Incorporating oligopoly, CO_2 emissions trading and green certificates into a power generation expansion model

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Abstract. This paper presents a generation expansion model for the power sector which incorporates several features that make it very interesting for its application to current electricity markets: it considers the possible oligopolistic behavior of firms, and incorporates relevant policy instruments, carbon emissions trading and tradable green certificates. It combines powerful traditional tools related to the detailed system operation with techniques for modeling the economic market equilibrium and a formulation for the resolution of the emissions permit and tradable green certificates market equilibriums. The model is formulated as a Linear Complementarity Problem (LCP) which allows solving simultaneously the optimization problem for each firm considering the power, carbon and green certificate markets. The model has been implemented in GAMS. An application to the Spanish power system is also presented.

Keywords: generation-expansion modeling, carbon emissions trading, green certificates, oligopoly.

1. Introduction

The electricity industry around the world has been experiencing significant changes to an unprecedented pace in its history. Electricity markets worldwide are being deregulated on the generation and retail sides, and this is bringing about two major changes: on the one hand, there is an almost total freedom when deciding on the expansion of generation facilities. On the other hand, firms are subject to competition (which in most cases is imperfect) in the generation market.

In this new context, electricity generation firms are subject to much more significant challenges when making decisions. Also regulators face a more difficult task of monitoring the present and future evolution of the power sector. Therefore, both types of agents require new models and adequate tools to cover these new functions, since in most cases, traditional approaches become much less useful (Dyner and Larsen, 2001).

In addition, besides these changes in the organization of the industry, growing concerns about environmental issues have led to the establishment of several energy and environmental policies, of which the most relevant are those derived from the Kyoto Protocol for the reduction of greenhouse gas emissions as well as those promoting renewable energies. These policies have also to be adequately considered by electric utilities for their decision making, and regulators for their monitoring, since they may have a significant impact on the profitability of investments and on the economic and environmental performance of the power sector.

Currently, one of the major Kyoto Protocol consequences is the establishment of a carbon emissions trading scheme. Although the global market has barely started, the European Commission has introduced a Directive for an internal Emissions Trading Scheme (ETS) which started in 2005 (European Commission, 2003) and is already producing some trade. Although most models are just using exogenous carbon prices, the electricity sector is a major player in this market, and may therefore affect prices significantly with its behavior. Therefore, it seems appropriate to model together both the power and carbon markets and thus obtain endogenous prices from both.

Regarding renewable energy promotion policies, two options are mostly used: price systems (premiums) and quota systems (usually associated with tradable green certificates). Although the first are more widespread, due to their seemingly better performance (Menanteau et al, 2003), their modeling as an exogenous premium for deciding on generation expansion is somewhat short-sighted. Indeed, premiums are not static, but rather based on implicit quota objectives set by regulators. Therefore, we consider that they should be modeled anyway as quota systems, since that allows for an endogenous generation of the premium.

Combinations of both policies already exist in some power markets: the UK and Italy feature both tradable green certificate systems and the carbon trading system imposed by the European ETS. If we consider, as mentioned before, that also feed-in tariffs may be modeled as implicit quotas, then most of European countries are already experiencing the impacts of both policies.

In this paper, a generation-expansion model for the power sector is presented which incorporates all the above-mentioned aspects, so that it may respond adequately to the needs of firms and regulators in the current electricity markets: it considers the possible oligopolistic behavior of generating firms, and also introduces into the model carbon emissions and tradable green certificates markets. The paper is structured as follows: Section 2 presents the state of the art of generation-expansion models, while Section 3 describes in detail the model presented. Section 4 shows an application of the model to a real case, the Spanish electricity sector. Finally, Section 5 provides the conclusions drawn from the study.

2. State of the art

There are not many references in the literature for generation-expansion models for power systems which adequately address the challenges expressed abov: simulation of oligopolistic behavior and modeling of carbon emissions and green certificate markets. This may be due to the change in the conditions of power markets (basically, their deregulation and liberalization) which have made obsolete most of the previously existing models, as correctly pointed out by Dyner and Larsen (2001). However, there have been several partial approaches.

Regarding the simulation of oligopolistic power markets, a lot of research has been carried out lately, of which an extensive review is given in Ventosa et al (2005). In many of these models, generation companies are assumed to behave as Cournot players (see e.g. Rivier et al, 2001). However, a number of drawbacks seem to question the applicability of the Cournot model. The most important one stems from the fact that under the Cournot approach, generators' strategies are expressed in terms of quantities and not in terms of supply curves. Hence, equilibrium prices are determined only by the demand function, therefore highly sensitive to demand representation and usually higher than those observed in reality. This limitation may be overcome by introducing the Conjectural Variations approach described in traditional microeconomics theory (Vives, 1999). The CV approach is easy to introduce into Cournot-based models (García-Alcalde et al, 2002 and Day et al, 2002) since resulting models can be stated as Linear Complementarity Problem (LCP) (for an overview of LCP see e.g. Cottle et al, 1992).

As for the modeling of carbon emissions markets, this has generally been done only in larger scale, energy-economy-environment models, of which a very thorough review is presented for example in Huntington and Weyant (2004). However, these models have little detail for the electricity sector (which, as mentioned before, is a relevant player in carbon markets). Some studies in which the electricity sector is modeled together with emissions markets (for SO_2 and NO_x, not for carbon) were those developed in the US under the Clean Air Act (see e.g. Hobbs, 1993). The GETS initiative carried out by Eurelectric (Eurelectric, 2004) tried to represent carbon emissions markets within the European electricity sector. Also for Europe, Morthorst (2001), Hindsberger et al (2003), Jensen and Skytte (2003) or Unger and Ahlgren (2006) have looked at the specific impact of carbon trading on the Nordic countries electricity sector. In particular, these studies also model tradable green certificate schemes, so that they are the closest attempt we know at answering the modeling challenges mentioned before. The problems with these models are that they only look at the electricity sector and not the rest of sectors which might participate in a carbon emissions trading scheme, and that they are not able to represent adequately electricity sectors under imperfect competition.

Imperfect competition in the power sector and tradable emission allowances are addressed by Chen and Hobbs (2005), although they look at NO_x, not CO_2. We may also cite two studies which model an oligopolistic market under emissions trading regimes, Nagurney et al (1999) and Nagurney and Dhanda (2000).

However, the latter are too general and unable to cope with the technical specificities of the electricity sector. Neither of them model the promotion of renewable energies.

Finally, the authors of the present paper developed lately an oligopolistic, generation expansion model with carbon emissions trading (Linares et al, 2006a, b). However, this model did not consider the green certificate market and therefore the interesting interactions which result from these two policy measures (see e.g. Jensen and Skytte, 2003).

Therefore, as can be seen, there is a current need for generation-expansion models able to represent adequately carbon emissions and tradable green certificate markets in a power sector under imperfect competition. The GEPAC model, which tries to address all these issues, is presented below. This paper also presents a detailed mathematical description of the model, an element missing in previous work.

3. The GEPAC model

3.1. Model overview

The electricity market is modeled as one in which, in the short term, firms compete in quantity of output as in the Conjectural Variations approach wherein generators are expected to change their conjectures about their competitors' strategic decisions, in terms of the possibility of future reactions (García-Alcalde et al, 2002 and Day et al, 2002). In the long-term electricity market, firms compete in generating capacity as in the Cournot model. The structure of this problem corresponds to various simultaneous optimizations –for each firm *e*, the maximization of its profits subject to its particular technical constraints–. These optimization problems are linked together through the electricity price and the emissions permit price resulting from the interaction of all of them. The general structure of the problem is depicted in *Figure 1* (explained below).

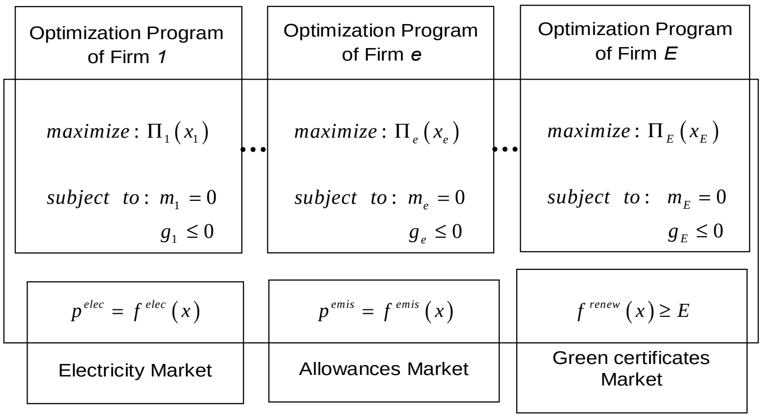

Figure 1. Scheme of the market equilibrium problem.

