Numerical performance assessment of heat pumps in Rankine-based Carnot battery systems for grid balancing services

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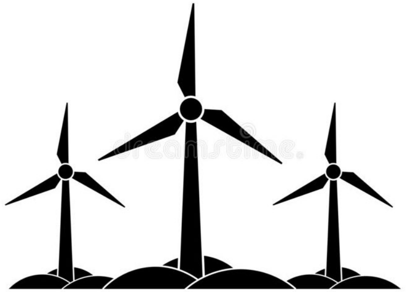
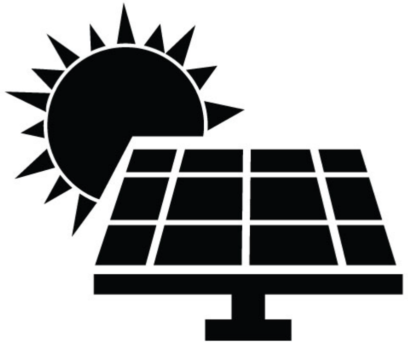
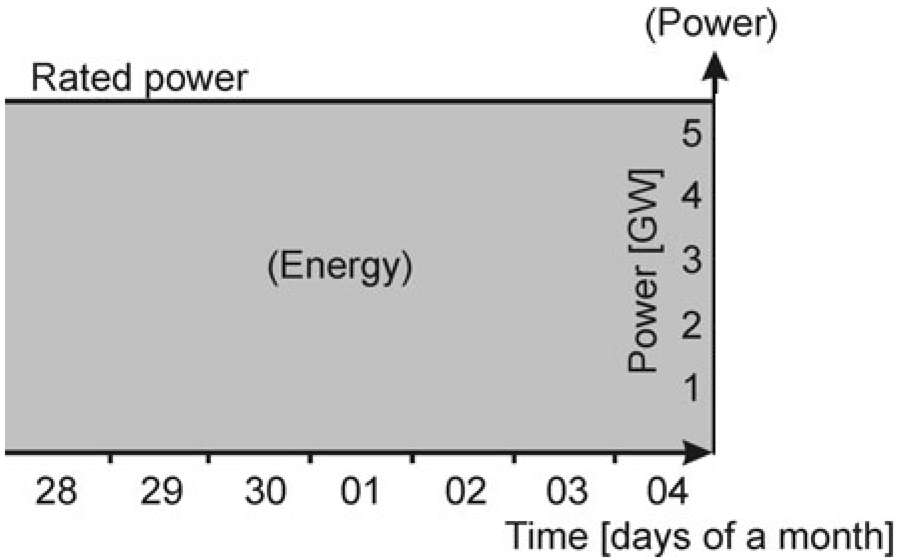
Intermittency of RES



