volcanic areas follow a nearly identical distribution. For the national system, the initial part of the curve (from 0 to approximately 31 TWh) the curve was assumed as hierarchical, whereas the subsequent part of the curve as identical. The same case was found for the northern interconnected system.

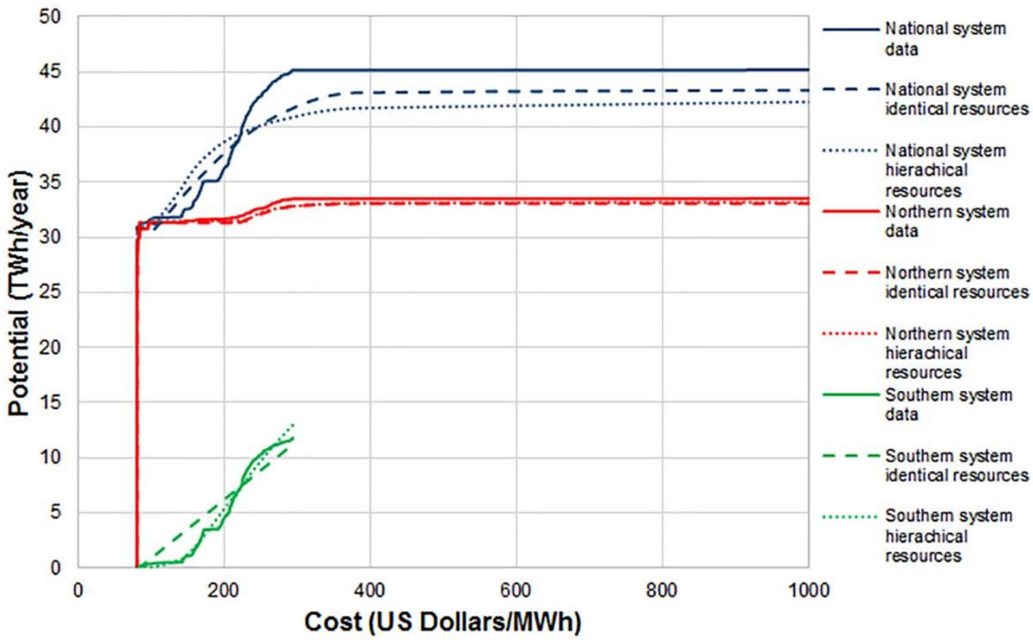

Figure A7. Original and fitted cost-supply curves for geothermal energy.

The adjusted cost-supply curves for hydropower, resembled the classification of [8], and as observed in Figure A8, the increase of costs is higher with a smaller increase in the use of this resource. Although the development of hydropower projects was significant during the 20th century, there are still water resources that can be used but as the remaining places with the highest potential are used, costs increase rapidly.

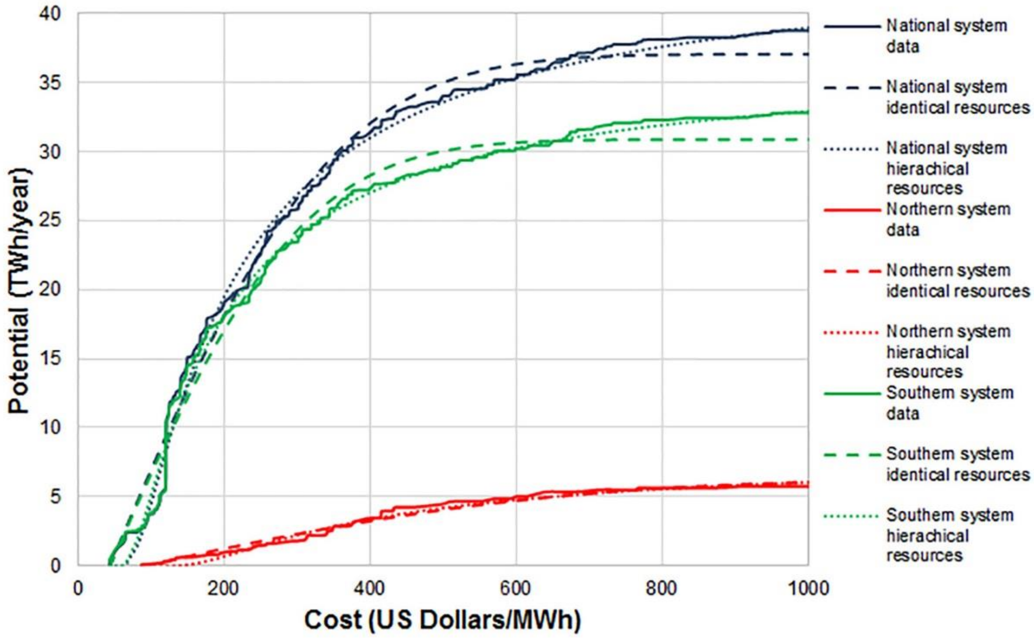

Figure A8. Original and fitted cost-supply curves for hydropower.

ABM model parameters

The following tables and figures contain a more detailed information of the information that was introduced to the ABM of the electricity sector of Mexico. Table A2 presents the engineering and economic data used in the ABM while Table A3 presents the data introduced to the model. Table A4 presents technology portfolios for agents. Figure A9, Figure A10, Figure A11, Figure A12, Figure A13 and Figure A14 present the demand and fuel price trajectories with the 50% and 90% confidence interval envelopes and the median values.

Table A2. Economic and engineering information for energy technologies.

	Fuel oil	NGT	NGCC	Coal	Wind	Geothermal	Hydro	Nuclear	Solar thermal with NGCC	Solar PV	IGCC[27] Coal CCS	IGCC Petcoke CCS	Coal with CCS	FBC[28]
Investment cost (US Dollars/kW)[29]	1,190	507	730	1,676	1,538	1,598	1,502	3,475	845	2,153	2,842	2,909	2,592	1,623
Gross generation capacity (MW)	350	275	814	350	100	27	375	1400	298	60	709	644	700	350
Operation and maintenance costs (US Dollars/MWh)	6.49	9.45	4.85	8.86	8.52	10.70	23.83	14.47	5.45	11.99	20.29	20.29	16.34	7.68
Capacity factors	0.75	0.13	0.80	0.80	0.40	0.85	0.16	0.90	0.78	0.20	0.70	0.70	0.80	0.80
Economic life (years)	30	30	30	30	25	30	50	60	30	25	30	30	30	30
Heat rate (kJ/kWh)	9,431	10,166	6,907	9,506	----	20,949	----	10,732	7,186	----	13,224	11,184	13,224	13,224

[27] Integrated gasification combined cycle (IGCC).
[28] Fluidised bed combustion (FBC).
[29] The source of information for this part was [13].

Table A3. Technical information introduced to the ABM model.

Technology	Capacity (MW)	Construction time (years)	Permit time (years)	Technical lifetime (years)	Depreciation time (years)	CO_2 capture efficiency (%)	Minimum running hours (h)	Base availability	Peak availability
Fuel oil	700	4	1	40	20	-----	5000	1.00	1.00
Diesel	250	4	1	40	20	-----	5000	1.00	1.00
Coal	700	4	1	40	20	-----	5000	1.00	1.00
Supercritical Coal	700	4	1	40	20	-----	5000	1.00	1.00
NGT	275	2	1	40	15	-----	5000	1.00	1.00
NGCC	814	2	1	40	15	-----	5000	1.00	1.00
Nuclear	1400	8	2	60	25	-----	0	1.00	1.00
Hydro	750	5	2	50	25	-----	0	0.00	0.80
Geothermal	250	3	1	25	15	-----	0	1.00	0.00
Wind	600	1	1	20	15	-----	0	0.40	0.05
Solar PV	150	1	1	25	15	-----	0	0.20	0.04
Coal with CCS	700	5	1	40	20	90	0	0.60	0.60

Table A4. Portfolio of technologies by agents considered in the ABM model.

