2020ne Purdue Conferences

Compressor Engineering | Refrigeration and Air Conditioning | High Performance Buildings

Experimental investigation of a thermally integrated Carnot battery using a reversible heat pump/organic Rankine cycle

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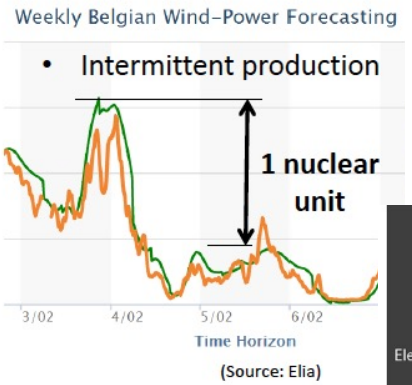
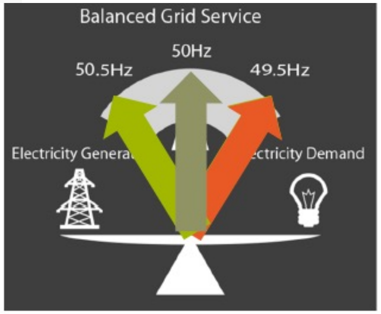
Introduction
Context

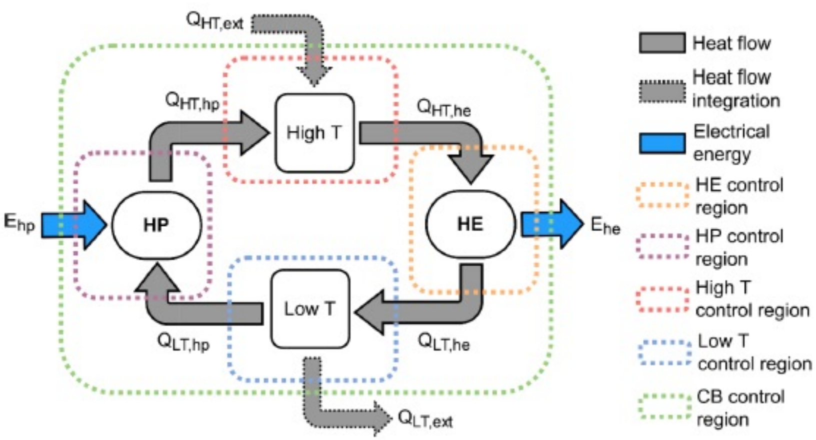
- **Intermittent** nature of **renewable energy** sources => need for energy storage (large grid balancing, development of micro grids).
- Batteries (straightforward solution):
  - ✓ Cost (rare materials)
  - ✓ Lifespan (<20 years)
  - ✓ Environmental footprint
- Gravity Energy Storage, PHES, CAES: site dependent.
- Pumped Thermal Energy Storage (PTES or **Carnot battery**) is a promising alternative to store electricity.





Introduction
Concept

<u>Carnot battery = system primarily used to store electricity</u>



- *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: $\varepsilon_{rt} = \frac{E_{he}}{E_{hp}}$

