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ECONOMIC ANALYSIS OF BATTERY ELECTRIC STORAGE SYSTEMS OPERATING IN ELECTRICITY MARKETS

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SUMMARY

- **Introduction, motivation and contributions.**
- ***Battery Electricity Storage System in Electricity Markets*** **optimization model** $(BESSEM)$**.**
- **Case study: economic viability of a BESS attached to a wind power plant.**
- **Conclusions.**

INTRODUCTION

- **Introduction:**
  - Battery electric storage systems (BESS) in the mid-range of 1-10 MWh is a key technology allowing a more efficient operation of small electricity market producer.
  - EMELCAT S.L. is an start-up company founded by researchers of the Universitat Politècnica de Catalunya and energy engineering to deploy mid-range energy storage systems with advanced energy management systems (EMS) and operation in electricity markets.
  - One of the first outcomes of this collaborations has been a mathematical optimization based methodology to asses the **economic viability of Li-ion based BESS systems for small electricity producers**.
  - The results of the ex-post economic analysis performed with real data from the Iberian Electricity Market shows the **economic viability of a Li-ion based BESS** thanks to the **optimal operation in day-ahead and ancillary electricity markets**.

MOTIVATION

- **Motivation:**
  1. Medium size BESS in the range of 1-10 MWh is a **technology specially appropriate for small producers** with non-dispatchable generator (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] [2].
  3. Some studies indicated that **profits from energy arbitrage were insufficient to achieve capital cost recovery** [3].
  4. The **participation in the ancillary services market** has been suggested as a way to achieve economic viability [3]. Nevertheless, recent works analysing Vanadium Redox Flow technology seemed to refute this possibility [4] .

[1] A. Poullikkas, *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 778-788, 2013.

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

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

[4] L. Johnston et al. «Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants,» *Applied Energy,* nº 137, pp. 660-669, 2015.

