DESTEC
DIPARTIMENTO DI INGEGNERIA
DELL'ENERGIA, DEI SISTEMI, DEL TERRITORIO E DELLE COSTRUZIONI

09 January 2024 – 2nd Year PhD Activity **XXXVII cycle** – Università di Pisa

Theme: «Analysis of the potential development of renewable energy sources for achieving the objectives of the coming decades»

The role of Redox Flow Batteries in the energy sector

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Abstract

To evaluate the possible role that Redox Flow Batteries (RFBs) can play in the energy sector, we conduct a bottom-up techno-economic analysis of different types of RFBs, first by assessing capital and levelized storage costs, and then by modelling these batteries in real-case scenarios, assessing revenue streams derived from the optimal dispatch of wind energy. Results show that, in terms of capital and levelized costs, Aqueous Organic Redox Flow Batteries (AORFBs) have higher projected costs on average than state-of-the-art Vanadium Redox Flow Batteries (VRFBs), although indicated in literature as a promising low-cost and environmentally safe alternative to inorganic flow batteries, due to cheap electrolyte active materials. The investigation of the optimal use of flow batteries along lithium-ion batteries, in a hybrid storage system, show that there are positive effects to the hybridization for the life of the lithium-ion battery, but that VRFB capital costs are still too high for effective deployment for energy arbitrage and balancing services.

Keywords
- *Energy systems modeling*
- *Techno-economic analyses*
- *Unit commitment and scheduling*
- *Redox Flow Batteries*
- *Renewable sources integration*
- *Hybrid storage systems*

