12° January 2022 - 1st Year PhD Activity **XXXVII cycle** – Università di Pisa

«ANALISI DEL POTENZIALE DELLO SVILUPPO DELLE FONTI RINNOVABILI PER IL RAGGIUNGIMENTO DEGLI OBIETTIVI DEI PROSSIMI DECENNI»

The role of Redox Flow Batteries in the energy sector

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INTRODUCTION

Abstract

- **Energy storage technologies** can facilitate the **integration of renewable energy**, e.g. to help smoothing out the fluctuations in the supply of renewable energy, by storing excess energy when it is available and discharging it when it is needed, improving the reliability and the stability of the energy system.
- In this research, we explore the use of **techno-economic assessments** and **mathematical optimization** to evaluate the potential of **redox flow batteries** for energy storage in the integration of renewable energy. Redox flow batteries are a promising technology for energy storage due to their scalability, long lifespan, and ability to store and discharge electrical energy through a redox reaction.
- Techno-economic assessments are used to evaluate the **costs and benefits** of implementing **different** types of **redox flow batteries** and to identify the most relevant **parameters** for **cost-effective deployment**.
- Mathematical optimization techniques are then used to determine the **optimal size, configuration** and **scheduling** of a **vanadium redox flow battery (VRFB)**, evaluated in real case scenarios. These techniques can help verify the results from techno-economic assessment.
- The aim of the research is to develop **innovative methodologies** for programming, managing, and controlling future energy networks to facilitate the integration of renewable energy sources.

Keywords

- *Energy systems modeling*
- *Techno-economic analyses*
- *Unit commitment and scheduling*
- *Redox Flow Batteries*

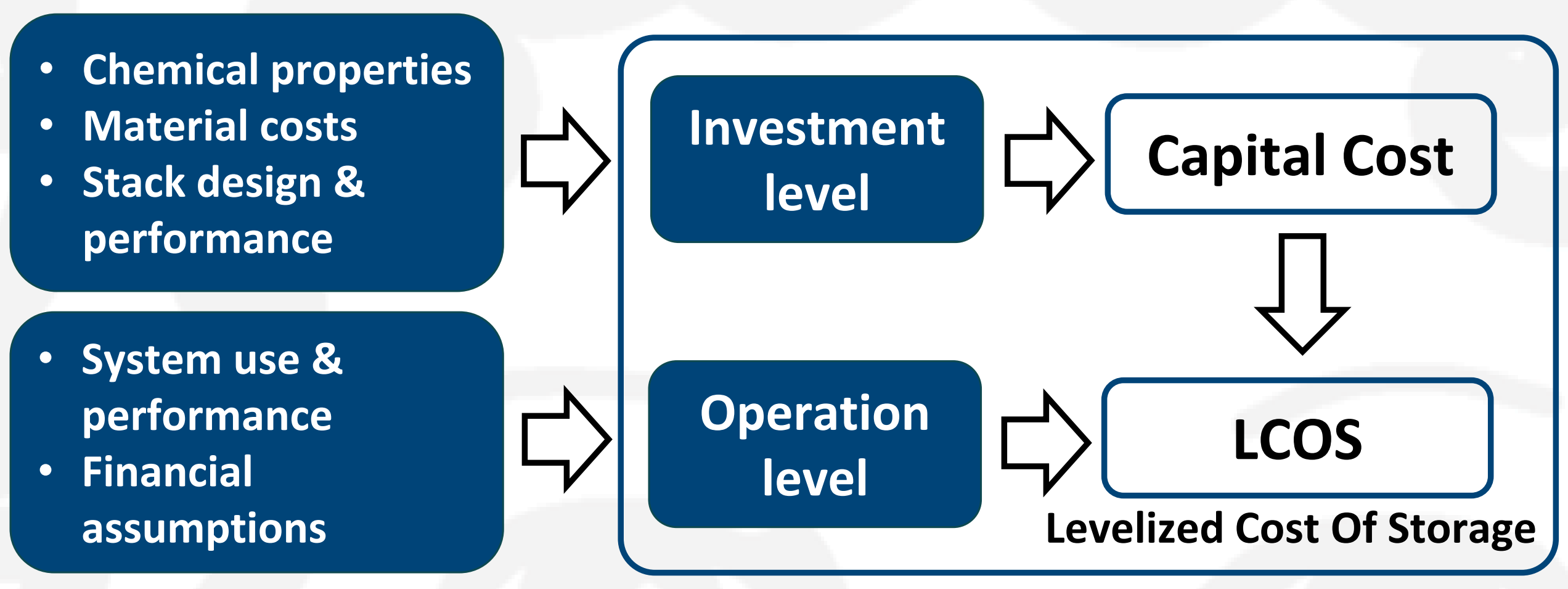
Objectives

1. Develop innovative methodologies for renewable integration.
2. Evaluate potential applications of redox flow batteries for energy storage.
3. Use techno-economic assessments and optimization techniques.

