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Short-term scheduling of a hybrid hydro-battery plant

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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

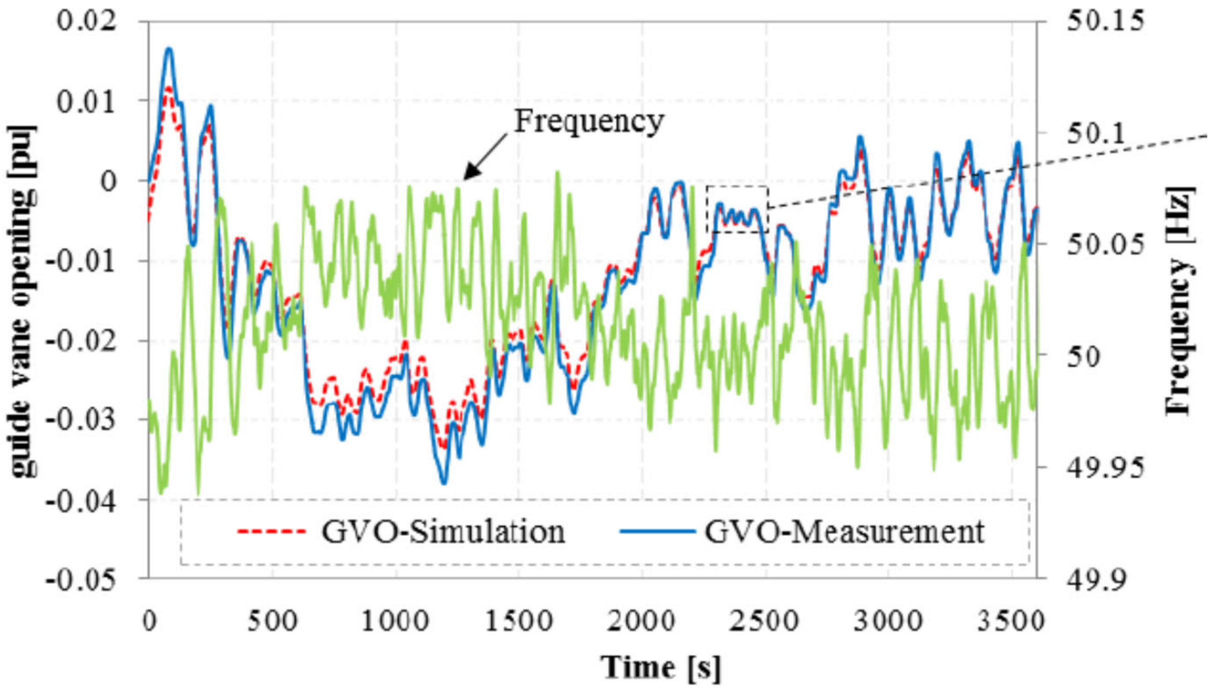
KURKIASKA run-of-river power plant 27 MW + xxMW/yyMWh Supercapacitor ESS