The objective of each generation firm e is to maximize its profit Π defined as market revenues minus operating costs, investment costs and cost of purchasing emission allowances. The sets of constraints m and g ensure that each company's optimization program provides decisions x that will be technically feasible. The set of constraints g also takes into account the bound of every decision variable x.

Formally, the whole model can be set as a Nash game (x,Π) where x is the set of strategy decisions $x=(x_1,...,x_E)$, Π is the set of profits $\Pi=(\Pi_1,...,\Pi_E)$ and e is a player or firm $e=(1,...,E)$. A Nash equilibrium is a set of strategy decisions $x^*=(x_1^*,...,x_E^*)$ such that $\Pi_e(x^*)\geq\Pi_e(x_e,x_{-e}^*)$ for all $e=(1,...,E)$, where x_{-e} is $x=(x_1,...,x_E)$ with x_e deleted. In other words, a set of strategies $x^*=(x_1^*,...,x_E^*)$ is a Nash equilibrium if no firm e can improve its profit $\Pi_e(x^*)$ by unilaterally changing its strategy x_e^*.

3.2. Modeling assumptions

For the sake of the clarity and computational tractability, generating units have been grouped into equivalent plants according to the corresponding technology. A complete list of the technologies considered in this model can be found in Section 4.1. In order to ensure the existence of a solution, constraints m and g are assumed to be linear.

The link between the electricity market and every firm's optimization program is the demand function that relates the demand supplied by every generator to the electricity price p^{elec} (see left hand side of Figure 1). It is assumed in this model that the electricity market price at each load level is a linear function $f^{elec}(\cdot)$ of the total demand (see equation 4).

The carbon allowance market is modeled as a perfectly competitive one. So the clearing price of the market p^{emis} will be the crossing of the allowances' aggregated demand curve with the whole supply curve. The whole supply curve is set to be a constant quantity of allowances determined by the government while the aggregated demand curve is the sum of demands of all sectors covered by the emissions trading scheme at every allowance price.

Part of this allowances' aggregated demand function is unknown, since for the electricity sector, their demand of allowances will depend on the utility (profit) generation firms obtain by means of these allowances: depending on the electricity price and on the allowance price, firms may be interested either in buying new allowances or in selling them, in order to produce more or less; but these prices are endogenous to the model and also depend on the production levels, and that is why the part of the allowances' demand function corresponding to the electricity sector is not known ex-ante, but rather determined endogenously by the model. The other sectors are much more difficult to model in the same way, because of their disaggregation and lack of data. However, this very disaggregation allows one to assume that they will behave as price-takers in the emissions market, and therefore to model them as a competitive fringe, with a demand function corresponding to their marginal abatement costs. Therefore, the residual supply curve considered in the emission allowance market is obtained by subtracting the total demand function for all these sectors to the whole supply curve (total amount offered by the government).

Then the emission allowance market is modeled by the residual supply function that relates the allowances purchased by every firm to the allowance price p^{emis} (see box of Allowances Market in Figure 1). It is assumed that the price is a linear function $f^{emis}(\cdot)$ of the purchases (see equation 5).

Finally, the green certificate market is also modeled as a perfectly competitive one, and therefore is represented by a global restriction on the amount of renewable electricity that has to be produced: the sum of all renewable electricity produced by all firms has to be larger than the quota set by the government E (see right hand side of Figure 1). The function $f^{renew}(\cdot)$ will be stated in equation 16.

The model assumes that firms make their capacity-expansion decisions in a Cournot manner: the investment market equilibrium defines a set of capacities such that no firm, taking its competitors' capacities as given, wishes to change its own capacity unilaterally (Ventosa et al, 2002). Thereby, each firm chooses its new maximum capacity so that its own profit is maximized. The Cournot assumption implies that firms' investment decision-making occurs simultaneously as it is modeled.

To summarize, the whole Nash-equilibrium model, which is a CV-market sub-model plus a Cournot-expansion planning sub-model, subject to the environmental restriction of the carbon allowances and tradable green certificates markets, defines the operation, the investment, allowances purchases and pricing of electricity, allowances and green certificates that simultaneously satisfy the first-order optimality conditions of all firms. It should be noted though that the model does not consider transaction costs, which may be relevant under some circumstances.

3.3. Mathematical structure

This market equilibrium problem can be stated in terms of a Linear Complementarity Problem (Rivier et al, 2001) by means of setting the first-order optimality Karush-Kuhn-Tucker conditions associated to the set of maximization programs (see Figure 2).

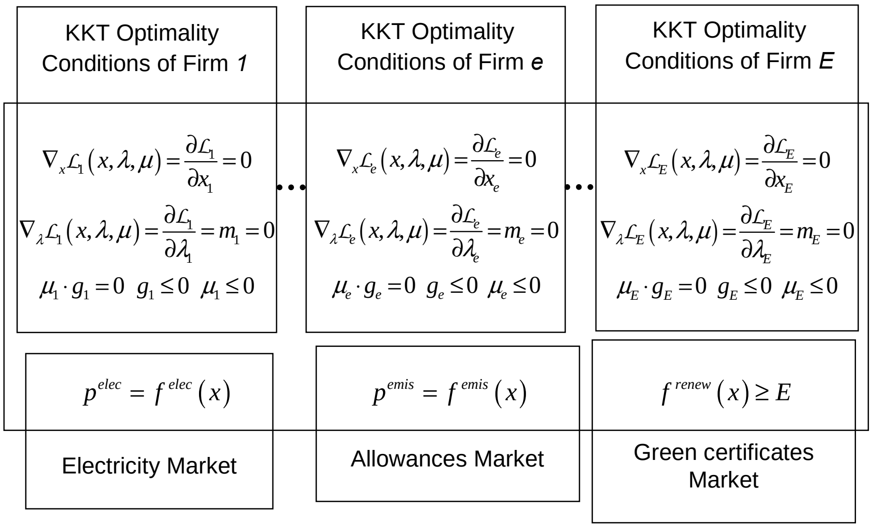

Figure 2. Mathematical structure of the market equilibrium model as a LCP.

In figure 2, $\mathcal{L}$ represents the Lagrangian function of the corresponding optimization problem and λ and μ represent the dual variables associated to the set of m and g constraints respectively. Note that the set g also takes into account the bound of every decision variable x. The optimality conditions can be written down as three sets of equations. The first one equates to zero the gradient of the Lagrangian function with respect to the decision variables x. The second set (the gradient of the Lagrangian function with respect to the dual variables λ) coincides with the equality constraints themselves m. The third one is formed by the complementary slackness conditions associated to the inequality constraints g.

As a result of the model assumptions, grouping together all companies' system of equations leads to a Linear Complementarity Problem or LCP. An LCP consists of finding a vector (x,λ,μ) that satisfies a certain system of inequalities (the abovementioned optimality conditions together with the market equations). Generally, given a vector $w \in R^n$ and a matrix $M \in R^{nxn}$, an LCP is to find a vector $z \in R^n$ such that $z \geq o$; $w + Mz \geq 0$; $z^T(w + Mz) = 0$. This LCP is denoted by the pair (w, M). There exists a solution for (w, M) if matrix M is positive semi-definite (see Theorem 3.1.2. in Cottle et al, 1992). The LCP-based model presented in this paper has a positive semi-definite matrix M since the source problem (Figure 1) is made of convex optimization programs with linear constraints.

The full mathematical formulation corresponding to the above structure is presented below.

3.4. Model statement

3.4.1. Notation

In this section all symbols used in this paper are identified and classified, according to their use, into indices, parameters, decision variables, auxiliary variables and dual variables.

