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Bidding Decision of Wind-Thermal GenCo in Day-Ahead Market

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Abstract

This paper deals with the self-scheduling problem of a price-taker having wind and thermal power production and assisted by a cyber-physical system for supporting management decisions in a day-ahead electric energy market. The self-scheduling is regarded as a stochastic mixed-integer linear programming problem. Uncertainties on electricity price and wind power are considered through a set of scenarios. Thermal units are modelled by start-up and variable costs, furthermore constraints are considered, such as: ramp up/down and minimum up/down time limits. The stochastic mixed-integer linear programming problem allows a decision support for strategies advantaging from an effective wind and thermal mixed bidding. A case study is presented using data from the Iberian electricity market.

Keywords: Bidding strategy; stochastic programming; mixed integer linear programming; wind thermal coordination.

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1. Introduction

Exploitation of renewable sources either alone or in coordination with other renewable or non-renewable sources is social and political supported as a major involvement to a sustainable development, avoiding the negative environmental impact of fossil fuel burning. Exploitation of renewable sources has been supported by political procedures providing subsidy and normative incentives [1]. Exploitation of wind power either onshore or offshore has been and will be further in usage, but as the wind power technology matures and goes into parity with conventional sources of energy incentives are due to be less significant. Already, incentives are in way of less significance, i.e., incentives are becoming flawed as wind power penetration increases [2].

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Nomenclature

R_t	revenue of a GenCo for hour t
λ_t^D	day-ahead market-clearing price
P_t^{offer}	power at the close of the day-ahead market accepted
I_t	imbalance income resulting from the balancing penalty of not acting in accordance with the accepted trade
Δ_t	total deviation for hour t
$F_{\omega i t}$	cost for a thermal unit
A_i	fixed production cost
$u_{\omega i t}$	binary variable, unit state of operation
$d_{\omega i t}$	added variable cost associated with the amount of fossil fuel consumed by the unit
$b_{\omega i t}$	start-up costs of the units
C_i	shut-down costs of the units
F_i^l	slope of each segment
$\delta_{\omega i t}^l$	segment power
$p_{\omega i \mathrm{t}}$	power of the unit
$p_{\omega t}^g$	actual power generated by the thermal units for the day-ahead market
p_{mt}^{bc}	power contracted in each bilateral contract m

Consequently, a generation company (GenCo) for having profit by the management of wind power conversion into electric energy has to go into the electricity market [3]. Although, in the future some normative incentive is expected to hold in the market environment in support of a GenCo exploiting wind power to account for the added exposition to the uncertainty of the source, bad bidding due to incorrect consideration of this uncertainty curtails profit.

The electric energy supply is reported as having fossil fuel majority usage, although of the increased worldwide renewable energy exploitation. Statistics for electric energy supply accounts that the usage of fossil fuel burning is more than 60% in 2012 [4]. But as time goes eventually a change will be laid down. In EU 2014 is the seventh year running that over 55% of all additional power capacity is form renewable energy and the added new deployment of wind power accounts for 43.7% all new renewable deployment in 2014 [5]. So, exploitation of wind power either alone or in coordination with other renewable or non-renewable sources is becoming a significant contribution to mitigate the need for fossil fuel burning in EU. The paradigms of smart grid ambient and cyber-physical systems (CPS) [6] is a convenient upbringing for exploiting wind power and facing the competition of electric energy market in order to obtain the economic revenue. But, the future smart grid ambient and CPS have to have a layered architecture of a cyber infrastructure accessing resilient power applications that are able to give security and reliability, having the ability to act in order to maintain and correct infrastructure components without affecting the service [7,8]. Also, this architecture based in the core of well design software, standing upon standards developed over the years, can offer a base tool to ease new standards and energy policies implementation [9]. A power systems CPS is schematically shown in Fig. 1.

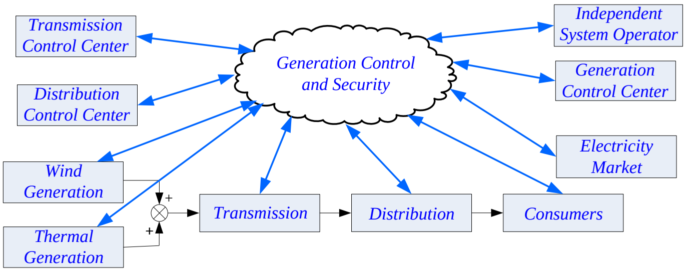

Fig. 1. Layout of the power systems cyber-physical infrastructure.