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

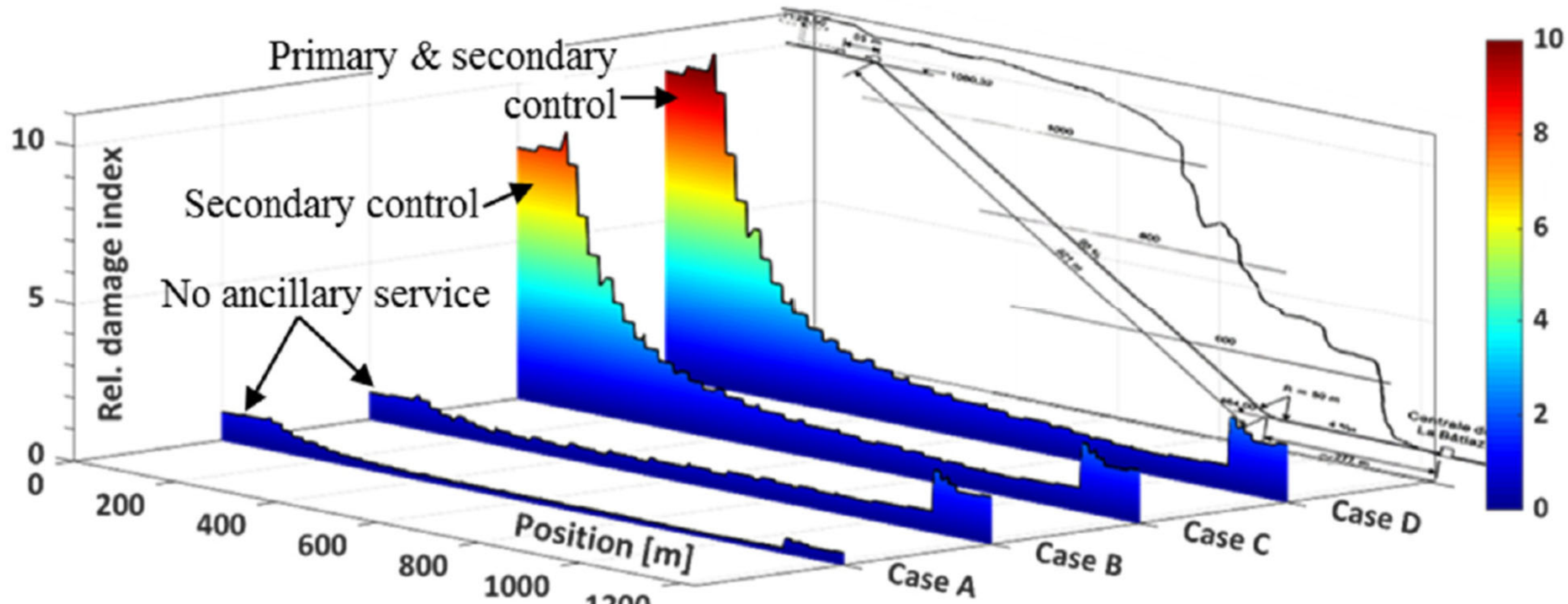
MOTIVATION



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

2. LITERATURE REVIEW

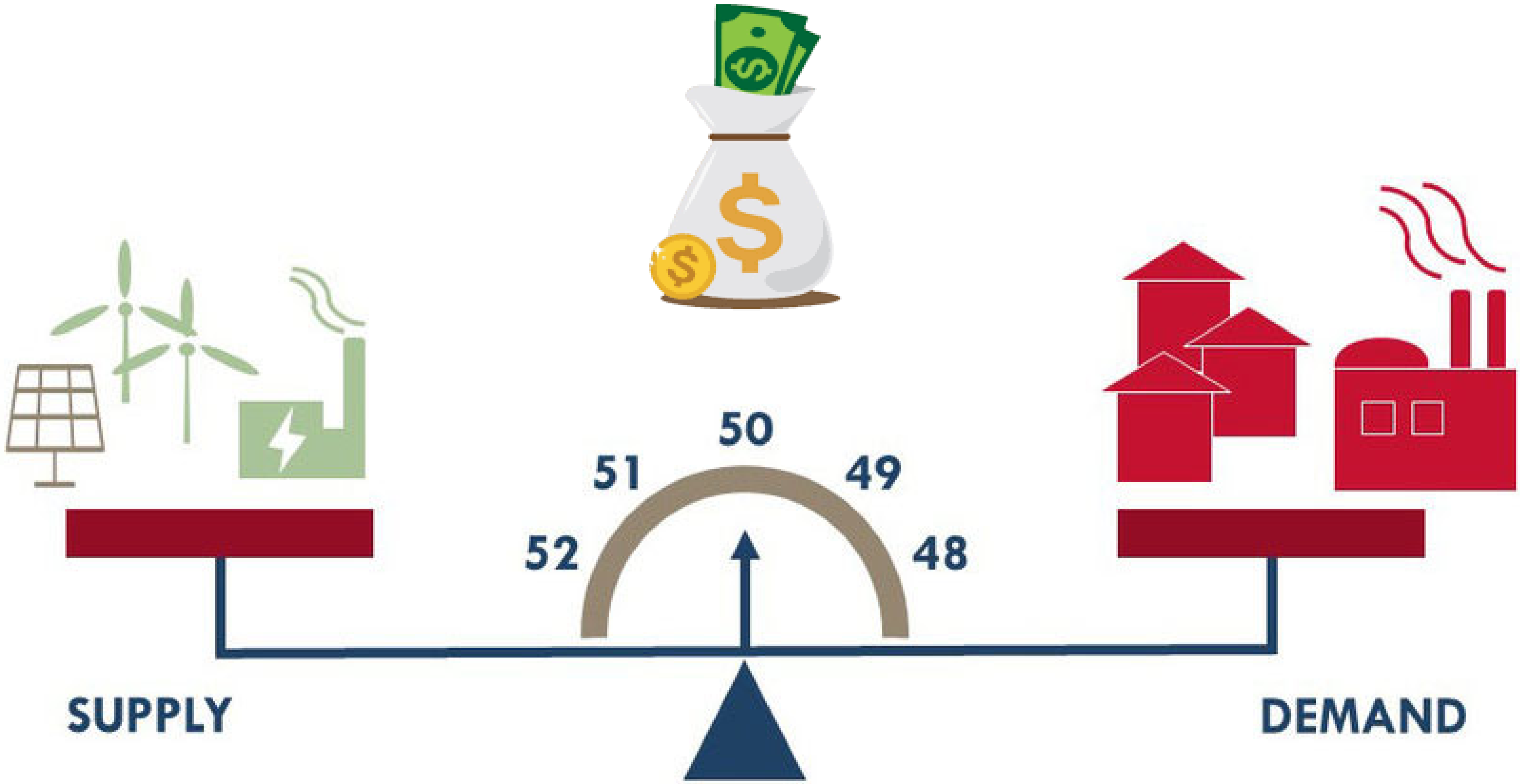
MOTIVATION



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

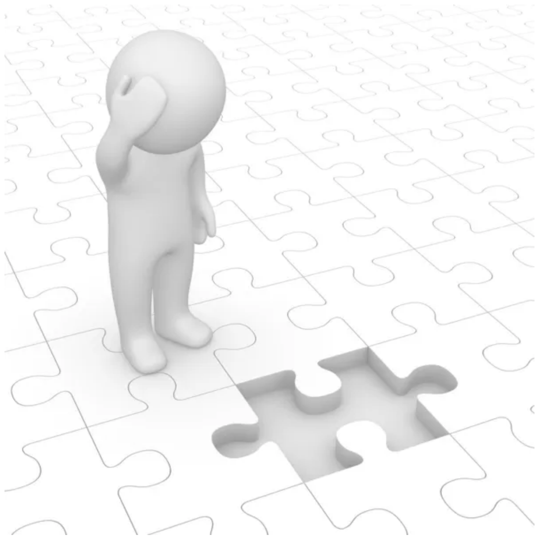
2. LITERATURE REVIEW

MOTIVATION



2. LITERATURE REVIEW

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

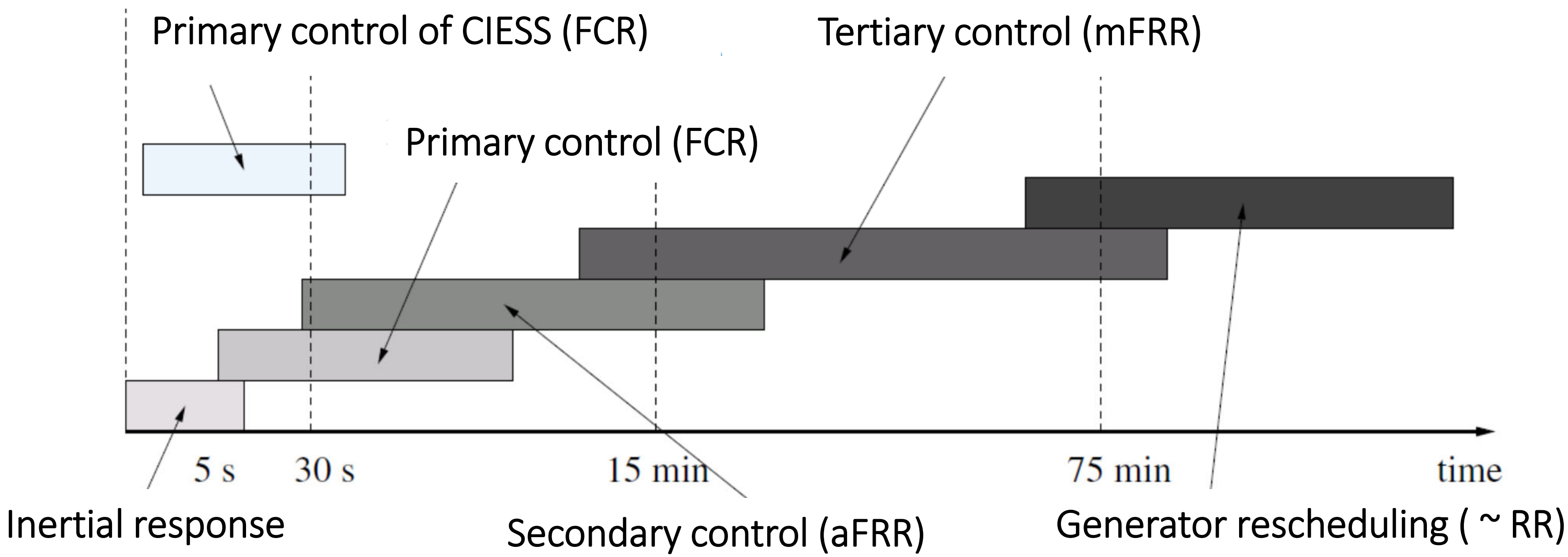
2. LITERATURE REVIEW

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

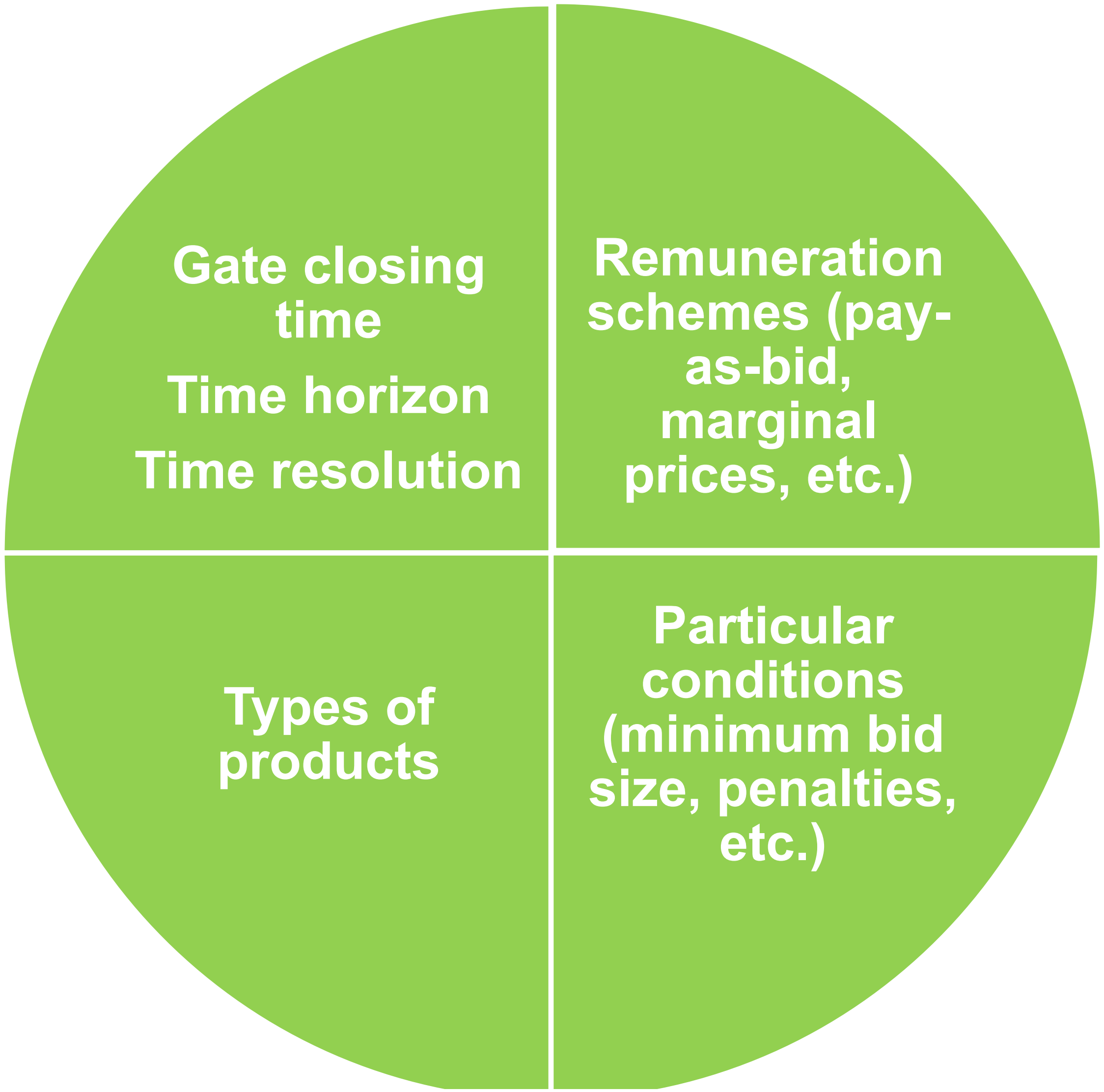
BALANCING SERVICES AND MARKETS GENERAL FEATURES



Adapted from Milano et al. (2018), “Foundations and Challenges of Low-Inertia Systems” in PSCC’18.

