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Stochastic Optimal Bid to Electricity Markets with Emission Risk Constraints

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Summary

- **Framework and motivation.**
- **Day-ahead Market Bid model**
- **Day−Ahead Market Bid model with Emission Risk Constraints**
- **Case study.**
- **Conclusions.**

Framework and motivation of the work

- **Framework:**
  - A **price-taker GenCo** owning:
    - A set of **fuel/coal thermal units** (**high emission technology**) and
    - A set of **Combined Cycle Gas Turbines** (CCGT) generation units ($20\%\sim30\%$ more efficient than thermal power plants, **low emission technology**).
  - The GenCo operates in the **Day-ahead Market** (DAM), a series of twenty-four hourly auctions where **the most important part of the electricity energy is negotiated** (78% in the case of the MIBEL).
  - In addition, the GenCo must cover a set of **bilateral and futures contracts**, agreement between a GenCo and a qualified consumer to provide a given amount of electrical energy. This energy is integrated into the energy production system through the DAM.
  - The GenCo must abide by the **Spanish National Emission Reduction Plan (NERP [1])**. The Spanish NERP imposes, for the period 2008-15, a global reduction of 81% of SO_2 and 15% of NO_x emissions, w.r.t. the emissions in 2001.
- **Motivation:** to develop a new stochastic programming model to cope with the optimal generation bid to the day-ahead market (DAM) that complies with the SO_2 and NO_x emission limits.

[1] ORDEN PRE/3420/2007, de 14 de noviembre. B.O.E. 284 de 20 de marzo 2007. Gouvernment of Spain, 2007.

Literature review

- Although the SO_2 and NO_x emission limits can modified modifies substantially the shape of the optimal bid strategy of an electricity producer quite few attention has been given in the bibliography to this problem.
- [2] develops a load dispatch model to minimize the NO_x emissions taking the fuel cost and stochastic wind power availability as constraints, disregarding the electricity market.
- [3] considers a deterministic unit commitment of both thermal and combined cycle units that minimizes the generation costs satisfying simple bounds to the SO_2 and NO_x emissions.
- [4, 5] use formulate multiobjective optimization models where both the profit and emissions are minimized.
- These works doesn't incorporate the bid rules of the electricity market (neither the DAM nor the bilateral and future contracts).

[2] X. Liu, IET Generation, Transmission & Distribution 5 (2011) 735–742.
[3] B. Lu, S. M. Shahidehpour, IEEE Transactions on Power Systems 20 (2005) 1022–1034.
[4] C. Peng, H. Sun, J. Guo, G. Liu, Energy Conversion and Management 57 (2012) 13–22.
[5] H. S. A. R. A. Ahmadi, J. Aghaei, Applied Soft Computing 12 (2012) 2137–2146.

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$(DAMB)$ base model (1/4)

- The starting point of this work is the **Day-Ahead Market Bid** model:

$$
(DAMB)\begin{cases}
\max & h(u,b,f,q,g,p) & & \\
\text{s.t.:} & & & \\
 & b_t \in P_t^{BC} & t \in \mathcal{T} & (c1) \\
 & f_{tj} \in P_{t,j}^{FC} & t \in \mathcal{T}, j \in \mathcal{F} & (c2) \\
 & u_i \in P_i^{UC} & i \in \mathcal{U} & (c3) \\
 & u_{ti}, b_{ti}, f_{ti}, q_{ti}, g_{ti}^s, p_{ti}^s \in P_{ti}^{DS} & i \in \mathcal{U}, t \in \mathcal{T}, s \in \mathcal{S} & (c4)
\end{cases}
$$

  - It incorporates the optimal bid model with futures and bilateral contracts developed in [6] and [7] and
  - the mathematical modeling of the CCGT unit commitment introduced in [8,9].

[6] C. Corchero, F.-J. Heredia, Computers & Operations Research 38 (2011) 1501–1512.

[7] C. Corchero, E. Mijangos, F.-J. Heredia, TOP 21 (2013) 84–108.

