Multi-energy systems hybridizing heat pumps and ORC power systems: some challenges and opportunities

Vincent Lemort and co-workers

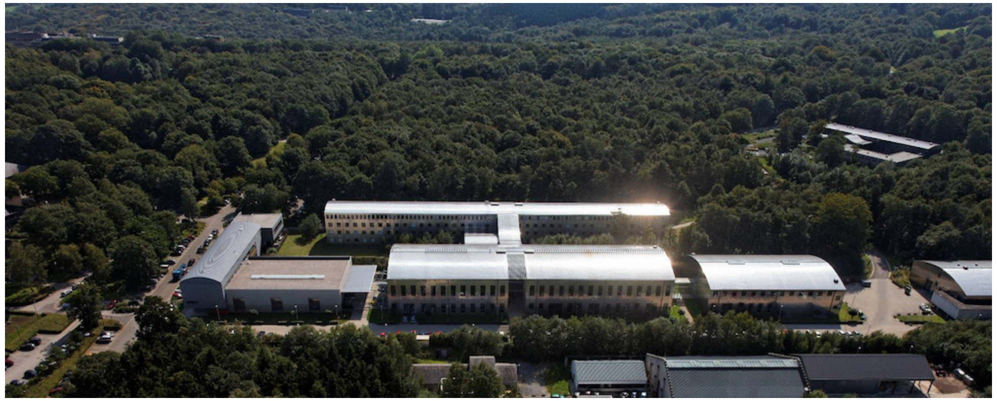
Thermodynamics Laboratory of the University of Liège

10th Anniversary of the Institute of Energy Engineering (Instituto Ingeniería Energética)

Universitat Politècnica de València, July 4th, 2025

Introduction
University of Liège

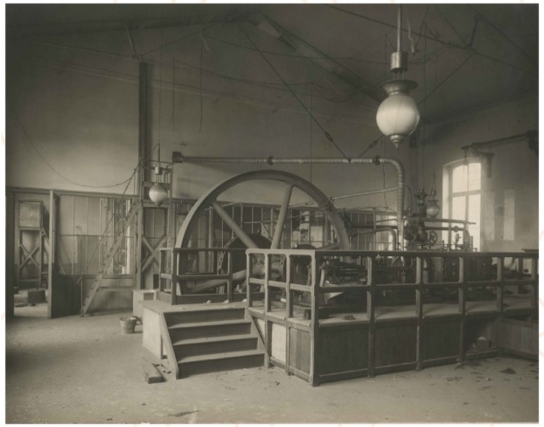
- Established in 1817 (when Liège was Dutch)
- 11 Faculties, including the Engineering school
- 4 campuses (Sart Tilman being the biggest)
- 26641 students and PhD students
- 5781 staff members
- 549 millions of Euro of annual budget
- Engineering School: 4 Departments, incl. Aerospace and Mechanical Engineering



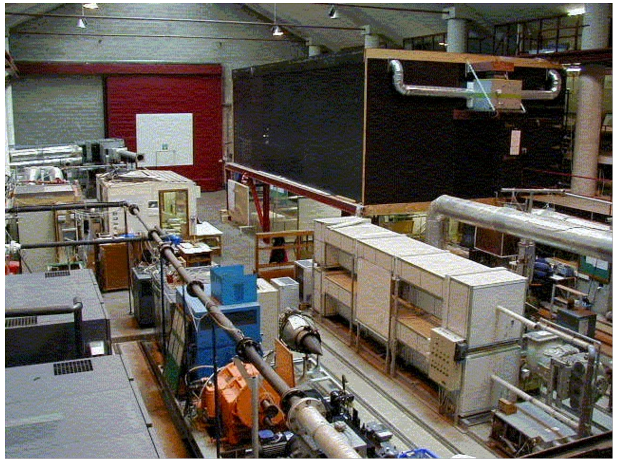
Introduction

Thermodynamics Laboratory of University of Liège

- Established in 1887 for investigating steam engines
- Aerospace and Mechanical Engineering Department
- Faculty of Applied Sciences of University of Liège
- Team of approx. **30 people**: 6 professors (1 emeritus), 1 research officer, 1 postdoc, +-12 PhD students, 4 technicians, 1 secretary, invited researchers, scientific collaborators
- Numerical/experimental research on thermal systems at different scales (components to energy communities)



