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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.**

MOTIVATION

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].

[1] F. Díaz-González et al *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 2154-2171, 2012.

[2] Lazard's Levelized Cost of Storage Analysis (https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf)

[3] M. Kintner-Meyer et al. «National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase 1, WECC,» Richland, 2012.

[4] F-Javier Heredia et al. 12th International Conference on the European Energy Market (EEM15), 2015 (http://hdl.handle.net/2117/82524).

CONTRIBUTION

- We present a new **two-stage stochastic programming model** $(WBVPP)$ 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 $(WBVPP)$ 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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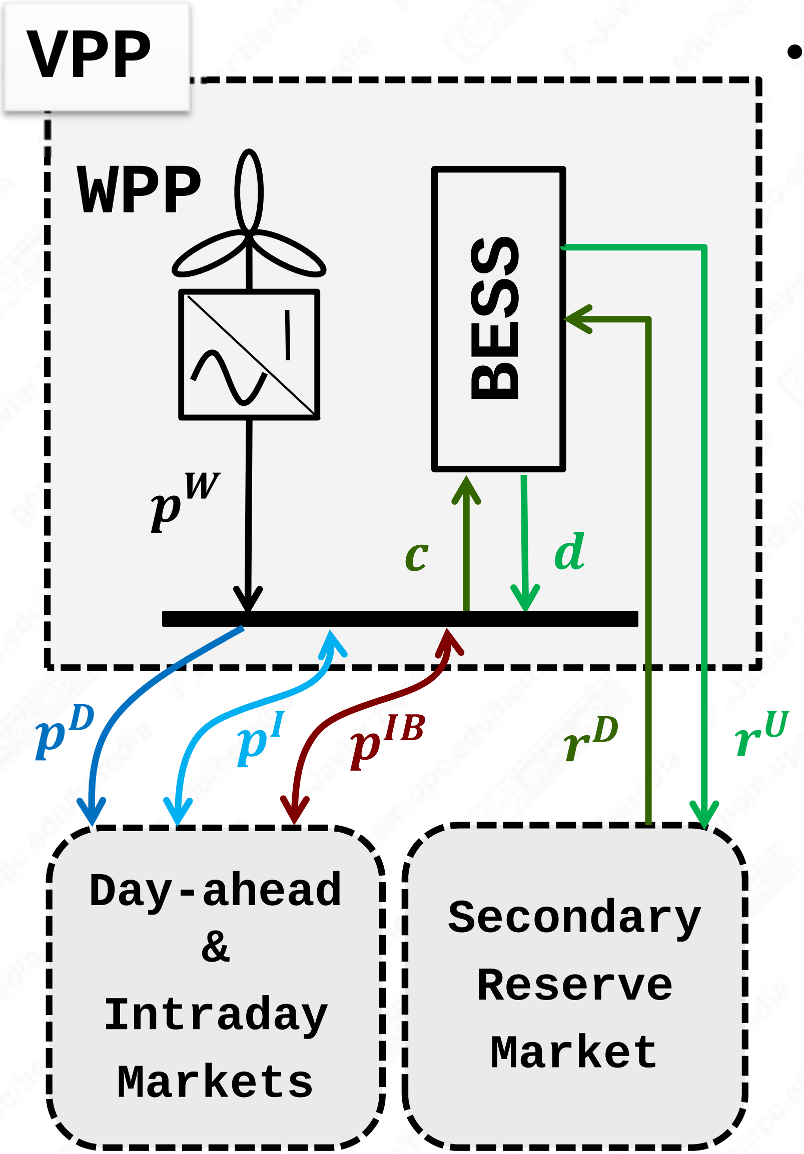
VPP AND STOCHASTICITY



- **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.

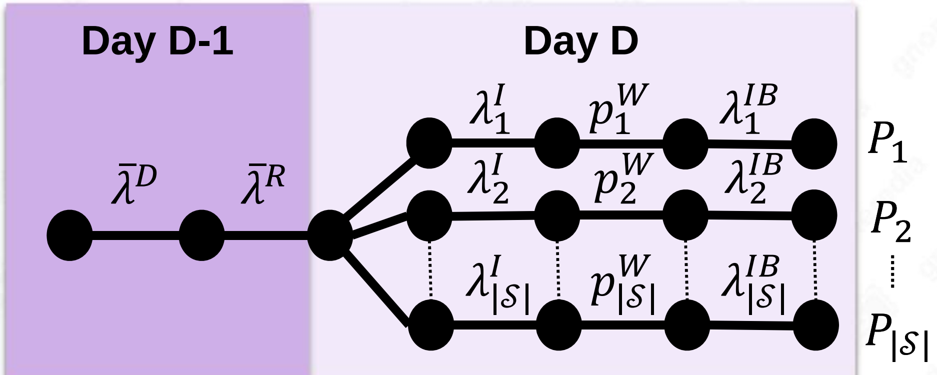
- **Second stage variables:** recourse actions taken during day D:

  p^I : bid to the IM.

  c, d : charges/disch.

