ON THE OPTIMAL PARTICIPATION IN ELECTRICITY MARKETS OF WIND POWER PLANTS WITH BATTERY ENERGY STORAGE SYSTEMS


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SUMMARY

- Motivation and contributions.
- Virtual Power Plant definition and stochasticity.
- Model development:
  - Participation in spot markets (day-ahead and intraday).
  - BESS operation.
  - Secondary Reserve Market.
  - Imbalances.
  - Profit maximization
  - The (WBVPP) stochastic programming model.
- Case study.
- Conclusions.
1. Medium size Battery Energy Storage Systems (BESS) is a technology specially appropriate for small producers with non-dispatchable (wind power plants or PV) or almost non-dispatchable generation (co-generation).

2. Lithium-ion (Li-ion) batteries provide high power and a large depth of discharge, fast charge and discharge capability and high round-trip efficiency [1]. Moreover, Li-ion is expected to experience the greatest five year battery capital cost decline (~50%) [2].

3. There is a general consensus that profits from energy arbitrage are insufficient to achieve capital cost recovery [3].

4. However, the participation in the ancillary services market has been proved recently as a way to achieve economic viability of a Wind Power +Li-ion BESS facility [4].

CONTRIBUTION

We present a new **two-stage stochastic programming model** \((\text{WBVPP})\) for the **optimal bid** of a wind producer both in spot and ancillary services electricity markets. This stochastic programming considers:

- A **Virtual Power Plant (VPP)** comprising a Wind Power Plant (WPP) and **Battery Storage System (BESS)**.
- The VPP’s bids to the spot electricity markets: **day-ahead and intraday**.
- The VPP’s bids to the **secondary reserve band market**.
- The **imbalances** management of the electricity market.

We use model \((\text{WBVPP})\) to analyse the effect of the BESS and the reserve market to the optimal bidding strategies of the VPP with **real data** from the **Iberian Electricity Market**.
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VPP AND STOCHASTICITY

- **First stage variables**: “here and now” decisions taken at day D-1:
  - \( p^D \): bid to the DM.
  - \( r^D, r^U \): bid to the RM.

- **Second stage variables**: recourse actions taken during day D:
  - \( p^I \): bid to the IM.
  - \( c, d \): charges/disch.
  - \( p^{IB} \): imbalances

- **Scenario fan with probabilities** \( P_s \):

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\( p^W \)

\( p^D \)

\( p^I \)

\( p^{IB} \)

\( r^D \)

\( r^U \)

Day D-1

\( \lambda^P \)

\( \lambda^R \)

Day D

\( \lambda_1^I, p_1^W, \lambda_1^{IB} \)

\( \lambda_2^I, p_2^W, \lambda_2^{IB} \)

\( \lambda_{|S|}^I, p_{|S|}^W, \lambda_{|S|}^{IB} \)

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Day-ahead & Intraday Markets

Secondary Reserve Market

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\( WBP \)
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DAY-AHEAD AND INTRADAY MARKET

- **Variables** (period $t \in T$, scenario $s \in S$)
  - $p^D_t$: price accepting bid to the DM [MWh].
  - $i p^D_t$: $1$ if $p^D_t > 0$, $0$ otherwise.
  - $p^l_{t,s}$: price accepting bid to the IM [MWh].

- **Parameters**: $\underline{p}^D, \overline{p}^D, \underline{p}^l > 0$, $\overline{p}^l < 0$

- **Coupling between day-ahead and intraday market bid**:
  \[
  \underline{p}^D_t \cdot i p^D_t \leq p^D_t \leq \overline{p}^D_t \cdot i p^D_t \quad t \in T \quad (1)
  \]
  \[
  \underline{p}^l_{t,s} \cdot i p^D_t \leq p^l_{t,s} \leq \overline{p}^l_{t,s} \cdot i p^D_t \quad t \in T, s \in S \quad (2)
  \]
  \[
  i p^D_t \in \{0,1\} \quad t \in T \quad (3)
  \]
The Battery Energy Storage System

- **Variables** (period $t \in T$, scenario $s \in S$)
  
  $c_{t,s}$: charging rate [MW].
  