3. METHODOLOGY

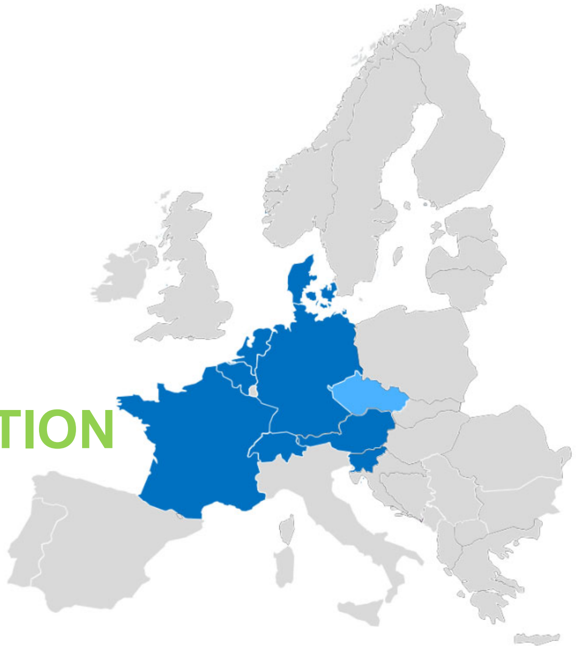
BALANCING SERVICES AND MARKETS GENERAL FEATURES



3. METHODOLOGY

EXPLORED BALANCING MARKETS

FCR COOPERATION



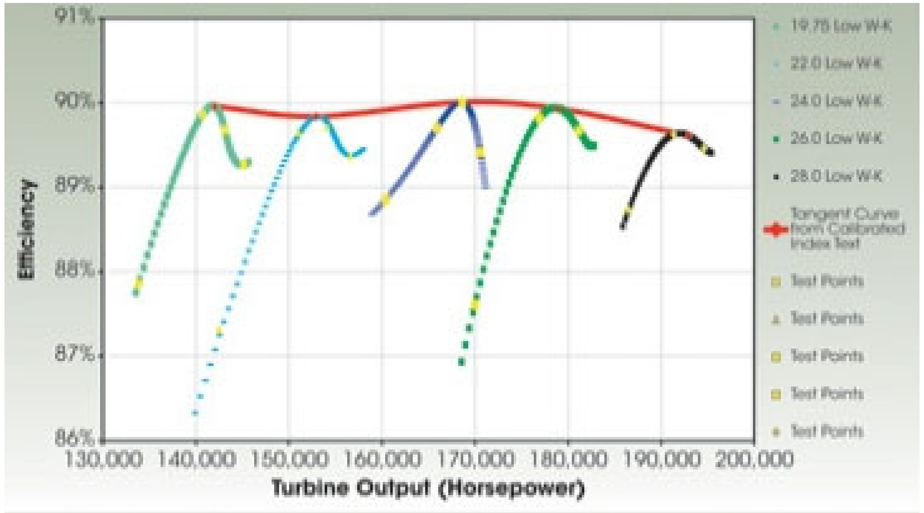
APG
elia | Elia Group
ELES
swissgrid
50hertz | Elia Group
amprion verbindet
TenneT
ENERGINET
Rte
TRANSNET BW

aFRR

RED ELÉCTRICA DE ESPAÑA

3. METHODOLOGY

TARGET HYDROPOWER PLANT TYPE



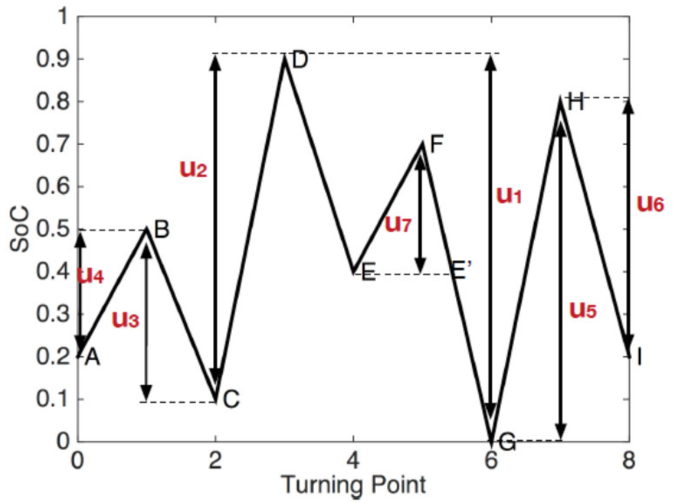
Taken from Sheldon (2011)
https://www.hydroreview.com/world-regions/turbine-control-method-to-develop-a-family-of-cam-curves-from-a-single-index-test/

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



Taken from Shi et al. (2018).
https://doi.org/10.23919/ACC.2018.8431814

Energy throughput

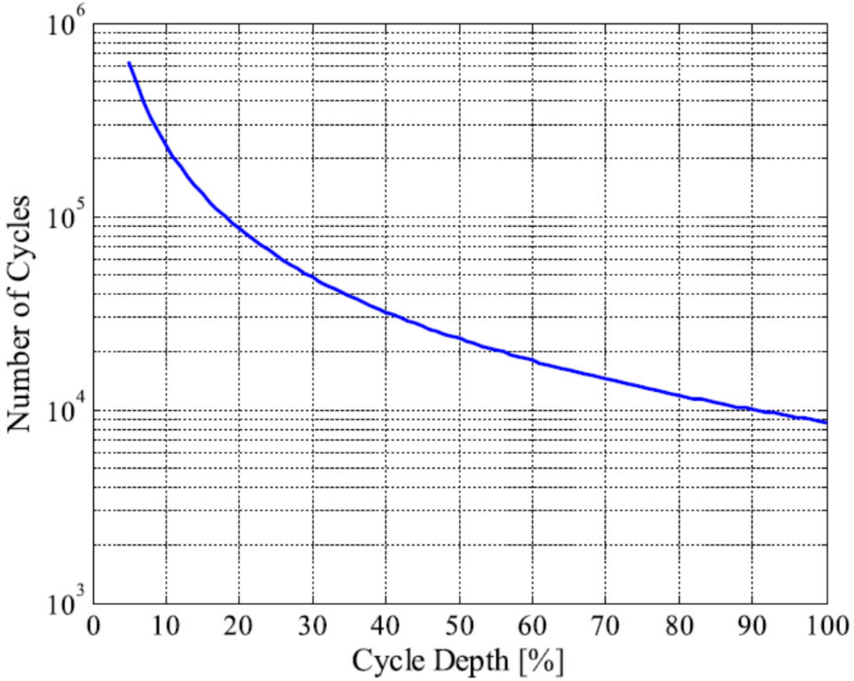
$$q = B_1 e^{B_2 I_c} \sum_{t \in \mathcal{H}} (p_t^- + p_t^+) \Delta t$$