In Fig. 1 the CPS, consisting of electronic field devices, communication networks, substation automation systems, and control centers, is embedded throughout the physical power system for efficient and reliable generation, transmission, and distribution of power. The control center is responsible for monitoring in real-time, control, and operational decision making. The independent system operators perform coordination between power utilities, and dispatch commands to their control centers. Producers participating in electric energy markets also interact with the independent system operators to support market functions based on real-time power generation, transmission, and demand. So a wind power producer is able to access periodic nodal variations of electric energy prices [10] to be taken into consideration under the uncertainty of wind power. But to circumvent the added uncertainty of wind power, to mitigate the eventual imbalances, coordination with sources having given lower uncertainty has to be considered and thermal power is one way to deal with imbalances. So a wind-thermal GenCo (WTGenco) addressing wind power and electric energy price uncertainties to decide for convenient bidding has advantages in facing the competition of electric energy market in order to obtain the economic revenue. WTGenco has advantages due to the fact that cost is owed in case of falling to deliver the energy of an accepted bidding, i.e., other power producers must be called to fill the so-called deviation [11] and this has a cost to be paid in the energy market. Although, WTGenco has backup power that can be available for matching the mismatch due to wind power uncertainty, a WTGenco needs to accurately bid in order to obtain the better economic revenue.

This paper is a contribution for a WTGenco accurately bidding.The paper is organized as follows: Section 2 presents the state of the art. Section 3 presents the problem formulation. Section 4 presents the case study for comparison of a WTGenCo. Finally, concluding remarks are given in Section 5.

2. State of the Art

Methods for solving the unit commitment (UC) to optimize thermal energy conversion into electric energy have a significant state of art, ranging from the old priorities list method to classical methods until the recently reported artificial intelligence methods [12]. The priority list method is easy implemented and requires a small processing time, but does not ensure an optimal solution [13]. Within the classical methods are included dynamic programming and Lagrangian relaxation-based methods [14]. The dynamic programming method is a flexible one but has a limitation known by the "curse of dimensionality". The Lagrangian relaxation can overcome the previous limitation, but does not necessarily lead to a feasible solution, implying further procedure for satisfying the violated constraints in order to find a feasible solution, which does not ensure optimal solution. The mixed integer linear programming (MILP) method has been applied with success for solving UC problem [15]. MILP is one of the most successful explored methods for scheduling activities because of flexibility and extensive modelling capability [16]. Although, artificial neural networks, genetic algorithms, evolutionary algorithms and simulating annealing have been applied, the major limitation of the artificial intelligence methods is the possibility to obtain a solution near the global optimum. So, classical methods are the main methods in use as long as the mathematical model has conveniently smoothness.

Deregulated market and variability of the source of wind power impose uncertainties to WTGenco. These uncertainties have to be conveniently considered in order to know how much to produce and the price for biddings [17]. AWTGenco in a competitive environment can benefit without depending on third-parties from: a coordination of wind power with thermal power [18]; a financial options as a tool to hedge against wind power uncertainty [19]; a stochastic model intended to produce optimal bid strategies participating in electric energy market [20]. The stochastic model is a formulation explicitly taking into account the uncertainties faced by a WTGenco [21], using uncertain measures and multiple scenarios built by computer applications for wind power and electric energy price forecasts [22]. Also, bilateral contracts are suitable for WTGenco in order to hedge against price uncertainty.

3. Problem Formulation

3.1. Day-ahead market

The revenue R_t of a GenCo for hour t is stated as:

$$R_t = \lambda_t^D P_t^{offer} + I_t \tag{1}$$

The total deviation for hour t is stated as:

$$\Delta_t = P_t^{act} - P_t^{offer} \tag{2}$$

In (2), a positive deviation means the actual power traded is higher than the traded in the day-ahead market and a negative deviation means the power is lower than the traded. Let λ_t^+ be the price paid for excess of production and λ_t^- the price to be charged for deficit of production. Consider the price ratios given by the equalities stated as:

$$r_t^+ = \lambda_t^+ \big/ \lambda_t^D \,, r_t^+ \le 1 \quad and \quad r_t^- = \lambda_t^- \big/ \lambda_t^D \,, r_t^- \ge 1 \tag{3}$$

In (3), the inequalities at the right of the equalities mean, respectively, that the positive deviation never has a higher price of penalization and the negative one never has a lower price of penalization in comparison with the value of the closing price.