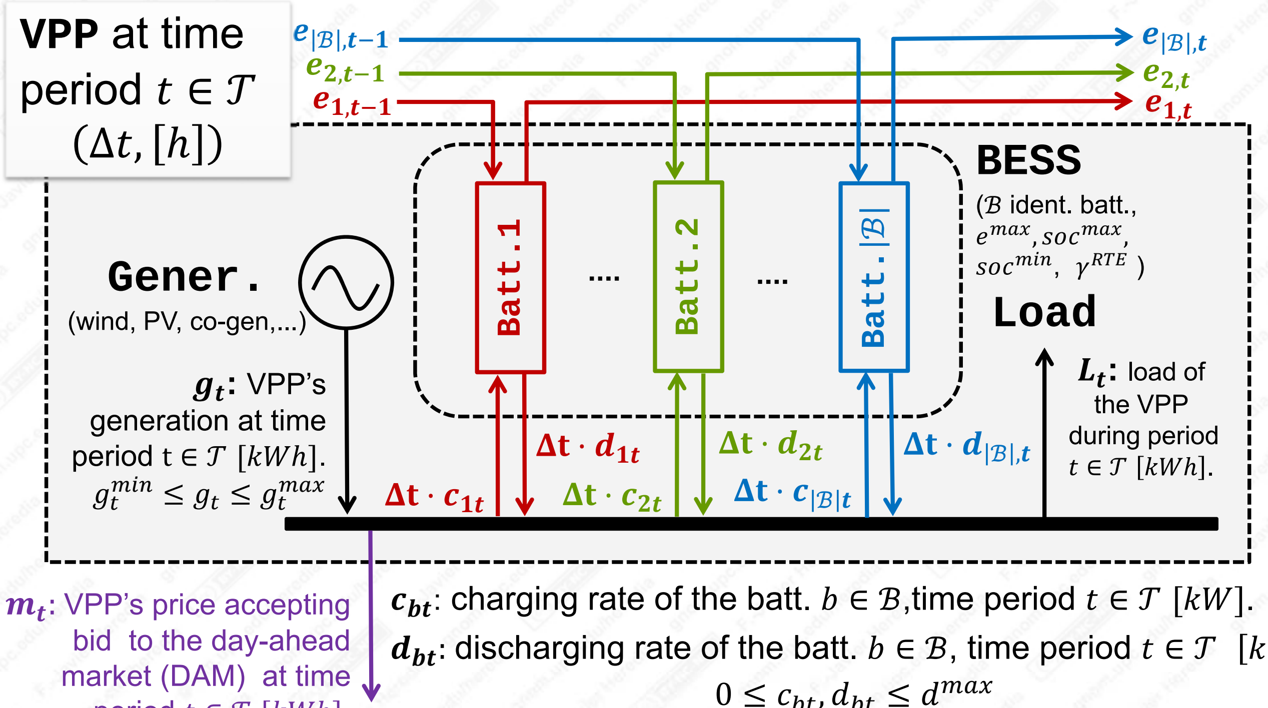
CONTRIBUTION

- **Contributions:** we show in this work the economic viability of Li-ion based BESS through an ex-post analysis of the annual profit associated to the optimal operation of a BESS device in the day-ahed and secondary reserve markets of the Iberian Electricity Market (IEM).
  - To this end we consider a ***Virtual Power Plant*** **(VPP)** comprising a **generation unit**, a **BESS** and some **own consumption**.
  - A **Mixed Integer Linear Programming problem (MILP)** is proposed to find an approximation to the optimal operation of the VPP during a whole year.
  - This MILP is used to show the **economic viability of a Li-ion based BESS associated to a Wind Prower Plant (WPP) with real data of the IEM**.
- Although the methodology presented in this study is applied to Li-ion batteries, **it can be easily extrapolated to other BESS technologies**.

SUMMARY

- ***Introduction and motivation.***
- **A mathematical optimization model for Battery Electricity Storage System in Electricity Markets $(BESSEM)$.**
  - BESS's Virtual Power Plant model.
    - VPP's day-ahead market bid.
    - Battery Electric Storage System modeling.
    - VPP's replicated system.
    - Secondary Reserve Market.
  - VPP's annual profit estimation.
  - The $(BESSEM)$ optimization model.
- ***Case study: economic viability of a BESS attached to a wind power plant.***
- ***Conclusions.***

BESS'S VIRTUAL POWER PLANT



e_{bt}: stored energy of battery $b \in \mathcal{B}$ at the end of period $t \in \mathcal{T}[kWh]$.

VPP at time period $t \in \mathcal{T}$ $(\Delta t, [h])$

Gener.
(wind, PV, co-gen,...)

g_t: VPP's generation at time period $t \in \mathcal{T}$ $[kWh]$.
$g_t^{min} \le g_t \le g_t^{max}$

BESS
($\mathcal{B}$ ident. batt., $e^{max}, soc^{max}, soc^{min}, \gamma^{RTE}$)

Load

L_t: load of the VPP during period $t \in \mathcal{T}$ $[kWh]$.

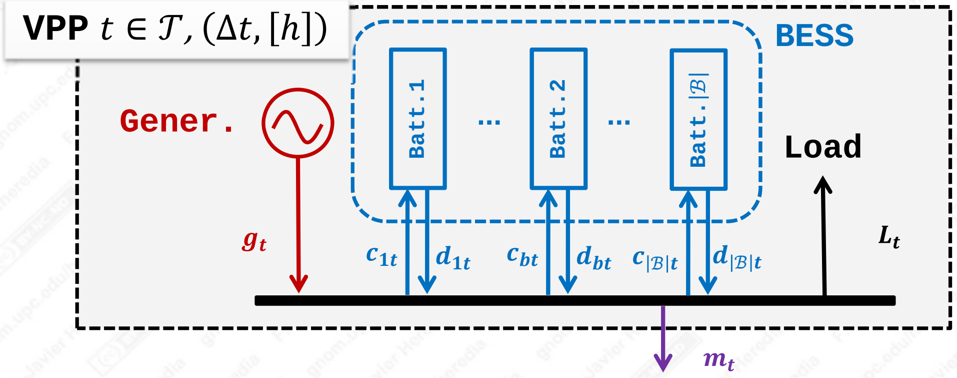
m_t: VPP's price accepting bid to the day-ahead market (DAM) at time period $t \in \mathcal{T}$ $[kWh]$.

c_{bt}: charging rate of the batt. $b \in \mathcal{B}$,time period $t \in \mathcal{T}$ $[kW]$.

d_{bt}: discharging rate of the batt. $b \in \mathcal{B}$, time period $t \in \mathcal{T}$ $[kW]$.