Indices

b	Pumped-storage technologies
ce	Existing thermal technologies
cr	Renewable thermal technologies
cn	New thermal technologies
e	Firms
f	Run-of-the-river technologies
h	Hydro technologies
n	Load levels
p	Periods
s	Subperiods
sp	Superperiods (corresponding to the emission trading periods)

Although technically incorrect, we have assumed that *ce* and *cn* may be considered subsets of *e* along the description of the model, in order to shorten and simplify the presentation.

Parameters

$A_{h,p,s}$	Hydro inflows for hydro technology h in subperiod s of period p [TWh]
$\overline{b}_b$, $\underline{b}_b$	Maximum and minimum capacity of pumped-storage technology b when pumping [GW]
ci_{cn}	Capacity investment cost [M€/GW]
$D_{p,s,n}$	Duration of load level n in subperiod s of period p [kh]
$d'_{p,s,n}$	Constant slope of electricity demand function in load level n in subperiod s of period p [(€/kWh)/GW]
$d'_{e,p,s,n}$	Constant slope of electricity residual demand function (conjecture) of firm e in load level n in subperiod s of period p [(€/kWh)/GW]
$d'^{emis,n}_{sp}$	Constant slope of allowance demand function of non-electricity sectors in superperiod sp [(€/t CO_2)/Mt CO_2]
$E_{p,cr}$	Minimum energy supplied in period p by renewable technologies with green certificates cr [TWh]
$F_{f,p,s,n}$	Power generation by run-of-the-river technology f in load level n in subperiod s of period p [GW]

$\overline{FI}_{e,p}$	Maximum financial investment of firm *e* in period *p* [M€]
$\overline{h}_h$, $\underline{h}_h$	Maximum and minimum capacity of pumped-hydro technology *h* [GW]
$\overline{h}_b$, $\underline{h}_b$	Maximum and minimum capacity of pumped-storage technology *b* [GW]
$\overline{I}_{cn,p}$	Maximum installed capacity for technology *cn* at period *p*[TW]
i_p	Discount rate for period *p* [p.u.]
i_{sp}	Discount rate for superperiod *p* [p.u.]
o'_{ce}, o''_{ce}	Heat rate (linear [Mcal/kWh] and quadratic [Mcal/(MW2·h)] terms) of existing thermal technology ce
o'_{cn}, o''_{cn}	Heat rate (linear [Mcal/kWh] and quadratic [Mcal/(MW^2·h)] terms) of new thermal technology *cn*
$p^0_{p,s,n}$	Electricity price at demand given in load level *n* in subperiod *s* of period *p* [€/kWh]
Q_{sp}	Total amount of emissions allowances offered by the government in superperiod *sp* [Mt CO$_2$]
$q^{elec,0}_{p,s,n}$	Electricity demand at price given in load level *n* in subperiod *s* of period *p* [GW]
$q^{ini}_{e,sp}$	Initial assignments of emission allowances of firm *e* in superperiod *sp* [Mt CO$_2$]
$q^{n,0}_{sp}$	Allowance demand function of non-electricity sectors at price zero [Mt CO$_2$] $\overline{R}_b$ Maximum hydro energy reserve of pumped-storage technology *b* [TWh]
$\overline{R}_h$, $\underline{R}_h$	Maximum and minimum hydro energy reserve of hydro technology *h* [TWh]
$\overline{t}_{ce}, \underline{t}_{ce}$	Maximum and minimum rated capacity of existing thermal technology *ce* [GW]
$\underline{t}_{cn}$	Minimum rated capacity of new thermal technology *cn* [GW]
v_{cn} , v_{ce}	Fuel cost of thermal technology *cn* and *ce* [€/Mcal]
$\varphi_{ce}, \varphi_{cn}$	Utilization factor of thermal technology *cn* and *ce* [p.u.]
ρ_b	Performance of pumped-storage technology *b* [p.u.]
τ_{cn}, τ_{ce}	Emission rate of thermal technology cn and ce [Mt CO2 /MW]

Decision Variables

$b_{b,p,s,n}$	Power consumption by pumped-storage technology *b* in load level *n* in subperiod *s* of period *p* [GW]
$h_{b,p,s,n}$	Power generation by pumped-storage technology *b* in load level *n* in subperiod *s* of period *p* [GW]

$h_{h,p,s,n}$	Power generation by pumped-hydro technology *h* in load level *n* in subperiod *s* of period *p* [GW]
$I_{cn,p}$	New capacity installed in new technology *cn* in period *p* [GW]
$Ir_{cn,p}$	New capacity installed in renewable technology $cr \in cn$ in period *p* [GW]
$q^{emis}_{e,sp}$	Amount of allowances owned by of firm *e* in superperiod *sp* [Mt CO_2]
$R_{h,p,s}$	Hydro energy reserve of hydro technology *h* at the beginning of subperiod *s* of period *p* [TWh]
$t_{ce,p,s,n}$	Power generation by thermal technology *ce* in load level *n* in subperiod *s* of period *p* [GW]
$t_{cn,p,s,n}$	Power generation by thermal technology *cn* in load level *n* in subperiod *s* of period *p* [GW]
$tr_{ce,p,s,n}$	Power generation by renewable technology $cr \in ce$ in load level *n* in subperiod *s* of period *p* [GW
$tr_{cn,p,s,n}$	Power generation by renewable technology $cr \in cn$ in load level *n* in subperiod *s* of period *p* [GW]
x_e	Generic decision variable of firm *e*

Auxiliary Variables

$p^{elec}_{p,s,n}$	Electricity price in load level *n*, subperiod *s*, of period *p* [€/kWh]
p^{emis}_{sp}	Allowance price in superperiod *sp* [€/t CO_2]
$q^{elec}_{e,p,s,n}$	Total power generation sold in the market of firm *e* in load level *n*, subperiod *s*, of period *p* [GW]
q^{n}_{sp}	Amount of allowances owned by non-electricity sectors in superperiod *sp* [Mt CO_2]

Dual Variables

$\mu^{\underline{b}}_{b,p,s,n}, \mu^{\bar{b}}_{b,p,s,n}$	Bounds of power consumption by pumped-storage technology *b* in load level *n* in subperiod *s* of period *p* [M€/MW]
$\mu^{q}_{e,sp}$	Constraint of emissions of firm *e* in superperiod *sp* [M€/Mt CO_2]
$\mu^{\underline{q}}_{e,sp}$	Bound of minimum emissions allowance stock of firm *e* in superperiod *sp* [M€/Mt CO_2]
$\mu^{\underline{h}}_{b,p,s,n}, \mu^{\bar{h}}_{b,p,s,n}$	Bounds of power generation by pumped-storage technology *b* in load level *n* in subperiod *s* of period *p* [M€/MW]
$\mu^{\underline{h}}_{h,p,s,n}, \mu^{\bar{h}}_{h,p,s,n}$	Bounds of power generation by hydro technology *h* in load level *n* in subperiod *s* of period *p* [M€/MW]
$\mu^{I}_{cn,p,s,n}$	Constraint of power generation by thermal technology *cn* in load level *n* in subperiod *s* of period *p* [M€/MW]
$\mu^{\underline{I}}_{cn,p}$	Bound of minimum installed capacity of new thermal technology *cn* in period *p* [M€/MW]

$\mu^{FI}_{e,p}$	Constraint of financial investment of firm e in period p [p.u.]
$\mu^{\underline{t}}_{ce,p,s,n}, \mu^{\bar{t}}_{ce,p,s,n}$	Bounds of power generation by thermal technology ce in load level n in subperiod s of period p [M€/MW]
$\mu^{\underline{t}}_{cn,p,s,n}$	Bound of minimum power generation by thermal technology cn in load level n in subperiod s of period p [M€/MW]
$\mu^{R}_{b,p,s}$	Constraint of scheduling of pumped-storage technology b in subperiod s of period p [M€/GWh]
$\mu^{R}_{h,p,s}$	Constraint of hydro scheduling of hydro technology h in subperiod s of period p [M€/GWh]
$\mu^{\underline{R}}_{h,p,s}, \mu^{\bar{R}}_{h,p,s}$	Bounds of hydro energy reserve of hydro technology h at the beginning of subperiod s of period p [M€/GWh]
$\mu^{\bar{R}}_{b,p,s}$	Constraint of Maximum hydro energy reserve of pumped-storage technology b in subperiod s of period p [M€/GWh]
$\mu^{TA}_{cn,p}$	Constraint of increasing maximum rated capacity [M€/MW]

3.4.2. *Objective function*

The objective of each generation company is to maximize its profit –market revenues, minus operating costs, investment costs and costs of purchasing allowances– for the entire decision horizon.