MORIN Lambert, Machine à vapeur du laboratoire de mécanique appliquée, faculté technique de l'Université de Liège, vers 1900. (Musée Wittert - Collections artistiques ULiège)



Introduction
Context: cooling, heating and electrification

- Massive deployment of REs imposes stabilization constraints on the grid.
  - **Electric heat pumps + thermal storages** can offer services (self-consumption of local RE production; DSM; ancillary services for clusters of HPs),
  - **Distributed electricity storages** can also participate in DSM, ancillary services and arbitrage

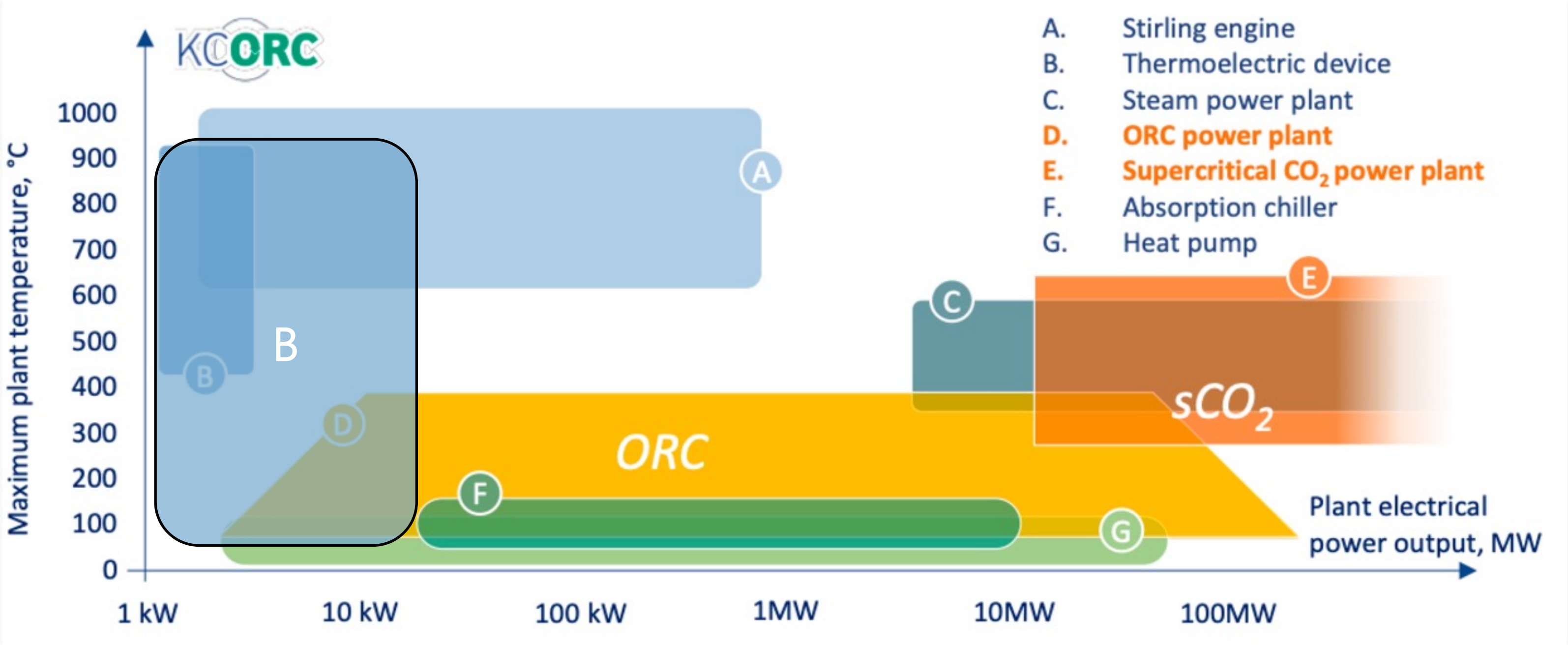
- **Cooling demand** is increasing significantly
  - Energy consumption for A/C may triple by 2050 (without appropriate management)
  - Stress on the grid (peak consumption)
  - Should be "resilient" versus heat waves, grid failure… (storage)
  - Break the vicious cycle (carbon-free cooling)