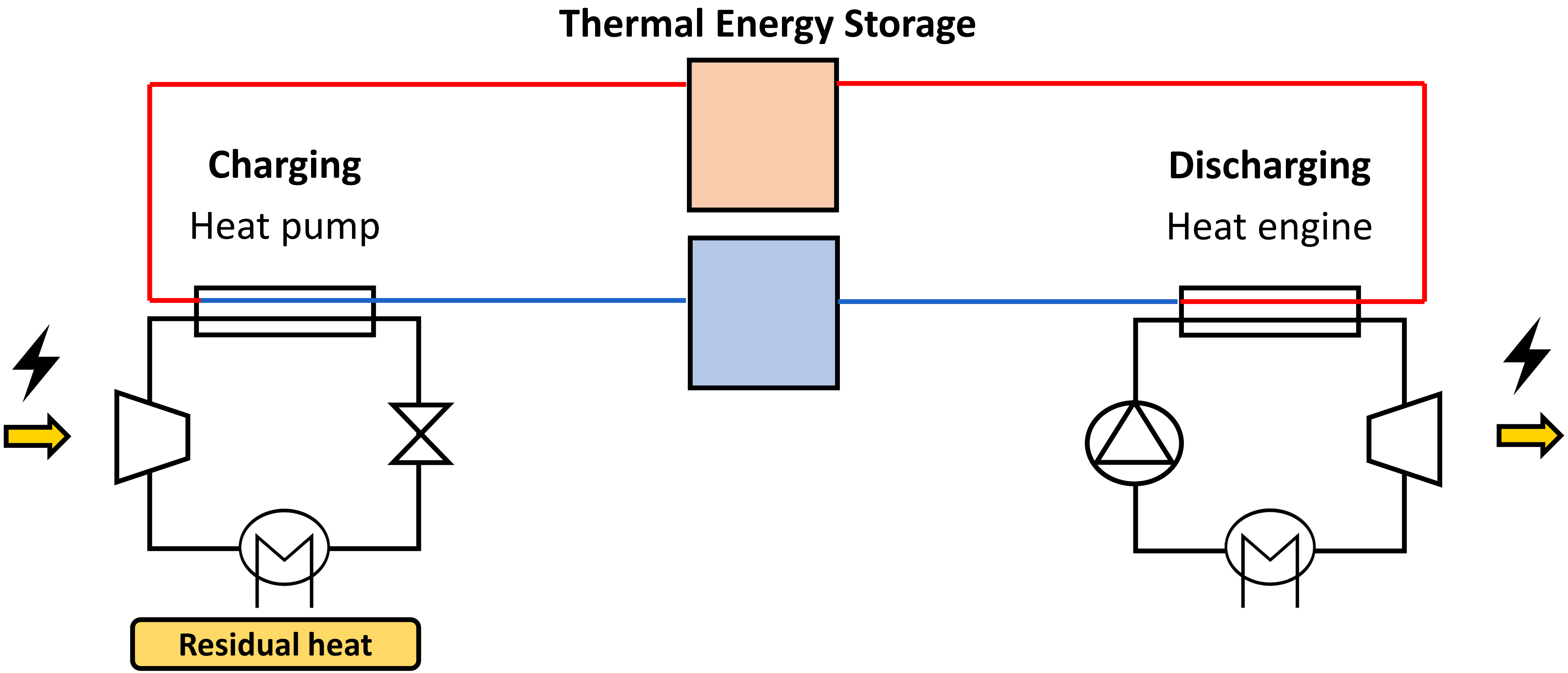


Non - intermittent → intermittent



Need for large scale electrical energy storage

Carnot battery



Carnot battery: state-of-the-art

Current research:

- Steady-state analysis and optimization
- Experimental proof-of-concept
- Techno-economics (load-shifting and arbitraging)

