Batteries de Carnot : *intégrations thermique et électrique dans des bâtiments*

Vincent Lemort, Olivier Dumont et Antoine Laterre

Journée micro et mini cogénérations

Paris, le 1er février 2023

LIÈGE université

LABORATOIRE DE THERMO DYNAMIQUE UNIVERSITE DE LIEGE

Introduction

What are we looking for?

- **Electricity storage** solution with high round-trip efficiency, low environmental impact and low cost
- Systems producing **multiple energy vectors** (electricity, heat/cold) from one single piece of equipment

BatRenew

What do we benefit from?

- **Low-grade heat** (district heating, waste heat)

=> Carnot battery with thermal integration and using a reversible HP/ORC is a promising solution

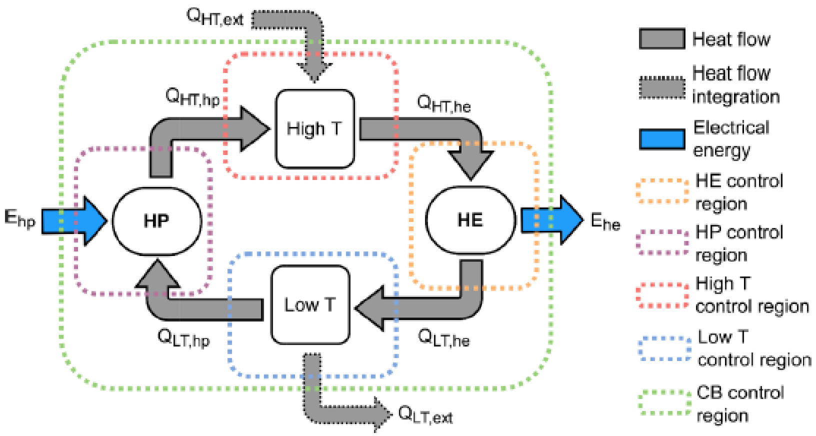
Agenda of the presentation

1. Introduction
2. **Carnot battery (CB)**
3. Reversible Heat pump/ORC
4. Integration of low-grade heat in CBs
5. First prototype
6. Second prototype
7. Conclusions

Carnot battery

Operating principle

Carnot battery = system primarily used to store electricity (Power-to-Heat-to-Power)



- *Charging*: electricity is used to establish a temperature difference between 2 reservoirs (high and low temp.) by means of a HP.
- Electricity is therefore stored as thermal exergy.
- *Discharging*: heat flows from high to low temp. reservoirs and part is converted into electricity by a HE.

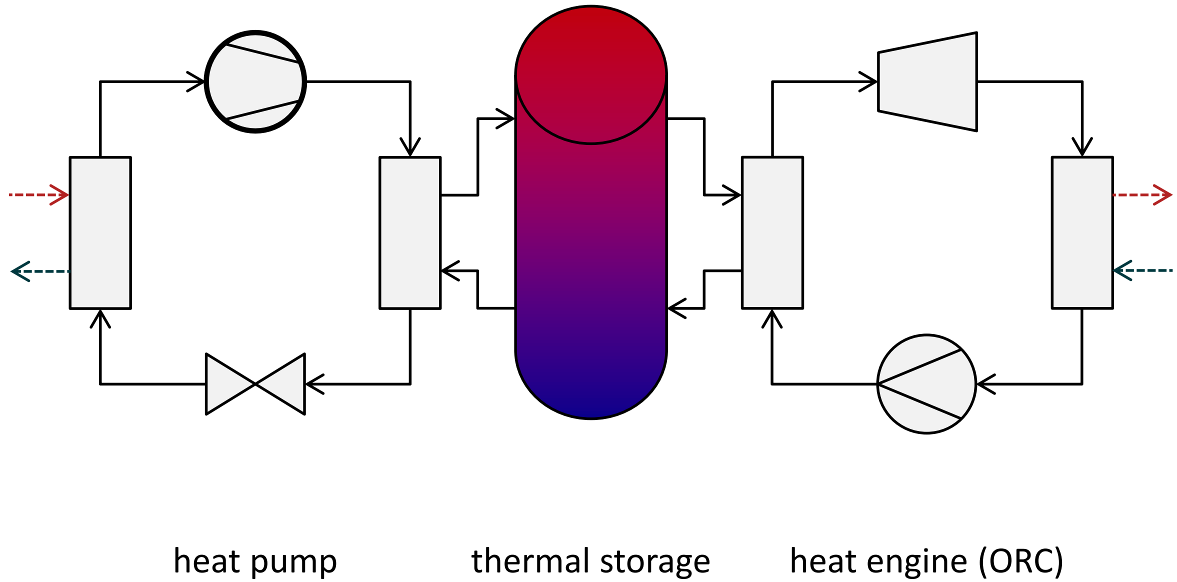
Round-trip effieincy: $\varepsilon_{rt} = \frac{E_{he}}{E_{hp}}$

- Different technologies of HP and HE: vapor compression systems, Brayton cycles, electrical heater.
- Vapor compression: off-the-shelf components, lower temperatures
- Different technologies of thermal energy storage for the heat reservoirs.
- Environment to replace one of the heat reservoirs.

Carnot battery

Atmosphere as one of the thermal reservoirs

Simple configuration using air as HP heat source and HE heat sink



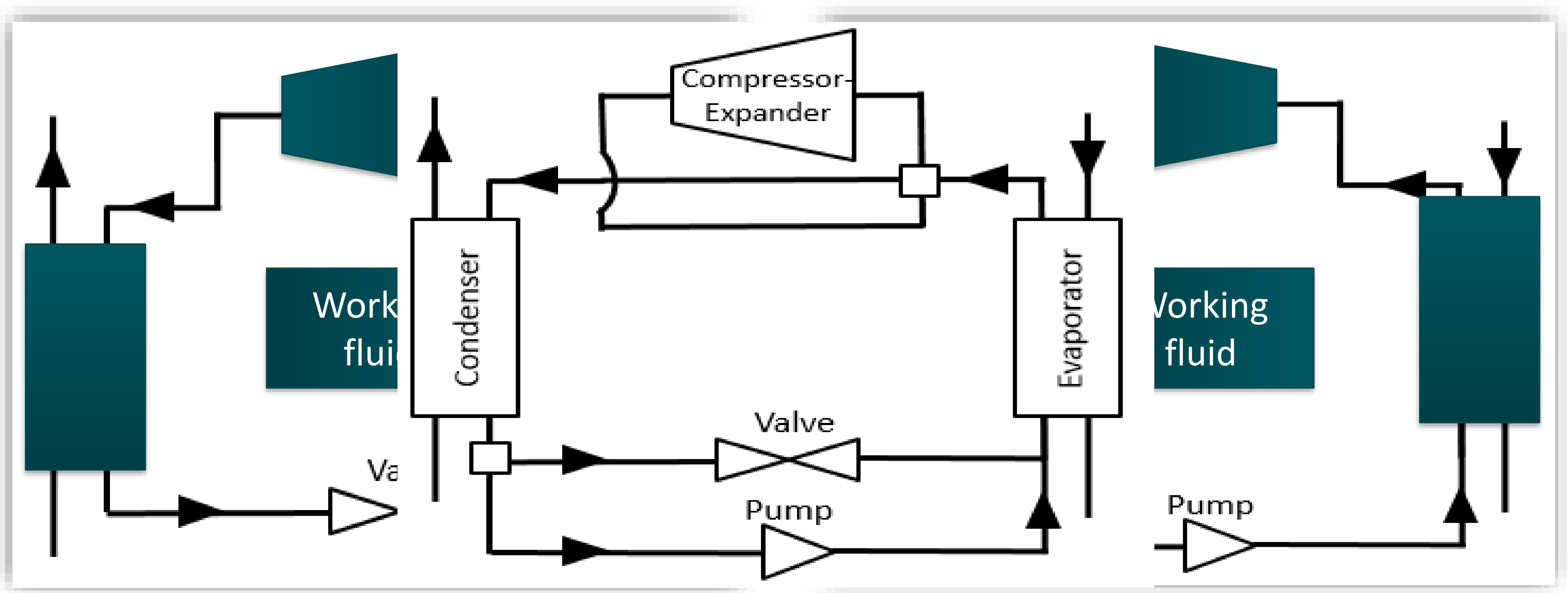
« Reversible » heat pump/ORC Carnot batteries