Technology	Agent A	Agent B	Agent C	Agent D	Agent E	Agent F	Agent G	Agent H	Agent I	Agent J	Agent K	Agent L
Fuel oil	1.0	0.0	1.0	1.0	0.0	1.0	0.0	0.0	0.0	1.0	1.0	1.0
Diesel	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0
Coal	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	1.0	1.0
Supercritical Coal	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
NGT	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NGCC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	1.0	1.0	1.0
Nuclear	1.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0
Geothermal	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	0.0	0.0	0.0
Solar PV	1.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	0.0
Coal with CCS	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0

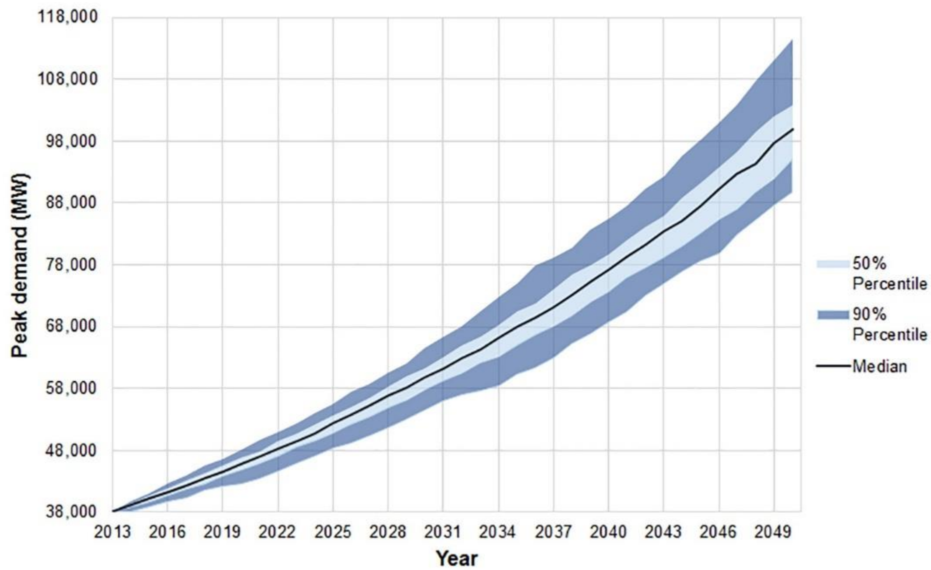

Figure A9. Demand trajectory used in the ABM model.

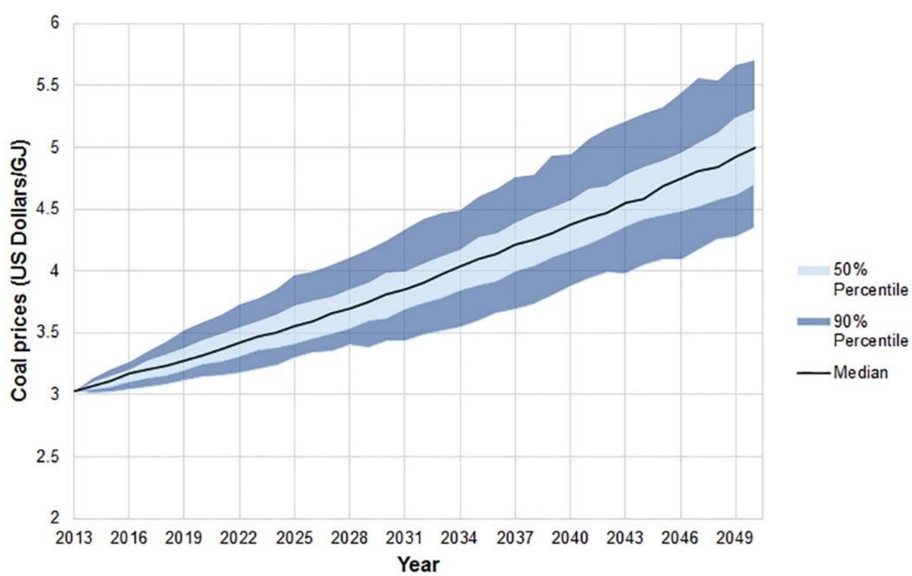

Figure A10. Coal price trajectories in the ABM model.

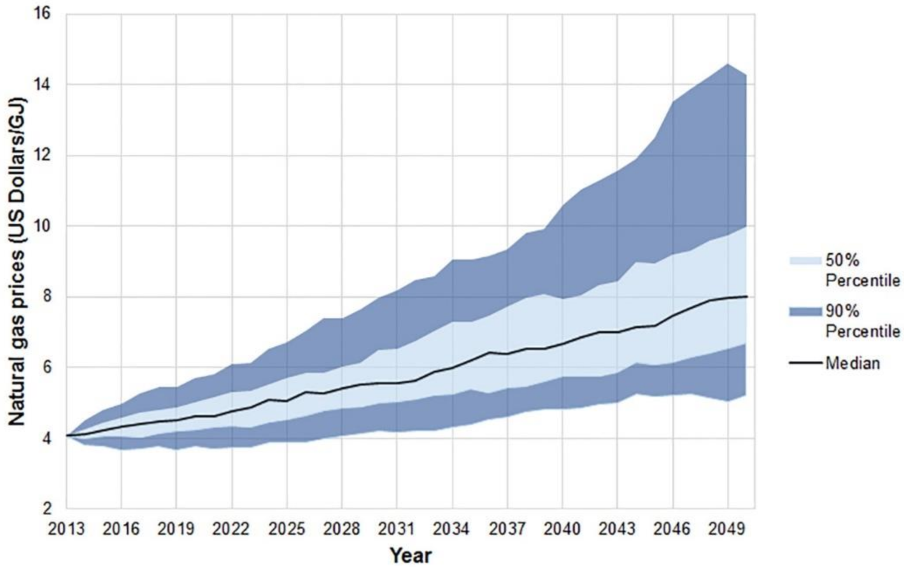

Figure A11. Natural gas price trajectories in the ABM model.

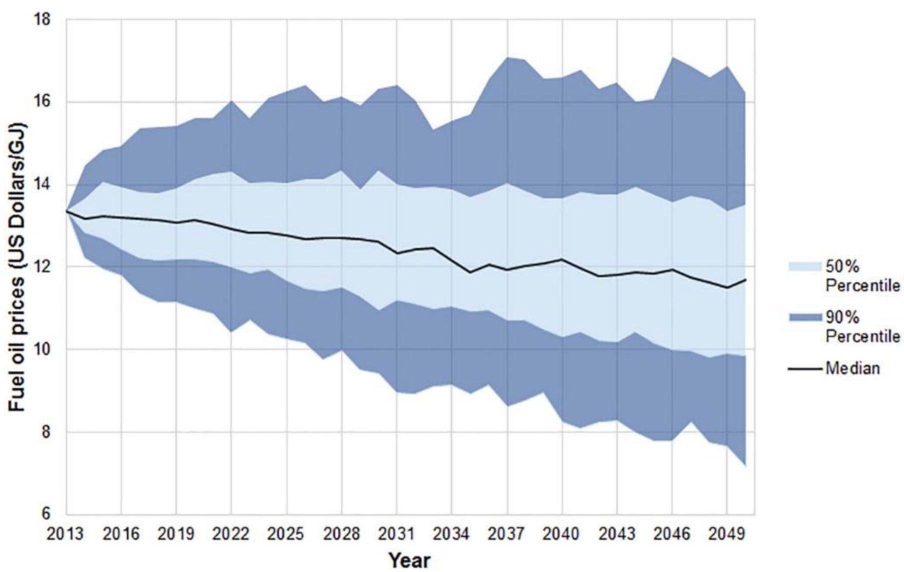

Figure A12. Fuel oil price trajectories in the ABM model.