  $d_{t,s}$: discharging rate [MW].
  
  $i_{d_{t,s}}$: discharge state (binary)

- **Parameters**

  $d_{\text{max}}$: maximum charging/disch. rate [MW].
  
  $e_{\text{max}}$: battery’s capacity [MWh].
  
  $cyc_{\text{max}}$: max. Number of charge/discharge cycles

- **Charging/discharging state and limits:**

  \[
  0 \leq d_{t,s} \leq d_{\text{max}} \cdot i_{d_{t}}
  \]
  $t \in T, s \in S$ \hspace{1cm} (4)

  \[
  0 \leq c_{t,s} \leq d_{\text{max}} \cdot (1 - i_{d_{t}})
  \]
  $t \in T, s \in S$ \hspace{1cm} (5)

  \[
  i_{d_{t}} \in \{0,1\}
  \]

  \[
  \sum_{t \in T, s \in S} P_{s} \cdot (d_{t,s} + c_{t,s})/(2 \cdot e_{\text{max}}) \leq cyc_{\text{max}}
  \]
  (7)

- **Maximum mean number of charge/discharge cycles:**

  $P_{s}$:
STATE OF CHARGE (SOC) CONS.

- **Variables** (period $t \in T$, scenario $s \in S$)
  - $soc_{t,s}$: SOC at the end of period $t \in T \cup \{0\}$.

- **Parameters**
  - $\gamma_{RTE}$: round-trip efficiency.
  - $e_{\max}$: battery’s capacity [MW·h].
  - $soc_{\min}$, $soc_{\max}$: minimum/maximum SOC.
  - $soc^{0}$, $soc^{T}$: initial and final SOC.

- **State of Charge (SOC) equations after DM and IM clearing:**

  
  \[
  soc_{t,s} = soc_{t-1,s} + \Delta t \cdot \left( c_{t,s} - d_{t,s} / \gamma_{RTE} \right) / e_{\max} \\
  soc_{\min} \leq soc_{t,s} \leq soc_{\max} \\
  soc_{0,s} = soc^{0}, soc_{T,s} = soc^{T}
  \]

  \[ (8) \quad (9) \quad (10) \]
The VPP submits a price accepting bid for the total available reserve up and reserve down of the BESS to the Secondary Reserve Band Market (RM).

- **Variables** (period $t \in T$, scenario $s \in S$)

  $r_t^U, r_t^D$: up/down secondary reserve bid of the BESS at time period $t \in T$ [MW].

- The battery’s reserve is limited by the gap between the maximum discharge $d_{max}$ and the current discharging rate and current charging rate:

  $0 \leq r_t^U \leq d_{max} - (d_{t,s} - c_{t,s})$  \hspace{1cm} $t \in T, s \in S$  \hspace{1cm} (11)

  $0 \leq r_t^D \leq d_{max} - (c_{t,s} - d_{t,s})$  \hspace{1cm} $t \in T, s \in S$  \hspace{1cm} (12)
The VPP submits a price accepting bid for the total available reserve up and reserve down of the BESS to the Secondary Reserve Band Market (RM).

Variables (period $t \in T$, scenario $s \in S$)

- $r_t^U, r_t^D$: up/down secondary reserve bid of the BESS at time period $t \in T$ [MW].

Parameters:
- $\Delta t^{SR}$: time response of the sec. reserve [h].

The incremental (A) / decremental (B) energy is limited by the maximum/minimum SOC:

\[
\begin{align*}
\text{(A)} & \quad soc_{t,s}^{\min} + \frac{\Delta t^{SR} \cdot r_t^U}{e^{\max} / \gamma_{RTE}} \\ 
& \leq soc_{t,s} \leq soc_{t,s}^{\max} - \frac{\Delta t^{SR} \cdot r_t^D}{e^{\max}} \\
& \quad t \in T, s \in S 
\end{align*}
\]
The VPP submits a price accepting bid for the total available reserve up and reserve down of the BESS to the **Secondary Reserve Band Market (RM)**.

