The Carnot battery: a promising technology for long-term electric energy storage

Frédéric Ransy[1], Vincent Lemort[2]

1.Uliege, Wingest

2.Uliege

frederic.ransy@uliege.be ; vincent.lemort@uliege.be

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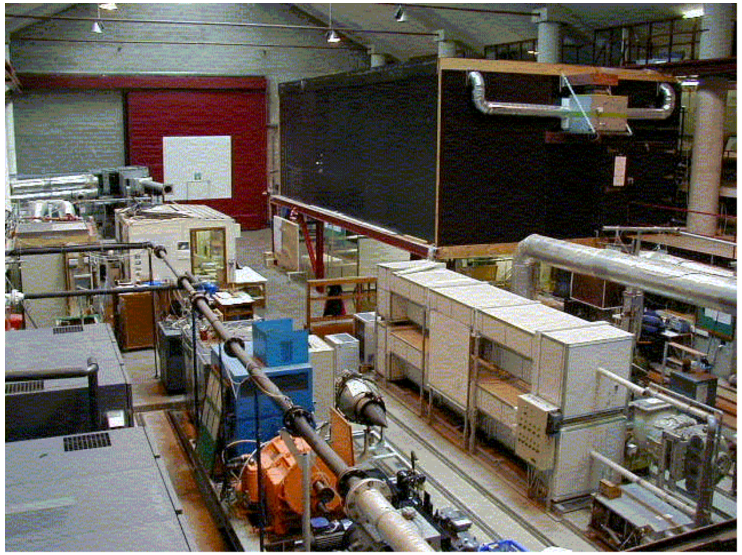
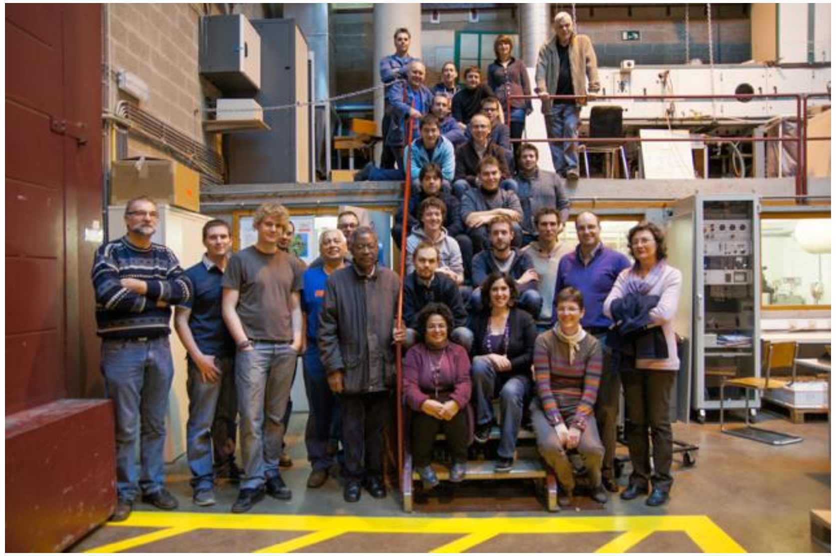
Uliege: the Thermodynamics Laboratory





- Thermodynamics Laboratory (est. 1887)
- Aerospace and Mechanical Engineering Department
- Engineering school of University of Liège
- Team of approx. **30 people**: 4 professors (1 emeritus), 3 postdoc, 12 PhD students, 4 technicians, 1 secretary, 5 invited researchers, 2 scientific collaborators

Uliege: the Thermodynamics Laboratory

- The Thermodynamics Laboratory collaborated for decades with Tsinghua University (Department of Building Science and Technology)
- 2004: Vincent Lemort made a research stay at Tsinghua University (Prof. Yi Jiang)
- ULiege and Tsinghua University are partners of the International Energy Agency project Annex 85 to assess the feasibility of passive cooling techniques (dew point cooling) for building and data centers cooling.

Key contributions about Carnot battery

O. Dumont, V. Lemort. *Mapping of performance of pumped thermal energy storage (Carnot battery) using waste heat recovery*, Energy, Volume 211, 2020.

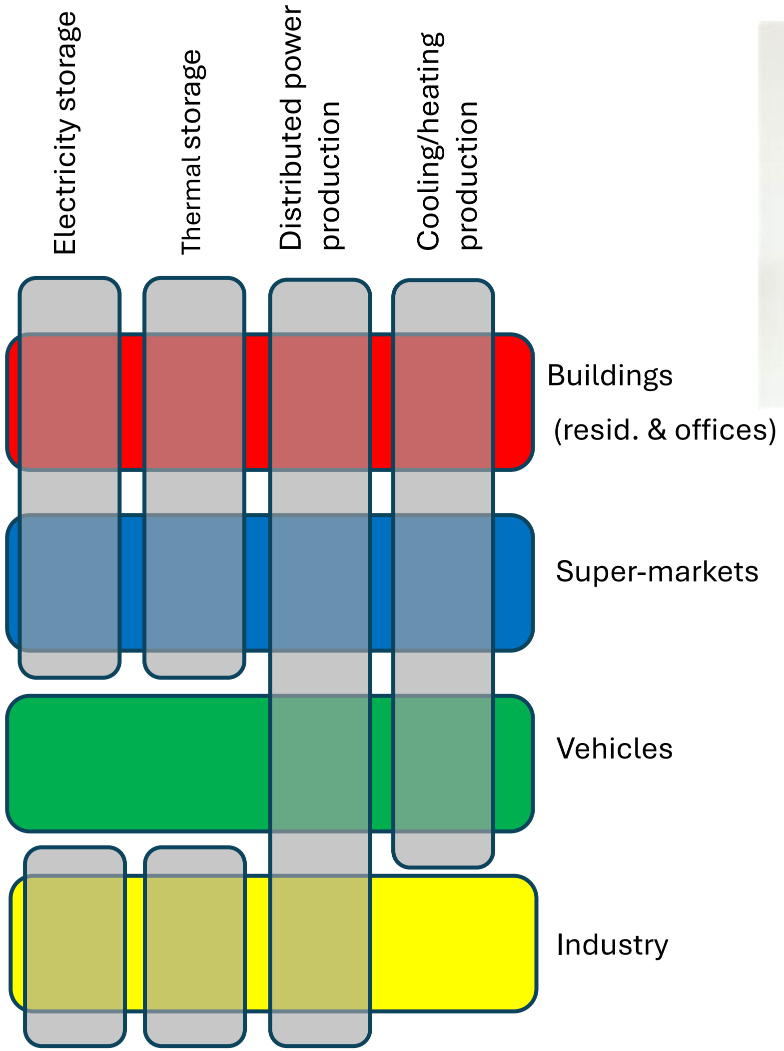
Olivier Dumont, Guido Francesco Frate, Aditya Pillai, Steven Lecompte, Michel De paepe, Vincent Lemort. *Carnot battery technology: A state-of-the-art review*, Journal of Energy Storage, Volume 32, 2020.

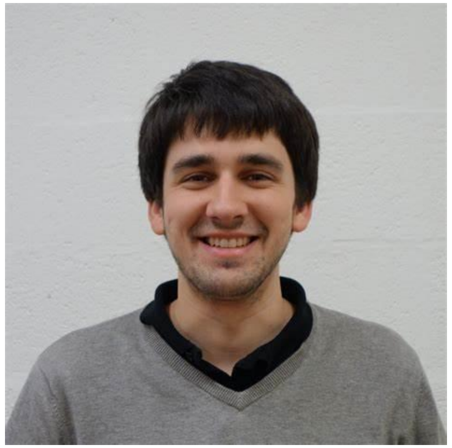
Antoine Laterre, Olivier Dumont, Vincent Lemort, Francesco Contino, *Is waste heat recovery a promising avenue for the Carnot battery? Techno-economic optimisation of an electric booster-assisted Carnot battery integrated into different data centres*. Energy Conversion and Management, Volume 301, 2024.

Antoine Laterre, Olivier Dumont, Vincent Lemort, Francesco Contino. *Extended mapping and systematic optimisation of the Carnot battery trilemma for sub-critical cycles with thermal integration*. Energy, Volume 304, 2024.