[8] C. Corchero, F.-J. Heredia, J. Cifuentes-Rubiano, in: IEEE (Ed.), Proceedings of the 2012 9th International Conference on the European Energy Market (EEM 2012), pp. 1–8. DOI: 10.1109/EEM.2012.6254676.

[9] F. J. Heredia, M. J. Rider, C. Corchero, Annals of Operations Research 193 (2012) 107–127. doi:10.1007/s10479-011-0847-x.

$(DAMB)$ base model (2/4)

- The starting point of this work is model $(DAMB)$:

$$
(DAMB)\begin{cases}
\max & h(u,b,f,q,g,p) & & \\
\text{s.t.:} & & & \\
& b_t \in P_t^{BC} & t \in \mathcal{T} & (c1) \\
& f_{tj} \in P_{t,j}^{FC} & t \in \mathcal{T}, j \in \mathcal{F} & (c2) \\
& u_i \in P_i^{UC} & i \in \mathcal{U} & (c3) \\
& u_{ti}, b_{ti}, f_{ti}, q_{ti}, g_{ti}^s, p_{ti}^s \in P_{ti}^{D^s} & i \in \mathcal{U}, t \in \mathcal{T}, s \in \mathcal{S} & (c4)
\end{cases}
$$

where:

- h, expected value of the total profit obtained by the GenCo = incomes (DAM, BC, FC) – operational costs(generation+start-up+shut-down).
- $\mathcal{T} = \{1,2,\ldots,24\}$ is the set of time periods.
- $\mathcal{U}$ is the set of generation units (both thermal and CCGT).
- $\mathcal{S}$ is the set of scenarios for the DAM price (λ_t^s) with probability P^s.
- $\mathcal{F}$ is the set of future contracts.

$(DAMB)$ base model (3/4)

- The starting point of this work is model $(DAMB)$:

$$
(DAMB)\begin{cases}
\max & h(u,b,f,q,g,p) & & \\
\text{s.t.:} & & & \\
& b_t \in P_t^{BC} & t \in \mathcal{T} & (c1) \\
& f_{tj} \in P_{t,j}^{FC} & t \in \mathcal{T}, j \in \mathcal{F} & (c2) \\
& u_i \in P_i^{UC} & i \in \mathcal{U} & (c3) \\
& u_{ti}, b_{ti}, f_{ti}, q_{ti}, g_{ti}^s, p_{ti}^s \in P_{ti}^{D^s} & i \in \mathcal{U}, t \in \mathcal{T}, s \in \mathcal{S} & (c4)
\end{cases}
$$

where the **first stage variables** are:

- b_{ti} is the scheduled energy for **bilateral contracts** [MWh] (continuous).
- f_{tij} is the scheduled energy for **future contract** [MWh] (continuous).
- u_i are the **unit commitment** variables (binary).
- q_{ti} are the energy of the **price-acceptant bid** (continuous).

$(DAMB)$ base model (3/4)

- The starting point of this work is model $(DAMB)$:

$$(DAMB)\begin{cases} \max & h(u,b,f,q,g,p) & & & \\ \text{s.t.:} & & & & \\ & b_t & \in P_t^{BC} & t\in\mathcal{T} & (c1) \\ & f_{tj} & \in P_{t,j}^{FC} & t\in\mathcal{T}, j\in\mathcal{F} & (c2) \\ & u_i & \in P_i^{UC} & i\in\mathcal{U} & (c3) \\ & u_{ti}, b_{ti}, f_{ti}, q_{ti}, g_{ti}^s, p_{ti}^s & \in P_{ti}^{D^s} & i\in\mathcal{U}, t\in\mathcal{T}, s\in\mathcal{S} & (c4) \end{cases}$$

where the **second stage variables** are:

- p_{ti}^s (continuous) is the **matched energy** [MWh] in the day-ahead market under scenario s.
- g_{ti}^s (continuous) is the **total output** [MWh] of the generation unit i at time period t under scenario s.