METHODS

Techno-economic analysis

- **Redox flow batteries** are a promising but still **developing technology** for energy storage, there is a high uncertainty around their cost and performance in real-world scenarios.
- Techno-economic assessments are used to evaluate upfront **capital costs** and ongoing **operating costs** (LCOS – Levelized Cost of Storage). These assessments can also consider factors such as the expected lifespan of the batteries, the potential for cost savings or revenue generation, and any externalities or external costs associated with their use.
- The goal of this analysis is to identify the most **cost-effective** flow batteries for a specific **application** and guide future research towards their development.



- **Chemical properties**
- **Material costs**
- **Stack design & performance**

- **System use & performance**
- **Financial assumptions**

Investment level → **Capital Cost**

Operation level → **LCOS**

Levelized Cost Of Storage

Lumped parameters model with daily resolution

Influence of technical properties on economic indicators:

- $C_b = C_E \cdot E_{b,nom} + C_P \cdot P_{b,nom}$ [€]
- $V_{cell,d} = OCV - i_d \cdot ASR$ [V]
- $\rho_E = conc_{act} \cdot F \cdot V_{eff,d} \cdot DOD \cdot n_{e^-}$ [Wh/L]
- $a_{act} = \frac{A_{cell}}{P_{cell}} = \frac{1}{\eta_{sys,d} \cdot i_d \cdot V_{cell,d}} \left[\frac{m^2}{kW}\right]$
- $LCOS = \frac{I_0 + \sum_{t=1}^{N_y} \frac{L_t + C_{rep} + C^f_{O\&M,t}}{(1+r_{d,y})^t} + \sum_{t=1}^{K} \frac{C^v_{O\&M,t}}{(1+r_{d,d})^t}}{\sum_t^K \frac{E_{dis,t}}{(1+r_{d,d})^t}} \left[\frac{€}{MWh}\right]$

	VRFB	AORFB *(FcVi)*
Cell		
$ASR\ [\Omega \cdot cm^2]$	1.35	4
$OCV\,[V]$	1.37	0.72
$Area\ [cm^2]$	600	600
Stack		
$N\ cells$	40	40
$conc_{act}[mol/l]$	1.6	0.5
$MW_{active}[g/mol]$	51	150
$i\ [mA/cm^2]$	85.8	24.2
$Q\ [L/\min]$	20.5	24.0
$RTE\ [\%]$	74.3	54.2
$R_{fade}\ [\%/c]$	0.442	1.0
$DOD\ range\ [-]$	0.6	0.4
$\boldsymbol{\rho_E\ [Wh/l]}$	**29.4**	**2.72**
$\boldsymbol{P_{eff}\ [kW]}$	**2.5**	**0.3**
Economic		
$c_{act}[€/kg]$	30.1	3.5
$c_m\ [€/m^2]$	300	
$Life\ [y]$	20	
$r_{debt}\ [\%/y]$	0.08	
$r_{discount}\ [\%/y]$	0.12	

Table 1 - Vanadium (VRFB) and Aqueous Organic Flow Battery (AORFB with FcVi chemistry) properties

Mathematical Optimization

Detailed optimization model with hourly data and the following features:

- ✓ Experimental data for **non-linear**, **non-convex** charge and discharge **efficiencies**, as a function of battery **power** and **state of charge** (SOC)
- ✓ Techniques of **convexification** and **linearization** of **variables** and **constraints** (Fig.1)
- ✓ Implemented **degradation** model due to **crossover** and **oxidative imbalance**, which cause linear **capacity decay** (Fig.2), with daily adjustment of capacity
- ✓ Calculation of scheduled **maintenance** cost and time, with rebalancing and servicing operations, to restore lost capacity