Scope of research activities

- *Thermal Energy System Research Groups (ca. 10 people)*:
  - Research activities aim at developing innovative and efficient **thermal energy** meeting our society's need
    - ✓ Design of components/systems
    - ✓ Integration
    - ✓ Control
  - Address 4 different sectors
  - Good balance between **experimental** and **numerical** research
  - Large proximity with **industry**





Scope of research activities

- Summary of research activities:

Heat pump and air-conditioning

- Development of a library of **models** of many types of **heat pumps**
- **Monitoring** of buildings with complex HVAC units
- Development of **models** (heat pump, storage, building) and experimental tests of systems (electric and heat pump water heater) for **demand response** at building level for ensuring grid stability
- **Dynamic simulation** and control of residential vapor injection heat pumps
- **Modeling** and **experimenta**l tests of **frost** formation on heat pump evaporator and impact of evaporator coating
- **Simulation** of **cooling** techniques to quantify the resilience of passive and active cooling technologies for Belgian building stock
- **Modeling** and **experimenta**l tests of different indirect evaporative cooling techniques for commercial buildings
- **Modeling** and **experimenta**l tests of advanced architecture of CO_2 refrigeration cycles for commercial buildings

Scope of research activities

- Summary of research activities:

Organic Rankine cycle

- Development of **simulation tools** and advanced **control strategies** for ORC utilized on internal combustion engines
- Development of **models** and **experimental tests** of working fluid **mass repartition** among the components in ORC
- Participation in the EU **Decagone** project: Design, build and operate a **MW-scale ORC demonstrator** working with cyclo-pentane as working fluid to recover **waste heat** from an industry

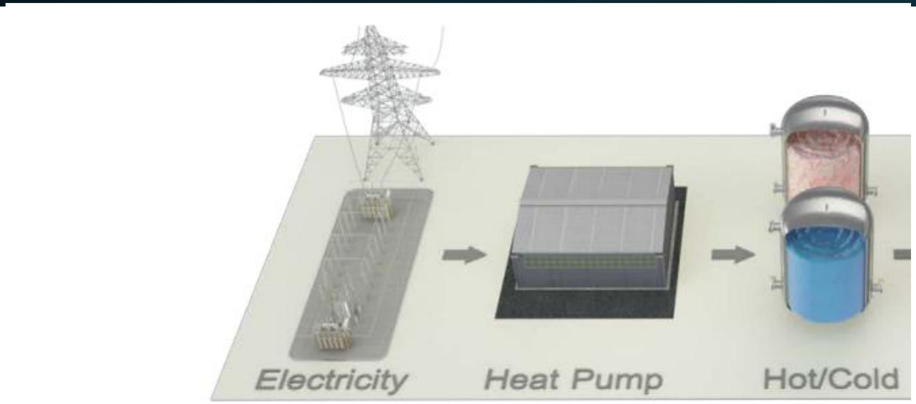
Scope of research activities

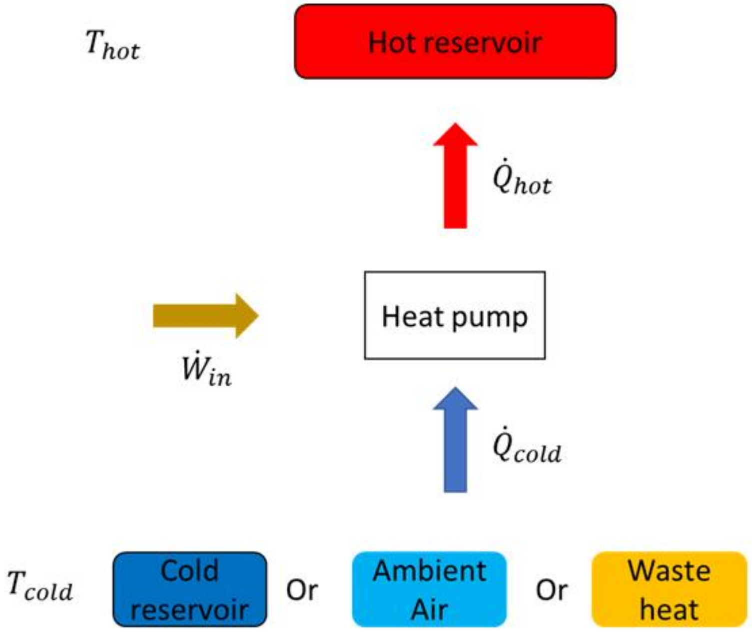
- Summary of research activities:

  Hybridization of heat pumps and ORC's

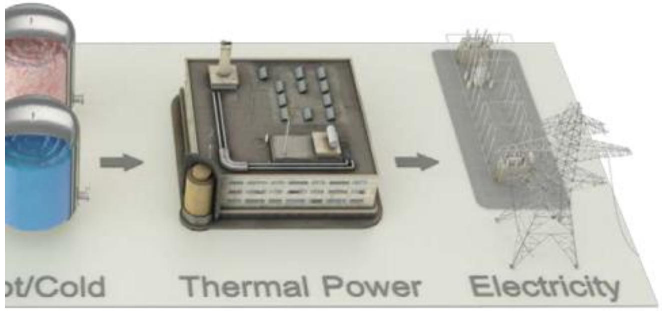
  - Development of a prototype of a **reversible Heat pump/ORC** unit integrated in a residential building
  - Development of a **lab-scale prototype** of a **Carnot battery** with 10 kWh of thermal energy storage
  - Development of a **lab-scale prototype** of a **Carnot battery** with 100 kWh of thermal energy storage and 10 kW_{el} output
  - Development of an **on-site prototype** of a **Carnot battery** with 15 MWh of thermal energy storage and 50 kW_{el} output