$(DAMB)$ base model (4/4)

- The starting point of this work is model $(DAMB)$:

$$(DAMB)\begin{cases} \max & h(u,b,f,q,g,p) & & & \\ \text{s.t.:} & & & & \\ & b_t & \in P_t^{BC} & t\in\mathcal{T} & (c1) \\ & f_{tj} & \in P_{t,j}^{FC} & t\in\mathcal{T}, j\in\mathcal{F} & (c2) \\ & u_i & \in P_i^{UC} & i\in\mathcal{U} & (c3) \\ & u_{ti}, b_{ti}, f_{ti}, q_{ti}, g_{ti}^s, p_{ti}^s & \in P_{ti}^{D^s} & i\in\mathcal{U}, t\in\mathcal{T}, s\in\mathcal{S} & (c4) \end{cases}$$

where the constraints are:

- $(c1)$ are the constraints for the **Bilateral Contracts** at time period t.
- $(c2)$ are the constraints for the **Future Contract** j at time period t.
- $(c3)$ are the **unit commitment constraints** of generation unit i.
- $(c4)$ are the constraints for the **day-ahead market rules** for unit i at time period t and scenario s.

Summary

- *Framework and motivation.*
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First approach: $(DAMB)$ with emission limits.

- Our concern was to extend model $(DAMB)$ to take into account the limits that the NERP imposes to the emissions of SO_2 and NO_x of the thermal units.
- Obviously a first approach [10,11,12] is modify the model $(DAMB)$ by simply imposing an emission limit to every scenario $s \in \mathcal{S}$ through the following set of constraints:

$$\sum_{t \in \mathcal{T}} e_i^{SO_2} g_{ti}^s \le \overline{SO_2} \qquad \sum_{t \in \mathcal{T}} e_i^{NO_x} g_{ti}^s \le \overline{NO}_x \quad s \in \mathcal{S}$$

  with g_{ti}^s the total generation at scenario s and $e_i^{SO_2}$ and $e_i^{NO_x}$ [kg/MWh] the emission coefficients .

- Nevertheless, this approach is quite restrictive as it forces the optimal bid to abide by the NERP limits even in the most extremes (unlikely) scenarios

[10] C. Corchero, F.-J. Heredia, J. Cifuentes-Rubiano, in: IEEE (Ed.), Proceedings of the 2012 9th International Conference on the European Energy Market (EEM 2012), pp. 1–8. DOI: 10.1109/EEM.2012.6254676.

[11] B. Lu, S. M. Shahidehpour, IEEE Transactions on Power Systems 20 (2005) 1022–1034. DOI: 10.1109/TPWRS.2004.840411

[12] H. S. A. R. A. Ahmadi, J. Aghaei, Applied Soft Computing 12 (2012) 2137–2146. DOI:10.1016/j.asoc.2012.03.020.

Conditional Emission at Risk $\Phi_{\gamma}^{\overline{SO_2},\overline{NO_x}}$ (1/4)

- A more flexible approach can be formulated by analogy to the well known $CVaR$ concept [13]. The ***Conditional Emission-at-Risk*** ($\boldsymbol{CEaR}$) is proposed as a tool to measure and control the risk of violating the NERP emission limits.
- To this end, we define **first** the auxiliary binary variables y^s such that:

$$y^s = \begin{cases} 1 & \text{, if scenario } s \text{ exceeds } \overline{SO_2} \left(\Rightarrow \sum_{t\in\mathcal{T},i\in\mathcal{I}} e_i^{SO_2} g_{ti}^s > \overline{SO_2} \right) \\ 0 & \text{, if scenario } s \text{ satisfies } \overline{SO_2} \end{cases}$$

through the following constraints :

$$(\overline{SO_2} + \epsilon) + M^{SO_2}(y^s - 1) \le \sum_{t\in\mathcal{T},i\in\mathcal{I}} e_i^{SO_2} g_{ti}^s \le \overline{SO_2} + M^{SO_2} y^s \quad s \in \mathcal{S} \quad (1)$$

($\epsilon \gtrsim 0$ and M^{SO_2} parameters)

[13] R. T. Rockafellar, S. Uryasev, The Journal of risk 2 (2000) 21–41.

