

Optimal electricity market bidding strategies considering emission allowances

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Abstract—There are many factors that influence the day-ahead market bidding strategies of a GenCo in the current energy market framework. In this work we study the influence of both the allowances and emission reduction plan and the incorporation of the derivatives medium-term commitments in the optimal generation bidding strategy to the day-ahead electricity market. Two different technologies have been considered: the coal thermal units, high-emission technology, and the combined cycle gas turbine units, low-emission technology. The operational characteristics of both kinds of units are modeled in detail. We deal with this problem in the framework of the Iberian Electricity Market and the Spanish National Emissions and Allocation Plans. The economic implications for a GenCo of including the environmental restrictions of these National Plans are analyzed.

I. INTRODUCTION

A. Emission allowances directives

The European Community, abiding with the Kyoto Protocol, was committed to reduce the aggregate emissions of Greenhouse Gasses GHG by 8 %, compared to 1990 levels, in the period 2008-2012, with different targets set among members states [1]. The European Union directive for greenhouse gas emission allowance trading (2003/87/CE) [2] establishes that each member has to elaborate the National Allocation Plan (NAP) to determine the total quantity of CO₂ emissions that Member States grant to their companies, which can then be sold or bought by the companies themselves. The Spanish NAP for the period 2008-12 was approved on 2007 (RD 1402/2007 [3]). This NAP imposed to the electricity generation sector a reduction in the CO₂ emissions for the period 2008-12 of almost a 60% with respect to the emissions in the period 2000-05. Emissions trading, as set out in Article 17 of the Kyoto Protocol, allows countries that have emission units to spare - emissions permitted but not "used" - to sell this excess capacity to countries that are over their targets. The EU Emission Trading Scheme [4] (EU ETS) is a cornerstone in the fight against climate change and the first international trading system for CO₂ emissions in the world. The aim of the EU ETS is to help EU Member States achieve compliance with their commitments under the Kyoto Protocol. Emissions trading does not imply new environmental targets, but allows for cheaper compliance with existing targets under the Kyoto Protocol.

Generation companies are subject to other environmental limitations besides the aforementioned CO₂ emission al-

lowances. The European Union (EU) also sets limits for emissions of pollutants from large combustion plants (Directive 2001/80/EC [5]). This Directive applies to combustion plants (technical apparatus in which fuels are oxidised in order to use the heat thus generated) with a rated thermal input equal to or greater than 50 MW, irrespective of the type of fuel used (solid, liquid or gaseous). Its purpose is to limit the amount of sulphur dioxide (SO₂), nitrogen oxides (NO_x) and dust emitted from large combustion plants each year. Following this commitment, the Spanish public administration launched in 2004 the Spanish National Emissions Plan (NEP, Real Decreto 430/2004 [6]). This NEP imposes, for the period 2008-15, a global reduction of a 81% and a 15% for the SO₂ and NO_x emissions respectively.

The impact of both National Allocation and Emissions Plans on the power industry seems very significant and whether these new restrictions are an opportunity or a threat for the power industry depends on several factors, specially the strategies set by power companies to integrate these new restrictions in their energy's market bid strategy. Indeed, NAP and NEP limitations have to be necessarily considered explicitly in the elaboration of the generation units' optimal sale bid to the wholesale electricity market. The study of the impact of NAP and NEP in the optimal operation of a generation company that operates in the day-ahead Iberian Electricity Market (IEM) is the main contribution of this work.

B. Literature review

Several authors have study the impact of the CO₂ emissions trading in the power industry, specially through mid-term models. In [7] a simulation was carried out for the Iberian Electricity Market. It was concluded that a rise in electricity prices is expected when CO₂ constraints are in place. Since this increase in power prices would affect all electricity producers, a generator that faces less carbon liabilities than market clearing technology, such as natural gas, would benefit from the higher power prices, leading to an increase in profits. In [8] the strategic technology options, especially the potential role of natural gas combined cycle and nuclear power plants, in mitigation of CO₂ emission in electricity sector in China are assessed using a least-cost probabilistic simulation and dynamic programming model. The results obtained in this study indicate that CO₂ emission mitigation through broad

implementation of Combined Cycle Gas Turbines (CCGT) can be accompanied with reduction of the total discounted cost of the generation system but is limited by the natural gas supply capacity. Finally, the work in [9] presents an assessment of the impact of the Kyoto Protocol on the Iberian Electricity Market. A market-equilibrium model is used in order to analyze different conditions faced by generation companies. One of the conclusions of this paper points again to the CCGT as the technology to replace coal generation in the thermal mix as the ETS CO₂ price increases. This replacement is particularly important for CO₂ prices under €15/tCO₂. Contrary to all these mid-term studies, the work in [10] addresses the short-term generation scheduling of a set of thermal generation units through the minimization of the generation plus start-up/shut-down costs of a MILP deterministic model that includes in the objective function the emission trading incomes and costs.