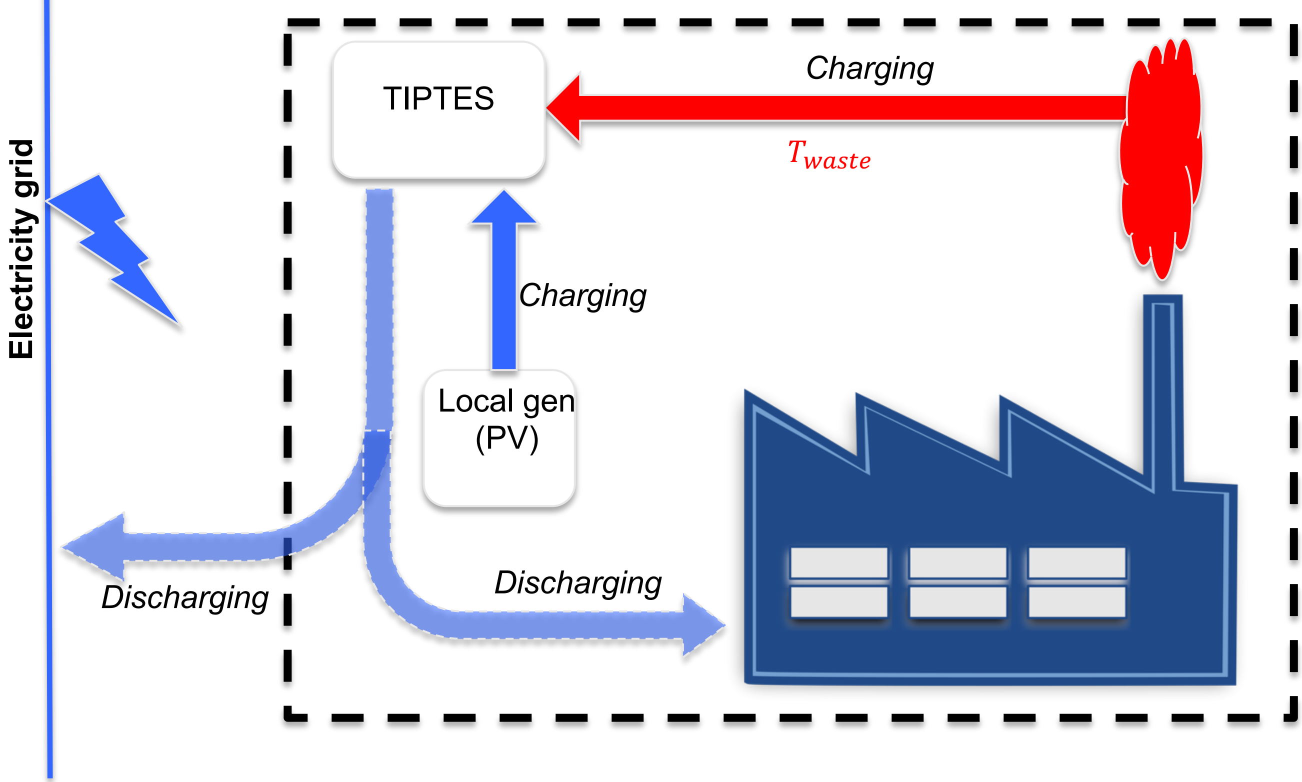
- Different technologies of HP and HE: vapor compression systems, Brayton cycles, electrical heater.
- Different technologies of thermal energy storage for the heat reservoirs.
- Environment to replace one of the heat reservoirs.

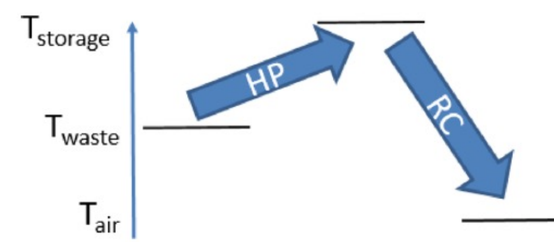
Introduction
Concept

- **Rankine** (vapor compression heat pump + Rankine cycle) PTES vs **Brayton** PTES:
  - ✓ larger energy density
  - ✓ lower temperatures of TES
    - ➢ use of PCM,
    - ➢ lower ambient losses,
    - ➢ simpler design of machines,
    - ➢ uses of off-the-shelf HVAC components (MW-scale storage could easily be built)
  - ✓ Similar max roundtrip efficiency of 62-65%
- Other performance criteria to consider: energy and power densities in [kWh/m^3] and [kW/m^3].

Introduction
Concept

- 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).