Maximize:

$$\begin{aligned}
&\sum_{p}\sum_{s}\sum_{n} D_{p,s,n} \cdot \left(i_p \cdot p^{elec}_{p,s,n} \cdot q^{elec}_{e,p,s,n}\right) + \\
&-\sum_{p}\sum_{s}\sum_{n} D_{p,s,n} \cdot \left[\begin{array}{l} \sum_{ce\in e} i_p \cdot v_{ce} \cdot \left(o_{ce} \cdot t_{ce,p,s,n} + o''_{ce,p,n} \cdot t^2_{ce,p,s,n}\right) \ + \\ + \sum_{cn\in e} i_p \cdot v_{cn} \cdot \left(o_{cn} \cdot t_{cn,p,s,n} + o''_{cn,p,n} \cdot t^2_{cn,p,s,n}\right) + \end{array}\right] \qquad \forall e \qquad (1) \\
&-\sum_{cn\in e}\sum_{p>1} i_p \cdot ci_{cn} \cdot \left(I_{cn,p} - I_{cn,p-1}\right) + \\
&-\sum_{sp} i_{sp} \cdot p^{emis}_{sp} \cdot \left(q^{emis}_{e,sp} - q^{ini}_{e,sp}\right)
\end{aligned}$$

3.4.3. *Auxiliary equations*

For the sake of clarity, the following auxiliary equations are stated although total power generation of each company, allowances owned by non-electricity sectors and prices might be substituted by these expressions.

The total power generation of each firm represents the effective output –thermal, hydro, pumped-storage and run-of-the-river– that is sold in the market.

$$\begin{aligned} q^{elec}_{e,p,s,n} = {} & \sum_{ce\in e} t_{ce,p,s,n} + \sum_{cn\in e} t_{cn,p,s,n} + \\ & + \sum_{h\in e} h_{h,p,s,n} + \sum_{b\in e}\left(h_{b,p,s,n} - b_{b,p,s,n}\right) + \sum_{f\in e} F_{f,p,s,n} \end{aligned} \qquad \forall e,p,s,n \qquad (2)$$

The allowances purchased by non-electricity sectors have to be equal to the total amount of emissions allowances offered by the government minus the allowances purchased by all electricity firms.

$$q^{n}_{sp} = Q_{sp} - \sum_{e} q^{emis}_{e,sp} \qquad \forall sp \qquad (3)$$

The electricity price is obtained as a linear function of the total generation sold in the market.

$$p^{elec}_{p,s,n} = p^{0}_{p,s,n} - d'_{p,s,n} \cdot \left(\sum_{e} q^{elec}_{e,p,s,n} - q^{elec,0}_{p,s,n} \right) \qquad \forall p,s,n \qquad (4)$$

Similarly to electricity price, the emission allowance price is obtained as a linear function of the total purchases of electricity firms.

$$p^{emis}_{sp} = d'^{\,emis,n}_{sp} \cdot \left(\sum_{e} q^{emis}_{e,sp} + q^{n,0}_{sp} - Q_{sp} \right) \qquad \forall sp \qquad (5)$$

3.4.4. Constraints

The constraints considered in a long term model are those related to hydro management, investment and emissions.

Hydro scheduling

This equation states that the energy produced during each period, expressed as a function of the hydro and pumped-hydro production for each load level, is limited by the hydro inflows and the initial and final reservoir levels of that period. The initial reservoir level of the first period and the final level of the last period are known for the optimization problem.

$$\sum_{n} D_{p,s,n} \cdot h_{h,p,s,n} - R_{h,p,s} + R_{h,p,s+1} - A_{h,p,s} \le 0 \qquad \perp \mu^{R}_{h,p,s} \qquad \forall p,s,h \qquad (6)$$

Pumped-storage scheduling

Pumped-storage units are used by each company to buy energy at lower prices and sell it within the same period at higher prices, making then a price arbitrage. The first constraint establishes for each pumped-storage unit that generated energy is lower than pumped energy, while the second one limits the total pumped energy in each period.

$$\sum_{n} D_{p,s,n} \cdot \left(h_{b,p,s,n} - \rho_{b} \cdot b_{b,p,s,n}\right) \le 0 \qquad \perp \mu^{R}_{b,p,s} \qquad \forall p,s,b \qquad (7)$$

$$\sum_{n} D_{p,s,n} \cdot h_{b,p,s,n} \leq \overline{R}_b \qquad \perp \mu^{\overline{R}}_{b,p,s} \qquad \forall p,s,b \qquad (8)$$

Investment Constraints

The built-capacity constraints state that total capacity in any period is to be greater or equal than capacity in the previous one.

$$I_{cn,p-1} - I_{cn,p} \leq 0 \qquad \perp \mu^{TA}_{cn,p} \qquad \forall p > 1, cn \qquad (9)$$

The second set of investment constraints limits the power generated by the new plants in a given period. It is to be less than their actual rated capacity. Energy limitations are deterministically modeled by derating the installed capacity by its utilization factor of that technology (which is not the efficiency, but rather the energy availability for a certain installed power, and which applies basically to non-storable renewables). This constraint is analogous to the upper bound in generation output, which affects conventional thermal plants. However, in the case of new plants this output cap is a decision variable.

$$t_{cn,p,s,n} \leq \varphi_{cn} \cdot I_{cn,p} \qquad \perp \mu^{I}_{cn,p,s,n} \qquad \forall p,s,n,cn \qquad (10)$$

Finally, in order to limit the financial impact of investment decisions, the following constraint is imposed on every firm so that the monetary investment per period is limited to a certain amount.

$$\sum_{cn \in e} ci_{cn} \cdot \left(I_{cn,p} - I_{cn,p-1} \right) \leq FI_{e,p} \qquad \perp \mu^{FI}_{e,p} \qquad \forall p > 1, e \qquad (11)$$

Emissions allowances

The amount of emissions into the atmosphere is limited by the allowances owned by each firm.

$$\sum_{p \in sp} \left(\sum_{ce \in e,s,n} D_{p,s,n} \cdot \left(\tau_{ce} \cdot p_{ce,p,s,n} \right) + \sum_{cn \in e,s,n} D_{p,s,n} \cdot \left(\tau_{cn} \cdot p_{cn,p,s,n} \right) \right) \leq q^{emis}_{e,sp} \quad \perp \mu^{q}_{e,sp} \quad \forall e, sp \qquad (12)$$

Tradable green certificates constraints

In order to simulate the green certificate market, the following constraints and bounds have been considered:

The power generated in every load level will be lower or equal than the installed capacity multiplied by the use coefficient of that technology.

$$tr_{cn,p,s,n} \leq \varphi_{cn} \cdot Ir_{cn,p} \qquad \forall p,s,n,cn \in cr \qquad (13)$$

Total cumulative power installed is a monotone decreasing function of time:

$$Ir_{cn,p-1} - Ir_{cn,p} \leq 0 \qquad \forall p, cn \in cr \qquad (14)$$

Installed power may be limited by the available renewable energy potential for a certain time horizon (here 2020 has been considered):

$$Ir_{cn,p=2020,ult} \leq \overline{I}_{cn,p=2020,ult} \qquad \forall p = 2020\_ult, cn \in cr \qquad (15)$$

The total energy generated by existing and new renewable energy technologies participating in the tradable green certificate market has to be larger or equal than the minimum quota set up by the regulator.

$$\sum_{ce}\sum_{s,n} D_n \cdot tr_{ce,p,s,n} + \sum_{cn}\sum_{s,n} D_n \cdot tr_{cn,p,s,n} \geq E_{p,cr} \qquad \forall ce\_cn \in cr, p, s, n \qquad (16)$$