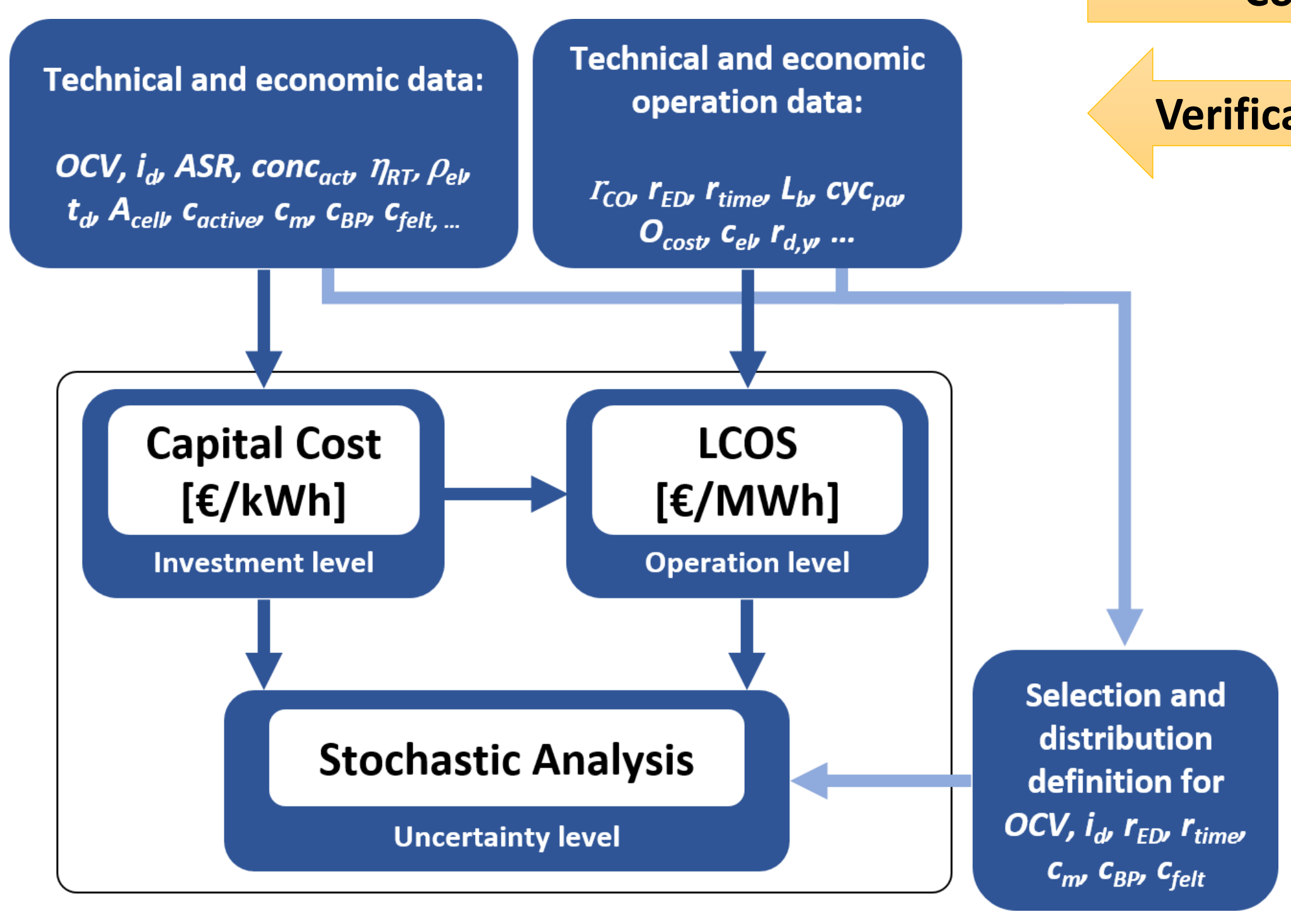
INTRODUCTION

- **Energy storage technologies** can improve the reliability and the stability of a system with an increasing **renewable energy integration**, smoothing out the fluctuations in the production, and by load-shifting.
- This research focuses on developing **innovative methodologies** for programming, managing, and controlling energy networks containing storage systems to facilitate the integration of RES.
- Through **techno-economic assessments** and **mathematical optimization** we aim to evaluate the potential role of **redox flow batteries,** a promising technology for renewable energy storage, due to their scalability, long lifespan, and versatility.
- Capital and levelized costs are evaluated for the **Vanadium Redox Flow Battery (VRFB)** and the **Aqueous Organic Redox Flow Battery (AORFB)**, to compare the technologies and identify the most relevant **parameters** for **cost-effective** deployment of the most successful alternative.
- Then mathematical optimization techniques are employed to determine the **optimal size, configuration** and **scheduling** of a **VRFB** along with a lithium-ion batteries in a hybrid battery system, for a Danish case.

METHODS

Techno-economic analysis

- **Capital cost:** bottom-up model, investment level cost for RFBs. Validated on Vanadium Redox Flow Batteries (VRFBs) and applied to innovative Aqueous Organic Redox Flow Batteries (AORFBs).
- **Levelized cost of storage** (**LCOS**): system's performance and financial assumptions to analyze the costs of battery operation. Validated on VRFBs and applied to AORFBs.
- **Stochastic analysis**: impact of uncertainty and variability range on capital cost and LCOS. Applied to AORFBs (technical and cost parameters uncertain), Montecarlo approach.


Technical and economic data:
OCV, i_d, ASR, $conc_{act}$, η_{RT}, ρ_{el}, t_d, A_{cell}, c_{active}, c_m, c_{BP}, c_{felt}, ...

Technical and economic operation data:
r_{CO}, r_{ED}, r_{time}, L_b, cyc_{pa}, O_{cost}, c_{el}, $r_{d,y}$, ...

Capital Cost [€/kWh]
Investment level

LCOS [€/MWh]
Operation level

Stochastic Analysis
Uncertainty level

Selection and distribution definition for *OCV, i_d, r_{ED}, r_{time}, c_m, c_{BP}, c_{felt}*

Cost inputs

Verification and targets

AORFB input data → **Uncertain parameters** → **Sensitivity analysis** → **Key parameters** → **Probability distributions** → **Random samples** → **Stochastic analysis**

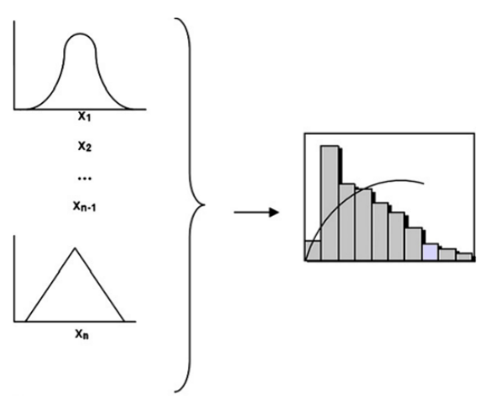


Table 1: Symbol, name, unit of measurement, and probability distribution characteristics for uncertain parameters, in present and future cost scenarios