- Heat driven chillers and heat pumps can mitigate the stress on electricity grids (heat must be carbon-free)

Introduction

Context: waste heat recovery

- Very **large potential of untapped thermal energy**: EU28 countries rejected approx. 980 TWh/yr in 2015 [1]
- ORCs, sCO2 cycle, vapor compression heat pumps and heat driven heat pumps cover a large zone of the map
- Waste heat valorization by ORCs **does not produce CO_2** and limits the demand of primary energy
- Local electricity production can cope with limitations of grid extension (especially if electrification of industry)



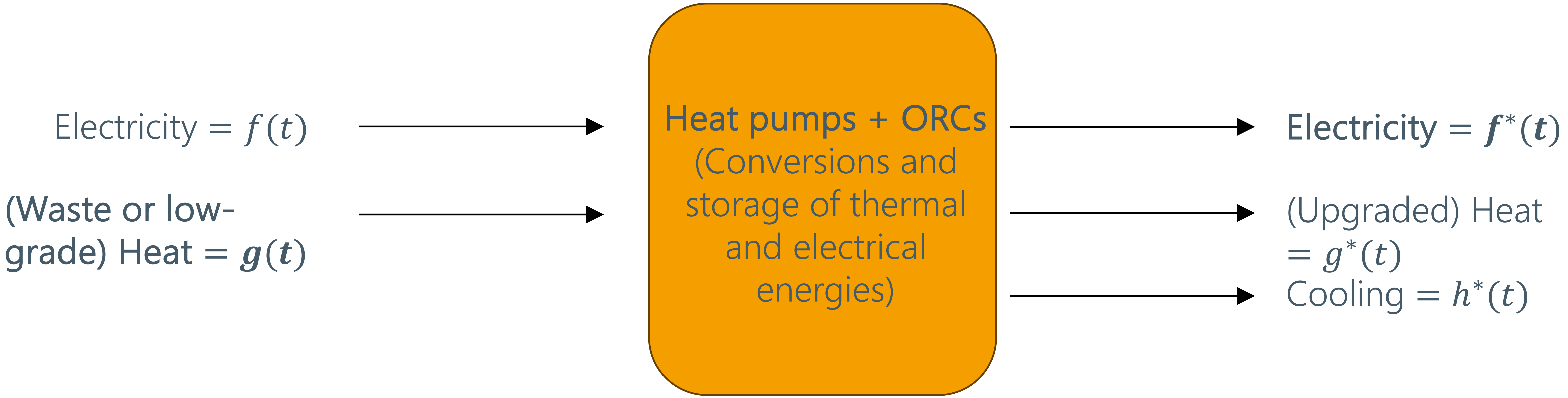
- But electricity production may be less an issue than electricity consumption and storage (PV, wind turbines)…

Range of applicability of waste heat recovery techniques (from KCORC, adpated by G. Roy)

[1] G. Bianchi, G.P. Panayiotou, L. Aresti, S.A. Kalogirou, G.A. Florides, K. Tsamos, and P. Christodoulides. Estimating the waste heat recovery in the European Union industry. Energy, Ecol Environ, 4:211–221, 2019.

Introduction
Why hybridization?

Not only single machines converting heat into electricity or electricity into heat are necessary. We need **versatile machines able to produce and store cooling** and/or **heating** and/or **electricity** following **time-varying demands**.