Principle

Technical "proximity" between ORC components and heat pump (chiller) components

=> Could we develop an **"reversible" (inversible) ORC/HP unit**? (question already asked in 2006)

Heat Pump → ORC → Reversible HP/ORC

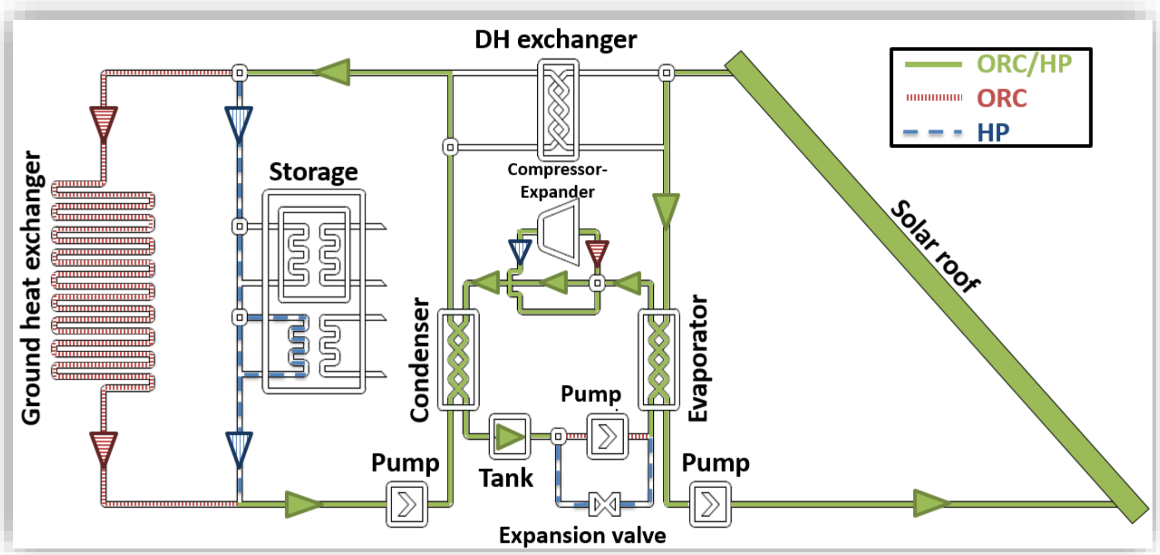


« Reversible » heat pump/ORC Carnot batteries

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



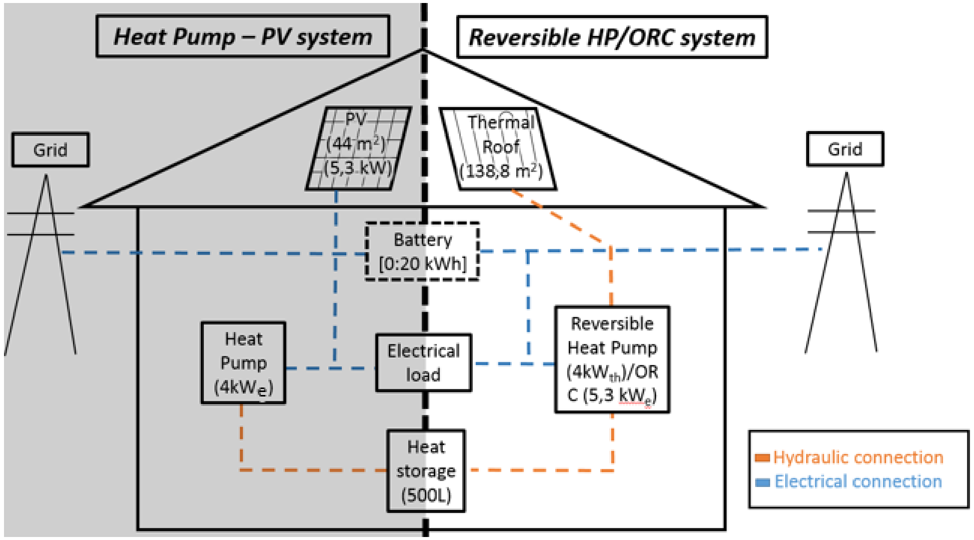
Eurostars Single HPA Unit project (2015-2016) coordinated by Innogie

« 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)

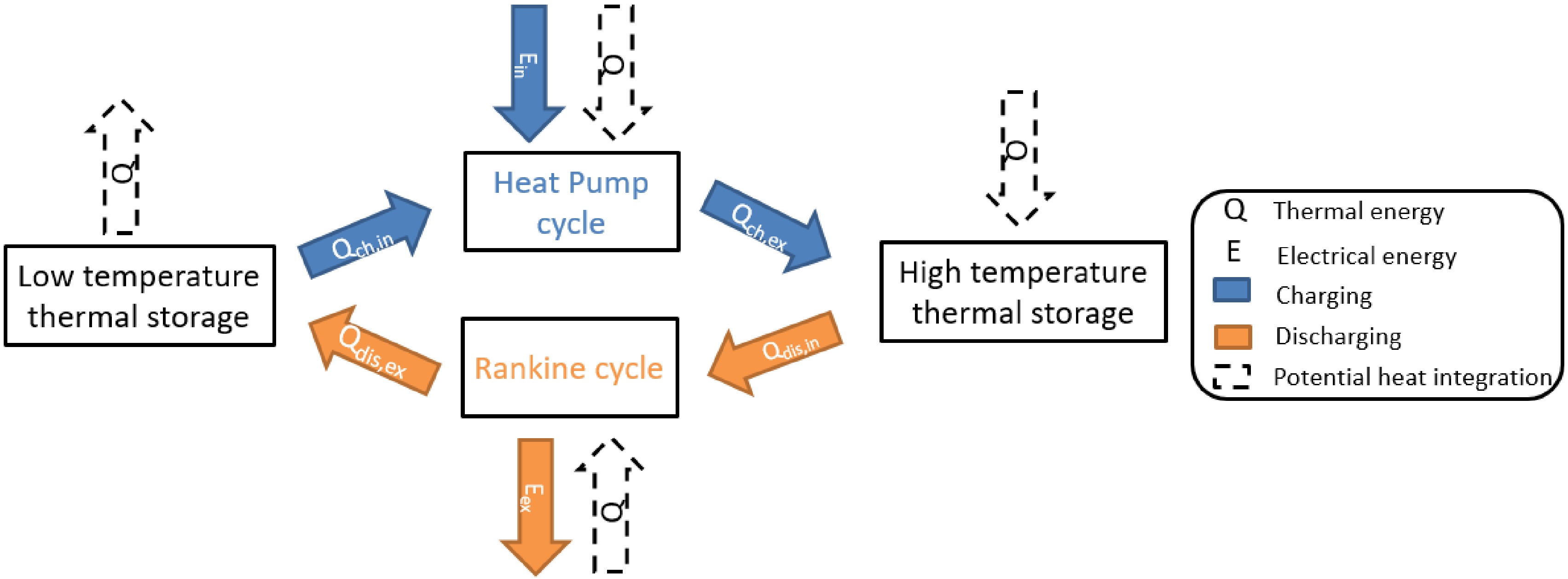
- Economical profitability not demonstrated versus **PV** + heat pumps (2016).
- Looking to other applications of reversible heat pumps/ORCs.