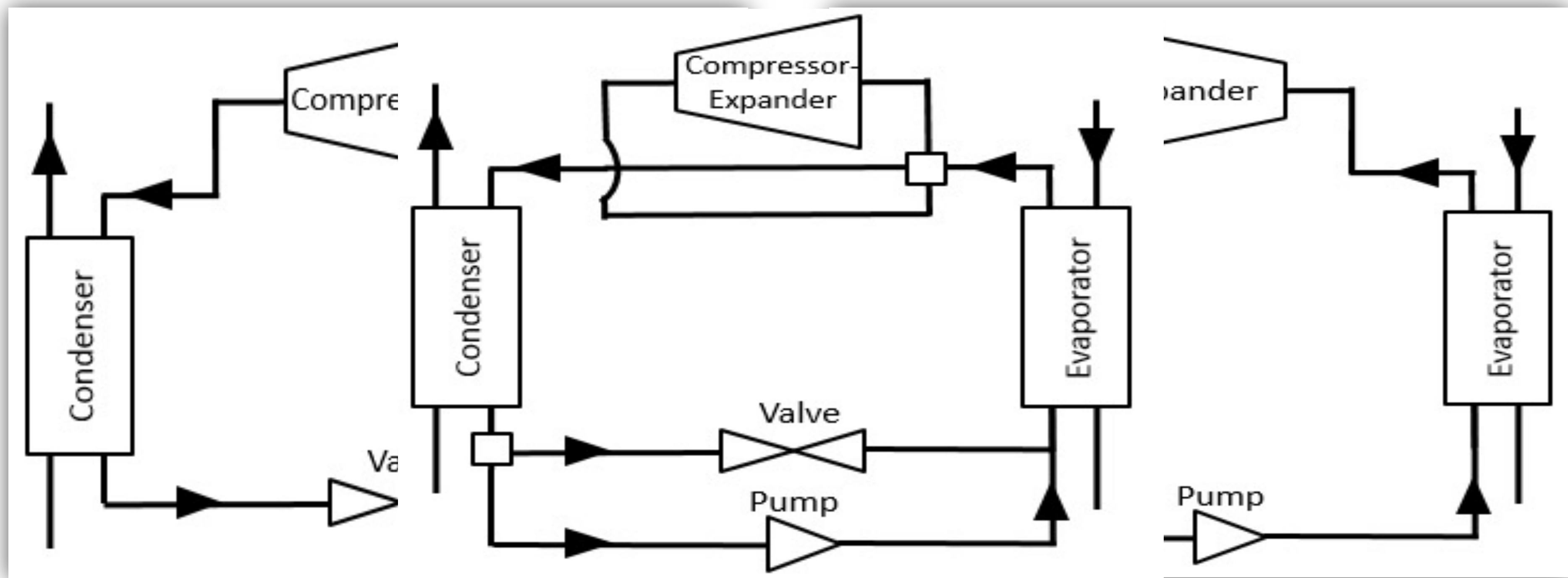




$$\varepsilon_{rt} = \eta_{TES} \cdot COP_{HP} \cdot \eta_{RC}$$

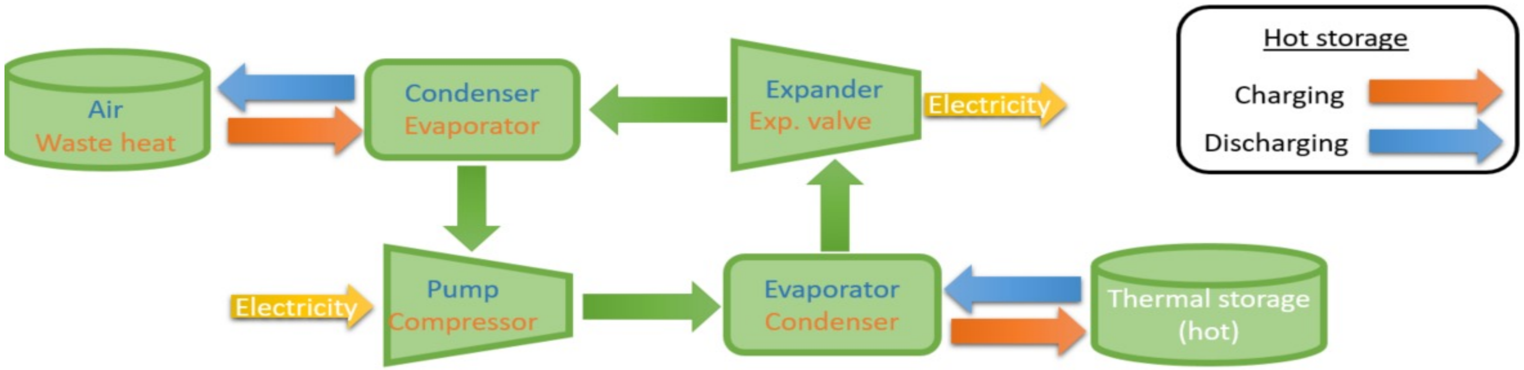
Introduction
Concept

- Cost of the system can be reduced by mutualizing components of the Heat Pump and ORC.