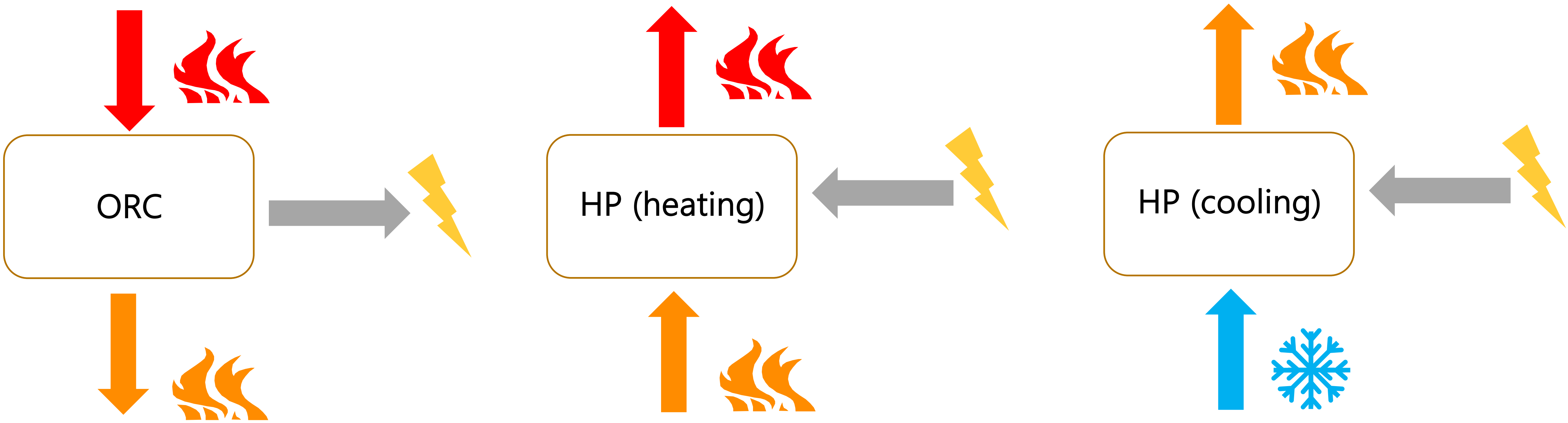


→ Hybridization of ORCs with heat pumps appears promising.

Agenda of the presentation

1. Introduction
2. Hybridization of heat pumps and ORCs
3. Polygeneration systems
4. Carnot batteries
5. Conclusions

Hybridization
How?