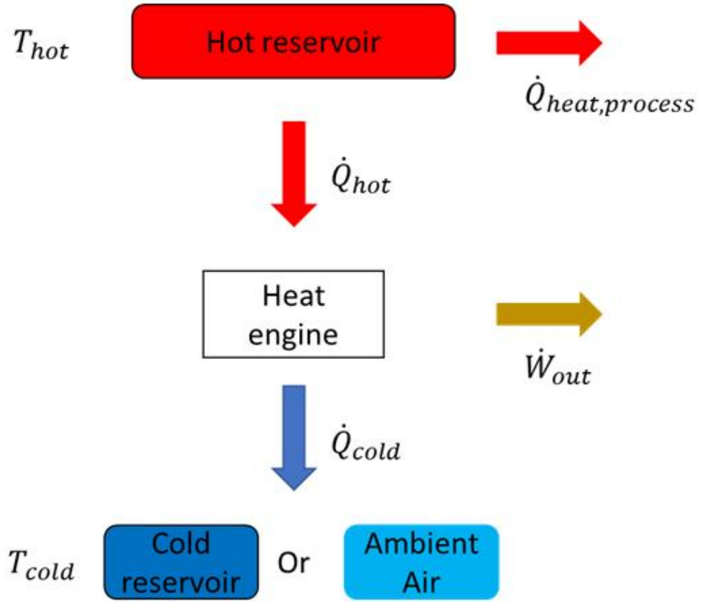
The Carnot Battery: concept





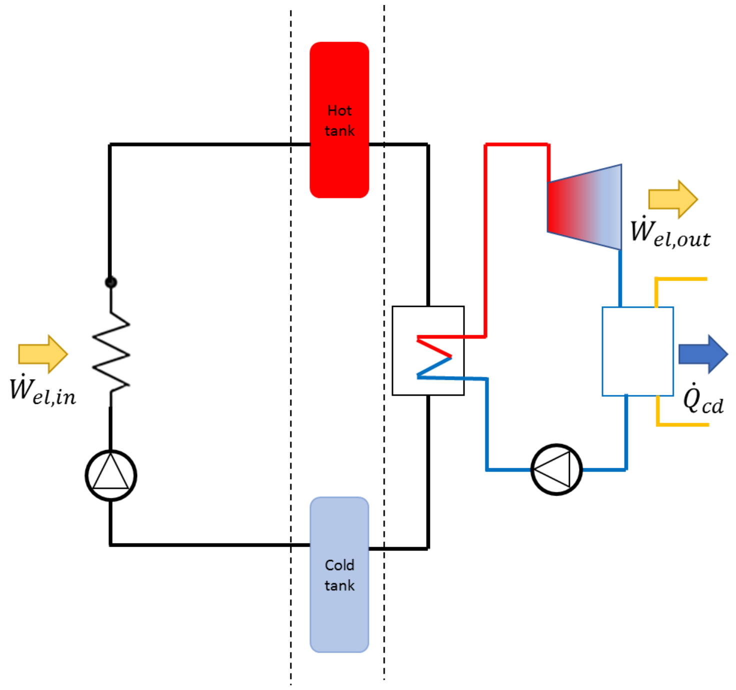
The Carnot Battery: concept



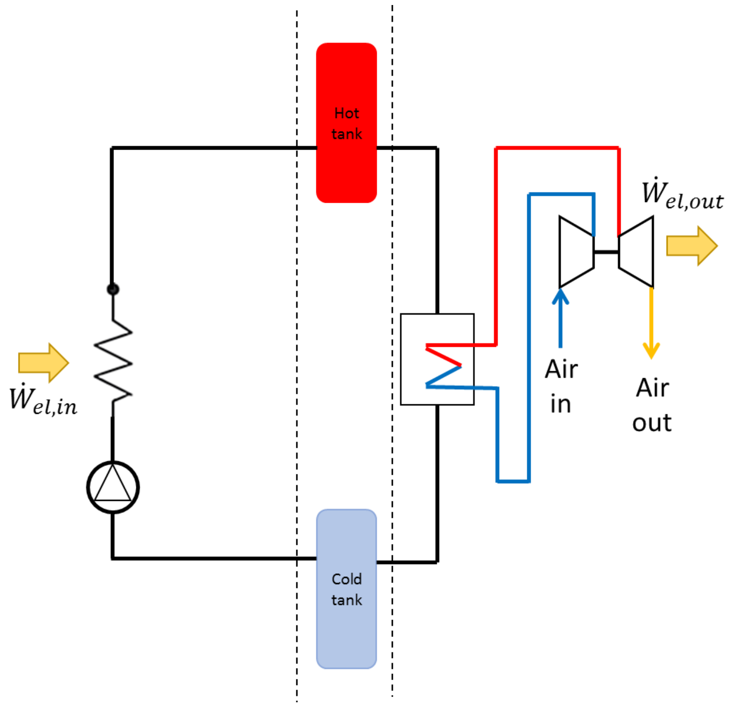


Existing architectures: charging the storage with electric resistance

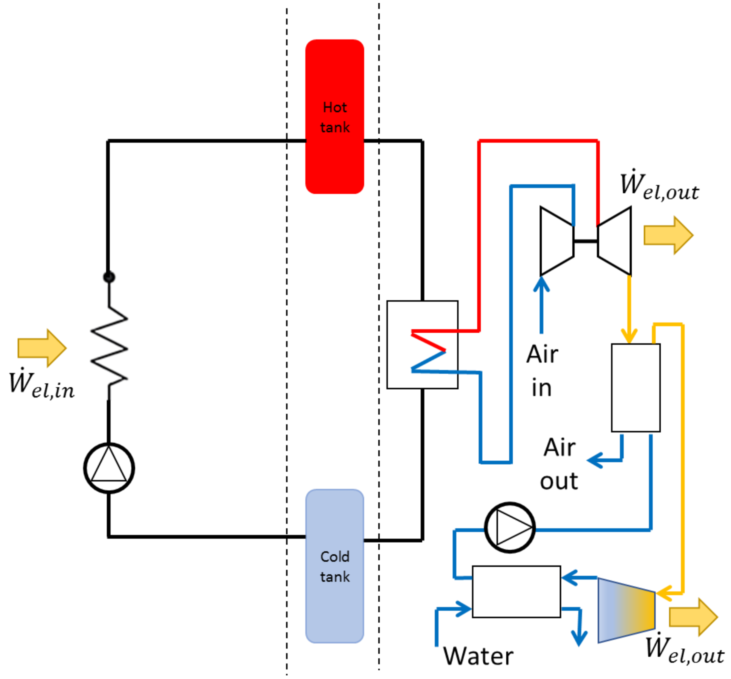
1. **Electric heater + Rankine cycle**



2. **Electril heater + Brayton cycle**

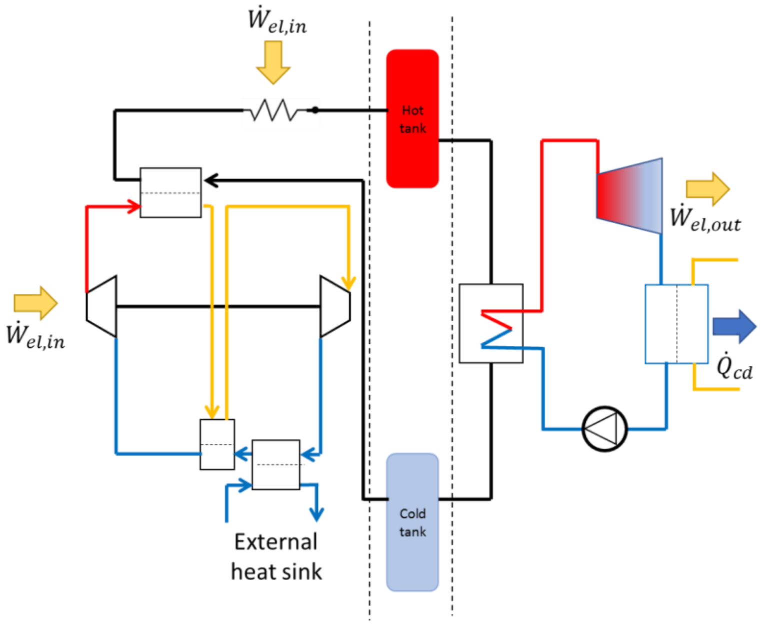


3. **Electric heater + Combined Brayton/Rankine cycle**

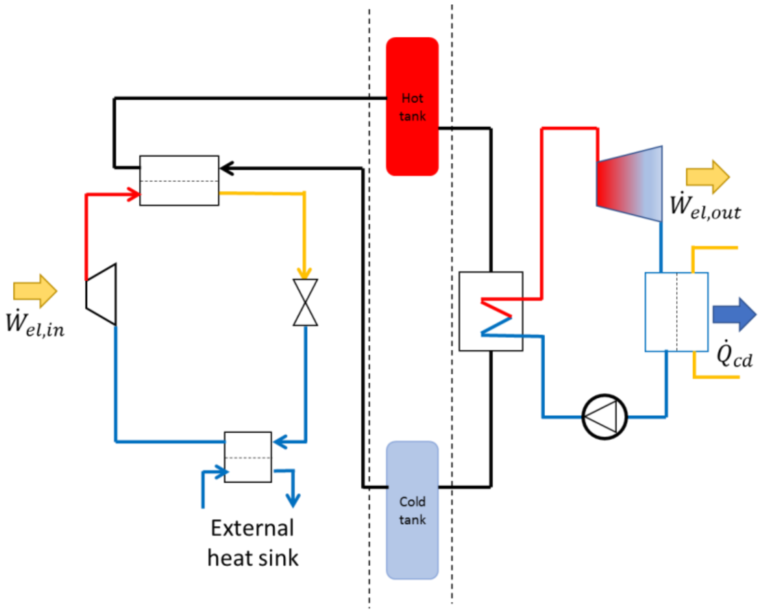


Existing architectures: charging the storage using a heat pump cycle

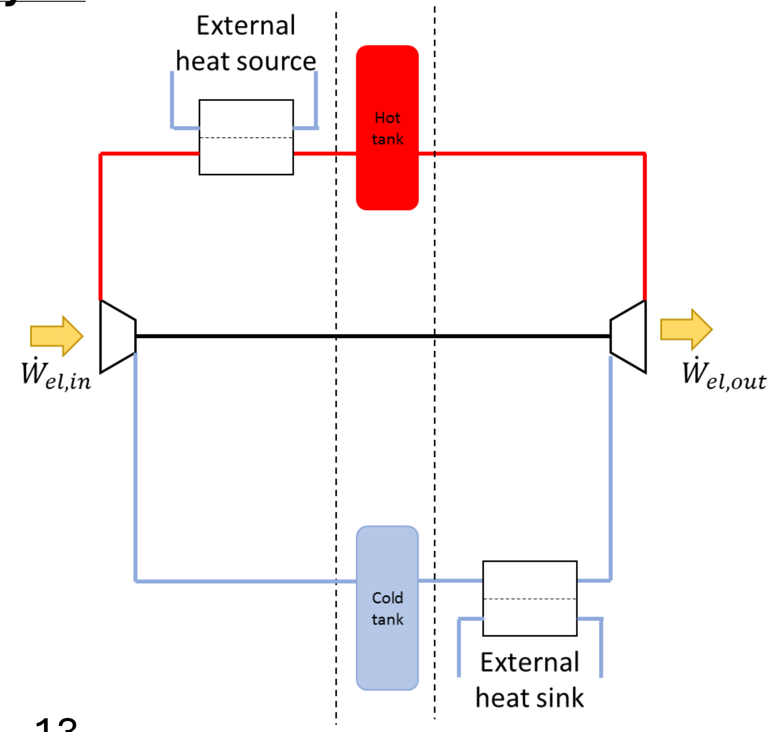
4. Reverse Brayton cycle + Rankine cycle



5. Vapor compression cycle + Rankine cycle



6. Reversible Brayton cycle



Possible architectures: Summary

System	Storage Temp [°C]	Round-trip Efficiency [%]	Estimated TRL
1. Electrical heater + Rankine cycle	400-600°C	[35-40]	9
2. Electrical heater + Brayton cycle	800-1400°C	[30-35]	5
3. Electrical heater + Combined Brayton/Rankine cycle	800-1400°C	[45-55]	5
4. Reverse Brayton cycle + Rankine cycle	500-600°C	[40-60]	5
5. Vapor compression cycle + Rankine cycle	100-200°C	[45-65]	7
6. Reversible Brayton cycle	-70-700°C	[52-65]	6

Existing technologies/concepts

1. Electric heater + Rankine cycle: Siemens Gamesa, RWE, E2S power
2. Electric heater + Brayton cycle: 247Solar, 1414Degrees, Peregrine Turbine Technologies
3. Electric heater + Combined Brayton/Rankine cycle: Project ENDURING
4. Reverse Brayton cycle + Rankine cycle: GE Renewable Energy
5. Vapor compression cycle + Rankine cycle: Climeon, Future Bay, Uliege
6. Reverse Brayton cycle: Malta, Stisdal, Echogen, Man/ABB, WindTP

Possible architectures: Summary

Carnot Battery

Advantages

- No site constraints
- Long life expectancies (20-30 years)
- Small environmental footprint
- Can supply electricity, heat and cold heat