$$0 \le c_{bt}, d_{bt} \le d^{max}$$

VPP DAY-AHEAD MARKET BID



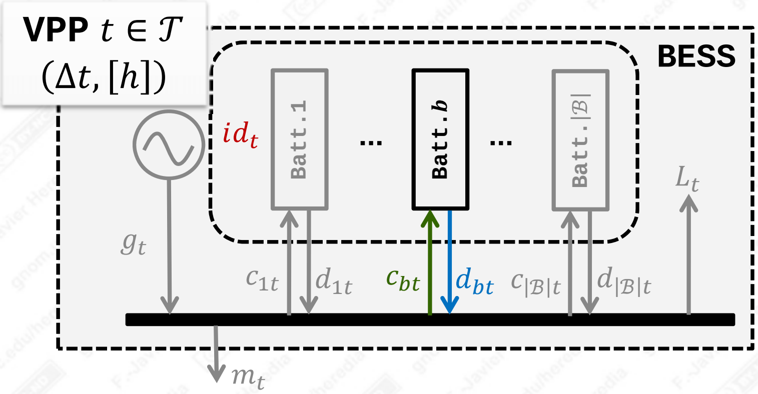
- **Day-ahead market bid constraints:**

$$m_t = g_t + \Delta t \cdot \sum_{b \in \mathcal{B}} (d_{bt} - c_{bt}) - L_t \qquad t \in \mathcal{T} \qquad (1)$$

$$g_t^{min} \le g_t \le g_t^{max} \qquad t \in \mathcal{T} \qquad (2)$$

$$\begin{cases} m_t \ge 0 & \text{if VPP is a producer} \\ m_t \le 0 & \text{if VPP is a consumer} \end{cases} \qquad t \in \mathcal{T} \qquad (3)$$

BESS MODELING 1: CHARGING STATE



d^{max}: battery's maximum charging/discharging rate $[kW]$.

id_t: binary variable establishing if the BESS is discharging ($id_t = 1$) or charging ($id_t = 0$) at time period $t \in \mathcal{T}$.

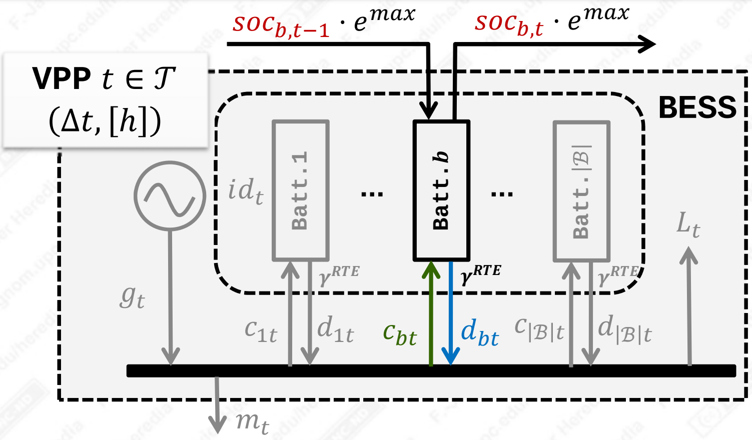
- **Charging/discharging state:**

$$0 \le d_{bt} \le d^{max} \cdot id_t \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (4)$$

$$0 \le c_{bt} \le d^{max} \cdot (1 - id_t) \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (5)$$

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

BESS MODELING 2: STATE OF CHARGE



γ^{RTE} : round-trip efficiency.

e^{max}: battery's capacity $[kWh]$.