Symbol	Name	Unit	Lower bound	Upper bound	Mean	Distribution
i_d	Current density	mA/cm^2	10	100	55	Uniform
OCV	Open circuit voltage	V	0	1.8	1.09	Lognormal
r_{ED}	Electrolyte decay rate	$\%/cycle$	$4{\cdot}10^{-4}$	0.1	0.018	Loglogistic
r_{time}	Calendar degradation	$\%/day$	0.014	0.76	0.39	Uniform
Scenario: present						
c_{BP}	Bipolar plate cost	€$/m^2$	37	418	125	Exponential
c_{felt}	Electrode felt cost	€$/m^2$	14	150	52	Gamma
c_m	Membrane cost	€$/m^2$	16	451	247	Triangular
Scenario: future						
c_{BP}	Bipolar plate cost	€$/m^2$	19	33	25	Lognormal
c_{felt}	Electrode felt cost	€$/m^2$	13	18	16	Normal
c_m	Membrane cost	€$/m^2$	16	156	66	Lognormal

AORFBs characteristics:
- **Novel alternative** to metallic RFBs, high molecular tunability
- Does not rely on **scarce resources**, can contribute to a **more sustainable** energy storage solution
- Potentially cheap materials (≃ 1/10 vanadium cost in €/kg)

Probability distributions (Table 1) from literature on organic redox species [1,2].

Mathematical Optimization

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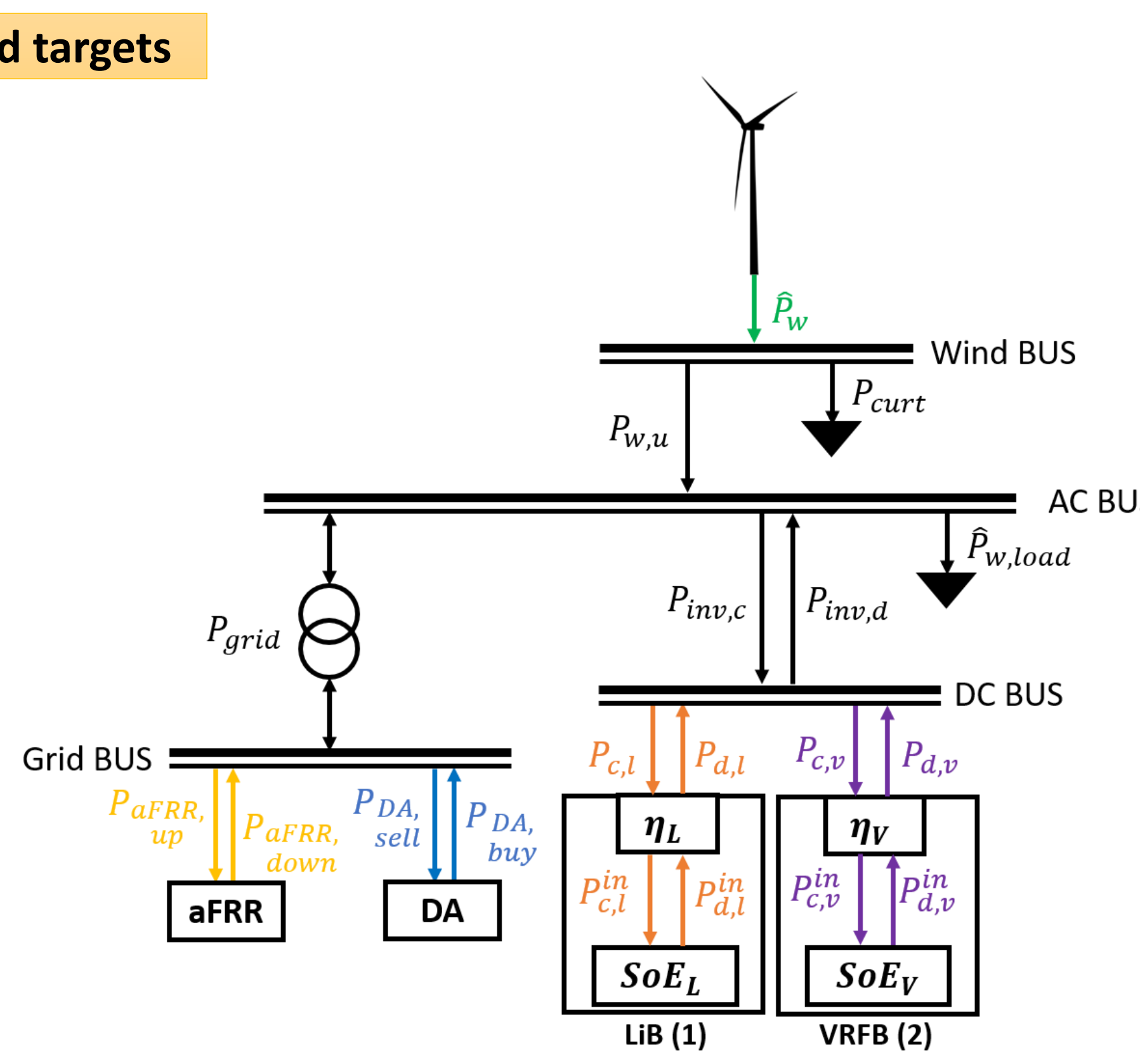
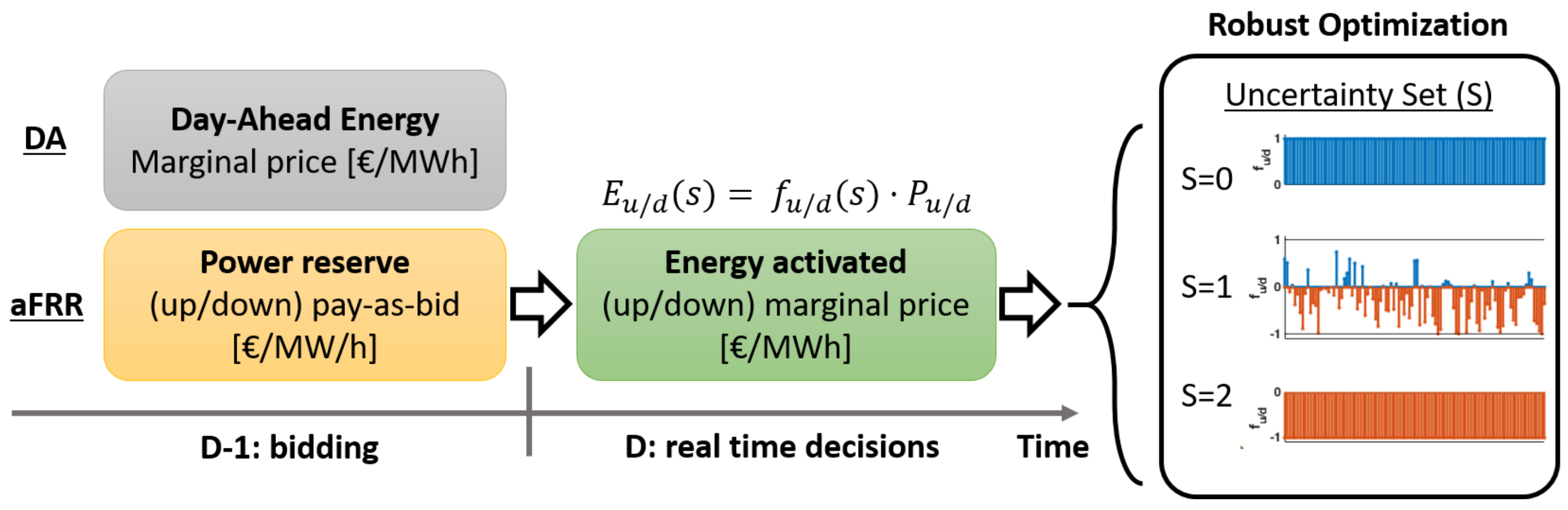


