EL COLEGIO DE MÉXICO, A.C.
CENTRO DE ESTUDIOS ECONÓMICOS

ESSAYS IN TRADABLE GREEN CERTIFICATES

TESIS PRESENTADA POR

ITZEL ROCÍO OSORIO ROSAS

PROMOCIÓN 2021-2024

CIUDAD DE MÉXICO ENERO DEL 2025

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Contents

Introduction

This thesis consists of three works on Tradable Green Certificates, known in Mexico as *Certificados de Energías Limpias*, CEL by its acronym in Spanish. The first chapter is on how certificates can incentivize green capacity investment; the second chapter compares two certificates granting schemes, technology neutral and non-neutral, and the last one studies how certificates can incentivize polluting generators to adopt technologies to reduce its emissions.

The first chapter focuses on how green certificates incentivize new investment in clean generation. I propose a partial equilibrium model for the electric market to study how the policy parameters, the green quota, and non-compliance fee, affect green investment, and analyze how the result changes under duopoly competition in the electric market and merit order energy dispatch.

In the second chapter, I study how a technology neutral approach to grant certificates cannot promote diversity of green generation resources, but a non-neutral one can. I propose a characterization of non-neutral certificate granting schemes, credit multipliers and carve-outs quotas, and compare them with the technology neutral approach in terms of their capability to reach their green energy generation objectives, electric tariffs, additional rents, and social welfare.

Finally, the third chapter studies the case where polluting (conventional) generators are allowed to participate in the certificates market if they invest in emission reduction technologies. I propose a two-stage game where the regulator decides granting green certificates to conventional (polluting) generators that invest in an abatement technology. Once the generator decides how much abatement to get, it competes à la Cournot in the certificates and energy market with the green (clean) generator. This may seem contrary to the zero emissions goal, but it is important to address the limitations many developing countries, like Mexico, face in reaching the global emissions mitigation goal given the major dependence on fossil fuels.

Chapter 1

DRIVING CHANGE: GREEN CERTIFICATES AND THE PATH TO CLEAN ENERGY INVESTMENT

1.1 Introduction

The transition towards a low carbon emissions' economy requires a substantial investment in clean energy generation, since the electric sector is key to reaching decarbonization. According to the National Institute of Ecology and Climate Change ("Inventario Nacional de Emisiones de Gases y Compuestos – México ante el cambio climático", 2023), the fuel burnt used to generate electricity represented 172 million tons of CO_2, equivalent to 23.3% of the total reported in the Mexican inventory of emissions for 2019. Energy generation is responsible for a significant amount of these emissions. In order to reduce them, it is necessary to have an integral strategy that considers the technological advances related to energy efficiency, a redesign and development of the electrical grid, and a massive transition towards clean energy.

As a part of the strategy to reduce CO_2 emissions, the Mexican regulation through the Electric Industry Law (LIE, by its acronym in Spanish) and the Energy Transition Law established the Long-Term Auctions and the Clean Energy Certificates (CEL, by its acronym in Spanish) market. The first three auctions assigned 68 contracts to new generators, which is equivalent to adding 7,654 MW (megawatts) of new green generation capacity (Proyectos México). On the other hand, the CEL market aims to facilitate investment in green projects by creating a certificate's demand as an obligation for consumers, determined by the Energy Ministry (Sener, by its acronym in Spanish). From 2018, when the mechanism began, to July 2023, the Energy Regulatory Commission (CRE, by its acronym in Spanish) has issued $114,848,578$ CEL, around 60%[1] coming from the Long-Term Auctions winner projects.

A few years ago, due to political reasons, the energy auctions were set on hold (CENACE, 2020). Thus, at the moment, green certificates or CEL are the only mechanism to attract new investment. However, they are perceived by public opinion more as a mechanism to get financial revenue and displace the generation owned by the Mexican government than as an instrument to increase the share of energy generated with non-fossil fuels.

The entry of a new ruling party, in 2018, has meant the redefinition of the Mexican energy policy. This is a strategic moment to evaluate the green certificates' performance, to decide if they are a useful policy tool for the future, and think about some regulatory changes to improve their efficacy since it seems that they are the only active mechanism to increase the generation mix with respect to green energy. In this study, I examine a partial equilibrium model to identify if a green certificate policy like the Mexican incentivizes generation firms to invest in new green capacity and how this new investment responds to the green quota set by the regulator.

This paper aims to contribute to a better-informed public debate about the benefit of green certificates on new generation capacity and identify how the green quota chosen by Sener affects this investment. To achieve this, I propose a two-stage model power market where electric energy and green certificates are consumed in separate markets, considering the interaction between the consumers, represented by a retailer, an intermittent green firm, and a conventional one. In the first stage, the green firm decides its generation capacity and certificates supply. Next, the retailer determines its certificate and energy demand. Using backward induction, I solve the subgame perfect equilibrium (SPE) of the game and the optimal levels of green investment and certificates supply.

[1] Not all the winner projects have started operations, so this is an approximate number.

To better represent the Mexican mechanism, the retailer's demand for certificates is downward sloping, as in Ciarreta et al. (2017). This demand comes from the retailer maximization problem. Unlike them, retailer also chooses its energy demand. This way, I can illustrate better the retailer as the intermediary between consumers and generators. Unlike other papers in the literature that assume an inelastic certificate demand, using an elastic one allows accounting for obligation non-compliance, so the required green energy quota is not reached. This is an important feature of the model because it highlights the importance of the non-compliance fees to make it to the green energy goal.

Regarding the energy market, I use two approaches to dispatch energy. First, I assume there is a merit order dispatch, as in the Mexican market. This means that generators are ordered from lower to greater marginal generation cost, and the price is set at the marginal cost of the last generator dispatched. To some extent, this case is similar to perfect competition. For the second case, I assume there is a Cournot duopoly in the electric market. This is a usual approach in the literature, and it also portrays the fact that conventional and green firms have some market power.

For both energy dispatch approaches, I find that when the regulator sets its green generation goal below a specific threshold, then the green firm decides to offer a portion of its certificates in the market. On the contrary, when the goal is greater than the threshold, the green firm offers its whole endowment of certificates. As in An et al. (2016), depending on the size of the goal, the firm restricts its certificates' supply to increase the price.

From a numerical exercise, I highlight the importance of non-compliance fees being high enough, so the retailer prefers getting its certificates' quota than paying the fee. The regulator has to pay attention to this for the policy to be successful, which means reaching the green generation goal.

I find that the green generation goal set by the regulator has a non-monotonic effect on green investment, just as in the findings of Amundsen and Nese (2009) and Requate (2015). As in Perino and Requate (2012) and Gama (2018), this means that an astringent policy does not result into more green generation capacity. However, a greater goal does reduce conventional generation. Although there is not necessarily more green energy, the policy decreases contaminant emissions.

Finally, the non-monotonic nature of the green investment suggest that there is an optimum goal that maximizes investment. Thus, keeping green certificates as the main policy to incentivize the entry of new capacity could not result into more investment once this optimum is reached.

The rest of the paper proceeds as follows. In the next section, I present the relevant literature related to the green certificates' policy. Section 1.1.2 briefly describes how the Mexican certificates' market works. Section 1.2 describes the model, followed by its analytical solution for the merit order dispatch and Cournot competition cases. Section 1.3 offers a numerical illustration of the results, and Section 1.4 shows the comparative statics regarding the green generation goal.

1.1.1 Literature review

Numerous policy instruments have been implemented in some countries, such as Australia, Canada, China, Germany, Italy, Japan, Poland, Spain, the United Kingdom, etc., to increase green generation as a way to reduce CO_2 emissions. The most popular are Feed-in tariffs (FIT), renewable portfolio standards (RPS) and tradable green certificates (TGC), and emission trading scheme (ETS).

The FIT (T. Wang et al., 2014) is a policy designed to accelerate investment in renewable energy technologies by offering guaranteed prices for electricity produced from renewable energy sources for fixed periods of time. In Mexico, this mechanism is similar to the SLP, where the winning projects got a Power Purchase Agreement (PPA) for 15 years to supply electric energy and capacity, and 20 years to provide CEL. Meanwhile, the RPS (Berry and Jaccard, 2002) is an instrument that requires the market to deliver a minimum amount of electricity (as a percentage of total sales) from specific fuels or generation technologies. The

TGC or Renewable Energy Certificates (REC) is the mechanism used to track and verify the compliance of RPS (T. Wang et al., 2014). This policy is equivalent to the CEL, and the RPS is parallel to the certificate obligation that has to be covered.

According to the United States Environmental Protection Agency (US EPA, 2016), an ETS aims to reduce pollution by limiting emissions and tradable allowances that authorize the holders to emit a specific quantity of the pollutant. Mexico is still implementing the pilot phase of this instrument, focused on industry and energy sectors.

As explained above, the three instruments are being implemented in Mexico to some extent. All of them came from several laws promoted to reach the energy transition and comply with the international greenhouse gasses reduction objectives acquired by the country.

To the extent of my knowledge, few studies focus on CEL in Mexico. Most of them use a legal approach to analyze the legal framework around the certificates (Venegas Álvarez, Sonia, 2016, Ibarra Sarlat, 2018) and only limit their conclusions to legal loopholes and other regulatory additions necessary for the operation of this mechanism.

An empirical analysis would be ideal to understand the structure and performance of the green certificate market. However, not much public data related to it is available to answer some questions associated with the market certificate price, compliance, sanctions, or whether the certificates' supply is enough to cover the market demand. To the best of my knowledge, the COFECE (Comisión Federal de Competencia Económica (COFECE), 2021) study is the only work that attempts to evaluate the performance of the green certificates' market. COFECE presents a qualitative study of the regulatory conditions that affect the demand and supply of certificates, monitoring, and sanctions. It shows that according to CRE information, there are not enough certificates to satisfy the demand until 2024 and that the recent changes in the regulation, such as, allowing old green generators property of the government and hydroelectric generation to receive green certificates, severely affect the certificates' supply and could leave the mechanism out of use. However, it does not discuss how the green certificates have affected the investment in new capacity.

The international literature analyzing the green certificate mechanism often focuses on the interaction between it and the energy market, assuming different market structures to identify changes in prices and energy supply. In addition, some studies describe how this policy promotes the increase of clean energy generation and thus displaces the conventional one and reduces CO_2 emissions. Other works are centered on the strategic behavior of green generators in the certificate market and how they control their generation to improve their benefits.

Some of the first studies on green certificates in the early 2000s aimed to study the interaction between the certificates and CO_2 emission permits. Amundsen and Mortensen (2001) propose a static equilibrium model considering both policies with upper and lower price bounds on the certificates. They found that the increase in the percentage requirement (RPS) does not lead to a larger capacity in the long run, but the share of green electricity compared to total consumption will increase. In this same line, Morthorst (2001) studies these mechanisms using an international market approach. He found that under a bidding mechanism for permits, international trade of certificates only benefits the country where the green plants are established.

In contrast, Widerberg (2011) found that increasing the green quota obligation decreases the electricity produced using non-renewable sources as well as the long-run total production of electricity. Even though renewable energy increases, the overall effect is negative due to the interaction with the ETS. Thus, combining both policy instruments could have unwanted results.

Regarding the influence of green certificates on the investment in new green generation capacity, Zhu et al. (2022) found that when the green quota is set too high, an increase in the certificate price will increase the renewable energy investment; otherwise, it will reduce the firm incentive to invest in new generation. In the same line, but with respect to green firm behavior, An et al. (2016) observe that when the RPS is low, renewable firms tend to withhold some certificates to raise their price. However, when the RPS is relatively high, they cannot withhold certificates, so they reduce their wholesale electricity output to reduce the amount of certificates and raise their price. On the contrary, Amundsen and Nese (2009) and Requate (2015) conclude that a green certificates policy does not necessarily lead to greater green electricity generation, but it does lead to a reduction of conventional electricity generation. The effect depends on the level of the percentage of requirement.

Although certificates can affect energy prices, using green certificates is always optimal for reaching renewable energy deployment goals (Jensen and Skytte, 2003). This market creates incentives for investors, electricity producers, and consumers to increase the power sources mix (Marchenko, 2008). Even in the absence of auctions, the certificates have motivated the signing of long-term contracts at fixed prices that facilitate the installation of new green generation projects, like in Texas and the United Kingdom (Finon, 2013). Even in the hypothetical scenario, the green certificates scheme could help to achieve the renewable energy target at lower costs compared with the FIT, as shown in Ciarreta et al. (2017) for the case of Spain.

The results presented in the papers above rely on the assumption of inelastic demand for certificates. Also, the price is set exogenously by the regulator. This means that the consumers' demand is exactly the number of certificates they need to cover their obligation, so there is no place for non-observance. This is not the case in Mexico. The regulation considers the case where the consumers do not get enough certificates and establishes an increasing fee with respect to the level of unfulfillment. Besides, it allows the intertemporal consumption of certificates to cover future obligations. This means that, depending on the price, it could happen that consumers do not cover their whole obligation.

A price-sensitive demand function would be ideal for representing a certificate market as the Mexican, like the one assumed in An et al. (2016). However, to my knowledge, Ciarreta et al. (2014) are the first to focus on the retailer decision, as a certificates' consumer, and the regulation design that leads to a decreasing green certificate demand. In a later paper (Ciarreta et al., 2017), the authors also highlight the role of the regulator as the one who sets the green target and the penalty function. That premise represents better the operation of the Mexican certificate market. Unlike Ciarreta et al. (2017), I study the investment decision in new green generation for a generation duopoly and a specific competition rule applied in some electric markets in the world, and in particular in Mexico, called merit order dispatch.

1.1.2 Green certificates in Mexico

Next, I present a summary of the Mexican certificates' mechanism operation. On the supply side, CRE issues green certificates to all green generators regardless of their clean technology (solar, wind, hydropower, etc.). The amount granted to the generators depends on their monthly energy generation, so their capacity and technology determine the quantity of certificates received. In my model, I assume the green firms know this certificates' granting rule, so they choose their generation accordingly.

With respect to the demand, the obligation of green certificates is on the consumers. According to Mexican regulation, five categories of consumers must comply with this duty: Basic Supply (SSB), Qualified Supply (SSC), Qualified Users that participate in the energy market (UCPM), final users that receive energy through isolated power supply, and holders of Legacy Interconnection Contracts (CIL). SSB supplies a great part of the total demand for energy, so it has the biggest obligation. It gets most of the certificates from Power Purchase Agreements derived from the SLP. To keep the model simple, I only focus on the retailer under the role of the SSB since it represents most of the electric demand in Mexico, this is the consumer side in my model.

The number of certificates the consumer needs to get corresponds to a proportion of their total energy consumption. This percentage requirement is the primary policy instrument (Amundsen and Nese, 2009). According to the Mexican regulation, it increases annually, and its value is determined by Sener. This means that if the obligation for this year is 5% and the total consumption is 100 MW, the retailer must buy five certificates. In my approach, I refer to this requirement as the green energy goal.

Once the retailer liquidates its obligation partially or totally, the used certificates are canceled. However, certificates have a lifetime validity, which means that one certificate issued today can be used to pay for the obligations in twenty years only if it has not been used before. In terms of monitoring, CRE is in charge of the surveillance, and in case it is not fulfilled, it can sanction depending on the magnitude of certificates not covered. Regarding the certificates' lifetime, my model does not consider intertemporal consumption.

The green quota, or obligation, is set by the Energy Ministry. Each year, it evaluates the availability of the different generation technologies (green or conventional), and the operative conditions of the electric system, considering the expected demand. Once those elements are taken into account, it determines the quota for the next three years. The following year, it repeats the same exercise and could update the figures from the last year to account for changes in the electric system. I assume the green quota is exogenous in my approach.

In the next section, I give the details of the model and find the equilibrium for the merit order and Cournot duopoly cases.

1.2 The model

Consider an electric market with two products: electric energy, q, and green certificates, x, and three agents: two generation firms, and a retailer that represents the final consumers' demand for electricity. In this setting, the energy inverse demand function of consumers is given by:

$$s(Q_s) = a - bQ_s, \tag{1.1}$$

where s is the electric tariff the consumer pays to the retailer, Q_s is the consumer's energy demand, with $a > 0$ and $b > 0$.

The power supplied to the electric market comes from a conventional, c, and a green generator, r, both of which are necessary to satisfy the energy demand such that $Q_s = Q_e =$

$q_r + q_c$, with Q_e equal to the energy supply.

The first term in the sum, $q_r > 0$, corresponds to the energy provided by an intermittent firm that generates power from clean sources, like the sun or wind, at zero marginal cost. However, the green firm needs to pay an investment cost of $\beta > 0$, which represents the cost of solar panels or wind turbines, for example.

In this context, intermittent means that energy generation is not continuously accessible and is related to the availability and intensity of the resource used to generate energy. This implies that the green firm is not able to know with certainty its real generation because it depends on the realization of the weather at a specific time. So green generation is given by $q_r = \tilde{q_r} k_r$, where $k_r > 0$ and $\tilde{q_r} \in [0, 1]$ is a random variable with mean μ and variance σ^2 that represents the availability of natural resources to generate green energy. This means that the green generator is not able to generate at 100% of its capacity, k_r. For example, at 8 o'clock in the morning, $\tilde{q_r}$ could be equal to 0.2, but between 10 and 15 o'clock, it could be around 0.6, which means that green generation would be 20% and 60% of the capacity, respectively.

The second term, $q_c > 0$, refers to the energy served by a dispatchable generator that produces energy using fossil fuels, such as natural gas or carbon, at a marginal cost of v. The term dispatchable means that the conventional firm is available at all hours to generate energy. So this generator is necessary to fulfill the energy demand at hours when the availability of natural resources is not so high or the green capacity is not enough, for example, when energy demand is high on hot or cold days.

In this setting, the regulator is interested in increasing the share of green generation capacity with respect to the total generation mix (the sum of conventional and green generation capacity). So, the regulator sets a green goal, $\alpha \in (0, 1)$, that represents the share of green capacity it would like to reach in the future. Since the objective is to increase the green capacity, the goal α will be strictly greater than zero. However, it also cannot be equal to one because of the intermittence of green energy described above, so conventional generation is necessary in the absence of storage to satisfy demand.

For this policy to be binding, it is important that the green goal is bigger than the current share of green capacity, i.e., $\alpha > \frac{k_r}{k_r+k_c}$, where k_c represents the conventional capacity. In this model, the conventional capacity generation is not known, only the electric generation. So, in this case, the green goal refers to the proportion of green energy the regulator would like the market to produce and $\alpha > \frac{q_r}{q_r+q_c}$.

That target is placed as an obligation of green energy consumption. Since it is impossible to distinguish green from conventional energy once they get into the system, this requirement is translated in terms of green certificates, which are financial instruments. The observance of this responsibility falls on the retailer, who, on behalf of consumers, has to get certificates equal to a proportion of consumers' energy demand, αQ_s. The retailer meets its certificate demand at the market at price P_c. If it does not fulfill its obligation, it faces a penalty, $f > 0$, depending on the certificates not covered.

In this sense, the retailer acts as an intermediary between consumers and generators because the former cannot go directly into the electric market and get their energy. Their relationship is merely financial. The consumers pay a tariff, s, for the energy they demand, and the retailer makes the purchase. Since energy is the only good consumers demand, the retailer has to take care of the certificate's obligation. However, the retailer transfers its costs to the consumer through the tariff, so it depends on the energy and certificate prices.

From the supply point of view, the regulator observes the energy generated by the green firm and gives one certificate per unit of energy (measured in MWh) produced. This means that the quantity of certificates available to trade in the market x_r is limited and equal to its total generation, $x_r = q_r$. The regulator's objective is that certificates work as a financial incentive to promote green capacity investment, so the green generator is a monopolist in the certificate market, with x_s as its certificate's supply.

This work focuses on identifying the effect of green certificate obligation on investment in green generation. For this purpose, I propose a two-stage model. First, the green firm decides its generation capacity, k_r, and certificates supply. Next, the retailer determines its certificate and energy demand. Using backward induction, I solve the subgame perfect equilibrium (SPE) of the game and the optimal levels of k_r and x_s.

1.2.1 Second stage: energy and certificate demand

First, I focus on the retailer's decision regarding its demand for energy and certificates. For this problem, I follow Ciarreta et al. (2017) approach. But unlike them, besides choosing the certificates' demand, here, the retailer also chooses its energy demand, instead of taking it as given. Thus, the optimization problem of the retailer in this stage is

$$\max_{Q_s, x_s} \quad \pi_s = Q_s(s - P_e) - x_s P_c - \frac{f}{2}(\alpha Q_s - x_s)^2. \tag{1.2}$$

The first term in the retailer's profit function corresponds to the income from energy sales to final users, which is the difference between the tariff the final user pays to the retailer, s, and the energy price, P_e, multiplied by Q_s. Next is the expenditure on green certificates, where P_c is the certificate price and, finally, a quadratic penalization function that increases with the non-compliance level, $\alpha Q_s - x_s$, and is scaled with the $f > 0$ parameter.

The retailer is a price taker, so the first-order conditions for its maximization problem are:

$$Q_s : \quad s - P_e - f\alpha(\alpha Q_s - x_s) = 0, \quad \text{and} \tag{1.3}$$

$$x_s : \quad -P_c + f(\alpha Q_s - x_s) = 0. \tag{1.4}$$

The retailer has a double role. The first one occurs in the retail market, between itself and the consumers, in which it compromises to carry out all the financial transactions with the generators to meet the consumers' energy demand at a tariff s.

