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Techno-economic analysis of sCO₂ Carnot batteries in ancillary services markets

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Education for the future

KTH is Sweden's largest and oldest tech university

18,000
students

2,300
international

> 35%
women

4,000
staff

336
professors

> 60%
in research

Excellent research

28 Departments for applied and basic research

Focus: Sustainable and secure societal development



**Mechanical Engineering
2026**

1

Nordics

5

EU27

25

World



Energy Department

Heat and Power Technology

- Applied research in collaboration with industry, universities and research centres
- Leveraging unique computational and lab infrastructure
- MSc. in Sustainable Energy Engineering
PhD in Energy Technology
- Active in +25 EU and national funded projects





Department of Energy Technology

Division of Heat and Power Technology

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Agenda

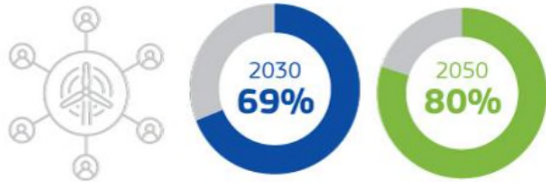
- Introduction
 - Power grid decarbonization
 - Flexibility needs, ancillary services
 - Thermal Energy Storage
 - Pumped TES
 - sCO₂OP-TES project
- Methodology
 - System (thermodynamics, off-design)
 - Optimization and integration with the grid
- Results
 - Dispatch optimization
 - Techno-economic comparison of cases
- Conclusion





Power grid decarbonization, EU

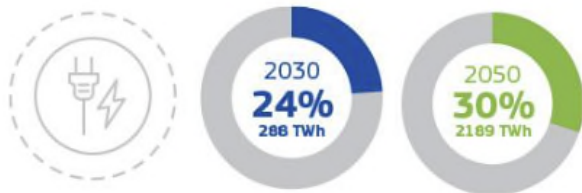
Renewable production, from 47% in 2024



Storage, 89 GW in 2024 (mainly pumped hydro)



Flexibility needs, from 11% in 2021



Energy storage for **flexibility, stability and reliability** of future energy systems, ensuring **security of supply** and energy systems **integration**.

Energy storage to overcome **mismatches in different time scales**.

https://energy.ec.europa.eu/topics/research-and-technology/energy-storage/key-facts-energy-storage_en#energy-storage-markets



Balancing demand and generation: Ancillary services

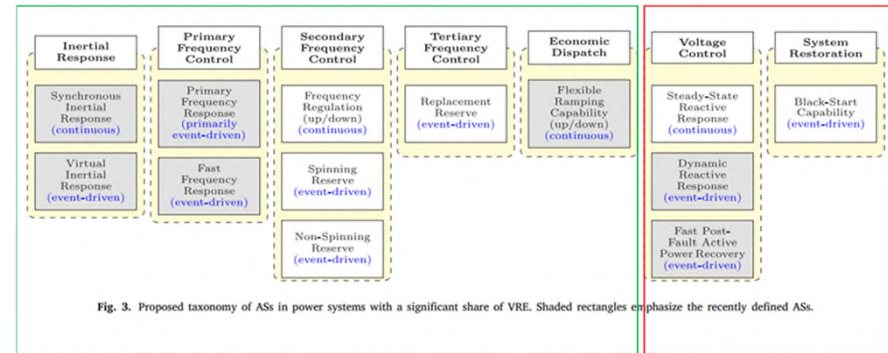
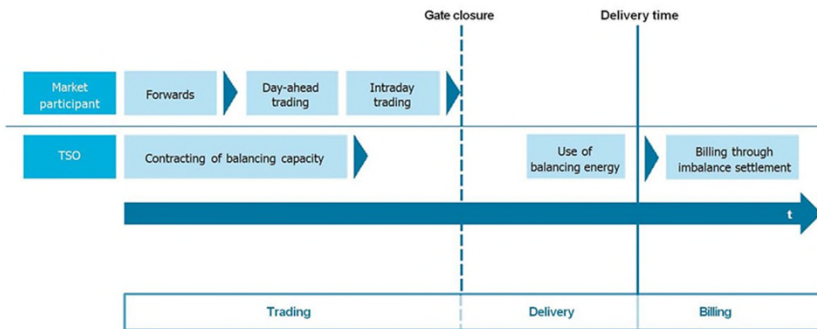
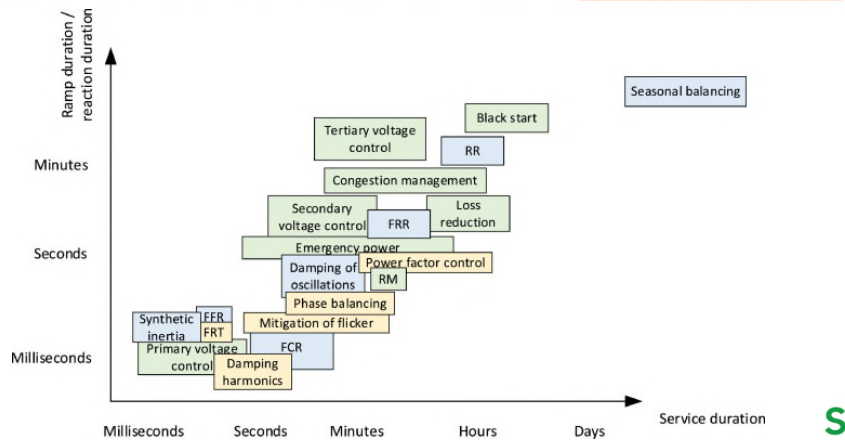