Agenda of the presentation

Integration of low-grade heat

CB round trip efficiency



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

with

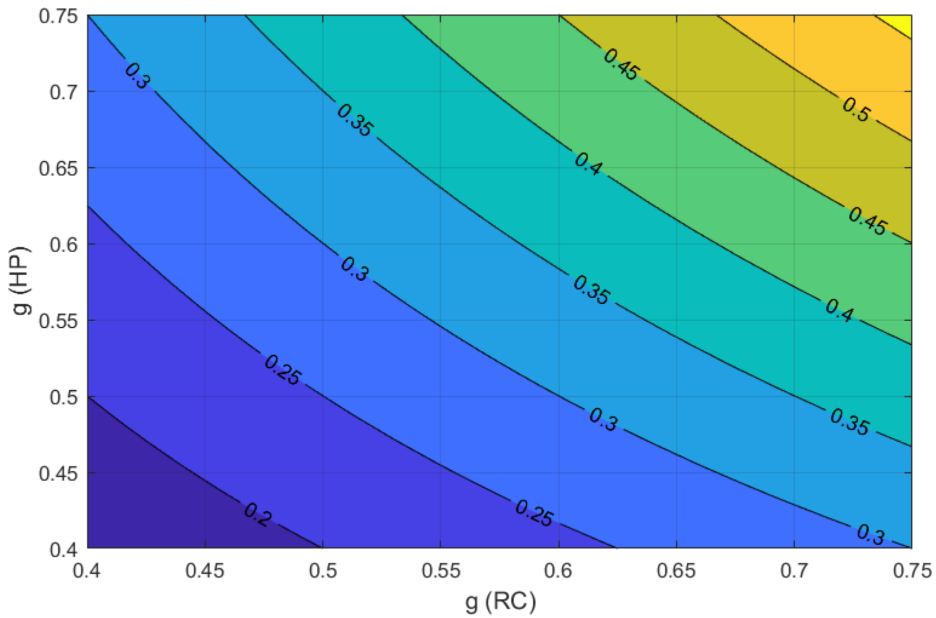
$$COP_{HP} = \frac{Q_{cd}}{E_{el}} = g_{HP}\frac{T_{hot}}{T_{hot} - T_{cold}}$$

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

Integration of low-grade heat

CB round trip efficiency

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

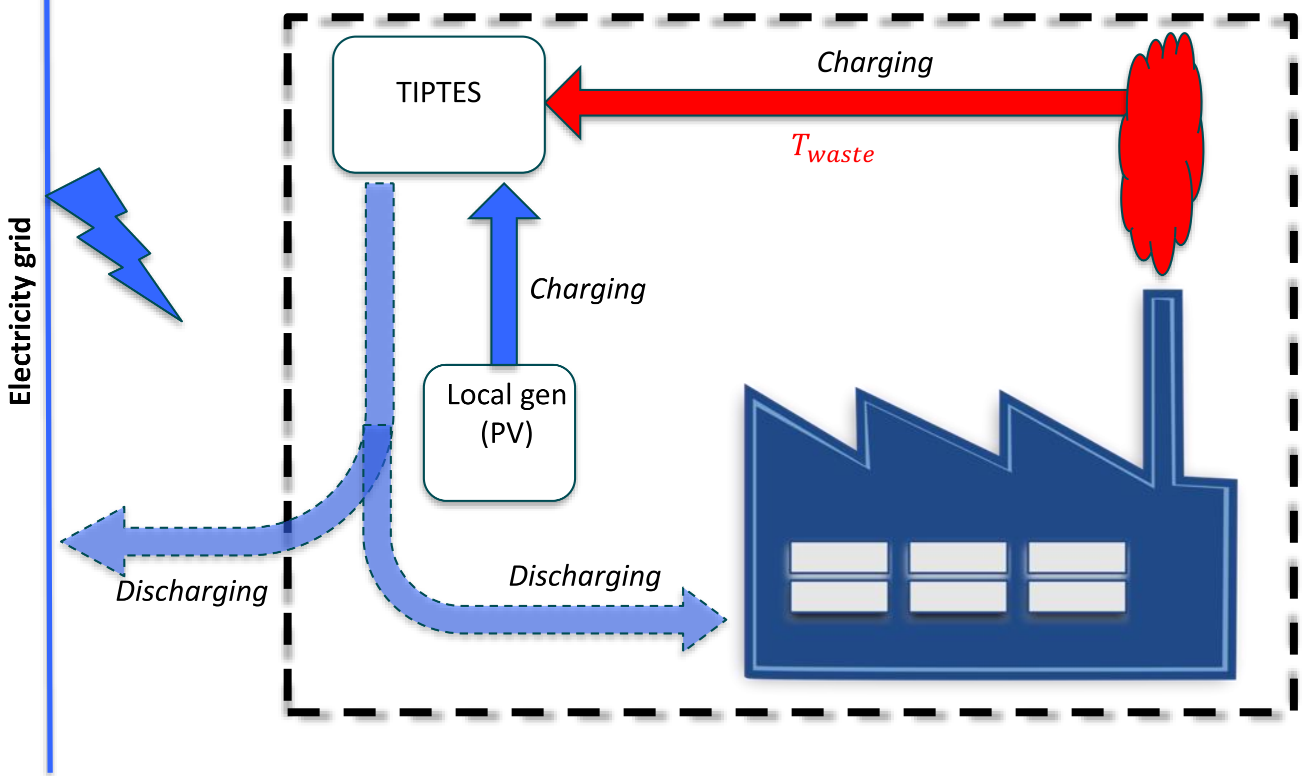


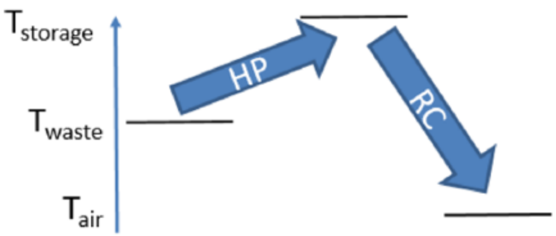
Roundtrip efficiencies don't easily reach values over 50%

Integration of low-grade heat

CB round trip efficiency

- 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).