The second role takes place in the energy and certificate market, and it represents the demand side, where it is a price taker. The Equations 1.3 and 1.1 are the clearing conditions for the retail market, and equation 1.4 corresponds to the certificate demand. After solving[2], the retailer's energy and certificate inverse demands, respectively, are given by:

$$P_e = a + \alpha f x_s - (q_r + q_c)(\alpha^2 f + b), \quad \text{and} \tag{1.5}$$

$$P_c = f(\alpha(q_r + q_c) - x_s). \tag{1.6}$$

1.2.2 First stage: capacity investment and certificates supply

In this section, I analyze the first stage of the game, in which the firms choose their generation and the green firm decides its certificate's supply, under two dispatch approaches for the electric market. The first tries to replicate the way the Mexican power market dispatches the generators according to their marginal costs of generation, known in the electric market as merit order. Here, the energy produced by each generator depends on its capacity and the energy demand. In the second one, I assume a duopoly competition. Even though most of the electric markets in the world are decentralized, and the regulation establishes that they try to resemble a perfect competition structure (like they do with merit order dispatch), still, conventional and green technologies have some market power. Thus, I assume a Cournot competition to try to resemble this fact.

For the rest of this Section, I characterize the second stage problem for both generators. In Sections 1.2.3 and 1.2.4 I solve the two-stage game considering the equations I got in Section 1.2.1 and the ones that result from the merit order and Cournot competition specific cases. I am starting by setting out the revenue for the conventional firm.

The conventional firm chooses its generation, q_c, that maximizes its revenue, $q_c P_e$, minus the variable production cost, $q_c v$, which in this case is given by the fuel cost. Even though conventional generation is not uncertain, it is important to note that in Equation 1.5 the energy price depends on the total generation, which is in terms of the conventional and intermittent sources. Thus, the conventional firm's expected profit maximization problem

[2]For intermediate steps see the Appendix.

is:

$$\max_{q_c \geq 0} \quad \pi_c = E[q_c(P_e - v)]. \tag{1.7}$$

The green firm gets its revenue from the energy and certificate market. Unlike the conventional firm, the green generator does not have variable generation costs, but it does face a quadratic capacity investment cost [3], βk_r^2. Also, its generation q_r is limited by the availability of the resource needed and the capacity the firm chooses, that is $q_r = \tilde{q}_r k_r$. So, the problem reduces to determine the investment in capacity generation.

Regarding the certificate market, the firm receives a stock of certificates equal to its generation q_r, so its monopoly certificate supply has to be less or equal to this stock. In this case, the green firm chooses the share $\omega \in [0,1]$ of its generation q_r that will become its certificate supply; this means that $x_s = \omega q_r$. Therefore, the expected profit maximization problem for the green firm is:

$$\max_{k_r \geq 0,\ 0 \leq \omega \leq 1} \quad \pi_r = E[\tilde{q}_r k_r P_e + \omega \tilde{q}_r k_r P_c - \frac{1}{2}\beta k_r^2]. \tag{1.8}$$

After substituting the expressions for green generation and the certificates' supply, the problem reduces to choose the investment in generation capacity and the share of green certificates the green firm offers to the certificate market. Notice that the share ω that determines the certificates' supply cannot exceed 1, because the firm cannot sell more than its certificates' stock so I will use the Kuhn-Tucker approach to find the solutions. The Lagrangian associated with this maximization problem is:

$$\mathcal{L}_r(k_r, \omega, \lambda_1, \lambda_2; P_e, P_c) = E[\tilde{q}_r k_r P_e + \omega \tilde{q}_r k_r P_c - \frac{1}{2}\beta k_r^2] - \lambda_1(-\omega) - \lambda_2(\omega - 1). \tag{1.9}$$

[3] Requate (2015) offers good intuition on why green generation has quadratic costs. In the case of wind power, turbines located close to the shore are more effective than those set up in the countryside far away from the coast. With solar panels, sites in Southern Europe are typically more effective than those in the North. In this sense, there are indeed increasing marginal costs, since at less-favored locations more RES-E units need to be installed to produce the same quantity of output than at good locations.

Finally, along with the usual first-order conditions, it is necessary to take into consideration the complementary slackness conditions to solve for the equilibrium:

$$\lambda_1 : \quad \omega \geq 0, \quad \lambda_1 \geq 0, \quad \lambda_1(-\omega) = 0; \tag{1.10}$$

$$\lambda_2 : \quad 1 - \omega \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2(1 - \omega) = 0. \tag{1.11}$$

By doing this, I will be able to analyze the extremes, so I can solve for the equilibrium in the cases where the green firm offers its whole stock of certificates, a proportion of it or zero certificates. Now that the basic setting has been shown, it is time to proceed to find the equilibrium for the first case of the model.

1.2.3 Case 1: merit order

I begin with a situation that describes the operation of most electric markets concerning the way that generators are assigned to deliver their power into the system; it is called merit order. In this case, the system operator sets an inelastic demand for each hour, quarter, or five-minute, and all the firms bid their generation and prices for each time interval. The basic idea of this mechanism is to order the marginal costs of each generator from lowest to highest and dispatch them until the power demand is covered. This way, the cheapest energy is dispatched first, minimizing energy production costs. Then, the energy price is set by the marginal cost of the last generator dispatched, and it is paid to all the generators independently of its marginal cost.

To try to replicate this mechanism in this setting, both the conventional and the green firms choose their energy outputs as price takers, considering that both generators are needed to satisfy the demand. In this case, the first firm that goes into the market is the green one since it has zero marginal cost and generates q_r. Next is the conventional generator with marginal cost $v > 0$, and produces q_c without curtailment in its energy supply, so the total generation is $Q_s = q_r + q_c$. Since the conventional firm is the last generator dispatched, energy price equals v, $P_e = v$.

The conventional generator decides its generation q_c, taking the energy price as given, so it solves 1.7. The first-order condition is:

$$q_c : P_e - v = 0. \tag{1.12}$$

Since the green firm is a monopolist in the certificate market, and after substituting 1.6 into 1.9, the Lagrangian that defines its profit maximization problem is:

$$\mathcal{L}_r = E[\tilde{q}_r k_r P_e + \omega \tilde{q}_r k_r f(\alpha(q_r + q_c) - x_s) - \frac{1}{2}\beta k_r^2] - \lambda_1(-\omega) - \lambda_2(\omega - 1). \tag{1.13}$$

After taking expectations and using $E[\tilde{q}_r{}^2] = \mu^2 + \sigma^2$, the first-order conditions are:

$$k_r : \quad - k_r \left(\beta + 2f\omega(\omega - \alpha)\left(\mu^2 + \sigma^2\right)\right) + \alpha f \mu q_c \omega + \mu P_e = 0; \tag{1.14}$$

$$\omega : \quad f k_r \left(k_r(\alpha - 2\omega)\left(\mu^2 + \sigma^2\right) + \alpha \mu q_c\right) + \lambda_1 - \lambda_2 = 0. \tag{1.15}$$

Thus, the equilibrium is given by the energy inverse demand, Eq. 1.5 , the first-order conditions for conventional and green generation, the share of stock of certificates, and the inequality restrictions represented by the Equations 1.10 to 1.15. Following the Kuhn-Tucker procedure, there are four cases [4] related to the restrictions for ω set in the Equations 1.10 and 1.11: a) $\omega = 0, \lambda_1 > 0$, and $\omega = 1, \lambda_2 > 0$; b) $\omega = 0, \lambda_1 > 0$, and $\omega < 1, \lambda_2 = 0$; c) $\omega > 0, \lambda_1 = 0$, and $\omega < 1, \lambda_2 = 0$, and d) $\omega > 0, \lambda_1 = 0$, and $\omega = 1, \lambda_2 > 0$.

After analyzing the four cases that result from the complementary slackness conditions, I found that two of them lead to different shares of certificates that the green firm offers to the market. The results are summarized in Proposition 1, and detailed calculations are in the Appendix.

Proposition 1.1 *Under a merit order dispatch with energy price $P_e = v$, there is an equi-*

[4] A detailed analysis of each case can be found in the Appendix.

librium where the green firm offers a portion of its certificates to the market and another in which it offers its whole certificates' stock.

$$\text{If} \quad \alpha < \alpha'_m, \qquad \begin{cases} q_c^* = \frac{(a-v)(2\beta-\alpha^2 f\sigma^2)-\mu^2(2bv+\alpha^2 fa)}{(\alpha^2 f+b)(\sigma^2+\mu^2)(\beta-\alpha^2 f\sigma^2)+\beta((\alpha^2 f+b)\sigma^2+\mu^2 b)}, \\ k_r^* = \frac{\mu\left(\alpha^2 f\left(a\left(\mu^2+\sigma^2\right)+\sigma^2 v\right)+2bv\left(\mu^2+\sigma^2\right)\right)}{(\alpha^2 f+b)(\sigma^2+\mu^2)(\beta-\alpha^2 f\sigma^2)+\beta((\alpha^2 f+b)\sigma^2+\mu^2 b)}, \\ \omega^* = \frac{\alpha\left(\beta(a-v)+\sigma^2 v\left(b+\alpha^2 f\right)\right)}{\alpha^2 f(a(\mu^2+\sigma^2)+\sigma^2 v)+2bv(\mu^2+\sigma^2)}, \end{cases} \tag{1.16}$$

$$\text{If} \quad \alpha > \alpha''_m, \qquad \begin{cases} q_c^* = \frac{(a-v)(\beta+2f(\mu^2+\sigma^2)(1-\alpha))-\mu^2 v(\alpha f(1-\alpha)-b)}{(\alpha^2 f+b)(\beta+f(1-\alpha)(\mu^2+2\sigma^2))+bf\mu^2}, \\ k_r^* = \frac{\mu(\alpha f(a+(\alpha-1)v)+bv)}{(\alpha^2 f+b)(\beta+f(1-\alpha)(\mu^2+2\sigma^2))+bf\mu^2}, \\ \omega^* = 1. \end{cases} \tag{1.17}$$

In the first equilibrium in 1.16, the green generator supplies the monopoly quantity of certificates when the green goal is small, α'_m. This result is in accordance with the findings of An et al. (2016), about the size of the green goal being small, so the firms restrict their certificate supply to increase the price. In fact, this threshold indicates that the share of green certificates is less than one in the interval $0 < \alpha < \alpha'_m$, once it reaches this limit, the share ω gets bigger than one. Thus, the green firm wants to offer more than its whole stock of certificates, which is not possible.

Now, the equilibrium in Equation 1.17 shows the case in which the green firm offers all its certificates, when the green goal is bigger than α''_m. Here, when the regulator sets a more aggressive policy, i.e. sets a bigger goal, then the green firm sells its whole stock of certificates.

Finally, it is important to be aware that depending on how α'_m compares to α''_m, it might be the case that there is no solution. If $\alpha'_m > \alpha''_m$, then it could be that $\alpha'_m > \alpha > \alpha''_m$ and the generators would be in a zone where 1.16 or 1.17 would be the solutions. In the same way, if $\alpha'_m < \alpha''_m$, it could happen that $\alpha'_m < \alpha$ and $\alpha > \alpha''_m$, so there is no solution.

1.2.4 Case 2: Cournot duopoly in the energy market

Now, consider that both the green and conventional firms compete à la Cournot in the energy market by choosing the capacity investment and conventional generation, respectively. Also, the green firm is a monopolist in the certificate market.

First, I look at the production decision of the conventional firm. After substituting the inverse energy demand P_e from the second stage, Equation 1.5 into 1.7, results in the profit maximization problem:

$$\max_{q_c} \quad \pi_c = E(q_c(a + \alpha f x_s - (\tilde{q}_r k_r + q_c)(\alpha^2 f + b) - v)). \tag{1.18}$$

The first-order condition, after taking expectation, is:

$$q_c: \quad a - v - 2(\alpha^2 f + b)q_c - (\alpha^2 f + b)\mu k_r + \alpha\mu\omega f k_r = 0. \tag{1.19}$$

Now, substituting the energy and certificate inverse demand, Equations 1.5 and 1.6, respectively, into 1.9 gives, as a result, the following Lagrangian:

$$\begin{aligned}\mathcal{L}_r =& E[\tilde{q}_r k_r(a + \alpha f \omega \tilde{q}_r k_r - (\tilde{q}_r k_r + q_c)(\alpha^2 f + b)) + \omega \tilde{q}_r k_r f(\alpha(\tilde{q}_r k_r + q_c) - \omega \tilde{q}_r k_r) \\ & - \frac{1}{2}\beta k_r^2] - \lambda_1(-\omega) - \lambda_2(\omega - 1).\end{aligned} \tag{1.20}$$

The first-order conditions, after taking expectations, are:

$$k_r: \quad \mu(a - q_c(b + \alpha f(\alpha - \omega))) - k_r(\beta + 2(\mu^2 + \sigma^2)(b + f(\alpha - \omega)^2)) = 0; \tag{1.21}$$

$$\omega: \quad f k_r(\alpha\mu q_c + 2k_r(\mu^2 + \sigma^2)(\alpha - \omega)) + \lambda_1 - \lambda_2 = 0. \tag{1.22}$$

The equations 1.10, 1.11, 1.19, 1.21, and 1.22 are needed to find the equilibrium for the conventional and green generators. Identically, as in the merit order case, four possible solutions are associated with the Kuhn-Tucker conditions. As in the merit order case, there are two complementary slackness conditions that lead to different shares of certificates offered into the market. The results are summarized in Proposition 2, and detailed calculations are in the Appendix.

Proposition 1.2 *Under a Cournot dispatch with energy price, $P_e = a+\alpha f x_s-(q_r+q_c)(\alpha^2 f+b)$, there is an equilibrium in which the green firm offers a proportion of its certificates to the market and another in which it offers its whole certificates' stock.*

$$\text{If} \quad \alpha < \alpha_c', \qquad \begin{cases} q_c^* = \frac{2(\mu^2+\sigma^2)((a-v)(\beta+2b\sigma^2)+b^m u^2(a-2v))}{(3\mu^2+4\sigma^2)(\alpha^2\beta f+2b(\mu^2+\sigma^2)(\alpha^2 f+b))+4b\beta(\mu^2+\sigma^2)}, \\ k_r^* \frac{\mu(2b(a+b)(\mu^2+\sigma^2)+\alpha^2 fa(3\mu^2+4\sigma^2))}{(3\mu^2+4\sigma^2)(\alpha^2\beta f+2b(\mu^2+\sigma^2)(\alpha^2 f+b))+4b\beta(\mu^2+\sigma^2)}, \\ \omega^* = \frac{\alpha(\beta(a-v)+a(\alpha^2 f+b)(3\mu^2+4\sigma^2))}{2b(a+b)(\mu^2+\sigma^2)+\alpha^2 fa(3\mu^2+4\sigma^2)}, \end{cases} \tag{1.23}$$

$$\text{If} \quad \alpha \geq \alpha_c', \qquad \begin{cases} q_c^* = \frac{(a-v)(\beta+2\sigma^2 b+2f(1-\alpha)(\sigma^2(1-\alpha)+\mu^2))+(a-2v)(\mu^2 b-\alpha(1-\alpha)f\mu^2))}{(\alpha^2 f+b)(2\beta+(3\mu^2+4\sigma^2)(f(1-\alpha)^2+b))+\mu^2 bf}, \\ k_r^* = \frac{\mu((a+v)(\alpha^2 f+b)+\alpha f(a-v))}{(\alpha^2 f+b)(2\beta+(3\mu^2+4\sigma^2)(f(1-\alpha)^2+b))+\mu^2 bf}, \\ \omega^* = 1. \end{cases} \tag{1.24}$$

The equilibrium in Equation 1.23 represents the case where the green firm offers less than its whole stock when the regulator sets a green goal lower than α_c'. Then, as α grows, the green firm wants to offer more certificates than the ones it has available, so it offers everything, as in Equation 1.24. Unlike, the merit order case, here there is a solution for all the green goals between zero and one.

The intuition of these results is that when the regulator pursues a small green goal, $0 < \alpha < \alpha_c'$, it also means that the market size, αQ_s is small too, then the green firm offers a portion of its certificates to the market so it can maximize its certificates' income. On the contrary, as the policy matures and the green goal becomes more ambitious, the market size becomes larger, so the firm offers all its certificates and prices decreases.

1.3 Numerical illustration

There is no easy way to compare the equilibrium results from the merit order and Cournot duopoly cases found in the last two sections. This is relevant since it would be useful for the regulator to know the size of the α threshold to identify the generator's choices in each case. In this section, I will make a numeric exercise to show the results using Mexican data. It is important to note that the purpose of this task is only to have an idea about how the equilibrium from merit order and Cournot competition compare, not the magnitude of them. To identify all the parameters, it is necessary to have data about consumer demand, generation costs, and regulatory parameters and to assume a probability distribution for the availability of green generation. A description of the sources of this information is detailed in the Appendix.

I determined the thresholds for the α in Equations 1.16, 1.17 and 1.23 that result in corner or interior solutions. For this data, I found that the α thresholds are very close to zero. This means that if the regulator decides to establish the 2018 green goal equal to 5%, then the green generator would choose to offer its whole stock of certificates. Thus, in this case, the green firm will offer all its certificates to the market because the green goal is high enough to incentivize it to offer more than just a portion of them.

The results regarding the green and conventional generation for both the merit order and Cournot analysis are shown in Table 1.1. Given that the green goal is greater than the threshold, the green generator chooses to offer its whole stock of certificates. However, it seems that the conventional and green generation are decreasing with respect to the green goal. This result is unexpected, since the regulator would count on an increase in the green goal, which will result in greater capacity investment. This result will be studied in detail in the next section about comparative statics.

Energy generation (MW)				
	Merit order		Cournot duopoly	
α	$q_r = \mu k_r$	q_c	$q_r = k_r \mu$	q_c
0.05	0.82μ	242,667	0.43μ	121,332
0.058	0.71μ	180,489	0.37μ	90,243
0.074	0.55μ	110,978	0.3μ	55,488
0.109	0.38μ	51,190	0.21μ	25,595
0.139	0.29μ	31,486	0.17μ	15,743

Table 1.1: Energy generation under the merit order and Cournot approaches.

In addition, the green generation, and consequently the capacity investment, is almost negligible compared to the conventional one. Regardless of whether the generation is potentially decreasing with respect to α, the magnitude of green investment gives an idea of the behavior of the retailer with respect to its certificate obligation, and it allows us to analyze if this public policy instrument works as expected. The clearing market condition for the certificates holds, and this means that the retailer buys the certificates offered by the green generator. To clarify, if the green goal for this year is 5%, then, using the data, the retailer needs to get $5\% \times Qs$, equivalent to 12,133 green certificates. This means the retailer gets less than one certificate in the market, so its obligation is unfulfilled by almost 100%.

The last example shows that the green certificate obligation as an energy policy to incentivize investment in green capacity may not be working because the green firm is not receiving enough income to increase its investment significantly. However, remember this data was not calibrated to fit into the model, so to make a better analysis, it would be useful to calibrate the parameters to identify the conditions under which this policy works as intended and analyze how feasible they are considering the actual data.

Additionally, it is important to analyze the retailer's behavior. Why is it not fulfilling its obligation? Why does it prefer to pay the fee? The answer to this question is simple. The retailer is not getting its certificates because this policy does not incentivize it.

Equation (1.2) shows the retailer maximization problem, where the fee, f, is exogenous. The certificate equilibrium price P_c depends on this fee. To give the retailer an incentive to get the certificates, it has to be that the certificates' price is less than the fee, $P_c < f$, so it is more attractive to get certificates than paying the fee. In this case, this fact also has to be considered in the calibration exercise to determine how big f needs to be and if this is feasible.

How should the model be changed to make it more real and show how a case where the retailer fulfills its obligation and, at the same time, increase green generation capacity investment? The fee could be made endogenous and depend on the fulfillment level. It could have a form like this $f(\alpha Q_s - x_s)$ where $f' \geq 0$, i.e., the fee is constant no matter how much the non-observance is or is increasing with respect to it.

This would complicate the model because of the penalty term, $\frac{f}{2}(\alpha Q_s - x_s)^2$, since now f is endogenous. Additionally, it will be necessary to ensure that regardless of the form of f, the model preserves its downward slope certificate demand. However, it would make it more realistic.

The findings of this exercise are summarized as follows. First, if the regulator sets a big enough green goal, then the market size for the certificates increases and the green firm offers a portion of its certificates. Second, green generation is decreasing with respect to the green goal, this suggests that there is an optimum α that maximizes green investment. Third, the retailer does not fulfill its certificate obligation. This result is expected because of the nature of the certificates' demand. However, it is still worrying the fact that there is non-compliance because this would mean that the regulator is supporting a policy that may not be able to reach the green energy goal. Thus, it is important that the non-compliance fee is greater than the certificates' price, so the retailer does not prefer paying the fee instead of buying the certificates.

1.4 On the effects of increasing the green goal

The main objective of this paper is to identify the effect of the green certificate policy on the investment in green generation capacity. In this section, I will analyze the comparative static results to see how the equilibrium responds to changes in the green goal. Proposition 3 summarizes the results for the case in which the green firm offers only a portion of its certificates to the market.

Proposition 1.3 *Let $\alpha < \alpha'_m$ and $\alpha < \alpha'_c$, the green goal thresholds for the merit order and Cournot cases, respectively, when the green generator does not offer its whole stock of certificates, $\omega^* < 1$. Then an increase in the green goal α*

a. raises the investment in green capacity k_r and increments green generation,

b. reduces conventional generation,

c. increases the share of certificates green generator offers to the market,

for both merit order and Cournot approaches.

Accordingly, for the merit order and Cournot cases, setting a higher green goal does lead to a larger investment in green capacity and more green generation. Consequently, since there is more availability of certificates, the share ω^* that the firm is willing to offer to the retailer is bigger. There is also a reduction in the energy produced by conventional technology, which is positive because it is associated with less contaminant emissions.