Conditional Emission at Risk $\Phi_{\gamma}^{\overline{SO_2},\overline{NO_x}}$ (2/4)

- **Second** we restrict the probability of exceed the limit $\overline{SO_2}$ to be below a prefixed value $\boldsymbol{\gamma} \in [\mathbf{0},\mathbf{1}]$ (**excess probability**):

$$\sum_{s\in\mathcal{S}} P^s y^s \le \boldsymbol{\gamma} \quad (2)$$

- **Third**, a new variable v^s will account for the SO_2 violation at scenario s:

$$v^s = \begin{cases} \sum_{t\in\mathcal{T},i\in\mathcal{I}} e_i^{SO_2} g_{ti}^s & \text{if } y^s = 1 \text{ (scenario } s \text{ exceeds } \overline{SO_2}) \\ 0 & \text{if } y^s = 0 \text{ (scenario } s \text{ satisfies } \overline{SO_2}) \end{cases}$$

Variables v^s are defined through the following constraints:

$$-M^{SO_2}(1 - y^s) \le v^s - \sum_{t\in\mathcal{T},i\in\mathcal{I}} e_i^{SO_2} g_{ti}^s \le M^{SO_2}(1 - y^s) \quad s \in \mathcal{S} \quad (3)$$

$$v^s \le M^{SO_2} y^s \qquad s \in \mathcal{S} \quad (4)$$

Conditional Emission at Risk $\Phi_{\gamma}^{\overline{SO}_2,\overline{NO}_x}$ (3/4)

- **Summarizing**: constraints $(1)-(4)$ stablishes that, for every scenario s with probability P^s:
  - If scenario s exceeds $\overline{SO}_2$, then $y^s = 1$ and $v^s =$ emissions
  - If scenario s satisfies $\overline{SO}_2$, then $y^s = 0$ and $v^s = 0$
- Lets consider now a solution g, y, v satisfying $(1)-(4)$.Then, for any given value of the excess probability γ and emission limit $\overline{SO}_2$, **the Conditional Emission at Risk ($CEaR$) $\Phi_{\gamma}^{\overline{SO}_2}$ associated to g, y, v is defined as the conditional expectation of the SO_2 emissions for those scenarios exceeding $\overline{SO}_2$**:

$$\boxed{\Phi_{\gamma}^{\overline{SO}_2} = \sum_{s\in\mathcal{S}} P^s v^s \Big/ \sum_{s\in\mathcal{S}} P^s y^s}$$

Conditional Emission at Risk $\Phi_{\gamma}^{\overline{SO}_2,\overline{NO}_x}$ (4/4)

- It is possible now to control the amount by which the expectation of the violating emissions $\Phi_{\gamma}^{\overline{SO}_2}$ can surpass the limit $\overline{SO}_2$:

$$\boxed{\Phi_{\gamma}^{\overline{SO}_2} \leq (1+\boldsymbol{\beta})\overline{SO}_2}$$

  This inequality ensures that the expected violation will be less than a fraction **$\beta \in]0,1]$** (**excess factor**) of the $\overline{SO}_2$ limit.

- Substituting in the last equation the definition of the $CEaR$ $\Phi_{\gamma}^{\overline{SO}_2}$ we obtain:

$$\sum_{s\in\mathcal{S}} P^s v^s \leq (1+\beta)\,\overline{SO}_2 \sum_{s\in\mathcal{S}} P^s y^s \quad (5)$$

- **Constraints $(1)-(5)$ defines the $CEaR$ constraints for the SO_2 limit and its associated polyhedron $P_{\gamma,\beta}^{SO_2}$.**
- Analogously, a polyhedron $P_{\gamma,\beta}^{NO_x}$ can be defined for the NO_x limits.