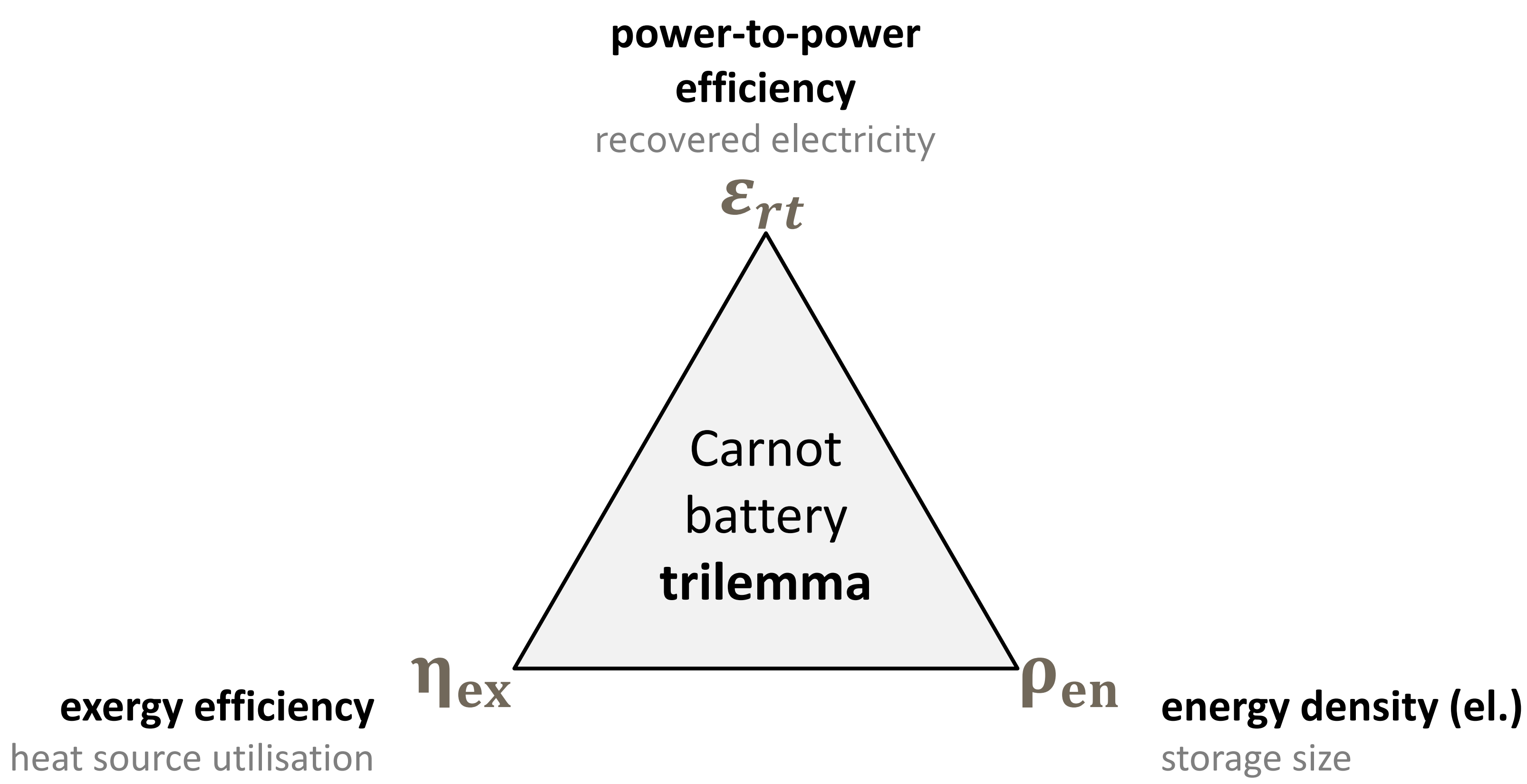




$$\varepsilon_{rt} = \eta_{TES} \cdot COP_{HP} \cdot \eta_{RC}$$

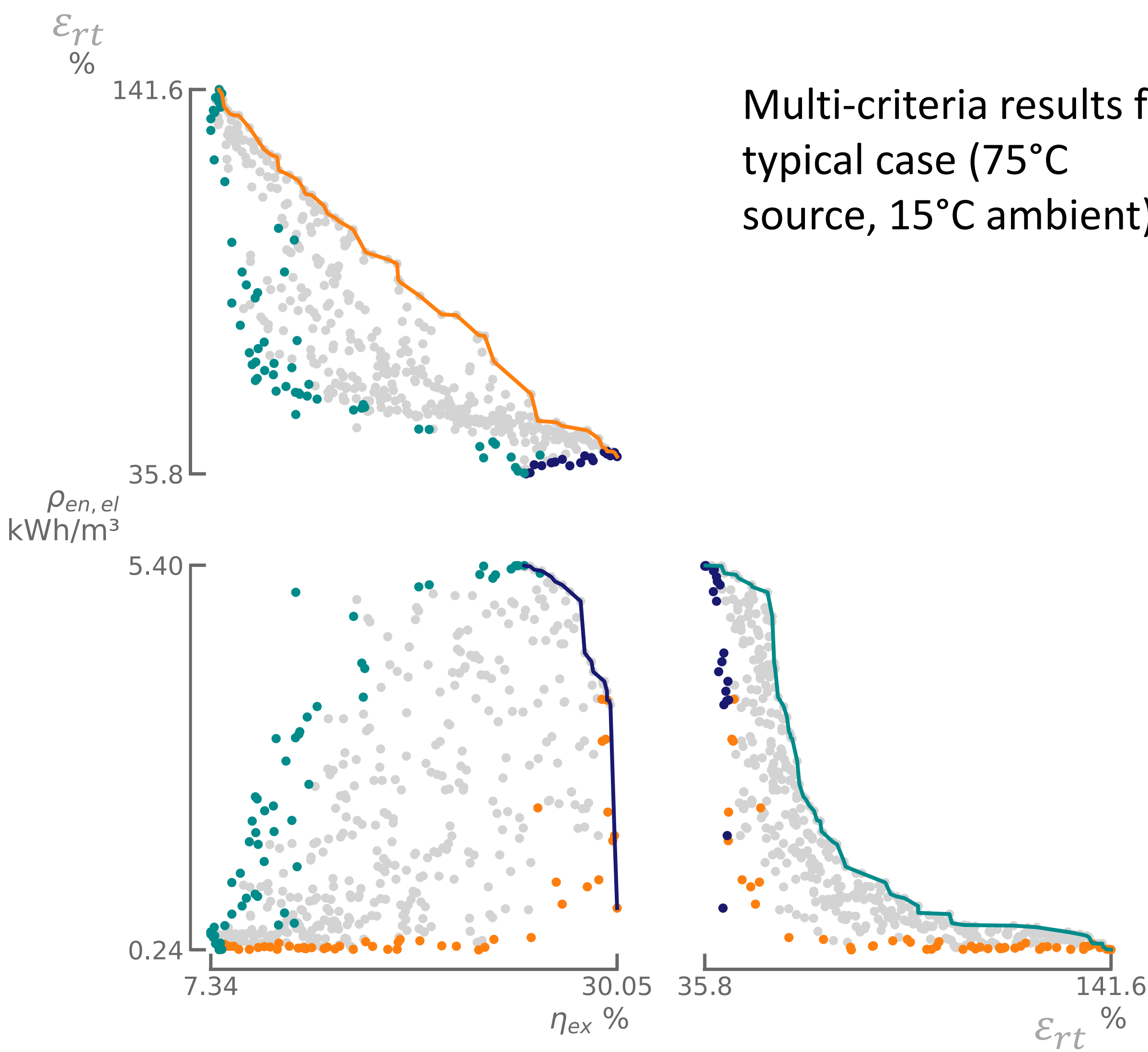
Integration of low-grade heat

CB round trip efficiency



Integration of low-grade heat

CB round trip efficiency



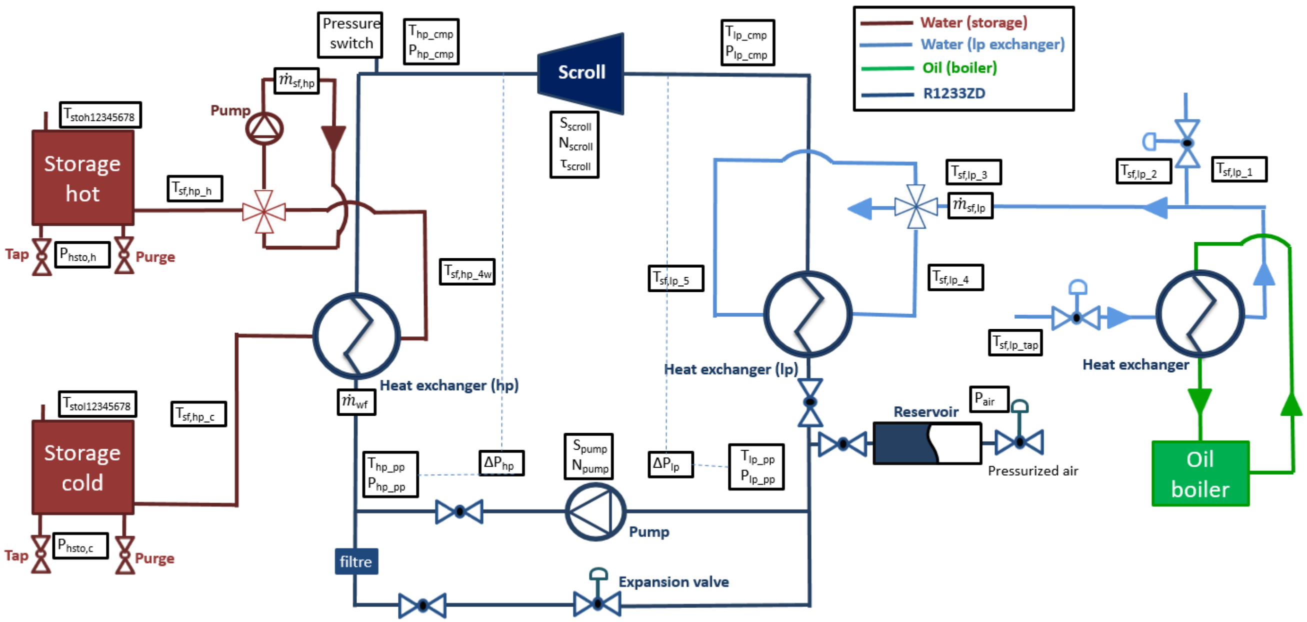
Multi-criteria results for typical case (75°C source, 15°C ambient)

Agenda of the presentation

1. Introduction
2. Carnot battery (CB)
3. Reversible Heat pump/ORC
4. Integration of low-grade heat in CBs
5. **First prototype**
6. Second prototype
7. Conclusions

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