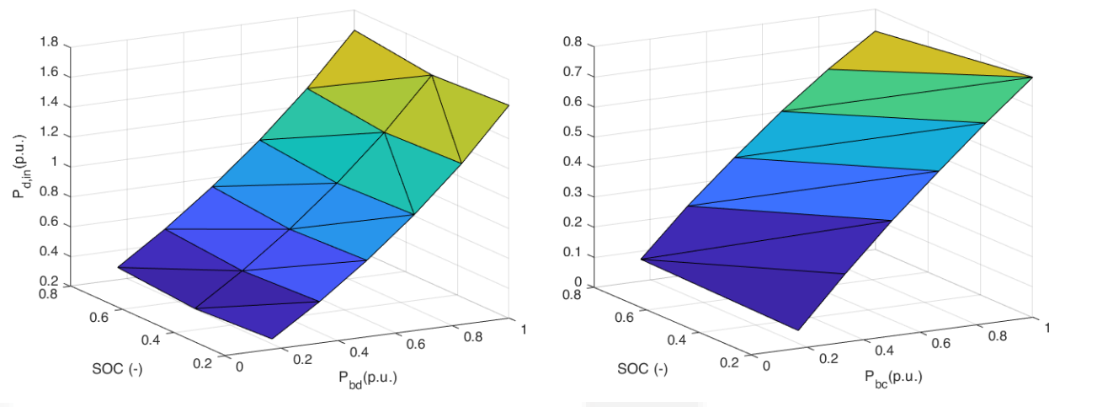


Fig. 1 - 3D convex hull of VRFB efficiencies – f(SOC,P)

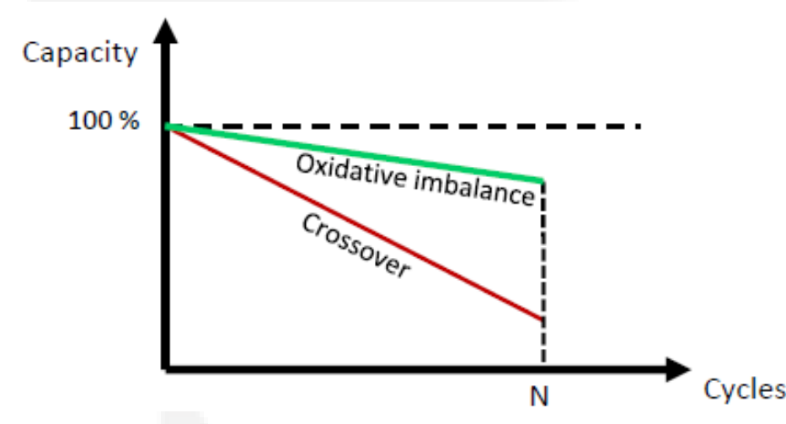
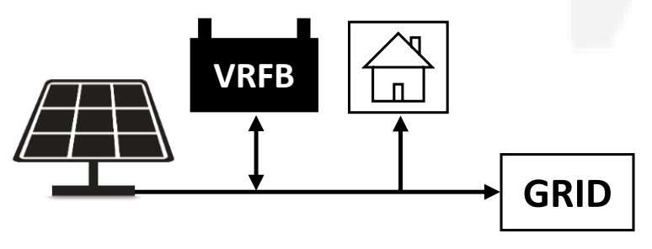


Fig. 2 – Linear capacity fade with cycling

Problem:
- Mixed-integer Linear
- Deterministic
- Single-objective
- Environment: Matlab with Yalmip toolbox
- Solving time (Gurobi™, daily-opt): **<9s**



Storage size:
45-10⁴ kW

Case Study:
1. Energy arbitrage
2. Residential case

Renewable source:
- Wind/PV solar

- Objective: maximization of the revenue from selling renewable energy to the grid:

$$Rev(d) = \tau \cdot \sum_{i=1}^{T} \hat{c}_s(i,d) \cdot P_{g,s}(i,d) - \tau \cdot \sum_{i=1}^{T} \hat{c}_p(i,d) \cdot P_{g,p}(i,d)$$