→ In general: investment cost > lifetime revenue

→ Need for a portfolio of grid services

Grid balancing services

1. Frequency containment reserve (FCR)
   - FAT < 30 s
   - Symmetric capacity

2. Automatically activated frequency restauration reserve (aFRR)
   - FAT < 5 min
   - Up / down

3. Automatically activated frequency restauration reserve (aFRR)
   - FAT < 15 min
   - Up / down

Carnot battery for grid balancing

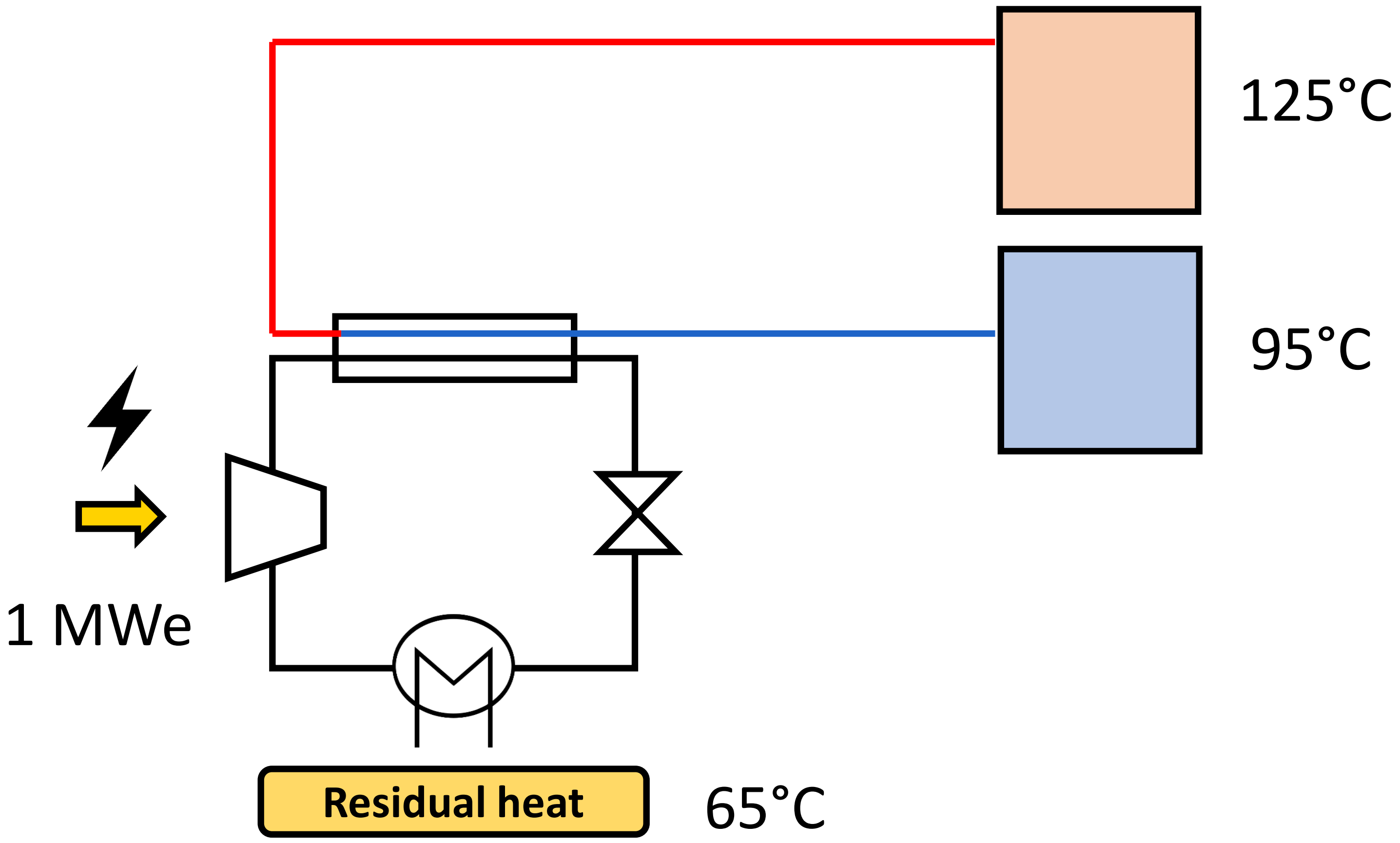
3 criteria:

- Power response
- Storage temperatures
- Service duration

Focus on heat pump component

→ Assumed duration criterium is fulfilled (TES correctly sized)

Topology and boundary conditions



Basic heat pump topology?

→ lowest system inertia
→ expected to have fastest response

Refrigerant: R-1233zd(E)

Grid scale system: 1 MWe

→ steady-state cycle calculation
→ component nominal conditions

Dynamic modelling

TLK energy
TIL Suite

SWEP plate HX (correct mass and volume)
Dynamic finite volume model TIL

Controllable through-flow area
Quasi-steady TIL - model

Axial gas compressor (scaled)
Quasi-steady performance map based

Ideal storage tank
- Perfect stratification
- Constant source temperature

→ Boundary-model

Controller design

PI-control:

Power uptake modulation → compressor rotational speed

Optimal operating point compressor → valve through flow area

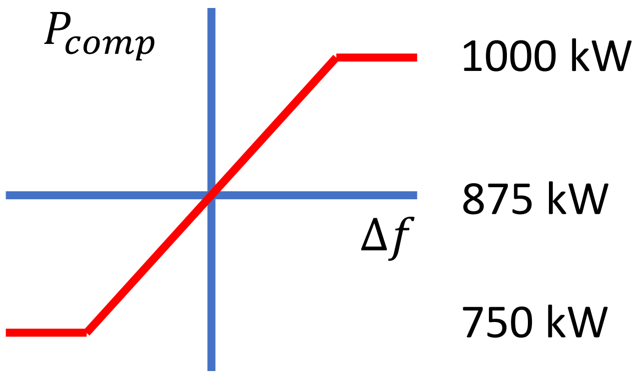
Correct storage temperature hot tank → mass flow rate condenser