- Plunger pump
  - 70 g/s
- Manual expansion valve

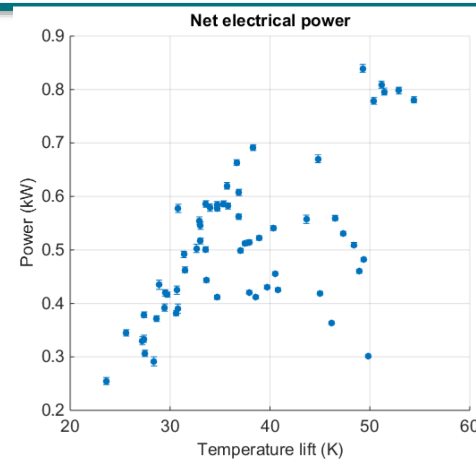
First prototype of reversible ORC/HP CB

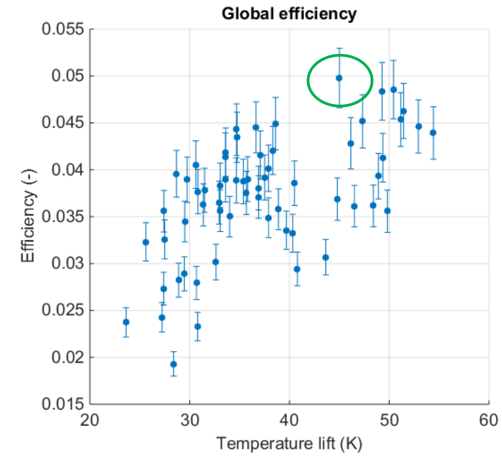
1 kWe Carnot battery

ORC

- Net electrical power and efficiency increase with temperature lift.
- Lower performance than expected (expander efficiency to be improved).

$$\eta_{global} = \frac{\dot{W}_{exp,el} - \dot{W}_{pp,el}}{\dot{Q}_{ev,r,oil}}$$



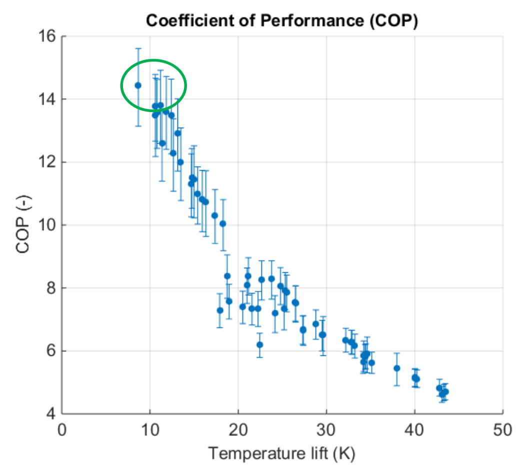


$$Temperature\ lift\ [K] = |T_{cond} - T_{ev}|$$

Heat Pump

- Very high COP at low temperature lift.