Fig. 3. Proposed taxonomy of ASs in power systems with a significant share of VRE. Shaded rectangles emphasize the recently defined ASs.

- Different market architecture per country.
- Specific ancillary services depending on power grid needs.
- Standardization: European platforms of
 - PICASSO – aFRR (automatic frequency restoration reserves)
 - MARI – mFRR (manual frequency restoration reserves)
 - TERRE – RR (restoration reserves)

Frequency related ancillary services

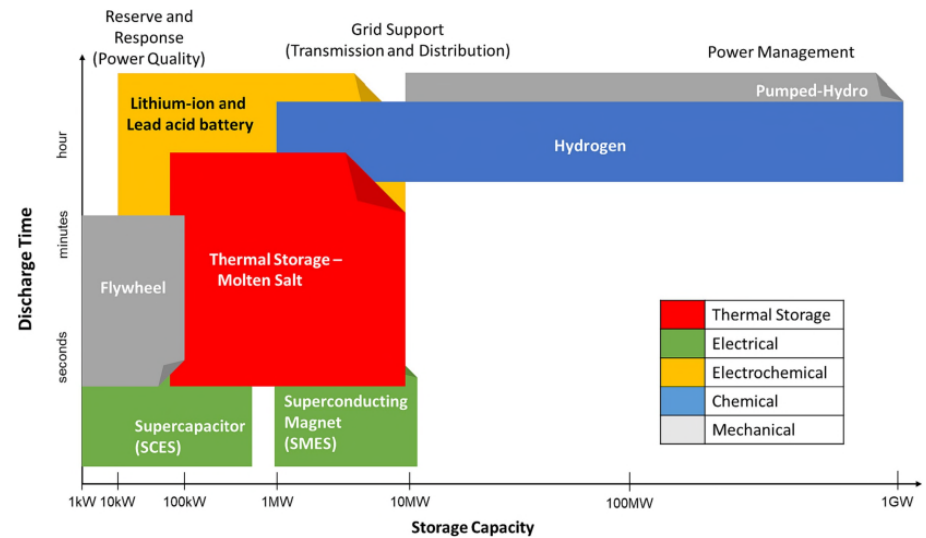
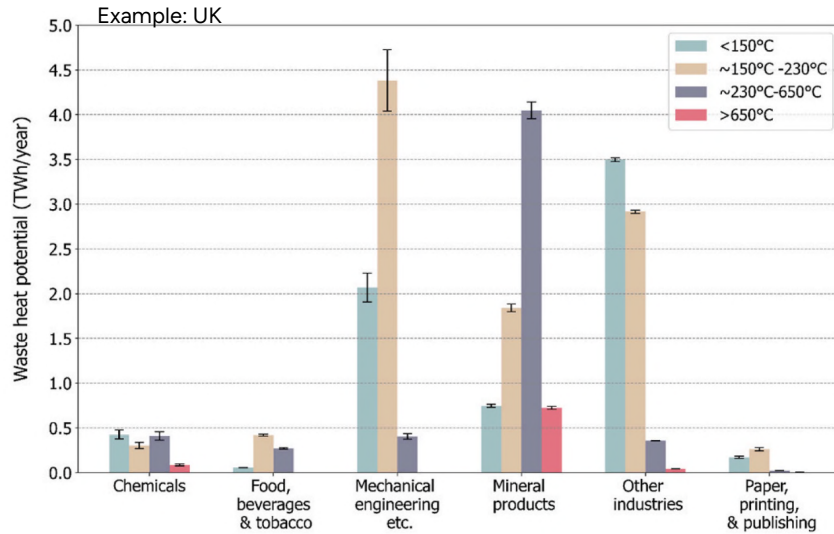