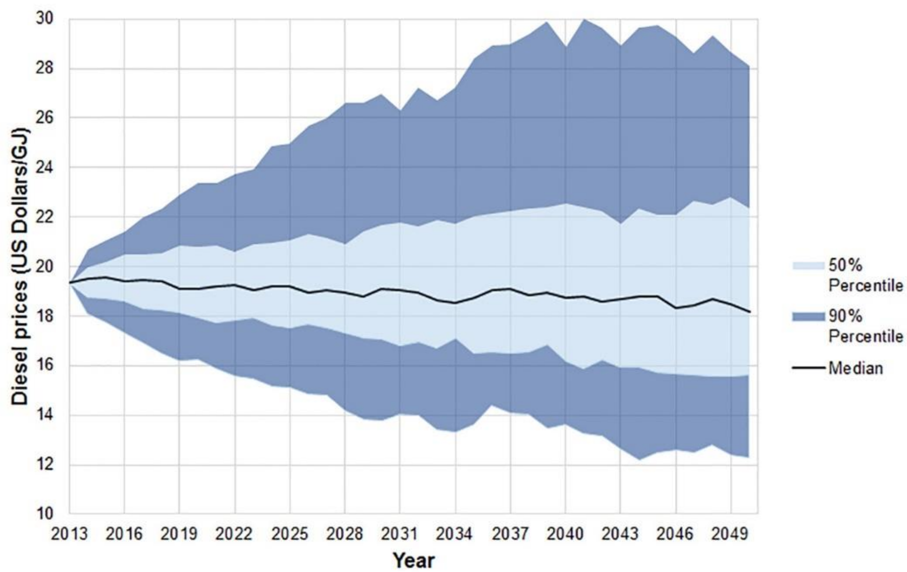

Figure A13. Diesel price trajectories in the ABM model.

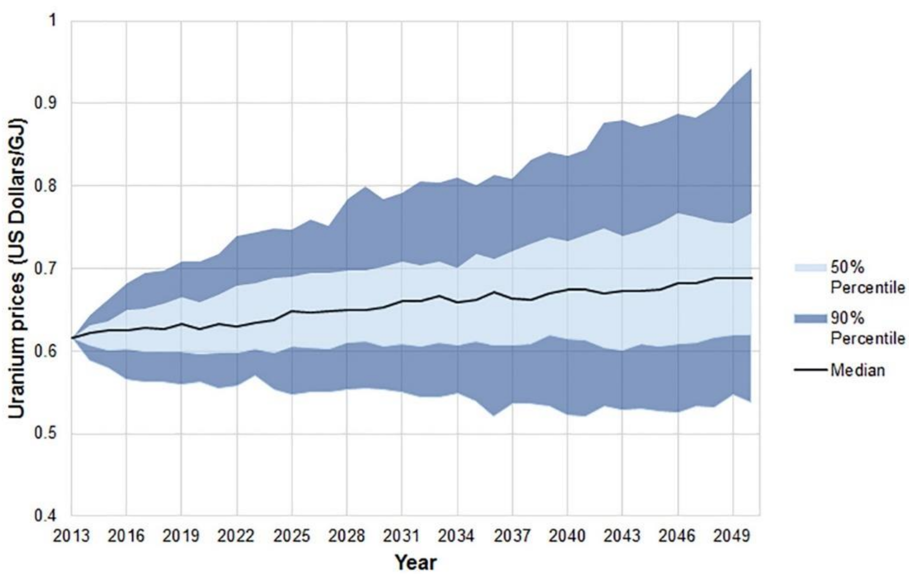

Figure A14. Uranium price trajectories in the ABM model.

Implementation of the ABM model

The narrative presented in the paper corresponds to a conceptual and theoretical description of the model. In this section, the main features that were added to the original model will be shown in terms of its technical structure. The structure of the ABM tool relies on Java classes that have different functions and properties. In basic terms, the model is mainly supported on three classes. Domain classes represent objects (agents) that have properties and can be linked to each other. Agent behaviour is not included in Domain classes but in Role classes. These classes can be executed by the agents. The data, parameters and the information needed for running the simulations are included in Scenario classes [20]. In order to implement the certificates market, several Domain and Role classes were added and modified in EMLab-Generation. In general, three Domain classes were added in order to establish the properties of the certificates market, the dispatch plan of the certificates and the certificates market clearing point, with two Role classes that correspond to the bidding of certificate prices and quantities by generators and the clearing of the market. Additionally, the Domain and Role classes for the national government and the generators were modified so that in the case of the first, the demand for certificates and the quota could be determined, and generators could bid certificate prices and volumes, and consider this in the evaluation of their investment alternatives. Finally, a main Role class was added so that the actions for the certificates market are performed and an option was added to the main model role (the class that coordinates all the actions in a simulation year) to turn on and off the certificates market.

Figure A15 presents a diagram that summarises the latter. In the diagram, the blue lines indicate the relationship between classes while the red lines indicate the Role classes that the main certificates market class role incorporated. The boxes contain general information regarding the classes. The main Role classes and their algorithms are described below.