**Variables** (period \( t \in T \), scenario \( s \in S \))

\[
\begin{align*}
    r_t^U, r_t^D : & \text{ up/down secondary reserve bid of the BESS at time period } t \in T \text{ [MW]}.
\end{align*}
\]

**Parameters**

\( \alpha^{SR} : \text{ ratio between the up/down band declared by the system operator.} \)

**Up/down reserve bid ratio:**

\[
    r_t^U = \alpha^{SR} \cdot r_t^D \quad t \in T \tag{14}
\]
IMBALANCES (1/2)

- For any given value of the variables $c, d, p^D$ and $p^I$ and wind generation scenario $p^W$ we define the **imbalance variables** (period $t \in T$, scenario $s \in S$):
  
  \[ p^{IB}_t, s \cdot \text{net imbalance [MWh].} \]
  
  \[ p^{IB+}_t, s, p^{IB-}_t, s \cdot \text{positive/negative imbalance [MWh].} \]

- **Imbalance definition** ($\Delta t = 1h$):
  
  \[ p^{IB}_t, s = \left( p^W_t + \Delta t \cdot d_t, s \right) - \left( p^D_t, s + p^I_t, s + \Delta t \cdot c_t, s \right) \]
  
  VPP energy inflow - VPP energy outflow

- **Neutral mean imbalance**:
  
  \[ \sum_{t \in T, s \in S} P_s \cdot p^{IB}_t, s = 0 \]
  
  $t \in T, s \in S$
For any given value of the variables $c, d, p^D$ and $p^I$ and wind generation scenario $p^W_s$ we define the **imbalance variables** (period $t \in T$, scenario $s \in S$):

- $p_{t,s}^{IB}$: net imbalance $[MW\text{h}]$.
- $p_{t,s}^{IB+}, p_{t,s}^{IB-}$: positive/negative imbalance $[MW\text{h}]$.

**Parameters:** $\bar{p}^{IB}, \bar{p}_{t,s}^{IB-}, \bar{p}_{t,s}^{IB+}$

**Imbalance coupling to DM and limitations:**

\[
p_{t,s}^{IB} = p_{t,s}^{IB+} - p_{t,s}^{IB-}
\]
\[
p_{t,s}^{IB+} + p_{t,s}^{IB-} \leq \bar{p}^{IB} \cdot ip_t^D
\]
\[
0 \leq p_{t,s}^{IB+} \leq \bar{p}_{t,s}^{IB-}, 0 \leq p_{t,s}^{IB-} \leq \bar{p}_{t,s}^{IB+}
\]
### Profit Maximization

**Terms of the objective function:**

- **DM incomes:**
  \[ DM(p^D) = \sum_{t \in T} \lambda_t^D \cdot p_t^D \]

- **RM incomes:**
  \[ RM(r^U, r^D) = \sum_{t \in T} \lambda_t^R \cdot (r_t^U + r_t^D) \]

- **IM incomes/debts:**
  \[ IM(p^I) = \sum_{t \in T, s \in S} P_s \cdot \lambda_{t,s}^I \cdot p_{t,s}^I \]

- **+ imbalances collection rights:**
  \[ IB^+(p^{IB+}) = \sum_{t \in T, s \in S} P_s \cdot \lambda_{s,t}^{IB+} \cdot p_{t,s}^{IB+} \]

- **- imbalances payment obligations:**
  \[ IB^-(p^{IB-}) = \sum_{t \in T, s \in S} P_s \cdot \lambda_{s,t}^{IB-} \cdot p_{t,s}^{IB-} \]

- **Expected value of the profit:**
  \[ EP^{VPP} = DM + RM + IM + IB^+ - IB^- \]
THE \textit{(WBVPP)} OPTIMIZATION MODEL

- Wind power- BESS Virtual Power Plant model \textit{(WBVPP)} can be expressed as:

\[
\max \quad EP^{VPP} \\
\text{s.t.:} \quad \text{DM} - \text{IM} : \quad (1)-(3) \\
\text{BESS} : \quad (4)-(10) \\
\text{RM} : \quad (11)-(14) \\
\text{IB} : \quad (15)-(19)
\]

- MILP with 21,572 continuous variables, 2,448 binary variables and 33,522 linear constraints.