<https://doi.org/10.1016/j.epsc.2021.107022>
<https://www.smdr.de/page/en/wiki-article/5884/5976/wholesale-prices>
<https://doi.org/10.1016/j.epsc.2024.110885>





Thermal Energy Storage as bridge



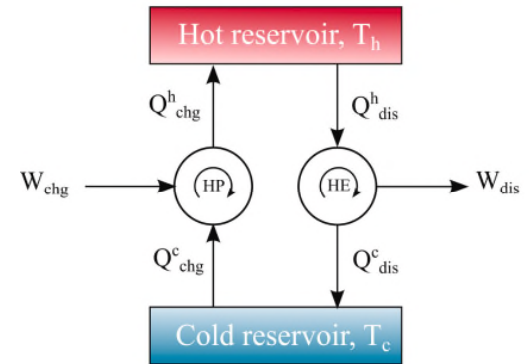
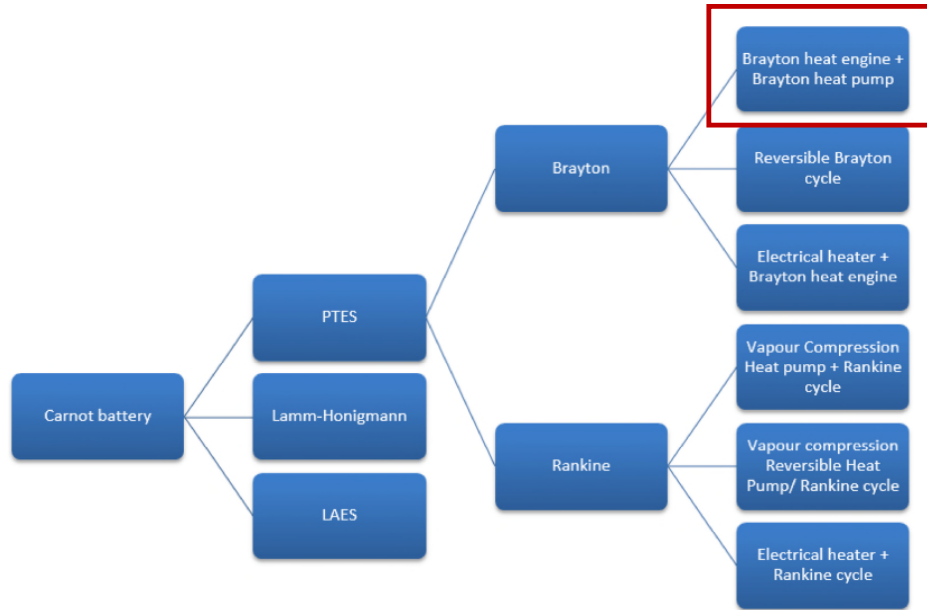
Thermal Energy Storage to:

- Decrease fossil fuel consumption
- Increase renewable penetration
- Aid in ancillary services provision
- Recover industrial waste heat
- Unlock unique sector coupling opportunities
- Decouple heat and power supply

<https://doi.org/10.1016/j.est.2023.108360>
<https://doi.org/10.1016/j.jclepro.2022.133759>



P2H2P solutions: Pumped TES



Brayton heat pump + Brayton heat engine:

- High energy density
- Low-capacity prices
- Projected RTE 40-70%

sCO₂ Brayton CB:

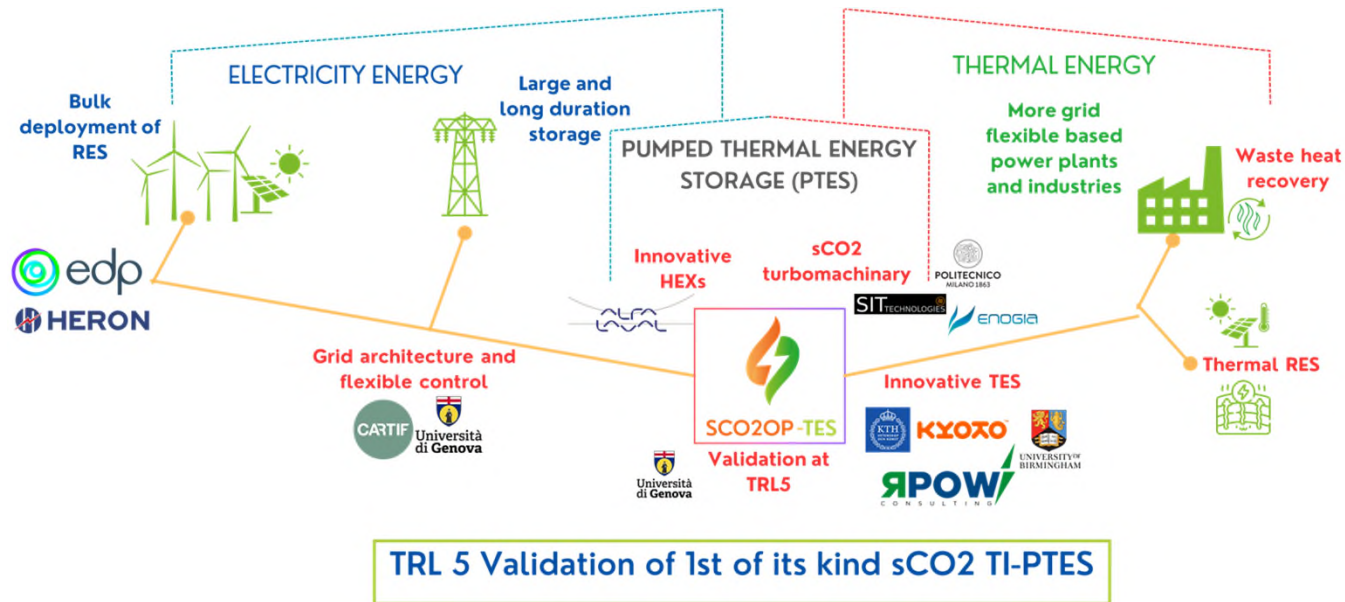
- Compactness + high conversion efficiencies

Advantages against other storage solutions:
Based on turbomachinery

<https://doi.org/10.1016/j.est.2020.101756>
<https://doi.org/10.1016/j.est.2022.105005>



sCO2OP-TES project



Waste heat driven sCO2 Carnot Battery with Molten Salt TES

- RES integration
 - New roles for fossil-based power plants
- Facilitate industrial decarbonization – Industries as grid flexibility actors
 - Environmentally friendly, when compared to other solutions