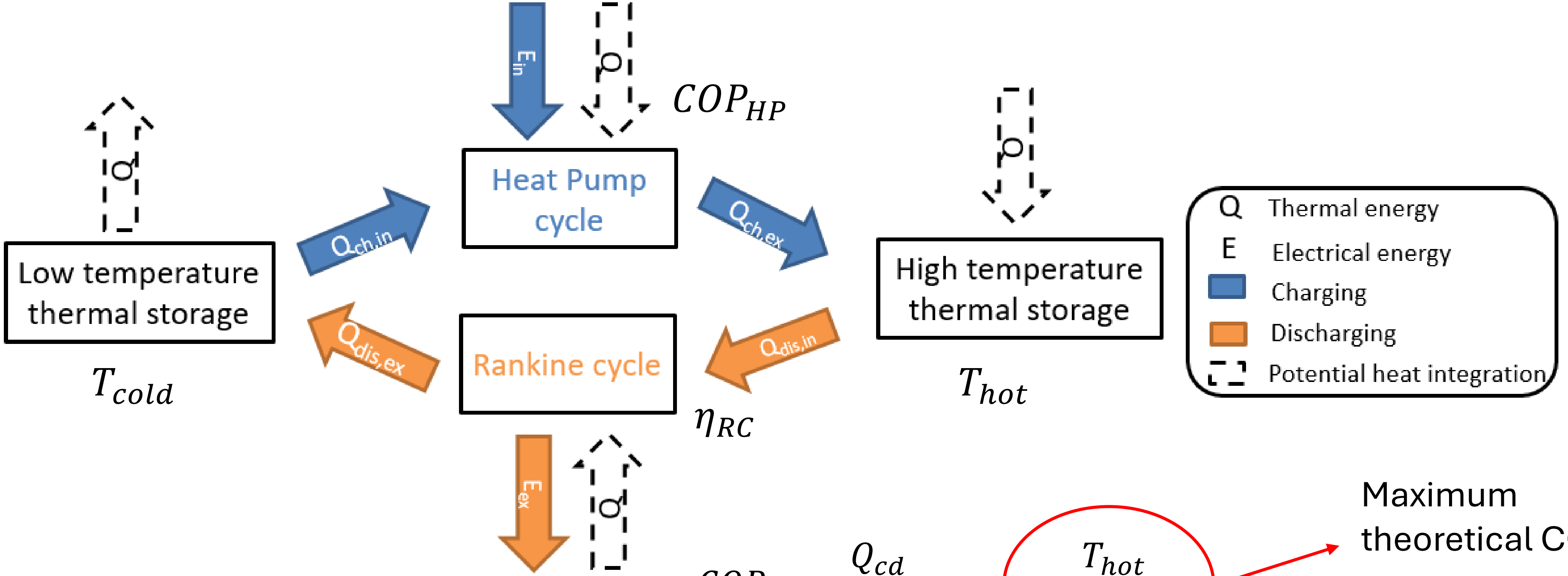
  => suitable for the future Smart energy systems

Disadvantages

- Low round-trip efficiency (30-60 %, to be compared with 65-85 % for the pumped-storage hydroelectricity)

Solution to increase the efficiency: the **Thermally Integrated** Carnot Battery

Efficiency of a Carnot battery



$$COP_{HP} = \frac{Q_{cd}}{E_{el}} = g_{HP}\frac{T_{hot}}{T_{hot} - T_{cold}}$$

Maximum theoretical COP

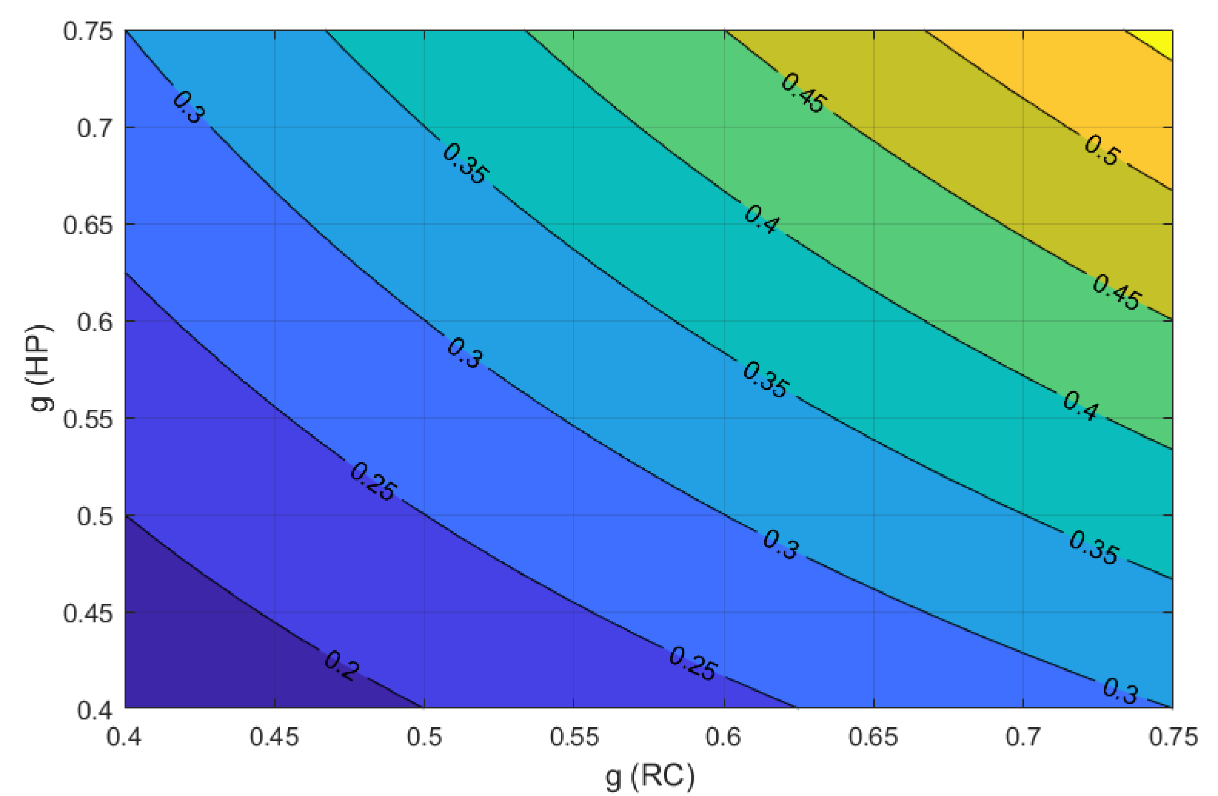
$\varepsilon_{rt} = (\eta_{TES}\,.)\ COP_{HP}.\eta_{RC}$ with

$$\eta_{RC} = \frac{E_{el}}{Q_{ev}} = g_{RC}\left(1 - \frac{T_{cold}}{T_{hot}}\right)$$

Maximum theoretical efficiency

Efficiency of a Carnot battery

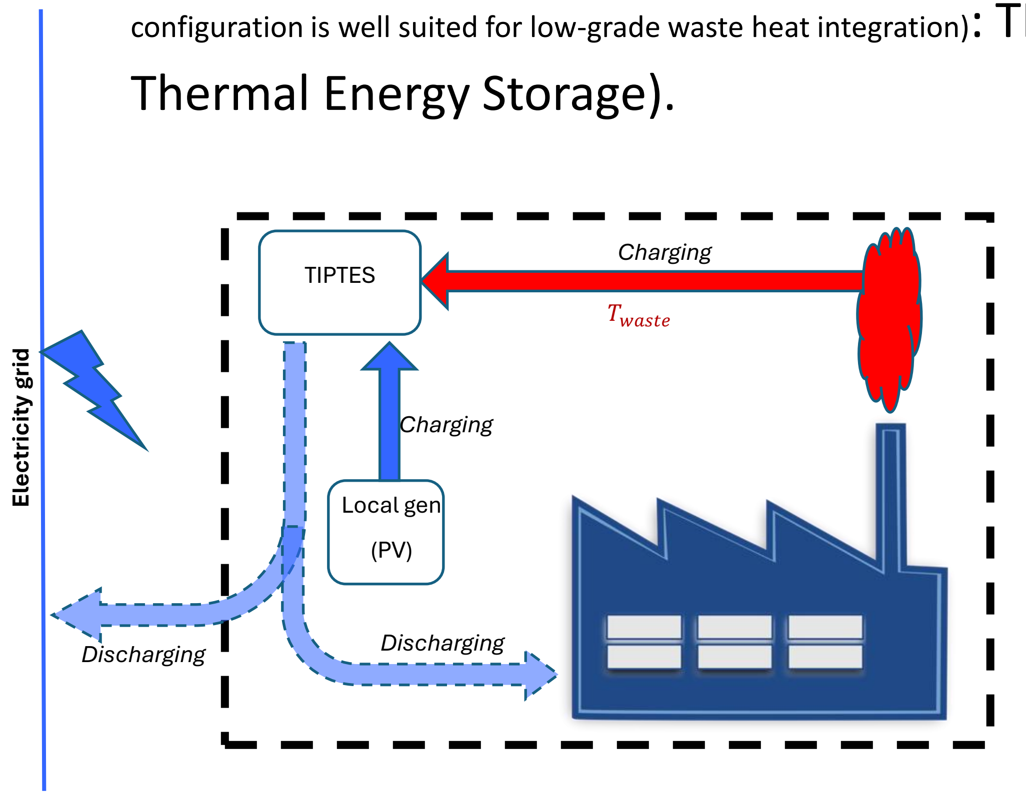
$$\varepsilon_{rt} = g_{HP}\frac{T_{hot}}{T_{hot}-T_{cold}}g_{RC}\left(1-\frac{T_{cold}}{T_{hot}}\right) = g_{HP}.g_{RC}$$