C. Contribution

This work presents a new stochastic programming model to cope with the optimal generation bid to the next day auctions of the IEM day-ahead market taking into account CO₂ allowances and SO₂ and NO_x emission constraints. We consider a price taker GenCo with a set of thermal coal and CCGT generation units subject to CO₂ allowances and SO₂ and NO_x emissions constraints. The objective is to find the generation scheduling and sales bid of each one of the generators that maximize the expected value of the net profit of a Genco including the start-up, shut-down and generation costs together with the incomes from the day-ahead market, futures and bilateral contracts as well as the incomes/costs of the CO₂ allowances. Several characteristics distinguish this paper from the previous works. Contrary to other studies, our model provides the optimal generation bid for each one of the generation units assuming the representation of optimal offer curve developed in [11], [12]. Moreover, CCGT units has been incorporated to the models following the CCGTs' unit commitment modelization introduced in [13]. Current electricity markets are organized not only around the short-term spot energy market but also around a variety of mid-term physical and financial products, as future and bilateral contracts, that each generation unit has to integrate in the sale bid submitted to the market operator following the specific rules of each national electricity market. Similar to [12], the model presented here consider the ex-ante negotiated Futures Contracts (FC) and Bilateral Contracts (BC) of the GenCo, that are integrated in the optimal bidding strategy according to the IEM directives. Finally, our model incorporates the stochasticity of the electricity market through stochastic programming [14]. Stochastic programming is a powerful optimization methodology that allows to incorporate in a single mathematical optimization model the same statistical information on the relevant random variables handled in simulation studies. Doing so, stochastic programming models are able to provide, in a single run, the best possible here-and-now decision with respect of the most complete available statistical information. Finally, the proposed model will be validated with

real data from generation units operating in the IEL and with real prices from both the Spanish day-ahead and emissions trading market.

II. MODEL DESCRIPTION

A. Variables

The random variable λ_t^D , the clearing price of the t^{th} hourly auction of the DAM, is represented in the two-stage stochastic model by a set of scenarios $s \in \mathcal{S}$ with probability P^s and by the associated clearing price $\lambda_t^{D,s}$ for auction t of the day-ahead market, $t \in \mathcal{T}$. Both $\lambda_t^{D,s}$ and P^s are input parameters for the model obtained through scenario generation and reduction techniques [15], [16]. Following [13] we consider a set of thermal units \mathcal{I} and a set of *pseudo-units* \mathcal{P} that represents the different generation configurations of the CC units. These pseudo-units behaves as a set of coupled thermal units (see section II-G for details of Combined Cycle units modeling). Therefore, the total set of generation units considered is $\mathcal{U} = \mathcal{I} \cup \mathcal{P}$. In stochastic programming models, those decision variables that doesn't depend on the scenarios s are called first stage variables which, in our model are, for every time period $t \in \mathcal{T}$ and generation unit $i \in \mathcal{U}$:

- The unit commitment variables, u_{ti} , c_{ti}^u , c_{ti}^d .
- The price acceptant offer bid, q_{ti} .
- The scheduled energy for futures contract $j \in \mathcal{F}$, f_{tij} .
- The scheduled energy for bilateral contract, b_{ti} .

All the first stage decision variables are continuous except the unit commitment variables u which are binary. Decision variables that can adopt different values depending on the scenario are called second stage variables. In our formulation these variables, all continuous, are, for each $t \in \mathcal{T}$, generation unit $i \in \mathcal{U}$ and scenario $s \in \mathcal{S}$:

- The total generation, g_{ti}^s .
- The matched energy in the day-ahead market, p_{ti}^s .

B. Futures and Bilateral Contracts Covering Constraints

The coverage of both the physical futures and bilateral contracts obligations must be guaranteed. If L_j^F is the amount of energy (MWh) to be procured at each hour t by the set of available generation units then the following constraint applies:

$$\left. \begin{aligned} \sum_{i \in \mathcal{I}_j} f_{tij} &= L_j^F \quad \forall j \in \mathcal{F}, \forall t \in \mathcal{T} & (a) \\ f_{tij} &\geq 0 \quad \forall i \in \mathcal{U}, \forall j \in \mathcal{F}, \forall t \in \mathcal{T} & (b) \end{aligned} \right\} (1)$$

where $\mathcal{I}_j \subset \mathcal{U}$ stands for the set of thermal and pseudo-units allowed to cover the FC j . Analogously, if L_{ik}^B is the amount of energy (MWh) to be procured during hour t of the delivery period to cover BC j , then the following bilateral contract constraints must be considered:

$$\left. \begin{aligned} \sum_{i \in \mathcal{U}} b_{ti} &= \sum_{k \in \mathcal{B}} L_{tk}^B \quad \forall t \in \mathcal{T} & (a) \\ 0 \leq b_{ti} &\leq P_i u_{ti} \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T} & (b) \end{aligned} \right\} (2)$$

C. Day-ahead market bid constraints

The IEM establishes the following rules to integrate energies L_j^F and L_k^B in the day-ahead market bid of a generation unit:

- 1) If generator $i \in \mathcal{U}$ contributes with f_{tij} MWh at period t to the coverage of the FC j , then the energy f_{tij} must be offered to the pool for free (*price acceptance sale bid*).
- 2) If generator $i \in \mathcal{U}$ contributes with b_{ti} MWh at period t to the coverage of any of the BCs, then this energy is excluded from the sale bid but the remaining unit's production capacity $\bar{P}_i - b_{ti}$ must be bid to the DAM.