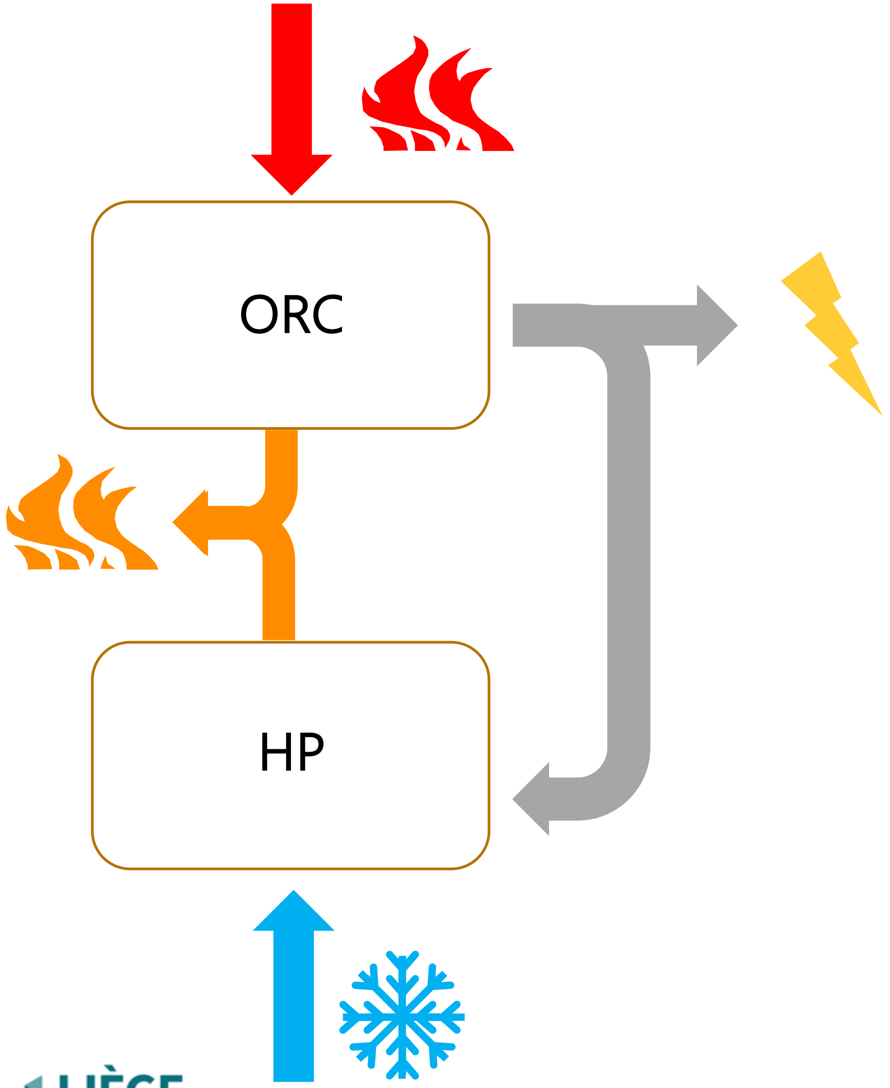


- ORCs and vapor compression HPs share many similar components and operate at similar temperatures regimes.

→ Different ways to hybridize them.