- Objective: potential market revenue from a wind plant with a **hybrid storage system (HESS)** of lithium-ion battery (LiB) and vanadium redox battery (VRFB).
- Market case: Danish **day-ahead** (**DA**) and **automatic frequency restoration reserve** (**aFRR**) market.
- Problem: Mixed Integer Linear Program (MILP), hourly resolution.
- Uncertainty: **robust optimization**. Historical data and two worst-case scenarios (max up/down-regulation) for aFRR.


Robust Optimization

DA — **Day-Ahead Energy** Marginal price [€/MWh]

aFRR — **Power reserve** (up/down) pay-as-bid [€/MW/h] ⇨ **Energy activated** (up/down) marginal price [€/MWh] ⇨

$$E_{u/d}(s) = f_{u/d}(s) \cdot P_{u/d}$$

D-1: bidding | **D: real time decisions** **Time**

Uncertainty Set (S)
S=0
S=1
S=2

RESULTS

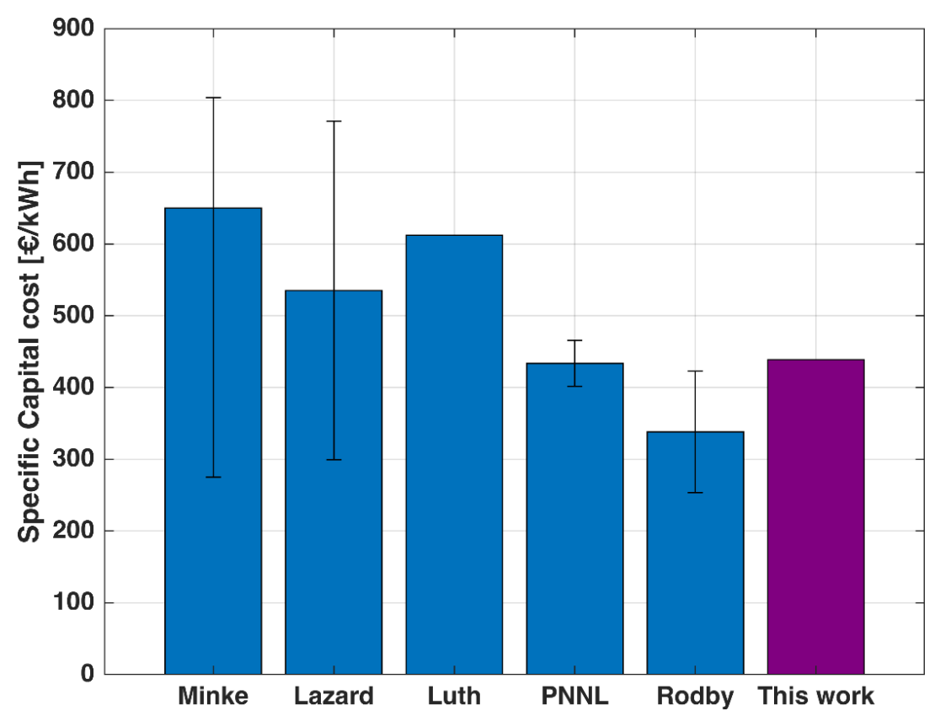


Figure 1: Validation of specific capital cost against literature for 4h VRFB

Symbol	Name	Relative variation [%]
Technical parameters		
OCV	Open circuit voltage	+14
$\eta_{sys,d}$	Auxiliary discharging efficiency	+15
i_d	Current density	+30
ASR	Area-specific resistance	<-90
$conc_{act}$	Concentration of active species	>+190
Economic parameters		
c_m	Cost of membrane	-40
c_{active}	Cost of active material	-89
c_{felt}	Cost of electrode felt	<-90
c_{BP}	Cost of bipolar plate	<-90

Table 2: Parameter and relative variation required to achieve a 10% reduction in the average capital cost of 4h AORFB

- Successful validation of cost model on VRFB for capital (Fig. 1) and LCOS.
- **Sensitivity analysis** of uncertain parameters of average AORFB (Table 2), changing the value of one parameter at the time.