Grid balancing capacity

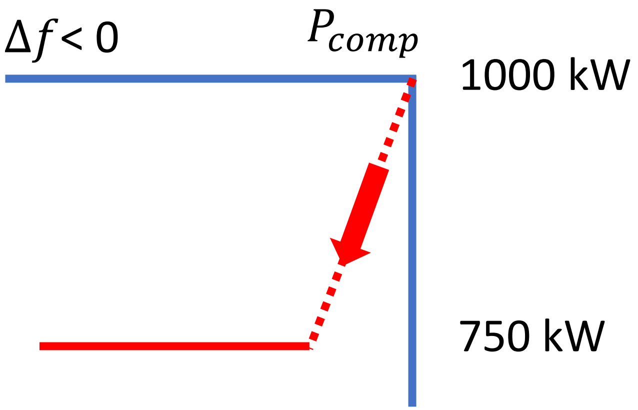
Part-load capacity may be limited by:

- Minimal rotational speed compressor (50%)
- Superheating at compressor inlet- and outlet → Minimum part-load capacity 750 kW
- Condenser temperature (TES-temperature of 125°C)

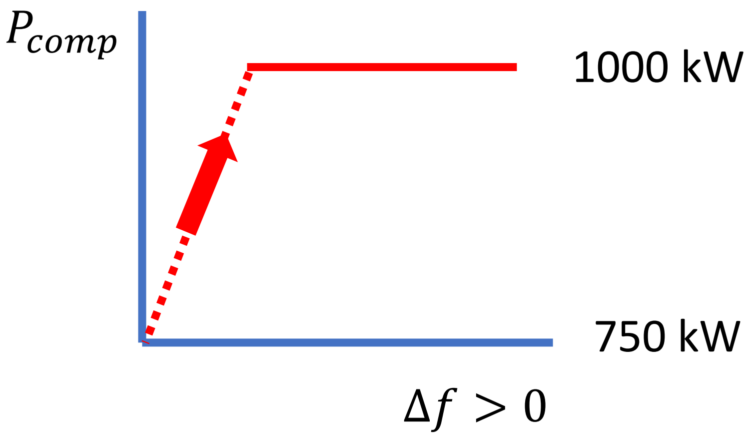
FCR: 125 kW



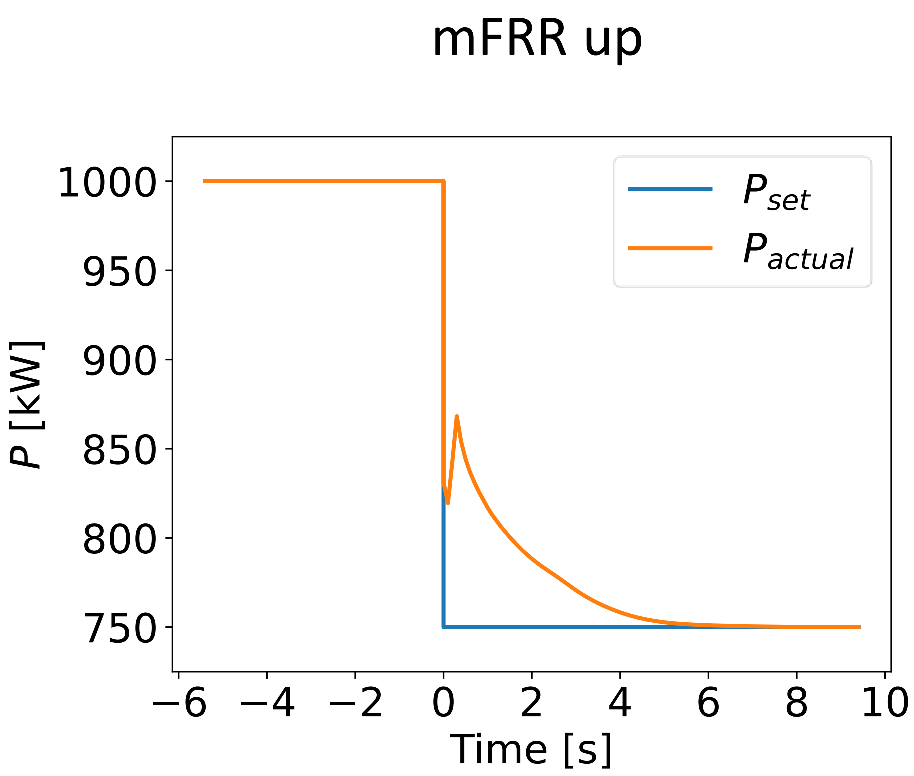
aFRR / mFRR up: 250 kW

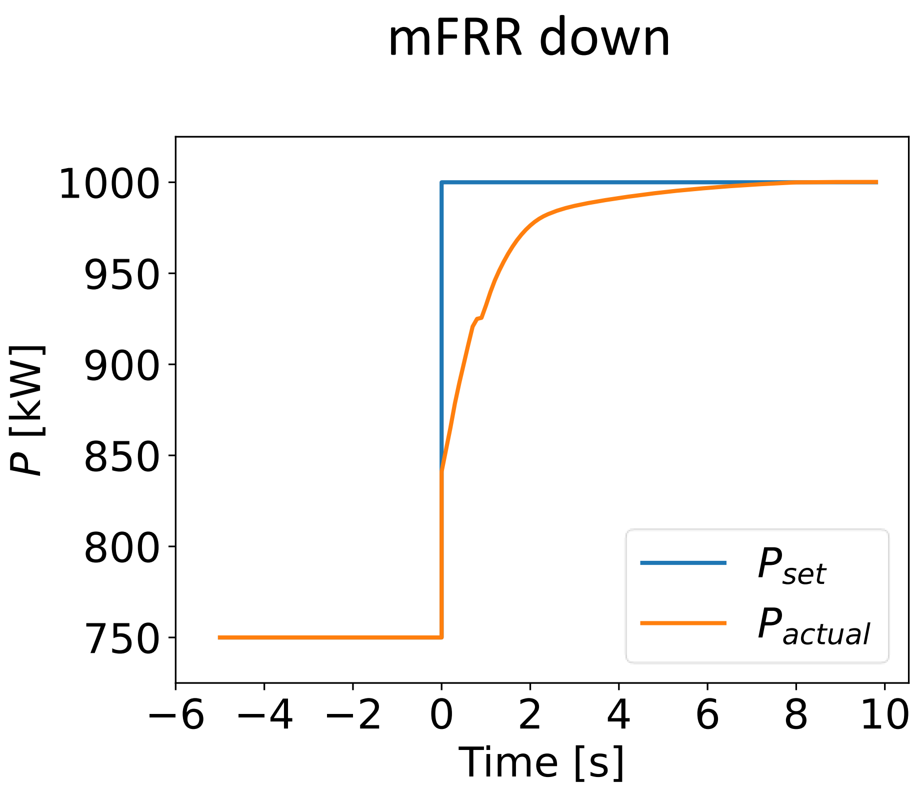