3.2. WTGenCo

The operating cost for a thermal unit $F_{\omega i t}$ for the scenario ω can be stated as:

$$F_{\omega i t} = A_i \, u_{\omega i t} + d_{\omega i t} + b_{\omega i t} + C_i \, z_{\omega i t} \quad \forall \, \omega , \quad \forall \, i, \quad \forall \, t \tag{4}$$

The functions used to quantify the variable, the start-up and shut-down costs of units in (4) are considered to be such that is possible to approximate those function by a piecewise linear or step functions. The variable cost, $d_{\omega i t}$ is stated as:

$$d_{\omega i t} = \sum_{l=1}^{L} F_i^{\,l} \delta_{\omega i t}^{l} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (5)$$

$$p_{\omega i t} = p_i^{\min} u_{\omega i t} + \sum_{l=1}^{L} \delta_{\omega i t}^{l} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (6)$$

$$(T_i^{\,1} - p_i^{\min}) t_{\omega i t}^{1} \le \delta_{\omega i t}^{1} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (7)$$

$$\delta_{\omega i t}^{1} \le (T_i^{\,1} - p_i^{\min}) u_{\omega i t} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (8)$$

$$(T_i^{\,l} - T_i^{\,l-1}) t_{\omega i t}^{l} \le \delta_{\omega i t}^{l} \qquad \forall \omega, \quad \forall i, \quad \forall t, \quad \forall l = 2, \ldots, L-1 \qquad (9)$$

$$\delta_{\omega i t}^{l} \le (T_i^{\,l} - T_i^{\,l-1}) t_{\omega i t}^{l-1} \qquad \forall \omega, \quad \forall i, \quad \forall t, \quad \forall l = 2, \ldots, L-1 \qquad (10)$$

$$0 \le \delta_{\omega i t}^{L} \le (p_i^{\max} - T_{\omega i t}^{L-1}) t_{\omega i t}^{L-1} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (11)$$

In (6), the power of the unit is given by the minimum power generation plus the sum of the segment powers associated with each segment. The binary variable $u_{\omega i t}$ ensures that the power generation is equal to 0 if the unit is in the state offline. In (7), if the binary variable $t_{\omega i t}^{l}$ has a null value, then the segment power $\delta_{\omega i t}^{1}$ can be lower than the segment 1 maximum power; otherwise and in conjunction with (8), if the unit is in the state on, then $\delta_{\omega i t}^{1}$ is equal to the segment 1 maximum power. In (9), from the second segment to the second last one, if the binary variable $t_{\omega i t}^{l}$ has a null value, then the segment power $\delta_{\omega i t}^{1}$ can be lower than the segment l maximum power; otherwise and in conjunction with (10), if the unit is in the state on, then $\delta_{\omega i t}^{1}$ is equal to the segment l maximum power. In (11), the segment power must be between zero and the last segment maximum power.

The nonlinear nature of the start-up costs function, $b_{\omega i t}$, is described by an exponential function. This exponential function is approximated by a piecewise linear formulation as in [3] stated as:

$$b_{\omega i t} \ge K_i^{\,\beta} \left(u_{\omega i t} - \sum_{r=1}^{\beta} u_{\omega i t-r} \right) \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (12)$$

In (12), the second term models the lost of thermal, i.e., if the unit is a case of being in the state online at hour t and has been in the state offline in the β preceding hours, the expression in parentheses is equal to 1. So, in such a case a start-up cost is incurred for the thermal energy that are not accountable for added value in a sense of that energy has not been converted into electric energy. The maximum number for β is given by the number of hours need to cool down, i.e., completely lose all thermal energy. So, for every hour at cooling and until total cooling one inequality like (12) is considered.