3.4.5. Bounds

The variables stated below are subject to the following bounds:

$$\underline{q} \leq q^{emis}_{e,sp} \qquad \perp \mu^{\underline{q}}_{e,sp} \qquad \forall \; e, sp \qquad (17)$$

$$\underline{b}_b \leq b_{b,p,s,n} \leq \overline{b}_b \qquad \perp \mu^{\underline{b}}_{b,p,s,n}; \mu^{\overline{b}}_{b,p,s,n} \qquad \forall \; b, p, s, n \qquad (18)$$

$$\underline{h}_h \leq h_{h,p,s,n} \leq \overline{h}_h \qquad \perp \mu^{\underline{h}}_{h,p,s,n}; \mu^{\overline{h}}_{h,p,s,n} \qquad \forall \; h, p, s, n \qquad (19)$$

$$\underline{h}_b \leq h_{b,p,s,n} \leq \overline{h}_b \qquad \perp \mu^{\underline{h}}_{b,p,s,n}; \mu^{\overline{h}}_{b,p,s,n} \qquad \forall \; b, p, s, n \qquad (20)$$

$$\underline{I}_{cn} \leq I_{cn,p} \qquad \perp \mu^{\underline{I}}_{cn,p} \qquad \forall \; cn, p \qquad (21)$$

$$\underline{t}_{ce} \leq t_{ce,p,s,n} \leq \varphi_{ce} \cdot \overline{t}_{ce} \qquad \perp \mu^{\underline{t}}_{ce,p,s,n}; \mu^{\overline{t}}_{ce,p,s,n} \qquad \forall \; ce, p, s, n \qquad (22)$$

$$\underline{t}_{cn} \leq t_{cn,p,s,n} \qquad \perp \mu^{\underline{t}}_{cn,p,s,n} \qquad \forall \; cn, p, s, n \qquad (23)$$

$$\underline{R}_h \leq R_{h,p,s} \leq \overline{R}_h \qquad \perp \mu^{\underline{R}}_{h,p,s}; \mu^{\overline{R}}_{h,p,s} \qquad \forall \; p, s, h \qquad (24)$$

Price of the green certificate

In this model, the price of the green certificate is not modeled as an auxiliary variable as in the general electricity market. Here the price of the certificate is obtained from the marginal renewable energy generation cost and from the electricity market price.

The marginal green generation cost corresponds to the dual variable of the quota constraint (eq. 16), and the electricity price comes from running the general electricity model. By subtracting these two terms we obtain the price of the green certificate.

3.4.6. The linear complementarity model

Here we state in detail the optimality conditions of each generation company[1] (schematically represented in figure 2), which define the market equilibrium. The first set of the Karush-Kuhn-Tucker optimality conditions of firm *e* is the gradient of the Lagrangian function with respect to the decision variables made equal to zero.

In the following equations it should be noted that $d'_{e,p,s,n}$ represents how the electricity price changes when each firm changes its production unilaterally. In contrast to Cournot-Based models which use the slope of the demand function, in CV-based models this parameter is different for each firm since it expresses the market conjecture of each firm. To be precise, this parameter represents the slope of electricity residual demand function of each firm.

It has to be noted that the tradable green certificates market has not been included, since this part of the model has been computed separately, as will be explained later in the paper.

Gradient of the Lagrangian function

$$\begin{aligned}\frac{\partial \pounds}{\partial t_{ce,p,s,n}} = {} & D_{p,s,n} \cdot i_p \cdot v_{ce} \cdot \left(o'_{ce} + 2 \cdot t_{ce,p,s,n} \cdot o_t''\right) + \\ & + D_{p,s,n} \cdot \left(-i_p \cdot p^{elec}_{p,s,n} + i_p \cdot d'_{e,p,s,n} \cdot q^{elec}_{e,p,s,n}\right) - \\ & - \left(\mu^{\bar{p}}_{ce,p,s,n} - \mu^{\underline{p}}_{ce,p,s,n}\right) - \tau_{ce} \cdot D_{p,s,n} \cdot \mu^{q}_{e,sp} = 0\end{aligned} \qquad \forall\, p,n,s,ce \qquad (25)$$

$$\begin{aligned}\frac{\partial \pounds}{\partial t_{cn,p,s,n}} = {} & D_{p,s,n} \cdot i_p \cdot v_{cn} \cdot \left(o'_{cn} + 2 \cdot t_{cn,p,s,n} \cdot o_{cn}''\right) + \\ & + D_{p,s,n} \cdot \left(-i_p \cdot p^{elec}_{p,s,n} + i_p \cdot d'_{e,p,s,n} \cdot q^{elec}_{e,p,s,n}\right) - \\ & - \left(\mu^{I}_{cn,p,s,n} - \mu^{\underline{p}}_{cn,p,s,n}\right) - \tau_{cn} \cdot D_{p,s,n} \cdot \mu^{q}_{e,sp} = 0\end{aligned} \qquad \forall\, p,n,s,cn \qquad (26)$$

$$\begin{aligned}\frac{\partial \pounds}{\partial h_{h,p,s,n}} = {} & D_{p,s,n} \cdot \left(-i_p \cdot p^{elec}_{p,s,n} + i_p \cdot d'_{e,p,s,n} \cdot q^{elec}_{e,p,s,n} - \mu^{R}_{h,p,s}\right) \\ & - \left(\mu^{\bar{h}}_{h,p,s,n} - \mu^{\underline{h}}_{h,p,s,n}\right) = 0\end{aligned} \qquad \forall\, p,n,s,h \qquad (27)$$

$$\begin{aligned}\frac{\partial \pounds}{\partial h_{b,p,s,n}} = {} & D_{p,s,n} \cdot \left(-i_p \cdot p^{elec}_{p,s,n} + i_p \cdot d'_{e,p,s,n} \cdot q^{elec}_{e,p,s,n} - \mu^{R}_{b,p,s} - \mu^{\bar{R}}_{b,p,s}\right) \\ & - \left(\mu^{\bar{h}}_{b,p,s,n} - \mu^{\underline{h}}_{b,p,s,n}\right) = 0\end{aligned} \qquad \forall\, p,n,s,b \qquad (28)$$

---

[1] In this paper has been considered the equivalent minimization problem of each firm.

$$\frac{\partial \mathcal{L}}{\partial b_{b,p,s,n}} = -D_{p,s,n} \cdot \left(-i_p \cdot p^{elec}_{p,s,n} + i_p \cdot d'_{e,p,s,n} \cdot q^{elec}_{e,p,s,n} - \rho_b \cdot \mu^{R}_{b,p,s} \right) - \left(\mu^{\bar{b}}_{b,p,s,n} - \mu^{\underline{b}}_{b,p,s,n} \right) = 0 \qquad \forall\, p,n,s,b \qquad (29)$$

$$\frac{\partial \mathcal{L}}{\partial R_{h,p,s}} = \mu^{R}_{h,p,s} - \mu^{R}_{h,p,s-1} - \left(\mu^{\bar{R}}_{h,p,s} - \mu^{\underline{R}}_{h,p,s} \right) = 0 \qquad \forall\, p, s>1, h \qquad (30)$$

$$\frac{\partial \mathcal{L}}{\partial I_{cn,p}} = \left(i_p - i_{p+1} \right) \cdot ci_{cn} + \varphi_{cn} \cdot \sum_{s,n} \mu^{I}_{cn,p,s,n} + \mu^{TA}_{cn,p} - \mu^{TA}_{cn,p+1} - ci_{cn} \cdot \mu^{FI}_{e,p} = 0 \qquad \forall\, p, cn, e \qquad (31)$$

$$\frac{\partial \mathcal{L}}{\partial I_{cn,p}} = \left(i_p - i_{p+1} \right) \cdot ci_{cn} + \varphi_{cn} \cdot \sum_{s,n} \mu^{I}_{cn,p,s,n} + \mu^{TA}_{cn,p} - \mu^{TA}_{cn,p+1} - ci_{cn} \cdot \left(\mu^{FI}_{e,p} - \mu^{FI}_{e,p+1} \right) = 0 \qquad \forall\, p, cn, e \qquad (32)$$

$$\frac{\partial \mathcal{L}}{\partial q^{emis}_{e,sp}} = p^{emis}_{sp} + \mu^{q}_{e,sp} + \mu^{\underline{q}}_{e,sp} = 0 \qquad \forall\, sp, e \qquad (33)$$

Complementary Slackness Conditions

As previously established, in order to complete the set of non-linear equations that define the market equilibrium problem in terms of a Linear Complementarity Problem, the following three sets of equations must be added to (25-33). First of all, the inequality constraints (6-24) multiplied by their corresponding dual variables μ; next, the explicit statement of dual variables μ as negative ones; and finally, the inequality constraints themselves.