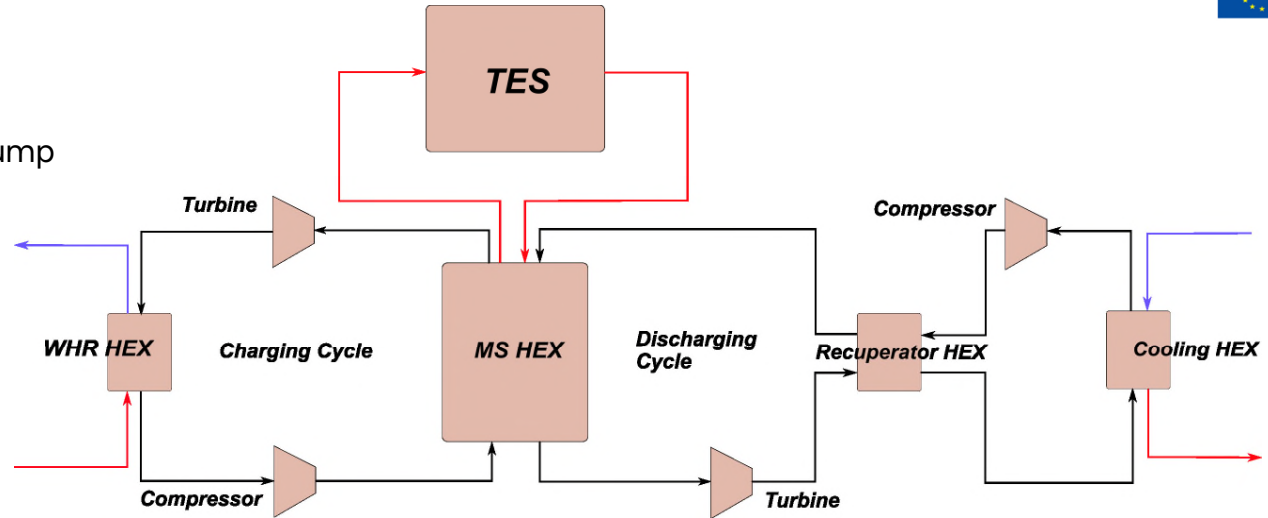


Studied system



sCO₂ Carnot Battery:

- **Charging Cycle (CC)** – sCO₂ heat pump
- **Discharging Cycle (DC)** – sCO₂ recuperated Brayton cycle
- **TES** – sensible molten salts



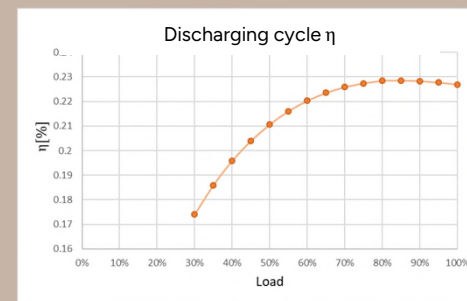
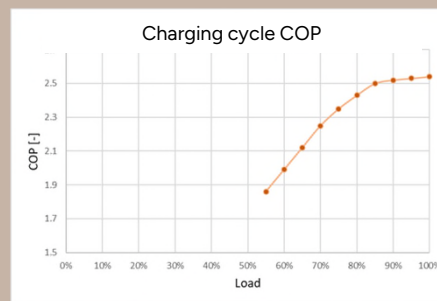
Key aspects of this work:

Provision of ancillary services – Spanish grid

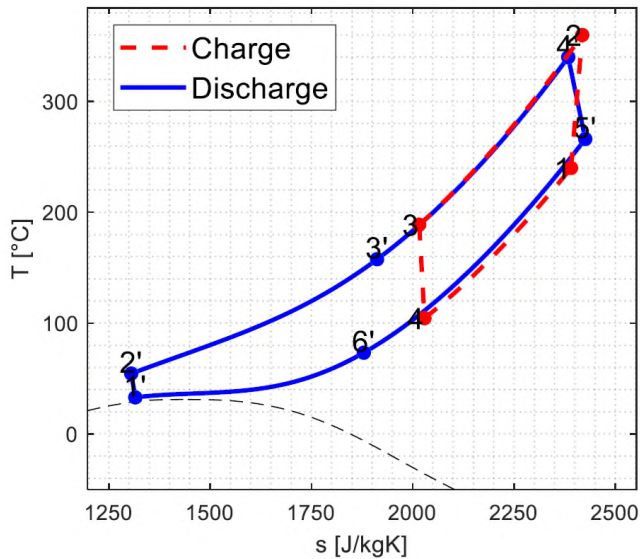
Automatic frequency restoration reserves – **aFRR**