aFRR / mFRR down: 250 kW



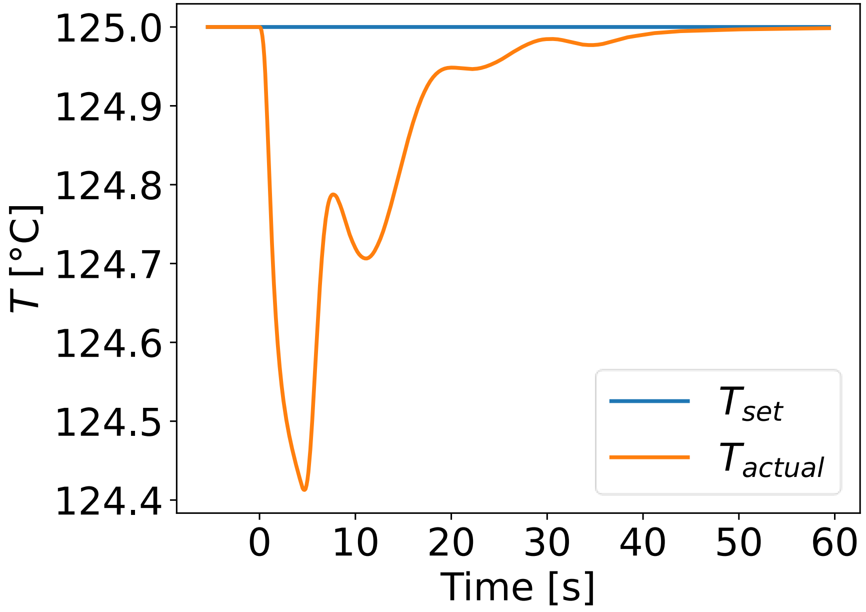
Tertiary reserve: FAT



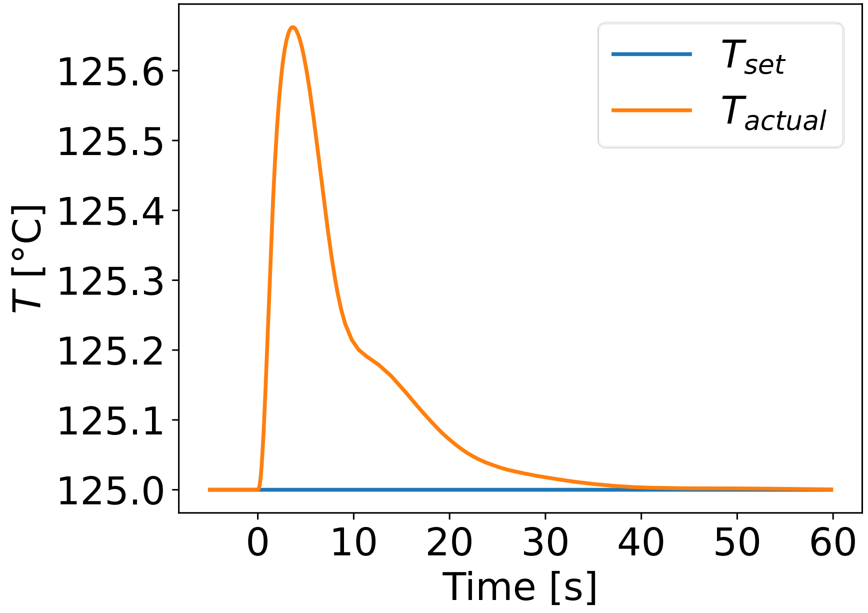


Tertiary reserve TES temperatures

mFRR up

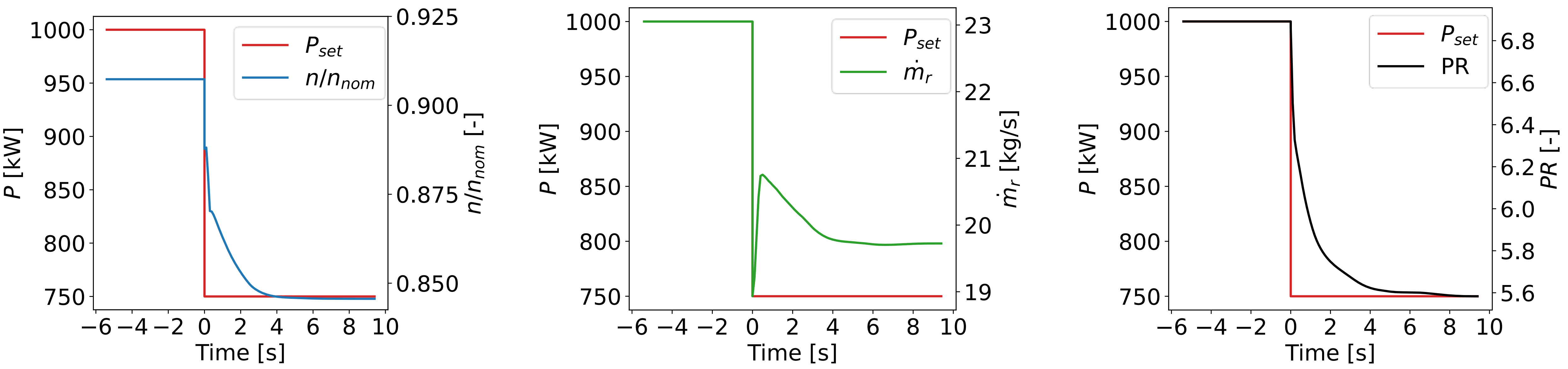


mFRR down