Proposition 1.4 *Let $\alpha > \alpha''_m$ and $\alpha \geq \alpha'_c$, the green goal thresholds for the merit order and Cournot cases, respectively, when the green generator does offer its whole stock of certificates, $\omega^* = 1$. Then an increase in the green goal α*

a. raises the investment in green capacity k_r and increments green generation if $b \geq \alpha^2 f$,

b. decreases the investment in green capacity k_r and reduces green generation if $b < \alpha^2 f$,

c. reduces conventional generation,

for both merit order and Cournot approaches.

When the green quota is higher than the threshold α for each case, setting a higher goal could increase investment in green capacity always that the demand parameter b is greater or equal to the product of the green goal and the non-compliance fee, in another case the change of the quota will result in a reduction in green investment.

When $b < \alpha^2 f$, the investment in green capacity is not monotonically increasing. This means that there is an optimal quota that maximizes investment. However, this is not necessarily good because it means that if the regulator pursues a high green generation goal and decides to establish a higher punishment as an incentive for the retailer to get more certificates, then increasing the green goal once it reaches the optimum, will not increase investment and the mechanism will be useless.

In addition, the fact that there is a green quota, α^* that maximizes the green investment is important for the success of this policy, understood as an increasing green generation capacity for all the green goals chosen. If the regulator sets a $\alpha > \alpha^*$, then green investment is decreasing with respect to α, so in this situation, the policy would fail to attract more green capacity compared to the one that it could get by setting a lower goal.

Propositions 1.3 and 1.4 suggest that, depending on the green goal set, a higher α does not necessarily lead to greater green energy production, but it does reduce conventional generation, just as in the findings of Amundsen and Nese (2009) and Requate (2015). In addition, these results are in consonance with the conclusions of Perino and Requate (2012) and Gama (2018), about an astringent policy not leading to the adoption of more abatement, but in this case, it also does not result into more green generation capacity. In the end, the conclusion is the same: there is less clean technology adoption.

1.5 Conclusions

This paper presented a model to examine whether green certificates work as an incentive to promote green capacity investment. Although the results show that green certificates promote green investment under certain conditions, that is not necessarily kept when the regulator increases its green energy generation goal. The fact that the quota α has a non-monotonic effect on green investment means that this policy is not enough by itself to promote the installation of new generation capacity. This finding is consistent with previous studies that show that an astringent environmental policy does not always lead to a greater adoption of clean technologies.

It is crucial that the regulator is aware about the non-monotonous nature of the green generation capacity. Although an ambitious green generation goal may seem attractive and an obvious choice, once the goal set is greater than the optimum goal, this may result counterproductive. Thus, this could result into a decrease in green investment, which would make the mechanism ineffective to promote green capacity, and lead to the abandonment of the policy.

Another key conclusion refers to the size of the green generation goal, as a determinant in the certificates' supply of the green firm. When the goal is relatively low, the firm offers a portion of its certificates to increase the price. However, as the regulator sets a more ambitious goal, the firm changes its strategy and offers its whole certificates' endowment. In this situation, the firm does not need to restrict its supply to get a higher price because the certificates' demand is big enough to take all its certificate stock.

It is important the regulator sets a big enough non-compliance fee , so the retailer prefers buying green certificates than paying the fee. Thus, the income from certificates' market can be used to invest in more green generation capacity.

The optimal design of a non-compliance tariff would be an interesting topic for future research. This way, the regulator will be able to implement more effective policies that increase investment in green capacity and speed up the transition towards a low carbon emissions electric market.

Chapter 2

NEUTRALITY AND NON-NEUTRALITY UNDER THE LOUPE: WHICH ONE IS BETTER?

2.1 Introduction

The Renewable Portfolio Standard (RPS) is known to be a technology-neutral policy. This means that all the green generation technologies (solar, wind, geothermal, bioenergy, etc.) are treated the same; this conveys they receive the same quantity of Tradable Green Certificates (TGC). As a consequence of this undifferentiated support, low cost types of renewable generation sources take most of the profits of this policy, because the certificates' price is greater than their marginal generation costs; while it gives no incentive to invest in high cost types of clean energy sources since the price is not enough to cover their marginal costs (Buckman, 2011).

To address this weakness of RPS policy, governments have opted to use another mechanism to support high-cost types of renewable energy resources, like a Feed-in Tariff (FIT) or budget financed subsidies. In other cases, governments redesign their RPS policy so they can provide a differentiated level of support to each technology according to their investment costs (Y. Wang et al., 2024). These policies are known as non-neutral technology, which usually are credit multipliers or banding and carve-out quotas or set-asides.

Credit multipliers policy is a price mechanism that instead of giving one certificate per MWh produced, it grants certificates according to the production costs of the green technologies. Thus, the most expensive ones receive more certificates to trade in the market. While carve-out quotas are a quantity mechanism that sets from the beginning the share of green energy produced with different technologies such that the sum of these quotas is equal to the green energy goal. Each energy producer with the same technology receives one certificate per MWh produced, and they are sold at different prices in submarkets created for each technology.

Why should governments or energy regulators care about these types of non-neutral policies? Bringing new green energy sources into the electric system is expensive, depends on each country's geography and the stage of adoption of generation technologies. Even if there is enough infrastructure to transport the energy from the generation centers to the final consumer, it is still costly to invest in green generators that can best take advantage of the countries' geographical characteristics or their abundance of resources.

In a setting where the RPS is the policy to attract new green generation and reduce the contaminant emissions, this is relevant for two reasons. The first is that the neutral approach could not be able to promote diversity of generation resources. This makes the electric system vulnerable because the energy mix is not so diverse and, usually, the investment in generation goes towards cheap technologies that may not perform as well as the expensive ones.

A diverse energy mix is healthy for the electric grid since the energy demand does not depend on a few generation technologies; in case of failure, other generators can be dispatched and serve the demand. From the point of view of reliability, incorporating new green technologies into the energy mix allows the System Operator (SO) to fight the green generation intermittency to meet energy demand. For example, it could be possible to have solar generation during the day and wind at night.

The second reason refers to the energy tariffs that the consumers pay and the additional rents the energy producers receive. In the words of Bergek and Jacobsson (2010), the TGC are a rent generation machine. However, it is important to mention that having a non-neutral scheme does not eliminate these additional rents, but it does reduce them.

In this paper I investigate how the neutral RPS policy compares to the non-neutral ones in terms of their capability to reach their green energy generation objectives, lower electric tariffs, and greater social welfare.

The main objectives of this paper are described as follows. The first is to provide a characterization of the non-neutral policies: credit multipliers and carve-outs. To the best of my knowledge, there are theoretical approaches to analyze the RPS as a neutral policy, but there is no such study for the non-neutral ones.

The second is to evaluate some empirical facts about these approaches found in the literature. In particular, I tackle the problem raised in the analysis of Gürkan and Langestraat (2014) and Fischlein and Smith (2013) about credit multipliers policy not being able to reach the green generation goal by proposing a green generation goal adjusted that allows to produce the desired green energy. After using an adjusted goal, I found that the three policies meet the target. Additionally, I compare the energy tariff paid by consumers under the three different approaches to determine which one is more costly for consumers, considering that for carve-outs there are markets for each generation technology, and for credit multipliers, apart from granting different amount of certificates, the adjusted green goal could increase the cost for the consumers. I calculate the additional rent the green technologies receive from the certificates' market according to the described in Kwon (2015a), Bergek and Jacobsson (2010), Haas et al. (2011), Toke (2007) and Buckman (2011). In line with the literature, my findings suggest that carve-outs policy offers the smallest additional income from the certificates market compared to the other two policies.

Finally, I solve the social planner problem to identify the approach that leads to the greatest welfare and green energy generation. I found that in the optimum, both carve-outs and multipliers lead to the same outcomes, even the green generation shares. Also, I conclude that under the RPS policy it is better to give a different treatment to the generation technologies rather than a homogeneous one.

The rest of the paper is organized as follows. Section 2.1.1 discuss some of the relevant literature regarding neutral and non-neutral RPS. Section 2.2 sets out the basic model, while Sections 2.2.1 and 2.2.2 provide the equilibrium analysis for the carve-outs and credit multipliers, it also derives the neutral policy as a particular case of the latter. Section 2.3 compares green generation, energy tariffs and additional rents from the certificate market for the three approaches. Finally, section 2.4 compares the outcomes under welfare maximization and identifies the optimum policy variables.

2.1.1 About neutral and non-neutral policies

Empirical evidence shows that policy neutrality often ends up financing the cheapest and most established generation technologies, and displaces or impedes the entrance of new, more expensive green technologies, like offshore wind or concentrated solar power. A good example is Flanders, Belgium, where an RPS policy was established to reduce electricity production using carbon as fuel. As a result, some carbon generators changed to biofuel, a cheap technology, to get the incentive, but there was no new investment in other generation resources, as it was initially intended (Carton, 2016).

Why is this important? In principle, giving the same treatment to the firms should encourage competition. However, this neutrality fails to promote the diversification of the green generation mix, as less mature technologies are less favored due to its higher costs (Y. Wang et al., 2024).

Kwon (2015a) and Bergek and Jacobsson (2010) explain that under a neutral RPS, the generation firms get a significant amount of producer surplus due to the cost difference between different technologies. This is due to the fact that technologies with lower marginal costs benefit from the certificate's price because it represents an income additional to the energy price they receive in the electricity market. While the more expensive ones need higher certificate's price to be profitable. As a consequence, mature technologies with low costs receive rents, whereas immature technologies are forced out of the market even if they have the potential to reduce production costs in the long run, this is known in the literature as rent-seeking.

Multipliers are a device in which different multiples of tradable certificates are issued for each unit of generation depending on the type of renewable energy source (Buckman, 2011). This mechanism has been implemented in the UK and some states in the US and Korea. Under this framework, the green certificate granting not only depends on the energy production but on a multiplier factor that escalates the number of certificates each green generator receives, according to their generation costs. So that the most expensive technology gets more certificates.

Among the advantages of multipliers are flexibility to change the multipliers value according to technological change. There is a unique market to sell certificates, which means more liquidity. One of the weaknesses is that there is no methodology to set the multipliers value, so it is determined by the regulator. The main flaw is that if the target of the RPS is expressed as a number of certificates, then the certificate's multipliers can reduce the actual target reached. To avoid this problem, the UK government sets a higher goal than the one it pretends to reach to account for the goal reduction caused by credit multipliers.

In the carve-outs or set asides setting, the regulator still pursues a green generation objective, but this is divided into different small goals to reach by generating specific quotas of energy from diverse technologies. In simple words, they are RPS submarkets (Buckman, 2011), but each technology in the same group is given one certificate per MWh generated. This policy is widely implemented in some states of the US.

Regarding which non-neutral policy is more effective, the literature is not conclusive. With respect to the credit multipliers, Gürkan and Langestraat (2014) warn that the UK banding policy cannot guarantee that the original obligation target is met, hence potentially resulting in more pollution. In an empirical analysis with data from the US, Fischlein and Smith (2013) suggest that banding allows energy utilities to take advantage to produce energy with the technologies that earn additional certificates and that not necessarily translates into more green energy.

In one of the first quantitative analysis for the UK, Y. Wang et al. (2024) examines the impact of this policy on the development of renewable technologies, focusing on onshore wind, offshore wind, and solar. They suggest that banding was crucial to help the UK to achieve its targets on electricity generation from renewable sources. Xin-gang et al. (2022) show that the introduction of credit multipliers promote TGC transactions, improve the social welfare and optimize the power source structure.

Kim and Tang (2020) show that solar carve-outs increase the diversity of generation technologies such as solar, wind, biomass and geothermal, but it does not happen the same way with credit multipliers. In a quantitative analysis for the US, Sarzynski et al. (2012) found that the presence of state RPS and specific solar carve-outs provisions heavily influenced the market deployment of solar technology.

2.2 The model

In this Section, I propose a set-up to model the credit multipliers and carve-outs policies based on the characteristics discussed above. I solve for the equilibrium and then compare them in terms of output, energy tariff and rent-seeking behavior.

Consider an electric market with two goods: electricity and green certificates. Electricity is a homogeneous good produced by three firms in a Cournot oligopoly market: conventional (pollutant), c, and two green technologies (zero emissions), v_1 and v_2. The energy output of all three firms, q_c, q_{v_1}, q_{v_2}, is necessary to satisfy the energy demand q, so in equilibrium, the total generation is $q = q_c + q_{v_1} + q_{v_2}$. Generation costs [1] are $C_i(q_i) = c_i q_i^2$, for $i = c, v_1, v_2$ and $c_{v_1} > c_{v_2} > c_c$.

In this economy, there is an ongoing TGC policy to increase green generation. The regulator sets a green goal α that represents the share of green energy with respect to the total

[1] In Chapter 1, I assumed that green energy has zero generation cost. In this Chapter, I am assuming there are generation costs for both green firms to account for the heterogeneity of costs among the three technologies. However, these costs can be interpreted as the Levelized Cost of Energy (LCOE) that shows the total cost of building and operating the asset per unit of total electricity generated over an assumed lifetime.

energy production. The environmental regulator can choose between three approaches to grant the certificates (j): neutral, credit multipliers and carve-outs, n, m and co, respectively. As I stated before, the difference between these granting mechanisms is the way they treat the different green technologies according to their generation costs. The neutral scheme allocates both green generators 1 certificate per unit of energy generated, regardless of their production costs. The multipliers and carve-outs allow for a differentiated treatment of each green technology to acknowledge this heterogeneity. While multipliers use a price mechanism, the carve-outs use a quantity one.

In this setting, all the firms maximize benefits by choosing their energy production, q_i, that is sold at a price P_e. While the green firms 1 and 2 also offer all their certificates stock and this is sold in a competitive market at a price P_c. Notice that the green firms do not choose their certificate supply, this is determined by their generation. Additionally, the market structure is characterized as follows under the three policies: neutral, credit multipliers and carve-outs, $j = n, m, co$, respectively:

(A1) the inverse energy demand function is linear, $P_e^j(q^j) = a - bq^j$, where $a > 0$ and $b > 0$ for $j = n, m, co$;

(A2) the certificates' market clearing conditions are

a. Neutral: $\alpha q^n = q_{v_1}^n + q_{v_2}^n$, where $0 < \alpha < 1$;

b. Credit multipliers: $\alpha q^m = \gamma_1 q_{v_1}^m + \gamma_2 q_{v_2}^m$, where $\gamma_1 > 0$ and $\gamma_2 > 0$;

c. Carve-outs: $\beta_1 q^{co} = q_{v_1}^{co}$ and $(\alpha - \beta_1) q^{co} = q_{v_2}^{co}$, where $0 < \beta_1 < \alpha$;

(A3) the damage function is given by $D(q_c^j) = \frac{d{q_c^j}^2}{2}$, with $d > 0$, for $j = n, m, co$.

The core of the model lies on the Assumption A2, that represents how the regulator treats the green technologies under every approach. Assumption A2.a shows that both firms receive one certificate per MWh produced. Thus, in the neutral case, the green goal α is equivalent to the supply of green certificates. Assumption A2.b breaks this equivalence.

Here, the multipliers γ_1 and γ_2 indicates how many certificates receive each technology, this means that A2.b is equivalent to a certificate requirement, not a green energy one. This issue is studied in detail in Section 2.2.1. Finally, regarding the carve-outs approach, Assumption A2.c shows the market clearing conditions for technologies 1 and 2. In this case, the green generation goal is divided between both technologies by assigning an energy quota to each of them, β_1 and $\alpha - \beta_1$, creating a market for each technology.

In the next Sections, I solve the market equilibrium for the neutral and credit multipliers (Section 2.2.1) and carve-outs (Section 2.2.2).

2.2.1 Credit multipliers

Under this scheme, the regulator allocates an amount of γ_i, $i = 1, 2$, certificates per unit of energy generated (MWh) to each green technology, where the most expensive technology gets more certificates, $\gamma_1 > \gamma_2 > 0$. The certificates are sold at the price P_c^m.

All firms maximize their benefits that consist of their income from the energy and certificate sales, which in the case of the conventional firm this last one is zero, minus their generation costs. The optimization problems for each generator are given by

$$\max_{q_c^m} \quad q_c^m[a - b(q_c^m + q_{v_1}^m + q_{v_2}^m)] - c_c(q_c^m)^2, \tag{2.1}$$

$$\max_{q_{v_1}^m} \quad q_{v_1}^m[a - b(q_c^m + q_{v_1}^m + q_{v_2}^m)] + \gamma_1 P_c^m q_{v_1}^m - c_{v_1}(q_{v_1}^m)^2, \tag{2.2}$$

$$\max_{q_{v_2}^m} \quad q_{v_2}^m[a - b(q_c^m + q_{v_1}^m + q_{v_2}^m)] + \gamma_2 P_c^m q_{v_2}^m - c_{v_2}(q_{v_2}^m)^2. \tag{2.3}$$

The first-order conditions from Equations (2.1), (2.2) and (2.3) along with Assumption (A2.b) should define the equilibrium under the credit multipliers approach. Considering that the ultimate goal of the TGC policy is to reach a green generation target, α, this equilibrium will lead to a result where the green goal is not achieved.

Does this imply that the credit multiplier policy is not effective to reach the green goal? The answer goes beyond a yes or no. To understand why this policy does not reach the expected generation, it is important to look at the clearing certificate market condition in Assumption (A2.b) compared to the one in (A2.a). In the neutral policy, this condition indicates that the supply of certificates is equal to the supply of green energy from both firms because the firms receive 1 certificate per unit of electricity produced, $\gamma_1 = \gamma_2 = 1$. However, under the credit multipliers policy this is not true because the amount of certificates each generator receives depends on their technology γ multiplier. As a result, the amount of certificates in the market does not reflect the amount of green energy produced.

The market clearing condition in Assumption (A2.b) for $\gamma_1, \gamma_2 \neq 1$ puts the green goal α in terms of certificates, but this α is different from the green generation share actually achieved under this credit multipliers scheme, $\frac{\gamma_1 q^m_{v_1} + \gamma_2 q^m_{v_2}}{q^m_{v_1} + q^m_{v_2} + q^m_c} = \alpha_{goal} \neq \frac{q^m_{v_1} + q^m_{v_2}}{q^m_{v_1} + q^m_{v_2} + q^m_c} = \alpha_{real}$. This happens because the multipliers affect the energy production decisions.

For example, assume the green goal is $\bar{\alpha}$ with $\gamma_1 > \gamma_2 > 1$, this means that less energy is necessary to reach the target since green generation is worth more in terms of certificates, so the green generation would be less than the one under the neutral scheme. In contrast, the opposite occurs when $\gamma_1 < 1$ and $\gamma_2 < 1$ because green energy is less valuable in terms of certificates, and more energy is needed to get to $\bar{\alpha}$. In both cases, the policy results into not reaching the green goal α, and the green energy ratio is either above or below α.

There are two lessons from the last paragraphs. The first is that under the credit multipliers scheme, the green energy is not equal to the quantity of certificates supply. And the second is that the multiplier size matters, especially when it is greater than one because it leads to a lower green energy production. These issues could mislead the unaware policymakers to assess the TGC policy as successful when it is not. Especially, in the second case, where firms receive income from the certificate market, but the energy market is not producing the green energy expected.

This issue has been identified in Fischlein and Smith (2013). They explain that credit multipliers have a negative impact on the share of renewable energy because utilities produce the type of energy that earn more certificates, and it lowers the quantity of renewable power to achieve the goal. To deal with this concern, the UK government considers the additional certificates to be created before adding on its headroom adjustment (Buckman, 2011 and Department for Energy Security & Net Zero, 2023).

Currently, the UK considers a headroom of 10%; however, the Guidance to calculate the Renewables Obligation for 2024 to 2025 does not specify how this headroom is obtained. As a part of my analysis, I calculate an adjusted green goal $\tilde{\alpha} = \tilde{\alpha}(\alpha)$ to account for the amount of certificates to be emitted and to achieve the green goal. This result is shown in Proposition 2.1 and the calculations are detailed in Section 2.6.

Proposition 2.1 *In the credit multipliers setting (A1), (A2.b) and the first-order conditions from problems (2.1), (2.2) and (2.3), there is a green requirement*

$$\tilde{\alpha}(\alpha) = \frac{\alpha(\gamma_1^2(b + 2c_{v_2}) + \gamma_2^2(b + 2c_{v_1})) - (1 - \alpha)(\gamma_1 - \gamma_2)^2(b + 2c_c)}{\gamma_1(b + 2c_{v_2}) + \gamma_2(b + 2c_{v_1})}$$

that allows to reach the green goal α when the regulator grants certificates from a credit multipliers perspective, this is $\alpha = \frac{q_{v_1}^m(\tilde{\alpha}) + q_{v_2}^m(\tilde{\alpha})}{q_{v_1}^m(\tilde{\alpha}) + q_{v_2}^m(\tilde{\alpha}) + q_c^m(\tilde{\alpha})}$.

The adjusted green goal in Proposition 2.1 can be read as the difference between the "marginal cost"[2] of the green generation (first term) and the "marginal cost" of the conventional one, weighted by the certificates' multipliers and the green generation cost. As expected, an increase in the desired green goal α, as well as conventional and green technology 2, result into a bigger adjusted goal. However, the effect of an increase in the green technology and both multipliers is not clear and depends on the size of α.