$$COP = \frac{\dot{Q}_{cd,r,oil}}{\dot{W}_{cp,el}}$$

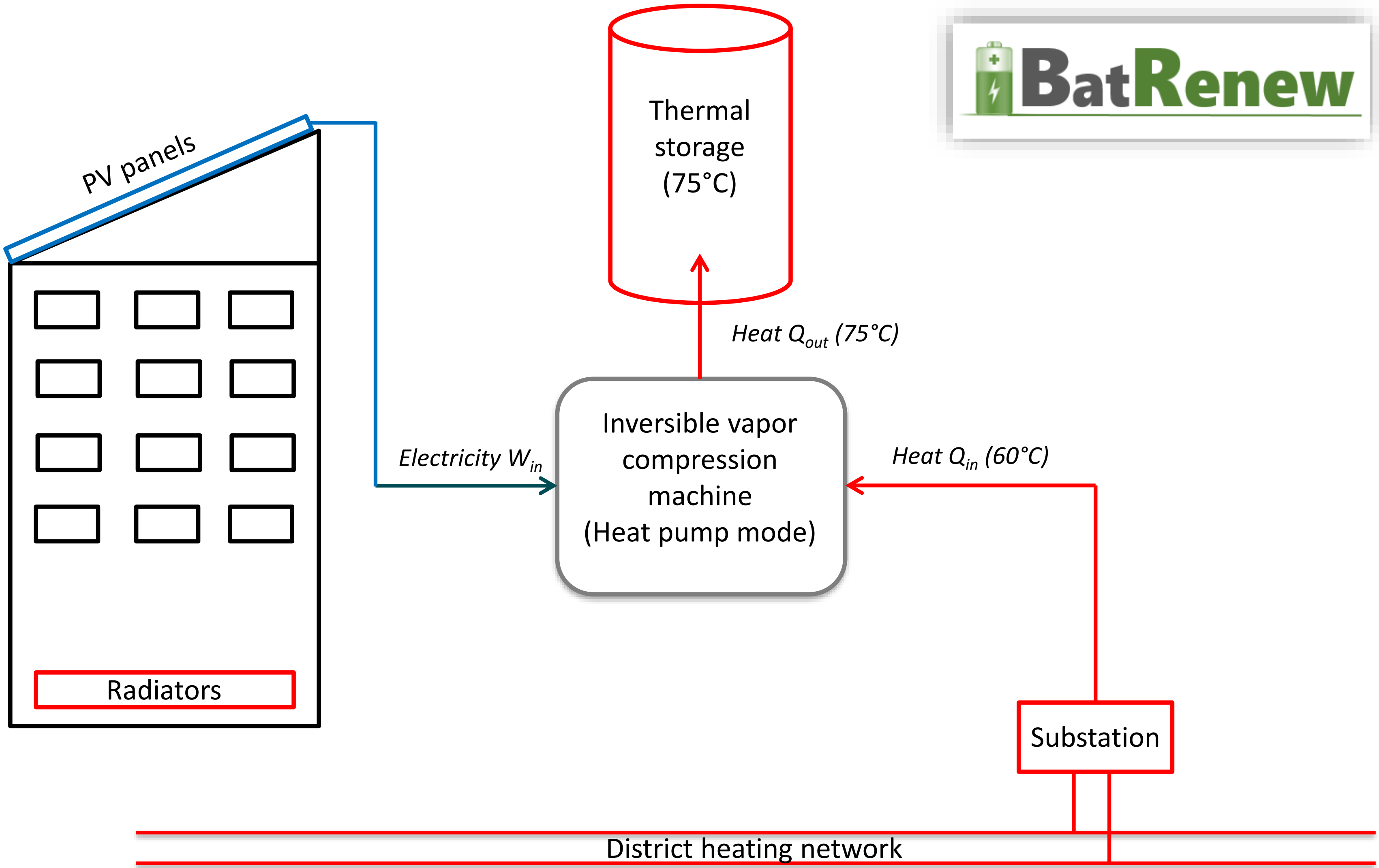


=> Roundtrip efficiency of **72.5%** (ORC efficiency of 5% (lift: 49 K) and COP of HP of 14.4 (lift: 8 K)).