These market rules can be included in the model by means of the following set of constraints:

$$p_{ti}^s \leq \bar{P}_i u_{ti} - b_{ti} \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T}, \forall s \in S \quad (3)$$

$$p_{ti}^s \geq q_{ti} \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T}, \forall s \in S \quad (4)$$

$$q_{ti} \geq \underline{P}_i u_{ti} - b_{ti} \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T} \quad (5)$$

$$q_{ti} \geq \sum_{j|i \in \mathcal{I}_j} f_{tij} \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T} \quad (6)$$

where:

- (3) and (4) ensures that if a unit is on, the matched energy p_{ti}^s will be between the instrumental price bid q_{ti} and the total available energy not allocated to a BC. \bar{P}_i , \underline{P}_i are the upper and lower bounds on the energy generation (MWh).
- (5) and (6) guarantee respectively that the minimum generation output of the committed units will be matched, and that the contribution of the unit to the FC coverage will be included in the instrumental price bid.

The analytical expression of the optimal generation bid of the generations units can be derived from this market constraints [12].

D. Total Generation Constraints

The total generation level of a given unit i , g_{ti}^s , is defined as the addition of the allocated energy to the BC, plus the matched energy in the DAM:

$$g_{ti}^s = b_{ti} + p_{ti}^s \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T}, \forall s \in S \quad (7)$$

The generation output of a any generation unit g_{ti}^s is a semi-continuous variable restricted to $g_{ti}^s \in \{0\} \cup [\underline{P}_i, \bar{P}_i]$, that is:

$$\underline{P}_i u_{ti} \leq g_{ti}^s \leq \bar{P}_i u_{ti} \quad \forall i \in \mathcal{U}, \forall t \in \mathcal{T}, \forall s \in S \quad (8)$$

E. SO_2 and NO_x Emission Constraints

The Spanish National Emission Plan imposes limits $\overline{SO_2}$ and $\overline{NO_x}$ to the joint emission of the thermal units (CC units are excluded). These limitations are included in the model by imposing an emission limit at every scenario s through the following set of constraints:

$$\sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} e_i^{SO_2} g_{ti}^s \leq \overline{SO_2} \quad s \in S \quad (9)$$

$$\sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} e_i^{NO_x} g_{ti}^s \leq \overline{NO_x} \quad s \in S \quad (10)$$

TABLE I
STATES OF THE CC UNIT AND ITS ASSOCIATED PSEUDO UNITS

CC unit with a CT and HRSG/ST					
State	Composition	Pseudounit 1	$u_{\mathcal{P}_c(1)t}$	Pseudounit 2	$u_{\mathcal{P}_c(2)t}$
0	0CT+0HRSG/ST	off	0	off	0
1	1CT+0HRSG/ST	on	1	off	0
2	1CT+1HRSG/ST	off	0	on	1

the emission coefficients $e_i^{SO_2}$ and $e_i^{NO_x}$ depend on the generation technology.

F. Thermal Unit Commitment Constraints

Following [12], let u_{ti} be the first-stage binary variable expressing the off-on operating status of the i^{th} unit and let c_{ti}^u , c_{ti}^d be continuous variables representing the startup and shutdown cost, respectively, of unit i in interval t . Let also constant G_i be the number of periods that unit i must be initially online, due to its minimum up-time t_i^{on} . Analogously let H_i be the number of periods that unit i must be initially offline, due to its minimum down-time t_i^{off} . Finally let parameter u_{0i} stands for the initial state of each thermal unit: $u_{0i} = 1$ if the unit is on and $u_{0i} = 0$ if the unit is off. The following set of constraints conveniently models the start-up and shut-down costs and the minimum operation and idle time for each unit, improving the formulation in [12]:

$$c_{ti}^u \geq c_i^{on} [u_{ti} - u_{(t-1),i}] \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I} \quad (11)$$

$$c_{ti}^d \geq c_i^{off} [u_{(t-1),i} - u_{ti}] \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I} \quad (12)$$

$$\sum_{j=n}^{G_i} (1 - u_{ji}) = 0 \quad \forall i \in \mathcal{I} \quad (13)$$

$$\sum_{j=1}^{H_i} u_{ji} = 0 \quad \forall i \in \mathcal{I} \quad (14)$$

$$\sum_{n=t}^{\min\{t+t_i^{on}-1, |\mathcal{T}|\}} u_{ni} \geq \alpha_{ti}^{on} [u_{ti} - u_{(t-1),i}] \quad t = G_i + 1, \dots, |\mathcal{T}|, \forall i \in \mathcal{I} \quad (15)$$