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

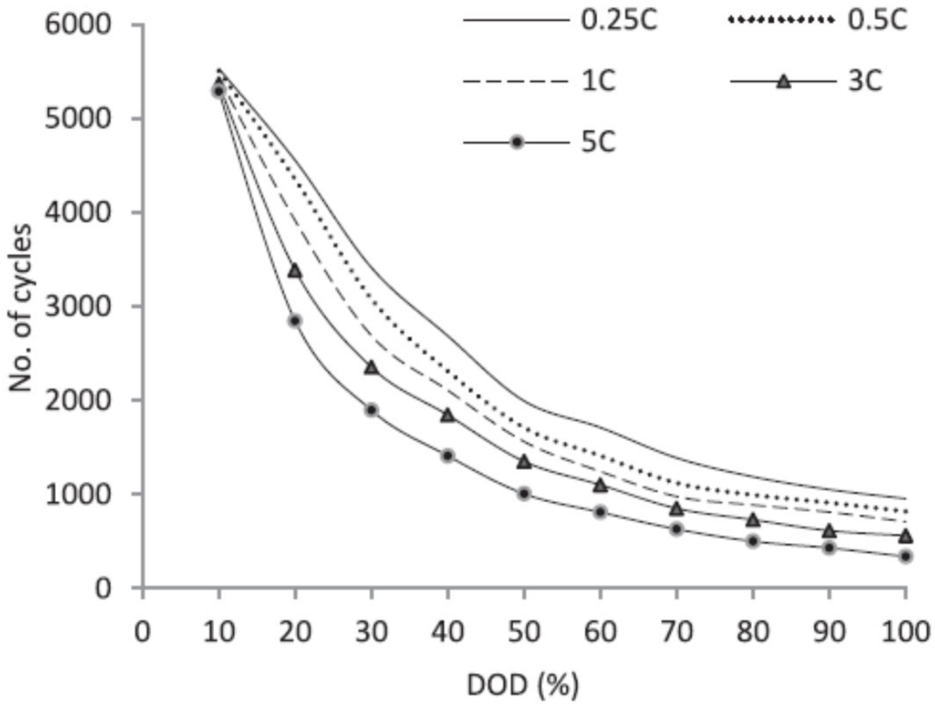
3. METHODOLOGY

TARGET MODEL FEATURES

Cycle counting



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

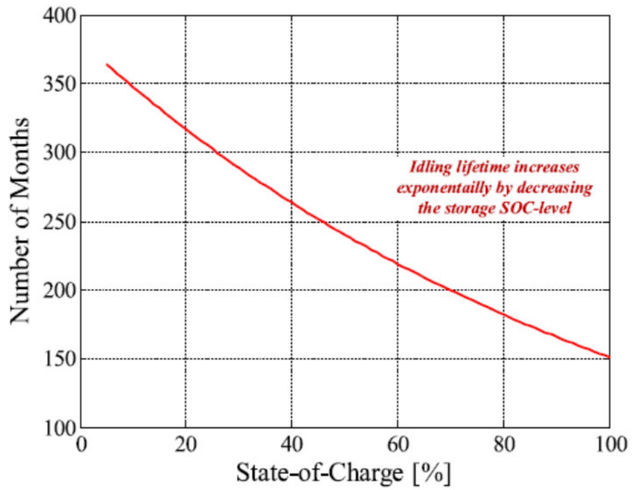


Taken from Padmanabhan et al. (2020).
https://doi.org/10.1109/TPWRS.2019.2936131

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



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

$$C_{f\_\mathrm{cal}} = 0.1723 \cdot e^{0.007388 \cdot \mathrm{SOC}\_l} \cdot t^{0.8}$$

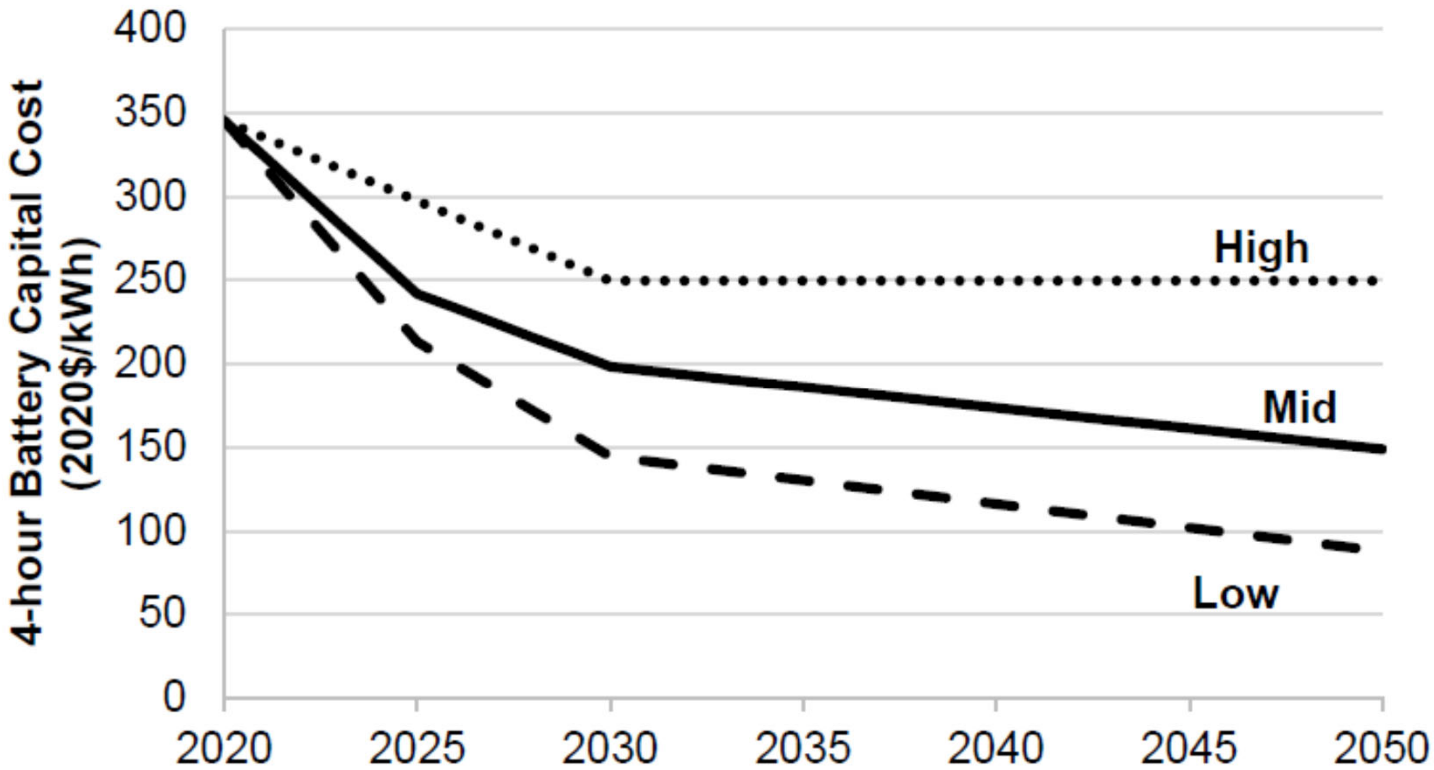
Taken from Stroe et al. (2017).
https://doi.org/10.1109/TIA.2016.2616319

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

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

3. METHODOLOGY

TARGET MODEL FEATURES

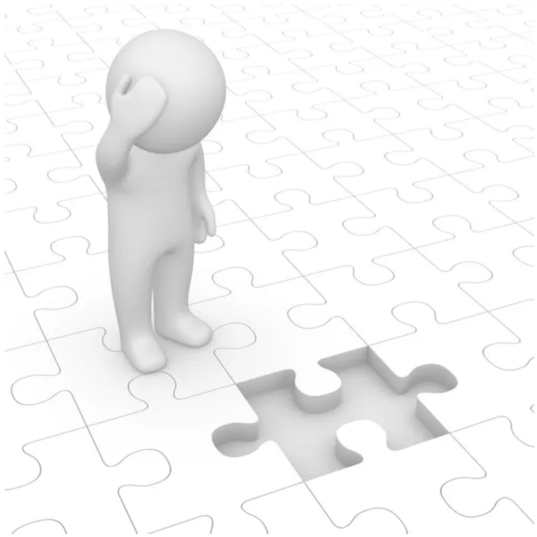


Taken from Cole et al. (2021), NREL/TP-6A20-79236.

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

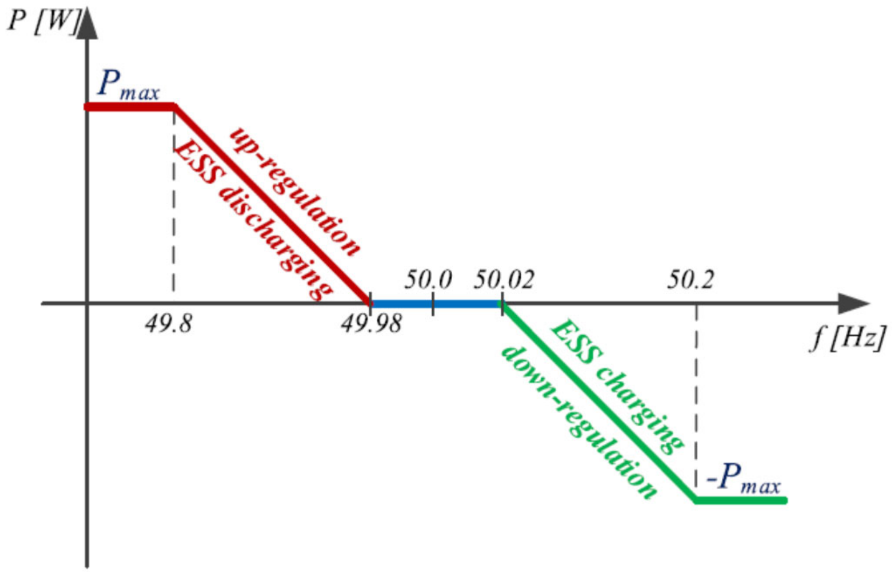
3. METHODOLOGY

TARGET MODEL FEATURES

Model uncertain inputs and robustness

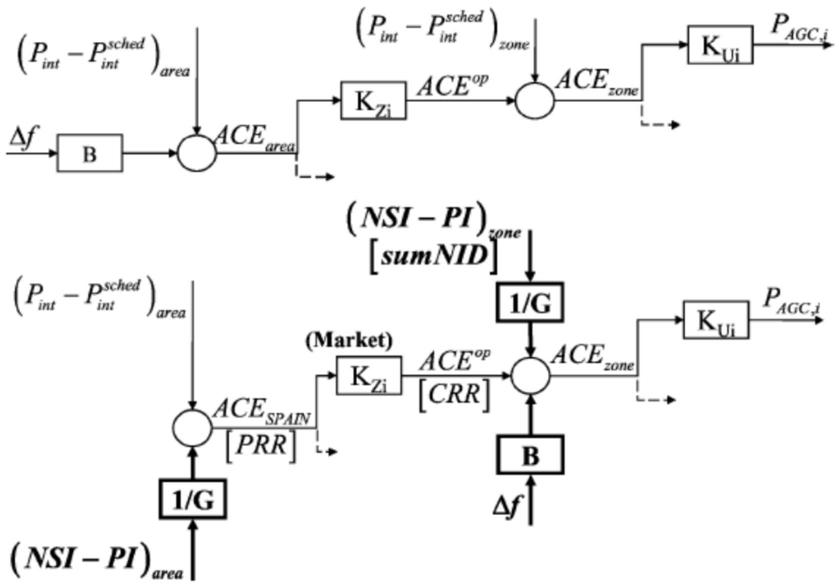
- Water inflows
- Market prices
- Regulation energy requested in real-time