  p^{IB}: imbalances

- **Scenario fan with probabilities P_s:**



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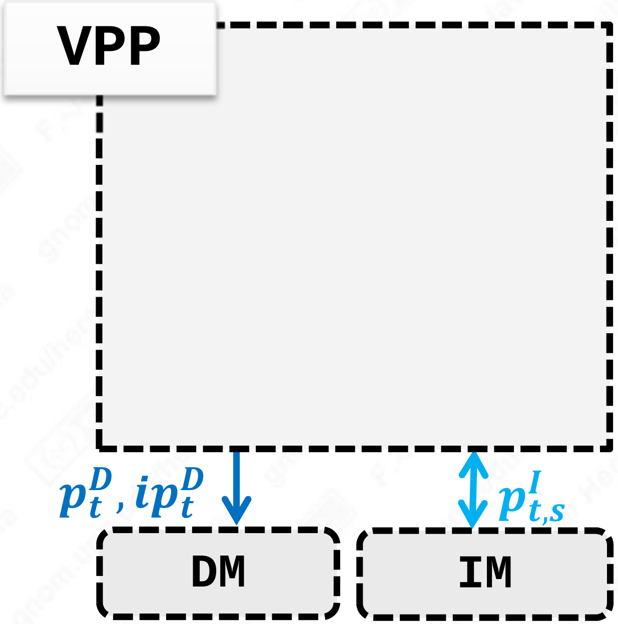
DAY-AHEAD AND INTRADAY MARKET



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

  p_t^D: price accepting bid to the DM $[MWh]$.

  ip_t^D: $= 1$ if $p_t^D > 0$, $= 0$ otherwise.

  $p^I_{t,s}$: price accepting bid to the IM $[MWh]$.

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

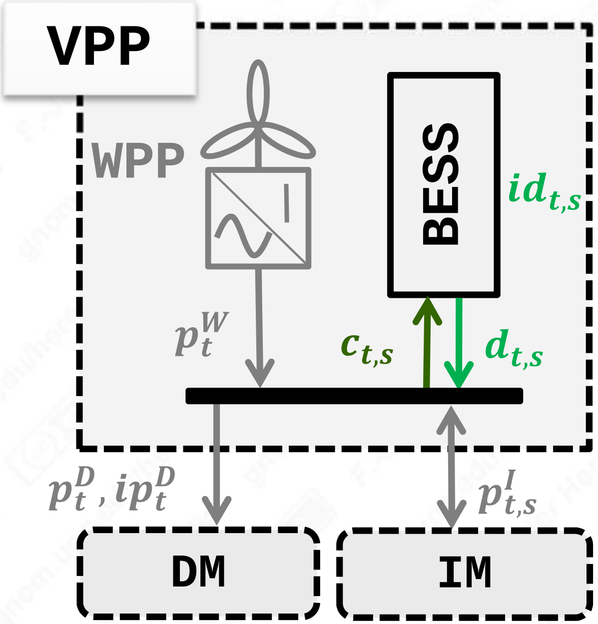
- **Coupling between day-ahead and intraday market bid:**

$$\underline{p}_t^D \cdot ip_t^D \le p_t^D \le \overline{p}_t^D \cdot ip_t^D \qquad t \in \mathcal{T} \qquad (1)$$

$$\underline{p}^I_{t,s} \cdot ip_t^D \le p^I_{t,s} \le \overline{p}^I_{t,s} \cdot ip_t^D \qquad t \in \mathcal{T}, s \in \mathcal{S} \qquad (2)$$

$$ip_t^D \in \{0,1\} \qquad t \in \mathcal{T} \qquad (3)$$

THE BATTERY ENERGY STORAGE SYSTEM



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

$c_{t,s}$: charging rate $[MW]$.
$d_{t,s}$: discharging rate $[MW]$.
$id_{t,s}$: discharge state (binary)

- **Parameters**

d^{max}: maximum charging/disch. rate $[\mathrm{M}W]$.
e^{max}: battery's capacity $[MWh]$.
cyc^{max}: max. Number of charge/discharge cycles

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

$$0 \leq d_{t,s} \leq d^{max} \cdot id_t \qquad t \in T, s \in S \qquad (4)$$

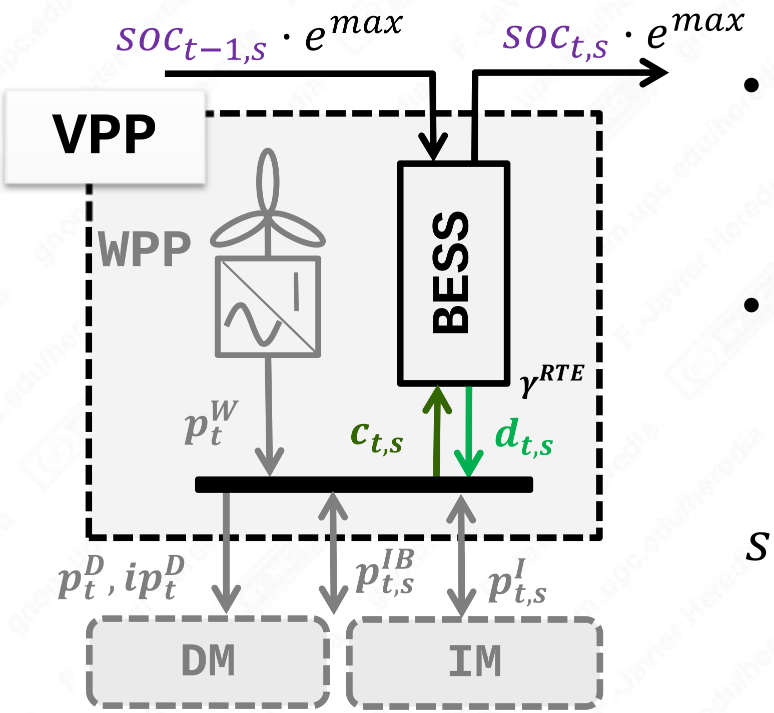
$$0 \leq c_{t,s} \leq d^{max} \cdot (1 - id_t) \qquad t \in \mathcal{T}, s \in S \qquad (5)$$

$$id_t \in \{0,1\} \qquad t \in \mathcal{T} \qquad (6)$$

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

$$\sum_{t \in \mathcal{T}, s \in \mathcal{S}} P_s \cdot (d_{t,s} + c_{t,s})/(2 \cdot e^{max}) \leq cyc^{max} \qquad (7)$$

STATE OF CHARGE (SOC) CONS.