$$\sum_{n=t}^{\min\{t+t_i^{off}-1, |\mathcal{T}|\}} (1 - u_{ni}) \geq \alpha_{ti}^{off} [u_{(t-1),i} - u_{ti}] \quad t = H_i + 1, \dots, |\mathcal{T}|, \forall i \in \mathcal{I} \quad (16)$$

where the parameters α_{ti}^{on} and α_{ti}^{off} are defined as:

$$\alpha_{ti}^{on} = \min\{t_i^{on}, |\mathcal{T}| - t + 1\} \quad (17)$$

$$\alpha_{ti}^{off} = \min\{t_i^{off}, |\mathcal{T}| - t + 1\} \quad (18)$$

G. Combined Cycle Unit Commitment Constraints

The CC units represent a combination of combustion and steam turbines within a power plant. Typically, a CC unit consists of several combustion turbines (CTs) and a set of an heat recovery steam generator (HRSG) and a steam turbine (ST). Based on the different combinations of CTs and HRSG/ST, a CC unit can operate at multiple states or configurations. The

first two columns of Table I show the states of a CC unit with a CT and an HRSG/ST considered in this study. The operational rules of a typical CC unit were formulated in [13] with the help of the so-called *pseudo units* (PUs). As the thermal units, the PUs of each CC unit have their own cost characteristics, real power generation limits, minimum on time limits, etc., and can be viewed as a special set of coupled single thermal units. Our formulation only considers two PUs, each one associated with states 1 and 2 of the CC respectively, with the subsequent saving in the number of variables and constraints with respect to earlier proposed models for CC [17]. The on/off state of these two PUs uniquely determines the state of the CC (see columns 3 and 5 of Table I), and allows a correct modeling of the operation of the state 0 without the need of any additional PU.

Let us define \mathcal{P}_c , the set of PUs of the CC unit $c \in \mathcal{C}$, and $\mathcal{P} = \cup_{c \in \mathcal{C}} \mathcal{P}_c$, the complete set of PUs. By $\mathcal{P}_c(j)$, we denote the PU associated with the state $j \in \{1, 2\}$ of the CC unit c . Thus, $\mathcal{U} = \mathcal{I} \cup \mathcal{P}$ represents the complete set of generation units (thermal and pseudo). The on/off state of each thermal and pseudo units at period t can be represented by the first-stage binary variables u_{ti} , $i \in \mathcal{U}$. Columns 4 and 6 of Table I illustrate the relation of the commitment binary variables of the PUs, $u_{t\mathcal{P}_c(1)}$ and $u_{t\mathcal{P}_c(2)}$, with the state of the associated CC unit. Each PU $i \in \mathcal{P}$ also has its own start-up cost, without shut-down costs, and no cost is associated to the transition from state 2 to state 1.

$$c_{t\mathcal{P}_c(1)}^u \geq c_{\mathcal{P}_c(1)}^{on} \left[[u_{t\mathcal{P}_c(1)} - u_{(t-1)\mathcal{P}_c(1)}] - [u_{(t-1)\mathcal{P}_c(2)} - u_{t\mathcal{P}_c(2)}] \right] \quad t \in \mathcal{T}, c \in \mathcal{C} \quad (19)$$

$$c_{t\mathcal{P}_c(2)}^u \geq c_{\mathcal{P}_c(2)}^{on} [u_{t\mathcal{P}_c(2)} - u_{(t-1)\mathcal{P}_c(2)}] \quad t \in \mathcal{T}, c \in \mathcal{C} \quad (20)$$

Each PU $i \in \mathcal{P}$ has its own minimum up time, t_i^{on} :

$$\min\{t+t_i^{on}-1, |\mathcal{T}|\} \sum_{n=t} u_{ni} \geq \alpha_{ti}^{on} [u_{ti} - u_{(t-1)i}] \quad t = G_i + 1, \dots, |\mathcal{T}|, i \in \mathcal{P} \quad (21)$$

where again u_{0i} represents the initial state of each pseudo unit $i \in \mathcal{P}$, α_{ti}^{on} is defined as in (17) and G_i is the number of the initial time periods along which the pseudo unit must remain on. So as in Eq. (13):

$$\sum_{t=1}^{G_i} (1 - u_{ti}) = 0 \quad i \in \mathcal{P}, t \in \mathcal{T} \quad (22)$$

Each CC unit also has a minimum down time, i.e., once shut down, the CC unit cannot be started up before $(t_c^{off})^c$ periods. As in the case of the thermal and pseudo units, the following constraints formulate the minimum down time condition for