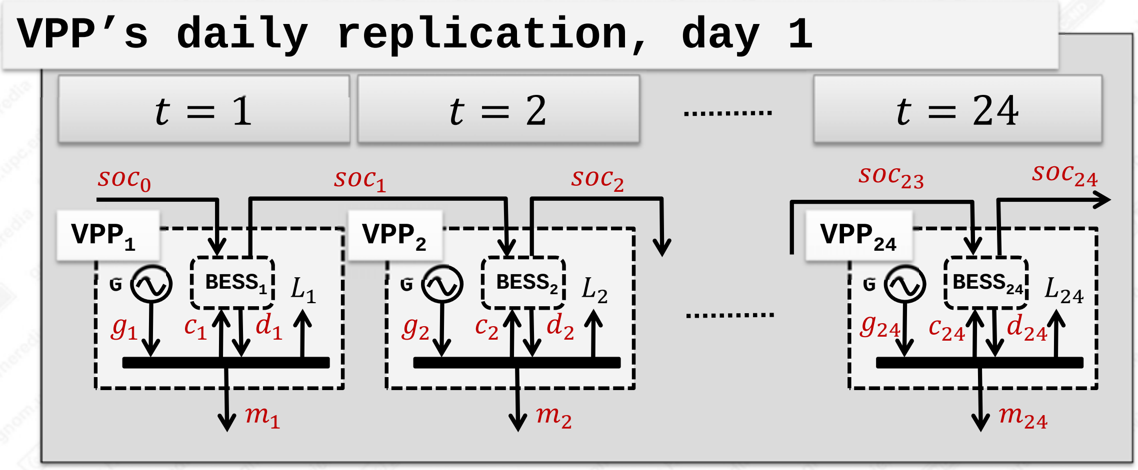
soc_{bt}: SOC of battery $b \in \mathcal{B}$ at the end of time period $t \in \mathcal{T} \cup \{0\}$.

- **State of Charge (SOC) equations after DAM clearing:**

$$soc_{bt} = soc_{b,t-1} + \Delta t \cdot (c_{bt} - d_{bt}/\gamma^{RTE})/e^{max} \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (7)$$

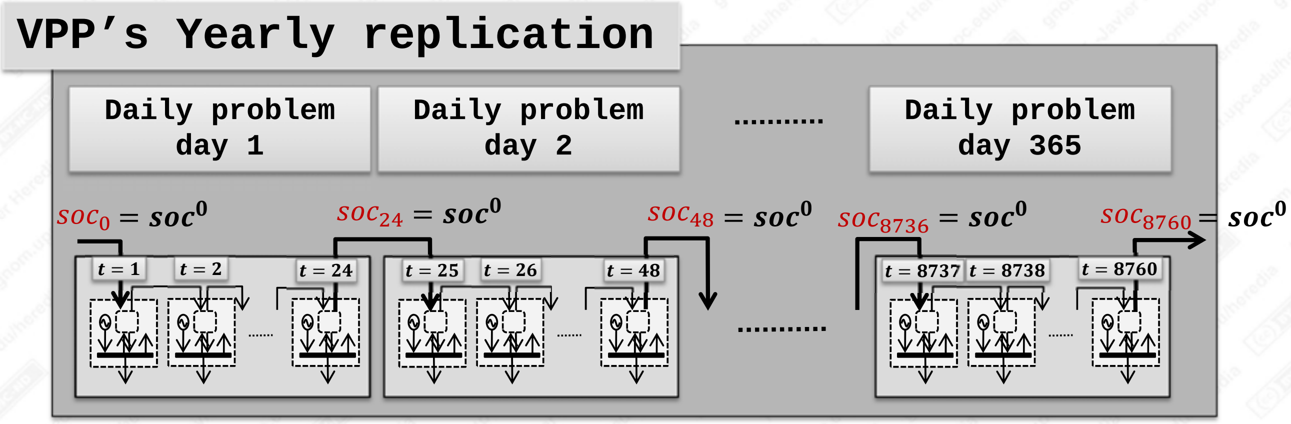
$$soc^{min} \le soc_{bt} \le soc^{max} \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (8)$$

VPP’S REPLICATED SYSTEM (1/2)



VPP’s daily replication, day 1

VPP’S REPLICATED SYSTEM (2/2)



VPP’s Yearly replication

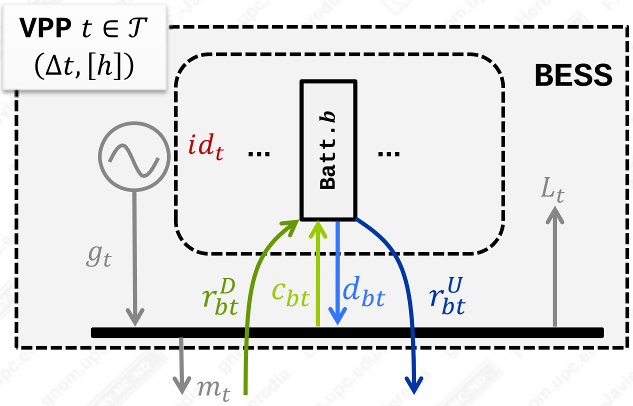
- To prevent de model to perform a “more than one day-ahead” optimization, anticipating unknown information at day D-1, we force the SOC at the end of every day to match a fixed pre-stablished level soc^0:

$$soc_{bt} = soc^0 \qquad b \in \mathcal{B}, t = k \cdot 24, k \in \mathbb{N}^0 \qquad (9)$$

- Should (9) be disregarded the model will probably overestimate the profits.