Proposition 2.1 shows how much the regulator will need to adjust up or down its certificate requirement in order to reach its green goal α. This means that the consumer needs to get more or less certificates, depending on the size of the multipliers. Considering that the new requirement will be different from the one required by the other two approaches, it

[2] This term is between quotation marks because it is not exactly the marginal cost, but it is close. Note that the green generation marginal cost is $2q_{v_1}c_{v_1} + 2q_{v_2}c_{v_2}$, but instead I got $\frac{q_{v_1}+q_{v_2}}{q_{v_1}+q_{v_2}+q_C}(\gamma_1^2(b+2c_{v_2})+\gamma_2^2(b+2c_{v_1}))$.

is reasonable questioning if this policy is more or less expensive for the consumers than the neutral or carve-outs ones. To answer this question, first, it is necessary to determine the generation equilibrium under the credit multipliers perspective. To this purpose, it is important to update the Assumption (A2.b) as follows.

(A2.b') the certificate market clearing condition for the credit multipliers case is $\tilde{\alpha}(\alpha)q^m = \gamma_1 q_{v_1}^m + \gamma_2 q_{v_2}^m$, where $\gamma_1 > 0$ and $\gamma_2 > 0$.

Using this new assumption for the credit multipliers approach, now I am ready to characterize the equilibrium. This result is shown in Proposition 2.2 and the calculations are detailed in Section 2.6.

Proposition 2.2 *In the credit multipliers setting under Assumption (A2.b') a Cournot equilibrium exists with outcomes*

$$\begin{aligned}
q_c^m &= \frac{a(1-\alpha)}{b+(1-\alpha)(b+2c_c)}, \quad q_{v_1}^m = \frac{a[\alpha\gamma_1(b+2c_{v_2}) - (1-\alpha)(\gamma_1-\gamma_2)(b+2c_c)]}{(b+(1-\alpha)(b+2c_c))(\gamma_1(b+2c_{v_2})+\gamma_2(b+2c_{v_1}))}, \\
q_{v_2}^m &= \frac{a[\alpha\gamma_2(b+2c_{v_1}) + (1-\alpha)(\gamma_1-\gamma_2)(b+2c_c)]}{(b+(1-\alpha)(b+2c_c))(\gamma_1(b+2c_{v_2})+\gamma_2(b+2c_{v_1}))}, \ \textit{and} \\
P_c^m &= \begin{cases} 0, \ if \ 0 < \alpha \leq \alpha_1, \ \alpha_1 = \frac{2(b+2c_c)(b+c_{v_1}+c_{v_2})}{3b^2+4c_{v_1}c_{v_2}+4c_c(c_{v_1}+c_{v_2})+4b(c_c+c_{v_1}+c_{v_2})}, \\ \frac{a[\alpha(b+2c_{v_1})(b+2c_{v_2})-(1-\alpha)((b+2c_c)(b+c_{v_1}+c_{v_2})-b^2)]}{(b+(1-\alpha)(b+2c_c))(\gamma_1(b+2c_{v_2})+\gamma_2(b+2c_{v_1}))}, \ if \ \alpha_1 < \alpha < 1. \end{cases}
\end{aligned}$$

Notice that the amount of conventional production is determined by $1-\alpha$. Also, considering that, under this approach, the most expensive technology receives more certificates $\gamma_1 > \gamma_2$, the second term in q_{v_1} shows how the generation of firm 1 adjusts to this incentive, so it produces less energy. On the contrary, firm 2 receives fewer certificates, so the second term of q_{v_2} is positive, thus, firm 2 produces produces more energy.

It is important to point out that the certificates' price, P_c^m, is not always positive. When the requirement α is lower than α_1, $P_c^m < 0$. This happens because without a certificates' market, there is an amount of green energy production traded in the oligopolistic energy market. Once a RPS policy is adopted and the regulator sets a green goal, it could happen that this goal is lower than the green energy production without the RPS policy, so there would be an excess of certificates' supply and the price would be zero. However, when the goal is greater than α_1, then the RPS policy induces a larger green energy production compared to the case without it.

To conclude the characterization of the outcomes under the credit multipliers approach, I derive the energy production and certificates price of equilibrium from the neutral policy as a particular case of the credit multipliers specification.

If $\gamma_1 = \gamma_2 = 1$, the regulator grants one certificate per unit of energy produced. This assignment rule corresponds to the one used under the neutral approach. When $\gamma_1 = \gamma_2 = 1$, Equations (2.1), (2.2) and 2.(3) along with (A2.b') define the equilibrium in the neutral scheme. This is characterized in the following Proposition, all the calculations are detailed in Section 2.6.

Proposition 2.3 *In the credit multipliers setting with $\gamma_1 = \gamma_2 = 1$, along with the first-order conditions from problems (2.1), (2.2) and (2.3), and Assumption (A2.a), a Cournot equilibrium exists with outcomes*

$$q_c^n = \frac{a(1-\alpha)}{b+(1-\alpha)(b+2c_c)},\ q_{v_1}^n = \frac{\alpha a(b+2c_{v_2})}{2(b+c_{v_1}+c_{v_2})(b+(1-\alpha)(b+2c_c))},\ q_{v_2}^n = \frac{\alpha a(b+2c_{v_1})}{2(b+c_{v_1}+c_{v_2})(b+(1-\alpha)(b+2c_c))},\ \textit{and}$$

$$P_c^n = \begin{cases} 0,\ if\ 0 < \alpha \leq \alpha_1, \\ \frac{a(\alpha(b+2c_{v_1})(b+2c_{v_2})-2(1-\alpha)(b+2c_c)(b+c_{v_1}+c_{v_2}))}{2(b+c_{v_1}+c_{v_2})(b+(1-\alpha)(b+2c_c))},\ if\ \alpha_1 < \alpha < 1. \end{cases}$$

In this case, the certificate clearing market condition and the green energy production share are the same, so it is not necessary to use the adjusted green goal. Even more, when $\gamma_1 = \gamma_2 = 1$, the adjusted objective is $\tilde{\alpha}(\alpha) = \alpha$. Contrary to the credit multipliers policy, here there is no need to modify energy production since both green generators receive the same amount of certificates, so the productions only depend on their costs.

2.2.2 Carve-outs quotas

Now, I analyze the carve-outs scheme. Under this setting, the regulator gives both generators one certificate per MWh of energy generated, as in the neutral policy. However, it sets a quota β_1 and β_2 that has to be covered by the consumer with certificates of each green technology. In this case, the total certificates' requirement is equal to the sum of both requirements, so that $\beta_2 = \alpha - \beta_1$. Notice that different from the credit multipliers and the neutral cases, there is a certificate market for each technology, the certificates are sold at prices $P^{co}_{c_1}$ and $P^{co}_{c_2}$.

The conventional firm optimization problem is equal to the one in Equation (2.1), but choosing q^{co}_c. The corresponding problems to the green firms are

$$\max_{q^{co}_{v_1}} \quad q^{co}_{v_1}[a - b(q^{co}_c + q^{co}_{v_1} + q^{co}_{v_2})] + P^{co}_{c_1} q^{co}_{v_1} - c_{v_1}(q^{co}_{v_1})^2, \tag{2.4}$$

$$\max_{q^{co}_{v_2}} \quad q^{co}_{v_2}[a - b(q^{co}_c + q^{co}_{v_1} + q^{co}_{v_2})] + P^{co}_{c_2} q^{co}_{v_2} - c_{v_2}(q^{co}_{v_2})^2. \tag{2.5}$$

The second term in Equations (2.4) and (2.5) shows that each technology will get a different amount of certificate market income depending on the quota β_1 and the equilibrium price for each one. Another important feature of this specification is that unlike the credit multipliers case, here there are no additional green certificates created, so it is not necessary to adjust the green energy share objective to effectively reaching it.

The equilibrium under the carve-outs quotas can be characterized in the following way, all the calculations are detailed in Section 2.6.

Proposition 2.4 *In the carve-outs setting (A1), (A2.c) and the first-order conditions from problems (2.1), (2.4) and (2.5), a Cournot equilibrium exists with outcomes*

$q^{co}_c = \frac{a(1-\alpha)}{b+(1-\alpha)(b+2c_c)}$, $q^{co}_{v_1} = \frac{a\beta_1}{b+(1-\alpha)(b+2c_c)}$, $q^{co}_{v_2} = \frac{a(\alpha-\beta_1)}{b+(1-\alpha)(b+2c_c)}$,

$$P_{c_1} = \begin{cases} \frac{a[\beta_1(b+2c_{v_1})-(1-\alpha)(b+2c_c)]}{b+(1-\alpha)(b+2c_c)}, \ if \ \alpha_1 < \alpha < 1, \ \frac{(1-\alpha)(b+2c_c)}{b+2c_{v_1}} < \beta_1 < \frac{\alpha(b+2c_{v_2})-(1-\alpha)(b+2c_c)}{b+2c_{v_2}} \\ 0, \ if \ 0 < \alpha \leq \alpha_1, \end{cases} \text{, and}$$

$$P_{c_2} = \begin{cases} \frac{a[(\alpha-\beta_1)(b+2c_{v_2})-(1-\alpha)(b+2c_c)]}{b+(1-\alpha)(b+2c_c)}, \ if \ \alpha_1 < \alpha < 1, \ \frac{(1-\alpha)(b+2c_c)}{b+2c_{v_1}} < \beta_1 < \frac{\alpha(b+2c_{v_2})-(1-\alpha)(b+2c_c)}{b+2c_{v_2}} \\ 0, \ if \ 0 < \alpha \leq \alpha_1. \end{cases}$$

Under this approach, the amount of green energy produced by each technology is automatically fixed when the regulator sets the quotas β_1 and α. Unlike the neutral and multipliers policy, productions for each technology do not depend on green technology costs, but only the conventional ones. This means that an increase in c_c, results into a reduction not only of conventional production but green. This may seem counterintuitive, however it is because of the design of the carve-outs scheme. A reduction in conventional production caused by an increase in c_c means that there is room to expand green energy production. However, since the quotas of each technology are fixed, the firms cannot respond accordingly. In this case, it seems useful the design used in some states of the US; they set quotas for specific technologies, but the green goal is bigger than the sum of the quotas, so it allows the energy production to respond to these kinds of external changes.

Now that I have calculated the equilibria in each case, I am ready to compare them to identify which one leads to more energy production, higher tariffs and identifying the additional rent the green generators receive under all the schemes.

2.3 Comparing equilibria and rent-seeking behavior

2.3.1 Energy production

In this section, I compare the generation equilibrium for both neutral and non-neutral approaches, to identify which one leads to a higher green output among technologies.

As expected, the share of green energy produced is identical among the three certificate granting approaches and equal to α, but not the generation of each green technology. The objective of non-neutral policies is to increase the generation of expensive technologies by giving them an incentive through certificate prices or quotas. Proposition 2.5 shows the results of comparing the production of technology 1 among the three schemes.

Proposition 2.5 *Let $q^j_{v_1}$, $j = n, m, co$ the generation of equilibrium under the three approaches, $0 < \beta_1 < \alpha$, and $\gamma_1 > \gamma_2 = 1$, then*

1. *When the green goal is small, $0 < \alpha < \alpha_1$, (high, $\alpha_1 \leq \alpha < 1$), the production*

of the green technology 1 is greater (lower) under the neutral scheme than the credit multipliers one.

2. *When the quota β_1 is small,* $0 < \beta_1 < \frac{\alpha(b+2c_{v_2})}{2(b+c_{v_1}+c_{v_2})}$, *(high,* $\frac{\alpha(b+2c_{v_2})}{2(b+c_{v_1}+c_{v_2})} \leq \beta_1$*) the production of the green technology 1 is greater (lower) under the neutral scheme than the carve-outs one.*

3a. *For a small green goal α,* $0 < \alpha \leq \alpha_2 = \frac{(\gamma_1-1)(b+2c_c)}{b(2\gamma_1-1)+2(\gamma_1-1)c_c+2\gamma_1 c_{v_2}}$, *the production of the green technology 1 is greater under the carve-outs approach than the credit multipliers one.*

3b. *When the quota β_1 is small (high) and the green goal is high,* $0 < \beta_1 \leq \tilde{\beta}_1$ *(*$\tilde{\beta}_1 < \beta_1 < \alpha$*) and* $\alpha_2 < \alpha < 1$, *with* $\tilde{\beta}_1 = \frac{\alpha\gamma_1(b+c_{v_2})-(1-\alpha)(\gamma_1-1)(b+2c_c)}{\gamma_1(b+2c_{v_2})+b+2c_{v_1}}$, *the production of the green technology 1 is greater (lower) under the multipliers scheme than the carve-outs.*

Even though the comparison is not conclusive on which of the three granting mechanisms incentives more energy production with the technology 1, this exercise allows having a clearer idea on the conditions that make one approach to perform better than another. The neutral scheme performs better when the green goal is low, this means that when the TGC policy is in its early stages it is more convenient to implement a neutral policy since it will lead to more energy produced with technology 1. However, when the policy is mature and the regulator aims to reach a bigger green goal, it is a good choice to execute a non-neutral policy.

Which one should the regulator choose? The second point in Proposition 2.5, shows that if the regulator chooses a quota β_1 greater than technology 2 weighted cost, $\frac{\alpha(b+2c_{v_2})}{2(b+c_{v_1}+c_{v_2})}$, the energy production with technology 1 is greater than the one under the neutral approach, no matter the size of the green goal. This is an advantage with respect to the credit multipliers policy. However, it is not clear how big the quota β_1 should be. This issue is analyzed in Section 4.

Regarding the total energy produced, notice that it is the same in all the cases, $q = \frac{a}{(2-\alpha)b+2(1-\alpha)c_c}$. In particular, conventional generation is equal in all the specifications. This is due to the clearing certificate market condition that sets the share of conventional generation as $(1-\alpha)$. As a consequence, the energy price is the same in every case. Thus, the difference in the electric tariff the consumer pays lies on the expenditure in certificates. In the next section, I identify which granting approach leads to a greater energy tariff.

2.3.2 Which approach makes the consumer to pay more for certificates?

This section compares the consumers' expenditure on energy for the three certificates' schemes, by comparing the electric tariff they would pay. This is important because even though the consumers do not demand green certificates, this obligation is indirectly transferred to them by the retailer through the energy tariff, that is the sum of the energy and certificates prices. For the neutral and carve-outs approaches, the consumer tariffs are $T^n = P_e + \alpha P_c^n$ and $T^{co} = P_e + \beta_1 P_{c_1} + (\alpha - \beta_1)P_{c_2}$, respectively. The tariff for the credit multipliers case is $T^m = P_e + \tilde{\alpha} P_c^m$. In this case, I consider that the regulator ask for $\tilde{\alpha}$ certificates per MWh of energy consumed instead of α as in the previous cases. The reason behind this is in Proposition 2.1, that says that in order to reach a green goal α, the regulator has to adjust this requirement to $\tilde{\alpha}$. Proposition 2.6 shows the results of this comparison.

Proposition 2.6 *Let $\gamma_1 > \gamma_2 > 0$ and $0 < \beta_1 < \alpha < 1$. Then,*

a) $P_e + \alpha P_c^n < P_e + \tilde{\alpha} P_c^m$;

b) $P_e + \alpha P_c^n < P_e + \beta_1 P_{c_1} + (\alpha - \beta_1)P_{c_2}$.

Interestingly, non-neutral policies do not result into cheaper energy tariffs for consumers. In the case of the credit multipliers approach, this is due to the use of the adjusted green goal, which means that regulators asks the consumers to pay a larger quota of certificates. When comparing the cost of getting an amount α of certificates under both policies, it results that $\alpha P_c^n > \alpha P_c^m$ when $\frac{2(b+2c_c)}{3b+4c_c+2c_{v_2}} < \alpha < 1$. so for a high green goal, it is cheaper opting for the credit multipliers scheme. In the carve-outs' scenario, the source of this elevated electric tariff is the fact that this policy creates one market for each technology, which reduces the certificates' supply according to the established quota and sets a higher certificates' price for both technologies.

This result is according to the literature that argues that green certificates' policy are an onerous burden for consumers who end up paying high electric bills to support established green generation technologies. Does this mean that non-neutral policies do not work? To answer this question, it is necessary to focus not only in consumer tariffs but in the social welfare that results of applying these policies. This issue is studied in Section 2.4, but before going there, in Section 2.3.3 I analyze in detail the certificates' prices in terms of marginal costs and identify the additional rents that each scheme provides to the generators.

2.3.3 Rent seeking behavior

Some preliminaries about rent seeking

One of the main criticisms of the neutral TGC policy is that it does not promote the technological change nor investment in immature technologies because the price offered is not enough to incentivize the expensive technologies, but it is high enough to attract mature and established technologies so they can benefit from the price differential; this behavior is known in the literature as rent seeking. The idea behind this is that investors in new renewable energy sources should be compensated fairly but by no means of exaggerated profits (Haas et al., 2011).

Bergek and Jacobsson (2010) distinguish between two types of rents. The first is generated by already profitable plants without the additional payment. The second one is related to the fact that the overall marginal cost curve for renewables consists of several different curves. At each point, the certificate price corresponds to the most expensive technology for each level of requirement α (marginal technology) and all technologies with lower costs will receive an extra profit. As more expensive technologies are required to fill the quota, the rents to submarginal technologies will increase.

Before banding were introduced in the UK, the critics argued that due to RPS policy arrangements, it was more profitable for onshore wind developments compared to offshore wind farms, even though the latter has greater energy production potential, but it is more expensive (Toke, 2007). To reduce the amount of additional rents, some countries implemented credit multipliers and carve-out quotas.

Following Kwon (2015a) credit multipliers can reduce RPS rents, but this reduction depends on the size of the multipliers (γ). The author claims that the ratio of multipliers must be proportional to the generation cost of each technology less the average electricity price. However, it would be difficult to find the right γ due to information asymmetry between green energy producers and the regulator. In the UK, this estimation is not done by the regulator but by consultant firms based on short and medium term green technologies generating costs (Buckman, 2011). Considering the difficulties to estimate the multipliers, carve-outs is a more effective policy design because it creates a market for each technology.

Identifying additional rents in the certificates price

In the remainder of this section, I will determine the additional rent the green generation firms receive under the three RPS approaches and weight up each of them to identify which one generates the minimum extra income for green energy producers.

The certificate prices P_c in Propositions 2.2, 2.3 and 2.4 can be written as

$$\begin{aligned}
neutral: \quad & P_c^n = \frac{\omega_2(MC_1 - P_e) + \omega_1(MC_2 - P_e) + b(q_{v_1}\omega_2 + q_{v_2}\omega_1)}{\omega_1 + \omega_2}, \\
credit\ multipliers: \quad & P_c^m = \frac{\omega_2(MC_1 - P_e) + \omega_1(MC_2 - P_e) + b(q_{v_1}\omega_2 + q_{v_2}\omega_1)}{\gamma_2\omega_1 + \gamma_1\omega_2}, \\
carve-outs: \quad & P_{c_1} = MC_1 - P_e + bq_{v_1} \quad and \quad P_{c_2} = MC_2 - P_e + bq_{v_2}, \\
& with\ \omega_i = b + 2c_{v_i},\ i = 1,2\ and\ MC_1,\ MC_2\ are\ the\ marginal \\
& costs\ of\ technologies\ 1\ and\ 2,\ respectively.
\end{aligned}$$

Now, I proceed to compare the certificates price for the three approaches with the ideal price that reduce the additional rents that the green producers receive, i.e., $P_c = MC_1 - P_e$, to identify which one transfers more extra income to the green firms.

The price in the neutral case corresponds to the weighted sum of the differences between the marginal cost of each technology and the energy price, plus the weighted sum of the energy production of green firms. As found empirically in the literature, under the neutral case, there is extra rent going to both generators, $P_c^n > P_c$. In particular, I found that the green firm 1 receives $rent_1^n = \frac{b(q_{v_1}\omega_2 + q_{v_2}\omega_1) - \omega_1(MC_1 - MC_2)}{\omega_1 + \omega_2} > 0$, while the green firm 2 gets $rent_2^n = \frac{b(q_{v_1}\omega_2 + q_{v_2}\omega_1) + \omega_2(MC_1 - MC_2)}{\omega_1 + \omega_2} > 0$. Since the firm 1 has greater marginal costs, then the rent received by the firm 2 is bigger than the one that firm 1 gets. As the green generation goal increases, the certificate price goes up, so the additional rent is bigger too.

The certificate price in the credit multipliers case is almost the same as in the neutral one, with the denominator also multiplied by the number of certificates granted to each technology, γ. Notice that the price in the neutral case is equivalent to the one for credit multipliers when $\gamma_1 = \gamma_2 = 1$.

As Kwon (2015b) suggests, credit multipliers may reduce the additional rent, but it depends on the size of the γ's. It all comes down to solve $P_c^m - P_c = 0$ to find γ_1 that makes zero the extra profit for firm 1. However, in this case, since there is only one equation it is not possible to determine the value of γ_2, so I will assume $\gamma_2 = 1$. When $\gamma_1 = \tilde{\gamma}_1 = \frac{b(q_{v_1}\omega_2 + q_{v_2}\omega_1) - \omega_1(MC_1 - MC_2) + \omega_2(MC_1 - P_e)}{\omega_2(MC_1 - P_e)}$, so that $P_c^m = MC_1 - P_e$, and the additional rent for firm 2 is the difference between the marginal costs of both generators, $rent_2^m = MC_1 - MC_2$, and $rent_2^n > rent_2^m$. However, if the regulator chooses $1 < \gamma_1 < \tilde{\gamma}_1$, there is an extra profit for the green firm 1, but it is smaller than the one under the neutral scheme. Also, when $\gamma_1 > \tilde{\gamma}_1$, $P_c^m < MC_1 - P_e$, this means that the certificate price is not enough to cover the costs of the most expensive technology. This is relevant because the regulator may think that the more certificates green expensive technologies receive, the better. However, this is not necessarily true, since more certificates in the market would decrease the price and send the wrong signal of plenty of green energy production in the economy when there is only abundance of certificates.