FCR COOPERATION



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

SPANISH aFRR

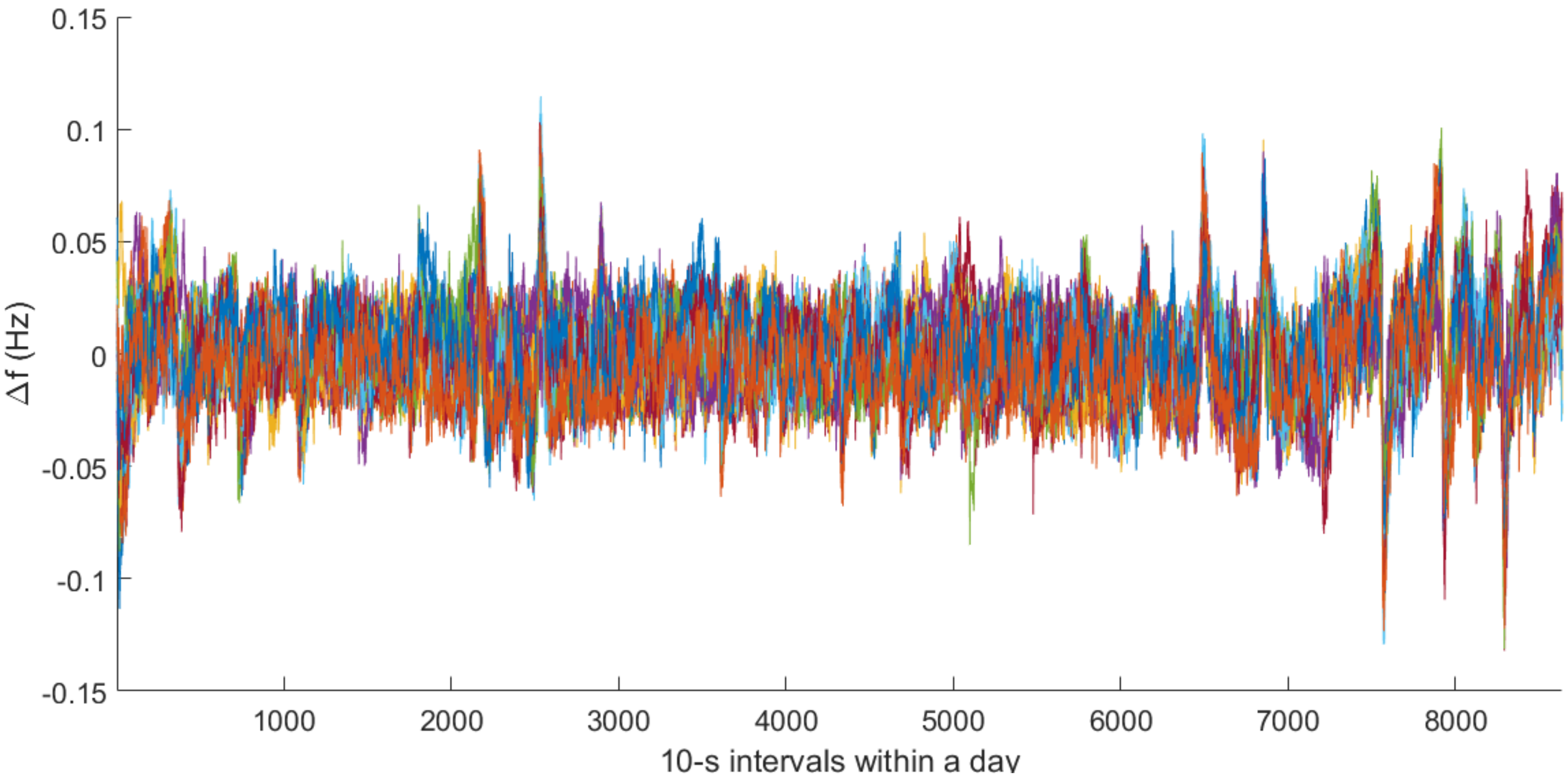


Taken from Egido et al. (2009)
https://doi.org/10.1109/TPWRS.2008.2007003

3. METHODOLOGY

TARGET MODEL FEATURES

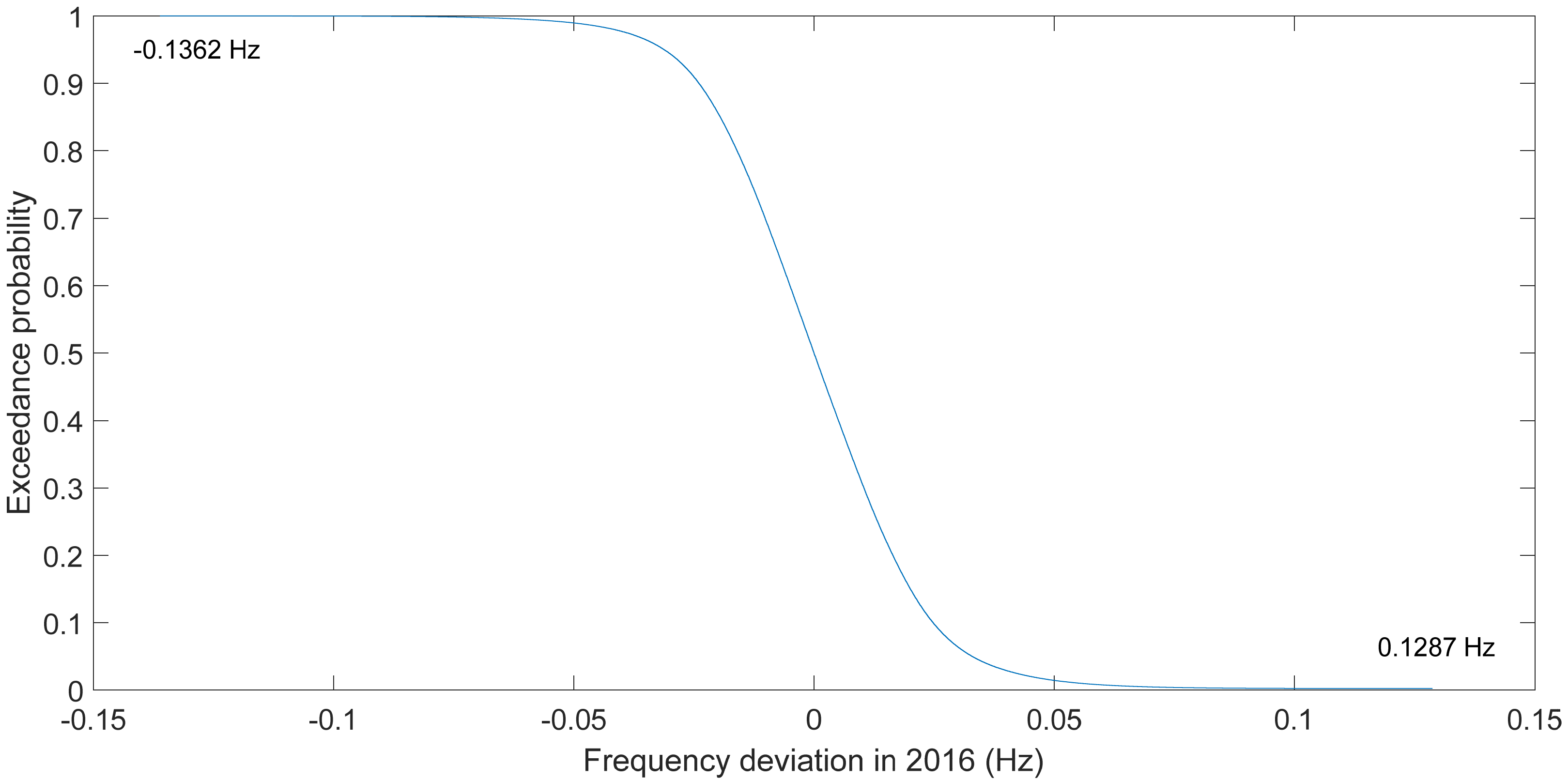
FCR COOPERATION