SRM: SECONDARY RESERVE BAND

- Model $(BESSEM)$ assumes that the VPP submits a price accepting bid for the total available reserve up and reserve down of all the batteries in the BESS to the **Secondary Reserve Band Market (SRB)**.



d_{bt}, c_{bt}: discharging/charging rate of the battery $b \in \mathcal{B}$, matched in auction $t \in \mathcal{T}$ of the DAM $[kW]$.

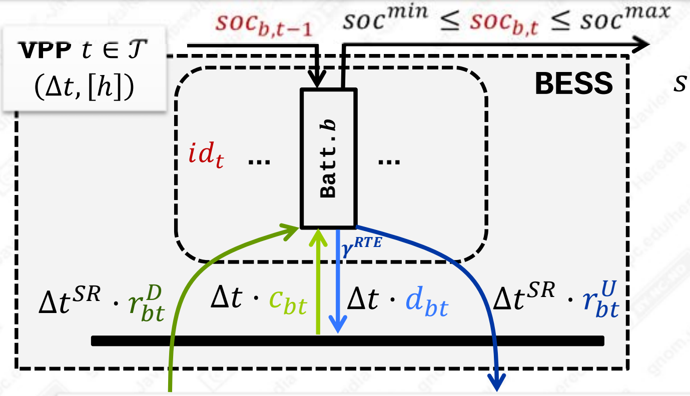
r^U_{bt}, r^D_{bt}: up/down secondary reserve bid of battery $b \in \mathcal{B}$ at time period $t \in \mathcal{T}$ $[kW]$ (maximum ramp variation of the matched energy $\Delta t \cdot d_{bt}, \Delta t \cdot c_{bt}$).

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

$$0 \le r^U_{bt} \le d^{max} - (d_{bt} - c_{bt}) \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (10)$$

$$0 \le r^D_{bt} \le d^{max} - (c_{bt} - d_{bt}) \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (11)$$

SRM: SOC'S LIMITATION TO SRB BID



$soc^{min,max}$: min/max SOC.
e^{max}: battery's capacity $[kWh]$.
Δt^{SR}: time response of the secondary reserve $[h]$.
$\Delta t^{SR} \cdot r^D_{bt}$: maximum down secondary reserve energy $[kWh]$.
$\Delta t^{SR} \cdot r^U_{bt}$: maximum up secondary reserve energy $[kWh]$.

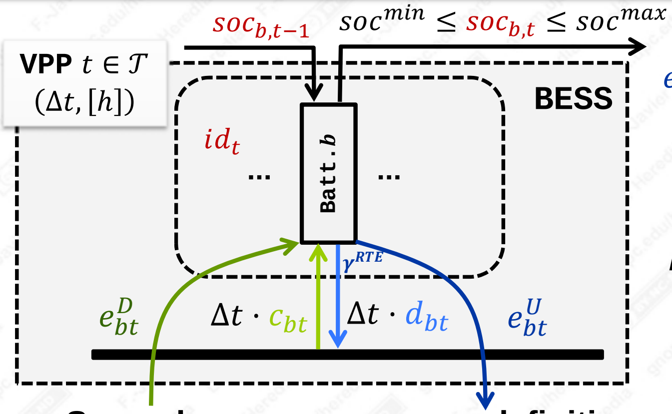
- SOC after the DAM's scheduled charge/disch. minus the max. SRB's discharge :

$$soc_{b,t-1} + \frac{\Delta t \cdot (c_{bt} - d_{bt}/\gamma^{RTE})}{e^{max}} - \frac{\Delta t^{SR} \cdot r^U_{bt}/\gamma^{RTE}}{e^{max}} \ge soc^{min} \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (14)$$

- SOC after the DAM's scheduled charge/discharge plus the max. SRB's charge :

$$soc_{b,t-1} + \frac{\Delta t \cdot (c_{bt} - d_{bt}/\gamma^{RTE})}{e^{max}} + \frac{\Delta t^{SR} \cdot r^D_{bt}}{e^{max}} \le soc^{max} \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (15)$$

SRM: UP/DOWN SECONDARY RESERVE ENERGY



e^U_{bt}, e^D_{bt}: actual **up/down secondary reserve energy** (SRE) allocated to the battery $b \in \mathcal{B}$ at time period $t \in \mathcal{T}$ $[kWh]$.