The case of carve-outs is a different scenario. Here, since there is one market for each technology, both prices are near to their own marginal cost. However, this does not mean the extra rent is zero but close. Both generators get an income of $rent_i^{co} = bq_{v_i}$ for $i = 1, 2$.

2.4 Social welfare

In this section, I endogenize the public policy variables (α, β_1 and γ_1, I assume $\gamma_2 = 1$) to allow the regulator to choose the ones that maximize the social welfare to identify which approach leads to a greater welfare, but also allows reaching a bigger green generation goal.

For this task, I assume the regulator wants to cut CO_2 emissions from conventional generation by increasing the green generation. The environmental harm caused by conventional production is represented through the damage function from (A3). From (A1) and (A3), the social welfare function [3] for this electric market under the three scenarios is $SW^i = U(q^i) - c_c q_c^i - c_{v_1} q_{v_1}^i - c_{v_2} q_{v_2}^i - \frac{d{q_c^i}^2}{2}$, for $i = n, m, co$.

Since the three approaches drive to the same output, the term that make welfare functions distinct is $-c_{v_1} q_{v_1}^i - c_{v_2} q_{v_2}^i$. This means that the difference in the optimal policy variables will depend on how the generation shares are distributed between the two green technologies under the neutral, credit multipliers and carve-outs policies.

Proposition 2.7 shows the results to the following problems, all the calculations are detailed in Section 2.6:

$$\text{neutral:} \quad \max_{\alpha} SW^n; \tag{2.6}$$

$$\text{multipliers:} \quad \max_{\alpha,\gamma_1} SW^m; \tag{2.7}$$

$$\text{carve-outs:} \quad \max_{\alpha,\beta_1} SW^{co}. \tag{2.8}$$

[3]The energy and certificates consumption terms cancel out as they are a transfer from consumers to firms.

Proposition 2.7 *Under assumptions (A1), (A3), and Propositions 2.2, 2.3 and 2.4,*

a) *the optimal green goal α is the same under the multipliers and carve-outs,* $\alpha^m = \alpha^{co} = \frac{(c_{v_1}+c_{v_2})(b^2+4c_c^2+b(6c_c+d))}{b^2(c_{v_1}+c_{v_2})+4c_c(c_{v_1}c_{v_2}+c_c(c_{v_1}+c_{v_2}))+b(4c_{v_1}c_{v_2}+(6c_c+d)(c_{v_1}+c_{v_2}))}$;

b) $\alpha^m = \alpha^{co} > \alpha^n$;

c) *the generation shares for both green technologies are the same under the multipliers and carve-outs, with* $\beta_1^{co} = \beta_1^m = \frac{c_{v_2}(b^2+4c_c^2+b(6c_c+d))}{b^2(c_{v_1}+c_{v_2})+4c_c(c_{v_1}c_{v_2}+c_c(c_{v_1}+c_{v_2}))+b(4c_{v_1}c_{v_2}+(6c_c+d)(c_{v_1}+c_{v_2}))}$ *and* $\gamma_1 = \frac{c_{v_2}(b^2+4c_c^2+2c_{v_1}d+b(6c_c-2c_{v_1}+d))\gamma_2}{c_{v_1}(b^2+4c_c^2+2c_{v_2}d+b(6c_c-2c_{v_2}+d))}$, $\gamma_2 > 0$;

d) $SW^{co} = SW^m > SW^n$.

Surprisingly, in the optimum, both non-neutral policies reach the same green generation goal, which is greater than the one for the neutral approach. These policies not only promote the production of more green energy for specific technologies, but also, this differentiated treatment incentivizes them to produce a greater green output compared with a neutral policy.

Even though the credit multipliers and carve-outs schemes seem costly in terms of identifying the right multipliers and adjusting the green goal or the administration of certificates market for each green technology, these non-neutral policies can end up in a greater participation of green energy sources as a proportion of the total production. At the same time, they also increase the energy production of both technologies compared to the neutral case. Another peculiarity of the non-neutral policies is that it does not matter if it is a quantity or a price mechanism, in the two cases the energy production for all the green technologies is the same.

Contrary to literature and my initial assumption, the optimum multiplier of technology 1 can be larger or smaller than γ_2, depending on the social cost of emissions, d. If it is low, $0 < d < \frac{2bc_{v_2}-b^2-6bc_c-4c_c^2}{(b+2c_{v_2})}$, then, the technology 1 receives more certificates than technology 2. This may indicate that there is a trade-off between the emission cost and the size of the multiplier for technology 1. Since this is the most expensive generator, the regulator cannot set $\gamma_1 > \gamma_2$ when d is high because the increase in the generation of firm 1 would result into larger generation costs and a welfare loss. On the contrary, when d is low, then the regulator can incentivize more energy production from the firm 1 by giving it more green certificates than firm 2.

This result is relevant because when policymakers decide to boost energy production from expensive technologies, it may seem reasonable to assume they should receive more certificates because they are more costly and need to receive more income from the certificates' market to cover their costs. However, when the social cost of emissions is considered, then keeping this assumption would end in a welfare reduction.

Finally, the result in Proposition 2.7 may result counterintuitive after Proposition 2.6. Even though the value of non-neutral policies does not rely on offering cheaper tariffs to consumers compared to the neutral policy, it allows reaching a higher green energy goal. A bigger α reduces energy prices that can compensate the expenditure in certificates. In addition, in the social optimum, there is more production of green energy, compared to the neutral approach, which also reduces the emissions of conventional generation.

Here, Proposition 2.7 explains that under the optimum policy variables α, β_1 and γ_1, both credit multipliers and carve-outs policies reach the same social welfare, thus they are equivalent. Again, it does not matter if it is a quantity or price approach, the non-neutral policies lead to identical outcomes in the optimum.

2.5 Conclusions

The neutral RPS policy promotes the competition in the same conditions for all the green generation technologies. However, this may hinder the diversification of generation resources and favor cheap and mature technologies. To face this limitation, some countries have implemented non-neutral policies which give a differentiated treatment to the green technologies depending on their costs.

I characterize the equilibria for the non-neutral policies: credit multipliers and carve-outs. The difference between the neutral approach and my specification lies in the clearing market conditions I proposed. The first one considers the additional certificates for each technology, so it breaks with the duality between certificates market equilibrium and green generation goal.

The literature about credit multipliers warns on not reaching the generation target because of the increase in the available certificates. This issue was also present in my specification; however, I solve it by calculating an adjusted $\tilde{\alpha}$. After using this instead of α, I found that the electric market reached the green generation goal.

This adjustment is similar to what is done in the UK with the headroom adjustment when this country sets its annual green energy goal. This is important because it sets a simple formula to calculate how big $\tilde{\alpha}$ needs to be in order to reach α, with the size of the multipliers and generation costs as inputs.

After comparing the energy outcomes, surprisingly, I noticed that the three policies ended up producing not only the same share of green energy but also the energy production, even though I used $\tilde{\alpha}$ to estimate the credit multipliers equilibrium. The only difference is how the generation distributes between green technologies in all the policies. This result is different from what Gürkan and Langestraat (2014) and Fischlein and Smith (2013) found in the UK and the US.

After calculating the electric tariff for the consumer in each case, I found that the neutral policy results in lower energy expenditure compared to both non-neutral scenarios. I expected them to be more expensive since the obligation for certificates creates a submarket for each technology and the quota sets the price, in the case of carve-outs. While for credit multipliers, the certificates granted to each technology determines the price.

Does this mean that the neutral policy is better than the non-neutral ones? No. I analyzed the rent-seeking behavior of the green firm under both approaches, and I observed that the neutral policy gives the biggest additional income, followed by the credit multipliers.

Since each technology is liquidated in a separated market, the carve-outs scheme is the one that gives the least additional income to green firms. This finding is in line to previous descriptive analysis in the literature, where carve-outs are characterized as the best option to finish with the rent-seeking behavior, although in practice having many submarkets incurs in additional administrative costs for the regulator.

Finally, in terms of social welfare, after comparing the three schemes, it turned out that both non-neutral policies lead to the same optimal green energy share, which is greater than the neutral one. On top of that, the production of the two technologies is the same under credit multipliers and carve-outs. I conclude that it does not matter which non-neutral policy the regulator chooses, in the social welfare optimum, they lead to the same outcomes and, even though they entail more administrative costs, the welfare is superior compared to implementing an RPS neutral policy.

Chapter 3

INVITING CONVENTIONAL GENERATION TO THE GREEN CERTIFICATES MARKET

3.1 Introduction

When discussing climate change and emissions reduction, the primary focus is often on decarbonizing the electricity sector. As a result, many countries have adopted various policies aimed at increasing clean energy production to meet these objectives. However, this ignores the fact that developing countries, even excluding China, are likely to emit more than half of the global greenhouse emissions in 2030 (Amar Bhattacharya and McArthur, 2023). It may seem that the efforts to transit to clean energies will not be enough, since the reliance on traditional energy sources hinders the transition to renewable energy sources. Only in 2022, the global coal demand hit a record high, reaching 8.42 billion tones (IEA, 2024).

Achieving significant emission reductions requires a diverse mix of generation technologies. But trusting on the adoption of clean energy sources to reach this goal makes it a harder task considering that carbon generation still plays a crucial role in electricity generation with around of one third of the total global (IEA, 2024). Why not looking at technologies that can turn this polluting generation into a cleaner one, while transitioning towards a more sustainable path?

In this paper, I propose a model to study a non-neutral tradable green certificates policy that allows partially clean generators to participate in the certificates market along with

100% clean energy producers. My work is inspired by the Mexican certificate granting scheme, where both types of generation firms are allowed to receive certificates. But also by the fact that Mexico, as many developing countries, faces important constraints in reaching the global emissions mitigation goal given the major dependence on fossil fuels.

Unlike other related papers, my work proposes to incentivize the investment in abatement technologies by granting them green certificates, instead of using carbon taxes, emissions trading or subsidies to abatement. Supporting polluting technologies to abate emissions could seem counterintuitive, but it is necessary, considering that even a clean energy generator with sufficient capacity may not be able to guarantee an effective supply of electricity (Zhang et al., 2020).

It is relevant to study how the resources at hand can contribute to reach the decarbonization objectives. Even though not all the energy is generated with clean resources, it could be helpful to retrofit generators to reduce its pollutant emissions. To meet this goal, it is critical to offer incentives to these firms. In this case, green certificates may have the same effect as in the clean energy generation case and incentivize the investment in new capacity.

By 2050, energy efficiency measures and renewable energy could attain 94% reductions in carbon emissions, while the remaining 6% would be achievable by Carbon Capture and Storage (CCS), nuclear energy use and fossil fuel switching (Tetteh et al., 2021). This 6% shows that there is enough room for a technology able to clean these polluting emissions. However, CCS cannot compete in costs against wind and solar energy, but it could extend their operational life and avoid the financial burden of early retirement.

Besides CCS, another technology to reduce emissions are the SO_2 scrubbers. They basically wash the polluting gases and absorb the contaminant particles. The most aggressive supporter of scrubber implementation is China. Between 2006 and 2009, this country gave subsidies to the generation of desulfurized electricity. As a result, around 71% of the coal power plants installed scrubbers, this is equivalent to 422,000 megawatt (MW). However, plant managers only got the technology to qualify for the subsidy, but they did not care about its specifications or efficiency. The scrubbers have high Operation and Maintenance (O&M) costs, thus the managers did not operate them and misreport emissions. For instance, official data indicated that SO_2 emissions in the electricity sector were approximately 11.5 million tons, whereas an independent study estimated the total at 16.4 million tons. Furthermore, while official reports stated that 73.2% of SO_2 was removed from coal power plants in 2007, the province with the strongest environmental protections reported a removal rate of only about 64.1% (Xu, 2011).

The CCS and the scrubbers are examples of technologies that reduce contaminant emissions. Even though they are expensive, they may be cost-effective, considering that about one-third of today's coal and gas plants were built in the last decade; so retrofitting these with CCS can extend their operational life. However, it would be unrealistic to expect any country to adopt these technologies in isolation without incentives.

As an effort to incentivize efficient energy generation processes, the Mexican Law considers as clean energy the one generated with hydrogen, cogeneration systems, including the one generated in sugar mills, CCS efficient and low carbon emission technologies (LIE, 2014). All these technologies are allowed to get Clean Energy Certificates (CEL, by its acronym in Spanish) provided that they meet the cleanliness criteria established in the law. In this sense, the Tradable Green Certificates (TGC) policy of Mexico is not neutral, this means that the law does not treat all generation technologies the same, but it distinguishes between 100% clean resources and partially clean, and grants certificates in a differentiated way.

In the literature, various mechanisms are available to signal the higher value of clean production: taxes on carbon, emissions trading, pollution charges, tradable certificates and feed-in tariffs. The policies on emissions' reduction mostly are focused on increasing the cost of the polluting firms, so they may find it more profitable to invest in abatement to avoid it, or offering subsidies to retrofit their generation technologies. In contrast, when the goal is promoting the installation of new clean generation, the idea is to give rewards, so the firms find it attractive to invest in additional capacity. In the end, both abatement and green generation go after the same objective, so why not try to reward polluting firms to become cleaner, and in particular giving them green certificates?

In previous analysis, this specific relationship has not been addressed because the green certificates' mechanism has been a policy exclusively used to incentivize the investment in green energy sources. Regarding the investment in emissions' abatement literature, this is mostly focused on CCS real options investment strategies (Agaton, 2021). There are some works that study the effect of subsidies on the investment in abatement strategy but using the same framework (Zhang et al., 2014 and X. Wang and Du, 2016).

There is another strand that studies the strategic choice of abatement technologies. Buccella et al. (2021) research the decision of undertaking emission-reduction actions when an emission tax is set, they found social welfare under abatement is greater compared to not abate. Poyago-Theotoky and Teerasuwannajak (2002) and Moner-Colonques and Rubio (2015) arrive to the same conclusion for not so differentiated goods and high commitment on the regulator side. On the emissions trading side, the works focus on incentives to invest in R&D to abate under international emissions trading (Greaker and Hagem, 2013), experimental studies to identify incentives for polluting firms to adopt cleaner technologies considering the nature of the emissions permits allocation (Camacho-Cuena et al., 2012), short and long term benefits of abatement investment (Huang et al., 2014). My work is set in this side of the literature about the policies to incentivize investment in emissions abatement but from the green certificates point of view.

The paper contributes to the works on environmental regulation to reduce pollutant emissions by studying both the green certificates mechanism and emissions abatement in a single framework in a duopoly. To do this, I propose a two-stage game where the regulator decides granting green certificates to conventional (polluting) generators that invest in an abatement technology. Once the generator decides how much abatement to get, it competes à la Cournot in the certificates and energy market with the green (clean) generator.

This paper is closely related to the work of Amir et al. (2018) where they study emissions and performance standards. Unlike Amir et al. (2018), I focus on the green energy production goal as the policy variable rather than the emissions cap. So in my approach, the firm chooses how much dirty energy it wants to produce given the energy goal, abatement investment and the clean energy production of its rival.

Additional to the usual investment costs, I assume there is an O&M cost associated to the abatement technology, as in Strandholm et al. (2021), that is increasing with respect to the dirty energy. I model it this way to resemble the problem that carbon generators faced in China described in Xu (2011). In this case, green certificates might be an incentive to produce energy (and operate the scrubbers) because they are granted according to the quantity of electricity generated.

I found that O&M costs are relevant for the quantity of certificates offered to the market. When they are low, the firm behaves as a symmetric duopolist; but when they are high, the generator offers its whole stock of certificates to the market. This means that depending on the size of the O&M costs for any level of abatement, the firm increase its certificates supply to maximize its profits.

Contrary to the effect of the green certificates policy on investment in green capacity, where an increase in the share of clean energy as a proportion of the total generation (green goal), rises the green capacity; a higher share of this goal does not mean a higher level of abatement. This is explained by the certificates granting rule because to be allowed to receive them it is necessary to invest in any amount of abatement. This means that to get more certificates it is enough with increasing the energy generation, not necessarily to get more abatement.

Unexpectedly, I found that conventional energy (green energy) is increasing (decreasing) with respect to O&M. This is explained by a substitution between clean and dirty energy. As the O&M rises, the dirty energy is more expensive, so the conventional generator reduces its production. But as O&M keeps increasing, the firm invests more in abatement so it produces more clean energy and displaces the one generated by the green generator.

For some specific examples, I found that under abatement investment, the green goal is bigger than the one reached in a scenario where only the green firm is allowed to sell certificates, and the total energy free of emissions is also greater when the investment costs are low. In terms of social welfare, a certificate market with clean and partially clean participants lead to greater welfare when the social value of pollutant emissions is high.

The rest of the paper is organized as follows. The next section sets out the basic model and the equilibrium analysis. Section 3.3 analyzes the equilibrium for the two-stage game, and Section 3.3.1 presents some comparative statics. Section 3.4 compares the energy production and welfare under emissions' abatement against the scenario without it.

3.2 The model

Consider an electric market with two firms: one green and one conventional generator, g and c, respectively. The firms produce electric energy for which the inverse demand is given by the function $P_e(Q)$. The power generated by each firm is denoted by q, while the aggregated quantity produced is given by Q. For simplicity, I assume that both generators have been in the market for a while, so they have already recovered their investment costs. Also, I consider that, in this case, the generation cost of conventional energy is low, so the firm obtains positive profits from conventional energy production. Thus, I assume that the marginal energy generation cost is zero in order to focus only on the abatement investment decision. The generation with the conventional technology entails contaminant emissions, e, that damage the environment and are equal to the energy it produces, $e = q_c$.

In this electric market, there is an ongoing Tradable Green Certificate (TGC) policy that aims to reduce emissions by increasing green generation. Initially, the certificates are only granted to the green firm, so it behaves as a monopolist, with inverse demand $P_c(x_g)$, where x_g is the green firm's TGC supply. In this case, both firms choose simultaneously their energy production, along with the green firm choosing its certificate supply.

However, the authority in charge of the energy policy announces that green certificates will be granted to green generators as well as conventional generators that adopt emission abatement technologies. By investing in this technology, the conventional firm will be able to participate in both the electric and certificate markets. In this case, the firm will produce energy that will go through a cleaning process, so that a proportion z will result in energy free of emissions. The amount of certificates it will receive depends on the energy free of emissions the conventional source produces, this means that if it generates 10 MWh and its efficiency to produce clean energy is 20%, then it will be granted 2 certificates. Under this setting, the conventional firm chooses its investment in abatement, z, that results into energy free of emissions considering that its generation costs will increase because of the operation and maintenance costs associated to the abatement technology.

Under this setting, the electric energy and certificates as well as the abatement investment decision are made in a two-stage game. First, the conventional firm first chooses its emission abatement investment in terms of the percentage of clean energy it wants to produce. Next, both firms choose their energy and certificate supply, q_c, q_g, x_c and x_g in a duopoly setting.

The market structure is characterized as follows:

(A1) the energy inverse demand function is linear, $P_e(Q) = a - Q$, where $a > 0$;

(A2) the certificate inverse demand is

a. $P_c(x_g) = \alpha Q - x_g$ if only the green firm participates in the TGC market and

b. $P_c(x_g + x_c) = \alpha Q - x_g - x_c$ if both generators are in the market,

with $x_g \leq q_g$, $x_c \leq zq_c$, $0 < \alpha < 1$, and $0 \leq z \leq 1$;

(A3) energy generation costs increase by $\rho(1-z)q_c$, with $\rho > 0$;

(A4) the abatement technology investment cost is $F(z) = \frac{1}{2}\beta z^2$, where $\beta > 0$.

In this two-stage game, the conventional firm moves first by choosing its investment in abatement, z. Next, the green and conventional firms compete in output in the energy and certificates' market. Using backwards induction, I solve the subgame perfect equilibrium of the game that entails the optimal level of conventional energy emissions' abatement, z (Section 2.1).

3.3 TGC market with a conventional polluting firm

In this model, the regulator allows the conventional firm to join the certificates' market under the condition that this polluting firm adds emissions' abatement technology to its generators so it can produce partially clean energy depending on the level of abatement chosen. In the second stage of the game, the green and conventional firm simultaneously choose their energy production, q_g and q_c, and their green certificate supplies, x_g and x_c, such that they maximize their profits given their certificate stock, q_g and zq_c, the investment in emissions abatement, z, and its rival's energy production. Hence, the optimization problems for each firm g and c in this stage are given by

$$\max_{q_g, x_g} \quad \pi_g = q_g[a - (q_c + q_g)] + x_g[\alpha(q_c + q_g) - x_g - x_c], \quad s.t. \quad x_g < q_g, \tag{3.1}$$

$$\max_{q_c, x_c} \quad \pi_c = q_c[a - (q_c + q_g)] + x_c[\alpha(q_c + q_g) - x_g - x_c] - \rho(1 - z)q_c, \quad s.t. \quad x_c < zq_c. \tag{3.2}$$

Remember that the total amount of certificates each firm receives depends on their energy generation. In this way, the green firm receives 1 certificate per each MWh generated, so its stock is q_g. Regarding the conventional firm, it gets its certificates according to its level of energy free of emissions, z. In this way, it obtains z certificates per unit of energy produced, and its stock is zq_c. In both cases, as can be seen in Equations (3.1) and (3.2), the firms cannot offer more certificates than the ones they have in stock.

Also, notice that the conventional generator has to cover an additional generation cost associated with the operation and maintenance (O&M) of the abatement technology equal to $\rho(1 - z)$. This means that producing polluting energy $(1 - z)$, or in other words, not abate, is more costly than abate for this energy producer. As in Amir et al. (2018), this cost is decreasing in the R&D investment (abatement level) the firm chooses.