3. METHODOLOGY

TARGET MODEL FEATURES

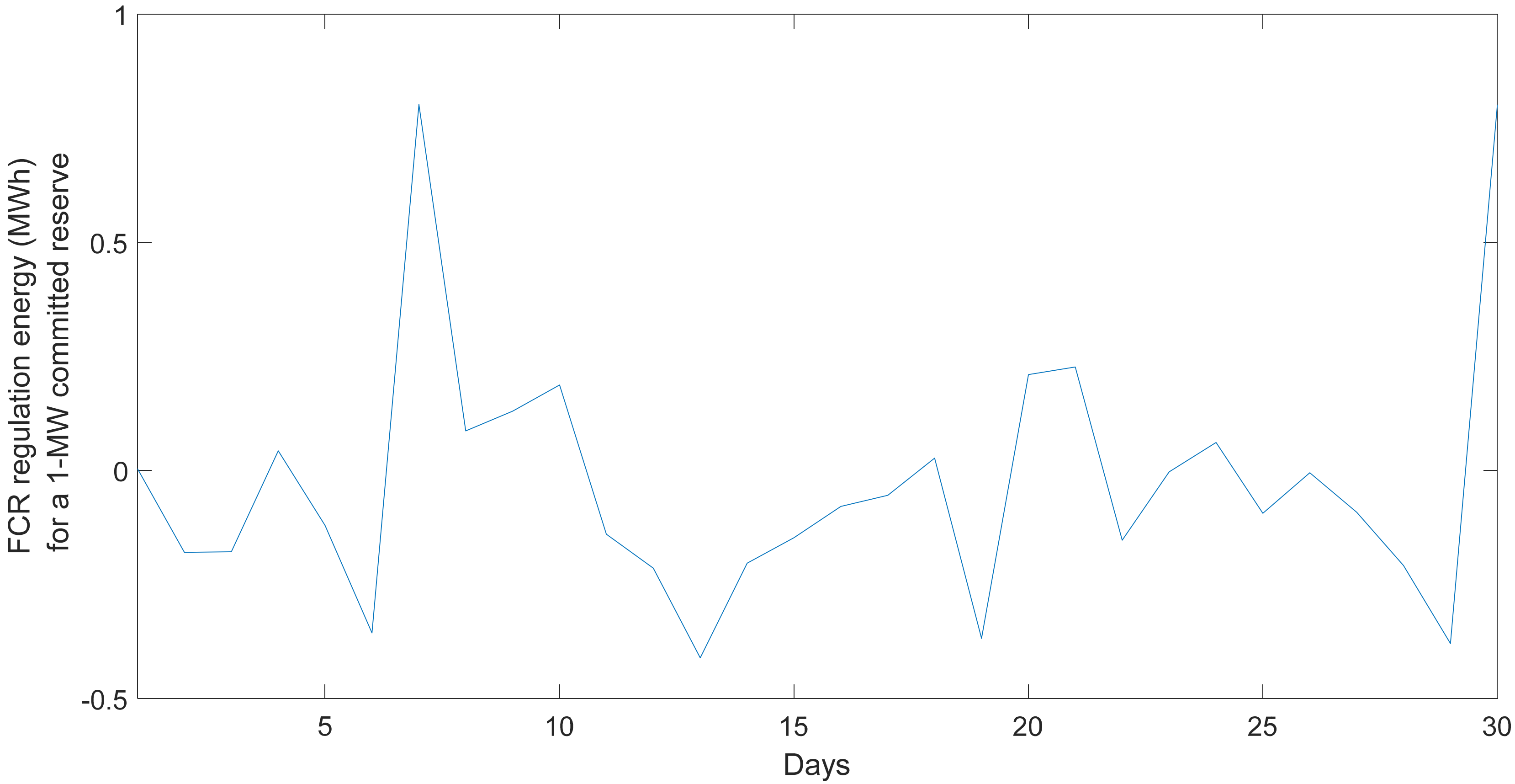
FCR COOPERATION



3. METHODOLOGY

TARGET MODEL FEATURES

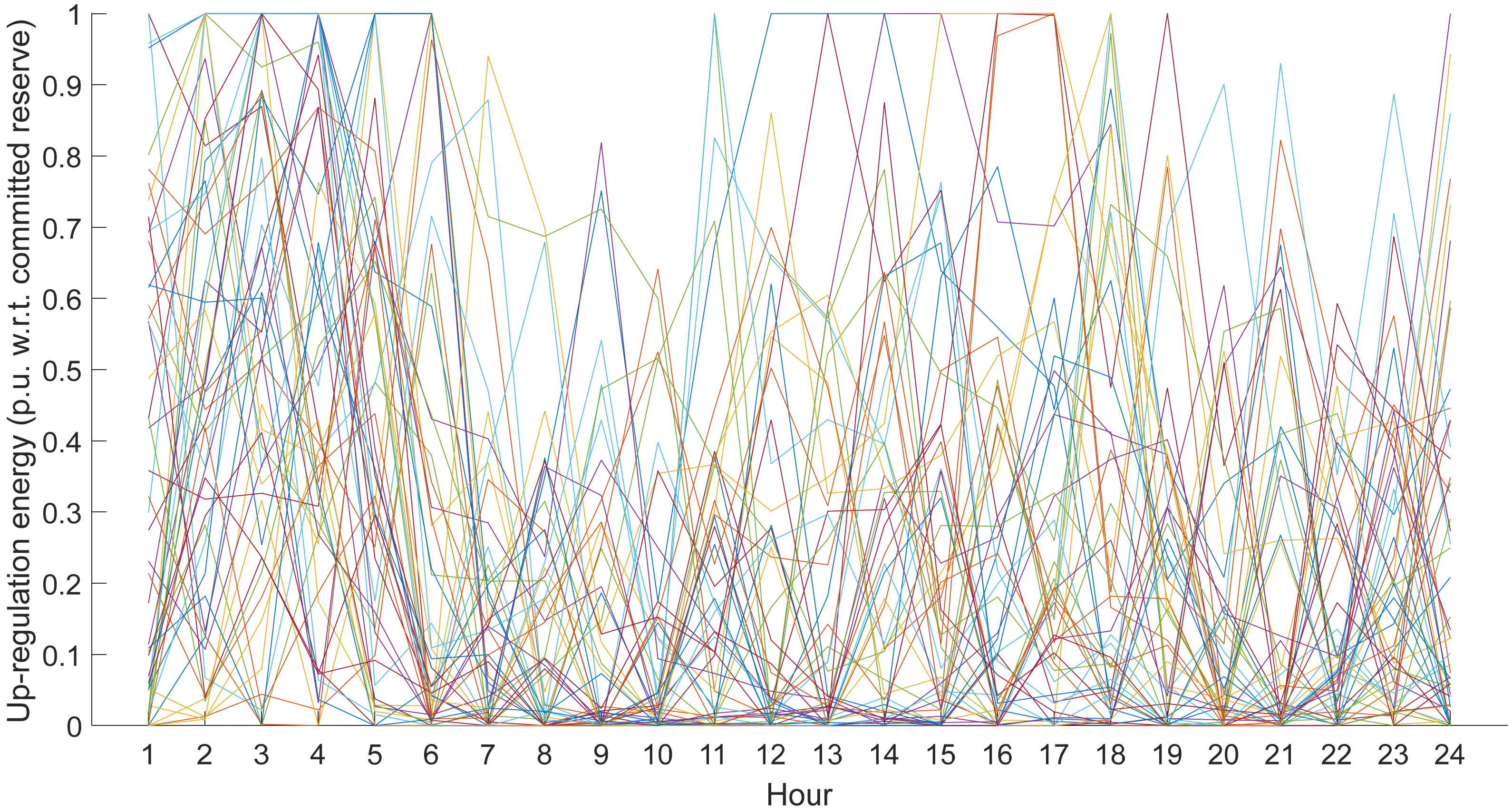
FCR COOPERATION



3. METHODOLOGY

TARGET MODEL FEATURES

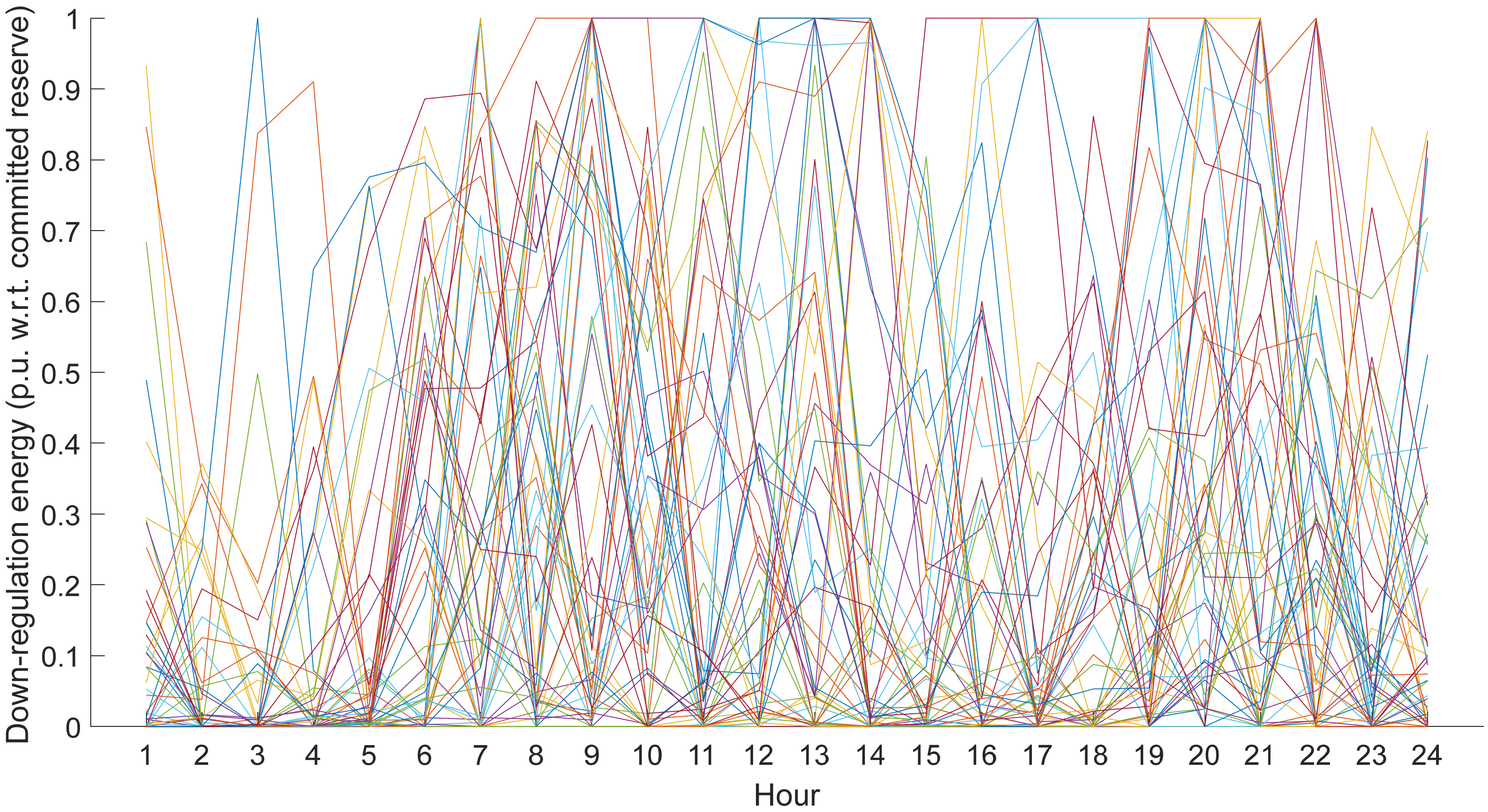
SPANISH aFRR



3. METHODOLOGY

