Short-term scheduling of a hybrid hydro-battery plant

Juan I. Pérez-Díaz

1 Universidad Politécnica de Madrid (UPM)

ji.perez@upm.es

The work here presented has been funded by the Spanish Ministry of Education under the mobility grant PRX21/00474
1. OBJECTIVE

The objective of the grant which funded this research was twofold:

- Perform a literature review on the short-term generation and reserve scheduling of a hybrid hydro-battery power plant
- Develop a beta version of a robust optimization model for the short-term generation and reserve scheduling of a hybrid hydro-battery power plant
2. LITERATURE REVIEW

EXISTING AND PLANNED HYBRID HYDRO-BATTERY POWER PLANTS

PFREIMD pumped-storage power plant 135 MW + 12.5MW/13MWh Li-ion BESS
FORSHUVUND run-of-river power plant 44 MW + 5MW/6.2MWh Li-ion BESS
WALLSEE run-of-river power plant 210 MW + 8MW/14MWh Li-ion BESS
VOGELGRUN run-river power plant 142 MW + 650kW/300kWh Li-ion BESS
LANDAFORS run-of-river power plant 11 MW + 1MW/250kWh Li-ion BESS (2nd life)
EDSELE run-of-river power plant 6 MW + XXMW/YYMWH Li-ion BESS
LÖVÖN run-of-river power plant 12 MW + XXMW/YYMWH Li-ion BESS
MANKALA run-of-river power plant 37 MW + xxMW/yyMWh Li-ion BESS
KURKIASKA run-of-river power plant 27 MW + xxMW/yyMWh Supercapacitor ESS
BODUM run-of-river power plant 12 MW + xxMW/yyMWh Li-ion BESS
FJÄLLSJO run-of-river power plant 12 MW + xxMW/yyMWh Li-ion BESS
2. LITERATURE REVIEW

MOTIVATION

Taken from W. Yang et al. (2016) IOP Conf. Ser.: Earth Environ. Sci. 49 052013
2. LITERATURE REVIEW

MOTIVATION

Taken from Dreyer et al. (2019) IOP Conf. Ser.: Earth Environ. Sci. 405 01213
2. LITERATURE REVIEW

MOTIVATION
There are a few papers and MSc Theses dealing with the real-time (or close to real-time) energy management of hybrid hydro-battery power plants.

There is only 1 paper dealing with the day-ahead energy and reserve scheduling of a hybrid wind-solar-pumped-battery generation and storage system.
2. LITERATURE REVIEW

Features of the model proposed by Parasteragui et al. (2015) relevant to the goal of the grant

- 24-h time horizon
- 1-h time resolution
- Energy, spinning and non-spinning reserve markets
- Scenario-based mixed integer program
- Regulation energy requested in real-time is NOT considered
- Battery aging is NOT considered
- Hydro equipment aging is NOT considered
3. METHODOLOGY

BALANCING SERVICES AND MARKETS GENERAL FEATURES

- Primary control of CIESS (FCR)
- Secondary control (aFRR)
- Tertiary control (mFRR)
- Inertial response
- Generator rescheduling (~ RR)

3. METHODOLOGY

BALANCING SERVICES AND MARKETS

GENERAL FEATURES

- Gate closing time
- Time horizon
- Time resolution

- Remuneration schemes (pay-as-bid, marginal prices, etc.)

- Types of products

- Particular conditions (minimum bid size, penalties, etc.)
3. METHODOLOGY

EXPLORED BALANCING MARKETS

FCR COOPERATION

aFRR
3. METHODOLOGY

TARGET HYDROPOWER PLANT TYPE

Taken from Sheldon (2011)
3. METHODOLOGY

TARGET MODEL FEATURES

- Turbine’s CAM curve
- Turbine’s operational constraints (e.g. min/max discharge)
- BESS operational constraints (e.g. min/max SOC, max charge/discharge power)
- BESS cycle aging

Cycle counting

\[ q = B_1 e^{B_2 I_c} \sum_{t \in H} (p_t^- + p_t^+) \Delta t \]

Energy throughput

Taken from Antoniadou-Plytaria et al. (2021).
https://doi.org/10.1109/TSG.2020.3037120

Taken from Shi et al. (2018).
https://doi.org/10.1109/TSG.2020.3037120
3. METHODOLOGY

TARGET MODEL FEATURES

Cycle counting

Taken from Stroe et al. (2017).
https://doi.org/10.1109/TIA.2016.2616319

Taken from Padmanabhan et al. (2020).
https://doi.org/10.1109/TPWRS.2019.2936131
3. METHODOLOGY

TARGET MODEL FEATURES

- Turbine’s CAM curve
- Turbine’s operational constraints (e.g. min/max discharge)
- BESS operational constraints (e.g. min/max SOC, max charge/discharge power)
- BESS cycle aging
- BESS calendar aging

\[
C_{f_{cal}} = 0.1723 \cdot e^{0.007388 \cdot SOC_{\downarrow}} \cdot t^{0.8}
\]