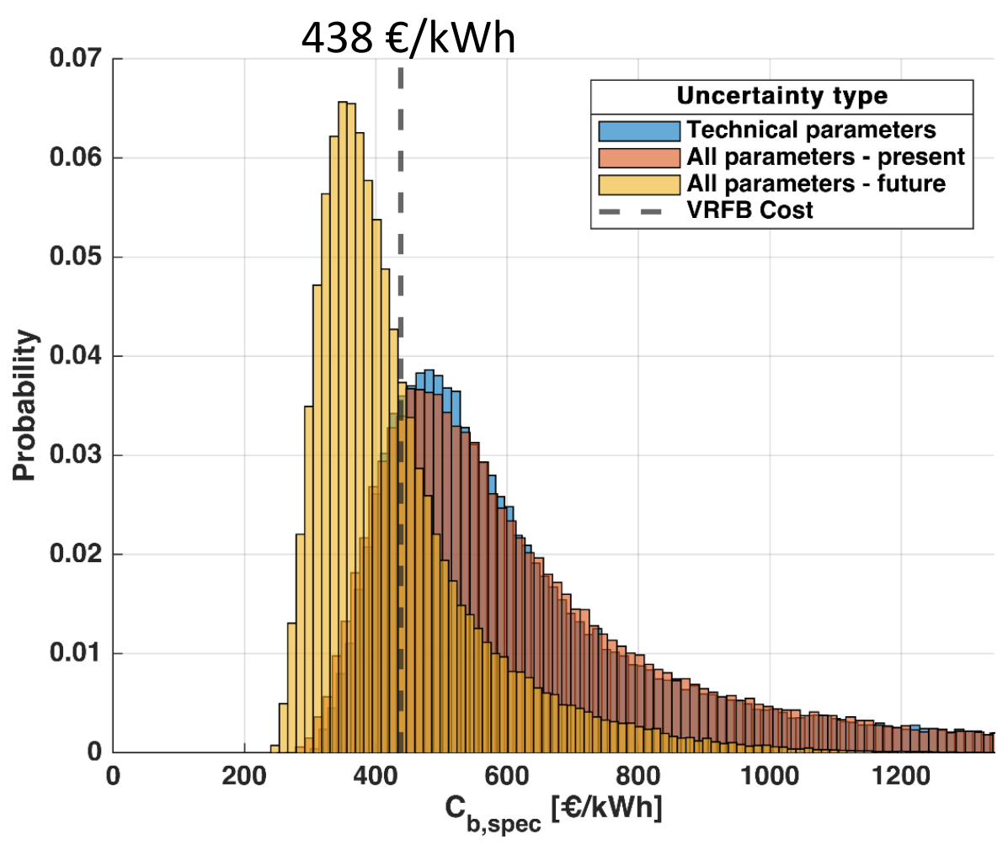


Figure 2: Specific capital cost of 4h AORFBs against VRFB cost

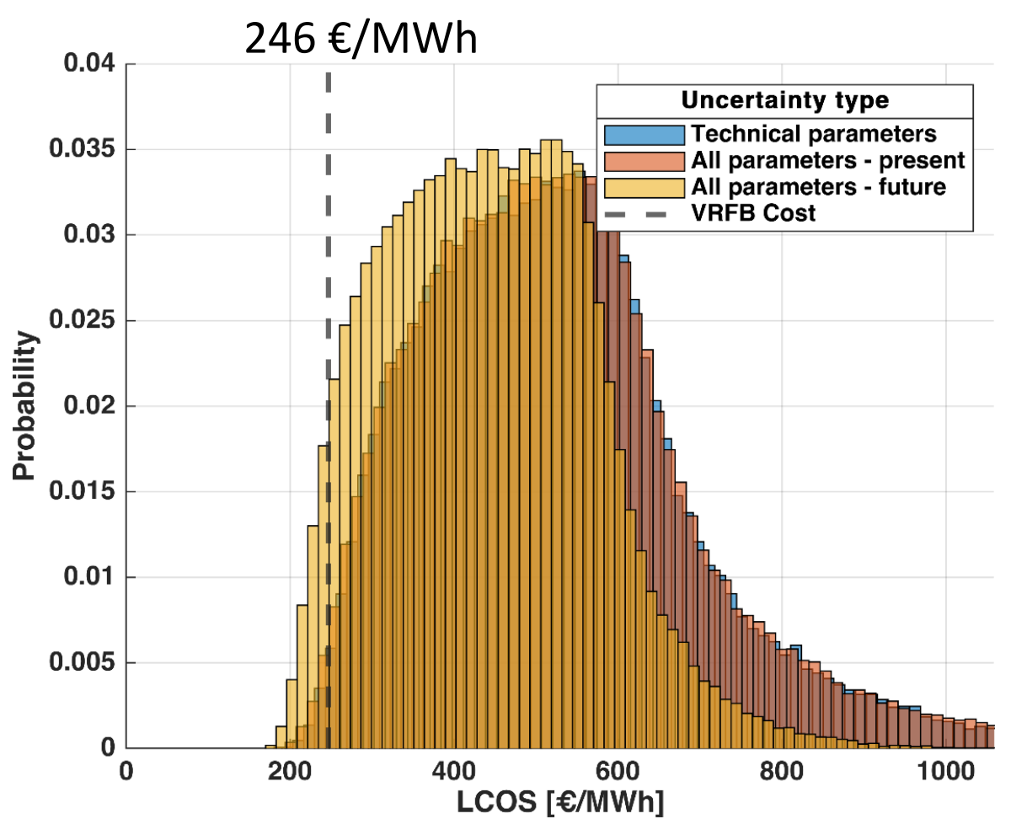


Figure 3: Net LCOS of 4h AORFBs against VRFB LCOS

Cost results for AORFBs with 4h discharge time:
- Average specific capital cost of **674 €/kWh,** 16.9%-29.6% chance of costs lower than VRFB's (438 €/kWh).
- Average net LCOS, of **530 €/MWh**, less than 1% chance of LCOS lower than VRFB's (246 €/MWh).