RESULTS

- Flow batteries with **organic materials** (**AORFB**) have undesirable properties: low open-circuit voltage (**OCV**), low efficiency (**RTE**), limiting cell current (**i**). These properties result in **low energy and power density**, leading to high costs, particularly for stack-related components such as membranes and electrodes.
- For a **4h** (**energy-to-power ratio**) system, the **total specific capital cost** (Fig. 3) of a VRFB is **450 €/kWh**, while the cost of an **AORFB FcVi** battery is **1876 €/kWh,** even if the cost of active species is much lower (c_{act} in Table 1).
- To compete with VRFB, AORFB should have lower costs and better properties (Fig. 4):
  - ❖ Battery D: $i = 49\ mA/cm^2, ASR = 1\Omega \cdot cm^2$
  - ❖ Battery E: $i = 49\ mA/cm^2, OCV = 1.25\ V$
- The LCOS is primarily influenced by the initial power-related costs of the battery and the capacity fade due to molecular degradation, which causes frequent chemical replacements (Fig. 5 and 6).

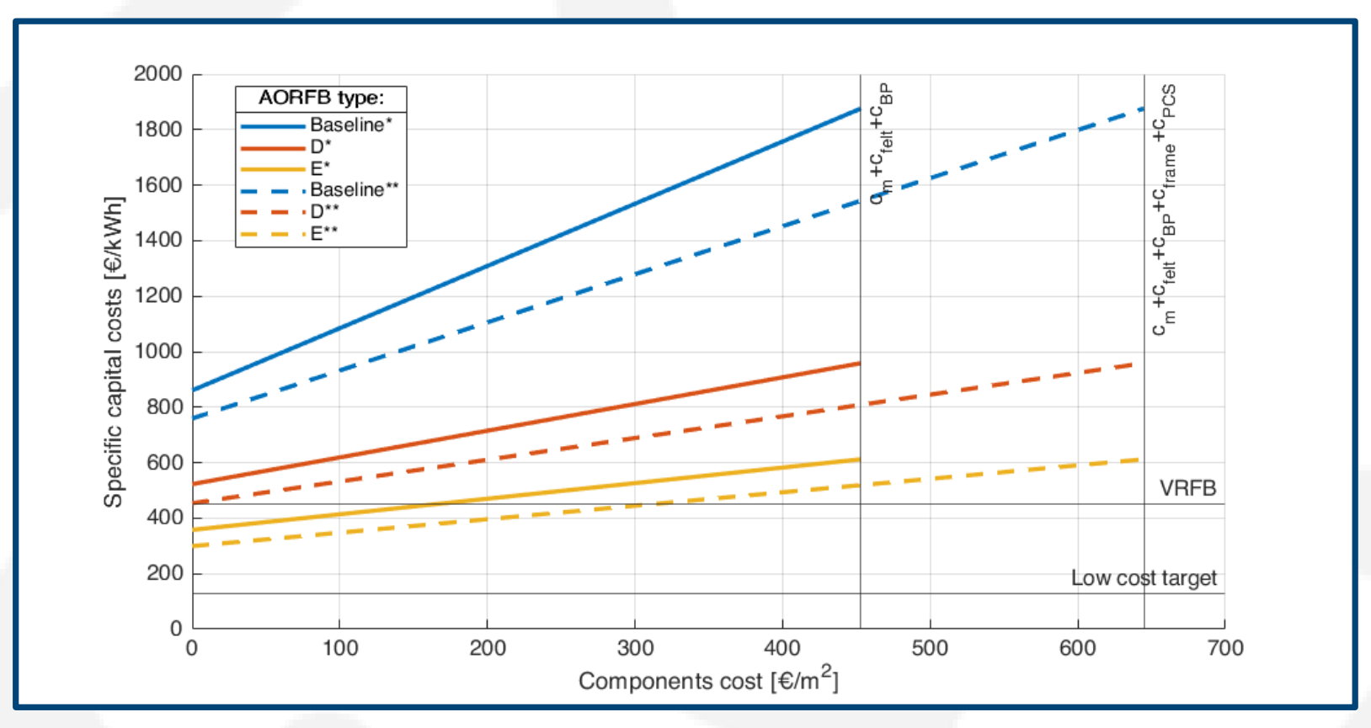


Fig. 4 - AORFB Capital Cost sensitivity analysis – 4h

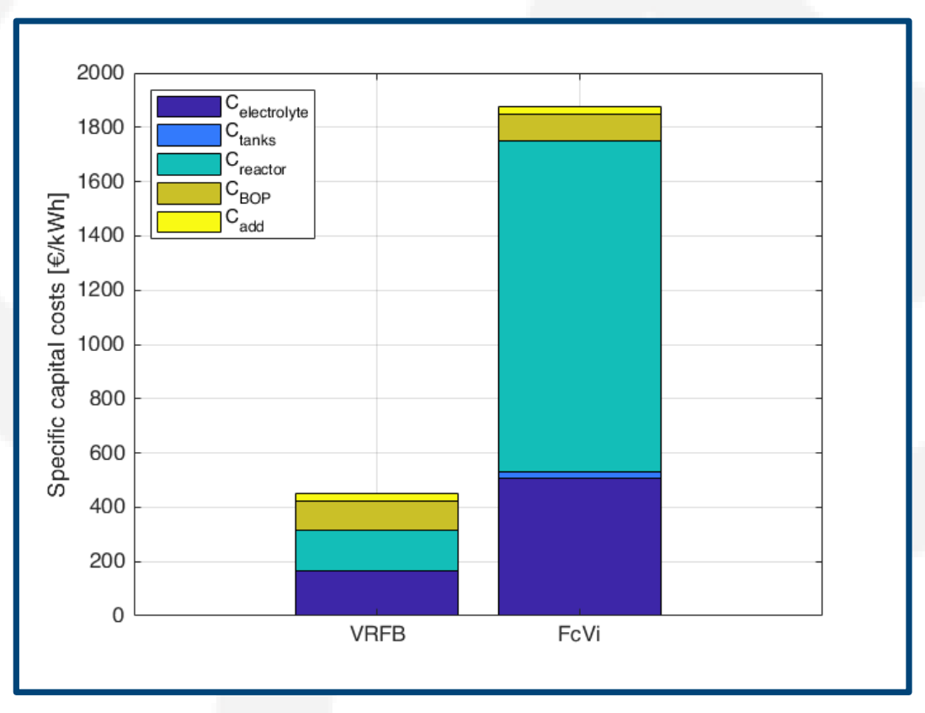


Fig.3 - Capital Cost – VRFB vs. FcVi – 4h

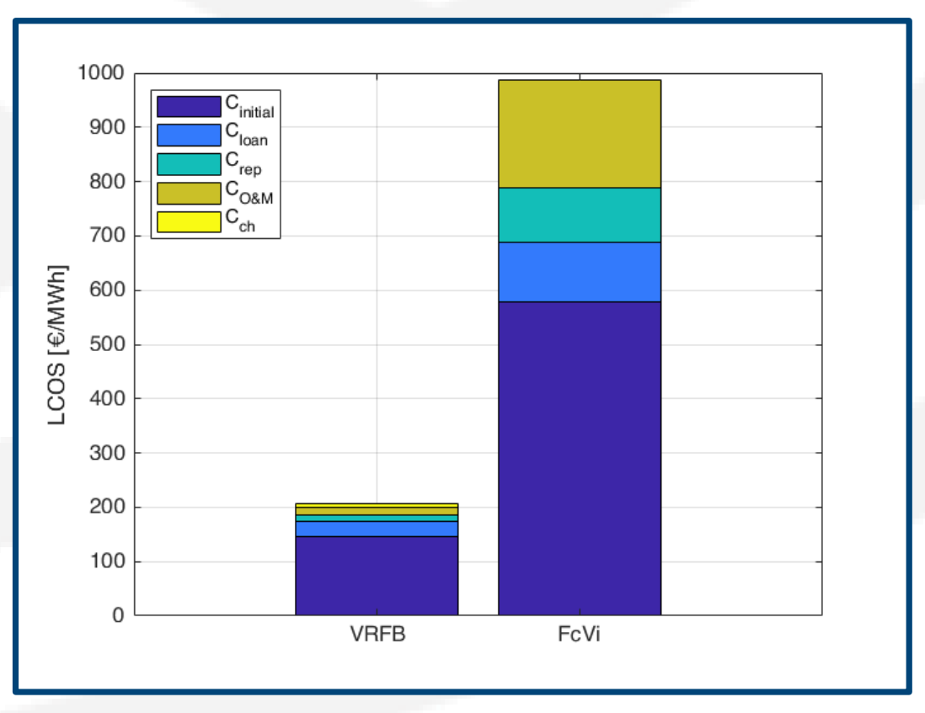


Fig. 5 - Levelized Cost – VRFB vs. FcVi – 4h

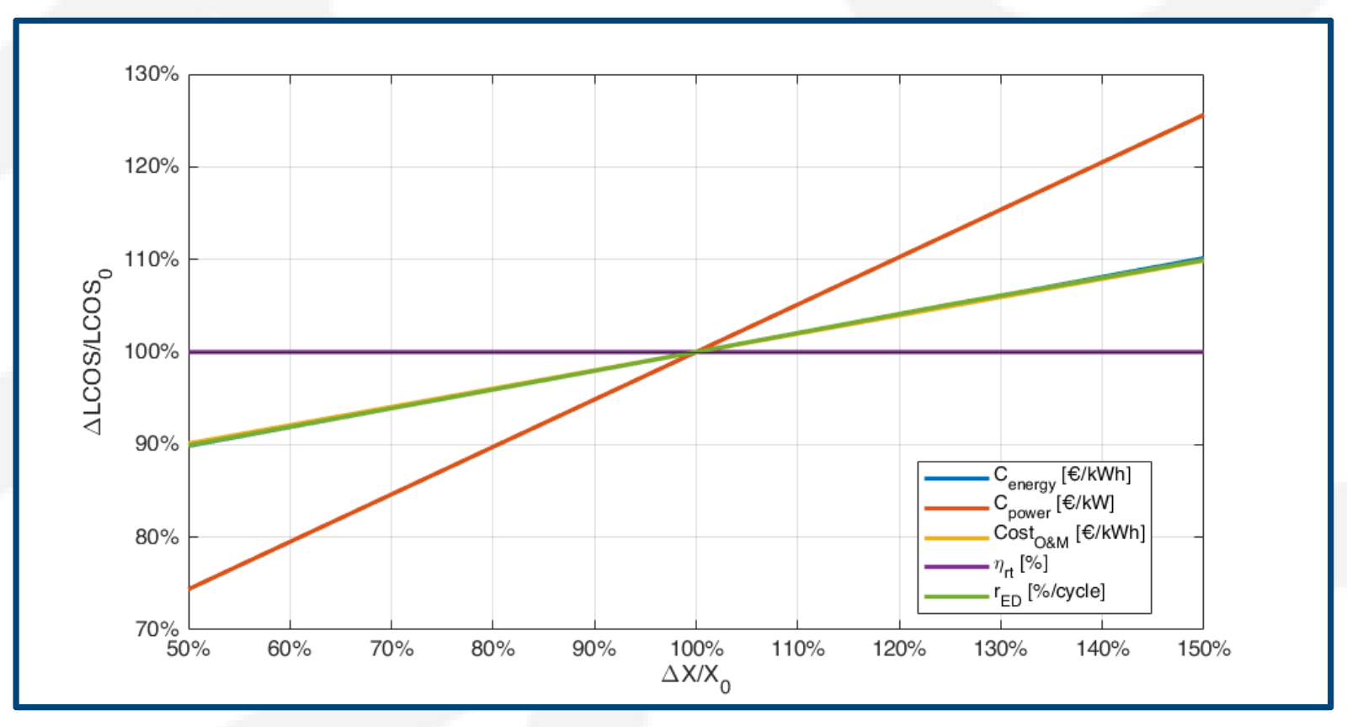


Fig. 6 - FcVi Levelized Cost sensitivity analysis – 4h

Results are shown in terms of comparison between the **detailed optimization model** and **two simple models** with **constant efficiencies** and **no degradation**:

- Fig. 8: while there are slight differences SOC optimal management for different models, the results are similar, driven by the demand and production of renewable energy (see Fig. 7).
- Fig. 9: the **annual number of charge-discharge cycles** . Neglecting the capacity fade of the battery leads to an **overestimation** of the **number of ideal cycles**: up to 15%. Neglecting both variable efficiencies and degradation leads to even higher **overestimation**: up to 32%.