$(DAMB)$ model with Emission Risk $(DAMBER)_{\gamma,\beta}$

- Finally, the **Day-Ahead Market Bid model with Emission Risk** that incorporates the emission risk constraints to the $(DAMB)$ model is:

$$(DAMBER)_{\gamma,\beta}\left\{\begin{array}{llr} \max & h(u,b,f,q,g,p) & (1) \\ \text{s.t.:} & u,v,f,q,g,p \in P^{DAMB} & (c2) \\ & g,y,v \in P^{SO_2}_{\gamma,\beta} & (c3) \\ & g,z,w \in P^{NO_x}_{\gamma,\beta} & (c4) \end{array}\right.$$

  where:
  - (1) and $(c2) \equiv (DAMB)$ model.
  - Constraints $(c3)$ define the SO_2 $CEaR$ constraints associated to the excess probability γ and factor β.
  - Constraints $(c4)$ define the NO_x $CEaR$ constraints associated to the excess probability γ and factor β.
- $(DAMBER)_{\gamma,\beta}$ is a linearly constrained mixed-integer concave quadratic maximization problem with a well defined global optimal solution.

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Case Study

- Model $(DAMBER)_{\gamma,\beta}$ can be used to asses the impact of the emission limits onto the **optimal generation bid** and the **expected profits**.
- **Data set** (further details at http://hdl.handle.net/2117/20640):
  - 50 scenarios of the day-ahead market spot prices generated from the complete set of historic data available from June 2007 to May 2010 [14].
  - Four thermal units and two combined cycle units currently operating in the MIBEL.
  - Emission limits $\overline{SO_2}$ and $\overline{NO_x}$ from the National Emission Reduction Plan [15].
  - SO_2 and NO_x emissions rates e^{SO_2} and e^{NO_x} published by the intergovernmental Panel on Climate Change Emission [16].

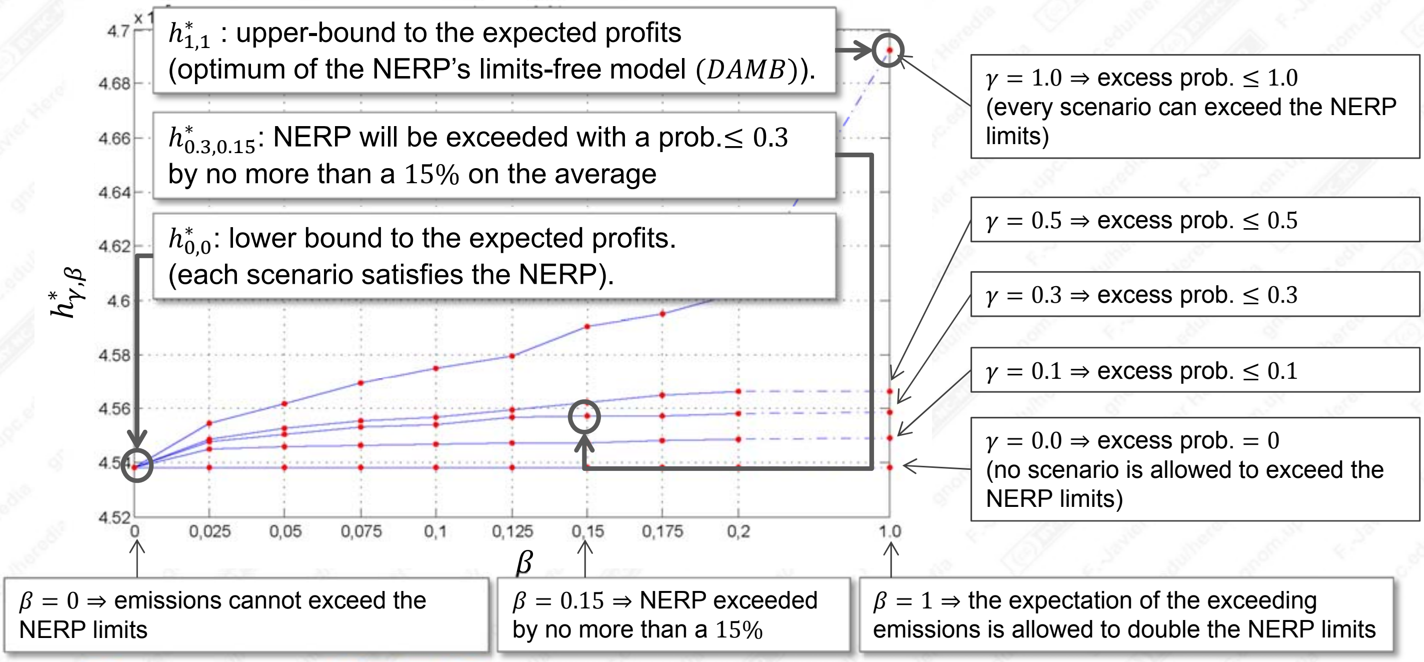
[14] National emission reduction plan, ORDEN PRE/3420/2007, de 14 de noviembre. B.O.E. 284 de 20 de marzo 2007. Gouvernement of Spain, 2007.