Introduction
Concept

- Principle of operation of a Carnot battery with a reversible HP/ORC system with waste heat integration.



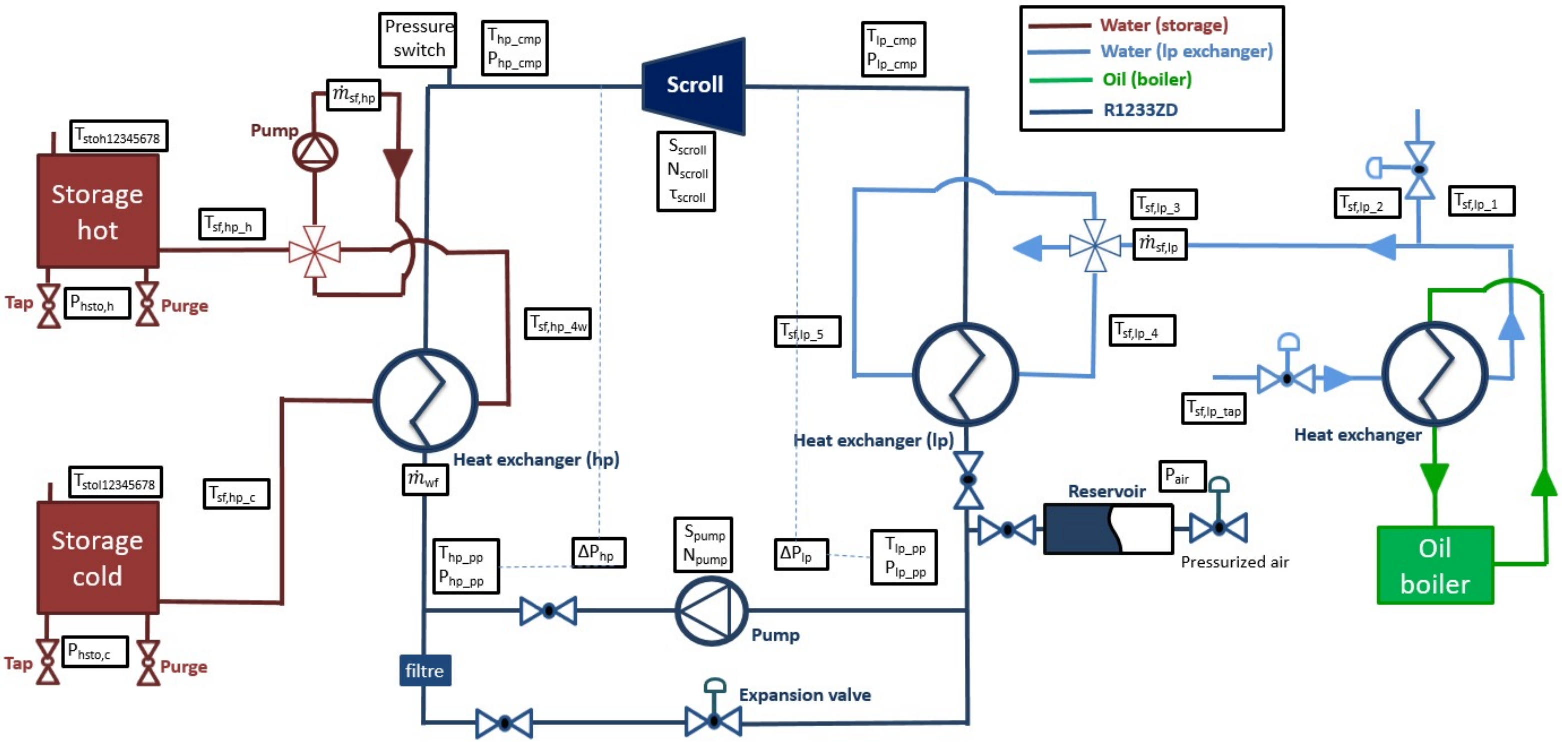
$$\varepsilon_{rt} = \eta_{TES}.\left(\frac{COP_{HP}}{Q_{cd,HP}}\right).\left(\eta_{RC}Q_{ev,RC}\right) = \eta_{TES}.COP_{HP}.\eta_{RC}$$

- Rem: a second law-efficiency could be used to consider the difference of thermodynamic quality of heat and electricity.