Manual frequency restoration reserves – **mFRR**

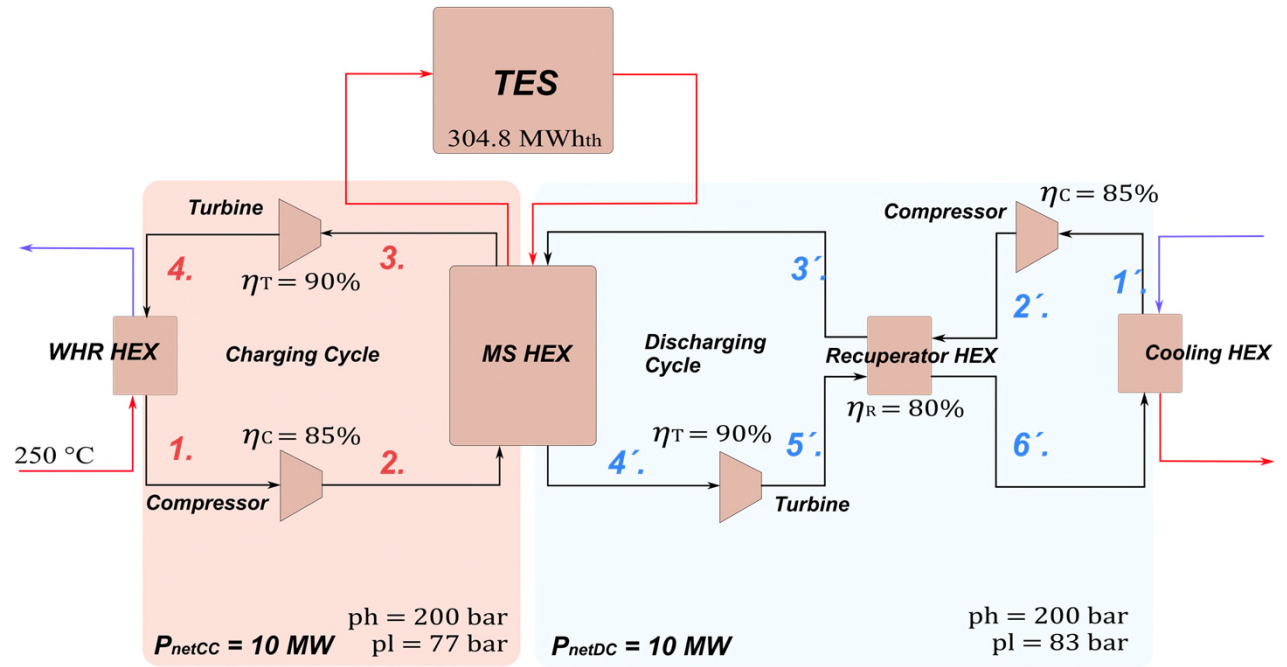
Off-design performance



System design



Off design performance curves: system simulated on EBSILON at part load, applying non-dimensional performance maps of sCO₂ machines.



Nominal COP (charging cycle)	2.54
Nominal cycle eff. (discharging cycle)	22.7%
Nominal round-trip efficiency	57.6%

Dispatch optimization - MILP



- **Short description:**
 - MILP model on Python (Pyomo)
 - Objective function – Maximization of revenues – two strategies
 - Only spot
 - Spot + ancillary services (AS) – **stacked revenues**
 - Time step – 1 hour
 - 1-year operation optimization (prices from 2023)
 - Cases
- **Assumptions**
 - Perfect price foresight
 - Heat is always available for charging
 - Constant TES discharge temperature (independent from SOC)