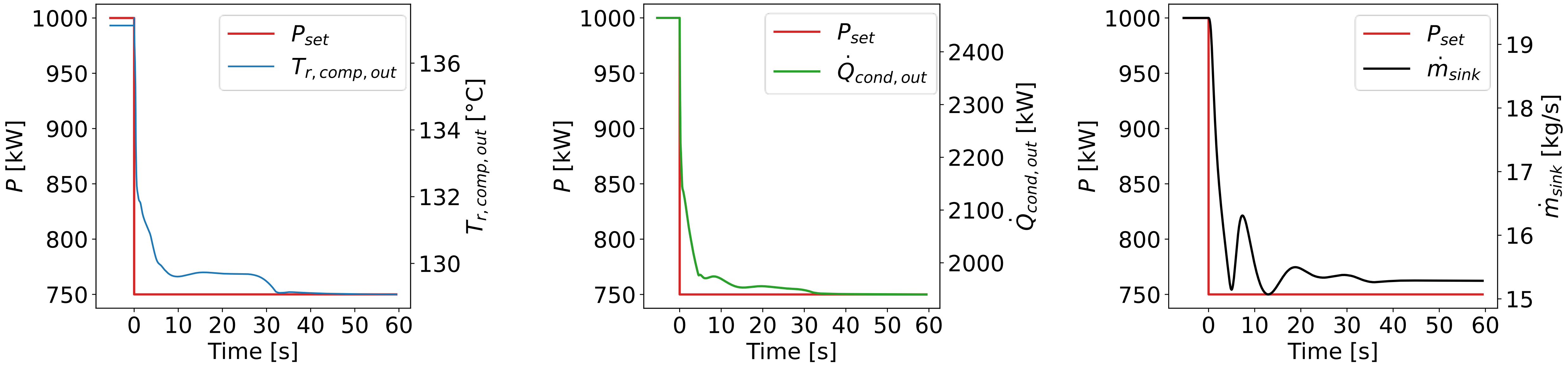


Fast power response + correct TES temperatures → mFRR

Power modulation (mFRR up)



Power modulation (mFRRup)



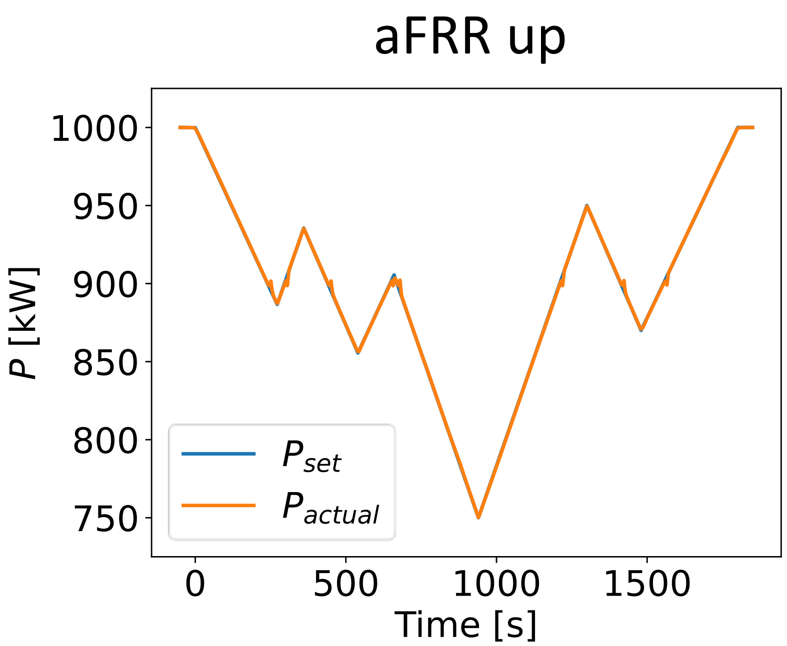
Secondary reserve (aFRR)