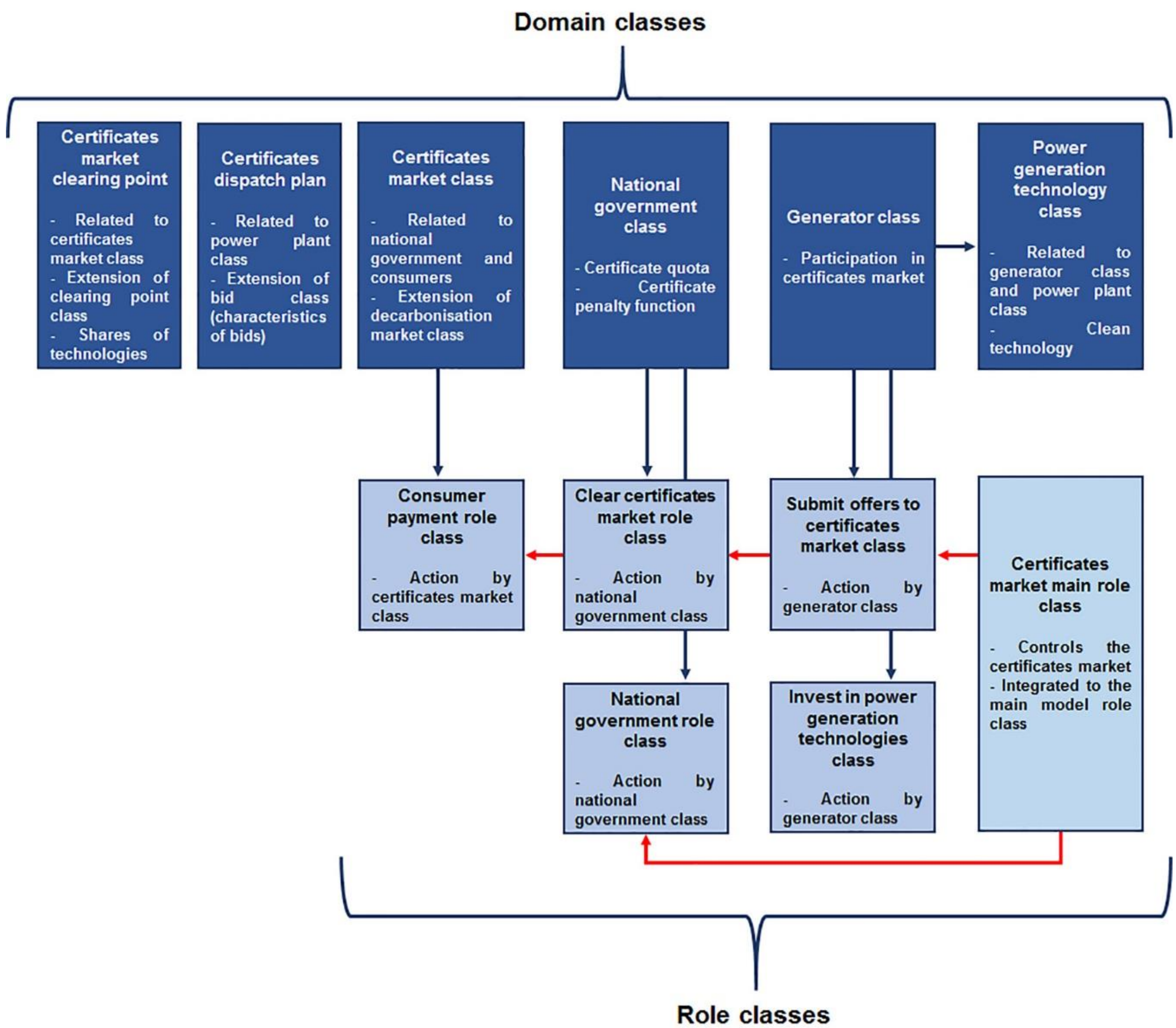

Figure A15. Summary of the main classes modified and implemented for the certificates market.

Generator actions

With the implementation of the certificates market, a role for submitting certificate prices and volumes was added for electricity generators. In the case of the volume, it considers the electricity amount sold in the electricity market. This role's algorithm is described by Figure A16. The investment algorithm for every agent was also modified and Figure A17 shows the flow diagram of the algorithm. Points A, B and C refer to the points where this algorithm is connected to the rest of the investment module shown in Figure A18. The dark blue boxes represent the algorithm additions to the original model.

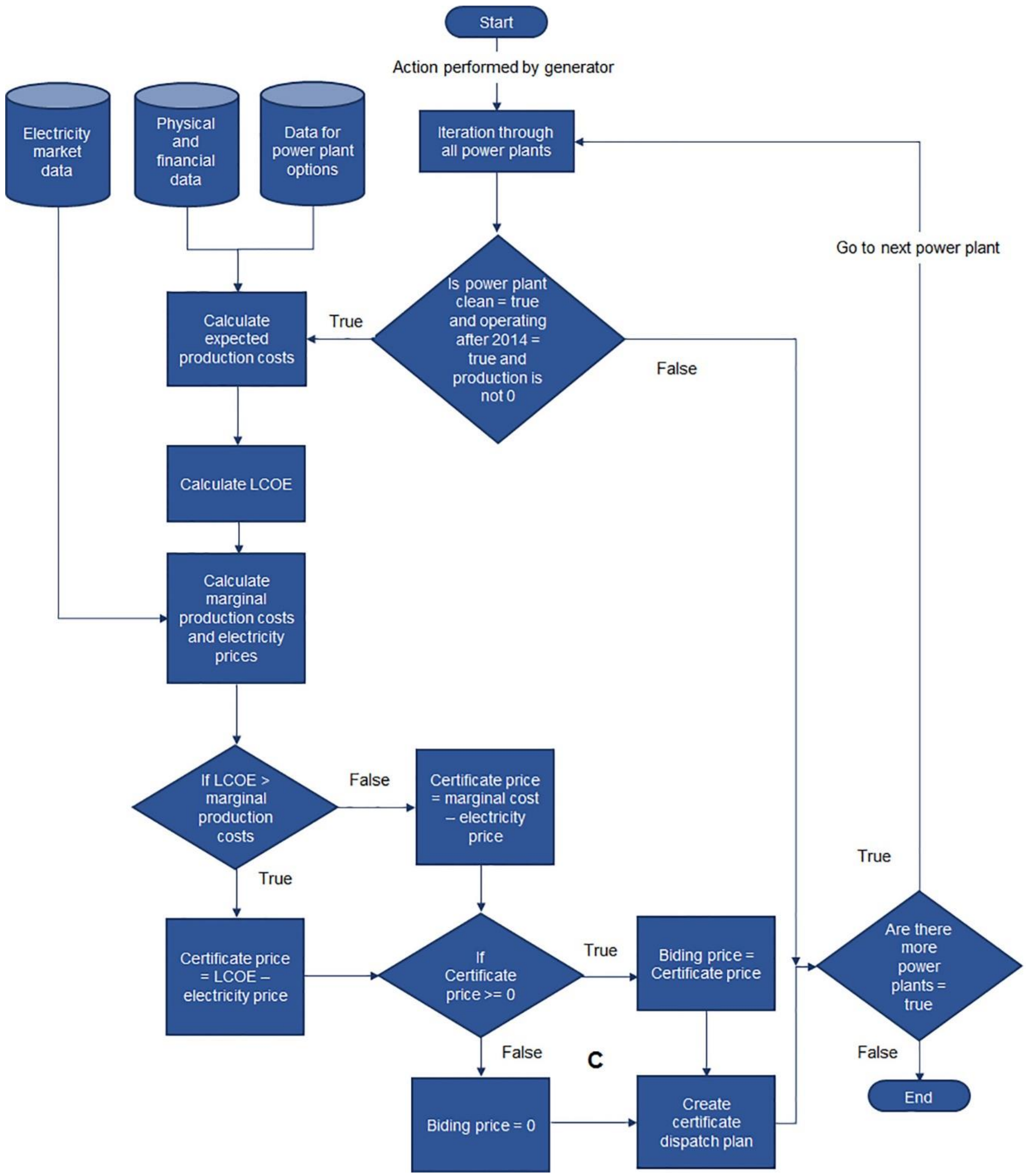

Figure A16. Flow diagram of certificates market price bids.