[15] C. Corchero, F.-J. Heredia, E. Mijangos, in: M. Delimar (Ed.), Proceedings of the 2011 8th International Conference on the European Energy Market (EEM), pp. 244–249

[16] Intergovernmental panel on climate change emission factor database(ipcc-efdb), http://www.ipcc-nggip.iges.or.jp/efdb/.

Impact of the NERP in the expected profits

- The **parameterized efficient frontier** of the problem $(DAMBER)_{\gamma,\beta}$ shows the change in the value of the optimal expected profits h^* as a function of the risk parameters: $h^*_{0,0} \le h^*_{\gamma,\beta} \le h^*_{1,1}$



$h^*_{1,1}$: upper-bound to the expected profits (optimum of the NERP's limits-free model $(DAMB)$).

$h^*_{0.3,0.15}$: NERP will be exceeded with a prob.≤ 0.3 by no more than a 15% on the average

$h^*_{0,0}$: lower bound to the expected profits. (each scenario satisfies the NERP).

$\gamma = 1.0 \Rightarrow$ excess prob. ≤ 1.0 (every scenario can exceed the NERP limits)

$\gamma = 0.5 \Rightarrow$ excess prob. ≤ 0.5

$\gamma = 0.3 \Rightarrow$ excess prob. ≤ 0.3

$\gamma = 0.1 \Rightarrow$ excess prob. ≤ 0.1

$\gamma = 0.0 \Rightarrow$ excess prob. $= 0$ (no scenario is allowed to exceed the NERP limits)

$\beta = 0 \Rightarrow$ emissions cannot exceed the NERP limits

$\beta = 0.15 \Rightarrow$ NERP exceeded by no more than a 15%

$\beta = 1 \Rightarrow$ the expectation of the exceeding emissions is allowed to double the NERP limits

Impact of the NERP in the optimal generation bid

Cases	Cont. var.	Binary var.	Constraints	Exec. Time[1]
$(DAMB)$	20.160	200	49.458	$\boldsymbol{6\ min}$
$(DAMBER)_{\gamma=0.3,\beta=0.15}$[2]	20.260	300	49.962	$\boldsymbol{48\ min}$