The units have to perform in accordance with technical constraints that limit the power between successive hours stated as:

$$p_i^{\min} u_{\omega i t} \le p_{\omega i t} \le p_{\omega i t}^{\max} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (13)$$

$$p_{\omega i t}^{\max} \le p_i^{\max} (u_{\omega i t} - z_{\omega i t+1}) + SD\, z_{\omega i t+1} \qquad \forall \omega, \quad \forall i, \quad \forall t \qquad (14)$$

$$p^{\max}_{\omega it} \le p^{\max}_{\omega i\,t-1} + RU u_{\omega it-1} + SU y_{\omega it} \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, t \tag{15}$$

$$p_{\omega it-1} - p_{\omega it} \le RD u_{\omega it} + SD z_{\omega it} \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, t \tag{16}$$

In (13), $p^{min}_{\omega it}$ and $p^{\max}_{\omega it}$ are respectively the maximum and the minimum available powers of the unit, i.e, this box constraint sets limits on the power. But unit's actual hourly power capacity has to be considered, due to start-up/shut-down ramp rate limits, and ramp-up limit in the operation of the units. In (14)–(16), the relation between the start-up and shut-down variables of the unit are given, using binary variables for describing the states and data parameters for ramp-down, shut-down and ramp-up rate limits. In (16), the ramps-down and shut-down ramp rate limits are considered. The minimum down time constraint is imposed by a linear formulation stated as:

$$\sum_{t=1}^{J_i} u_{\omega it} = 0 \quad \forall\, \omega, \quad \forall\, i \tag{17}$$

$$\sum_{t=k}^{k+DT_i-1} (1-u_{\omega it}) \ge DT_i\, z_{\omega it} \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, k = J_i + 1 \ldots T - DT_i + 1 \tag{18}$$

$$\sum_{t=k}^{T} (1-u_{\omega it} - z_{\omega it}) \ge 0 \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, k = T - DT_i + 2 \ldots T \tag{19}$$

$$J_i = \min\{T, (DT_i - s_{\omega i0})(1-u_{\omega i0})\}$$

In (17), if the unit is offline at hour 0 and the minimum down time has not been achieved, then the unit remains offline at hour 0. In (18), the minimum down time constraint is imposed to be satisfied for all the possible sets of consecutive hours of size DT_i. In (19), the minimum down time constraint is imposed to be satisfied for the last $DT_i - 1$ hours. The minimum up time constraint is also imposed by a linear formulation stated as:

$$\sum_{t=1}^{N_i} (1-u_{\omega it}) = 0 \quad \forall\, \omega, \quad \forall\, i \tag{20}$$

$$\sum_{t=k}^{k+UT_i-1} u_{\omega it} \ge UT_i\, y_{\omega it} \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, k = N_i + 1 \ldots T - UT_i + 1 \tag{21}$$

$$\sum_{t=k}^{T} (u_{\omega it} - z_{\omega it}) \ge 0 \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, k = T - UT_i + 2 \ldots T \tag{22}$$

$$N_i = \min\{T, (UT_i - U_{\omega i0})\, u_{\omega i0}\}$$

In (20), if the minimum up time constraint has not been achieved, then the unit remains offline at hour 0. In (21), the minimum up time constraint has to be satisfied for all the possible sets of consecutive hours of size UT_i. In (22), the minimum up time constraint has to be satisfied for the last $UT_i - 1$ hours. The relation between the 0/1 variables to identify start-up, shutdown and forbidden operating zones is stated as:

$$y_{\omega it} - z_{\omega it} = u_{\omega it} - u_{\omega it-1} \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, t \tag{23}$$

$$y_{\omega it} + z_{\omega it} \le 1 \quad \forall\, \omega, \quad \forall\, i, \quad \forall\, t \tag{24}$$

The total power generated the thermal units is stated as:

$$\sum_{i=1}^{I} p_{\omega it} = p^{g}_{\omega t} + \sum_{m=1}^{M} p^{bc}_{mt} \quad \forall\omega, \forall i, \forall t, \forall m \tag{25}$$

3.3. Objective function

The bid submitted by the WTGenco is the sum of the power bid associated with the thermal units $p^{th}_{\omega t}$ and the power bid associated with the wind farm $p^{D}_{\omega t}$. The bid submitted has a power stated as:

$$p^{offer}_{\omega t} = p^{th}_{\omega t} + p^{D}_{\omega t} \quad \forall \omega, \ \forall t \tag{26}$$

The actual power that the WTGenco is able to assign in the real time operation, i.e., the sum of the power generated by the thermal units and the power generated by the wind farm is assumed not to be the same as the one submitted by the WTGenco. The actual power is stated as:

$$p^{act}_{\omega t} = p^{g}_{\omega t} + p^{\omega d}_{\omega t} \quad \forall \omega, \ \forall t \tag{27}$$