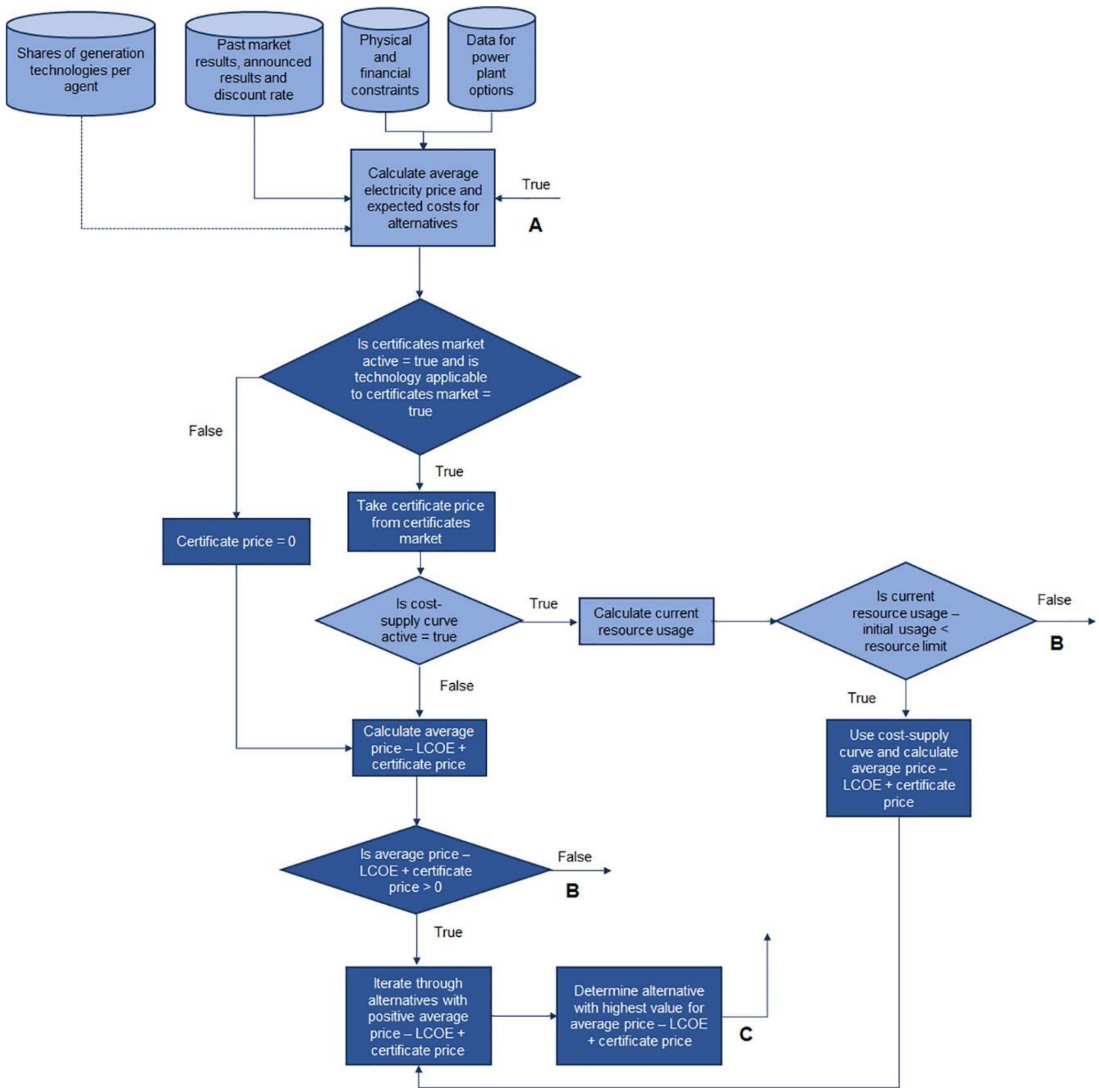

Figure A17. Flow diagram of the investment algorithm considering the certificates market price.

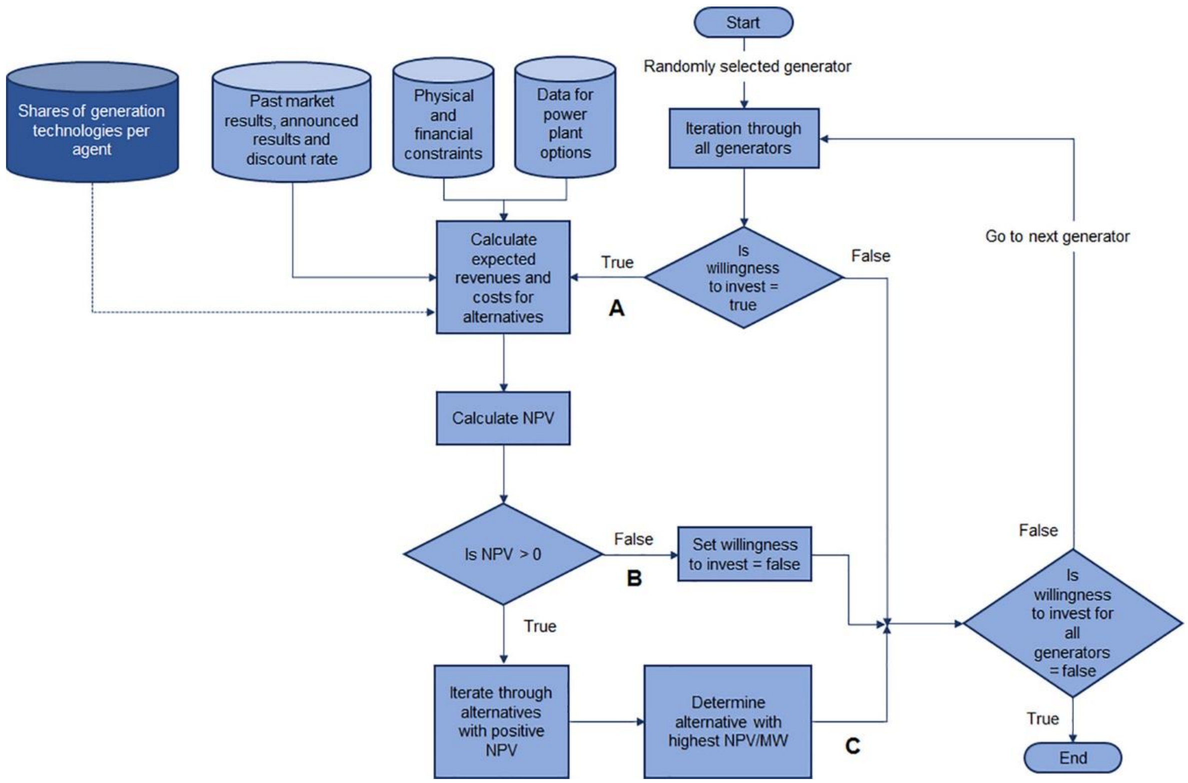

Figure A18. Diagram of the original investment algorithm.[30]

National government role

The national government was in charge of establishing the certificate quotas and the penalty values. The quota was simply adjusted linearly increasing by a certain percentage every year while the penalty was set at a constant value during the entire simulation period. When a dynamic quota and a sloped demand function were considered, the role of the national government was to determine the level of the penalty according to the set of 6 and to adjust the quotas required for the following year on the basis of the excess in certificates (equation 2). Figure A19 presents the flow diagram of the national government role.

[30] Constructed from [21].