- **Variables** (period $t \in \mathcal{T}$, scenario $s \in \mathcal{S}$)
  - $soc_{t,s}$: SOC at the end of period t ∈ $\mathcal{T} \cup \{0\}$.
- **Parameters**
  - γ^{RTE} : round-trip efficiency.
  - e^{max}: battery's capacity $[MWh]$.
  - soc^{min}, soc^{max}: minimum/maximum SOC.
  - soc^0, soc^T: initial and final SOC.

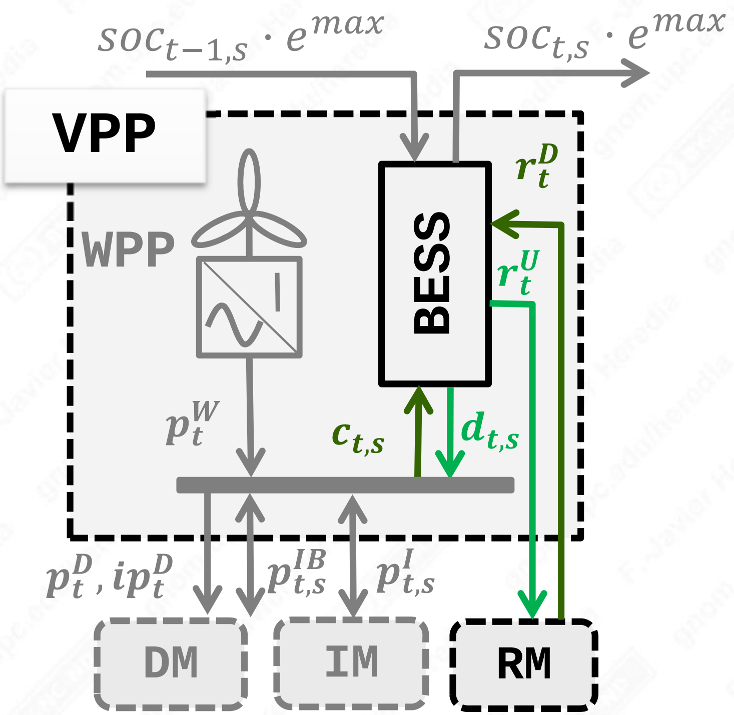
- **State of Charge (SOC) equations after DM and IM clearing:**

$$soc_{t,s} = soc_{t-1,s} + \Delta t \cdot \left(c_{t,s} - d_{t,s}/\gamma^{RTE}\right)/e^{max} \qquad t \in \mathcal{T}, s \in \mathcal{S} \qquad (8)$$

$$soc^{min} \leq soc_{t,s} \leq soc^{max} \qquad t \in \mathcal{T}, s \in \mathcal{S} \qquad (9)$$

$$soc_{0,s} = soc^0, soc_{T,s} = soc^T \qquad (10)$$

SECONDARY RESERVE MARKET (1/3)



- 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 $t \in \mathcal{T}$, scenario $s \in \mathcal{S}$)

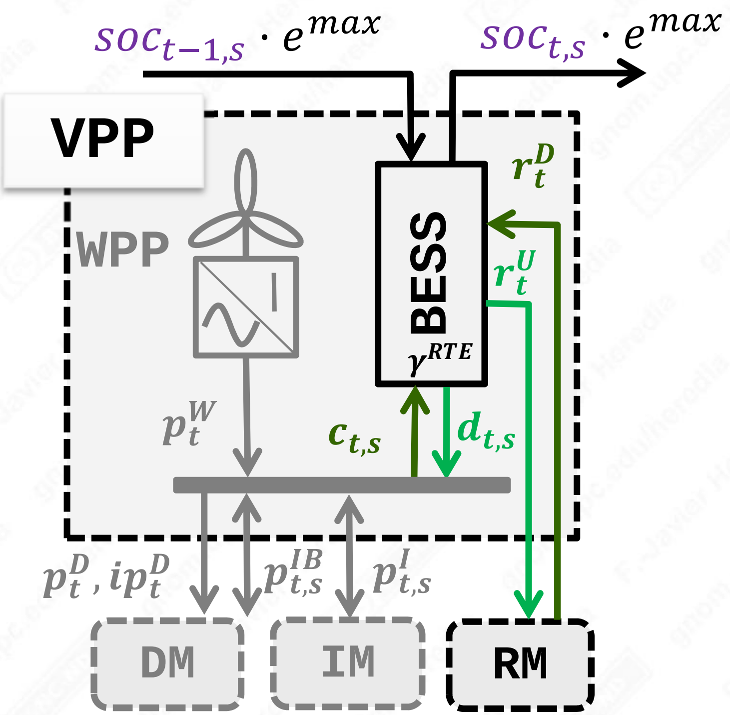
r_t^U, r_t^D: up/down secondary reserve bid of the the BESS at time period $t \in \mathcal{T}$ $[MW]$.