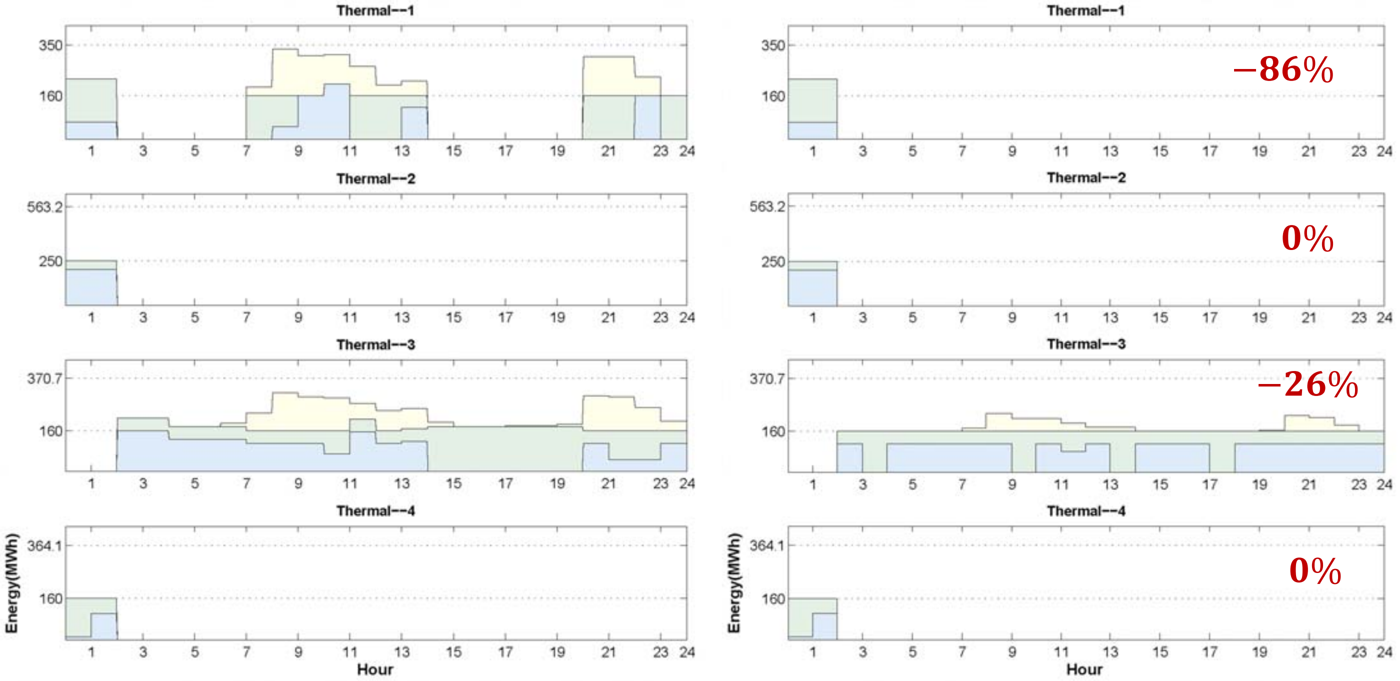
(1) AMPL+ CPLEX 12.4 (mipgap=0.01, threads=20). 2 x CPUs Intel Xeon X5680 six core – 12 threads 3.33 GHz, 64Gb RAM
(2) Emission limits will be violated with a probability ≤ 0.3 by no more than a 15% on the average.

Cases	$E[SO_2]$ ($\overline{SO_2} = 3.900\ kg$)	$E[NO_x]$ ($\overline{NO_x} = 11.460\ kg$)	$E[profit]$
$(DAMB)$	$6.139\ kg$	$14.665\ kg$	469.597 €
$(DAMBER)_{\gamma=0.3,\beta=0.15}$	$3.903\ kg$	$7.104\ kg$	455.757 €
Variation	$\boldsymbol{-36.4\%}$	$\boldsymbol{-51.6\%}$	$\boldsymbol{-2.9\%}$

Cases	Total generation (thermal units)	Total generation (CCGT units)	Total generation (thermal + CCGT units)
$(DAMB)$	9.151,5 MWh	11.802,7 MWh	20.954,3 MWh
$(DAMBER)_{\gamma=0.3,\beta=0.15}$	4.969,4 MWh	14.384,4 MWh	19.353,9 MWh
Variation	-46%	$+22\%$	-8%