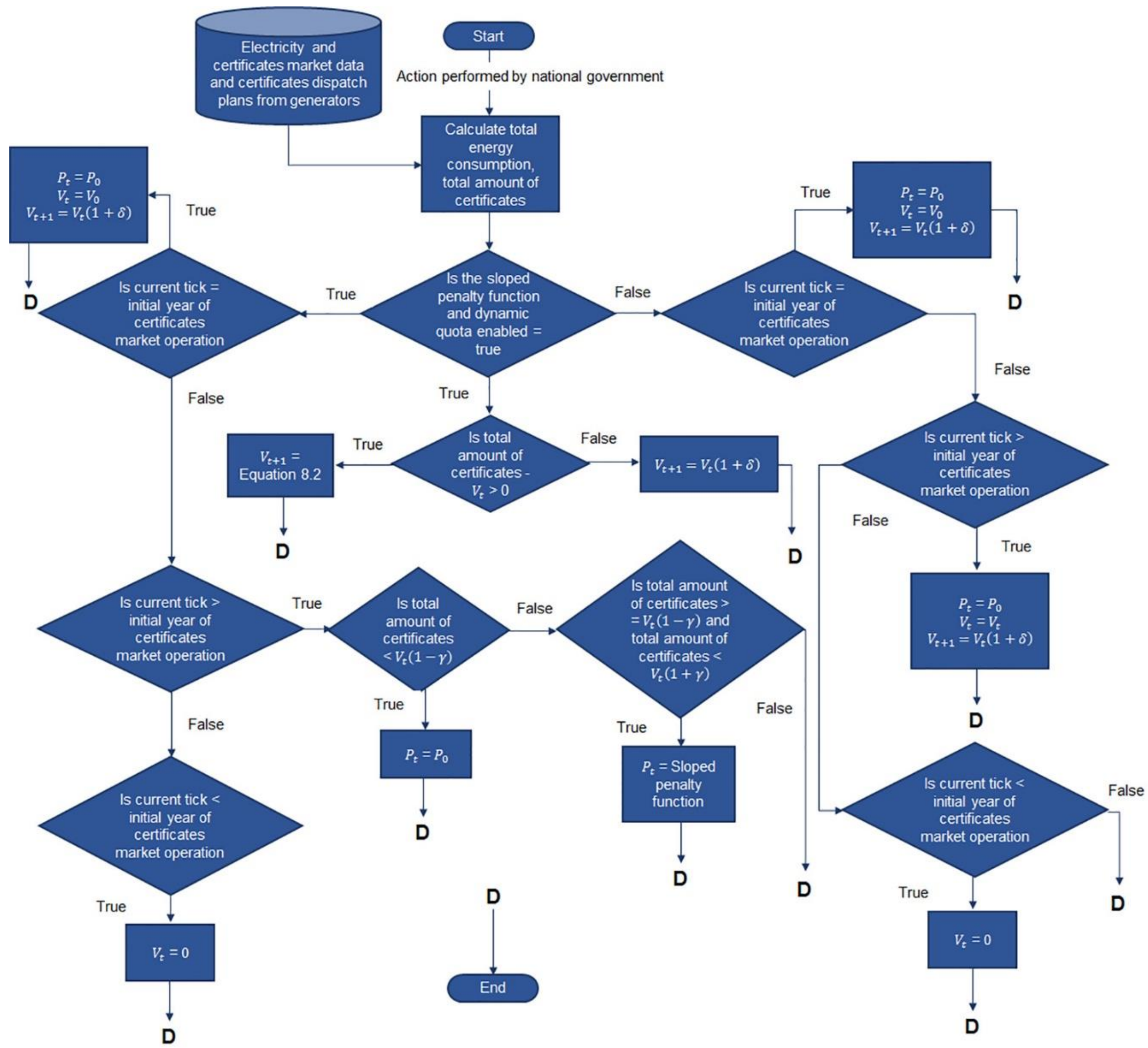

Figure A19. Flow diagram of the national government role.

Certificates market clearing

The certificate market clearing role was implemented to receive certificate bids from generators in clearing the market according to the quantities (CVB_t) and prices (CPB_t) received (in a merit order). An important aspect is that since the market was cleared after renewable production was scheduled within the electricity market, the national government actor that in this work was assumed to clear the market as well, had a previous knowledge of the volume of low-carbon energy which was offered in the certificates market. In this regard, the calculated penalty and the quota were used as a reference to schedule the bids from the generators in a cost incremental manner. If there were not enough certificates compared to the established quota, the penalty value was set as the clearing price. On the contrary, if there were more certificates than the quota, the price was determined where supply met demand. The model also assumed that if the market was not cleared but there were generators that offered bids with higher prices than the penalty value, their offers were also considered but received the penalty value. Figure A20 presents the flow diagram of the certificate market clearing role.

Figure A20. Flow diagram of the certificate market clearing role.

Additional simulation results

This sectios presents additional results for sections 5.2 and 5.3. These results are mainly focused on the evolution of electricity prices and total costs for the different scenarios.

Results for section 5.2

Figure A21 shows the evolution of the mean of yearly average electricity prices for all the scenarios. The establishment of a carbon tax, a TGC market or both increased them. The stability of the prices was greater for the tax scenarios, compared to the pure TGC market scenarios. The combination of policies showed that a high carbon tax, could reduce the problem of volatility of electiricty prices as shown in scenarios where this tax value was combined with a TGC market (both HighCTHighCMP and HighCTLowCMP scenarios).

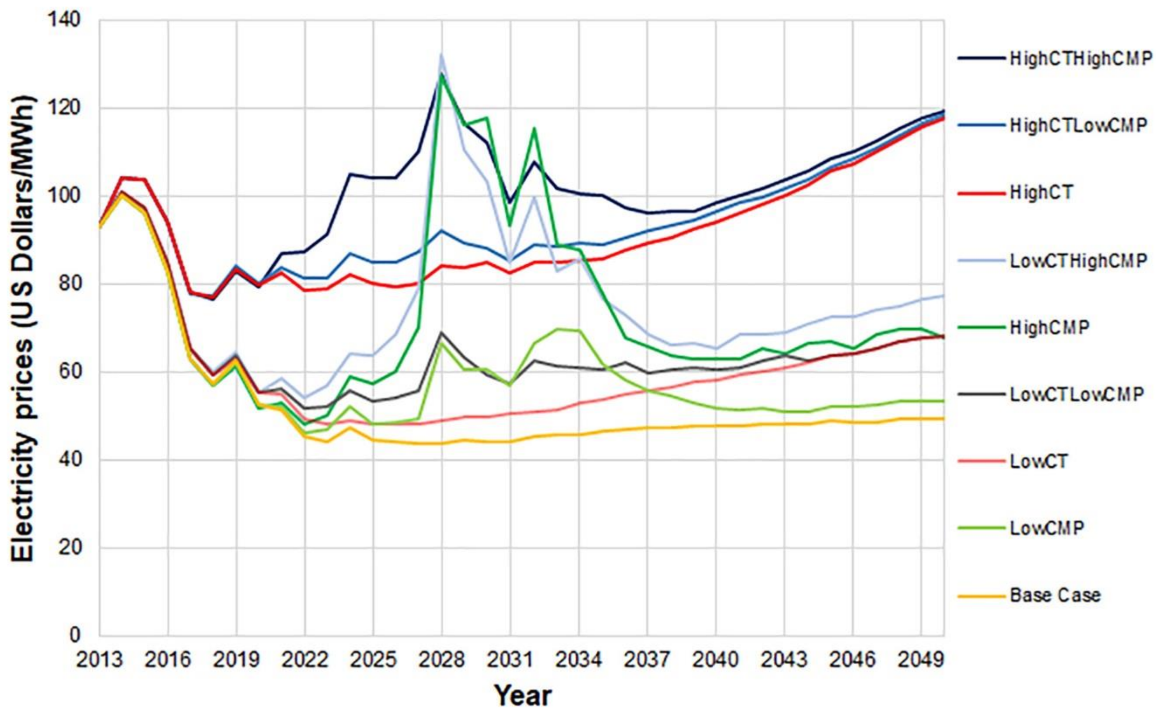

Figure A21. Evolution of electricity prices for scenario set 1.

The total cost to consumers for electricity supply was calculated[31]. The total discounted average costs to consumers for the Base Case and the entire simulation period was equivalent to

[31] The calculation considered the total discounted costs (social discount rate of 10%) that consumers would have to pay for electricity and for complying with their low-carbon quota, for the clean energy certificates market and the carbon tax.

223 billion US Dollars (0.9% of cumulative gross domestic product, GDP)[32]. The scenario with the highest investment in low-carbon technologies (HighTaxHighCMP scenario) presented a 74% increase in average costs (2% of cumulative GDP) to consumers in comparison to the Base Case, whereas the LowCT scenario increased costs by 7% (1% of cumulative GDP). The combination of instruments presented higher costs as well, when compared to the single mechanism scenarios.

Figure A22 presents the costs to consumers per MWh of low-carbon electricity added and the CO_2 mitigation costs, taking the Base Case scenario as reference[33]. For CO_2 mitigation costs, increasing the level of the penalty value when combined with the carbon tax (both levels) significantly increased the costs for almost the same emission reductions. In the specific case of of the scenarios that combined a high carbon tax with the TGC market (HighCTLowCMP and HighCTHighCMP scenarios) mitigation costs were higher in comparison to only having a tax. However, the previously mentioned scenarios presented mitigation costs that were lower than the scenario with the TGC market alone (HighCMP). These results show that the effect of a carbon tax on emission reductions was significant, indicating that a strong carbon price is more cost efficient and effective[34] in achieving emission reductions.

The combination of instruments resulted in more cost-efficient investment in low-carbon generation than the single instruments. For instance, the combination of a low carbon tax and a low TGC penalty (LowCTLowCMP scenario) was more cost-efficient in comparison to only having a low carbon tax (LowCT scenario); and the combination of a low carbon tax with a high penalty (LowCTHighCMP scenario) was more cost-efficient in comparison to only having a high penalty (HighCMP scenario). The latter highlights the dominance of a carbon tax level over a TGC penalty value in some cases and the opposite dominance (TGC penalty over carbon tax level) for others. From the previous observation, the effect of a low carbon tax level diminished as the level of the penalty value of the TGC market increased. However, if the level of the tax was set high enough, this tax level eliminated the impact of the high TGC penalty value increasing costs.