Taken from Stroe et al. (2017).
https://doi.org/10.1109/TIA.2016.2616319

\[
Q_r = Q_{r,0} - a_c \Delta t
\]

Taken from Antoniadou-Plytaria et al. (2021).
https://doi.org/10.1109/TSG.2020.3037120
3. METHODOLOGY

TARGET MODEL FEATURES

![Graph showing 4-hour Battery Capital Cost (2020$/kWh) from 2020 to 2050 with three scenarios: High, Mid, and Low.](Taken from Cole et al. (2021), NREL/TP-6A20-79236.)
3. METHODOLOGY

TARGET MODEL FEATURES

- Turbine’s CAM curve
- Turbine’s operational constraints (e.g. min/max discharge)
- BESS operational constraints (e.g. min/max SOC, max charge/discharge power)
- BESS cycle aging
- BESS calendar aging
- Hydro equipment aging (RESEARCH GAP)
3. METHODOLOGY

TARGET MODEL FEATURES

- Turbine’s CAM curve
- Turbine’s operational constraints (e.g. min/max discharge)
- BESS operational constraints (e.g. min/max SOC, max charge/discharge power)
- BESS cycle aging
- BESS calendar aging
- Hydro equipment aging
- Consistency with market rules
3. METHODOLOGY

TARGET MODEL FEATURES

Model uncertain inputs and robustness

- Water inflows
- Market prices
- Regulation energy requested in real-time

FCR COOPERATION

Taken from Stroe et al. (2017).
https://doi.org/10.1109/TIA.2016.2616319

SPANISH aFRR

Taken from Egido et al. (2009)
https://doi.org/10.1109/TPWRS.2008.2007003
3. METHODOLOGY

TARGET MODEL FEATURES

FCR COOPERATION
3. METHODOLOGY

TARGET MODEL FEATURES

FCR COOPERATION
3. METHODOLOGY

TARGET MODEL FEATURES

FCR COOPERATION
3. METHODOLOGY

TARGET MODEL FEATURES

SPANISH aFRR
3. METHODOLOGY

TARGET MODEL FEATURES

SPANISH aFRR
3. METHODOLOGY

TARGET MODEL FEATURES

SPANISH aFRR

![Graph showing exceedance probability versus net-regulation energy (p.u. w.r.t. committed reserve).]
3. METHODOLOGY

TARGET MODEL FEATURES

SPANISH aFRR
4. CASE STUDY FOR MODEL VALIDATION

- Spanish run-of-river power plant equipped with a 3-MW Kaplan unit
- Turbine’s CAM curve (with and w/o “deloading”)
- Turbine’s operational constraints (e.g. min/max discharge)
- BESS 0.5 MW / 2 MWh
- BESS operational constraints (e.g. min/max SOC, max charge/discharge power)
- BESS cycle aging (replacement cost based on Wallsee Project)
- Consistency with market rules (Spanish aFRR)
4. CASE STUDY FOR MODEL VALIDATION

Scenarios of the hourly up/down regulation energy requested in real-time:

1. Perfect knowledge
2. Historic worst case with maximum daily net regulation energy
3. Historic worst case with minimum daily net regulation energy”

All other uncertain variables are assumed known (energy prices, reserve prices, regulation energy prices, inflows)
4. CASE STUDY FOR MODEL VALIDATION

Model variants:

A. Only the BESS provides aFRR
B. The BESS and the hydropower plant provide aFRR
C. Fully robust solution

* Based on Chazarra et al. (2016), https://doi.org/10.1016/j.epsr.2015.08.014
5. VALIDATION RESULTS

<table>
<thead>
<tr>
<th>Cases</th>
<th>Spot market</th>
<th>Availability</th>
<th>Energy</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect knowledge only BESS</td>
<td>1955</td>
<td>595</td>
<td>196</td>
<td>2746</td>
</tr>
<tr>
<td>Perfect knowledge BESS and hydro</td>
<td>1921</td>
<td>676</td>
<td>235</td>
<td>2832</td>
</tr>
<tr>
<td>Worst-case max. daily net regulation energy only BESS</td>
<td>1949</td>
<td>487</td>
<td>203</td>
<td>2640</td>
</tr>
<tr>
<td>Worst-case max. daily net regulation energy BESS and hydro</td>
<td>1904</td>
<td>612</td>
<td>250</td>
<td>2766</td>
</tr>
<tr>
<td>Worst-case min. daily net regulation energy only BESS</td>
<td>2191</td>
<td>492</td>
<td>-31</td>
<td>2651</td>
</tr>
<tr>
<td>Worst-case min. daily net regulation energy BESS and hydro</td>
<td>2186</td>
<td>636</td>
<td>-23</td>
<td>2799</td>
</tr>
<tr>
<td>Perfect knowledge fully robust solution only BESS</td>
<td>1963</td>
<td>526</td>
<td>190</td>
<td>2678</td>
</tr>
<tr>
<td>Perfect knowledge fully robust solution BESS and hydro</td>
<td>1930</td>
<td>642</td>
<td>232</td>
<td>2804</td>
</tr>
</tbody>
</table>