TARGET MODEL FEATURES

SPANISH aFRR



3. METHODOLOGY

TARGET MODEL FEATURES

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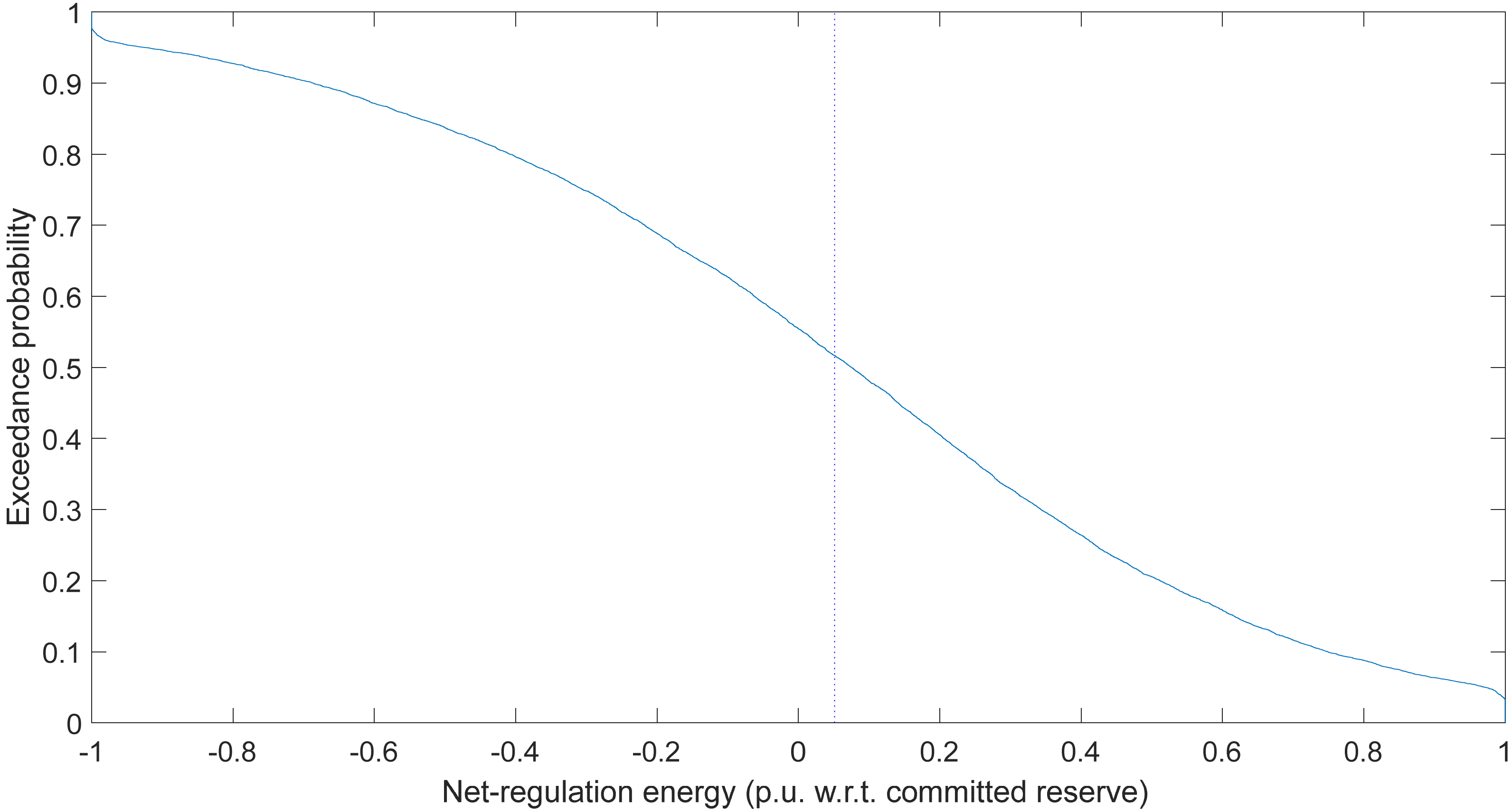

3. METHODOLOGY

TARGET MODEL FEATURES

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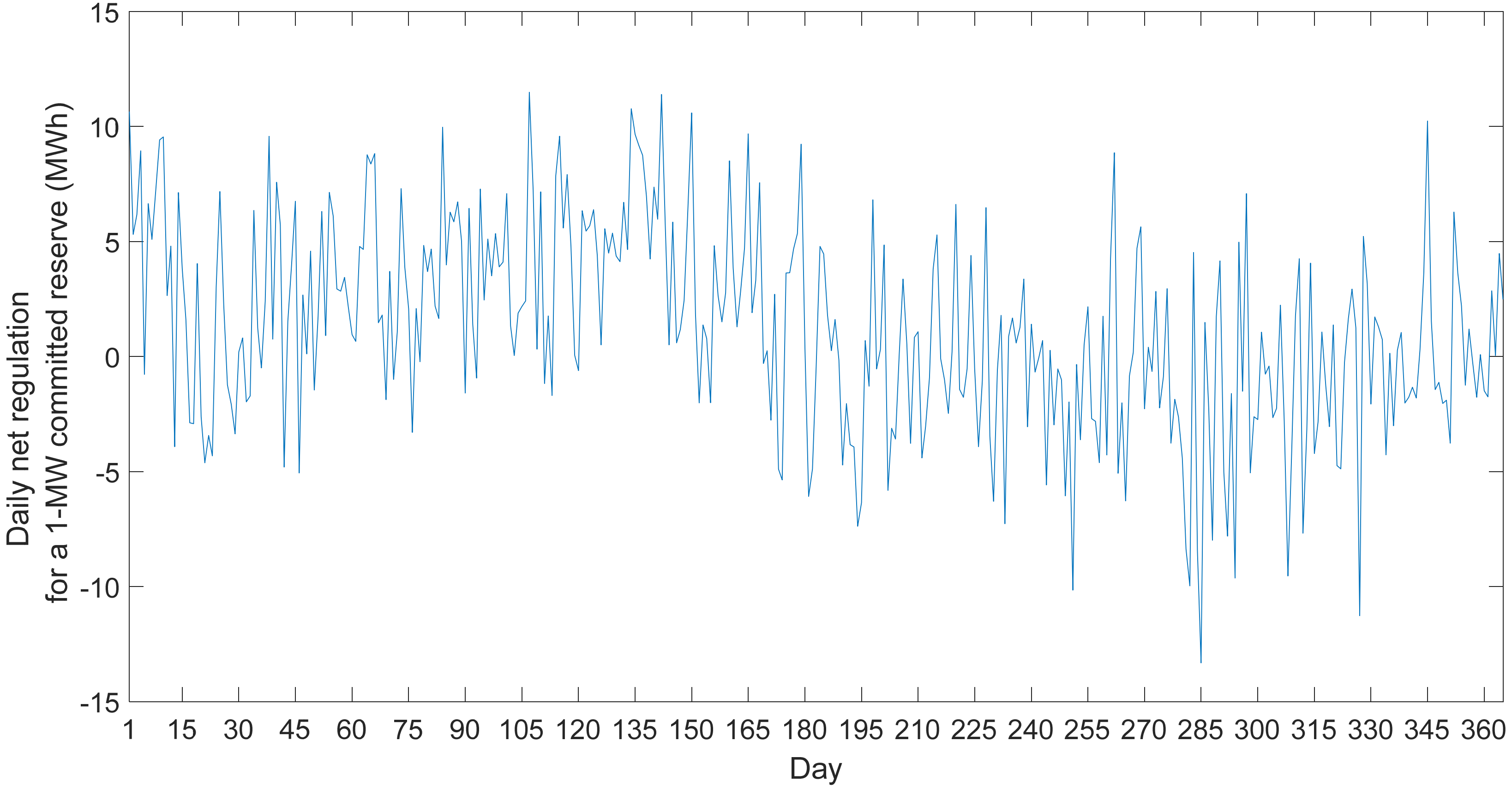