Case 1 – Base case

Constant COP and η ,
heat at 0 €/MWh,th

Case 2 – Heat price

Constant COP and η ,
heat at 40 €/MWh,th

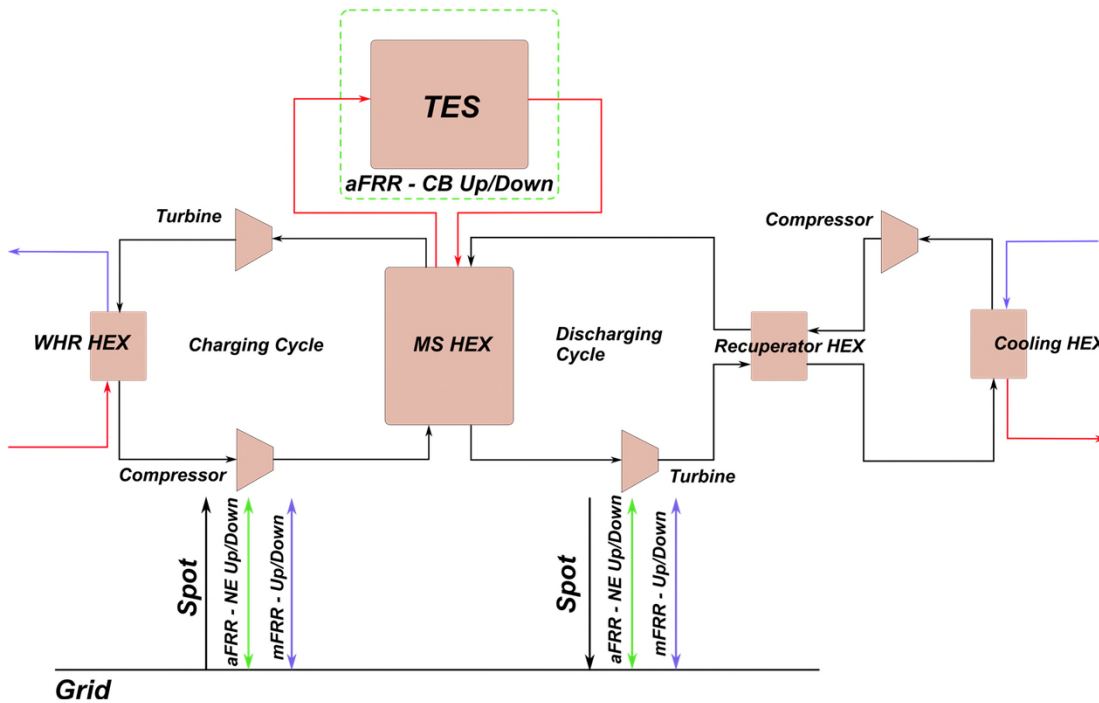
Case 3 – Off design

Variable COP and η ,
heat at 40 €/MWh,th





Integration of system with grid services



Product	aFRR Capacity Band	aFRR Net Energy	mFRR
Activation time	-	5 min	12.5 min
Duration	15 min	15 min	>5 min
Minimum bid size	1 MW	1 MW	1MW

Double remuneration

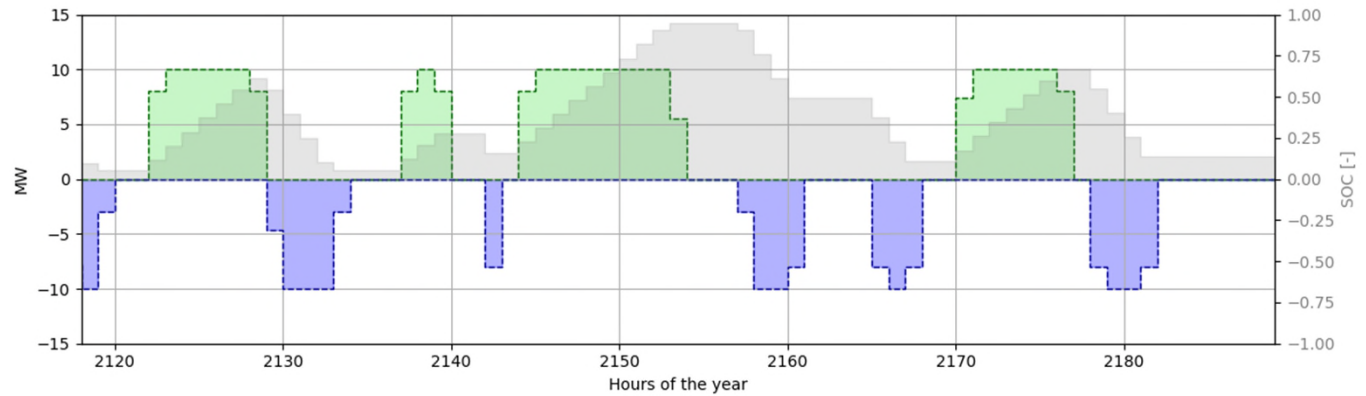
- **Energy activation services (aFRR and mFRR):**
 - Up/down regulation both in charging and discharging mode
- **Capacity reservation services (aFRR):**
 - Up/down regulation in TES