The revenue with BESS and hydro providing aFRR is always higher.
5. VALIDATION RESULTS

<table>
<thead>
<tr>
<th>Cases</th>
<th>Spot market</th>
<th>Availability</th>
<th>Energy</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect knowledge only BESS</td>
<td>1955</td>
<td>595</td>
<td>196</td>
<td>2746</td>
</tr>
<tr>
<td>Perfect knowledge BESS and hydro</td>
<td>1921</td>
<td>676</td>
<td>235</td>
<td>2832</td>
</tr>
<tr>
<td>Worst-case max. daily net regulation energy only BESS</td>
<td>1949</td>
<td>487</td>
<td>203</td>
<td>2640</td>
</tr>
<tr>
<td>Worst-case max. daily net regulation energy BESS and hydro</td>
<td>1904</td>
<td>612</td>
<td>250</td>
<td>2766</td>
</tr>
<tr>
<td>Worst-case min. daily net regulation energy only BESS</td>
<td>2191</td>
<td>492</td>
<td>-31</td>
<td>2651</td>
</tr>
<tr>
<td>Worst-case min. daily net regulation energy BESS and hydro</td>
<td>2186</td>
<td>636</td>
<td>-23</td>
<td>2799</td>
</tr>
<tr>
<td>Perfect knowledge fully robust solution only BESS</td>
<td>1963</td>
<td>526</td>
<td>190</td>
<td>2678</td>
</tr>
<tr>
<td>Perfect knowledge fully robust solution BESS and hydro</td>
<td>1930</td>
<td>642</td>
<td>232</td>
<td>2804</td>
</tr>
</tbody>
</table>

The revenue with BESS and hydro providing aFRR is always higher

The revenue of the fully robust solution is always lower
5. VALIDATION RESULTS

<table>
<thead>
<tr>
<th>Cases</th>
<th>Spot market</th>
<th>Availability</th>
<th>Energy</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect knowledge only BESS</td>
<td>1955</td>
<td>595</td>
<td>196</td>
<td>2746</td>
</tr>
<tr>
<td>Perfect knowledge BESS and hydro</td>
<td>1921</td>
<td>676</td>
<td>235</td>
<td>2832</td>
</tr>
<tr>
<td>Worst-case max. daily net regulation energy only BESS</td>
<td>1949</td>
<td>487</td>
<td>203</td>
<td>2640</td>
</tr>
<tr>
<td>Worst-case max. daily net regulation energy BESS and hydro</td>
<td>1904</td>
<td>612</td>
<td>250</td>
<td>2766</td>
</tr>
<tr>
<td>Worst-case min. daily net regulation energy only BESS</td>
<td>2191</td>
<td>492</td>
<td>-31</td>
<td>2651</td>
</tr>
<tr>
<td>Worst-case min. daily net regulation energy BESS and hydro</td>
<td>2186</td>
<td>636</td>
<td>-23</td>
<td>2799</td>
</tr>
<tr>
<td>Perfect knowledge fully robust solution only BESS</td>
<td>1963</td>
<td>526</td>
<td>190</td>
<td>2678</td>
</tr>
<tr>
<td>Perfect knowledge fully robust solution BESS and hydro</td>
<td>1930</td>
<td>642</td>
<td>232</td>
<td>2804</td>
</tr>
</tbody>
</table>

The revenue with BESS and hydro providing aFRR is always higher

The revenue of the fully robust solution is always lower

Regulation energy is higher/lower in the worst case max./min. daily net regulation energy scenarios
6. OPEN RESEARCH QUESTIONS

- Is BESS cycle aging being properly estimated? (Intrahourly regulation energy profiles)
- How should BESS calendar aging and turbine fatigue considered?
- Is it worth it to use a fully robust approach? (Stoch. programming with penalties/recourse)
- How to fairly compare the results? (Monte Carlo simulations, close-to-real-time dispatch)
- How to guarantee the fulfillment of the reserve obligations in real-time (real-time energy management system)
- Might the pond storage capacity be exploited for reserve provision? (On/off control as a function of level thresholds)
7. OTHER IMPORTANT QUESTIONS

- Are Li-ion batteries a good companion of hydropower?
- Is the investment in the BESS integration feasible?
APPLICATION TED2021-132794B-C21 “Hybrid power plants comprising hydropower, Li-ion batteries and supercapacitors” (HYBRIDHYDRO)
Thanks for your attention!

Juan I. Pérez-Díaz
Universidad Politécnica de Madrid (UPM)
ji.perez@upm.es