The profit maximization problems in Equations (3.1) and (3.2) lead to equilibrium outputs in the energy and certificates' market, $q_g(z), q_c(z), x_g(z)$ and $x_c(z)$.

In the first stage, the conventional firm chooses its level of abatement, z, given the energy production and certificates supply obtained in the last stage. Thus, firm c solves the following problem,

$$\begin{aligned}\max_{z} \quad \pi_{c_z} =& q_c(z)[a - (q_c(z) + q_g(z))] + x_c(z)[\alpha(q_c(z) + q_g(z)) - x_g(z) - x_c(z)] \\ & - \rho(1-z)q_c(z) - \frac{1}{2}\beta z^2, \;\; s.t.\; 0 \leq z \leq 1.\end{aligned} \tag{3.3}$$

There is an additional term present in (2.3), $\frac{1}{2}\beta z^2$. This denotes the cost that the conventional generator incurs when it invests the proportion of z in abatement. Notice that the abatement variable z can take values between zero and one, included the extremes. In this case, an abatement of zero means that the conventional firm would be better off by not retrofitting its generation technology. On the other side, an abatement level of one means that the firm would abate all its polluting emissions so it would produce 100% of clean energy. I will use the Kuhn-Tucker (K-T) approach to find the solutions. The Lagrangian associated with this maximization problem is

$$\mathcal{L}_r(z, \lambda_1, \lambda_2) = \pi_{c_z}(z) + \lambda_1 z - \lambda_2(z-1). \tag{3.4}$$

Finally, along with the usual first-order conditions, it is necessary to take into consideration the complementary slackness conditions to solve for the equilibrium:

$$\lambda_1: \quad z \geq 0, \quad \lambda_1 \geq 0, \quad \lambda_1 z = 0; \tag{3.5}$$

$$\lambda_2: \quad 1 - z \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2(1-z) = 0. \tag{3.6}$$

By doing this, I will be able to analyze the extremes, so I can solve for the equilibrium in the cases where the conventional firm chooses to abate all its emissions, a proportion of them or not abate.

Complementary slackness conditions in Equations (3.5) and (3.6) lead to four cases to analyze in order to find the optimal abatement: *i)* $z = 0$ & $\lambda_1 > 0$ *and* $z = 1$ & $\lambda_2 > 0$, *ii)* $z = 0$ & $\lambda_1 > 0$ *and* $z < 1$ & $\lambda_2 = 0$, *iii)* $z < 0$ & $\lambda_1 = 0$ *and* $z = 1$ & $\lambda_2 > 0$, and *iv)* $z < 0$ & $\lambda_1 = 0$ *and* $z < 1$ & $\lambda_2 = 0$. At first glance, case i is discarded because z cannot take the value of zero and one at the same time. In case ii, $\lambda_1 < 0$, so the condition is not met. Proposition 3.1 shows the abatement levels of equilibrium from cases *iii* and *iv* which meet the K-T conditions. There is a detailed analysis of each of these cases in the Appendix.

Proposition 3.1 *Under assumptions (A1) to (A4), and $a > 4\rho$, the equilibria in the energy and certificate markets, and the abatement emissions investment are*

a. If $0 < \beta \leq \frac{a(4-\alpha^2)\rho}{9-2\alpha^2}$, *then* $z_1 = 1$, $q_{c,1} = q_{g,1} = \frac{3a}{9-2\alpha^2}$, *and* $x_{c,1} = x_{g,1} = \frac{2a\alpha}{9-2\alpha^2}$;

b. If $\beta > \frac{a(4-\alpha^2)\rho}{9-2\alpha^2}$, *then* $z_2 = \frac{\rho(a-2\rho)(4-\alpha^2)}{(9-2\alpha^2)\beta-2(4-\alpha^2)\rho^2}$, $q_{c,2} = \frac{3a-(1-z_2)(6-\alpha^2)\rho}{9-2\alpha^2}$, $q_{g,2} = \frac{3a+(1-z_2)(3-\alpha^2)\rho}{9-2\alpha^2}$, $x_{c,2} = x_{g,2} = \frac{\alpha(2a-(1-z_2)\rho)}{9-2\alpha^2}$.

Proposition 3.1 shows that depending on the investment cost of abatement β, the firm could choose either to abate all its emissions or just a fraction of them. When the cost is below $\frac{a(4-\alpha^2)\rho}{9-2\alpha^2}$, then the firm reduces its pollutant emissions to zero and there is a symmetric equilibrium in the energy and certificates' markets. On the contrary, when the abatement investment cost is higher than $\frac{a(4-\alpha^2)\rho}{9-2\alpha^2}$, the conventional firm chooses to abate only a fraction of its emissions. As a result, the generator still has to pay the O&M costs associated to the dirty energy it produces, contrary to the equilibrium in the Point a, in which it becomes a 100% clean generator. Thus, the equilibrium in the energy market is not symmetric.

Proposition 3.1 highlights the importance of abatement costs when choosing the abatement level. Point b can be interpreted as the situation the conventional firm faces when it adopts a technology in its early stages. In this case, the cost is so elevated that the firm only can afford to abate a fraction z_2 of its emissions. However, as the abatement technology becomes cheaper, the firm would choose to abate all its emissions, as in Point a. Notice that despite the high costs, it is not optimal for the conventional firm to choose an abatement equal to zero.

3.3.1 Comparative statics

In this section, I will show the comparative statics for the abatement investment and energy generation in Proposition 3.1 with respect to the market size, investment and O&M costs, and green energy goal. I focus on the equilibrium in Point b because the one in a shows a situation where there are two 100% clean generators, so the comparative statics is the usual. For the equilibrium in Point b, I found that an increase in the O&M costs do not reduce investment in abatement due to an increase in the cost of the dirty energy, which makes the conventional generator to invest in more abatement. Regarding the green energy goal, it turns out that a higher α does not mean more abatement because the conventional generator does not need more abatement to get more certificates, but it only has to increase its energy production. Finally, an increase in the O&M costs does not reduce conventional generation because of a substitution effect between the clean and dirty energy produced by the conventional firm as ρ increases, so the firm produces more clean energy and reduces the production of the green firm.

Abatement investment

Notice that, as in Asproudis and Gil-Moltó, 2014, z_2 is increasing in the market size $\left(\frac{\partial z_2}{\partial a} > 0\right)$; this means that conventional firms would invest more in abatement when the size of the electric market is larger. Essentially, as the market size grows, the potential profits from investing in abatement also increase, encouraging firms to produce more $\left(\frac{\partial q_{g,2}}{\partial a} = \frac{\partial q_{c,2}}{\partial a} > 0\right)$ and to allocate more resources towards reducing pollution.

As is expected, elevated investment expenses (β) act as a deterrent to the adoption of cleaner technologies $\left(\frac{\partial z_2}{\partial \beta} < 0\right)$. However, it is not the case regarding O&M costs. Here, the higher O&M cost, the more the conventional firm would want to invest in emission abatement $\left(\frac{\partial z_2}{\partial \rho} > 0\right)$. To understand why, it is necessary to look at the term $\rho(1-z)q_c$ in equations (1) and (3) that represents the additional cost the conventional firm incurs when it invests in abatement. In this case, an increase in O&M means that dirty generation $(1-z)q_c$ becomes more expensive, so the conventional generator wants to be cleaner to reduce this cost.

The literature regarding investment in green capacity generation indicates that in the presence of a Tradable Green Certificate policy, a higher green goal α incentives the investment in green energy. Nevertheless, in this case a higher α does not mean more emission abatement$\left(\frac{\partial z_2}{\partial \alpha} < 0\right)$, but it does increase energy generation of both technologies $\left(\frac{\partial q_{g,2}}{\partial \alpha} > 0 \text{ and } \frac{\partial q_{c,2}}{\partial \alpha} > 0\right)$. This result is unexpected because a larger green goal means that the regulator is increasing the certificate obligation of consumers, so more certificates are demanded and, as a consequence, the firm would get more abatement.

Considering that the conventional firm receives certificates in accordance to the proportion of energy free of emissions it produces, it would be expected that the firm invests more in abatement. However, this is not necessarily true. The policy says that conventional generation is allowed to receive green certificates if it gets the emissions' abatement technology. This means that no matter how much it gets, it will be eligible to get the certificates and sell them in the market. This suggests that to increase its certificate stock, it does not need more abatement, it is enough with increasing its generation $\left(\frac{\partial q_{c,2}}{\partial \alpha} > 0\right)$. Even with low abatement level, the firm can reach the desired amount of certificates with a larger energy production.

Thus, the conventional firm is not interested in investing more in abatement. Since it has already secured its participation in the certificate market, it can get more certificates by producing more energy. This represents a drawback of integrating partially clean technologies into the TGC market, because there is not a minimum abatement level necessary to qualify, and the decision is left to the firm.

Still, this does not necessarily mean that the mechanism failed. It only reminds that it is important not putting all the responsibility of emission reduction in abatement technologies and even the TGC mechanism. Considering that the regulator increases the green goal over time, it would be recommendable to allow partially clean technologies to participate in the certificates market at the early stages of the policy implementation because the level of abatement at that moment will be higher than the one it could get later, since abatement is decreasing on α.

Also, it is crucial to remember that independently of the proportion of energy free of emissions produced, an increase in energy production also represents more dirty energy. Thus, it is essential to considerate until what point this policy makes the conventional generation pollute more than it would do in case of not participating in the certificate market.

Generation and green certificates

As it was shown above, energy generation increases with the green goal. Regarding a rise in the abatement investment cost, the production behaves as usual; the conventional generation reduces and the green one increases $\left(\frac{\partial q_{g,2}}{\partial \beta} > 0 \text{ and } \frac{\partial q_{c,2}}{\partial \beta} < 0\right)$. However, the story is different respecting the O&M cost ρ, energy generations do not react the same way in the green goal domain. When $0 < \alpha < \frac{1}{\rho}(4a - \rho - \sqrt{7\rho^2 + 16a^2 - 14a\rho})$ the conventional generation is decreasing in the O&M cost while the green production is increasing $\left(\frac{\partial q_{g,2}}{\partial \rho} > 0 \text{ and } \frac{\partial q_{c,2}}{\partial \rho} < 0\right)$, as expected. On the contrary, when $0 < \alpha < \frac{1}{\rho}(4a - \rho - \sqrt{7\rho^2 + 16a^2 - 14a\rho})$, the signs revert and now the conventional generation rises and the green one reduces.

In this case, there is a substitution between the dirty and clean energy produced by the conventional generator. When ρ increases, the polluting energy becomes more expensive, so the profit of conventional firm reduces, but when ρ and the green goal get bigger when $0 < \alpha < \frac{1}{\rho}(4a - \rho - \sqrt{7\rho^2 + 16a^2 - 14a\rho})$, this means that the conventional firm wants to produce more energy, but this will result in more expensive dirty energy. So the only way to reduce this cost is to invest more in abatement $\left(\frac{\partial q_g}{\partial z} > 0\right)$, so the increase in generation in this interval associated to a bigger α dominates the reduction in generation related to a higher ρ. In the case of the green firm the contrary occurs, here the increase in generation motivated by a higher green goal is surpassed by the reduction in green production that accompanies more investment in abatement from the conventional firm.

3.4 Consequences of inviting the polluting generators

3.4.1 Green goal and energy production

In this section, I follow the analysis of Amir et al., 2018 to identify the direct and strategic effects of investment in emissions abatement. In Amir et al., 2018 they compare both propensities for higher R&D and output generated by the emission and performance standards. For the purpose of this paper, I compare the performance of inviting the polluting generators to the certificate market versus having an only green firms one. Considering that only in the first scenario occurs investment in abatement, I restrict my analysis to the increase in clean energy generation, that is the strategic effect.

To make both scenarios comparable, it is important that the two of them lead to the same level of clean energy. Since I am comparing two cases of the same policy, then the green goal α is identical. So, independently of the participants in the certificates market, each case should be able to reach the same green generation goal. However, when the certificate market is not competitive, the share of clean energy as a proportion of total generation induced by imperfect competition in the certificate market is different from the one, α, set by the regulator. I limit to compare the shares of clean energy, to identify which one is closer to α. Before weighting up these situations, I state some results necessaries for this task. In an energy market with no generation costs where green certificates are granted only to 100% clean firms, the equilibrium in both energy (conventional and green generation, q_c^{na}, q_g^{na}) and certificate markets (x_g^{na}) is $q_c^{na} = \frac{a\left(2-\alpha^2\right)}{6-\alpha^2}$, $q_g^{na} = \frac{a\left(\alpha^2+2\right)}{6-\alpha^2}$ and $x_g^{na} = \frac{2a\alpha}{6-\alpha^2}$. I will refer to this as the no abatement case (na).

The share of clean energy under no abatement is $\alpha^{na} = \frac{q_g^{na}}{q_g^{na}+q_c^{na}}$, while the one with abatement is $\alpha^a = \frac{q_g^a+zq_c^a}{q_g^a+q_c^a}$. Notice that α^a accounts for the energy free of emissions produced by the conventional and green firms. Considering that the production under a duopoly is greater than the monopoly one, it would be easy to affirm that $\alpha^a > \alpha^{na}$. However, this is not necessarily true because of the investment and O&M costs the conventional firm incurs under the abatement case that affect the energy production.

Remark 1. *The share of clean energy resulting from the equilibrium in Proposition 3.1b is greater than the one under no abatement, $\alpha^a > \alpha^{na}$, with $\beta < \beta(\alpha, \rho)$* [1].

Remark 1 shows that even after incurring in O&M and investment costs, the green goal is bigger when the conventional firm invests in emission abatement. In spite of this promising result, it could be still not true that the clean energy production in this case is greater. For example, consider a situation where $\alpha^{na} = \frac{4}{16} < \alpha^a = \frac{2}{6}$, even though the share of green energy is bigger with abatement, both the clean and the total energy production is larger when there is only the 100% clean firm participating in the certificate market.

So, it is important to compare energy productions in each scenario to guarantee that this green energy share is due to an increase in generation.

Remark 2. *For the equilibrium in Proposition 3.1b, the output comparison between a green only certificate market and one with partially clean generation is:*

1. *If $\frac{a\left(\alpha^2-4\right)\rho}{2\alpha^2-9} < \beta < \frac{a\left(5\alpha^6-52\alpha^4+164\alpha^2-144\right)\rho^2}{(2\alpha^2-9)\left((\alpha^2-6)^2\rho+2a(\alpha^2-5)\alpha^2\right)}$ and $0 < \alpha < \sqrt{\frac{8a+9\rho-\sqrt{64a^2+9\rho^2}}{4a+2\rho}}$ or $\beta > \frac{a\left(\alpha^2-4\right)\rho}{2\alpha^2-9}$ and $\sqrt{\frac{8a+9\rho-\sqrt{64a^2+9\rho^2}}{4a+2\rho}} \leq \alpha < 1$, the abatement investment equilibrium leads to more conventional generation, $q_c^a > q_c^{na}$.*

2. *If $\beta > \frac{a\left(5\alpha^6-45\alpha^4+118\alpha^2-72\right)\rho^2}{(2\alpha^2-9)((\alpha^4-9\alpha^2+18)\rho+2a(\alpha^2-4)\alpha^2)}$ and $0 < \alpha < \sqrt{\frac{5a+6\rho-\sqrt{a(25a-12\rho)}}{2a+\rho}}$, the abatement investment equilibrium leads to more green generation, $q_g^a > q_g^{na}$.*

The key message of Remark 2 is that investment costs are critical to determine whether

[1] $\beta(\alpha,\rho) = \frac{\rho(4-\alpha^2)}{2\alpha\left(2\alpha^2-9\right)(2a-\rho)}\left[3(a-2\rho)^2 + \alpha\rho((a-2\rho)(1+\alpha)+6a) + \rho\sqrt{9(a-2\rho^2)+\alpha\rho(2a(21+3\alpha-4\alpha^2)) - \rho(3-\alpha)(1+\alpha)(4+\alpha)}\right]$

the abatement investment leads to greater conventional or green generation. Lower (higher) investment cost incentivizes (disincentivizes) the adoption of abatement and increases (decreases) conventional production, while it decreases (increases) green generation.

However, there is neither investment cost nor green goal for which conventional and green energy productions are simultaneously greater than the ones obtained through no abatement.

Example 1 Suppose that $a = 6\rho$, $\beta = 4\rho^2$ and $\rho = 8$.[2] Then, under abatement investment

1. If $0.502 < \alpha < 1$, conventional generation is greater,$q_c^a > q_c^{na}$;

2. If $0 < \alpha < 0.394$, green generation is greater, $q_g^a > q_g^{na}$;

3. If $0.773 < \alpha < 1$, total energy production is greater, $q_g^a + q_c^a > q_g^{na} + q_c^{na}$;

4. If $0 < \alpha < 1$, total clean energy production is greater $q_g^a + zq_c^a > q_g^{na}$.

Example 1 provides a more detailed characterization of how generation compares between the two settings. The main message of example 1 is that no matter if conventional or green generations are bigger than the ones without abatement, the clean energy production under emissions' abatement (as the sum of conventional energy free of emissions and green energy) is always larger for any green goal.

Even though this supports Remark 1, it is not conclusive about why the green energy share is larger when there is emission abatement. In this example, when $0 < \alpha < 0.773$, the green goal reached is greater because the total generation is lower, but in $0.773 < 1$ this happens due to the total clean energy being bigger than the total production even though there is an increase.

3.4.2 Social welfare

In this section, I compare the resulting social welfare associated to the equilibrium in Proposition 3.1b and the scenario without abatement. I start by defining the social welfare

[2]These values hold the conditions for a, β and ρ in Proposition 3.1b.

functions, as

$$
\begin{aligned}
\text{Abatement:} \quad & a(q_c^a(\alpha) + q_g^a(\alpha)) - \frac{(q_c^a(\alpha) + q_g^a(\alpha))^2}{2} - \rho(1 - z(\alpha))q_c^a(\alpha) - \frac{\beta}{2}z^2(\alpha) \qquad (3.7) \\
& - \frac{d}{2}(1 - z(\alpha))^2 q_c^2(\alpha); \\
\text{No abatement:} \quad & a(q_c^{na}(\alpha) + q_g^{na}(\alpha)) - \frac{(q_c^{na}(\alpha) + q_g^{na}(\alpha))^2}{2}) - \frac{d}{2}q_c^2(\alpha). \qquad (3.8)
\end{aligned}
$$

Equation (3.7) shows the social welfare function for the equilibrium in Proposition 3.1b. The first two terms refer to the quasi-linear utility function associated to the linear energy demand function. The third and fourth terms correspond to the costs, O&M and abatement investment, the conventional firm incurs when it abates emissions. The last term is the most interesting because it shows the damage associated to the conventional generation. In the presence of abatement, the total damage is reduced because this function considers only the pollutant energy after abatement that the conventional firm produces, this is represented with the term $(1-z(\alpha))$. The total damage is given by $\frac{d}{2}(1-z(\alpha))^2 q_c^2(\alpha)$, where d represents the society valuation of contaminant emissions.

Meanwhile, Equation (3.8) represents the social welfare function for the equilibrium with no abatement. As in the abatement case, the first two terms represent the quasi-linear utility evaluated in the not abatement equilibrium. In this case, the conventional firm does not incur in any additional cost. Thus, the last term of this welfare function refers to the damage from contaminant emissions. Unlike the abatement case, here, all the energy production is dirty, so the social damage considers all the conventional energy produced. Remark 3 presents the results of the comparison between the welfare under both scenarios.

Remark 3. *If $a > 4\rho > 0$, $\beta < \beta(\alpha, \rho)$[3] , and $d > d(a, \alpha, \beta, \rho)$, the social welfare under the abatement equilibrium is greater than the one without it.*

Remark 3 shows that when the damage valuation of pollution is higher than $d(a, \alpha, \beta, \rho)$, the welfare of producing energy free of emissions through the abatement technology and

[3] $\beta(\alpha,\rho) = \frac{\rho(4-\alpha^2)}{2\alpha(2\alpha^2-9)(2a-\rho)}\left[3(a-2\rho)^2 + \alpha\rho((a-2\rho)(1+\alpha)+6a) + \rho\sqrt{9(a-2\rho^2) + \alpha\rho(2a(21+3\alpha-4\alpha^2)) - \rho(3-\alpha)(1+\alpha)(4+\alpha)}\right]$

allowing the conventional firm to participate in the certificate market is greater than the situation without abatement and a green only certificate market. Unlike the energy generation comparisons shown in Remark 2, this outcome does not depend on the abatement investment cost or the green goal, this suggests that if the society values emissions high enough, then retrofitting the conventional generators would improve the welfare independently of the green goal the regulator sets.

This result goes in the same direction as in Buccella et al. (2021), where if societal awareness toward a clean environment is high and abatement cost is low, then firms choose to invest in abatement to reduce their polluting emissions, and, as a consequence, the society is better off. It does not matter if the regulator grants green certificates to the conventional generation or if it sets an emission tax (as in Buccella et al., 2021), the result would be the same.

Example 2. Suppose that $\beta = \frac{a\rho}{2}$. Then, under abatement investment,

1. If $a > 4\rho > 0$, $0 < \alpha < 1$ and $d > d(a, \alpha, \rho)$, social welfare is greater than the one reached without abatement;

2. If $0 < d < d(a, \alpha, \rho)$, and

   (a) $0 < \alpha < 1$ and $4\rho < a \leq a_1(\rho)$, or

   (b) $0 < \alpha < \alpha(a, \rho)$ and $a > a_1(\rho)$, social welfare is smaller than the one reached without abatement.

