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Real-world optimization of Vanadium Redox Flow and Lithium-Ion Hybrid Energy Storage with Thermal Coupling for Electrical and Thermal Self-Sufficiency

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1. Abstract

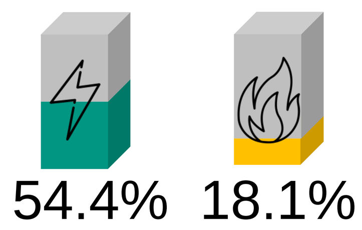


Fig 1. Germany 's renewable energy share in electricity and heat sector as of 2024 [1]

- Multi-energy systems (MES) combining electricity and heat sectors are steadily on a rise in Germany.
- Optimal operation of MES remains a challenge, as it requires a balance of profitability, asset aging reduction and self-sufficiency.

This study discusses a mixed-integer linear programming (MILP) approach for real-time optimal dispatch of a real-life MES combining a hybrid energy storage system (HESS) and a thermal coupling module (TCM) to serve the electrical and thermal loads of a residential building.

2. Conclusion

- Proposed MILP **models variable losses and auxiliary loads**.
- **Optimization result (Sec. 4):**
  - ~50% loss reduction with same operation cost as rule based
  - Optimal operation of VFB by strategically operation to reduce unwanted auxiliary loads.
  - Strategically dispatches LIB to avoid calendric aging.
- Tested on four renewable energy (RES) generation scenarios (Sec. 5)
- **Longer forecast benefit optimal MES operation**, by strategically aiming self sufficiency in both electrical as well as thermal sector.

3. Test setup

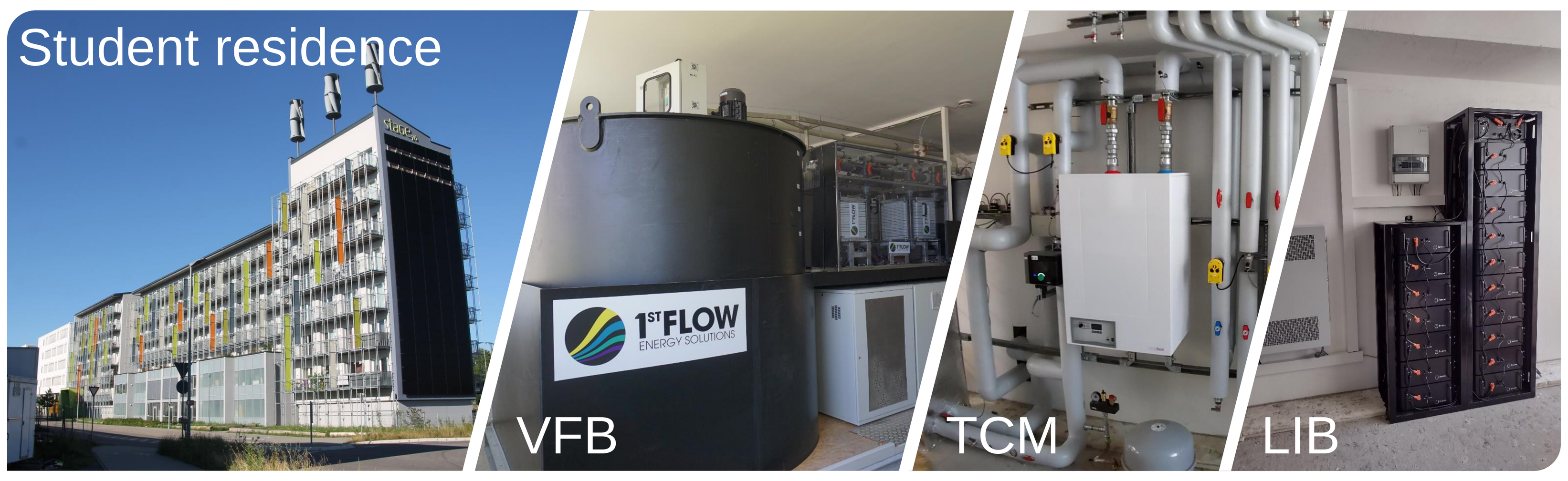


Fig 2. Real-life setup of a multi energy system. LIB: Lithium-Ion battery, VFB: Vanadium-Redox Flow battery, TCM: Thermal coupling module [2].