- The battery's reserve is limited by the gap between the maximum discharge d^{max} and the current discharging rate and current charging rate :

$$0 \le r_t^U \le d^{max} - \left(d_{t,s} - c_{t,s}\right) \qquad t \in \mathcal{T}, s \in \mathcal{S} \qquad (11)$$

$$0 \le r_t^D \le d^{max} - \left(c_{t,s} - d_{t,s}\right) \qquad t \in \mathcal{T}, s \in \mathcal{S} \qquad (12)$$

SECONDARY RESERVE MARKET (2/3)



- 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 $t \in \mathcal{T}$, scenario $s \in \mathcal{S}$)

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

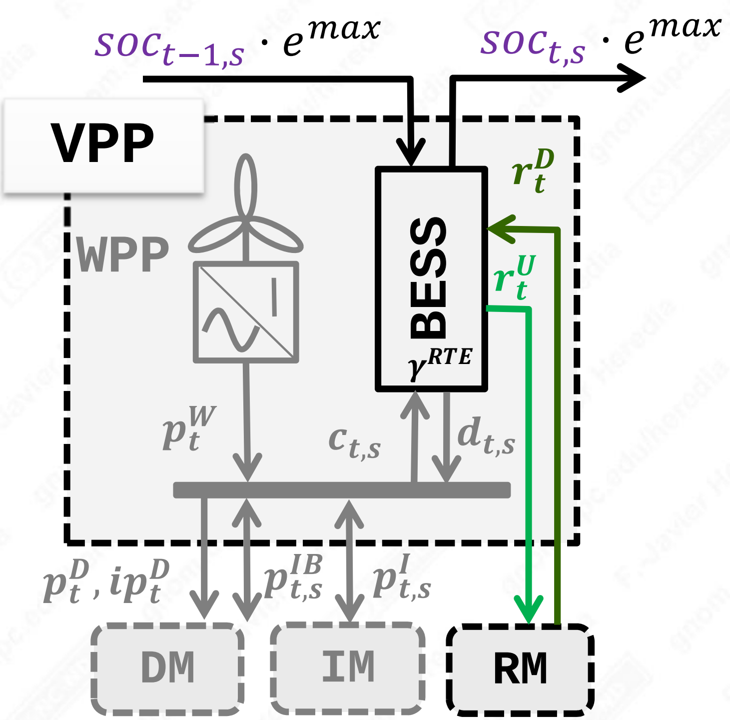
- **Parameters:**

Δt^{SR}: time response of the sec. reserve $[h]$.

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

$$soc^{min} + \overbrace{\frac{\Delta t^{SR} \cdot r_t^U / \gamma^{RTE}}{e^{max}}}^{\textbf{(A)}} \leq soc_{t,s} \leq soc^{max} - \overbrace{\frac{\Delta t^{SR} \cdot r_t^D}{e^{max}}}^{\textbf{(B)}} \qquad t \in \mathcal{T}, s \in \mathcal{S} \qquad (13)$$

SECONDARY RESERVE MARKET (2/3)



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

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

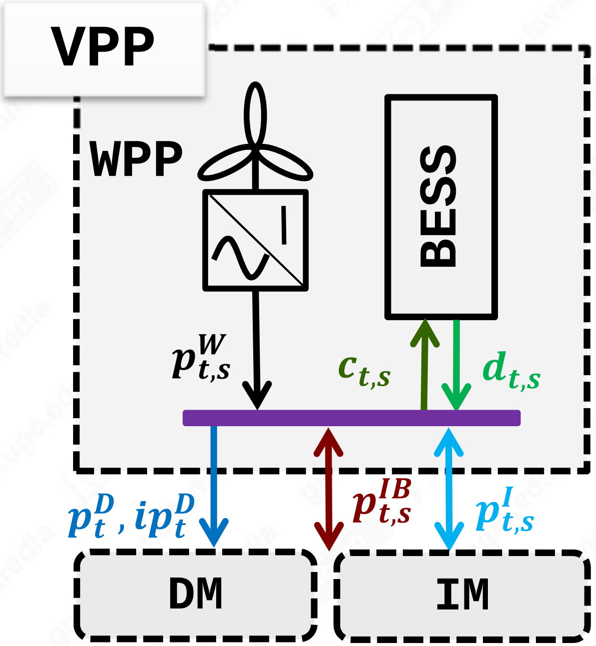
- **Parameters**

α^{SR}: ratio between the up/down band declared by the system operator.

- **Up/down reserve bid ratio:**

$$r_t^U = \alpha^{SR} \cdot r_t^D \qquad t \in \mathcal{T} \tag{14}$$

IMBALANCES (1/2)



- For any given value of the variables $\boldsymbol{c}, \boldsymbol{d}, \boldsymbol{p}^D$ and $\boldsymbol{p}^I$ and wind generation scenario $\boldsymbol{p}^W_s$ we define the **imbalance variables** (period $t \in \mathcal{T}$, scenario $s \in \mathcal{S}$) :

$p^{IB}_{t,s}$: net imbalance $[MWh]$.

$p^{IB+}_{t,s}, p^{IB-}_{t,s}$: positive/negative imbalance $[MWh]$.