The central idea of the second point in Example 2 refers to the case where society is better off by not including conventional generation in the certificate market. This happens when the damage valuation of contaminant emissions is positive but below the threshold $d(a, \alpha, \rho)$. However, contrary to the case where welfare is greater, here as the market size gets bigger, the welfare is smaller for abatement investment but not for any green goal.

In the case made in Part 2a, this would mean that if society does not care about the environment and the market size is below the threshold $a_1(\rho)$, then a green certificates policy that allows conventional generation to participate in the certificates market by investing in abatement, would lead to a lower social welfare, compared to the case where there is a green only certificate market. However, I find Part 2b as the most concerning because as the electric market gets bigger and surpasses $a_1(\rho)$, the low valuation of contaminant emissions would make not abating emissions more attractive and result into the production of more polluting energy.

3.5 Conclusions

This paper analyses if allowing the participation of conventional (polluting generation) in the certificates market incentivizes the firms to invest more in abatement, so they produce more energy free of emissions, and contribute to reach the clean energy goal. While in the equilibrium, the conventional firm does invest in abatement, this is decreasing with respect to the green objective. This not only means that a higher goal does not lead to more abatement, but also that the highest level of abatement is reached when the goal is zero.

Does this mean that the entry of conventional generation in the certificate market does not have the desired effect? No necessarily. This result may indicate that the timing is important. To get higher levels of abatement, then the regulator has to consider granting certificates to the polluting firms with emissions abatement technology from the beginning of the policy, when the green goal the regulator set is small. Considering that the regulator increases the green goal over time, if the regulator allows the conventional firm to enter the certificates' market when the goal is high, then it will invest in a lower abatement level compared to the one it could do if it had been invited in the early stages.

Since emissions abatement represents a positive change towards the reduction of contaminant emissions, it is important to keep in mind that firms may want to get the minimum abatement that allows them to get certificates. If they want to sell more certificates, it is enough to increase generation while keeping the same abatement level. This may lead to the production of more polluting emissions because with lower abatement, the amount of dirty energy is higher.

My analysis shows that, for some values of the investment costs, allowing the participation of partially clean conventional generators in the green certificates' market contributes positively to reach the emission reduction and clean energy production goals. It also improves the social welfare, in particular when society values high the reduction of pollution.

This work could be greatly improved by studying in detail the zones of the green goal and the investment cost that make the green energy production and the social welfare greater when there is abatement compared to a situation without it. The analysis shown in Section 2.4 is limited in terms of the generality of the conclusions it reaches. A numerical exercise could help to identify better these zones and set intervals to analyze green energy production and social welfare. Even though these results are conditioned by specific values for the green goal and investment cost, it provides good intuition about the potential benefits of the investment in abatement.

However, it is critical to have an appropriate design of this policy in order to get the most of the benefits of this policy. The following proposals are based on my comparative statics results, it is important to consider them to benefit the most from the participation of conventional generation in the certificates' market:

1. Setting a green certificates' market where 100% clean and partially clean technologies can participate from the beginning of the policy, this way there would be incentives for the early adoption of abatement technologies.

2. Implementing a reward system based on the emission reduction efficiency, so the most efficient firms could get more certificates. This approach would help to avoid an increase in conventional energy production as a way for the conventional firm to increase the number of certificates it receives. In this case, the regulator could set increasing efficiency thresholds and grant certificates accordingly, so it guarantees a minimum of energy free of emissions to get certificates and displace the firms that only want to invest in low efficiency, so they can benefit from the certificates' market.

Taking into account these ideas in the green certificates' market policy design would help to promote a more effective and sustainable energy transition that improves environmental conditions and society welfare.

Contrary to my initial intuition, in which I expected that investing in abatement technologies would not be attractive for conventional firms, basically because of the onerous investment costs, I found the conditions that entice the participation of conventional firms in the certificates market, low investment costs and a small green goal, so they can benefit the most from this policy. Besides proposing an analytical approach to study this policy, my analysis shows that rewarding conventional generation for abating emissions reduces emissions associated to energy production, as other policies such as pollution taxes, carbon trading or abatement subsidies. Thus, inviting conventional generation to the certificates market is not as bad as it seems.

Conclusions

Each chapter of this thesis is a sole paper by itself and contribute to the analysis of the tradable green certificates mechanism from different point of views: as an incentive for green investment, technology neutrality and non-neutrality, and as an incentive to adopt abatement technologies.

My motivation to study the green certificates policy was this common idea among the politicians about the certificates not being an incentive to invest in more green capacity, but another way to take money from the consumers. That is why, in the first chapter, my goal was to determine if they worked as an incentive to attract more investment. I found that they do it, but not in all cases. The regulator needs to be aware that a more ambitious green generation goal will not lead to more green capacity, which would make the mechanism ineffective to promote green capacity, and lead to the abandonment of the policy.

Regarding the green certificates as a *rent-generating machine*, in words of Bergek and Jacobsson (2010), I studied in the second chapter how technology non-neutral green certificates policies lead to lower additional rents for the green firms. Additionally, I found that these also result into higher green generation and social welfare, compared to the technology neutral alternative. The technology neutral version of this policy does lead to additional rents for green firms. However, it is important policymakers are aware of how to face this situation by implementing a non-neutral approach.

Finally, related to technology non-neutral schemes, in the third chapter, I studied how green certificates can be used to incentivize polluting generators to adopt abatement technologies. I found that it is more valuable to invite polluting firms from the beginning of the policy, so the portion of emissions abated is greater. However, polluting firms can choose a minimum abatement just to be allowed to get green certificates. In this case, it is important setting abatement thresholds and granting certificates according to them.

As the world approaches the point of no return, new technologies and policies to reduce emissions are being developed. I am not an engineer, but an economist and as such, I want to provide insights that help policymakers design more effective and equitable mechanisms. By doing so, I hope to contribute to a more prosperous future.

Appendix A

Chapter 1

Energy and certificates demand. Here, I find the energy and certificates demand for the retailer.

Substituting 1.1 into (1.3), we have:

$$a - bQ_s - P_e - \alpha f(\alpha Q_s - x_s) = 0;$$
$$a - bQ_s - P_e - \alpha^2 f Q_s + \alpha f x_s = 0;$$
$$a - P_e + \alpha f x_s - Q_s(\alpha^2 f + b) = 0;$$

$$Q_s = \frac{a - P_e + \alpha f x_s}{\alpha^2 f + b}. \tag{A.1}$$

Now, substituting A.1 into 1.4:

$$-P_c + \alpha f \left(\frac{a - P_e + \alpha f x_s}{\alpha^2 f + b} \right) - x_s f = 0;$$
$$-P_c(\alpha^2 f + b) + \alpha a f - \alpha f P_e - b f x_s = 0;$$
$$\alpha f(a - Pe) - P_c(\alpha^2 f + b) - b f x_s = 0;$$

$$x_s = \frac{\alpha f(a - P_e) - P_c(\alpha^2 f + b)}{bf}. \tag{A.2}$$

Substituting A.2 into A.1:

$$Q_s = \frac{a - P_e + \alpha f\left(\frac{\alpha f(a-P_e)-P_c(\alpha^2 f+b)}{bf}\right)}{\alpha^2 f + b};$$
$$Q_s = \frac{b(a - P_e) + \alpha^2 f(a - P_e) - P_c(\alpha^2 f + b)}{\alpha^2 f + b};$$

$$Q_s = \frac{a - P_e - \alpha P_c}{b}. \tag{A.3}$$

Equilibrium merit order case. In this Section, I find the equilibrium for the merit order case.

The energy inverse demand determines the equilibrium, the first-order conditions associated with the conventional and green generators' profit maximization problems, and the Kuhn-Tucker conditions (Equations 1.5 and 1.10 to 1.15), shown below.

$$\begin{aligned}
&P_e = a - \alpha f x_s - (q_r + q_c)(\alpha^2 f + b);\\
q_c :\quad & P_e - v = 0;\\
k_r :\quad & -k_r\left(\beta + 2f\omega(\omega - \alpha)\left(\mu^2 + \sigma^2\right)\right) + \alpha f \mu q_c \omega + \mu P_e = 0;\\
\omega :\quad & f k_r\left(k_r(\alpha - 2\omega)\left(\mu^2 + \sigma^2\right) + \alpha\mu q_c\right) + \lambda_1 - \lambda_2 = 0;\\
\lambda_1 :\quad & \omega \geq 0, \quad \lambda_1 \geq 0, \quad \lambda_1(-\omega) = 0;\\
\lambda_2 :\quad & 1 - \omega \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2(1 - \omega) = 0.
\end{aligned}$$

Following the Kuhn-Tucker procedure, analyzing each of the four cases associated with the problem is necessary to identify the conventional generation, q_c, green investment, k_r, and share of certificates, ω, equilibrium.

a) $\boldsymbol{\omega = 0, \quad \lambda_1 > 0}$ ***and*** $\boldsymbol{\omega = 1, \quad \lambda_2 > 0}$

This case is dismissed because ω cannot be equal to 0 and 1 simultaneously.

b) $\omega = 0, \quad \lambda_1 > 0 \quad$ *and* $\quad \omega < 1, \quad \lambda_2 = 0$

In this instance, the restrictions over ω are met since $\omega = 0 < 1$. So, it is left to validate if $\lambda_1 > 0$. After solving for λ_1, I get:

$$\lambda_1 = -\frac{\alpha f \mu^2 v \left(\beta(a - v) + \sigma^2 v \left(b + \alpha^2 f\right)\right)}{\beta^2 \left(b + \alpha^2 f\right)}. \tag{A.4}$$

Since $a > v$, then $\lambda_1 < 0$, and the restriction over λ_1 is not fulfilled. This means the green firm will not choose a share equal to zero as a proportion of its certificate's stock; consequently, its certificate's supply will be greater than zero.

c) $\omega > 0, \quad \lambda_1 = 0 \quad$ *and* $\quad \omega < 1, \quad \lambda_2 = 0$

For this case, it is necessary to verify that $\omega > 0$ and $\omega < 1$. After solving the equation system implied by the equations mentioned before, I got two solutions for ω. The first is negative, $\omega_1 = -\frac{v\left(b+\alpha^2 f\right)}{\alpha f(a-v)} < 0$, so it does not meet the requirement.

Identifying whether the second solution meets the conditions required is not as straightforward as in the first one. So, it is important to analyze it in detail.

$$\omega_2 = \frac{\alpha \left(\beta(a - v) + \sigma^2 v \left(b + \alpha^2 f\right)\right)}{\alpha^2 f \left(a \left(\mu^2 + \sigma^2\right) + \sigma^2 v\right) + 2bv \left(\mu^2 + \sigma^2\right)}. \tag{A.5}$$

Given that $a > v$, ω_2 is always positive, and the first constraint is met, $\omega_2 > 0$. To prove that $\omega_2 < 1$, it has to be that the value in the numerator is smaller than the denominator, so the difference between them is negative. It is not easy to know the sign of this difference. However, since the interest of this study is the green goal, it is possible to analyze how it behaves with respect to different values of α.

When $\alpha = 0$, the difference is negative, $-2bv \left(\mu^2 + \sigma^2\right) < 0$. However, if $\alpha = 1$, this value could be positive if $\beta(a - v) - af \left(\mu^2 + \sigma^2\right) - bv \left(2\mu^2 + \sigma^2\right) > 0$. Apparently, ω is increasing in α. So, what are the values of α for which the green generator decides to supply a share between 0 and 1 of its certificate's stock?

By solving the equation given by $\omega_2 = 1$, I get two imaginary and positive solutions. In this last case the value for α is

$$\alpha'_m = \frac{\sqrt[3]{\sqrt{\left(27dx^2 - 9xyz + 2y^3\right)^2 - 4\left(y^2 - 3xz\right)^3} + 27dx^2 - 9xyz + 2y^3}}{3\sqrt[3]{2}x}$$
$$- \frac{\sqrt[3]{2}\left(3xz - y^2\right)}{3x\sqrt[3]{\sqrt{\left(27dx^2 - 9xyz + 2y^3\right)^2 - 4\left(y^2 - 3xz\right)^3} + 27dx^2 - 9xyz + 2y^3}} + \frac{y}{3x},$$

where $x = \alpha^3 f\sigma^2 v$, $y = f\left(a\left(\mu^2 + \sigma^2\right) + \sigma^2 v\right)$, $z = \beta(a - v) + b\sigma^2 v$, and $d = 2bv\left(\mu^2 + \sigma^2\right)$. In this case, the green generator chooses ω_2 as its share of certificates supply when $\alpha < \alpha'_m$.

d) $\boldsymbol{\omega > 0, \quad \lambda_1 = 0 \quad \textit{and} \quad \omega = 1, \quad \lambda_2 > 0}$

For this case, the requirement is fulfilled because $\omega = 1 > 0$. Thus, it is necessary to verify $\lambda_2 > 0$, whose analytical solution is shown below.

$$\lambda_2 = \frac{f\mu^2(\alpha f(a + (\alpha - 1)v) + bv)(v(\alpha\left(b\sigma^2 - \beta\right) - 2b\left(\mu^2 + \sigma^2\right) + \alpha^3 f\sigma^2 - \alpha^2 f\sigma^2) - a\alpha\left(\alpha f\left(\mu^2 + \sigma^2\right) - \beta\right))}{\left(b\left(\beta + (\alpha - 2)(-f)\mu^2 - 2(\alpha - 1)f\sigma^2\right) + \alpha^2 f\left(\beta - (\alpha - 1)f\left(\mu^2 + 2\sigma^2\right)\right)\right)^2}. \tag{A.6}$$

In the same way as in c), I analyze how λ_2 behaves with respect to α. Assume $\alpha = 0$, then $\lambda_2 = -\frac{2f\mu^2 v^2\left(\mu^2+\sigma^2\right)}{\left(\beta+2f\left(\mu^2+\sigma^2\right)\right)^2} < 0$, so the restriction does not fulfill. Now, consider that $\alpha = 1$, then $\lambda_2 = \frac{f\mu^2(af+bv)\left(\beta(a-v)-af\left(\mu^2+\sigma^2\right)-bv\left(2\mu^2+\sigma^2\right)\right)}{\left(b(\beta+f\mu^2)+\beta f\right)^2} > 0$ if$\beta(a - v) - af\left(\mu^2 + \sigma^2\right) - bv\left(2\mu^2 + \sigma^2\right) > 0$. So, it could be that λ_2 is increasing regarding α, but not for its entire domain $(0, 1)$. What are the values of α for which the green firm decides to supply its whole stock of certificates, i.e., $\omega = 1$?

The sign of λ_2 is given by its numerator. After solving $\lambda_2 = 0$, I got two negative roots, two imaginary, and one positive, apparently . The specific form of the last solution is

$\alpha''_m = -\frac{1}{6fv\sigma^2}(2^{2/3}\sqrt[3]{x_m + \sqrt{y_m}} - 2f(v\sigma^2 + a(\mu^2+\sigma^2)) + \frac{m_m}{\sqrt[3]{x_m + \sqrt{y_m}}})$, where

$$\begin{aligned}
x_m =& - f^2(2a^3 f(\mu^2+\sigma^2)^3 + 3a^2\sigma^2 v(\mu^2+\sigma^2)(2f(\mu^2+\sigma^2) - 3\beta) + 3a\sigma^2 v^2(3\beta\mu^2 \\
&- \sigma^2(3b-2f)(\mu^2+\sigma^2)) + \sigma v^3(9\sigma^3(6b\mu^2 + 5b\sigma^2 + \beta) + 2f)) \\
y_m =& f^3(f(2a^3 f(\mu^2+\sigma^2)^3 + 3a^2\sigma^2 v(\mu^2+\sigma^2)(2f(\mu^2+\sigma^2) - 3\beta) + 3a\sigma^2 v^2(3\beta\mu^2 \\
&- \sigma^2(3b-2f)(\mu^2+\sigma^2)) + \sigma^4 v^3(54b\mu^2 + 45b\sigma^2 + 9\beta + 2f\sigma^2))^2 \\
&+ 4(3\sigma^2 v(a\beta + b\sigma^2 v - \beta v) - f(a(\mu^2+\sigma^2) + \sigma^2 v)^2)^3) \\
m_m =& 2\sqrt[3]{2} f \left(a^2 f\left(\mu^2+\sigma^2\right)^2 + a\sigma^2 v\left(2f\left(\mu^2+\sigma^2\right) - 3\beta\right) + \sigma^2 v^2\left(\sigma^2(f-3b) + 3\beta\right)\right).
\end{aligned}$$

In this case, selling the whole stock of certificates is a solution when the regulator sets a green goal greater than α''_m.

Cournot equilibrium. Here, I found the equilibrium for the Cournot duopoly approach.

Analogously to the merit order case, the equilibrium is determined by the first-order conditions derived from the conventional and green generators' problems and the Kuhn-Tucker conditions (1.10, 1.11, 1.19, 1.21 y 1.22), as it shows below for quick reference.

$$\begin{aligned}
\lambda_1 :& \quad \omega \geq 0, \quad \lambda_1 \geq 0, \quad \lambda_1(-\omega) = 0; \\
\lambda_2 :& \quad 1-\omega \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2(1-\omega) = 0; \\
q_c :& \quad a - v - 2(\alpha^2 f + b)q_c - (\alpha^2 f + b)\mu k_r + \alpha\mu\omega f k_r = 0; \\
k_r :& \quad \mu(a - q_c(b + \alpha f(\alpha-\omega))) - k_r(\beta + 2(\mu^2+\sigma^2)(b + f(\alpha-\omega)^2)) = 0; \\
\omega :& \quad f k_r(\alpha\mu q_c + 2k_r(\mu^2+\sigma^2)(\alpha-\omega)) + \lambda_1 - \lambda_2 = 0.
\end{aligned}$$

Now, I will solve each of the four cases associated with the Kuhn-Tucker conditions.

a) $\boldsymbol{\omega = 0, \quad \lambda_1 > 0}$ *and* $\boldsymbol{\omega = 1, \quad \lambda_2 > 0}$

This case is dismissed because ω cannot be equal to zero and one simultaneously.

b) $\boldsymbol{\omega = 0, \quad \lambda_1 > 0 \quad \textit{and} \quad \omega < 1, \quad \lambda_2 = 0}$

In this instance, the restrictions over ω are met since $\omega = 0 < 1$. So, it is left to validate if $\lambda_1 > 0$. After solving for λ_1, I get:

$$\lambda_1 = -\frac{\alpha\mu^2 f(a+v)(\beta(a-v) + a(\alpha^2 f + b)(3\mu^2 + 4\sigma^2))}{(\alpha^2 f + b)(2\beta + (\alpha^2 f + b)(3\mu^2 + 4\sigma^2))^2}. \tag{A.7}$$

Since $a > v$, then $\lambda_1 < 0$, and the restriction over λ_1 is not fulfilled. Identically to the merit order case, so the green firm will not choose a share equal to 0.

c) $\boldsymbol{\omega > 0, \quad \lambda_1 = 0 \quad \textit{and} \quad \omega < 1, \quad \lambda_2 = 0}$

After solving the equation system given by the first-order conditions, it results in two solutions for ω. The first is negative, $\omega_1 = -\frac{(a+v)(\alpha^2 f + b)}{\alpha f(a-v)} < 0$, so it does not meet the requirement $\omega \in (0, 1)$.

The sign of the second one is not so clear, so it is important to analyze it in detail:

$$\omega_2 = \frac{\alpha\left(a\left(3\mu^2 + 4\sigma^2\right)\left(b + \alpha^2 f\right) + \beta(a-v)\right)}{2ab\left(\mu^2 + \sigma^2\right) + a\alpha^2 f\left(3\mu^2 + 4\sigma^2\right) + 2bv\left(\mu^2 + \sigma^2\right)}. \tag{A.8}$$

Given that $a > v$, ω_2 is always positive, and the first constraint is met, $\omega_2 > 0$. To prove that $\omega_2 < 1$, it has to be that the value in the numerator is smaller than the denominator, so the difference is negative. Now, when $\alpha = 0$, the difference is negative, $-2b(a+v)\left(\mu^2 + \sigma^2\right) < 0$. However, if $\alpha = 1$, this value is positive $b\mu^2(a - 2v) + 2b\sigma^2(a - v) + \beta(a - v) > 0$. As in the third case, it seems that ω is increasing in α. So, what are the values of α for which the green generator decides to supply a share between zero and one of its certificate's stock?