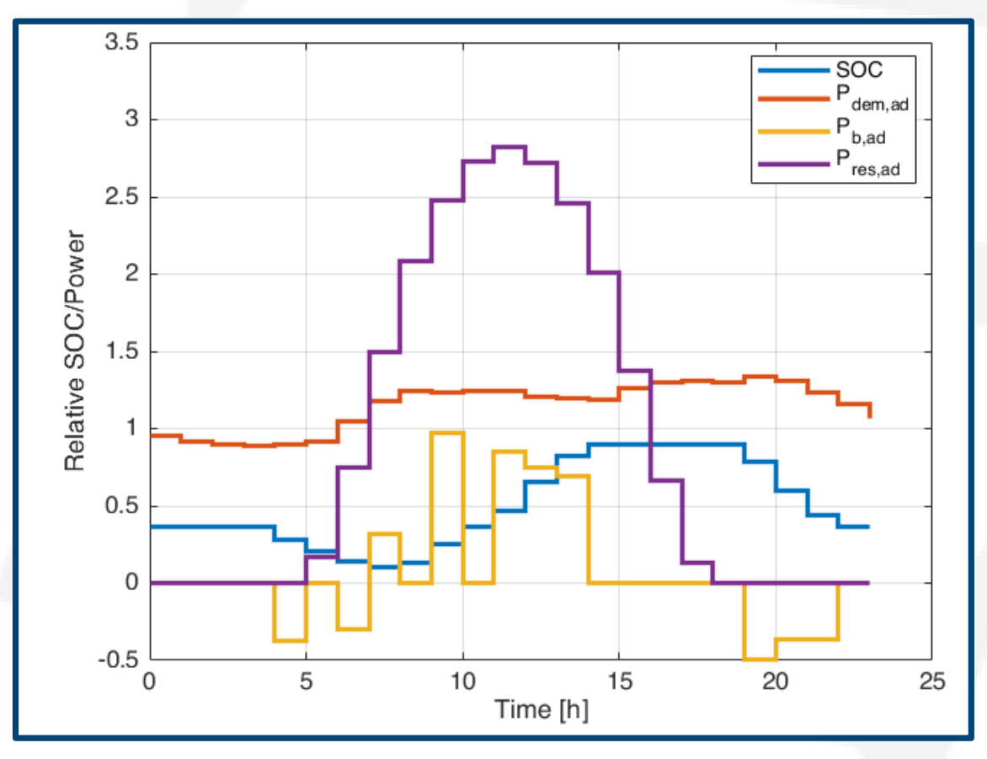


Fig.7 – Daily SOC, power and input data - PV

In fact, models that do not take into account capacity fade and variable efficiencies, underestimate energy losses and overestimate the **energy available** in the battery. This results in an overestimation of the **optimal cycle number** and therefore of the **total economic revenue**.