Hybridization

How? Coupling heat pumps and ORCs: heat driven heat pump

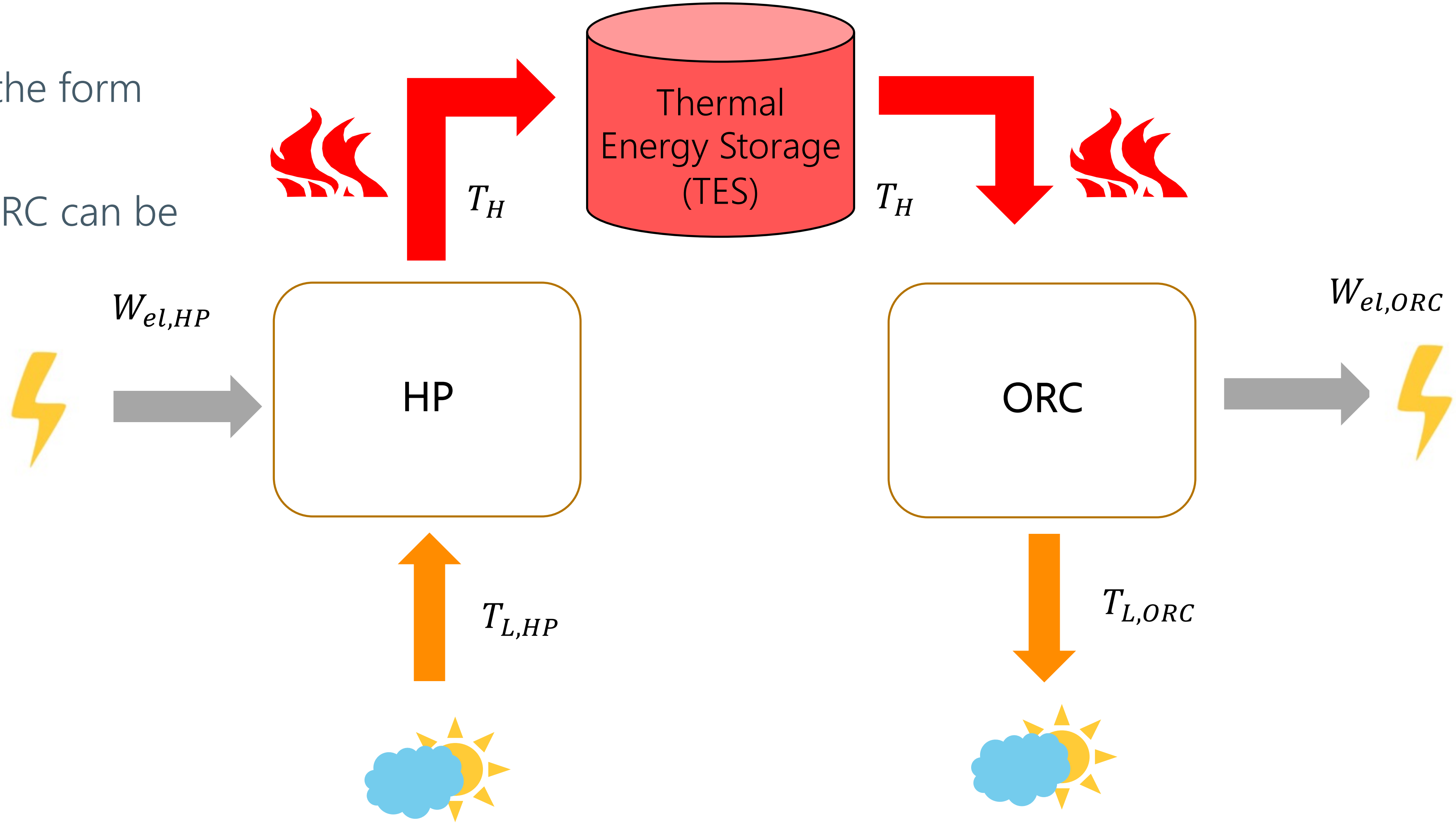


- Combined production of cooling, heat and electricity from a low-grade heat source (waste heat, solar energy…)

Hybridization

How? Coupling heat pump/ORC/storage: Carnot battery

- Electricity is stored in the form of thermal exergy
- The heat pump and ORC can be different machines