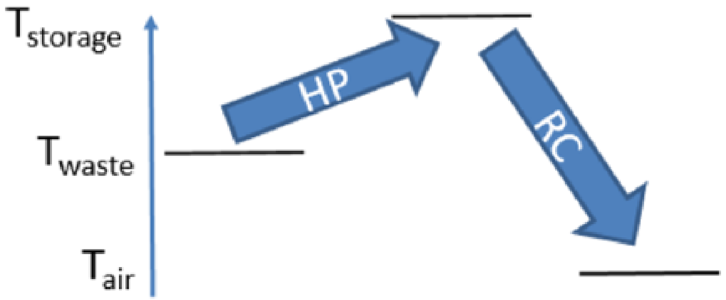


Roundtrip efficiencies don’t easily reach values over 50%

Carnot battery: integration of waste heat

- Performance can be improved by integrating **waste heat** into the process (Heat Pump + ORC configuration is well suited for low-grade waste heat integration): TIPTES (Thermally Integrated Pumped Thermal Energy Storage).





$$\varepsilon_{rt} = \eta_{TES} . COP_{HP} . \eta_{RC}$$

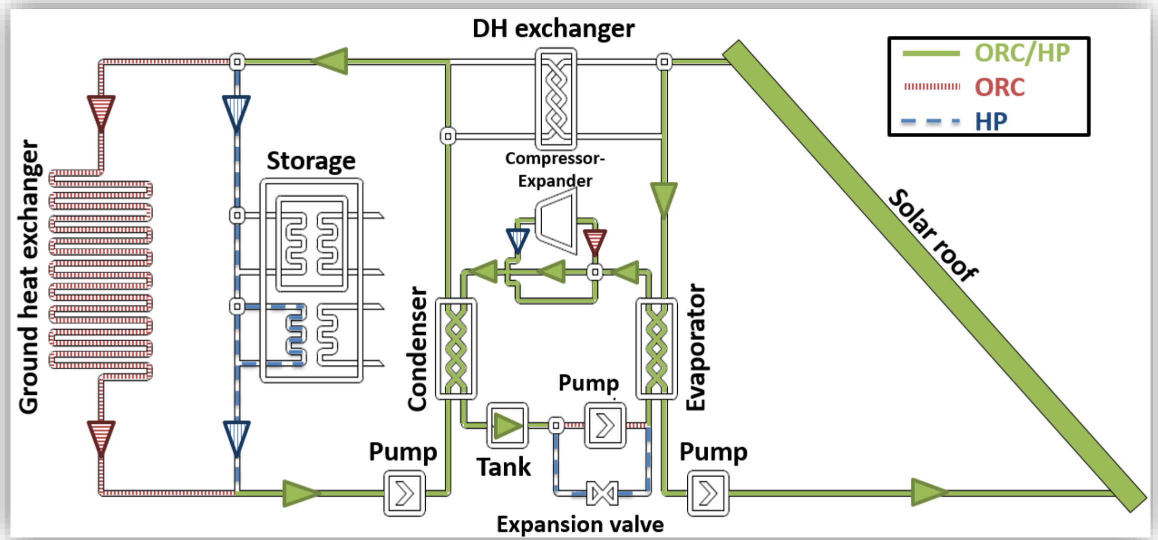
Development of Carnot battery at Uliege

2015	• Development of a reversible heat pump/ORC unit for residential buildings	TRL 5
2018	• Development of a first lab-scale Carnot battery prototype	TRL 5
2021	• Development of a second lab-scale Carnot battery prototype	TRL 6
2023	• Development of an on-site Carnot battery prototype connected with massive underground thermal storage	TRL 7

« Reversible » heat pump/ORC Carnot batteries
First prototype: conversion of solar energy into electricity

Reversible HP/ORC unit instead of a classical residential heat pump

- Components and costs close to a classical residential heat pump (cheap)
- Large solar roof (absorber) + horizontal ground heat exchanger
- 3 operating modes (DH,HP,ORC) with low cost architecture

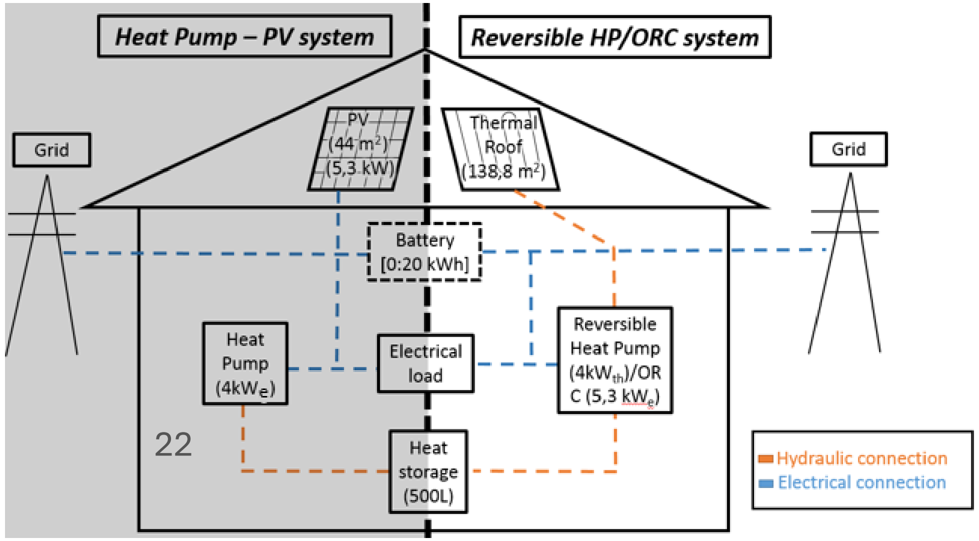


Eurostars Single HPA Unit project
(2015-2016) coordinated by Innogie

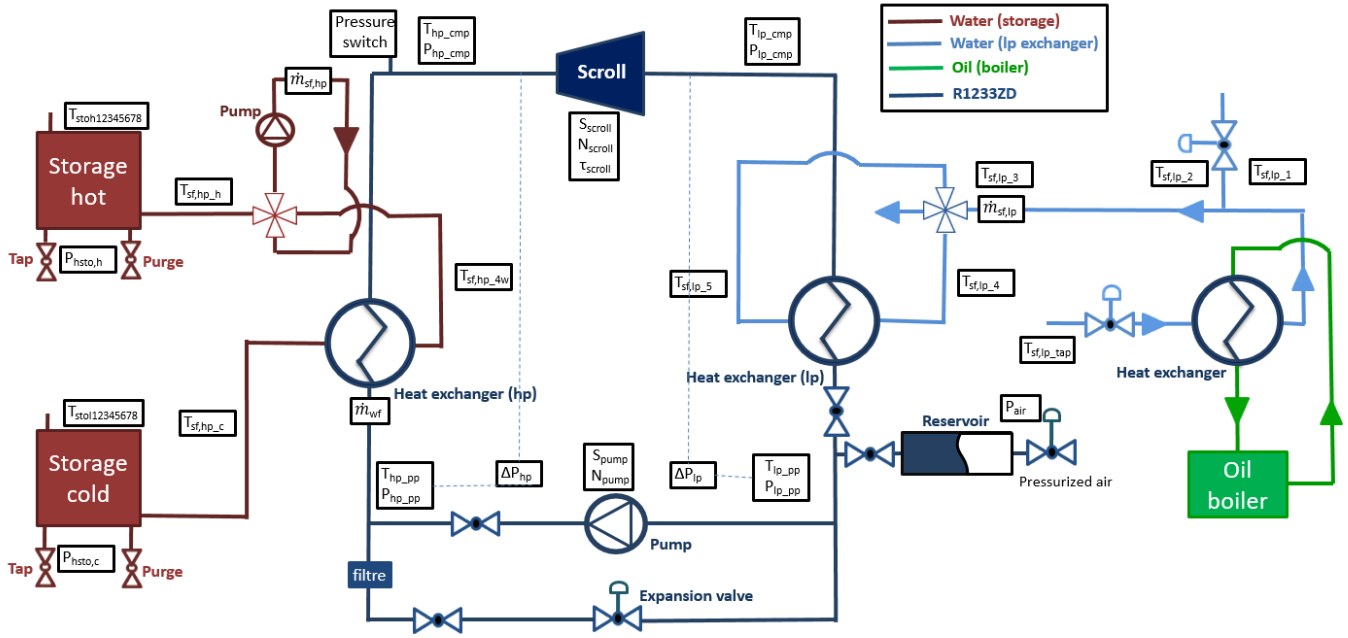
« Reversible » heat pump/ORC Carnot batteries
First prototype: conversion of solar energy into electricity

- **Prototype**:
  - Sized to produce 4030 kWhe per year
  - COP of 4.21 (Tev=21°C/Tcd=61°C)
  - ORC efficiency of 5.7% (Texcd=25°C/Tsuev=88°C)

- Economical profitability not demonstrated versus **PV** + heat pumps (2016).
- Looking to other applications of reversible heat pumps/ORCs.