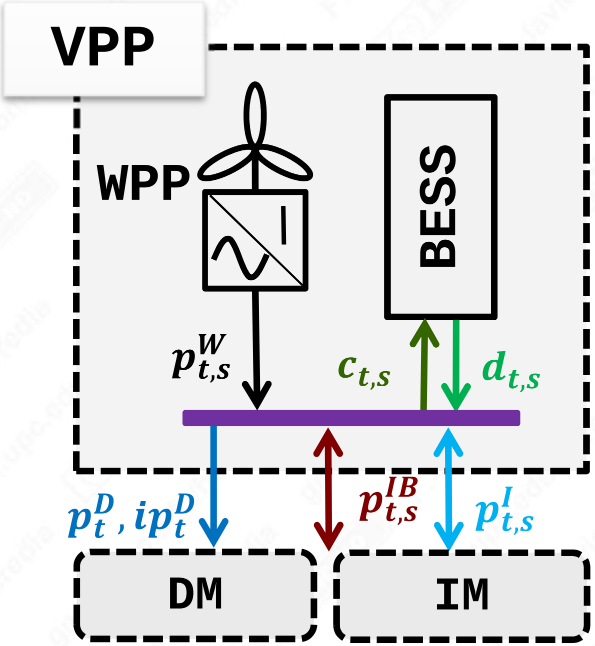
- **Imbalance definition** $(\Delta t = 1\text{h})$**:**

$$p^{IB}_{t,s} = \underbrace{\left(p^W_{s,t} + \Delta t \cdot d_{t,s}\right)}_{\text{VPP energy inflow}} - \underbrace{\left(p^D_{t,s} + p^I_{t,s} + \Delta t \cdot c_{t,s}\right)}_{\text{VPP energy outflow}} \qquad t \in T, s \in S \qquad (15)$$

- **Neutral mean imbalance :**

$$\sum_{t \in \mathcal{T}, s \in \mathcal{S}} P_s \cdot p^{IB}_{t,s} = 0 \qquad t \in T, s \in S \qquad (16)$$

IMBALANCES (2/2)



- For any given value of the variables $\boldsymbol{c}, \boldsymbol{d}, \boldsymbol{p^D}$ and $\boldsymbol{p^I}$ and wind generation scenario $\boldsymbol{p^W_s}$ we define the **imbalance variables** (period $t \in \mathcal{T}$, scenario $s \in \mathcal{S}$) :

  $p^{IB}_{t,s}$: net imbalance $[MWh]$.

  $p^{IB+}_{t,s}, p^{IB-}_{t,s}$: positive/negative imbalance $[MWh]$.

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

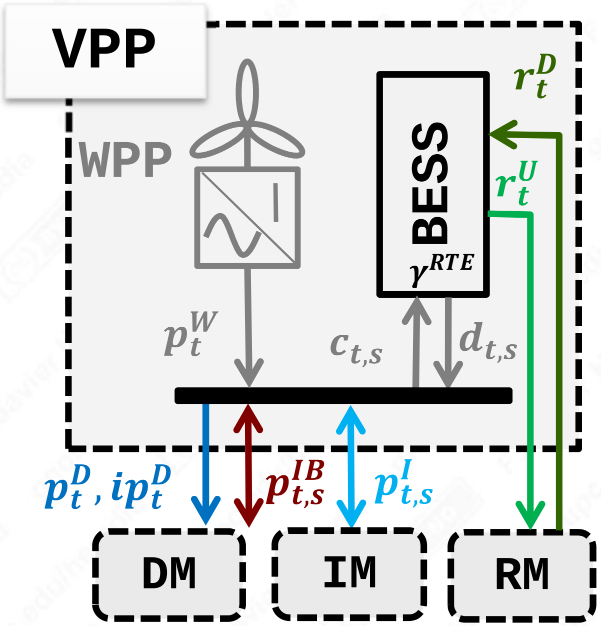
- **Imbalance coupling to DM and limitations :**

$$p^{IB}_{t,s} = p^{IB+}_{t,s} - p^{IB-}_{t,s} \qquad t \in \mathcal{T}, s \in S \qquad (17)$$

$$p^{IB+}_{t,s} + p^{IB-}_{t,s} \le \bar{p}^{IB} \cdot ip^D_t \qquad t \in \mathcal{T}, s \in S \qquad (18)$$

$$0 \le p^{IB+}_{t,s} \le \bar{p}^{IB-}_{t,s}, 0 \le p^{IB-}_{t,s} \le \bar{p}^{IB+}_{t,s} \qquad t \in \mathcal{T}, s \in S \qquad (19)$$

PROFIT MAXIMIZATION



Terms of the objective function:	
DM incomes:	$DM(p^D) = \sum_{t\in\mathcal{T}} \bar{\lambda}_t^D \cdot p_t^D$
RM incomes:	$RM(r^U, r^D) = \sum_{t\in\mathcal{T}} \bar{\lambda}_t^R \cdot (r_t^U + r_t^D)$
IM incomes/debts:	$IM(p^I) = \sum_{t\in\mathcal{T}, s\in\mathcal{S}} P_s \cdot \lambda_{t,s}^I \cdot p_{t,s}^I$
+ imbalances collection rights:	$IB^+(p^{IB+}) = \sum_{t\in\mathcal{T}, s\in\mathcal{S}} P_s \cdot \lambda_{s,t}^{IB+} \cdot p_{t,s}^{IB+}$
- imbalances payment obligations:	$IB^-(p^{IB-}) = \sum_{t\in\mathcal{T}, s\in\mathcal{S}} P_s \cdot \lambda_{s,t}^{IB-} \cdot p_{t,s}^{IB-}$

- **Expected value of the profit:** $\boldsymbol{EP^{VPP} = DM + RM + IM + IB^+ - IB^-}$

THE $(WBVPP)$ OPTIMIZATION MODEL

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

$$
\text{(WBVPP)} \left\{ \begin{array}{rc} \max & EP^{VPP} \\ \text{s.t.:} & \\ \text{DM−IM :} & (1)−(3) \\ \text{BESS :} & (4)−(10) \\ \text{RM :} & (11)-(14) \\ \text{IB :} & (15)-(19) \end{array} \right.
$$