---

[32] A simple GDP projection was performed using an annual growth rate of 5% based on nominal GDP data between 2000 and 2013 obtained from [22] and discounted to 2013 using a 10% discount rate.

[33] The calculation incorporates the difference between total costs in the Base Case scenario and the policy scenarios divided by their respective CO_2 emission reductions and increase in low-carbon energy generation.

[34] We refer to efficiency in terms of added costs for CO_2 emission mitigation and low-carbon energy increase; and to effectiveness in terms of percentage decrease and increase in CO_2 emissions and low-carbon energy penetration, respectively.

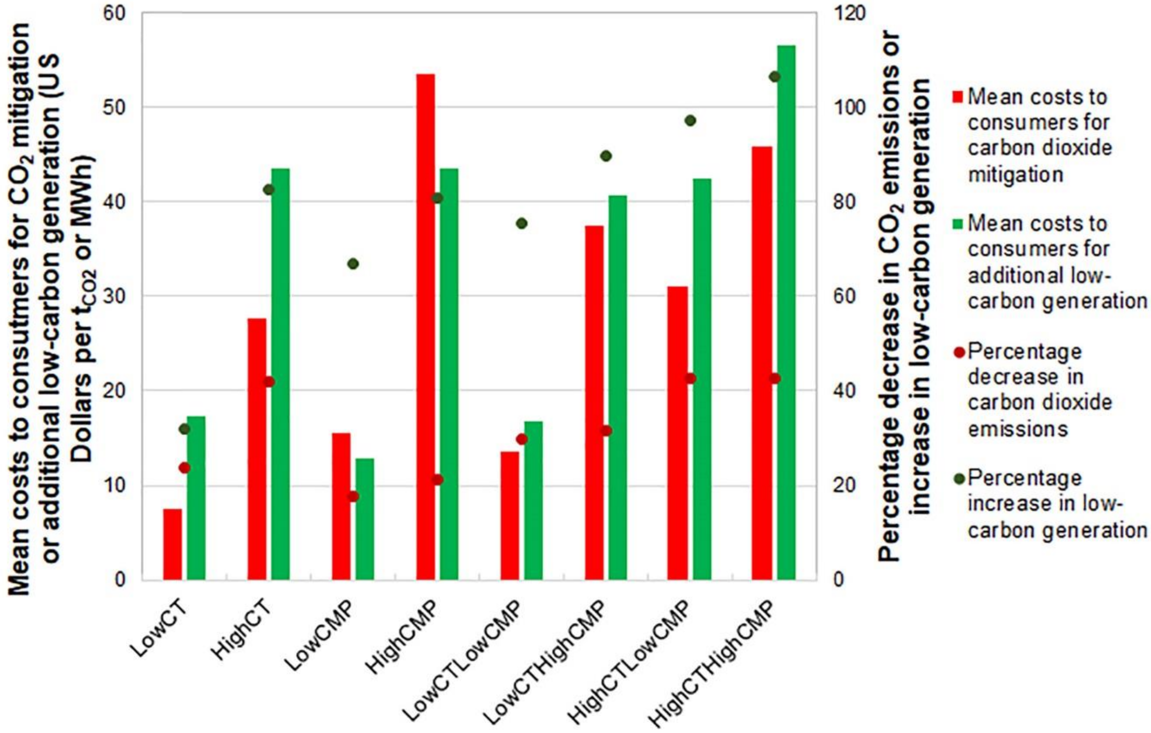

Figure A22. Policy effectiveness and cost to consumers for scenario set 1.[35]

Results for section 5.3

The higher penetration of low-carbon energy sources also affected electricity prices and the total cost of the policies. The introduction of TGC market policies had a negative impact, increasing electricity prices significantly (Figure A23). In the scenario with a high carbon tax, a high level of reduction in the demand slope and a low level of the quota adjustment (HighCTHighγLowα), prices increased since the beginning of the simulation due to an initial rapid investment in wind energy. As explained in section 5.2, this had a negative effect on the supply of electricity, which was reduced. The later adoption of Coal CCS reduced prices to lower levels.

[35] Mean costs are represented by bar charts and plotted on the left-hand vertical axis while percentages are represented by dots and plotted on the right-hand vertical axis.

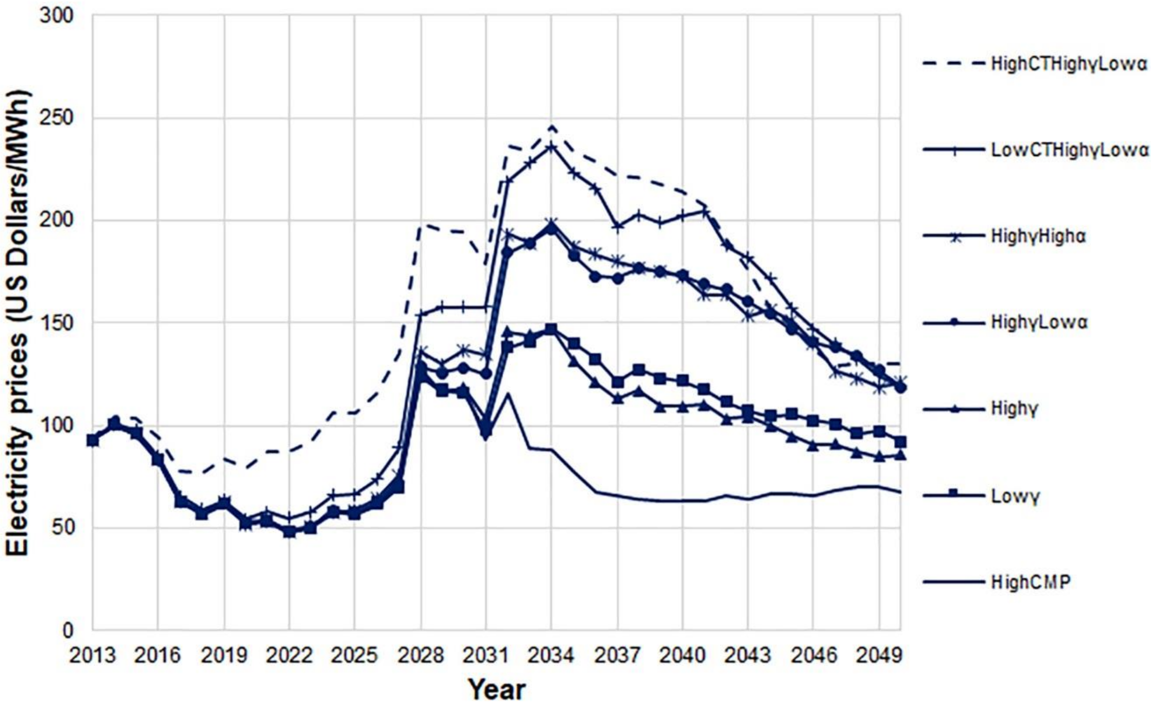

Figure A23. Evolution of electricity prices for scenario set 2.

The addition of the sloped penalty function and the dynamic quota to the high TGC penalty scenario (HighCMP), increased the overall costs to consumers for electricity supply (calculated as in the previous section). However, increasing the value of γ from the Lowγ to the Highγ scenarios, reduced total costs. The reason for this relies on the lower and more stable certificate prices mentioned at the beginning of this section. While the costs to consumers from the electricity prices were similar in both scenarios, there was a difference in average total costs of 5 billion US Dollars from certificate market payments. The incorporation of the dynamic quota, increased costs by raising the amount of low-carbon generation and the level of certificate prices. Finally, the addition of a carbon tax increased total costs.