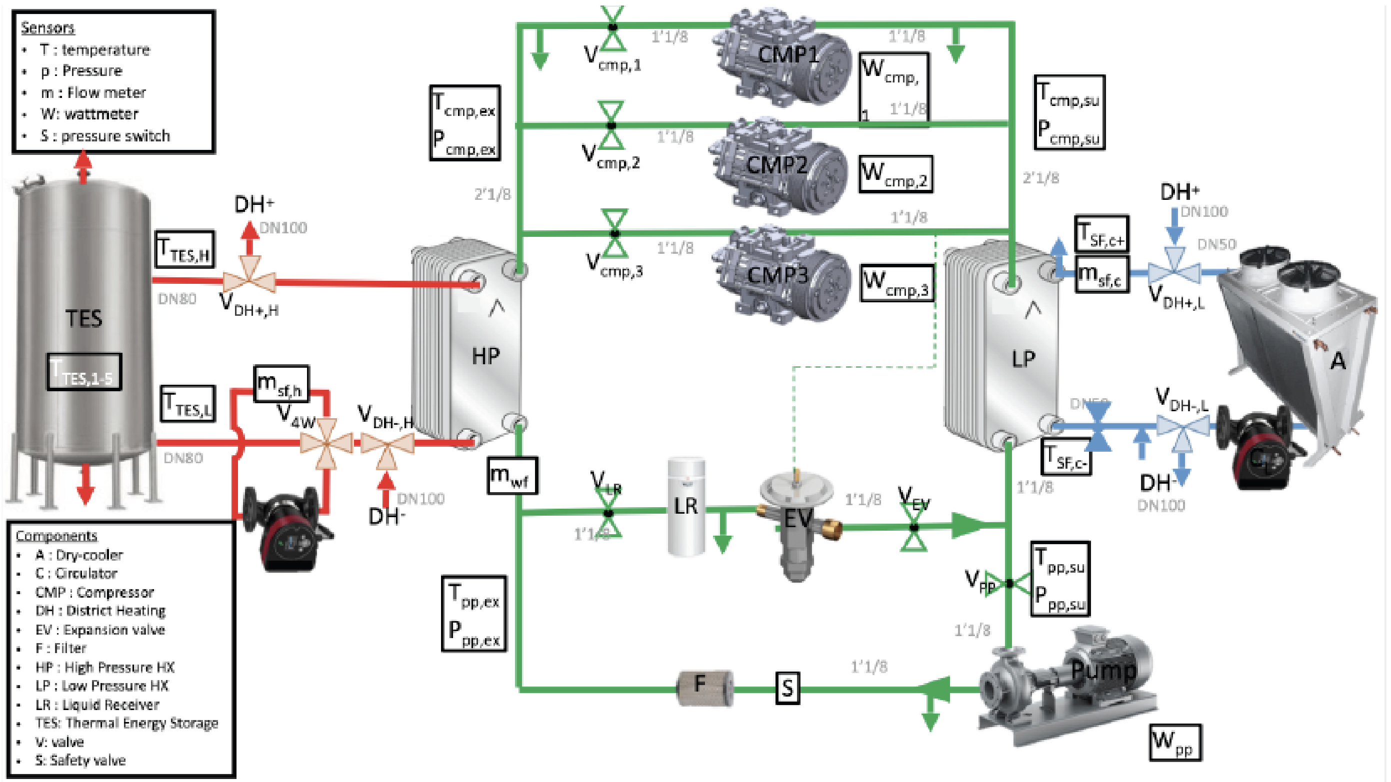


First prototype of reversible ORC/HP CB
1 kWe Carnot battery



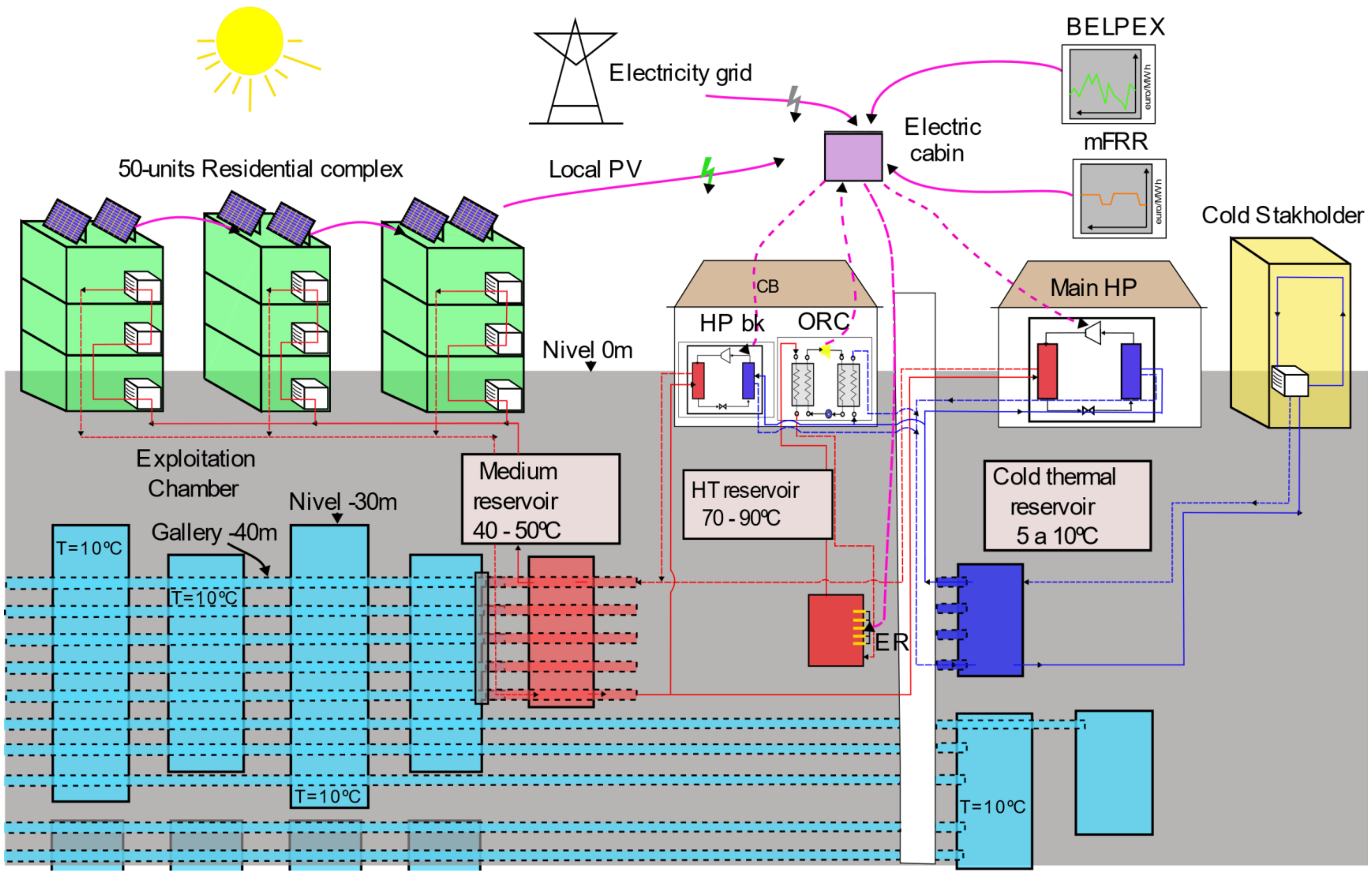
- Mechanical scroll
  - Variable speed
  - VR=2.2
  - Swept volume = 121 cm^3
- Plate heat exchangers
  - 25 kW
- Hot and cold water storage
  - Perfect stratification
  - 2X900 L (10 kWh thermal energy)
- Plunger pump
  - 70 g/s
- Manual expansion valve

Second Carnot battery prototype 10 kWe



- 8.1 m^3 water tank
- HP: nominal electrical consumption of 10.7 kWe and a COP of 7.69
- ORC: nominal electrical production is 5.6 kWe with the efficiency is 5.5%

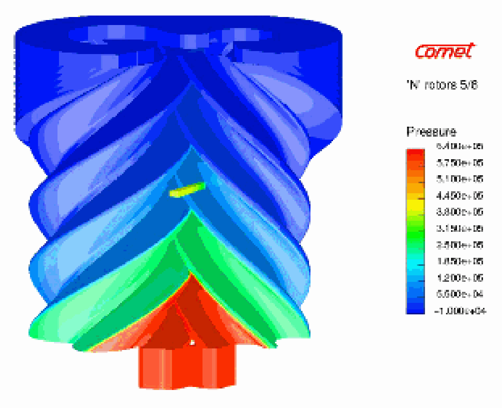
On-site prototype of a Carnot battery
15 MWh of thermal energy storage, 50 kWel