- Implemented and solved with AMPL/CPLEX on a desktop PC (i7@2.93GHz, 8GB RAM, Windows 7 Professional).
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CASE STUDY

- Optimal bid of a programming unit (VPP) of the Iberian Electricity Market (IEM) composed by:
  - An on-shore wind plant located in the north of Spain with 9 wind turbine and a total nominal output of 18MW.
  - A Li-ion based BESS with the following characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d^{max} )</td>
<td>10 MW</td>
</tr>
<tr>
<td>( e^{max} )</td>
<td>30 MWh</td>
</tr>
<tr>
<td>( EOL )</td>
<td>20 years</td>
</tr>
<tr>
<td>( cyc^{EOL} )</td>
<td>6000</td>
</tr>
<tr>
<td>( soc^0 = soc^T )</td>
<td>0.6</td>
</tr>
<tr>
<td>( soc^{min} )</td>
<td>0.3</td>
</tr>
<tr>
<td>( soc^{max} )</td>
<td>0.9</td>
</tr>
<tr>
<td>( \gamma^{RTE} )</td>
<td>0.8</td>
</tr>
</tbody>
</table>
The scenarios for the random variables $\lambda^D, \lambda^R, \lambda^I, p^W$ and $\lambda^{IB}$ are based on the historical data from January 1st 2014 to June 30th 2014 to elaborate the optimal bid for July 1st 2014.

The complete set of observations has been reduced to 100 scenarios through standard scenario reduction techniques [6].

RESULTS: WPP + DM + IM

1. Wind generation scenarios
2. DM+IM bid with SR band
3. Battery charge (-) / discharge (+)
4. State Of Charge (SOC)
5. Imbalances
6. Scenario # 29

Profit: $DM = 2635.8\,\€$ \hspace{1cm} $IM = -109.46\,\€$ \hspace{1cm} $RM = 0\,\€$ \hspace{1cm} $IB = -4.7\,\€$
RESULTS: VPP+DM+IM

1. Wind generation scenarios
2. DM+IM bid with SR band
3. Battery charge (-) / discharge (+)
4. State Of Charge (SOC)
5. Imbalances
6. Scenario #29

Profit: $DM = 2706.98\€$, $IM = -41.30\€$, $RM = 0\€$, $IB = 11.47\€$
RESULTS: VPP+DM+IM+RM

1. Wind generation scenarios

2. DM+IM bid with SR band

3. Battery charge (-) / discharge (+)

4. State Of Charge (SOC)

5. Imbalances

6. Scenario #29

Profit: $DM = 2578.56€$, $IM = -127.30€$, $RM = 10,024.50€$, $IB = 13.06€$
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CONCLUSIONS

- A two stage stochastic programming model has been developed to find the optimal bid to spot and reserve markets of a WPP+BESS.

- The model has been used to find the optimal bid to DM and RM of a test case with real data from the Iberian Electricity Market.

- The preliminary results show that:
  - With respect to the optimal bidding strategies, the participation in the RM strongly reshapes both the charge/discharge profile and the optimal bid to the DM.
  - The uncertainty in the operation of the BESS (charge/discharge/SOC) vanishes when the participation in the RM is allowed.
  - The increase in the total profit of the VPP w.r.t. the WPP is not relevant when the bids are restricted to the DM and IM.
  - However, the participation in the RM induces a strong increase in profits, a results that agrees with previous studies.
Thank you very much for your attention!!