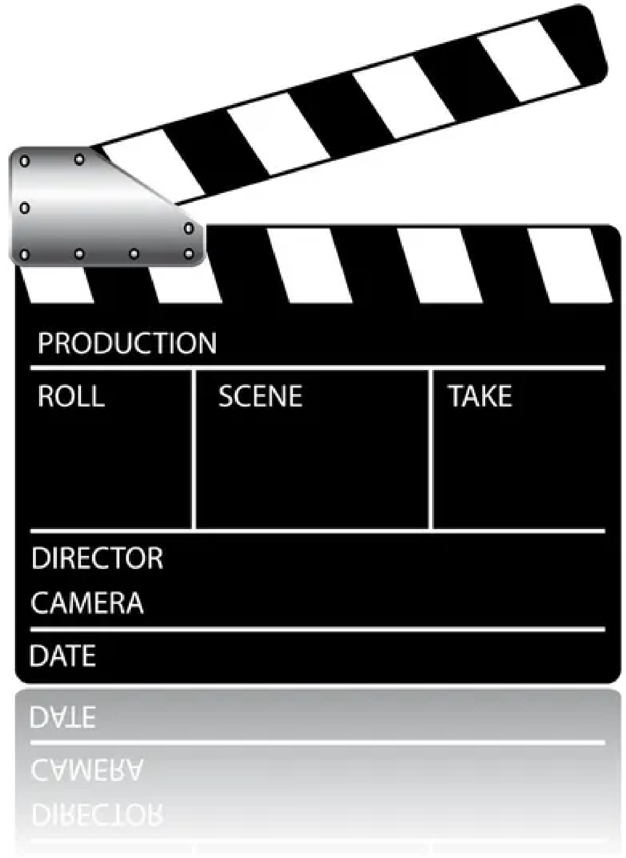
4. CASE STUDY FOR MODEL VALIDATION

- 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"**

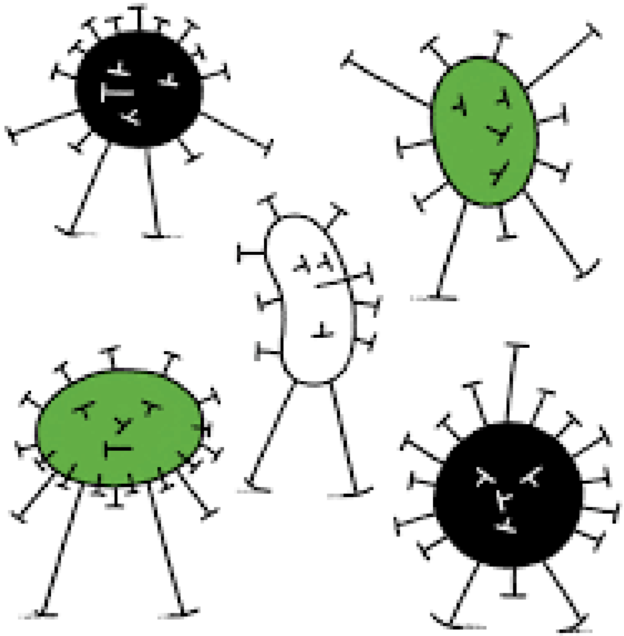


All other uncertain variables are assumed known (energy prices, reserve prices, regulation energy prices, inflows)

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

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

The revenue with BESS and hydro providing aFRR is always higher ☑

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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 ☑

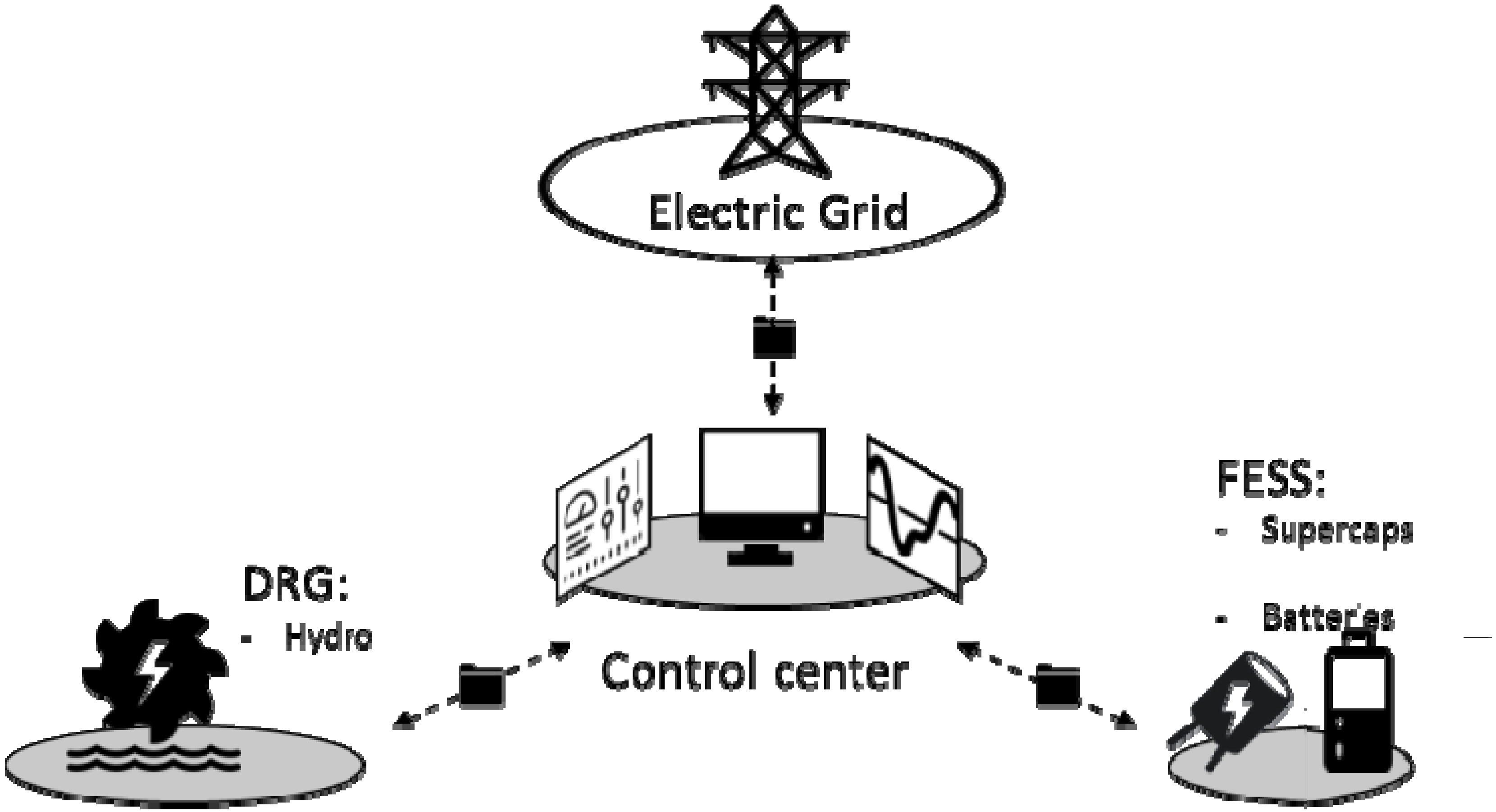
6. OPEN RESEARCH QUESTIONS

- **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!

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