β^U_t, β^D_t: fraction of the up/down reserve bid of the VPP allocated during Automatic Generation Control:

$$0 \le \beta^U_t, \beta^D_t < 1, \beta^U_t \cdot \beta^D_t = 0$$

- **Secondary reserve energy definition:**

$$e^D_{bt} = \Delta t^{SR} \cdot \beta^D_t \cdot r^D_t \quad ; \quad e^U_{bt} = \Delta t^{SR} \cdot \beta^U_t \cdot r^U_{bt} \qquad b \in \mathcal{B}, t \in \mathcal{T} \qquad (17)$$

- **State of Charge (SOC) equations after DAM clearing and SRE allocation:**

$$soc_{bt} = \quad soc_{b,t-1}$$

Charge/discharge after DAM: $+\Delta t \cdot (c_{bt} - d_{bt}/\gamma^{RTE})/e^{max}$ $\quad b \in \mathcal{B}$

Charge/discharge after SRE allocation: $+\left(e^D_{bt} - e^U_{bt}/\gamma^{RTE}\right)/e^{max}$ $\quad t \in \mathcal{T}$ $\quad$ (7)

SUMMARY

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VPP'S PROFIT ESTIMATION : INCOMES

- Our *ex-post* analysis aims at approximate as fair as possible the situation of a **VPP manager that has to decide on day $D-1$ the optimal bid of the VPP to the day-ahead and reserve markets for the next day D** without knowing the true value of the day-ahead and reserve markets clearing prices λ_t^{DAM}, λ_t^{SRB}.
- **To not to assume any *a priori* knowledge of the clearing prices**, we use the prices of the same weekday of the previous week which is an information available at day $D-1$.
- This is equivalent to assume that **at day $D-1$ the VPP manager finds the optimal bid with respect to the one-week-ago clearing prices**. This assumption results in the following (likely under-)***estimated market revenue functions***:

$$ER^{DAM}(m) = \sum_{t\in\mathcal{T}} \lambda_{t-168}^{DAM} \cdot m_t \qquad (19)$$

$$ER^{SRB}(r^U, r^D) = \sum_{b\in\mathcal{B}, t\in\mathcal{T}} \lambda_{t-168}^{SRB} \cdot \left(r_{bt}^U + r_{bt}^D\right) \qquad (20)$$

VPP'S PROFIT ESTIMATION : COSTS (1/2)

- **Operation costs of the generation unit of the VPP**: let $C^G(g)$ represent the operation costs of the generation unit of the VPP.
- **Life cycle costs of the BESS:**
  - These are the operation cost associated to the charge/discharge cycles of the Li-ion battery.
  - The ***cycle life* cyc^{max} of a battery is the estimated maximum number of complete charge/discharge processes (cycles) before reaching EOL**. The cycle life depends on several factors (temperature, charging rate,…) but above all, the **maximum and minimum allowed SOC**.
  - Let cyc^{max} be the cycle life associated to some pair (soc^{min}, soc^{max}). The total number of cycles performed during horizon $\mathcal{T}$ by the battery b is

$$cyc(c_b, e_b^D) = \frac{\text{Total energy charged along } \mathcal{T}}{\text{BESS capacity}} = \frac{\Delta t \cdot \sum_{b\in\mathcal{B},t\in\mathcal{T}} c_{bt} + \sum_{b\in\mathcal{B},\in\mathcal{T}} e_{bt}^D}{e^{max}} \qquad (21)$$

VPP’S PROFIT ESTIMATION: COSTS (2/3)

- **Life cycle costs of the BESS (cont):**
  - If the BESS has been operated satisfying $soc^{min} \leq soc_t \leq soc^{max}$, the ***life cycle cost during $\mathcal{T}$*** of the BESS is [€].

$$C^{LCC}(c,e^D) = \delta^{REP} \cdot C^{CAP} \cdot \sum_{b\in\mathcal{B}} cyc(c_b,e_b^D)/cyc^{max} \tag{22}$$

  - where:

δ^{REP}: ratio of replacement cost to the fraction of the capital cost that corresponds to the replacement of the exhausted battery by a new one at its EOL after reaching cyc^{max} cycles.