- Real-life **MES** at a student residence for 150 students and 220 kWp Photovoltaics.
- **AC connected HESS**
  - VFB → 120 kWh (P_{nom} = 21 kW)
  - High energy and long lasting
  - LIB → 60 kWh (P_{nom} = 30 kW)
  - High power and high efficiency
- **Heat sector coupling** → Pre-heating of fresh water supply with TCM to reduce dependence on district heating

Different operation modes of TCM :

- ***PV2Heat***: PV surplus converted to heat and directly fed
- ***Store heat***: Heat the electrolyte of VFB with surplus
- ***Extract heat***: Transfer (waste) heat accumulated in VFB's electrolyte to fresh water supply

Additionally, the above modes could also be combined

4. Optimization result

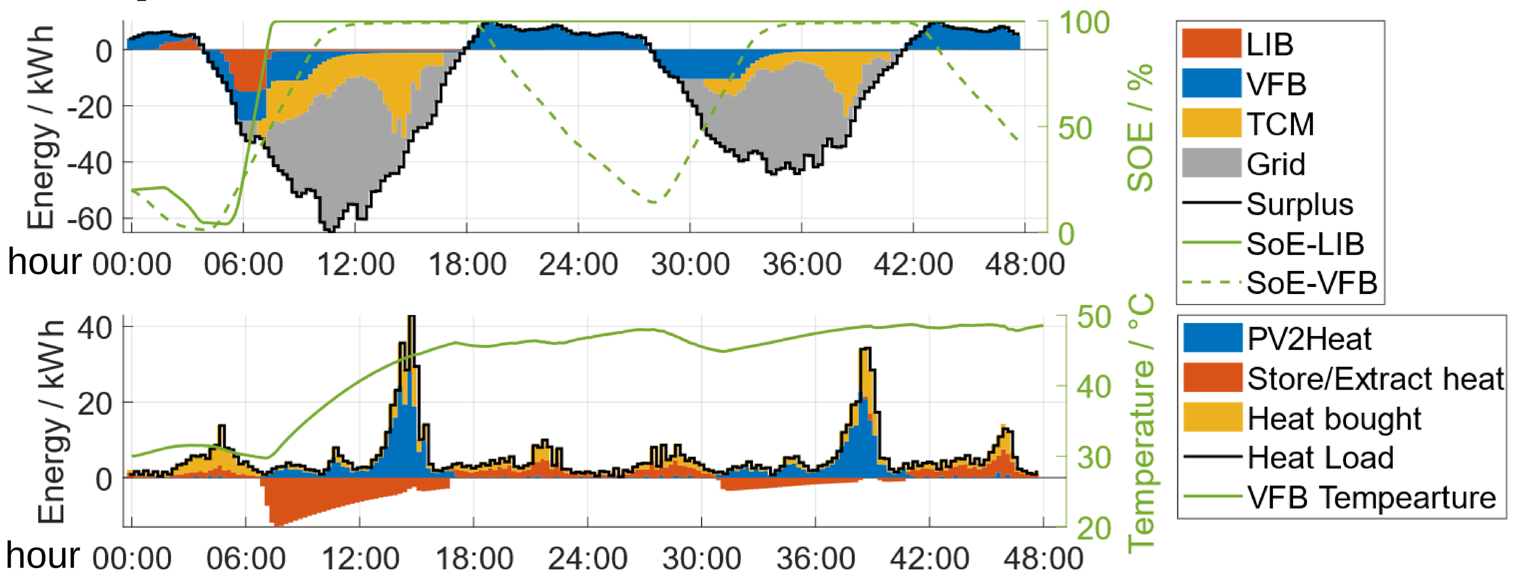
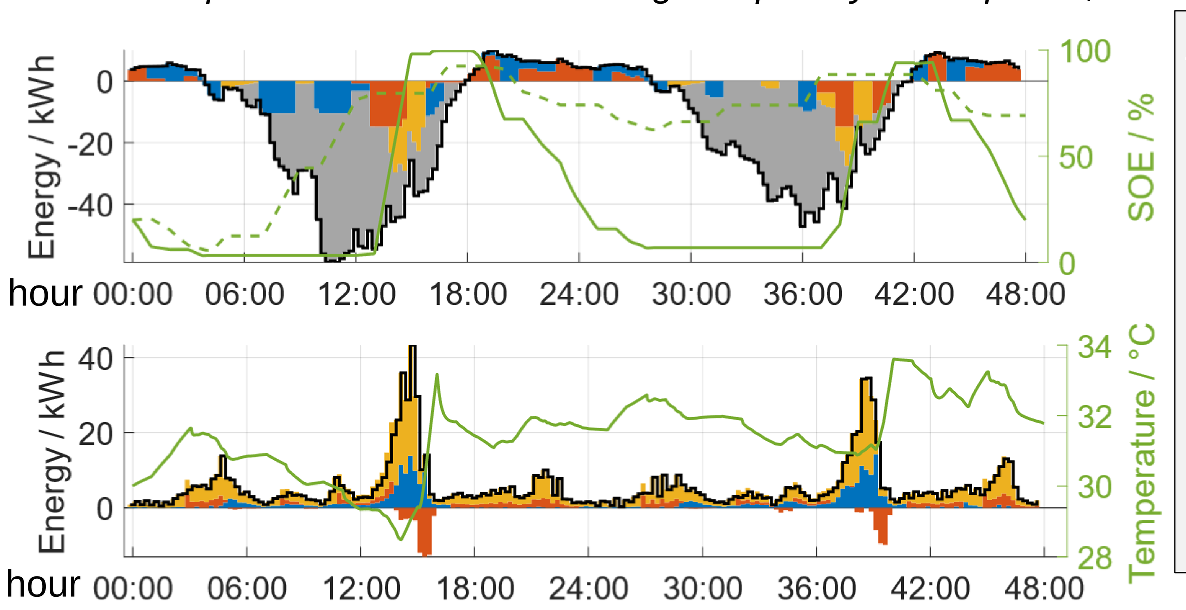