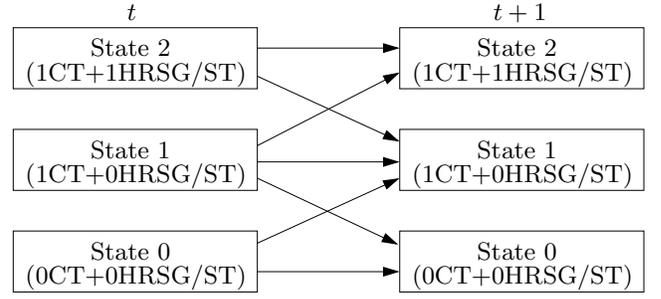


Fig. 1. Feasible transitions of the CC unit with a CT and HRSG/ST

the CC units:

$$\min\{t+(t_c^{off})^c-1, |\mathcal{T}|\} \sum_{n=t} [1 - (u_{n\mathcal{P}_c(1)} + u_{n\mathcal{P}_c(2)})] \geq \alpha_{tc}^{off} \left[(u_{(t-1)\mathcal{P}_c(1)} + u_{(t-1)\mathcal{P}_c(2)}) - (u_{t\mathcal{P}_c(1)} + u_{t\mathcal{P}_c(2)}) \right] \quad t = H_c^C + 1, \dots, |\mathcal{T}|, c \in \mathcal{C} \quad (23)$$

where

$$\alpha_{tc}^{off} = \min\{(t_c^{off})^c, |\mathcal{T}| - t + 1\}$$

and H_c^C represents the number of the initial time periods along which the CC unit must remain off. So as in Eq. (14):

$$\sum_{t=1}^{H_c^C} u_{t\mathcal{P}_c(1)} + u_{t\mathcal{P}_c(2)} = 0 \quad c \in \mathcal{C}, t \in \mathcal{T} \quad (24)$$

The satisfaction of the feasible transitions rules (Fig. 1) impose additional constraints to the operation of the PUs associated to the same CC unit, $c \in \mathcal{C}$. First, the PUs in \mathcal{P}_c are mutually exclusive Eq. (25)(a), i.e., only one of them can be committed at a given period (a CC can only be in one state simultaneously). Second, the change of the commitment of the PUs in \mathcal{P}_c between periods $t-1$ and t are limited to the feasible transitions depicted in Fig. 1. These feasible transitions impose that, if the CC unit c is in state 0 at period $t-1$ ($u_{(t-1)\mathcal{P}_c(1)} + u_{(t-1)\mathcal{P}_c(2)} = 0$), it cannot be in state 2 at period t ($u_{t\mathcal{P}_c(2)} = 0$) (Eq. (25)(b)). Conversely, if $u_{(t-1)\mathcal{P}_c(2)} = 1$, then $u_{t\mathcal{P}_c(1)} + u_{t\mathcal{P}_c(2)} \geq 1$ (Eq. (25)(c)). The following set of constraints formulates the specific operation rules of the CC units:

$$\left. \begin{aligned} \sum_{m \in \mathcal{P}_c} u_{tm} &\leq 1 & (a) \\ u_{t\mathcal{P}_c(2)} &\leq u_{(t-1)\mathcal{P}_c(1)} + u_{(t-1)\mathcal{P}_c(2)} & (b) \\ u_{(t-1)\mathcal{P}_c(2)} &\leq u_{t\mathcal{P}_c(1)} + u_{t\mathcal{P}_c(2)} & (c) \end{aligned} \right\} \begin{array}{l} c \in \mathcal{C}, \\ t \in \mathcal{T} \end{array} \quad (25)$$

H. Objective Function

The expected value of the profit function of the GenCo with respect to the spot market price random variable λ^D can be expressed as :

$$E_{\lambda^D} [\text{Profit}] = h(u, c^u, c^d, g, p, b, f) \quad (26)$$

$$|\mathcal{T}| \left[\sum_{k \in \mathcal{F}} \lambda_k^F L_k^F \right] + \sum_{t \in \mathcal{T}} \sum_{j \in \mathcal{B}} \lambda_{tj}^{BC} L_{tj}^{BC} \quad (26)$$

$$- \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}} [c_{ti}^u + c_{ti}^d + c_i^b u_{ti}] \quad (27)$$

$$- \sum_{t \in \mathcal{T}} \sum_{c \in \mathcal{C}} \left[c_{tP_c(1)}^u + c_{tP_c(2)}^u + \sum_{i \in P_c} c_i^b u_{ti} \right] \quad (28)$$

$$+ \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{U}} \sum_{s \in \mathcal{S}} P^s [\lambda_t^{D,s} p_{ti}^s - (c_i^l g_{ti}^s + c_i^q (g_{ti}^s)^2)] \quad (29)$$

$$- \lambda^{CO_2} \left[\sum_{t \in \mathcal{T}} \sum_{s \in \mathcal{S}} P^s \left[\sum_{i \in \mathcal{U}} e_i^{CO_2} (c_i^b u_{ti} + c_i^l g_{ti}^s + c_i^q (g_{ti}^s)^2) \right] - \overline{CO_2} \right] \quad (30)$$

where:

- (26) corresponds to the incomes of the FCs and the BCs and is a constant term. λ_k^F and λ_{tj}^{BC} are the prices of FCs and BCs respectively.
- (27) accounts for the on/off fixed cost of the unit commitment of the thermal units. It is independent of the realization of the random variable λ^D . c_i^b are the constant coefficients of the generation costs (€).
- (28) CC's start-up and fixed generation costs. This term does not depend on the realization of the random variable λ^D .
- (29) represents the expected value of the benefits from the day-ahead market, where P^s is the probability of scenario s . The term between brackets corresponds to the expression of the quadratic generation costs with respect to the total generation of the unit, g_{ti}^s .
- (30) this term accounts for the cost/incomes associated to the purchase/sale of the CO₂ emissions rights [9], where $\overline{CO_2}$ corresponds to the GenCo's aggregated free emission allowances (tCO₂) and λ^{CO_2} is the estimated CO₂-emission price (€/tCO₂) in the emission trading market [4]. The model for the CO₂ emission follows the assumption in [10] and [18] that the nonlinear emission function is proportional to the quadratic generation cost function of each unit.

TABLE II
CHARACTERISTICS OF FUTURES AND BILATERAL CONTRACTS

j	$L_{j,t=1...24}^{BC}$ MW	$\lambda_{j,t=1...24}^{BC}$ €/MWh	$L_{j,t=1...24}^{FC}$ MW	$\lambda_{j,t=1...24}^{FC}$ €/MWh
1	164	43,35	120	45,6
2	50	43,35	120	46,1
3	150	43,35	120	51,2

TABLE III
DAILY EMISSION ALLOWANCES AND LIMITS DATA

λ^{CO_2}	$\overline{CO_2}$	$\overline{SO_2}$	$\overline{NO_x}$
15.28 €/t	1.527 t	3.900 kg	17.651 kg

I. Final model

The model defined so far can be represented as:

$$\begin{cases} \max & h(u, c^u, c^d, g, p, b, f) \\ \text{s.t. :} & \\ & \text{Eq. (1) - (2)} \quad \text{FC and BC} \\ & \text{Eq. (3) - (6)} \quad \text{Day-ahead market} \\ & \text{Eq. (7) - (8)} \quad \text{Total generation} \\ & \text{Eq. (9) - (10)} \quad \text{Emission} \\ & \text{Eq. (11) - (16)} \quad \text{Thermal unit commitment} \\ & \text{Eq. (19) - (25)} \quad \text{CC unit commitment} \end{cases} \quad (31)$$

Problem (31) is a mixed, continuous-binary concave quadratic maximization problem with linear constraints. This optimization problem can be solved with the help of standard optimization software.

III. CASE STUDY

A. Generators, Market and Emission Data

The data for the day-ahead market prices has been downloaded from the website of the Independent Iberian Market Operator OMEL [19]. This study uses the same set of 50 scenarios generated in [20] for the random day-ahead market spot prices λ^D as the result of the application of a scenario reduction algorithm [21] to the complete set of historic data available from June 2007 to May 2010 [20]. The generation units of this study corresponds to the same four thermal units and two combined cycle units considered in [13] from which the technical characteristics (generation cost function, limits to the generation, etc) can be obtained. They correspond to actual generation units currently operating in the IEM. Table II shows the number, energy and price of the bilateral and futures contracts.

All the data related with CO₂, SO₂ and NO_x can be obtained from tables III and IV. The emissions trading price for the CO₂ rights corresponds to the mean of the spot European Unit Allowances prices for May 2010, which can be downloaded from [22]. The total free emission allowances $\overline{CO_2}$ corresponds to the 60% reduction imposed by the Spanish National Allowances Assignment Plan [3] and the emission limits $\overline{SO_2}$ $\overline{NO_x}$ derives from the National Emission Reduction Plan [6].

TABLE IV
GENERATION UNIT'S EMISSIONS DATA

	$e_i^{CO_2}$ t/€	$e_i^{SO_2}$ kg/MWh	$e_i^{NO_x}$ kg/MWh
Thermal units (Coal)	0.07228	0.7848	1.368
CC units (Gas)	0.0104	-	-

The generation unit's emission data shown in table IV are adapted from [18] while the SO_2 and NO_x emissions rates correspond to the values published by the Intergovernmental Panel on Climate Change Emission [23] for coal thermal units.

IV. NUMERICAL RESULTS

Three case studies was used to evaluate the impact of the CO_2 allowances and emission constraints in the optimal scheduling and bid of the generation units:

- BASE: optimal bid problem without neither emission constraints nor CO_2 allowances. Corresponds to problem (31) excluding both the CO_2 rights incomes/cost term (30) and emission constraints (9)-(10).
- EC: optimal bid problem with only emission constraints. Corresponds to problem (31) excluding the CO_2 rights incomes/cost term (30) but retaining emission constraints (9)-(10).
- CO2EC: The complete model (31) with both CO_2 allowances and emission constraints.

All the cases have been implemented with the AMPL modeling language [24] and solved with CPLEX 12.0 [25] (mipgap=0.05, threads=20) over a SunFire X2200 with 32 Gb of RAM memory and two dual core processors AMD Opteron 2222 at 3 GHz, taking advantage of the multithreading capabilities of CPLEX. The number of continuous and binary variables is 20.448 and 200 respectively and the number of linear constraints is 49.458 for the BASE case and 49.558 for the other two cases. The execution time is below one minute in all the cases.