Second prototype of reversible ORC/HP CB

10 kWe CB - connection to a DHN

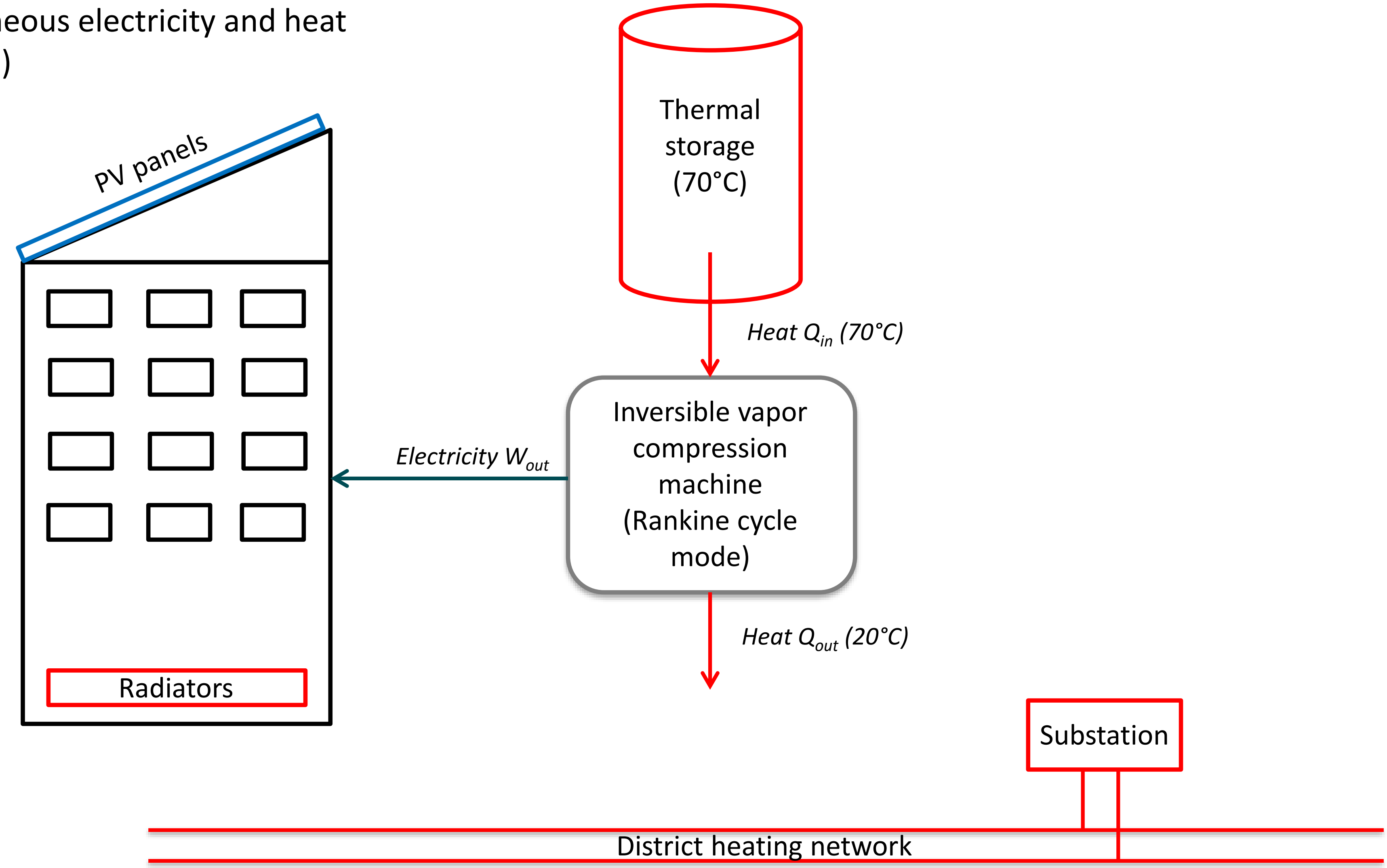
Electricity storage mode



Second prototype of reversible ORC/HP CB

10 kWe CB - connection to a DHN

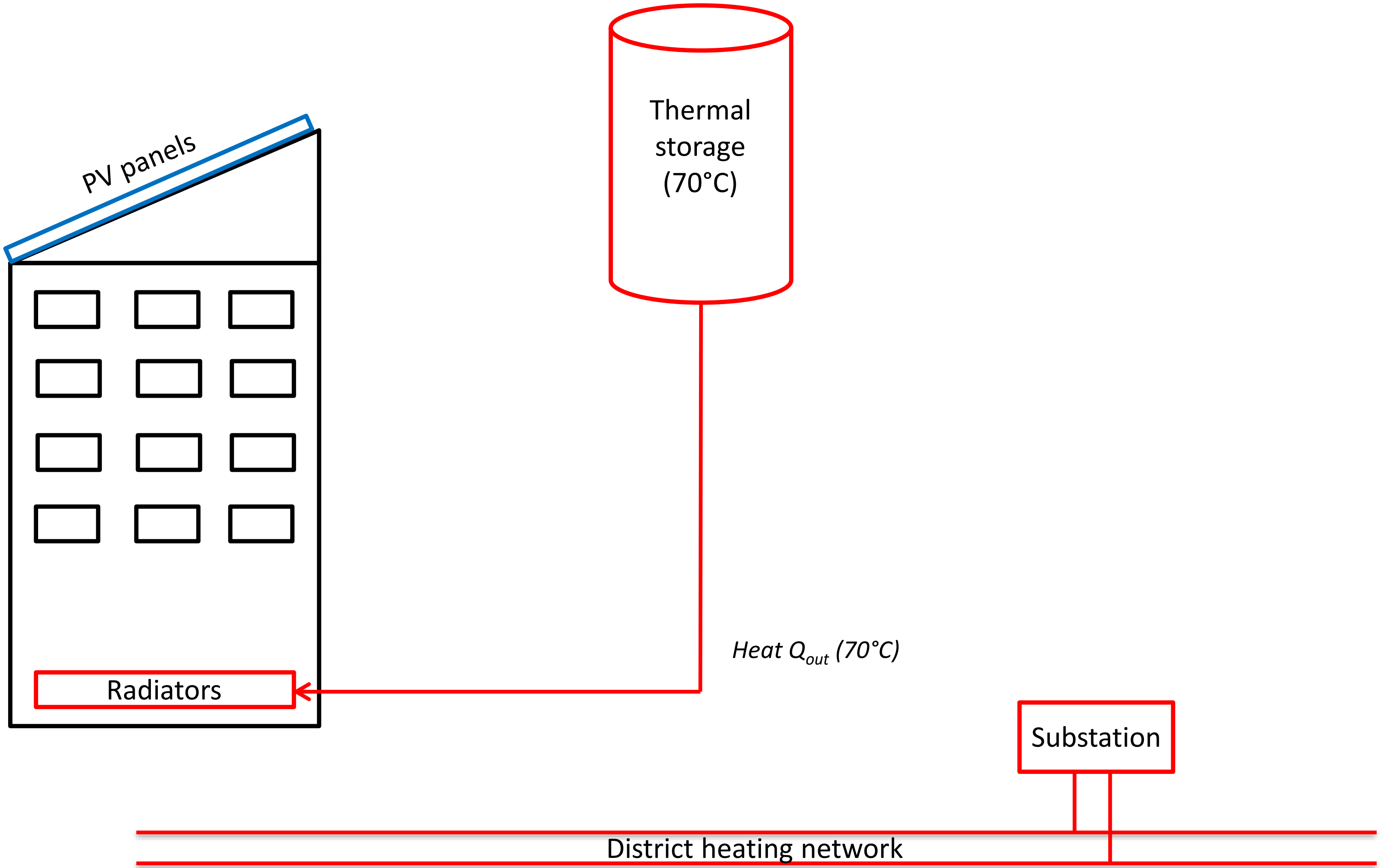
Electricity discharge mode
(simultaneous electricity and heat demands)