- **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

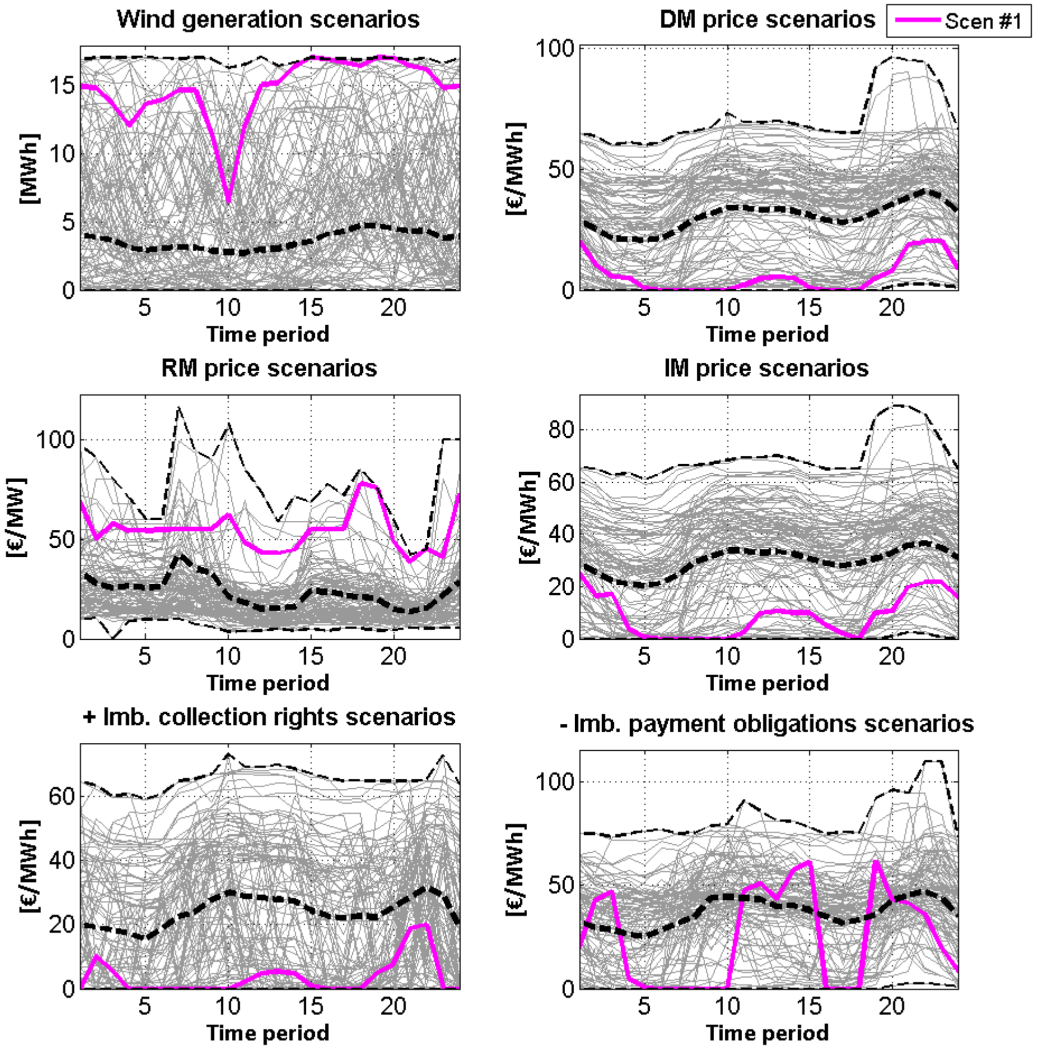
- Optimal bid of a programming unit (VPP) of the **Iberian Electricity Market (IEM)** composed by:
  - An on-shore wind plant located in the north of Spain with 9 wind turbine and a total nominal output of 18MW.
  - A Li-ion based BESS with the following characteristics:

$d^{max} = 10\ MW$	$EOL = 20$ years	$soc^0 = soc^T = 0.6$	$soc^{min} = 0.3$
$e^{max} = 30\ MWh$	$cyc^{EOL} = 6000$	$soc^{max} = 0.9$	$\gamma^{RTE} = 0.8$