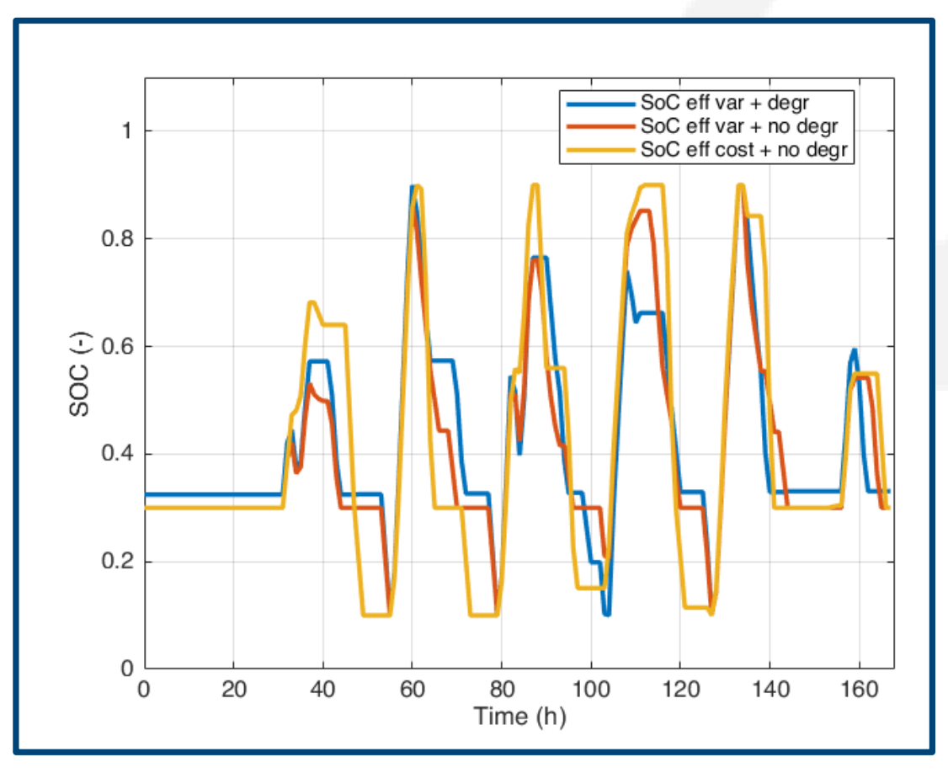


Fig. 8 – Daily SOC for different models – PV

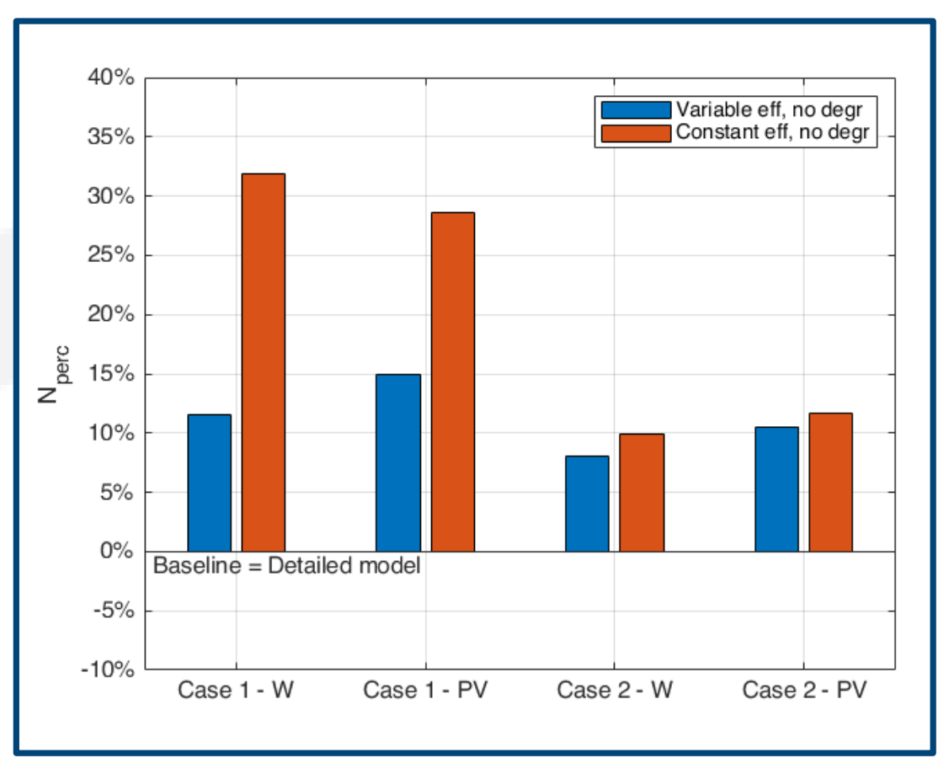


Fig. 9 - Cycle number: detailed vs. simple models

CONCLUSIONS

1. Investigation of redox flow batteries for storage of renewable energy via techno-economic assessments and optimization.
2. Flow batteries with organic materials have undesirable properties that lead to higher system and operational costs if compared to vanadium battery.
3. Simple mathematical optimization models without capacity fade and efficiencies overestimate number of cycles and revenue.

PUBLICATION & CONFERENCES

- ✓ D. Cremoncini, G.F. Frate, A. Bischi, L. Ferrari, "Mixed Integer Linear Program model for optimized scheduling of a vanadium redox flow battery with variable efficiencies, capacity fade, and electrolyte maintenance", in Journal of Energy Storage

- European Project (GA n. 875565)

- Conference: International Flow Battery Forum - Brussels, June 2022

FUTURE RESEARCH

- Aarhus University (Denmark): hybrid energy storage systems; energy markets on different time scales
- ENEA (Rome, IT): Isolated system efficiency and energy management

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[3] Rodby K.E. et al. «Assessing the levelized cost of vanadium redox flow batteries with capacity fade and rebalancing». In: Journal of Power Sources 460.227958 (2020). Issn: 0378-7753.