Table V depicts the expected value of the CO_2 , SO_2 and NO_x emissions, at the optimal solution of the three cases. Focusing on the CO2EC case, the CO_2 , SO_2 and NO_x emissions has been reduced by 70%, 74% and 75% respectively. Finally, table VI shows the optimal value of the expected profits (objective function of problem (31) for the three cases together with the disclosure of the value of the different terms (26)-(30). Although the reduction in the total generation forced by the SO_2 and NO_x limits (case EC) causes a decrease of 14% in the total profit, the expected incomes due to the CO_2 rights (266.114€) compensates this loss increasing the total expected profits in a 32%.

Finally, the impact of the CO_2 allowances and emission constraints over the individual units commitment of each generation unit, together with the optimal dispatch of the bilateral and future contracts can be judged from Fig. 2 and 3. Fig. 2 depicts the optimal unit commitment for the BASE case. The blue area corresponds to the energy allocated to the

TABLE V
DAILY EMISSIONS AT OPTIMAL SOLUTION

	$E[CO_2]$	$E[SO_2]$	$E[NO_x]$
BASE	2.761 t	15.381 kg	26.811 kg
EC	835 t	3.900 kg	6.798 kg
CO2EC	801 t	3.898 kg	6.796 kg

TABLE VI
OPTIMAL INCOMES AND COSTS

	BASE	EC	CO2EC
E [Profit]	554.479€	472.677€	734.052€
BC Incomes	419.122€	419.122€	419.122€
FC Incomes	374.543€	374.543€	374.543€
E [market incomes]	1.101.440€	482.469€	398.955€
E [Generation Costs]	-1.334.540€	-799.772€	-720.998€
Start-up/shut-down Costs	-6.088€	-3.683€	-3.683€
E [CO_2 rights cost/incomes]	-	-	266.114€

bilateral contracts (variable b_{ti}); the green area is the energy of the price acceptance bid q_{ti} that includes the energy allocated to the futures contracts f_{tij} . Finally, the yellow area is, for each generation i and period t , the expected value of the matched energy in the day-ahead market $\sum_{s \in \mathcal{S}} P^s p_{ii}^s$. Comparing the generation profiles in both figures it is clear how the environmental constraints are affecting the unit commitment: all the high-emission coal thermal generators are shut-down as soon as t_i^{off} allows, except thermal unit 3, which is maintained on to satisfy future contract 3. This effect is due mainly to the opportunity of profits in the CO_2 market by reducing the emission below the GenCo's free emission allowances. Although the energy matched in the day-ahead market (the addition of the green plus yellow areas) is reduced from the BASE to the CO2EC cases, the overall profits increases due to the CO_2 rights incomes.

V. CONCLUSIONS

A new stochastic programming model has been described, implemented and tested that allow generation companies with bilateral and futures contracts obligations to find the optimal unit commitment and bidding to wholesale electricity markets compliant with National Allocations and Emissions Plans. The numerical test provides a reduction of the overall CO_2 , SO_2 and NO_x emissions by 70% together with 30% increase in the expected total profit, availing of the CO_2 emissions rights market. Although more evidence is needed, the results suggest that, with the day-ahead market and CO_2 allowances prices used in this study, the CO_2 rights market can be a valid tool for utilities to reduce their emissions without any loss in their overall profits.