SCENARIOS

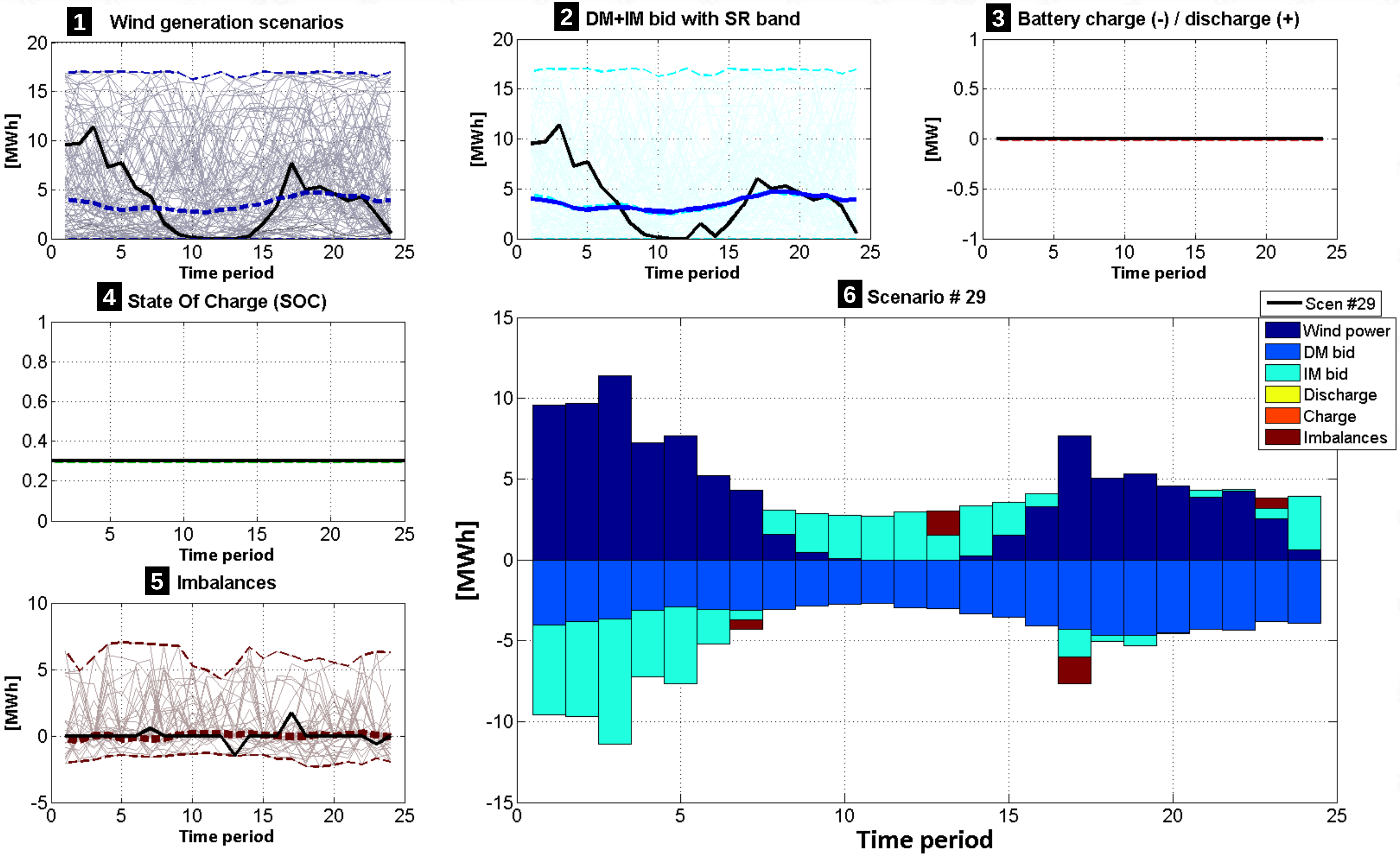
- The scenarios for the random variables $\lambda^D, \lambda^R, \lambda^I, p^W$ and λ^{IB} are based on the historical data from **January 1st 2014 to June 30th 2014** to elaborate the **optimal bid for July 1st 2014**.

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



[6] N. Gröwe-Kuska, H. Heitsch, and W. Römisch, “Scenario reduction and scenario tree construction for power management problems,” in Power Tech Conference Proceedings, 2003 IEEE Bologna, vol. 3, 23-26 June 2003.

RESULTS: WPP + DM + IM



Profit:	$DM = 2635.8€$	$IM = -109.46€$	$RM = 0€$	$IB = -4.7€$

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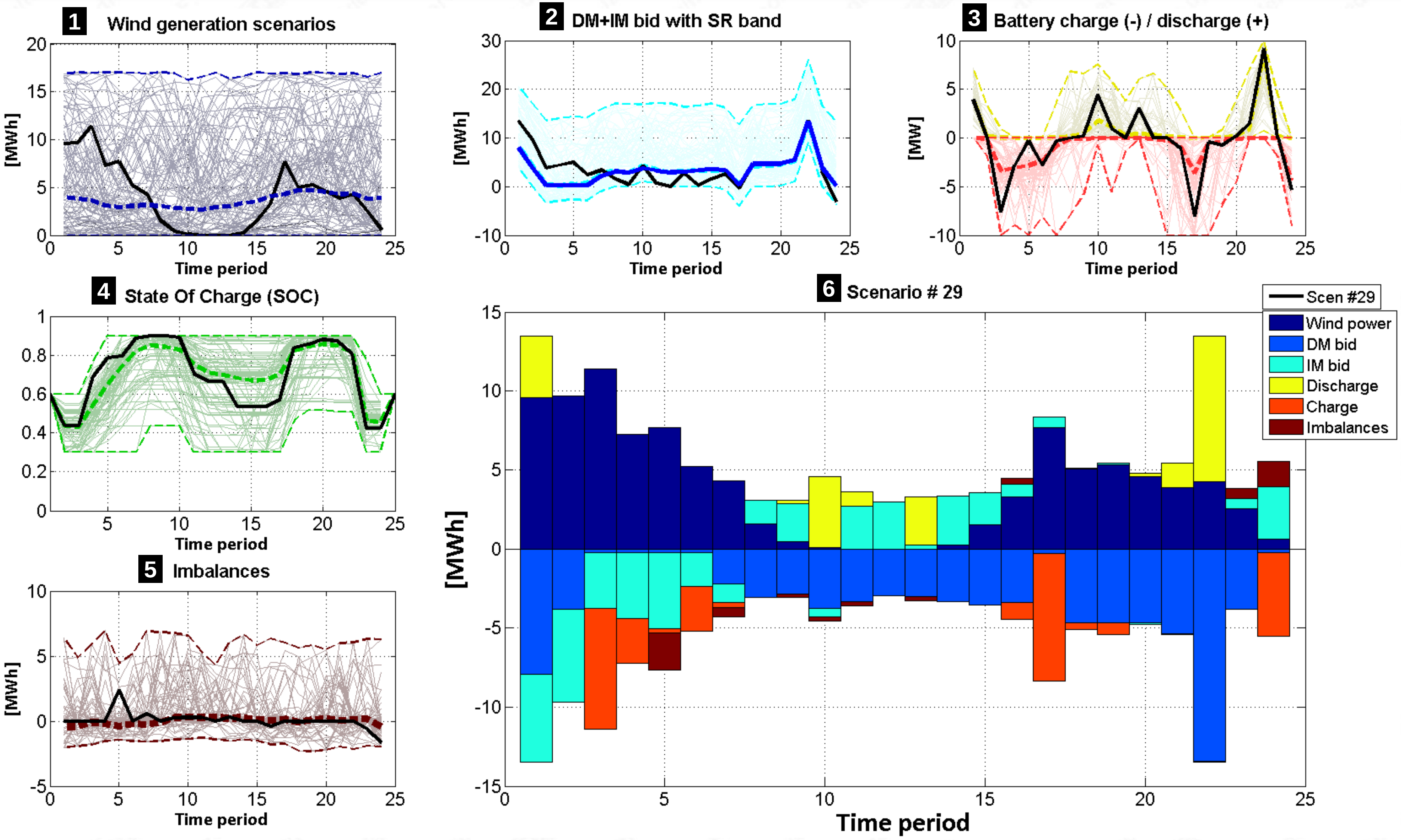
RESULTS: VPP+DM+IM