The equation $\omega = 1$ has two imaginary roots and one real, given by

$$\alpha'_c = \frac{x - 3y}{3\sqrt[3]{\frac{3}{2}\sqrt{3}\sqrt{x^3\left(4x^2 z - x\left(y^2 + 18yz - 27z^2\right) + 4y^3\right)} - \frac{9}{2}x^2(y - 3z) + x^3}}$$
$$+\frac{\sqrt[3]{\sqrt{x^3\left(x(2x - 9y + 27z)^2 - 4(x - 3y)^3\right)} - 9x^2 y + 27x^2 z + 2x^3}}{3\sqrt[3]{2}x} + \frac{1}{3},$$

where $x = af(3\mu^2 + 4\sigma^2)$, $y = \alpha(ab + \beta(a - v))$ and $z = 2b(\mu^2 + \sigma^2)(a + v)$. In this case, the green generator chooses to sell a share of its certificates, i.e., $\omega \in (0, 1)$, when $\alpha < \alpha'_c$.

d) $\omega > 0, \quad \lambda_1 = 0 \quad$ *and* $\quad \omega = 1, \quad \lambda_2 > 0$

Since $\omega = 1 > 0$, the condition required is observed. Thus, it is only left to verify if $\lambda_2 > 0$.

$$\lambda_2 = \frac{\begin{array}{r}\mu^2 f((a+v)(\alpha^2 f + b) + \alpha f(a-v))(\mu^2(3a\alpha(b - \alpha f(1-\alpha)) - 2b(a+v)) \\ + \alpha\beta(a-v) + 2\sigma^2(2a\alpha(b - \alpha f(1-\alpha)) - b(a+v)))\end{array}}{\begin{array}{r}(b^2(3\mu^2 + 4\sigma^2) + 2b(\beta + (3\alpha^2 - 3\alpha + 2) f\mu^2 + 2(2\alpha^2 - 2\alpha + 1) f\sigma^2) \\ + \alpha^2 f(2\beta + (\alpha-1)^2 f(3\mu^2 + 4\sigma^2)))^2\end{array}}. \tag{A.9}$$

Analogously as the merit order case, I analyze how λ_2 behaves with respect to α. Assume $\alpha = 0$, then $\lambda_2 = -\frac{2f\mu^2(a+v)^2(\mu^2+\sigma^2)}{(b(3\mu^2+4\sigma^2)+2\beta+4f(\mu^2+\sigma^2))^2} < 0$, so the restriction does not fulfill. Now, consider that $\alpha = 1$, then $\lambda_2 = \frac{f\mu^2(a(b+2f)+bv)(b\mu^2(a-2v)+2b\sigma^2(a-v)+\beta(a-v))}{(b^2(3\mu^2+4\sigma^2)+2b(\beta+2f(\mu^2+\sigma^2))+2\beta f)^2} > 0$ with $a > 2v > v$, so the condition over λ_2 is met. It seems that λ_2 is increasing with respect to α, but not for the entire domain. What are the values of α for which the green firm decides to supply its whole stock of certificates, i.e., $\omega = 1$?

The equation given by $\lambda_2 = 0$ has five roots: two of them are imaginary, another two are negative, and one is possibly positive. Interestingly, this last solution is identical to the one found in c). For this case, $\omega = 1$ is a solution with $\alpha > \alpha'_c$.

Numerical exercise.

In the model, energy consumer demand is linear, $s(Q_s) = a - bQ_s$, so it is required to identify the parameters a and b from the function. I used the data of maximum demand and the average Locational Marginal Price (LMP) of energy provided by CENACE(Centro Nacional de Control de Energía, by its acronym in Spanish), so the demand is $s = 65,640 - 0.000858Q_s$, where the sensitivity -0.000858 reflects a price elasticity of demand of -0.641 at a reference LMP of 22 USD/MW and a maximum demand of 40,000 MW.

Rosas-Flores et al. (2017) estimated the energy demand price elasticity using the Almost Ideal Demand System approach, which assumes demand comes from a Constant Elasticity Substitution (CES) utility function. In contrast, linear demand comes from a quadratic or quasi-linear utility function, and elasticity is not constant through the demand curve. However, although it does not have the same utility function, this data could be used assuming that CES and linear demand are tangent at the point where elasticity is -0.0641.

I assume the conventional generator has a gas turbine technology, and its fuel cost is 35 USD/MWh (CENACE). Regarding the investment in green generation capacity, I consider it has a Solar PV technology, and its cost is 900,000 USD/MW (OECD).

The Mexican regulation establishes the non-compliance penalty, f, that increases with respect to the green certificate obligation not covered (CRE). This means that a low default level is less costly than a larger one. However, in this case, it is not possible to know the non-compliance level beforehand and thus choose the corresponding fee bracket level, so I assume f = 107.8 USD/green certificate, corresponding to the average penalties for each non-compliance level.

For what it does to the regulator's green goal, I am using the ones set by the regulator for each year from 2018 to 2023 (5%, 5.8%, 7.4%, 10.9%, and 13.9%, respectively) to see how the results change across each.

Finally, I assume the intermittency parameter $\tilde{q}_r \sim Bernoulli(1/2)$. Kök et al. (2018) argues that a two-point distribution can represent the hours of the day when the natural resources present more availability. For example, during the day, solar generation reaches its peak during the day and is zero at night.

Appendix B

Chapter 2

Proof of Proposition 2.1. The conventional, green 1 and green 2 firms solve their optimization problems in (2.1), (2.2) and (2.3), respectively, that leads to the following first-order conditions (FOC). Since this problem refers to credit multipliers' approach, I will omit the superscript m.

$$q_c: \quad a - b(2q_c + q_{v_1} + q_{v_2}) - 2c_c q_c = 0, \tag{B.1}$$

$$q_{v_1}: \quad a - b(q_c + 2q_{v_1} + q_{v_2}) - 2c_{v_1} q_{v_1} + P_c\gamma_1 = 0, \tag{B.2}$$

$$q_{v_2}: \quad a - b(q_c + q_{v_1} + 2q_{v_2}) - 2c_{v_2} q_{v_2} + P_c\gamma_2 = 0. \tag{B.3}$$

The objective functions are strictly concave, the second-order condition (SOC) is $-2b - c_i$, $i = c, v_1, v_2$. Thus, there is a maximum. Solving the system equation in (2.9), (2.10) and (2.11)

$$q_c = \frac{a(b + 2c_{v_1})(b + 2c_{v_2}) - bP_c(b(\gamma_1 + \gamma_2) + 2(\gamma_2 c_{v_1} + \gamma_2 c_{v_2}))}{4b^3 + 6b^2(c_c + c_{v_1} + c_{v_2}) + 8b(c_c(c_{v_1} + c_{v_2}) + c_{v_1}c_{v_2}) + 8c_c c_{v_1} c_{v_2}}, \tag{B.4}$$

$$q_{v_1} = \frac{a(b + 2c_c)(b + 2c_{v_2}) + P_c\left(b^2(3\gamma_1 - \gamma_2) + b(4\gamma_1 c_c - 2\gamma_2 c_c + 4\gamma_1 c_{v_2}) + 4\gamma_1 c_c c_{v_2}\right)}{4b^3 + 6b^2(c_c + c_{v_1} + c_{v_2}) + 8b(c_c(c_{v_1} + c_{v_2}) + c_{v_1}c_{v_2}) + 8c_c c_{v_1} c_{v_2}}, \tag{B.5}$$

$$q_{v_2} = \frac{a(b + 2c_c)(b + 2c_{v_1}) + P_c\left(-b^2(\gamma_1 - 3\gamma_2) + b(-2\gamma_1 c_c + 4\gamma_2 c_c + 4\gamma_2 c_{v_1}) + 4\gamma_2 c_c c_{v_1}\right)}{4b^3 + 6b^2(c_c + c_{v_1} + c_{v_2}) + 8b(c_c(c_{v_1} + c_{v_2}) + c_{v_1}c_{v_2}) + 8c_c c_{v_1} c_{v_2}}. \tag{B.6}$$

Using (A2.b) to find the certificates' price, $P_c(\alpha, \gamma_1, \gamma_2)$ to obtain the equilibrium outcomes in terms of the policy parameters.

Now, I verify if credit multipliers policy reaches the green generation goal $\frac{q_{v_1}+q_{v_2}}{q_{v_1}+q_{v_2}+q_c}=\alpha$

$$\frac{q_c}{q_{v_1}+q_{v_2}+q_c}=\frac{b\left(-\alpha(\gamma_1+\gamma_2)+\gamma_1^2+\gamma_2^2\right)+2\gamma_2 c_{v_1}(\gamma_2-\alpha)+2\gamma_1 c_{v_2}(\gamma_1-\alpha)}{2\left(b\left(\gamma_1^2-\gamma_1\gamma_2+\gamma_2^2\right)+c_c(\gamma_1-\gamma_2)^2+\gamma_2^2 c_{v_1}+\gamma_1^2 c_{v_2}\right)}\neq(1-\alpha). \tag{B.7}$$

To find the adjusted green goal, it is necesary to solve for $\tilde{\alpha}$ that refers to the goal the regulator should set to reach its original goal α, this is $\frac{q_{v_1}(\tilde{\alpha})+q_{v_2}\tilde{\alpha}}{q_{v_1}\tilde{\alpha}+q_{v_2}\tilde{\alpha}+q_c\tilde{\alpha}}=\alpha$

$$\frac{b\left(\tilde{\alpha}(\gamma_1+\gamma_2)+(\gamma_1-\gamma_2)^2\right)+2\left(c_c(\gamma_1-\gamma_2)^2+\tilde{\alpha}\gamma_2 c_{v_1}+\tilde{\alpha}\gamma_1 c_{v_2}\right)}{2\left(b\left(\gamma_1^2-\gamma_1\gamma_2+\gamma_2^2\right)+c_c(\gamma_1-\gamma_2)^2+\gamma_2^2 c_{v_1}+\gamma_1^2 c_{v_2}\right)}=\alpha;$$

$$\tilde{\alpha}=\frac{(2\alpha-1)b\gamma_1^2-2(\alpha-1)b\gamma_1\gamma_2+(2\alpha-1)b\gamma_2^2+2(\alpha-1)c_c(\gamma_1-\gamma_2)^2+2\alpha\left(\gamma_2^2 c_{v_1}+\gamma_1^2 c_{v_2}\right)}{b(\gamma_1+\gamma_2)+2(\gamma_2 c_{v_1}+\gamma_1 c_{v_2})}.$$

Notice that when $\gamma_1=\gamma_2=1$, then $\tilde{\alpha}=\alpha$ because it is the neutral policy case and there is no need of additional adjustment for the green generation goal.

Proof of Proposition 2.2. To obtain the new outcomes after adjusting with $\tilde{\alpha}$, it is enough with replacing $\tilde{\alpha}$ in $P_c(\tilde{\alpha})$ and then plug it into equations (2.12), (2.13) and (2.14).

$$q_c^m=\frac{a(\alpha-1)}{(\alpha-2)b+2(\alpha-1)c_c}, \tag{B.8}$$

$$q_{v_1}^m=-\frac{a(b((2\alpha-1)\gamma_1-\alpha\gamma_2+\gamma_2)+2((\alpha-1)c_c(\gamma_1-\gamma_2)+\alpha\gamma_1 c_{v_2}))}{((\alpha-2)b+2(\alpha-1)c_c)(b(\gamma_1+\gamma_2)+2(\gamma_2 c_{v_1}+\gamma_1 c_{v_2}))}, \tag{B.9}$$

$$q_{v_2}^m=\frac{a(b((\alpha-1)\gamma_1-2\alpha\gamma_2+\gamma_2)+2(\alpha-1)c_c(\gamma_1-\gamma_2)-2\alpha\gamma_2 c_{v_1})}{((\alpha-2)b+2(\alpha-1)c_c)(b(\gamma_1+\gamma_2)+2(\gamma_2 c_{v_1}+\gamma_1 c_{v_2}))}. \tag{B.10}$$

Proof of Proposition 2.3. To obtain the outcome under the neutral policy, I assume

$\gamma_1 = \gamma_2 = 1$ and replace them in (2.17), (2.18) and (2.19).

$$
\begin{aligned}
q_c^n &= \frac{a(\alpha-1)}{(\alpha-2)b+2(\alpha-1)c_c},\\
q_{v_1}^n &= -\frac{a\alpha(b+2c_{v_2})}{2((\alpha-2)b+2(\alpha-1)c_c)(b+c_{v_1}+c_{v_2})},\\
q_{v_2}^n &= -\frac{a\alpha(b+2c_{v_1})}{2((\alpha-2)b+2(\alpha-1)c_c)(b+c_{v_1}+c_{v_2})}.
\end{aligned}
$$

Proof of Proposition 2.4. The conventional, green 1 and green 2 firms solve their optimization problems in (2.1), (2.4) and (2.5), that leads to the following FOC. Since this problem refers to carve-outs approach, I will omit the superscript *co*.

$$q_c: \quad a - b(2q_c + q_{v_1} + q_{v_2}) - 2c_c q_c = 0, \tag{B.11}$$

$$q_{v_1}: \quad a - b(q_c + q_{v_1} + q_{v_2}) - bq_{v_1} - 2c_{v_1}q_{v_1} + P_{c_1} = 0, \tag{B.12}$$

$$q_{v_2}: \quad a - b(q_c + q_{v_1} + q_{v_2}) - bq_{v_2} - 2c_{v_2}q_{v_2} + P_{c_2} = 0. \tag{B.13}$$

Solving the system equation gives as result,

$$q_c = \frac{a(b+2c_{v_1})(b+2c_{v_2}) - b(b(P_{c_1}+P_{c_2}) + 2(c_{v_1}P_{c_2} + c_{v_2}P_{c_1}))}{4b^3 + 6b^2(c_c + c_{v_1} + c_{v_2}) + 8b(c_c(c_{v_1}+c_{v_2}) + c_{v_1}c_{v_2}) + 8c_c c_{v_1} c_{v_2}}, \tag{B.14}$$

$$q_{v_1} = \frac{a(b+2c_c)(b+2c_{v_2}) + b^2(3P_{c_1} - P_{c_2}) + b(4c_cP_{c_1} - 2c_cP_{c_2} + 4c_{v_2}P_{c_1}) + 4c_c c_{v_2} P_{c_1}}{4b^3 + 6b^2(c_c + c_{v_1} + c_{v_2}) + 8b(c_c(c_{v_1}+c_{v_2}) + c_{v_1}c_{v_2}) + 8c_c c_{v_1} c_{v_2}}, \tag{B.15}$$

$$q_{v_2} = \frac{a(b+2c_c)(b+2c_{v_1}) - (b^2(P_{c_1} - 3P_{c_2})) + b(-2c_cP_{c_1} + 4c_cP_{c_2} + 4c_{v_1}P_{c_2}) + 4c_c c_{v_1} P_{c_2}}{4b^3 + 6b^2(c_c + c_{v_1} + c_{v_2}) + 8b(c_c(c_{v_1}+c_{v_2}) + c_{v_1}c_{v_2}) + 8c_c c_{v_1} c_{v_2}}. \tag{B.16}$$

Using (A2.c) to find the prices P_{c_1} and P_{c_2},

$$P_{c_1} = \frac{a[\beta_1(b+2c_{v_1}) - (1-\alpha)(b+2c_c)]}{b(2-\alpha) + 2c_c(1-\alpha)}, \tag{B.17}$$

$$P_{c_2} = \frac{a[(\alpha-\beta_1)(b+2c_{v_2}) - (1-\alpha)(b+2c_c)]}{b(2-\alpha) + 2c_c(1-\alpha)}. \tag{B.18}$$

Substituting P_{c_1} and P_{c_2} in (2.23), (2.24) and (2.25),

$$q_{v_1}^{co} = -\frac{a\beta 1}{(\alpha-2)b+2(\alpha-1)c_c},$$
$$q_{v_2}^{co} = \frac{a(\beta 1-\alpha)}{(\alpha-2)b+2(\alpha-1)c_c}.$$

Proof of Proposition 2.5. The regulator solves the following social welfare maximization problems

$$\text{neutral:} \quad \max_{\alpha} SW^n = U(q^n) - c_c q_c^n - c_{v_1} q_{v_1}^n - c_{v_2} q_{v_2}^n - \frac{d(q_c^n)^2}{2}, \tag{B.19}$$
$$\text{multipliers:} \quad \max_{\alpha,\gamma_1} SW^m = U(q^m) - c_c q_c^m - c_{v_1} q_{v_1}^m - c_{v_2} q_{v_2}^m - \frac{d(q_c^m)^2}{2}, \tag{B.20}$$
$$\text{carve-outs:} \quad \max_{\alpha,\beta_1} SW^{co} = U(q^{co}) - c_c q_c^{co} - c_{v_1} q_{v_1}^{co} - c_{v_2} q_{v_2}^{co} - \frac{d(q_c^{co})^2}{2}. \tag{B.21}$$

The SW^n function is strictly concave, the SOC $SW^n_{\alpha,\alpha} < 0$, thus, there is a maximum. The SW^{co} is concave with $M_1 \leq 0$ and $M_2 \geq 0$, thus, there is a maximum. The SW^m has two critical points $P_1 = (\alpha', \gamma_1')$, and $P_2 = (\alpha'', \gamma_1'')$. The determinant of the Hessian matrix in P_1 is positive and $SW^m_{\alpha,\alpha} < 1$, thus, P_1 is maximum. Regarding P_2, the determinant is negative, thus, P_2 is a saddle point.

Appendix C

Chapter 3

Proof of Proposition 3.1. In the second stage, both firms choose their energy production and green certificate supply; they solve the optimization problems in (3.1) and (3.2). Thus, the first-order conditions are

$$q_g : a - q_c - 2q_g + \alpha x_g = 0, \tag{C.1}$$

$$x_g : \alpha(q_g + q_c) - 2x_g - x_c = 0, \tag{C.2}$$

$$q_c : a - 2q_c - q_g + \alpha x_c - \rho(1 - z) = 0, \tag{C.3}$$

$$x_c : \alpha(q_g + q_c) - 2x_c - x_g = 0. \tag{C.4}$$

The FOC given by equations (3.9) to (3.12), lead to the following reaction functions of the firms

$$\begin{aligned} q_c(q_g, x_c) &= \frac{1}{2}(a - (1 - z)\rho + \alpha x_c - q_g), \\ q_g(q_c, x_g) &= \frac{1}{2}(a + \alpha x_g - q_c), \\ x_c(x_g, q_c, q_g) &= \frac{1}{2}(\alpha(q_c + q_g) - x_g), \\ x_g(x_c, q_c, q_g) &= \frac{1}{2}(\alpha(q_c + q_g) - x_c). \end{aligned}$$

The objective functions are concave, both determinants of the Hessian matrix are equal to $4 - \alpha^2$, thus, there is a maximum. Solving simultaneously the four reaction functions of the firms for q_g, q_c, x_c and x_g, in equilibrium

$$q_c(z) = \frac{3a - (1-z)(6-\alpha^2)\rho}{9-2\alpha^2}, \tag{C.5}$$
$$q_g(z) = \frac{3a + (1-z)(3-\alpha^2)\rho}{9-2\alpha^2}, \tag{C.6}$$
$$x_c(z) = x_g(z) = \frac{\alpha(2a - (1-z)\rho)}{9-2\alpha^2}. \tag{C.7}$$

In the first stage, the conventional firm chooses the proportion of energy free of emissions z given $q_g(z), q_c(z), x_c(z)$ and $x_g(z)$ that maximizes Equation (3.3) with the abatement between zero and one. This restriction leads to the Lagrangian in Equation (3.4). The first-order conditions along with the complementary slackness conditions are

$$z: \quad \frac{(\alpha^2-4)\,\rho(a-2\rho) + (9-2\alpha^2)\,\beta z + 2\,(\alpha^2-4)\,\rho^2 z +}{2\alpha^2 - 9} + \lambda_1 - \lambda_2 = 0, \tag{C.8}$$
$$\lambda_1: \quad z \geq 0, \quad \lambda_1 \geq 0, \quad \lambda_1 z = 0, \tag{C.9}$$
$$\lambda_2: \quad 1-z \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_2(1-z) = 0. \tag{C.10}$$

The slackness conditions give place to four possible solutions: *i)* $z = 0$ & $\lambda_1 > 0$ *and* $z = 1$ & $\lambda_2 > 0$, *ii)* $z = 0$ & $\lambda_1 > 0$ *and* $z < 1$ & $\lambda_2 = 0$, *iii)* $z < 0$ & $\lambda_1 = 0$ *and* $z = 1$ & $\lambda_2 > 0$, and *iv)* $z < 0$ & $\lambda_1 = 0$ *and* $z < 1$ & $\lambda_2 = 0$

Now, I will solve each of the four cases to identify the equilibrium.

i) $z = 0$ & $\lambda_1 > 0$ *and* $z = 1$ & $\lambda_2 > 0$

This case is discarded because z cannot be equal to zero and one at the same time, so the condition is not fulfilled.

ii) $z = 0$ & $\lambda_1 > 0$ *and* $z < 1$ & $\lambda_2 = 0$

When $z = 0 < 1$ and $\lambda_2 = 0$, the value for λ_1 in Equation (16) is $\lambda_1 = -\frac{(4-\alpha^2)\rho(a-2\rho)}{9-2\alpha^2} < 0$, which is negative under the assumptions $0 < \alpha < 1$ and $a > 4\rho > 0$. Thus, there is no equilibrium in which the conventional firm chooses to not abate.

iii) $z < 0$ & $\lambda_1 = 0$ *and* $z = 1$ & $\lambda_2 > 0$

When $z = 1 > 0$ and $\lambda_1 = 0$, the value for λ_2 in Equation (16) is $\lambda_2 = \frac{a\left(4-\alpha^2\right)\rho-\left(9-2\alpha^2\right)\beta}{9-2\alpha^2}$. In this case, $\lambda_2 > 0$ for $0 < \beta \leq \frac{a\left(\alpha^2-4\right)\rho}{2\alpha^2-9}$. Thus, $z_1 = 1$ is an equilibrium when the investment costs are low.

iv) $z < 0$ & $\lambda_1 = 0$ *and* $z < 1$ & $\lambda_2 = 0$

This case refers to the interior solution. When $\lambda_1 = \lambda_2 = 0$, the value for z in Equation (16) is $z_2 = \frac{\rho(a-2\rho)(4-\alpha^2)}{(9-2\alpha^2)\beta-2(4-\alpha^2)\rho^2}$. In this case, $0 < z < 1$ for $\beta > \frac{a\left(\alpha^2-4\right)\rho}{2\alpha^2-9}$. Thus, z_2 is the equilibrium when the investment costs are high.

After replacing z_1 and z_2 in Equations (3.13), (3.14) and (3.15), the equilibria in the energy and certificates market are obtained.

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