Second prototype of reversible ORC/HP CB

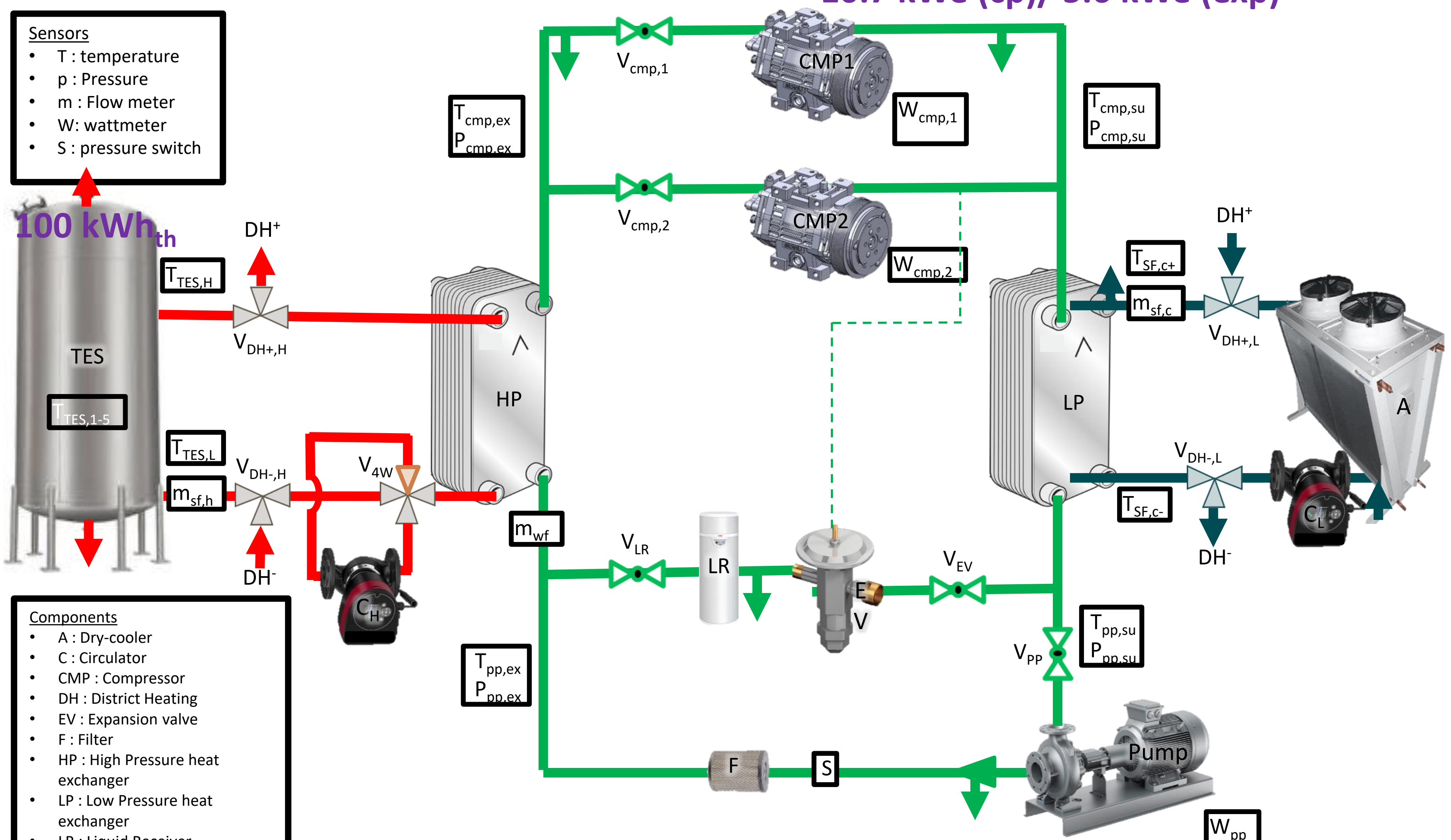
10 kWe CB - connection to a DHN

Heating mode



Second prototype of reversible ORC/HP CB

10 kWe CB - connection to a DHN

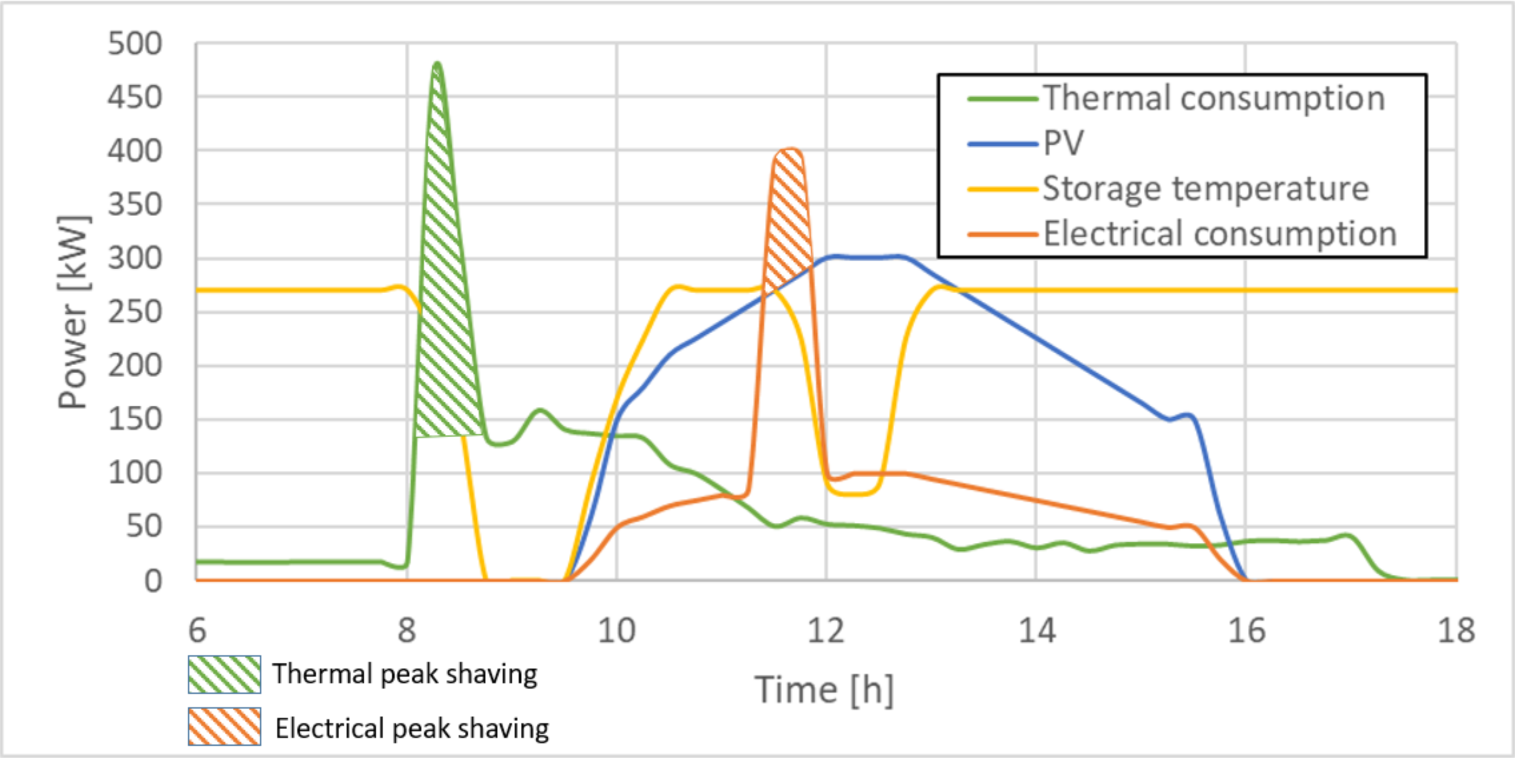


Sensors
- T : temperature
- p : Pressure
- m : Flow meter
- W: wattmeter
- S : pressure switch

Components
- A : Dry-cooler
- C : Circulator
- CMP : Compressor
- DH : District Heating
- EV : Expansion valve
- F : Filter
- HP : High Pressure heat exchanger
- LP : Low Pressure heat exchanger
- LR : Liquid Receiver
- TES: Thermal Energy Storage
- V: valve

Second prototype of reversible ORC/HP CB

10 kWe CB - connection to a DHN



Yearly COP ≃ 5
Yearly ORC efficiency ≃ 8%

Charging time: 1967 hours
Discharging time: 1296 hours
Direct heating: 290 hours

Conclusions and perspectives

- Carnot batteries are a promising technology for electricity storage with heat sector coupling
- 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

Merci pour votre attention!

Merci aux contributeurs à cette présentation

Vincent Lemort

Vincent.Lemort@uliege.be

Thermodynamics Laboratory

University of Liège

Belgium

Integration of low-grade heat

CB round trip efficiency

power-to-power efficiency

recovered electricity

ε_{rt}

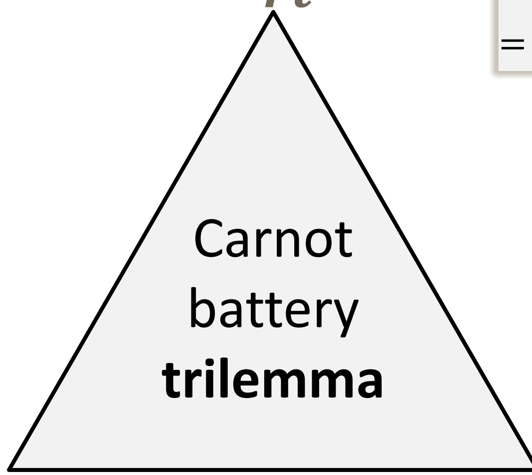
$$= \frac{W_{he,el,out}}{W_{hp,el,in}}$$
$$= \frac{Q_{hp,th,out}}{W_{hp,el,in}} \cdot \frac{W_{he,el,out}}{Q_{he,th,in}}$$
$$= \mathbf{COP_{hp} \cdot \eta_{he,cyclen}}$$

$$Q_{he,ex,in} = \dot{m}_{hs}(e_{st,ht} - e_{st,lt})$$

$$Q_{hp,ex,in} = \dot{m}_{cs}(e_{su} - \boldsymbol{e_{ref}})$$

$$P^*_{hp,ex,in} = Q_{hp,ex,in} + W_{hp,el,in}$$

$$\boldsymbol{\eta_{hp,totex} \cdot \eta_{he,totex}} = \frac{Q_{hp,ex,out}}{P^*_{hp,ex,in}} \cdot \frac{W_{he,el,out}}{Q_{he,ex,in}} = \frac{W_{he,el,out}}{P_{hp,ex,in}} =$$



η_{ex}

exergy efficiency

heat source utilisation

ρ_{en}

$$= \frac{\mathbf{h_{st,ht} - h_{st,lt}}}{\mathbf{v_{st,ht} + v_{st,lt}}} \cdot \boldsymbol{\eta_{he,cyclen}}$$
$$= \frac{E_{el}}{V}$$

energy density (el.)

storage size