KKT Conditions

Following from the last paragraph, the precise KKT conditions which result for the problem and which constitute the LCP are then:

Equations (25)-(33)

Equations (6)-(16)

Equations (17-24)

Equations (6)-(16) x μ_i

Equations (17)-(24) x μ_i

$\mu_i \leq 0, \forall i$

Where μ_i is the dual variable corresponding to each equation.

3.4.7. Computing the model

As commonly known, LCP models are difficult to solve. Commercial solvers such as PATH have several size limitations, so some “tricks” have to be used for its application to a real-size problem such as the case study shown here.

First, we have reduced the size of the model by aggregating all the power plants in the system into just one representative plant per technology type and firm.

Second, we have further reduced the size by running the green certificate model as a parallel market. This is due basically to two reasons: first, the variables considered for this model are totally decoupled from the general model: renewable production will be subtracted from the total electricity demand, and therefore will only compete in the green certificate model. Of course, there might be some situations where renewables may compete in both markets, but this will typically be the case only for biomass, and only when the latter has some capacity to fix price, which is unlikely. Second, modeling the green certificates market as a separate one allows inclusion of more details in the model. Although here it has been considered as in perfect competition, separate modeling might allow for representing possible oligopolistic conditions in the green certificate market, by firms different from the general electricity market. Again, the drawback here is that when large oligopolistic firms have also an oligopolistic behavior in the green certificate market, then it would be more advisable to model both markets jointly. But then, this is not usually the case.

This separate green certificate market model is formed by an objective function in which all renewable energy costs (investment and operation costs) are minimized, and by the applicable constraints (eqs. 13-16). That is a linear model which presents no problems for a conventional solver.

Finally, we “help” the solver by providing an initial solution which is close enough to the final one. This initial solution is obtained by running a similar model which does not consider oligopoly, and which can therefore be stated as a linear programming one. This allows us to obtain a solution to our model for real-size cases for which the solver does not converge in absence of this initial solution.

All this adjustments allow us, as said, to run a real size problem with some 30,000 equations and variables. But then we have to guarantee that there is a solution to the problem.

To this we can say that the existence of the solution is guaranteed in the case where the thermal units’ marginal costs are strictly monotone increasing and the firms’ marginal revenue are strictly monotone decreasing (Wei and Smeers, 1999; Day et al, 2002; Metzler et al, 2003). This latter aspect is ensured by using a decreasing demand curve and a negative conjecture (slope of the residual demand curve), which are both rather usual assumptions. When these conditions are met, then the LCP-based model has a positive semi-definite matrix M, and therefore, based on Theorem 3.1.2 from Cottle et al (1992) or Theorem 3.2 from Harker and Pang (1990), the existence of a solution is guaranteed, as already mentioned in section 3.3. This solution would be unique in case the system had no hydro resources, since these hydro resources can be moved from one period to another and therefore may produce degenerated solutions.

4. Application to the Spanish electricity sector

4.1. Description

The model described above has been used to simulate the impact of the European ETS and of a tradable green certificate market on the new investments in the Spanish electricity sector (for a description of the Spanish electricity sector see e.g. Crampes and Fabra, 2005), as an example of how the model can be applied to any real-size electricity market. First the general conditions for the simulation are shown, and then the specific results on investments are presented.

The case study analyses the expansion of the Spanish electricity system for the next sixteen years (2005-2020). The six existing generating firms have been considered (although their names have been omitted), plus other possible new entrants and the special regime REGESP (that is, renewable energy producers, which operate under the assumption of perfect competition).

As mentioned before, all the power plants belonging to the generators have been aggregated into one group per technology and firm, in order to reduce the size of the model. The existing technologies considered are nuclear (NCL), fuel (FO), natural gas (GN), gas combined cycles (ECCGT), domestic coal (HLL), imported coal (CI), brown lignite (LGP), black lignite (LGN), regulating hydro (REG), run-of-the-river hydro (FLU), pumping units (BOMB), biomass (EBIO), cogeneration (ECOG), small hydro (EMINH), wind (EEOL), and solar (ESOL). In addition, future technologies have been considered for the new investments: supercritical coal (CSC), advanced nuclear (NCLAV), gas combined cycles (CCGT), three types of biomass (BIO1: energy crops, BIO2: agricultural waste, and BIO3: forest waste), three types of wind depending on the wind speed of the site (EOL1, EOL2, EOL3), small hydro (MINH), cogeneration (COG), and solar thermal (SOLT). Their parameters are presented below.

It should be noted that large hydro (REG, FLU, BOMB) is not included under the renewable obligation in most countries, and certainly not in Spain. There are a number of reasons for this which will not be discussed here.

Table 1. Parameters for current thermal power plants

FIRM	TECHNOLOGY	LINEAR VARIABLE COST	QUADRATIC VARIABLE COST	INSTALLED POWER	CO$_2$ EMISSIONS RATE
		C€/MWH	C€/MW^{2}H	MW	T/MWH
1	NCL-1	330	0.02	3358	0
	HLL-1	1500	0.41	1021	0.95
	CI-1	1560	0	220	0.90
	FO-1	4140	0.13	2337	0.78
	GN-1	3930	0.35	830	0.79
	CCGT-1	2173	0.16	1500	0.40
2	NCL-2	330	0.02	3641	0
	HLL-2	1785	0.06	1462	0.96
	LGP-1	1845	0.07	1469	0.99
	LGN-1	1986	0	1100	0.93
	CI-2	1380	0.02	1712	0.92
	FO-2	4440	2.12	400	0.77
	GN-2	4065	0.16	1543	0.72
	CCGT-2	1978	0.14	1200	0.40
3	NCL-3	330	0.03	739	0
	HLL-3	1530	0.23	1498	0.90
	LGP-2	1725	0	583	1.27
	FO-3	4140	0.74	447	0.76
	GN-3	4218	0	155	0.99
4	HLL-4	1881	0.06	544	0.90
	LGN-2	1788	0.52	400	0.94
	FO-4	3690	0.35	682	0.76
5	NCL-4	348	0	165	0
	HLL-5	1470	0.41	1588	0.92
	CCGT-3	2554	0	450	0.40
6	CCGT-4	1978	0.20	800	0.40
OTHER	CCGT-5	2304	0	400	0.40

Source: Own elaboration based on CSEN (1997)

Table 2. Parameters for renewables and cogeneration power plants

FIRM	TECHNOLOGY	LINEAR VARIABLE COST	INSTALLED POWER	USE RATIO	CO$_2$ EMISSIONS RATE
		C€/MWH	MW		T/MWH
Special regime	EBIO	781	436	0.413	0
	ECOG	2887	5785	0.319	0.55
	EMINH	0	1637	0.305	0
	EEOL	0	7782	0.211	0
	ESOL	0	16	0.107	0

Source: Own elaboration based on CSEN (1997)

Use ratio: Since renewable power plants are not able to produce continuously, the use ratio expresses the relationship between the installed power and the energy produced

Table 3. Parameters for current hydro power plants

FIRM	REG		FLU	BOMB		
	MAXIMUM POWER (MW)	ANNUAL INFLOWS (GWH)	MAXIMUM POWER (MW)	MAXIMUM POWER (MW)	PUMPING YIELD (%)	MAXIMUM CAPACITY (GWH)
1	3150	8930	360	628	70	300
2	2100	2839	390	1409	70	515
3	850	1538	188	208	70	90
4	475	243	41	340	70	50
5	270	264	38	0	70	0
6	0	0	0	0	70	0
OTHER	0	0	0	0	70	0

Source: Own elaboration based on CSEN (1997)

Table 4. Parameters for new technologies

TECHNOLOGY	LINEAR VARIABLE COST	INVESTMENT COST	MAXIMUM POWER	USE RATIO	CO_2 EMISSIONS RATE
	C€/MWH	€/KW	MW		T/MWH
CCGT	2100	466		1	0.40
NCLAV	790	2000		1	0
CSC	1500	992		1	0.80
BIO1	5017	1272	1131	0.799	0
BIO2	1003	1406	1212	0.799	0
BIO3	6688	1142	687	0.799	0
MINH	0	2700	743	0.267	0
COG	4700	600	1315	0.426	0.63
EOL1	0	900	2444	0.247	0
EOL2	0	900	3665	0.212	0
EOL3	0	900	6109	0.159	0
SOLT	0	6000	200	0.109	0

Source: Own elaboration based on European Commission (2004)

As for the carbon emissions market, the amount of allowances allowed is that established by the Spanish National Allocation Plan (RD 60/2005), that is, 160 Mt. However, as said before, the Plan only covers the period 2005-07. From 2008, the government envisions that emissions should not be higher than those of 1990 incremented by 24% (a 15% increase over 1990, plus 7% obtained from clean development mechanisms, plus 2% from carbon sinks), so the total amount of allowances from 2008 to 2014 should be 147.8 Mt.