Impact of the NERP in the optimal generation bid

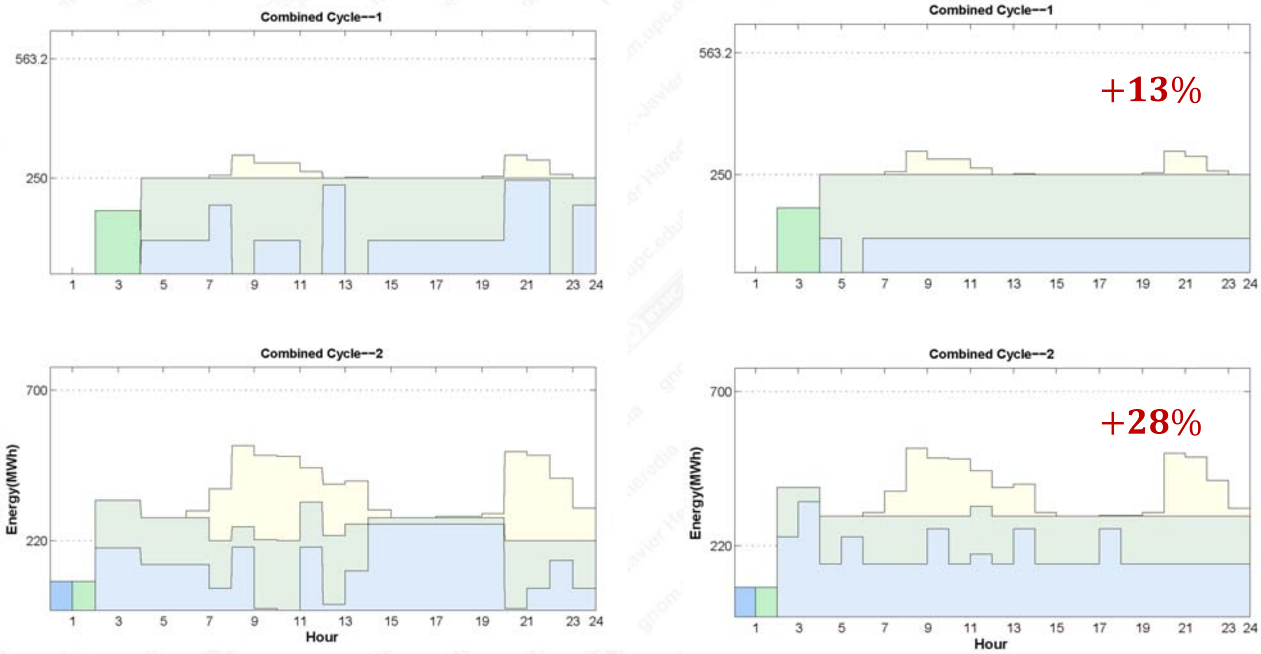
$(DAMB)$ $(DAMBER)_{\gamma=0.3,\beta=015}$



🟦 b_{ti} (bilateral contracts) 🟩 q_{ti} (price acceptant bid/FC) 🟨 $E[p_{ti}]$ (expectation of the matched energy)

Impact of the NERP in the optimal generation bid

$(DAMB)$ $(DAMBER)_{\gamma=0.3,\beta=015}$



🟦 b_{ti} (bilateral contracts) 🟩 q_{ti} (price acceptant bid/FC) 🟨 $E[p_{ti}]$ (expectation of the matched energy)

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Conclusions

- This work proposes a new two-stage stochastic programming model to cope with the **optimal generation bid to the day-ahead electricity market of a GenCo** taking into account the MIBEL market rules and the **SO_2 and NO_x emission limits of the current Spanish National Emission Reduction Plan regulation**.
- A new measure of risk called **Conditional Emissionat-Risk ($CEaR$)** that allows the formulation of a **family of models** $(DAMBER)_{\gamma,\beta}$ parameterized by the excess probability γ and level β which give a flexible tool to asses a wide range of decisions related with the electricity generation under NERP regulations.
- The numerical results show that, for a given representative risk level, the SO_2 and NO_x **NERP obligations can be met by reducing the expected total energy production by 8%, with a 3% decrease in the expected profits**.
- This reduction of the total energy production is unevenly distributed among the generation technologies, with a **46% decrease of the thermal production against a 22% increase of the CCGT generation**, confirming the central role of the CCGT technology in an environmental friendly energy production system.

Thank you very much for your attention!!