The expected revenue of the WTGenco is for a 24 hour period is given by the maximization of the objective function stated as:

$$\sum_{\omega=1}^{N_\Omega}\sum_{t=1}^{N_T}\pi_\omega\left[\left(\lambda^{D}_{\omega t}P^{offer}_{\omega t}+\lambda^{D}_{\omega t}r^{+}_{\omega t}\Delta^{+}_{\omega t}-\lambda^{D}_{\omega t}r^{-}_{\omega t}\Delta^{-}_{\omega t}\right)-\sum_{i=1}^{I}F_{\omega i t}\right] \quad \forall \omega, \ \forall t \tag{28}$$

subject to:

$$0 \le p^{offer}_{\omega t} \le p^{M}_{\omega t} \quad \forall \omega, \ \forall t \tag{29}$$

$$\Delta_{t\omega} = \left(p^{act}_{\omega t} - p^{offer}_{\omega t}\right) \quad \forall \omega, \ \forall t \tag{30}$$

$$\Delta_{t\omega} = \Delta^{+}_{t\omega} - \Delta^{-}_{t\omega} \quad \forall \omega, \ \forall t \tag{31}$$

$$0 \le \Delta^{+}_{t\omega} \le P_{t\omega}\, d_t \quad \forall \omega, \ \forall t \tag{32}$$

In (28), the revenue from the bilateral contracts are not included, however the cost of thermal production includes the total power generated by the thermal units stated in (25). In (29), $p^{M}_{\omega t}$ is maximum available power, limited by the sum of the installed capacity in the wind farm, $p^{E\max}$, with the maximum thermal production. The maximum available power is stated as:

$$p^{M}_{\omega t} = \sum_{i=1}^{I} p^{\max}_{\omega i t} + p^{E\max} \quad \forall \omega, \ \forall t \tag{33}$$

Some system operators require non-decreasing bids to be submitted by GenCo's. Non-decreasing bids are formulary considered by a constraint stated as:

$$(p^{offer}_{\omega t} - p^{offer}_{\omega' t})(\lambda^{D}_{\omega t} - \lambda^{D}_{\omega' t}) \ge 0 \quad \forall\ \omega, \omega', \quad \forall\ t \tag{34}$$

In (34), if the increment in price in two successive hours is not null, then the increment in bids in the two successive hours has two be of the same sign of the increment in price or a null value.

4. Case Study

The stochastic MILP approach is illustrated by a case study of a WTGenco, having 8 thermal units with installed capacity of 1440 MW and a wind farm with an installed power of 360 MW. The data used for the thermal units are in [23] and the ten wind power scenarios are obtained from the power generated from wind in June 2014 in the Iberian Peninsula [23]. The bilateral contracts have 10 levels of energy to be considered and the contracts have to be decided for the same market conditions. The energy prices data used is from day-ahead electric energy market MIBEL. The energy and the wind power are respectively shown in Fig. 2. The coordination of bids and the bids without coordination with the imposed constraint of the non-decreasing energy bids in hour 5 and in hour 20 are respectively shown in Fig. 3. In Fig. 3 the advantage of coordination is revelled by the ability to have higher power bids for the same bid price and lower price within same power bids.

As normal, the power to be associated with the bilateral contracts and the impact of bilateral contracts is treated as a deterministic formulation in the self-scheduling problem of the WTGenco, i.e., there are no extra scenario considerations due to the contracts. The power schedule for the bilateral contracts and market scenarios energy average are respectively shown in Fig. 4. In Fig. 4, the energy stands for the average of the ten market scenarios for each level of energy from the bilateral contract. The energy from the wind is practically constant and the committed energy is always lower than the energy of the thermal units. As the energy contracted increases and approaches the limit capacity of the thermal units, the difference between the committed energy and the energy from the thermal units wind decreases as decreases the energy given by the wind power. The results with and without coordination in the absence of bilateral contracts are shown in Table 1.

Table 1. Results with and without coordination

Case	Expected profit (€)	Imbalance cost (€)	Execution time (s)
Wind uncoordinated	119200	-17826	0.02
Thermal uncoordinated	516848	229398	0.13
Sum uncoordinated wind and thermal	636047		0.15
Coordinated Wind and thermal	642326	3643	0.13
Gain (%)	0.99	5	

The expected profit of the coordinated approach is 0.99% higher, than the without coordinated one. The CPU time does not represent a significant burden in computational resources when compared with the uncoordinated schedule. The CPU time measured by Gams is about the same for both approaches, since the processing CPU time for the schedule wind power is irrelevant when compared with the processing CPU time for the schedule thermal.