The calculation of the mitigation costs and the costs for added low-carbon generation (both in reference to the scenario with a high level of the TGC penalty, HighCMP), also showed their cost-efficiency in comparison to using a single instrument. In both cases, for the scenarios that combined a carbon tax with the TGC market adjustment mechanisms (LowCTHighγLowα and HighCTHighγLowα scenarios), the costs of added generation were 34% and 43% lower than only having the TGC market adjustment mechanisms (scenario HighγLowα). The mitigation costs were also lower by 56% and 61%, respectively. Figure A 24 presents the costs discussed above. The scenario that incorporated a high carbon tax achieved the required CO_2 and low-carbon energy targets set by the government. The combination of the TGC market and its adjusting mechanisms with the carbon taxes (both levels) were more effective in promoting a higher penetration of low-carbon energy sources and lower CO_2 emissions.

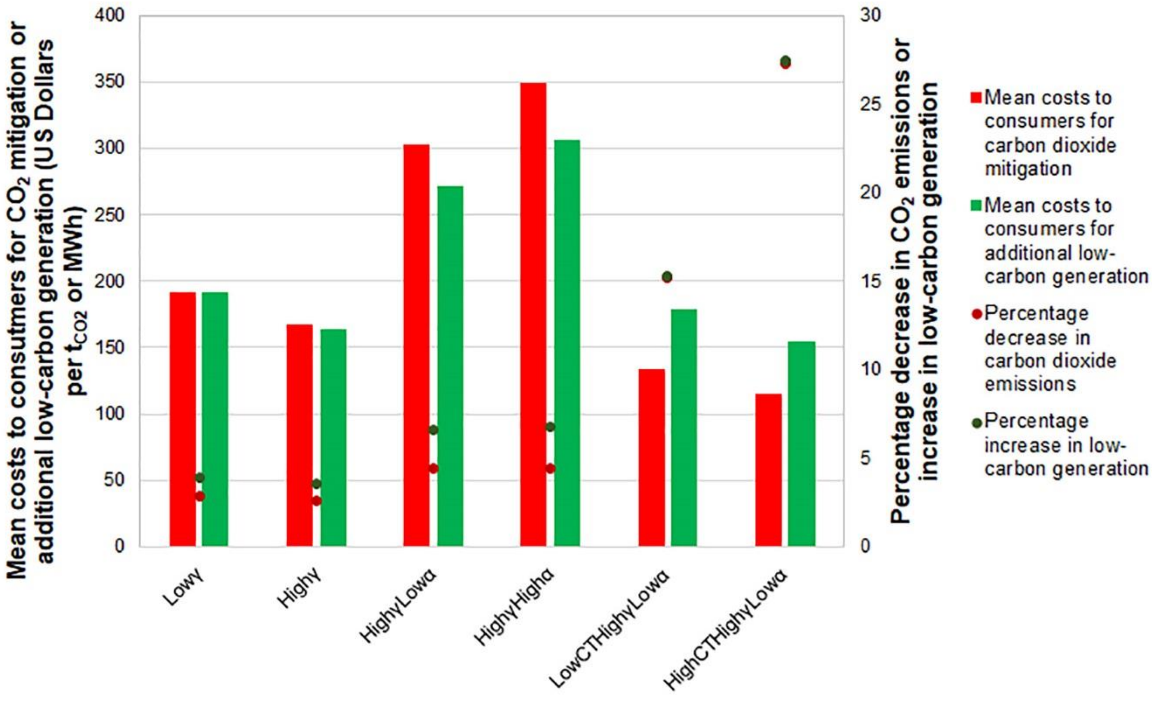

Figure A 24. Policy effectiveness and costs to consumers for the scenario set 2.[36]

[36] Mean costs are represented by bar charts and plotted on the left-hand vertical axis while percentages are represented by dots and plotted on the right-hand vertical axis.

BIBLIOGRAPHY

[1] Hoogwijk M. On the Global and Regional Potential of Renewable Energy Sources [PhD Thesis]. Utrecht: Universiteit Utrecht; 2004.

[2] Hoogwijk M, De Vries B, Turkenburg W. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energ Econ 2004; 26 (5): 889 – 919.

[3] Mckenna R, Hollnaicher S, Ostman v. d. Leye P, Fichtner W. Cost-potentials for large onshore wind turbines in Europe. Energ 2015; 83: 217 – 229.

[4] Mercure JF, Salas P. An assessment of global energy resource economic potentials. Energ 2012; 46 (1): 322 – 336.

[5] NASA. Surface meteorology and solar energy. Available from: https://eosweb.larc.nasa.gov/sse/; 2015 [Accessed 11 December 2015].

[6] Ellis EC, Goldewijk KK, Siebert S, Lightman D, Ramankutty N. Anthropogenic Biomes of the World, Version 2: 2000. City of New York: NASA Socioeconomic Data and Applications Center (SEDAC); 2013.

[7] NASA. NASA Earth observations. Available from: http://neo.sci.gsfc.nasa.gov/view.php?datasetId=SRTM_RAMP2_TOPO; 2015 [Accessed 11 December 2015].

[8] SENER. Prospectiva de Energías Renovables 2012 – 2026. Mexico City: Secretaría de Energía (SENER); 2012.

[9] DOF. Programa especial para el aprovechamiento de energías renovables. Mexico City: Diario Oficial de la Federación (DOF); 2014.

[10] Deng YY, Haigh M, Pouwels W, Ramaekers L, Brandsma R, Schimschar S, Grözinger J, De Jager D. Quantifying a realistic worldwide wind and solar electricity supply. Global Environ Chang 2015; 31: 239 – 252.

[11] Abed KA, El-Mallah AA. Capacity factor of wind turbines. Energ 1997; 22 (5): 487 – 491.

[12] Lysen EH. Introduction to wind energy. Amersfoort: Consultancy Services Wind Energy Developing Countries; 1982. CWD 82-1.

[13] CFE. Costos y parámetros de referencia para la formulación de proyectos de inversión en el sector eléctrico 2013. Mexico City: Comisión Federal de Electricidad (CFE); 2013.

[14] Pasqualetti MJ. Opposing wind energy landscapes: A search for common use. Ann Assoc Am Geogr 2011; 101 (4): 907 – 917.

[15] AMDEE. El potencial eólico mexicano. Oportunidades y retos en el nuevo sector eléctrico. Mexico City: Asociación Mexicana de Energía Eólica (AMDEE); 2012.

[16] IRENA. Renewable energy prospects: Mexico. Abu Dhabi: International Renewable Energy Agency (IRENA); 2015.

[17] SENER. Inventario nacional de energías renovables. Available from: http://inere.energia.gob.mx/version4.5/; 2015 [Accessed 6 January 2016].

[18] Toledo C, Chávez-Arroyo R, Loera L, Probst O. A surface wind speed map for Mexico based on NARR and observational data. Meteorol Appl 2015; 22: 666 – 678.

[19] Hiriart le Bert G, Gutiérrez-Negrín L, Quijano-León JL, Ornelas-Celis A, Espíndola S, Hernández I. Evaluación de la energía geotérmica en México. Mexico City: Comisión Reguladora de Energía (CRE); 2011.

[20] Richstein J. AgentSpring coding instructions and conventions. Available from: https://github.com/EMLab/emlab-generation/wiki/AgentSpring-Coding-Instructions-&-Conventions; 2013 [Accessed 10 June 2016].

[21] Bhagwat PC, Richstein J, Chappin E, De Vries L. The effectiveness of a strategic reserve in the presence of a high portfolio share of renewable energy sources. Util Policy 2016; 39: 13 – 28.

[22] World Bank. GDP (current US$). 2016. Available from: http://data.worldbank.org/indicator/NY.GDP.MKTP.CD [Accessed 15 October 2016].