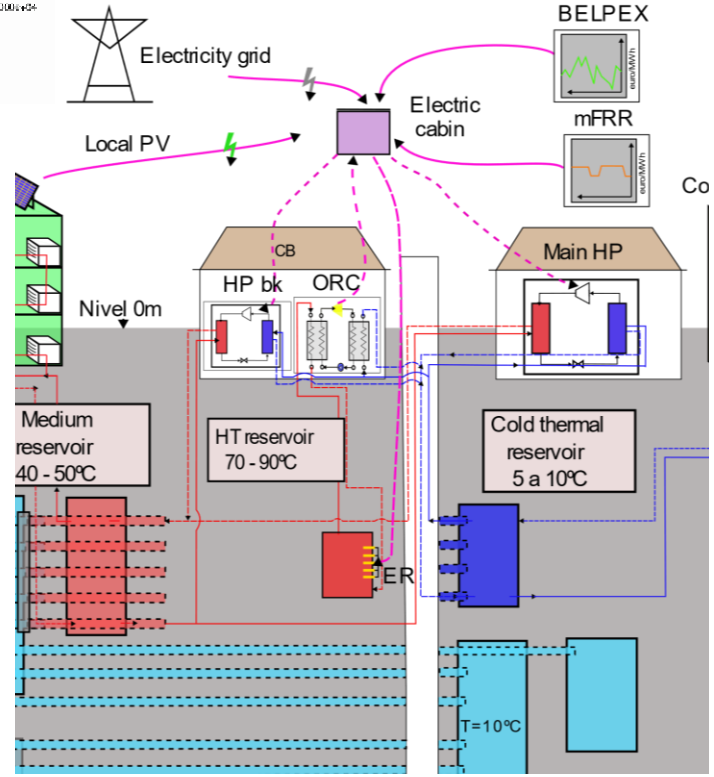


- WeForming project
- 3 chambers
  - **800 m^3 at HT (80-60°C)**
  - 6840 m^3 at MT (50-40°C)
  - 80000 m^3 at LT (10-5°C)
- ORC
- Electric resistances (less efficient than a heat pump, but with a shorter time constant)

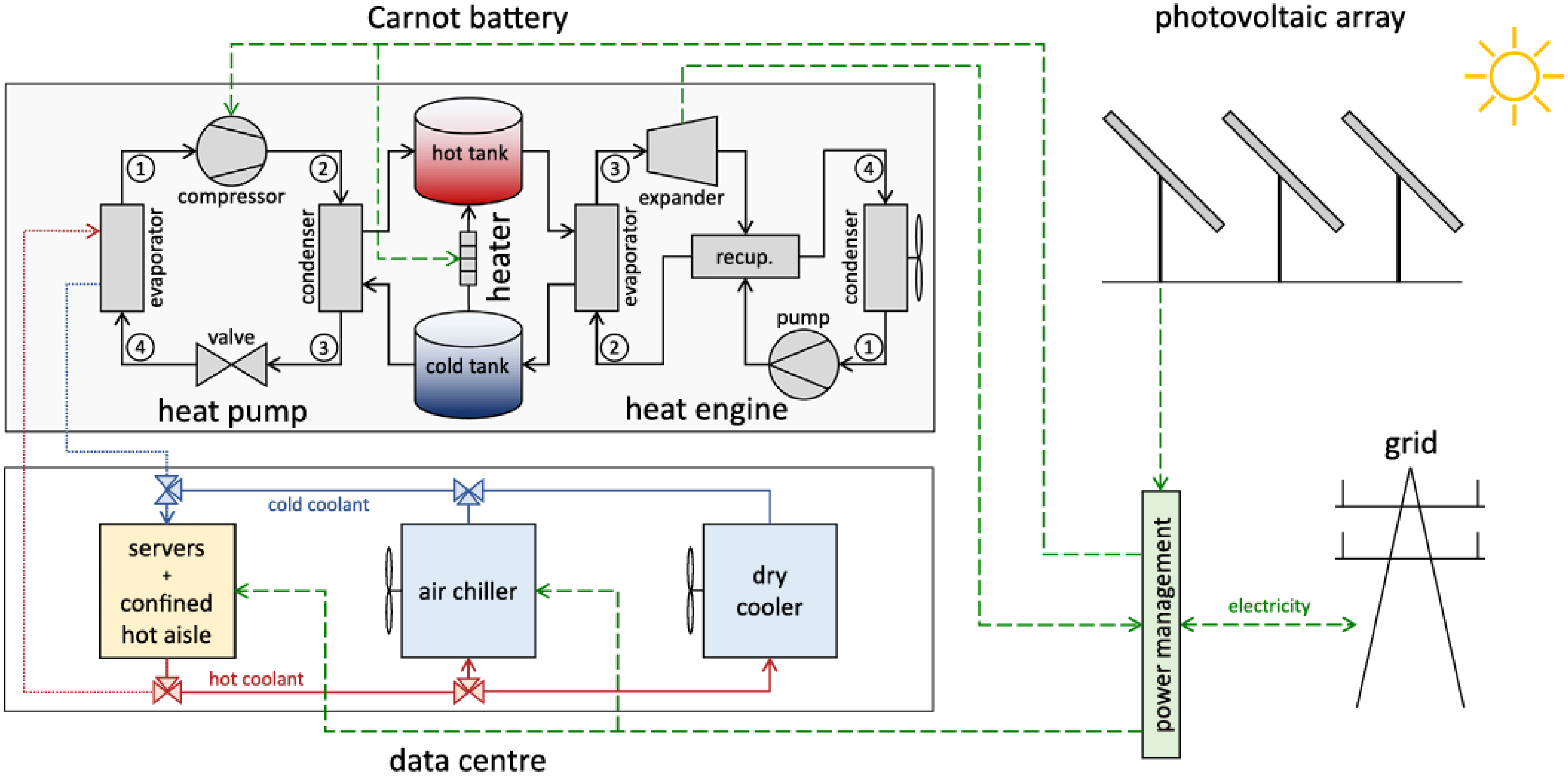
On-site prototype of a Carnot battery
15 MWh of thermal energy storage, 50 kWel

- Technical characteristics
  - ✓ ORC
    - 48 kWe (90°C at the evap. and 10°C at the cond.),
    - Operating with R1233zd(e)
    - Screw expander
    - Activated if BELPEX price >100 EUR/MWh or mFRR signal upward
  - ✓ Electric resistances
    - 200 kWe
    - Activated if BELPEX electricity price < 0 or, prioritized if mFRR signal downward





Integration of Carnot battery in data centers



Antoine Laterre, Olivier Dumont, Vincent Lemort, Francesco Contino, *Is waste heat recovery a promising avenue for the Carnot battery? Techno-economic optimisation of an electric booster-assisted Carnot battery integrated into different data centres.*

Integration of Carnot battery in data centers

Advantages of integrating Carnot batteries in data centers

- Possibility to decouple the power (kW) from the storage capacity (kWh)
- Possibility to reduce the chiller consumption
- Possibility to replace the diesel generator
- Able to exploit low-temperature (40-80°C) waste heat generally not utilized
- Provide medium-term storage (6-20 h) to increase PV self-consumption, self-sufficiency and manage peak power

Integration of Carnot battery in data centers

Key fixed parameters

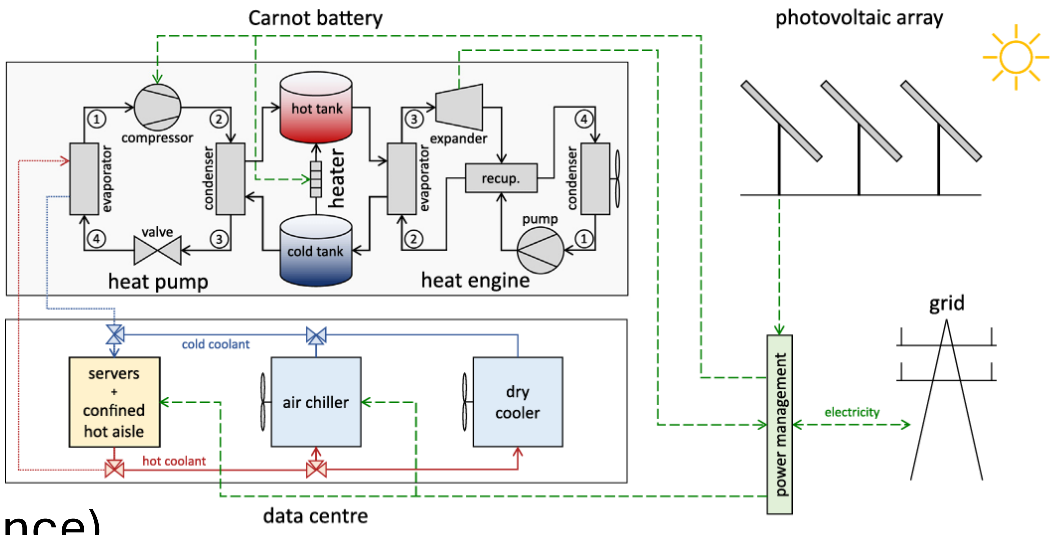
- 100 kW data center
- 2 locations: Belgium and South of Spain
- Sensile heat storage: water at 7,5 bar (max 150°C)
- Fluid: R1233zd(E)

Key parameters to optimize

- PV peak power
- Carnot battery inlet power (Heat pump and electric resistance)
- Carnot battery outlet power (Organic Rankine Cycle power)
- Volumes of the storages
- Low and high storage temperatures