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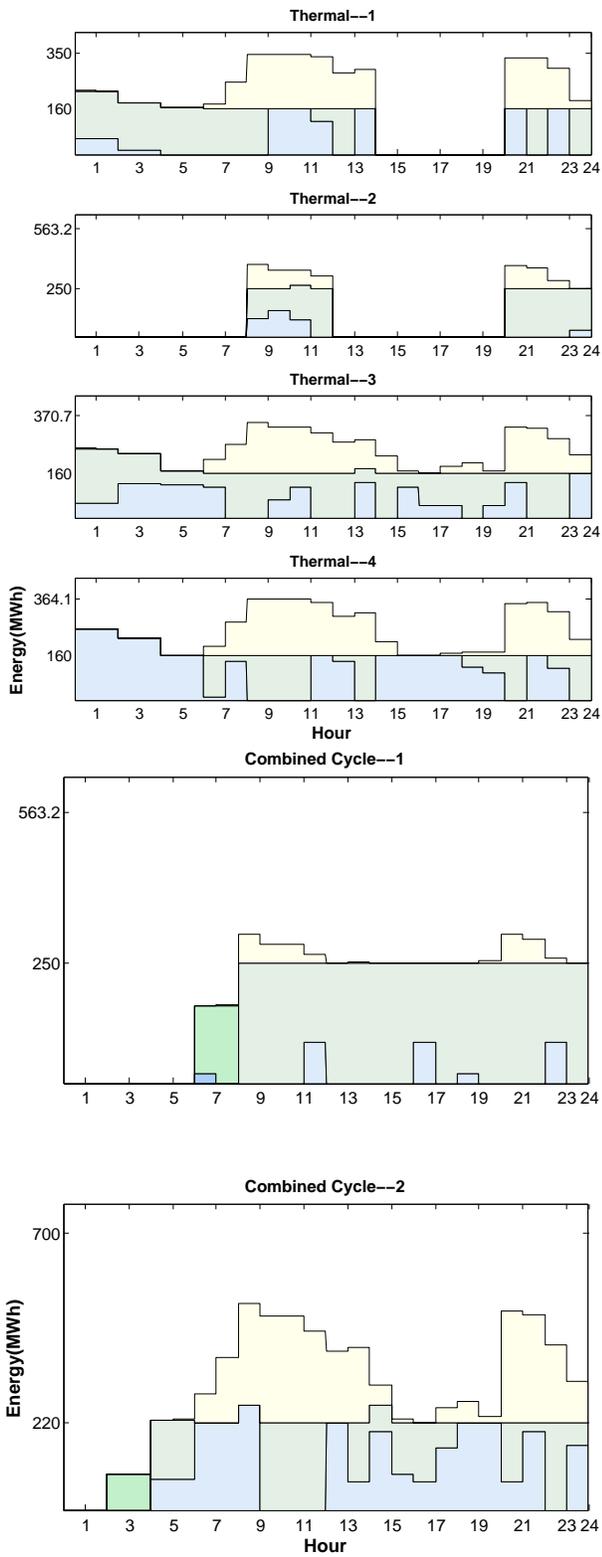


Fig. 2. Unit commitment of the generation units for the BASE case: b_{ti} (blue), q_{ti} (green). In yellow the expected value of matched energy. For the CC units, dark colors are for state 1 and light colors for state 2.

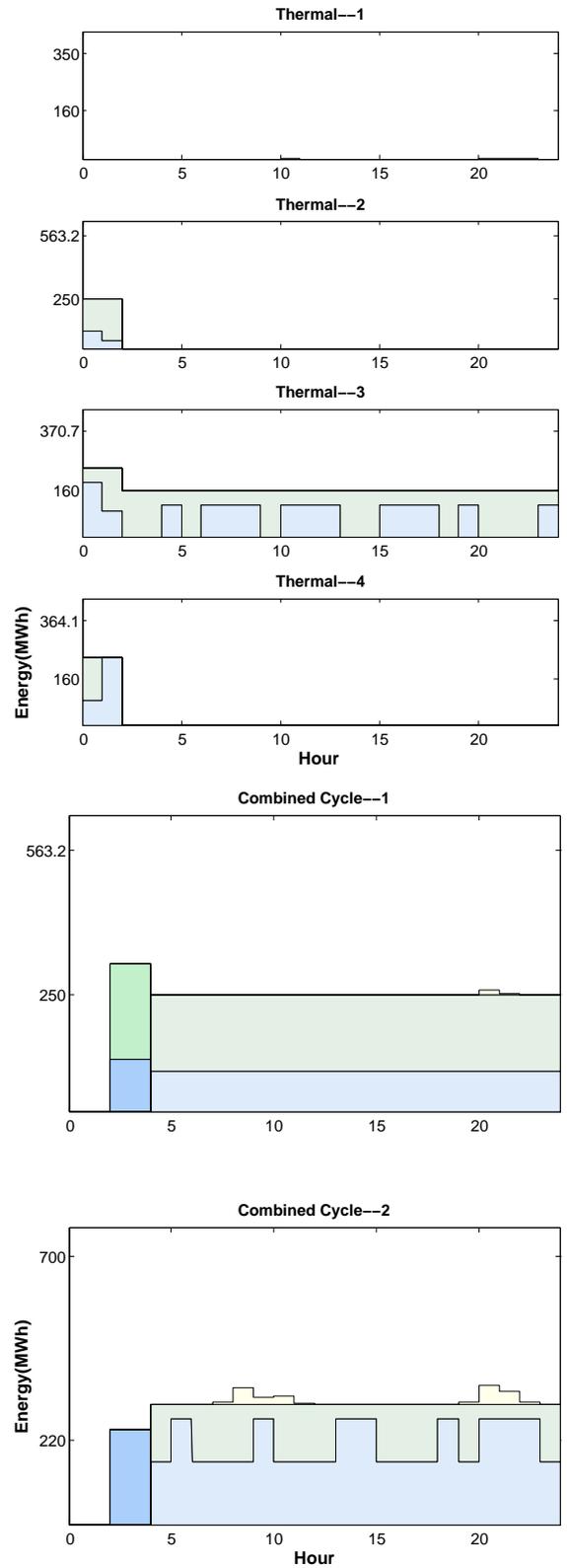


Fig. 3. Unit commitment of the generation units for the CO2EC case: b_{ti} (blue), q_{ti} (green). In yellow the expected value of matched energy. For the CC units, dark colors are for state 1 and light colors for state 2.

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