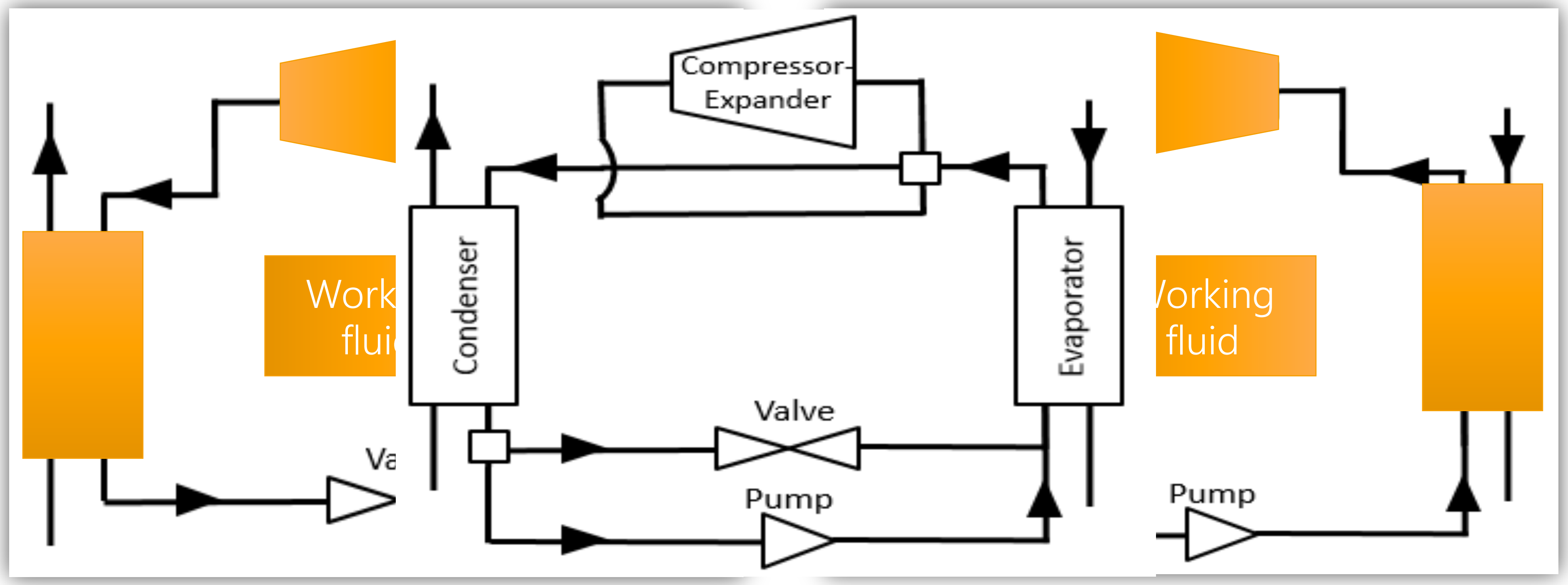


Power-to-power efficiency :

$$\eta_{P2P} = \frac{W_{el,ORC}}{W_{el,HP}}$$

Hybridization
Reversible heat pump/ORC

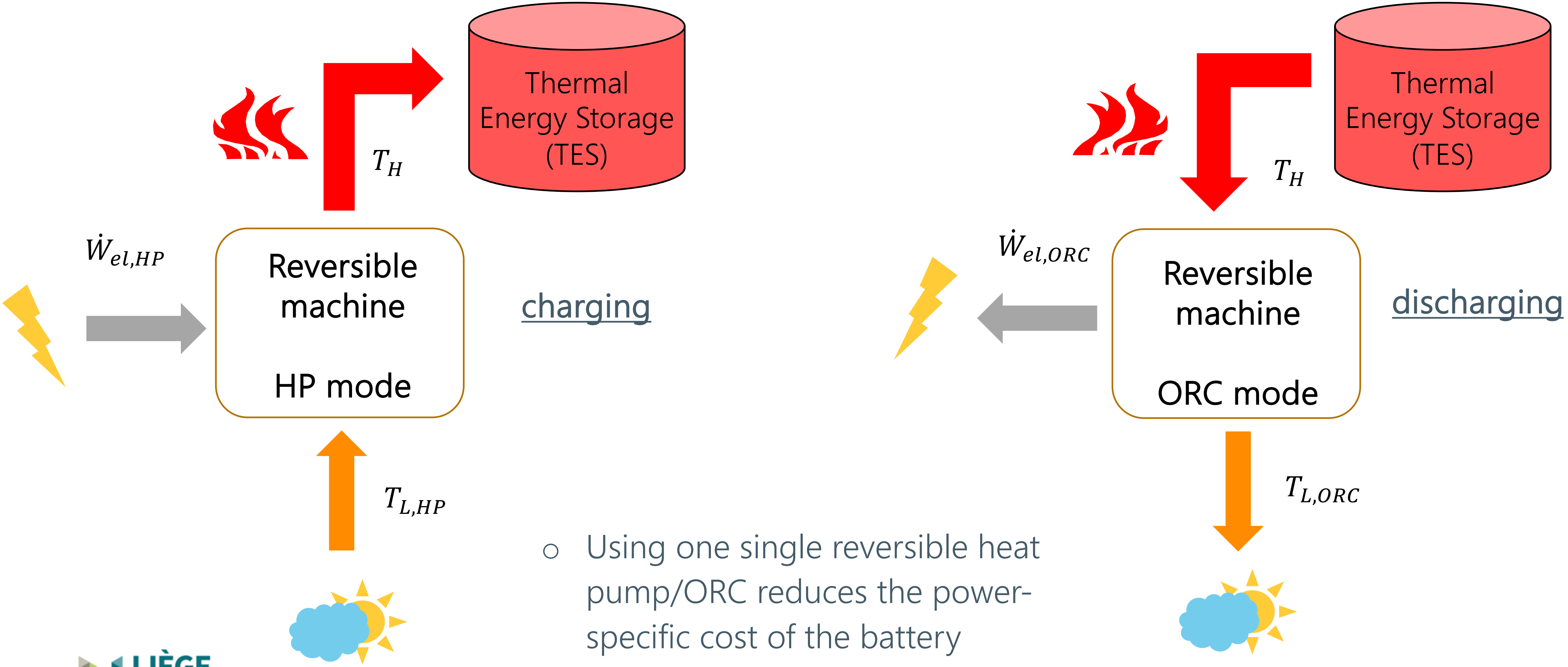
Heat pump (HP) → ORC → Reversible HP/ORC