Robust model and hybridization effects:
- 10MW of wind power, 1MW/1MWh LiB, 500kW/2MWh VRFB
- **Non-robust formulation:** overestimates the optimal annual revenue by **132%**.
- Number of average charge/discharge cycles per day: 4.3 (LiB) and 2.6 (VRFB) - non-robust case; 1.1 and 1.2 - robust case.
- **Hybrid system**: increases life of LiB up to **31%.**

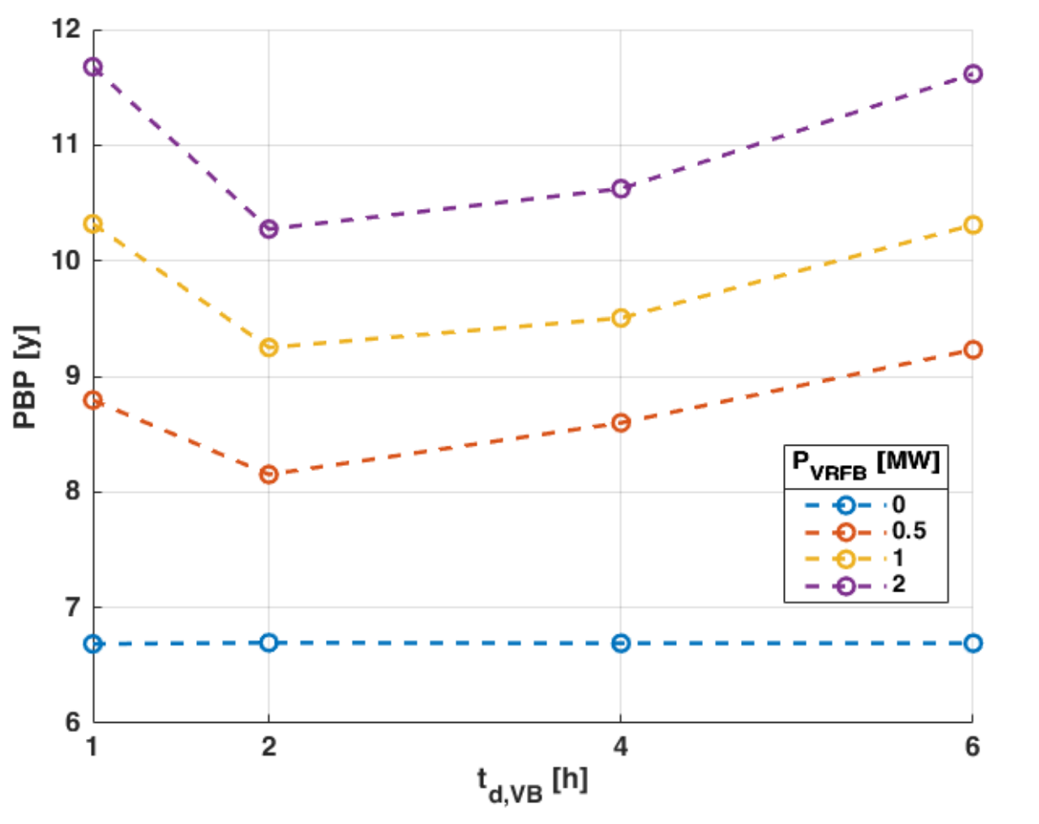


Figure 5: Payback period of the investment compared to a case without HESS, versus VRFB size, for a 1MW/1MWh LiB