Fig 3. Example day with decreasing surplus trend over days (see Sec. 5 for further explanation). Rule based operation where VFB has highest priority to the power, then LIB and TCM

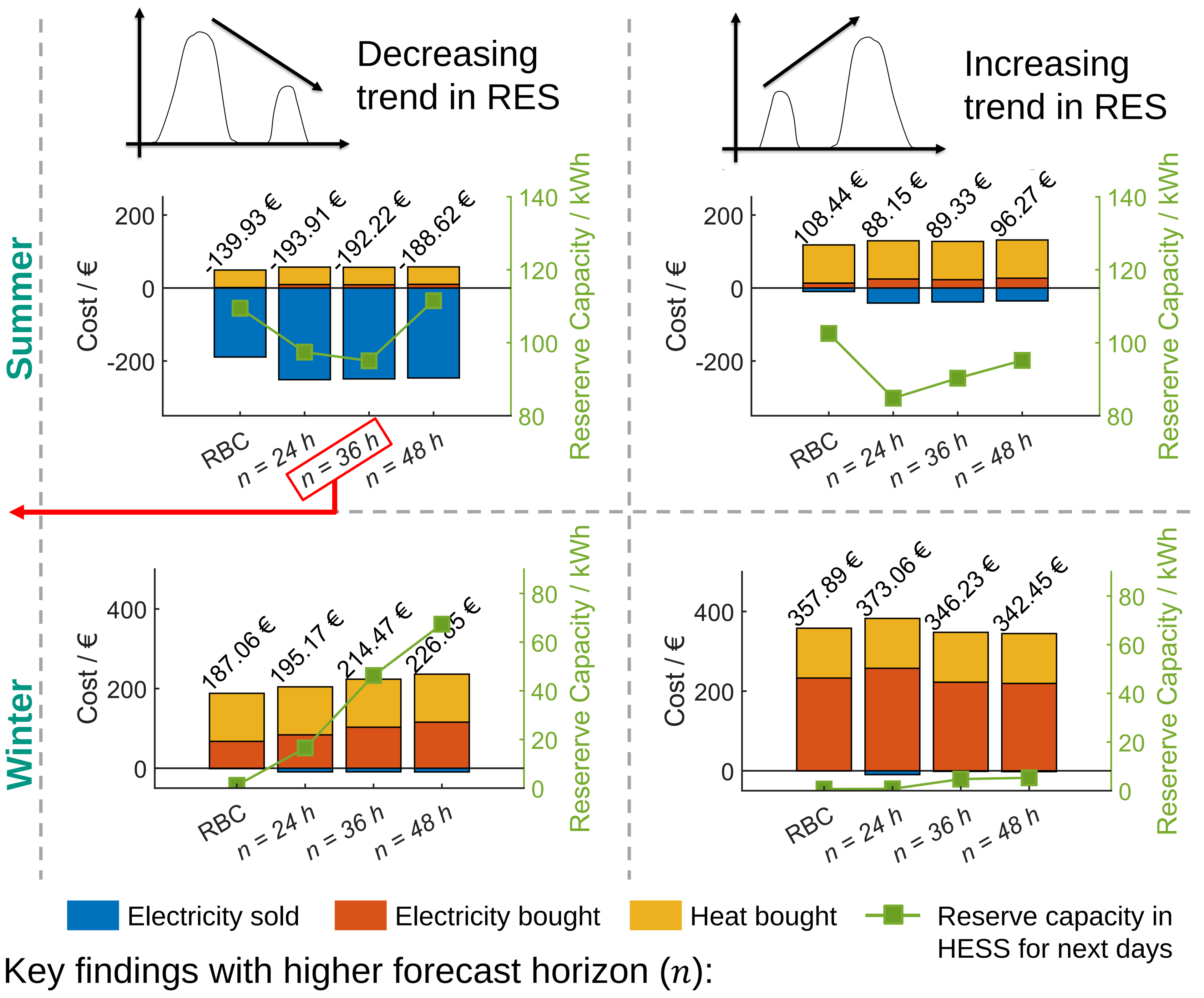


Plot helper
- Surplus = RES – Load
- SoE: State of Energy
- Sign meaning
  +ve: generation,
  -ve: consumption
- Upper plot: Electricity sector
- Lower plot: Heat sector
- Left axis: Energy / kWh
- Right axis: SOE / % or Temperature / °C

Fig 4. Same day as Fig.3 when run optimally. (Rolling horizon applied every 3 hrs with n = 36 h)

Metrics	RBC	MILP	Notes
Operation cost	-139.9 €	-192.22 €	**+ 52.32 €** profit by selling more
Losses occurred (including aux)	207 kWh	114.9 kWh	**55.5 %** losses reduced by strategically operating the HESS
LIB calendric aging as per [3]	0.102 %	0.06%	**58.8%** calendric aging reduced by strategic charging schedule
VFB average temperature	43.18 °C	31.4 °C	Optimal temperature held. Higher temperature → faster degradation

5. Effect of forecast horizon (n)



Key findings with higher forecast horizon (n):
- In decreasing trend the reserve capacity left at the end of day is higher.
- MILP algorithm reserves energy to use efficiently in the coming days.
- In increasing trend the energy sold is less (thus lower profit) and used as soon as possible as forecast ensures enough energy for coming days.
- Here MILP algorithm focuses on loss reduction more than profit.

References
[1] Umweltbundesamt, "Renewable energies in figures," Mar. 7, 2025 [online]
[2] N. Munzke, C. Kupper, and M. Mast, "Thermisches Koppelmodul, thermisches Koppelungssystem und Verfahren zur Wärmeübertragung zwischen mindestens einem elektrischen Energiespeicher und mindestens einem Wärmeabnehmer,", Patent granted, Mar. 14, 2024
[3] M. Naumann, M. Schimpe, P. Keil, H. C. Hesse, and A. Jossen, "Analysis and modeling of calendar aging of a commercial LiFePO4/graphite cell," Journal of Energy Storage, vol. 17, pp. 153–169, Jun. 2018.

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