It has to be noted that this is the whole amount of allowances distributed among all sectors covered by the ETS Directive. However, only the electricity sector has been modeled in detail. The rest of the sectors are much more difficult to model adequately~~,~~ because of their disaggregation (there are many small CO_2-producing facilities, with very different characteristics) and lack of data. However, this same disaggregation allows us to assume that they will behave as price-takers in the emissions market, and therefore they may be modeled as a competitive fringe by means of a residual demand function. This demand function is the aggregated marginal abatement cost curve for all these sectors in Spain, and has been obtained from the PRIMES model (Capros et al., 2001).

As for the tradable green certificate system, it has been assumed a renewable quota so that in 2010 17.5% is reached, according to the European Directive 2001/77 on renewables.

As may be expected, results are very sensitive to the participation of nuclear energy in the system. The assumption has been made that, for the business-as-usual case, investments in nuclear energy are not attempted because of the current investment risks linked to this technology.

Regarding other relevant assumptions for the model, the annual growth of electricity demand has been set as an annual average of 2.5%, based on the estimations of the Spanish government (MINER, 2002). The discount rate used for investments has been 9%. The slope of the electricity demand curve has been set at 600€/MWh.MW. Also, a residual demand curve slope of 1.3€/MWh.MW has been considered for the two largest firms. These last parameters have been calibrated to produce results consistent with the real Spanish electricity market prices (García-Alcalde et al, 2002). This methodology is based on fitting the residual demand curve slope by means of an evaluation of the conjectural variations model on past data. This procedure is similar to the implicit or implied valuation of financial models.

4.2. Results

In this section, the major indicators provided by the model regarding new investments are analyzed. As may be seen, the model is capable of providing relevant indicators such as prices, installed power, and costs and profits. For the sake of simplicity, results are only shown for some years of the simulation.

The model has been programmed in GAMS language (the source code is available upon request from the authors). The mixed complementarity problem has been solved with the PATH solver, and the cost minimization problem with the CPLEX solver.

The problem had 33389 equations and 33394 variables with 111797 non-zero elements. It took 30 seconds in a Pentium M processor (1.2 GHz, 640 Mb RAM) to solve it.

In order to validate the results and the interest of considering an oligopolistic model, we also ran it under a perfectly competitive scenario. The results we obtained were that, without ETS, market prices are lower, as would be expected. The operation of the system does not change much under oligopoly, but prices do increase (producing results consistent with the real Spanish electricity market).

In addition, under certain circumstances, we may observe some interesting results for the oligopoly: if we assume a non-zero demand elasticity – which is reasonable for the long-term scope of the model – then we see that firms produce less energy, and so require less allowances. This results in lower prices for the carbon allowances, and therefore in lower electricity prices.

Therefore, we see that there are differences (quite significant) between these two market assumptions, and therefore that it is justified to use the oligopolistic approach, from which the following results have been obtained.

Table 5. Prices and emissions

		2005	2012	2020
BASE CASE	Electricity price (€/MWh)	25.94	27.04	27.3
	CO_2 emissions from electricity production (Mt)	90.61	114.68	138.9
ETS-ONLY	Electricity price (€/MWh)	26.78	30.04	36.13
	CO_2 emissions from electricity production (Mt)	89.70	82.24	81.09
	CO_2 allowance price (€/t)	0	6.01	22.05
TGC-ONLY	Electricity price (€/MWh)	25.03	27.08	27.28
	CO_2 emissions from electricity production (Mt)	80.17	97.15	116.71
	Green certificate price (€/MWh)	14.98	26.27	56.59
CASE WITH ETS, TGC	Electricity price (€/MWh)	25.03	29.41	33.05
	CO_2 emissions from electricity production (Mt)	80.17	81.54	81.72
	CO_2 allowance price (€/t)	0	4.68	14.71
	Green certificate price (€/MWh)	14.98	23.94	50.82

As may be seen, prices increase with the introduction of ETS, and emissions are reduced. There appears a CO_2 price from 2008, since in the first period there is a surplus of allowances. These prices are quite consistent with those predicted by other studies. There appears also a green certificate price due to the introduction of renewable energies through a tradable green certificate system, which is also showing quite reasonable values.

We may also point out here some of the interactions observable between the green certificate, carbon allowances and electricity markets: It may be seen that the electricity price is reduced for 2005. This is due to the introduction of the TGC quota, which basically reduces the demand to be supplied by conventional energy sources, and thus reduces the marginal price.

The TGC quota also reduces electricity prices in an indirect way: by increasing the share of non-carbon technologies, it also reduces the carbon allowance price (which reflects the marginal cost of abatement) and therefore the electricity price. Therefore, even in the case of 2012 or 2020 when there is a carbon allowance price, electricity prices are lower than in the absence of a TGC system (although this may or not be compensated by the direct cost of green certificates, which is not incorporated directly into the electricity price).

The introduction of green certificates also produces additional impacts on the electricity market: by reducing the amount of non-renewable energy required, the demand becomes less elastic (the slope of the curve is the same, but the intercept changes). This increases the market power in the non-renewable electricity market, which would increase oligopoly prices compared to the perfectly competitive case. However, this is compensated by the reduced prices for allowances (as explained before), and also by the smaller size of the non-renewable market.

Table 6. Installed power in 2020 per technology (MW)

	BASE CASE	ETS-only	TGC-only	CASE WITH ETS, TGC
CCGT	9988	18967	7310	12723
CSC	2333			
BIO1			1021	1021
BIO2		1094	1094	1094
BIO3			225	225
EOL1		2206	2206	2206
EOL2			3308	3308
EOL3			5513	5513
TOTAL	**12321**	**22267**	**20676**	**26089**

Investments in coal are displaced by gas when the ETS-TGC are simulated, and renewables are further stimulated by the combined effect of both the ETS (which by itself is not able to promote much renewables) and the tradable green certificate system. The power installed is much larger in the second case basically due to the lower load factor of renewables.

Table 7. Electricity produced in 2020 per technology (% over total energy)

	BASE CASE	ETS-only	TGC-only	CASE WITH ETS, TGC
NCL	24.48%			24.48%
HLL	16.27%			11.15%
LGP	5.99%			2.41%
LGN	4.01%			1.21%
CI	5.98%			5.88%
ECCGT	4.80%			6.28%
EBIO	0.56%			0.56%
ECOG	5.72%			5.72%
EMINH	1.55%			1.55%
EEOL	5.09%			5.09%
ESOL	0.01%			0.01%
REG	5.41%			5.41%
FLU	3.49%			3.49%
CCGT	9.32%			16.89%
CSC	7.34%			
BIO1				0.81%
BIO2				3.00%
BIO3				0.05%
EOL1				1.87%
EOL2				2.15%
EOL3				2.00%
TOTAL	**100.00%**			**100.00%**

Here what may be seen is that the ETS and TGC system displace domestic coals and supercritical coal, and promote a larger operation of gas combined cycles and renewables, as might be expected.

Finally, one of the most interesting features of the GEPAC model is that it provides detailed figures for the costs and profits of the system. We see in this table that the introduction of ETS and TGC increase both production and consumer costs, but at a larger extent for the second.

Although, as mentioned before, TGC decrease the marginal electricity price, they also raise consumer costs because of the green certificate price to be paid. Added up to the effect of the carbon allowance price, the overall result is an increase in costs (although possibly lower than in the absence of TGC).

Therefore, generating firm profits are largely increased by the introduction of these regulations. The share of this increase is not even, some firms basically remaining the same, while others (the smaller ones) increasing largely their profits.