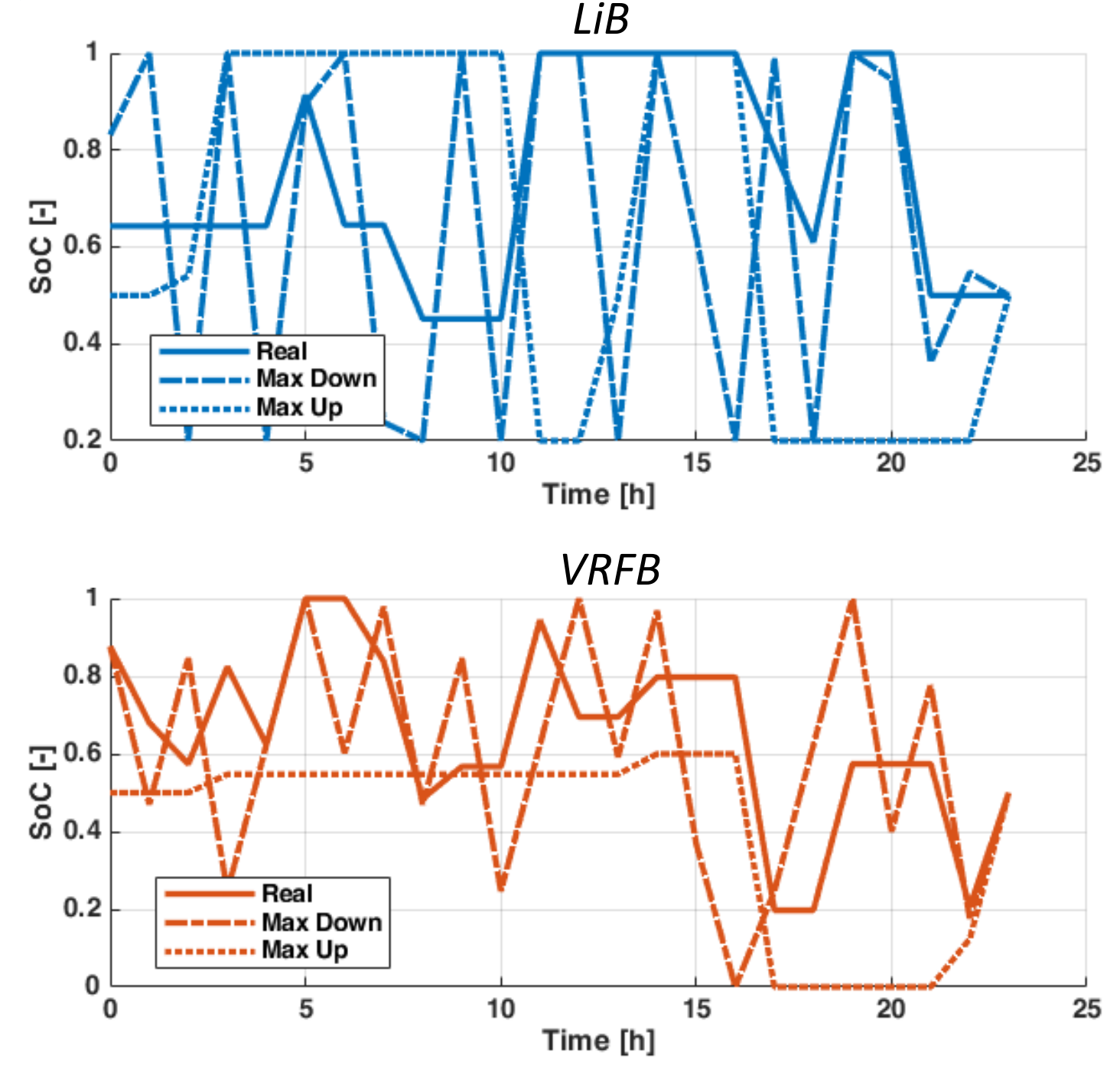


Figure 4: Optimal LiB and VRFB state of charge for different scenarios of the robust optimization

Results of the sensitivity to size analysis:
- Optimal scenario with the lowest VRFB power and nominal discharge time of 2h (Fig. 5).
- If any size of VRFB is installed, the optimal LiB size is 1 MW/1MWh (energy cost of 200 €/kWh [3], total replacement after 6-9 years).

CONCLUSIONS

1. Organic flow batteries (AORFBs) cannot compete with state-of-the-art vanadium flow batteries
2. High uncertainty on the cost of AORFBs, high and uncertain degradation rates.
3. VRFBs do not constitute a good investment for DA and aFRR market bidding.
4. Promising hybridization effects on batteries

PUBLICATION & CONFERENCES

- D. Cremoncini, G. Di Lorenzo, G.F. Frate, A. Bischi, A. Baccioli, L. Ferrari, "Techno-Economic Analysis of Aqueous Organic Redox Flow Batteries: Stochastic Investigation of Capital Cost and Levelized Cost of Storage", (revision stage) in *Applied energy*

Conferences:
- International Flow Battery Forum – Prague, June 2023
- Zero Emission conference – Rome, October 2023

compbat
- European Project (GA n. 875565)

IFBF

FUTURE RESEARCH

ENEA Research Center:
- Renewable energy production and management in domestic context. Maximize self-consumption and promote energy independence of the condominium.
- Design and management of hybrid **electrical** and **thermal energy storage** systems.
- **Centralized** and **distributed storage cases** comparison.

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[1] D. G. Kwabi, Y. Ji, and M. J. Aziz, "Electrolyte lifetime in aqueous organic redox flow batteries: A critical review," Chemical Reviews, vol. 120, no. 14, pp. 6467–6489, 2020
[2] V. Singh, S. Kim, J. Kang, and H. R. Byon, "Aqueous organic redox flow batteries," Nano Research, vol. 12, p. 1988–2001, 2019
[3] K. Mongird, V. Viswanathan, J. Alam, C.Vartanian, and V. Sprenkle. "2020 Grid Energy Storage Technology Cost and Performance Assessment". Technical report, PNNL, 2020