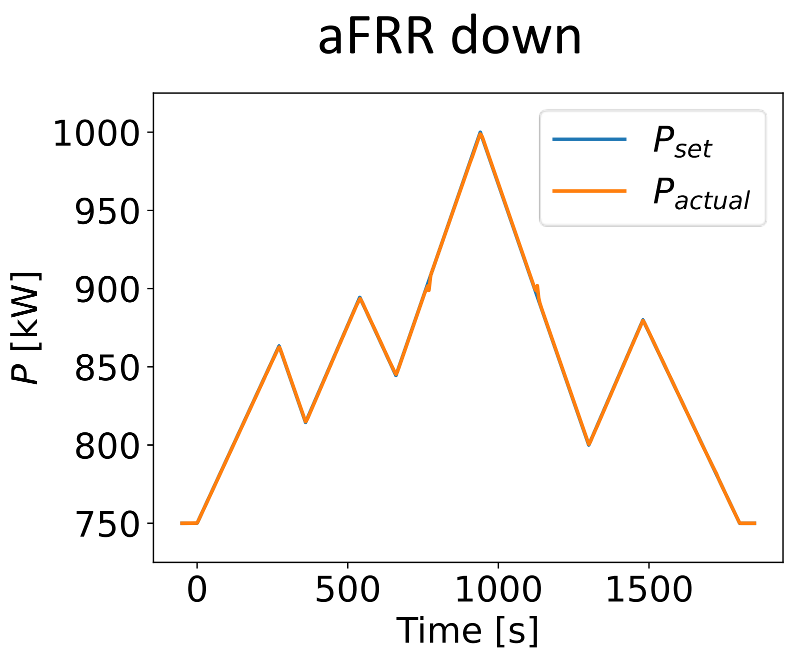
Full activation time < 5 min

Load-following test: follow pattern within 7.5 % margin

Correct TES temperatures

aFRR





Primary reserve (FCR)

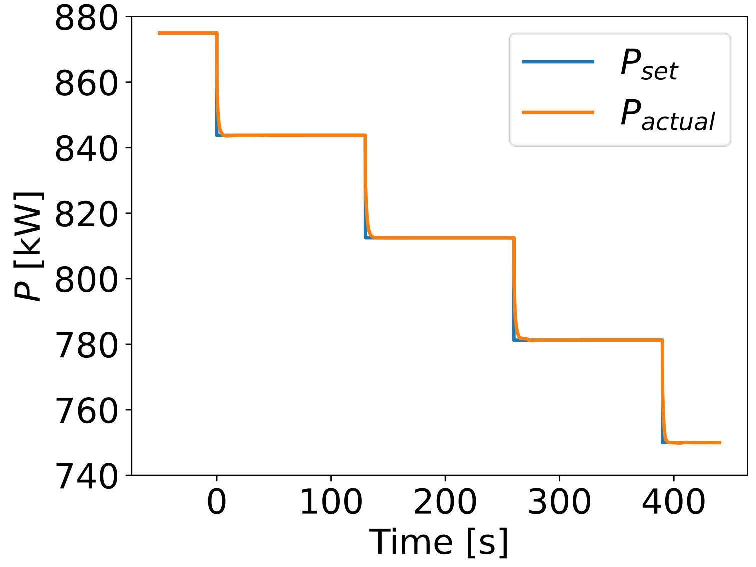
Full activation time < 30 s

Modularity test: within margin of 10 % after 12.5 s for 4 capacity steps

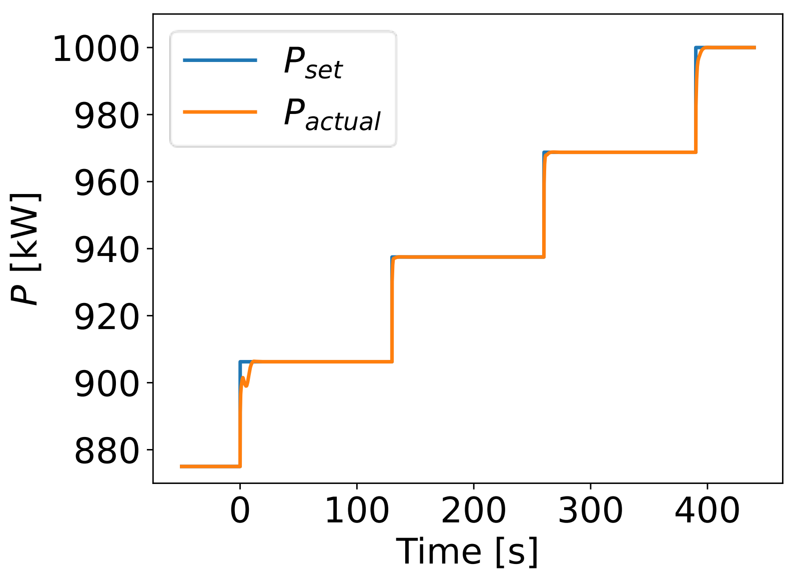
Correct TES temperatures

FCR

Upward direction



Downward direction



Conclusion

Under the assumption of quasi-steady compressor modelling and ideal storage tanks:

- 250 kW mFRR (up and down)
- 250 kW aFRR (up and down)
- 125 kW FCR

Grid balancing services thus can be studied as additional revenue streams in techno-economic studies

Future work:

- Sensitivity to compressor inertia
- More complex heat pump cycles: trade-off efficiency VS inertia
- Extension to full Carnot battery model (including TES and ORC)