C^{CAP}: capital cost of each individual battery (equip. capital + first installation)

$cyc\left(c_b,e_b^D\right)$: total number of charge/discharge cycles of battery $b \in \mathcal{B}$.

cyc^{max}: battery’s cycle life for a prefixed soc^{min} and soc^{max}.

VPP’S PROFIT ESTIMATION: COSTS (3/3)

- ***Estimated profit of the VPP*** **:** difference between total estimated revenues and total costs

$$EP^{VPP}(m,r^U,r^D,g,c,e^D) = ER^{DAM}(m) + ER^{SRB}(r^U,r^D) - C^G(g) - C^{LCC}(c,e^D) \tag{23}$$

where:

$ER^{DAM}(m)$: estimated revenues from the DAM.

$ER^{SRB}(r^U,r^D)$: estimated revenues from the SRB market.

$C^G(g)$: generation costs of the VPP [€].

$C^{LCC}(c,e^D)$: life cycle costs of the BESS [€].

THE $(BESSEM)$ OPTIMIZATION MODEL

- ***Battery Electricity Storage System in Electricity Markets*** **model ($BESSEM$):**

$$(BESSEM)\begin{cases} \max & EP^{VPP}(m, r^U, r^D, g, c, e^D) \\ s.t.: & \\ \text{DAM :} & (1)-(3) \\ \text{BESS :} & (4)-(9) \\ \text{SRM :} & (10), (11), (14)-(18) \end{cases}$$

- $(BESSEM)$ model is a large scale mixed integer linear or quadratic (depending on $C^G(g)$) optimization problem. It must be noticed that actually problem $(BESSEM)$ is decomposable in 365 daily independent subpropblems due to constraints (9).
- The optimal solution $x^* \overset{\text{def}}{=} argmax\{(BESSEM)\}$ is a suboptimal approximation of the optimal operation of the VPP because it could be easily improved in the real-time management (for instance, with a better forecasting of λ^{DAM} and λ^{DRM}or relaxing constraints (9)).

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- **Case study: economic viability of a BESS attached to a wind power plant.**
- ***Conclusions.***

ACTUAL ANNUAL PROFIT OF THE VPP

- The actual ***annual profit*** earned by the VPP is calculated as:

$$AP^{VPP}(x^*) =$$

$$\underbrace{\sum_{t\in\mathcal{T}} \lambda_t^{DAM}\cdot m_t^*}_{AR^{DAM}(m^*)} + \underbrace{\sum_{b\in\mathcal{B},t\in\mathcal{T}} \lambda_t^{SRB}\cdot\left(r_{bt}^{U^*}+r_{bt}^{D^*}\right)}_{AR^{SRB}(r^{U^*},r^{D^*})} \qquad (24)$$

$$+\underbrace{\sum_{b\in\mathcal{B},t\in\mathcal{T}} \left(\lambda_t^{SURE}\cdot e_{bt}^{U^*}-\lambda_t^{SDRE}\cdot e_{bt}^{D^*}\right)}_{AR^{SRE}(e^{U^*},e^{D^*})} \qquad (25)$$

$$-C^G(g^*) \qquad (26)$$

where:

(24) are the actual revenues from the DAM and SRB market

(25) are the revenues (>0)/payments (<0) of the secondary up and down reserve energy.

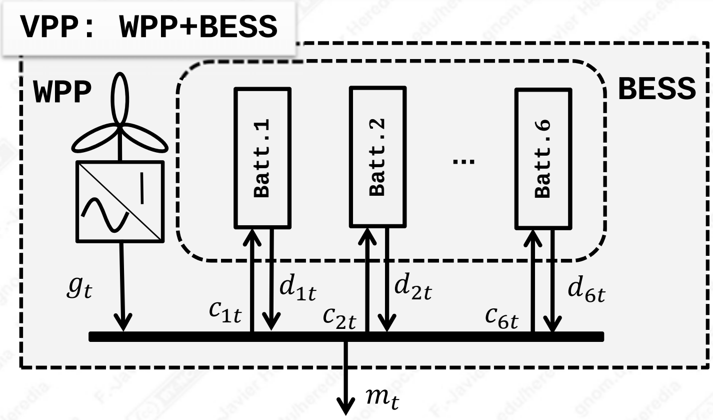
(26) is the generation cost.