Table 8. Costs and profits (M€, net present value 2005-2020)

	BASE CASE	ETS-only	TGC-only	CASE WITH ETS, TGC
Production costs	32661	36840	37578	39731
Consumer costs	66462	74258	72783	76838
Generating firms profits	33800	37418	35205	37107
Firm 1	9205			9736
Firm 2	10394			10501
Firm 3	2690			3019
Firm 4	100			340
Firm 5	715			826
Firm 6	-153			234
Other firms	-135			77
REGESP*	10984			12373

*We have assigned to REGESP all income due to green certificates, although of course this is not necessarily so.

5. Conclusions

This paper has presented an oligopolistic, generation-expansion model for the electricity sector, capable of simulating adequately new regulatory instruments such as carbon emissions trading and tradable green certificate in an endogenous way.

This model presents several characteristics which are likely to provide better estimates than other studies as to the consequences of a carbon emissions trading regime on the electricity sector, namely:

- the electricity sector is modeled in great detail, thus providing useful and more realistic information on the impact of new regulations on different utilities and technologies. Although the electricity sector is not the major carbon emitter, with some 20% of the total carbon emissions, it is certainly the major player within the emissions trading scheme (since it represents more than 50% of the total emissions covered by the Directive), and therefore it is important to model it adequately

- contrary to most modeling exercises, ours takes into account the oligopolistic structure of the sector, which produces different results in the incorporation of the allowance price into the electricity price, compared to a perfect competition assumption
- although most models looking specifically at the electricity sector rely on an exogenous allowance price, our model produces it endogenously, which provides more flexibility to the analysis
- the model is not a static one, but simulates the expansion of generation, thereby offering a view of the future effects on prices and technologies, and on the reaction of firms.

The results obtained seem quite reasonable, and in line with other studies. In addition, they are very much detailed at the firm level, so that the model can also provide useful insights into the evolution of the sector firm structure.

Although still an approximation considering it does not address in detail other economic sectors which might also trade in the carbon market, its application to a sample case clearly shows the impact of setting such a kind of market over an electricity system in that the costs of generating companies can be increased. Also, it shows how the share in the market of the different companies will be modified depending on the allowances market structure and allocation (see Linares et al, 2006b).

In addition, results also provide some insights into the possible interactions between tradable green certificates and carbon emission markets. This knowledge is fundamental for firms deciding on their future strategies, and also for regulators when designing energy and environmental policies.

Research is still to be continued on several issues to improve the applicability and usefulness of the model. Concerning the expansion planning aspects, uncertainty and risk should be treated adequately, as well as other possible criteria that firms may consider for their strategies. As for the allowances market, further work must be done so as to account for banking of allowances, as well as exploring allowances of types different from those used in this model. Of course, this expanded model should also include other economic sectors, possibly under a general equilibrium framework. Research is under way on these issues at our institution.

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References

Capros, P., N. Kouvaritakis, L. Mantzos (2001). Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Top-down analysis of greenhouse gas emission reduction possibilities in the European Union. National Technical University of Athens. March 2001.

Chen, Y. H., and Hobbs, B. F. (2005). An oligopolistic electricity market model with tradable NOx permits. IEEE Transactions on Power Systems 20: 119-129.

Cottle, R.W., J.S. Pang, and R.E. Stone (1992). The Linear Complementarity Problem. Academic Press, Boston.

Crampes, C. and N. Fabra (2005). The Spanish Electricity Industry: Plus ça change…The Energy Journal, Special Edition European Electricity Liberalisation: 127-153.

CSEN (1997). Una simulación del funcionamiento del Pool de Energía Eléctrica en España. Dirección de Regulación, Comisión del Sistema Eléctrico Nacional.

Day, C. J., Hobbs B.F., Pang, J.-S. (2002). Oligopolistic Competition in Power Networks: A Conjectured Supply Function Approach. IEEE Transactions on Power Systems 17(3) 597-607.

Dyner, I., E.R. Larsen (2001). From Planning to Strategy in the Electricity Industry. Energy Policy, 29: 1145-54.

Eurelectric (2004). GETS 4 - Greenhouse gas and energy trading simulations. Final Report, November 2004.

European Commission (2004). Sustainable Energy Technology Reference Information System (SETRIS). Joint Research Centre, European Commission, http://www.jrc.es

European Commission (2003). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. OJ L275.

García-Alcalde, A., Ventosa, M., Rivier, M., Ramos, A., Relaño, G. (2002). Fitting Electricity Market Models. A Conjectural Variations Approach. Proceedings 14th PSCC Conference, Seville. July.

Harker, P.T., J.S. Pang (1990). Finite-dimensional variational inequality and nonlinear complementarity problems: A survey of theory, algorithms and applications. Mathematical Programming 48: 161-220.

Hindsberger, M., M.H. Nybroe, H.F. Ravn, R. Schmidt (2003). Co-existence of electricity, TEP and TGC markets in the Baltic Sea Region. Energy Policy 31: 85-96.

Hobbs, B.F. (1993). Emissions dispatch under the underutilization provision of the 1990 US Clean Air Act Amendments: Models and analysis. IEEE Transactions on Power Systems 8: 177-183.

Huntington, H.G., and J.P. Weyant (2004). Modeling energy markets and climate change policy. In Cleveland, C.J. et al. Encyclopedia of Energy, pp. 41-53, Academic Press / Elsevier Science.

Jensen, S.G. and K. Skytte (2003). Simultaneous attainment of energy goals by means of green certificates and emissions permits. Energy Policy 31: 63-71.

Linares, P., F.J. Santos, M. Ventosa (2006a). An assessment of the consequences of the European Emissions Trading Scheme for the promotion of renewable electricity in Spain. In De Miguel, C., X. Labandeira y B. Manzano (eds). Economic Modelling of Climate Change and Energy Policies. Edward Elgar.

Linares, P., F.J. Santos, M. Ventosa (2006). Impacts of the European Emissions Trading Scheme Directive and permits assignment methods on the Spanish electricity sector. Energy Journal, 27: 47-66

MINER (2002). Planificación de los sectores de electricidad y gas. Ministerio de Economía y Hacienda.

Menanteau, P., D. Finon, M-L. Lamy (2003). Prices versus quantities: choosing policies for promoting the development of renewable energy. Energy Policy, 31: 799-812.

Metzler, C. Hobbs, B. F. and Pang J-S. (2003). Nash-Cournot Equilibria in Power Markets on a Linearized DC Network with Arbitrage: Formulations and Properties, Networks and Spatial Economics, Issue Volume 3, Number 2 / June, 2003, 123-150.

Morthorst, P.E. (2001). Interactions of a tradable green certificate market with a tradable permits market. Energy Policy 29(5): 345-353.

Nagurney, A. and K. K. Dhanda (2000). Marketable Pollution Permits in Oligopolistic Markets with Transaction Costs. Operations Research 48: 424-435.

Nagurney, A., K. K. Dhanda and J. K. Stranlund (1997). General multi-product, multi-pollutant market pollution permit model: a variation inequality approach. Energy Economics 19: 57-76.

Rivier, M., M. Ventosa, A. Ramos (2001). A Generation Operation Planning Model in Deregulated Electricity Markets based on the Complementarity Problem. In M. Ferris, O. Mangasarian, J. Pang (eds.). Applications and algorithms of complementarity. Kluwer Academic Publishers.

Unger, T., E.O. Ahlgren (2006). Impacts of a common green certificate market on electricity and CO2-emission markets in the Nordic countries. Energy Policy, 33: 2152-2163.

Ventosa, M., A. Baillo, A. Ramos, M. Rivier (2005). Electricity Market Modelling Trends. Energy Policy 33: 897-213.

Ventosa, M, R. Denis, C. Redondo (2002). Expansion Planning in Electricity Markets. Two Different Approaches. Proceedings 14th PSCC Conference Seville, Session 43-4, pp. 1-8. 2002.

Vives, X. (1999). Oligopoly Pricing. The MIT Press. Cambridge.

Wei, J.Y, Y. Smeers (1999). Spatial Oligopolistic Electricity Models with Cournot Generators and Regulated Transmission Prices. Operations Research, Vol. 47, No. 1, January - February 1999, pp. 102 - 112.