Agenda of the presentation

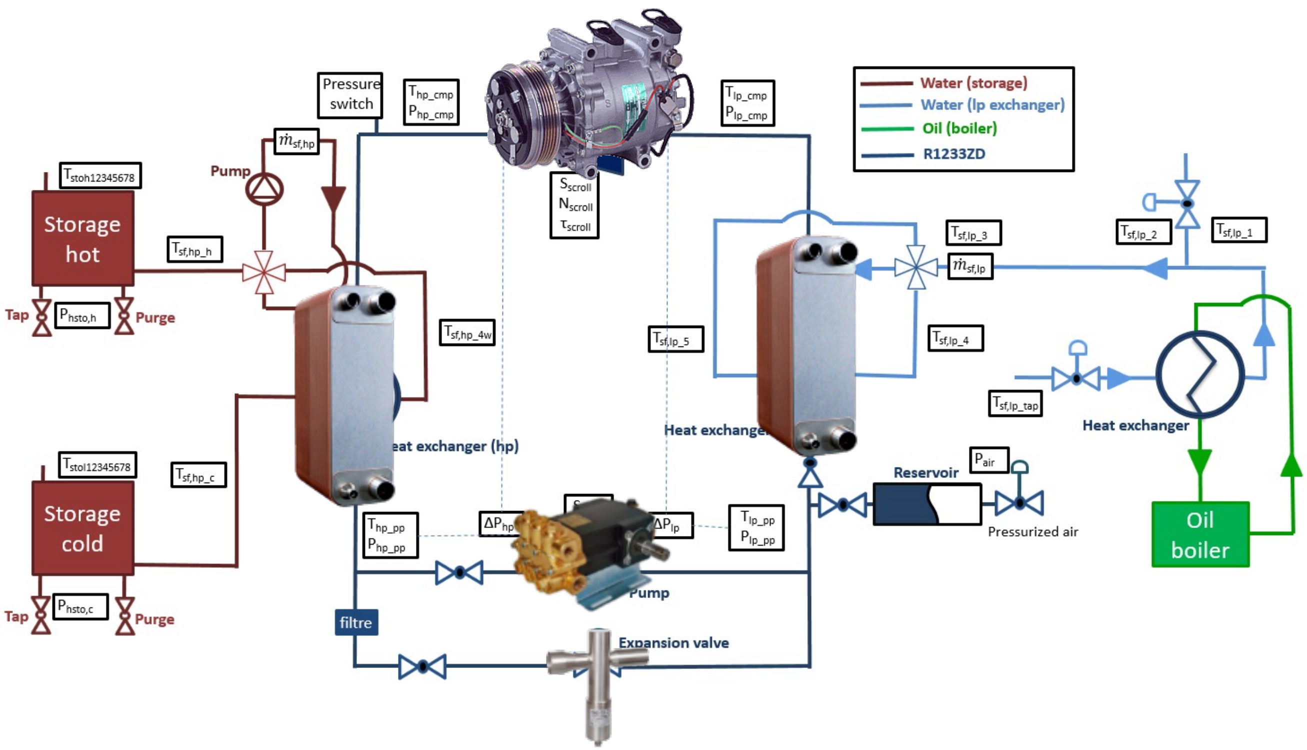
1. Introduction
2. **Experimental set-up**
3. Results
4. Conclusions