Indicators

- Net present value and discounted payback period
- Self-sufficiency factor

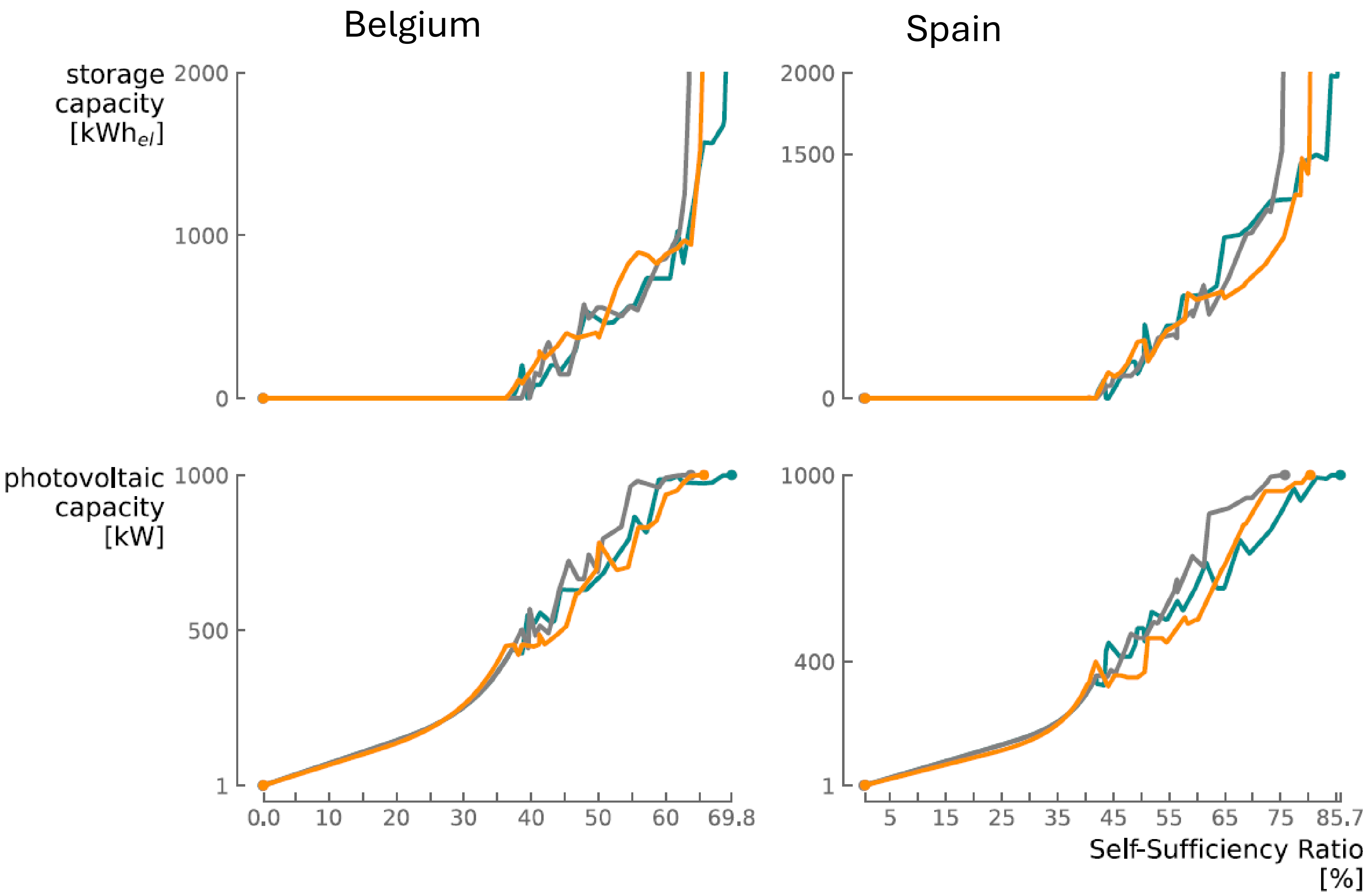


$$NPV = -C_0 + \sum_{n=1}^{LT} \frac{B_n - C_n}{(1+r)^n}$$

$$SSR = 1 - \frac{E^{el}_{grid}}{E^{el}_{servers} + E^{el}_{chiller}}$$

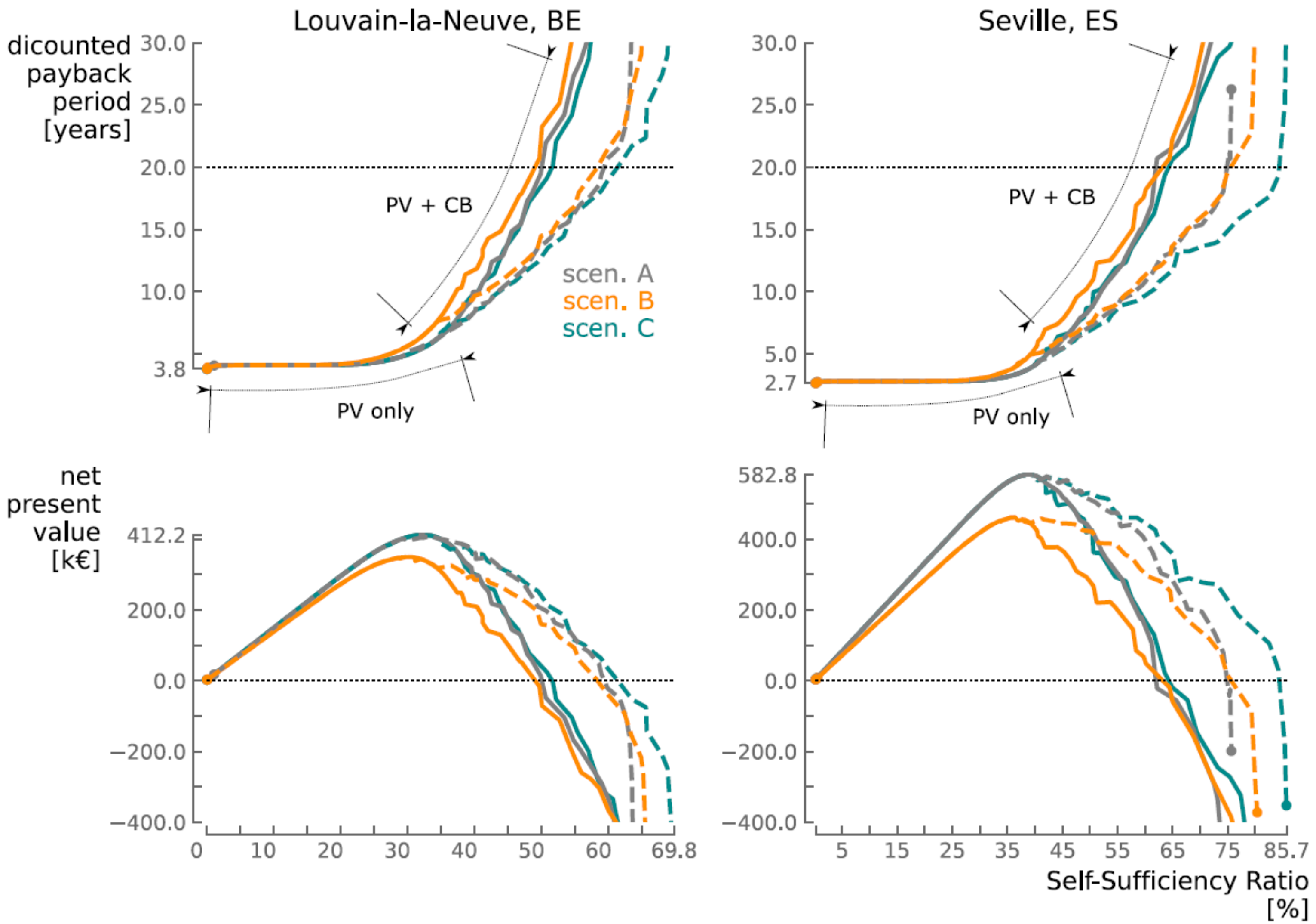
Integration of Carnot battery in data centers

A few results



Integration of Carnot battery in data centers

A few results



R&D pespectives

- Carnot batteries offer a lot of R&D perspectives, incl.:
  - ✓ Minimize performance degradation in **off-design** (other heat source/sink temperature) and **part load** (other capacity of HP/ORC)
  - ✓ Investigate what kind of service can be provided to the **electrical grid** (using calibrated and validated **transient** models).
  - ✓ Optimize **integration** with other systems: utilization of thermal “by-products” (low-temp heat at ORC condenser) and mutualization of thermal storages for covering H/C demands on-site
  - ✓ Optimal **control** strategies, Life cycle analysis (**LCA**), **Techno-economic** optimization
  - ✓ Improvement of the **thermodynamic cycle** and/or the **fluid** to increase the efficiency
  - ✓ Development **of prototypes** to show the real efficiency of this technology

Conclusion

- Carnot battery is a promising solution for medium-long term energy storage
- CBs proposes a solution to integrate high share of RES in the electrical grid
- RTEs of CBs are lower than PHES, CAES, and Li-ion batteries. It is therefore necessary to integrate waste heat in the system, decrease the CAPEX or increase the efficiency through R&D.
- CBs should be integrated in the whole energy ecosystem considering the electricity grid and district heating/cooling networks
- The technology needs experimental validation/prototypes