Dispatch optimization

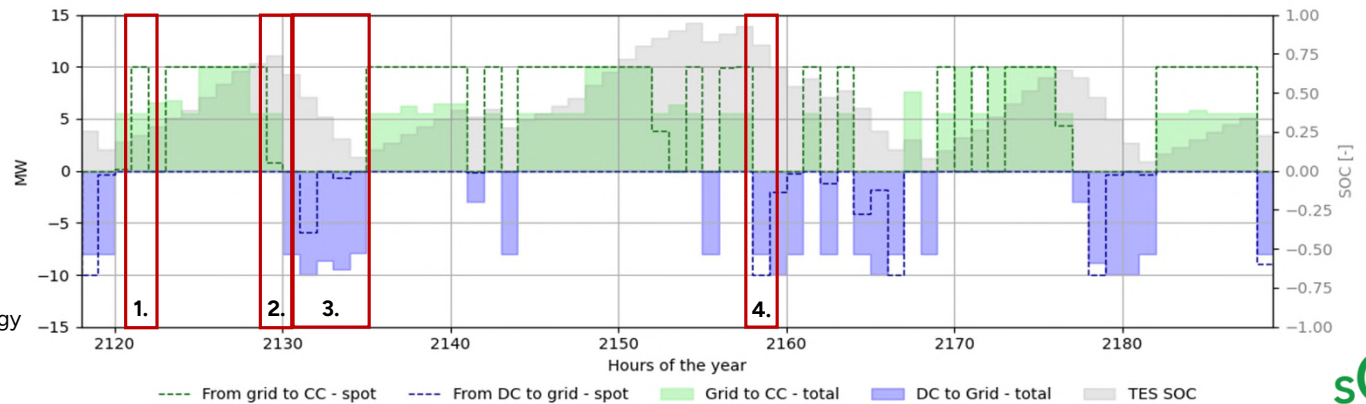
Constant COP and η , heat at 0 €/MWh,th

TES SOC and charging/discharging – Strategy 1: only spot



TES SOC and charging/discharging – Strategy 2: spot + AS

1. up regulation - charging (decrease energy extracted),
2. down regulation - charging (increase energy extracted),
3. up regulation - discharging (increase energy delivery),
4. down regulation - discharging (decrease energy delivery).





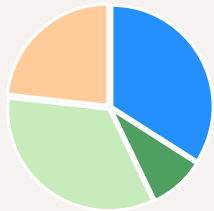
Techno-economic comparison of cases

Case 1 – Base case

Constant COP and η ,
heat at 0 €/MWh,th

Spot	Spot + AS
-6.6	+12.7
IRR [%]	

Revenue share – Spot + AS strategy



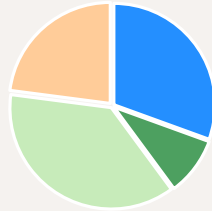
- Spot
- aFRR - Capacity Band
- aFRR - Net Energy
- mFRR

Case 2 – Heat price

Constant COP and η ,
heat at 40 €/MWh,th

Spot	Spot + AS
-17.2	+5.1
IRR [%]	

Revenue share – Spot + AS strategy



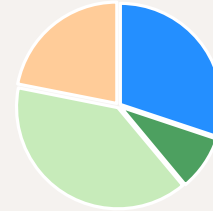
- Spot
- aFRR - Capacity Band
- aFRR - Net Energy
- mFRR

Case 3 – Off design

Variable COP and η ,
heat at 40 €/MWh,th

Spot	Spot + AS
-16.2	-5.31
IRR [%]	

Revenue share – Spot + AS strategy



- Spot
- aFRR - Capacity Band
- aFRR - Net Energy
- mFRR

Positive IRR when stacking revenues under design conditions operation.

Negative IRR when off-design is accounted for.

aFRR (capacity band + net energy) becomes the largest revenue stream when stacking revenues.

Conclusions



Techno-economic performance of a sCO₂ Carnot Battery that is connected to a waste heat source at 250 °C and operates in the Spanish spot and balancing markets.

- The spot + AS strategy provides revenues when charging the TES by trading ancillary services.
- Stacked revenues strategy provides an annual revenues increase > 500%, resulting in a positive NPV.
- Stacked revenues strategy remains profitable for a heat price below 40-42 €/MWh,th.
- Both strategies become unprofitable when variable COP and η are introduced for off-design operation.
- aFRR is the main revenue stream in both design and off-design operation.

Future work:

- Study other EU markets.
- Explore other waste heat temperatures and temperature boosting through electric heating.





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Thank you

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www.sco2op-tes.org



SCO2OP-TES Project



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