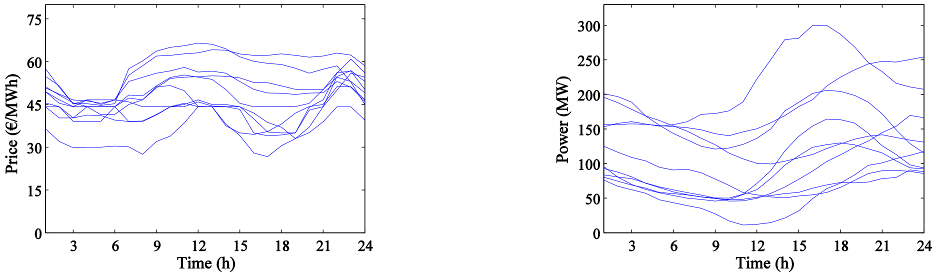

Fig. 2. June 2014 (ten days): left, MIBEL energy price; right, energy from wind.

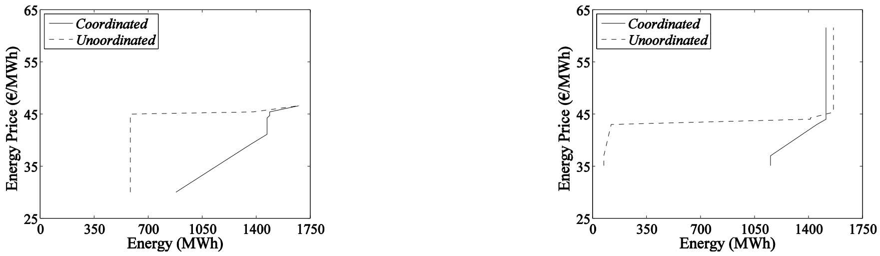

Fig. 3. Energy bids: left: hour 5; right: hour 20.

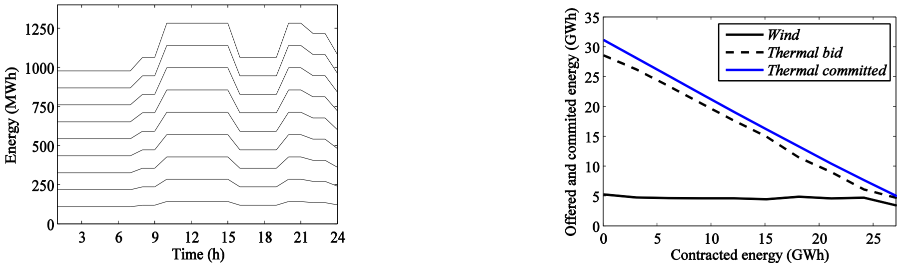

Fig. 4. Left: bilateral contract; right: market scenarios energy average.

5. Conclusions

The interests on the coordination of wind power with thermal power is discussed as an aid to mitigate energy imbalances owed by stumble into the compromise of satisfy assumed energy delivering due to the accepted bids in a day-ahead electricity market. Hence, management of coordination is stated as convenient advantage of a WTGenco, but this management needs a convenient addressing for supporting the biding strategy in order to achieve the best revenue from the day-ahead electricity market.

The stochastic programming is a suitable approach to address parameter uncertainty in modelling via scenarios, as is the case of the self-scheduling problem of a price-taker WTGenco and of particular practical interest is the stochastic MILP approach. Although the MILP formulation imposes an integer linear formulation, which have to be used as an acceptable approximation to model the main technical and economic characteristics of thermal units. The MILP approach benefits from good practical acceptance, flexibility, extensive modelling capability and computationally adequation. The computation time of a MILP approach scales up linearly with the involvedness of the mathematical programming problems and the integer linear formulation can be made as an acceptable realistic one for a WTGenco.

The proposed self-scheduling problem of a price-taker WTGenco benefits from the good practical acceptance of MILP, having both accurate and computationally adequation, scaling up linearly with the number of scenarios, units and hours on the time horizon. Also, bilateral contracting are considered by an integer linear formulation, which is suitable for hedging against price uncertainty. The main results of the self-scheduling problem are the short-term bidding strategies and the optimal schedule of the thermal units. The coordinated bidding of thermal and wind power allows to provide improved revenue results than the sum of the isolated bids.

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