Profit:	$DM = 2706.98€$	$IM = -41.30€$	$RM = 0€$	$IB = 11.47€$

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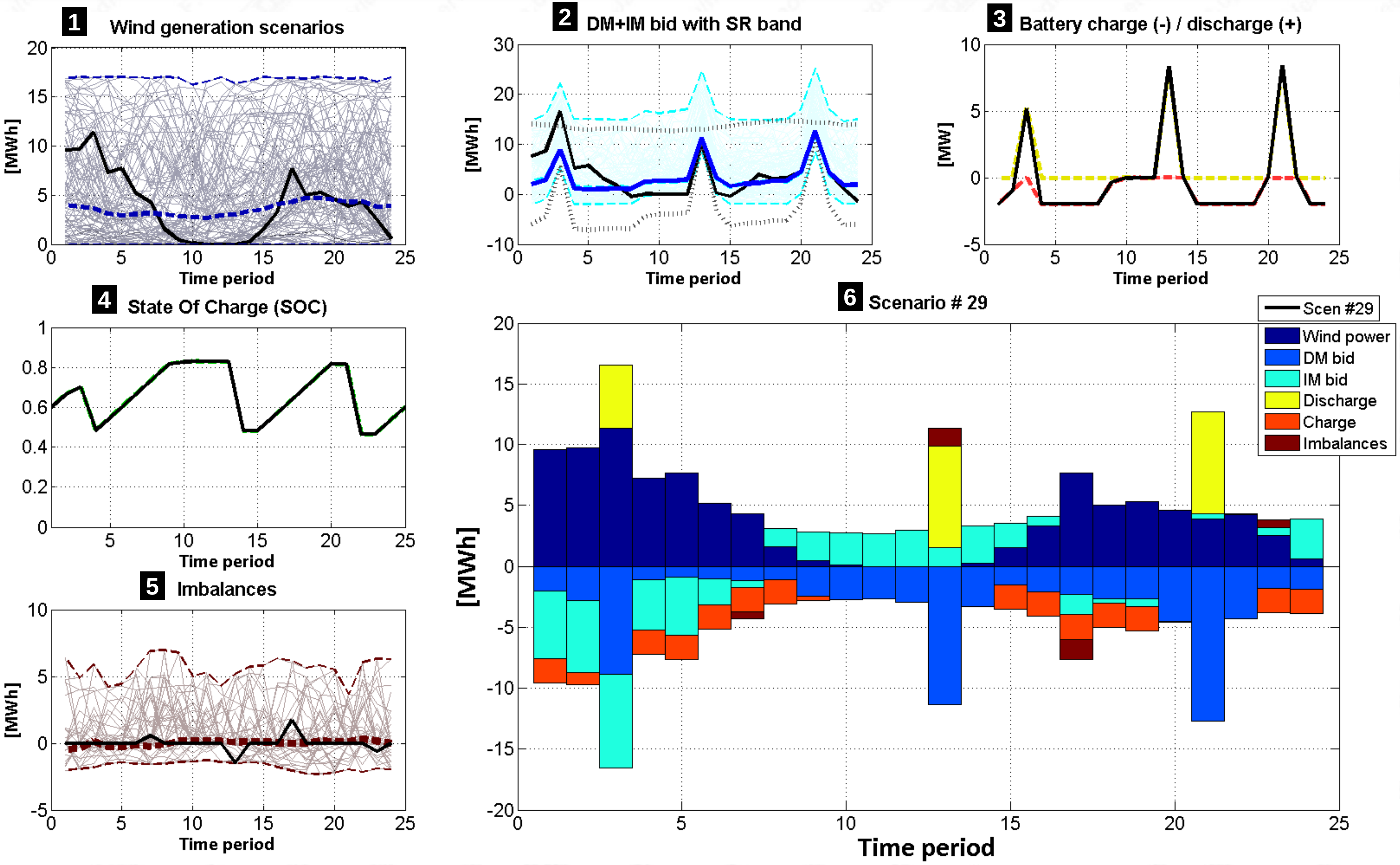
RESULTS: VPP+DM+IM+RM



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 biding 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 previos studies.

Thank you very much for your attention!!