Experimental set-up
Layout



Experimental set-up

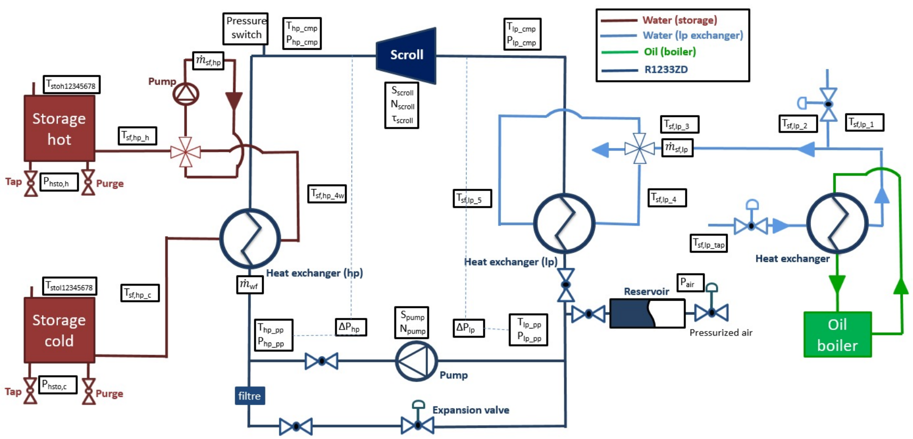
Components



- 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

Experimental set-up

Sensors



Experimental set-up
Performance criteria

- Overall performance: COP of Heat Pump and efficiency of ORC.

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

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

- Compressor/expander performance: isentropic efficiency, volumetric efficiency/filling factor.

$$\varepsilon_{cp,is} = \frac{\dot{m}_r\left(h_{r,cp,ex,is} - h_{r,cp,su}\right) + \dot{V}_{oil}\left(p_{cp,ex} - p_{cp,su}\right)}{\dot{W}_{cp,el}}$$

$$\varepsilon_{cp,vol} = \frac{\dot{V}_{cp,su,tot}}{\dot{V}_{cp,th}}$$

$$\varepsilon_{exp,is} = \frac{\dot{W}_{exp,el}}{\dot{m}_r\left(h_{r,exp,su} - h_{r,exp,ex,is}\right) + \dot{V}_{oil}\left(p_{exp,su} - p_{exp,ex}\right)}$$

$$FF_{exp} = \frac{\dot{V}_{exp,su,tot}}{\dot{V}_{exp,th}}$$

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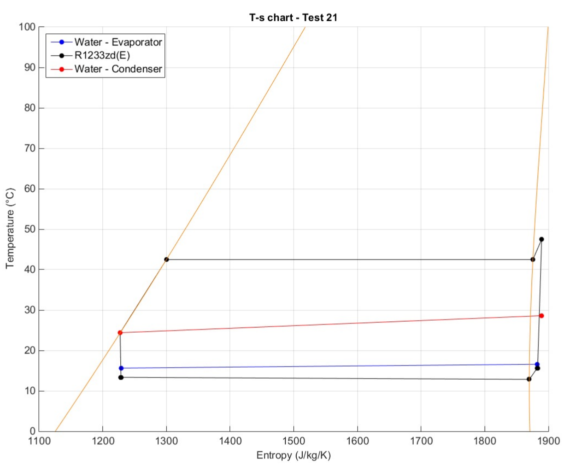
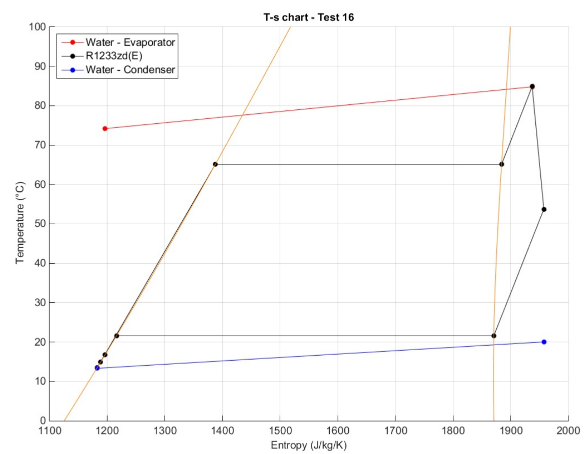
Results
Range of operating conditions

Parameter	ORC	HP
Evaporator thermal power [W]	[8423-18183]	[1203-13351]
Condenser thermal power [W]	[725-16231]	[1326-14495]
Evaporation pressure [bar]	[3.4-5.8]	[0.65-4.9]
Condensation pressure [bar]	[1.1-1.9]	[1.6-7.2]
Mass flow rate [kg/s]	[0.034-0.079]	[0.007-0.084]
Subcooling [K]	[6.2-8.8]	[4.1-28.9]
Superheating [K]	[4.0-25.7]	[3.3-6.3]