CASE STUDY: BESS + WPP

- Wind Power Plant:

$g_t = g_t^{min} = g_t^{max}, m_t \geq 0, C^G(g) = 0$

$\max\{g_t\} =$	$5464\ kWh$
$E[g_t] =$	$1541\ kWh$
$\sigma =$	$1978\ kWh$



- BESS including six identical Li-ion batteries with a total capacity of $6MWh$ and $3MW$ of charge/disch. power:

$\mathcal{B} =$	$\{1,2,\dots,6\}$
$d^{max} =$	$500\ kW$
$e^{max} =$	$1000\ kWh$
$C^{CAP} =$	$1250\frac{€}{kWh}\cdot e^{max}$
$cyc^{max} =$	6000

$\delta^{REP} =$	0.6
$soc^0 =$	0.5
$soc^{max} =$	0.9
$soc^{min} =$	0.3
$\gamma^{RTE} =$	0.8

Based on:

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

[5] Saft Batteries, Technical data [Online].

- The electricity market prices considered in this study ($\lambda^{DAM},\lambda^{SRB},\lambda^{SURE},\lambda^{SDRE}$) are the **actual prices during year 2013 of the Iberian Electricity Market**, available at the websites of the market and system operators.

BESS+WPP ECONOMIC ANALYSIS

DAM's annual revenue :	$AR^{DAM}(m^*) =$	529,430 €
SRM's annual revenue :	$AR^{SRB}(r^{U^*}, r^{U^*}) =$	736,258€
SRE's annual revenue :	$AR^{SRE}(e^{U^*}, e^{U^*}) =$	41,896 €
Annual profit of the VPP :	$\boldsymbol{AP^{VPP}(x^*)} =$	$\mathbf{1,307,584}$ €
Annual profit of the WPP [(a)] :	$\boldsymbol{AP^{WPP}} =$	$\mathbf{569,798}$ €
Increase of profit due to the BESS [(b)] :	$\boldsymbol{\Delta P^{BESS}(x^*)} =$	$\mathbf{737,786}$ €
Capital cost of the BESS [(c)] :	$C^{BESS} =$	7,500,000 €
Investment payback period [(d)] :	$\boldsymbol{IPP(x^*)} =$	$\mathbf{10.17}$ **years**
EOL of the first exhausted battery :	$\boldsymbol{FEOL(x^*)} =$	$\mathbf{20.35}$ **years**
Return of the investment [(e)] :	$\boldsymbol{ROI(x^*)} =$	$\mathbf{100\%}$

(a) : $AP^{WPP} = \sum_{t\in\mathcal{T}} \lambda_t^{DAM} \cdot g_t$

(b) : $\Delta P^{BESS}(x^*) = AP^{VPP}(x^*) - AP^{WPP}$

(c) : $C^{BESS} = |\mathcal{B}| \cdot C^{CAP}$

(d) : $IPP(x^*) = C^{BESS} / \Delta P^{BESS}(x^*)$

(e) : $ROI(x^*) = \left(EOL\left(c^*, e^{D^*}\right) \cdot \Delta P^{BESS}(x^*) - C^{BESS}\right) / C^{BESS}$

$(BESSEM)$ model:
- 385440 continuous variables, 8760 binary variables and 573120 linear constraints.
- Solved with the SAS/OR 9.3® in 4 minutes on a desktop PC (i7@2.93GHz, 8GB RAM, Windows 7 Professional).

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CONCLUSIONS

- A **MILP optimization model**, $(BESSEM)$ has been formulated to assess the **economic viability of BESS embedded in a VPP** that bids to both the DAM and the SRM.
- This model has been used to analyse a $6MWh/3MW$ **Li-ion BESS attached to a real Wind Power Plant** that operates in the **Iberian Electricity Market** with real data of year 2013.
- The numerical results shows the **profitability of the BESS**, with an investment payback period of 10 years, a 20 years EOL and a return of the investment (ROI) of 100%.
- The ex-post analysis of the $(BESSEM)$ model gives a **general methodology that can be easily applied to any BESS technology** and extended to incorporate other electricity markets as, for instance, intra-day markets.

Thank you very much for your attention!!