Heat pump



ORC

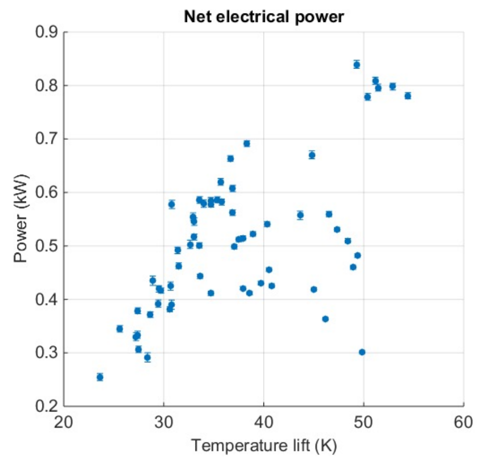
- 62 steady-state points in ORC mode and 60 in HP mode.
- Large range of operating conditions.
- All raw data are provided
- Energy residuals on systems and components are checked.

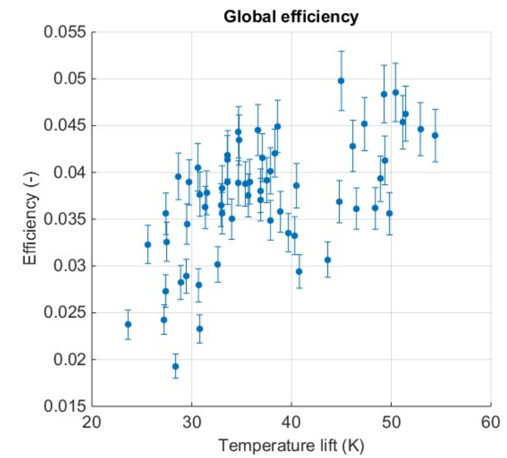
Results

Global performance

ORC

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

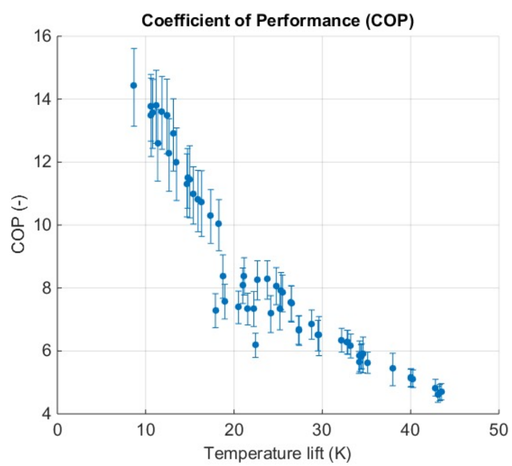




$$Temperature\ lift\ [K] = |T_{cond} - T_{ev}|$$

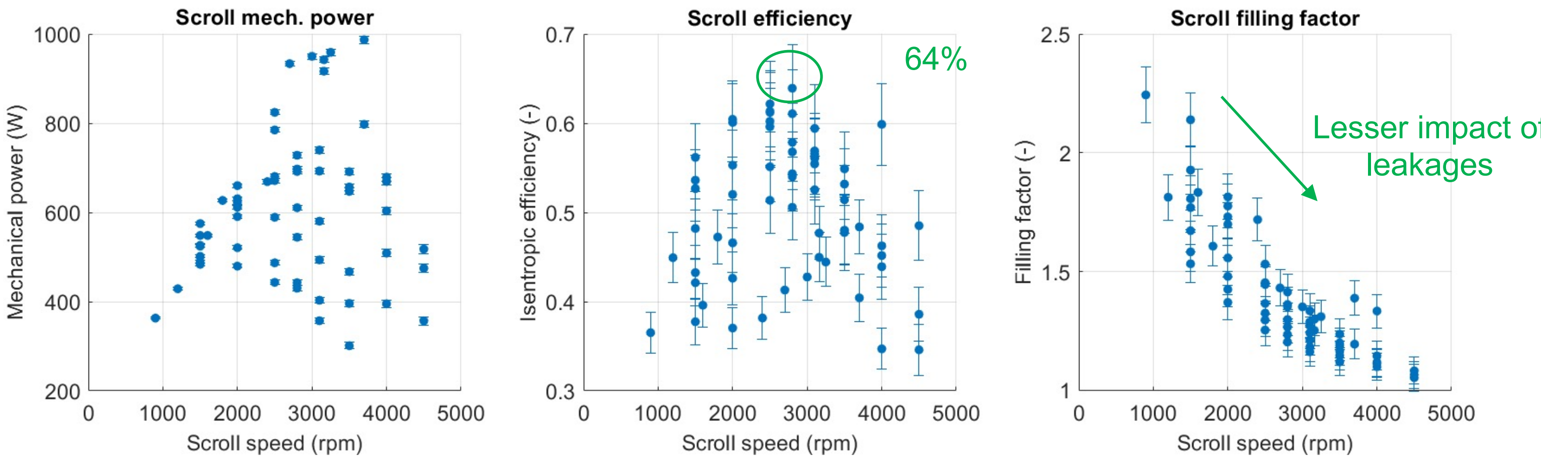
Heat Pump

- Very high COP at low temperature lift.

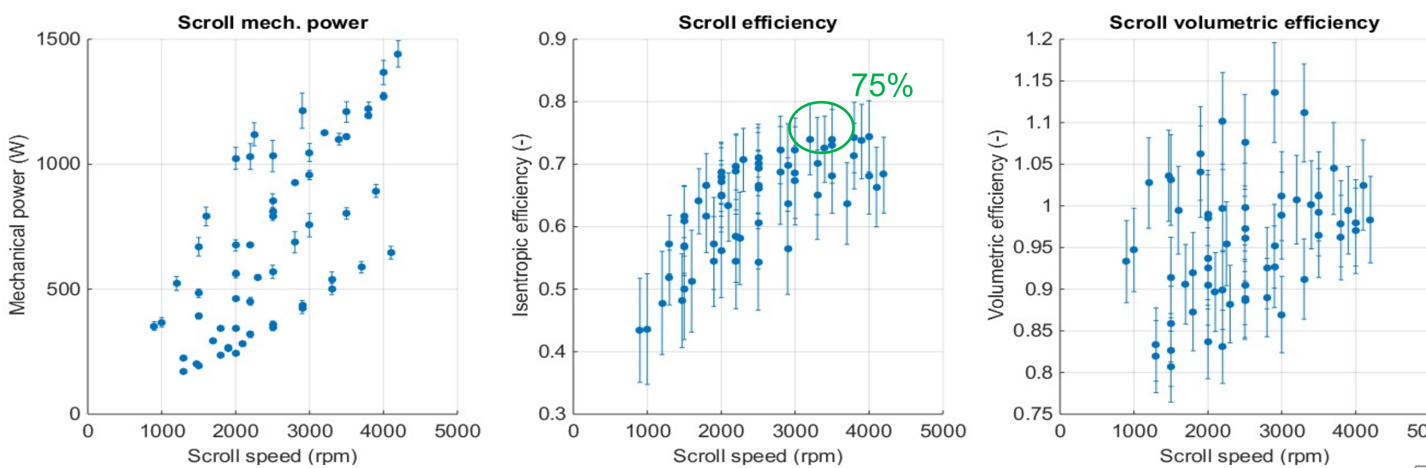


Results
Scroll machine performance

ORC (expander)



Heat Pump (compressor)



Conclusions

- **Prototype** of innovative technology to store electricity at low cost with a **reversible HP/ORC Carnot battery** is presented.
- Acceptable performance of components with **margin for improvement**.
- Roundtrip efficiency of **72.5%** (ORC efficiency of 5% (lift: 49 K) and COP of HP of 14.4 (lift: 8 K)).
- Roundtrip electrical energy ratio larger than 100% could be achieved by
  - ✓ Improving design of volumetric machine
  - ✓ Improving the control, improving thermal insulation
- Transient tests should be conducted to assess the **dynamics of the system** and the services that could be provided to the electricity grid (and on which time scale).

Thank you for your attention!