- Merging the ORC and HP (at least the working fluid circuit) into one single machine

Hybridization

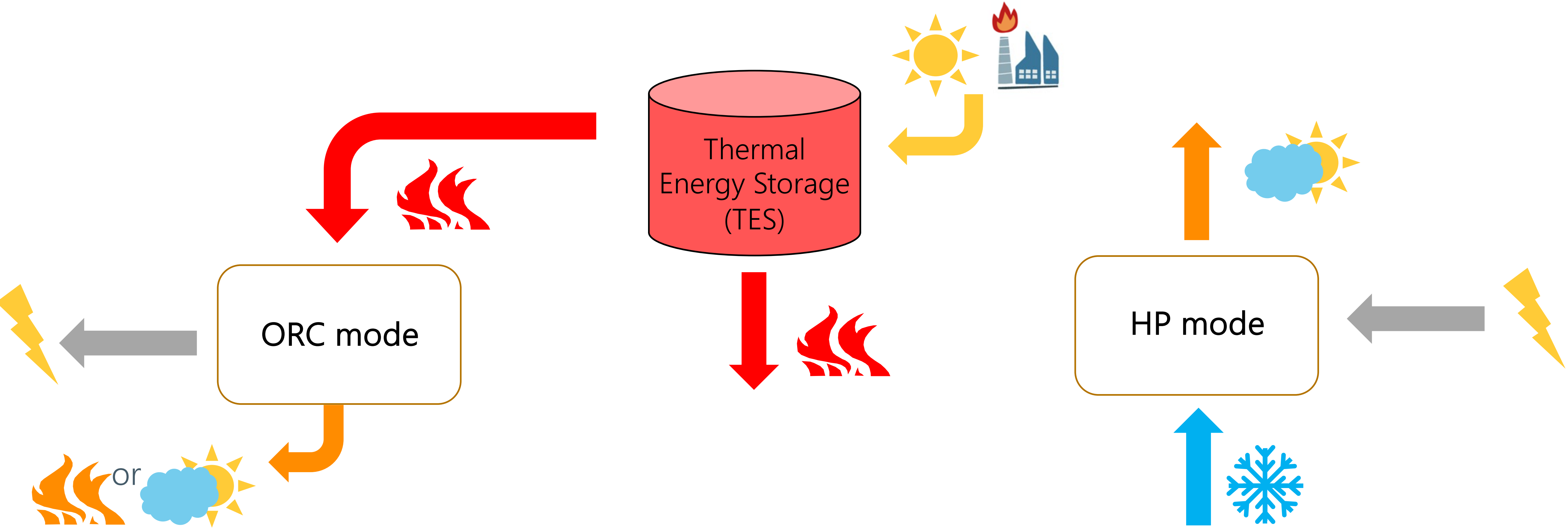
How? Reversible heat-pump/ORC + storage: Carnot battery



- Using one single reversible heat pump/ORC reduces the power-specific cost of the battery

Hybridization

How? Reversible heat-pump/ORC: polygeneration



- ORC or heat pump/chiller mode
- Thermal storage can allow for covering simultaneously heating, cooling and electricity demands and valorizing intermittent heat

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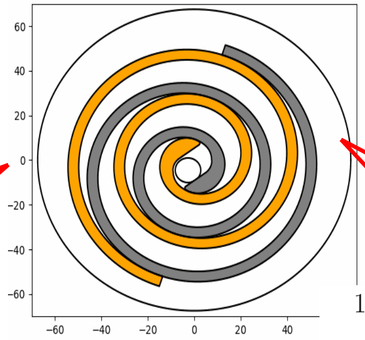
Polygeneration systems
With heat pumps - ORCs

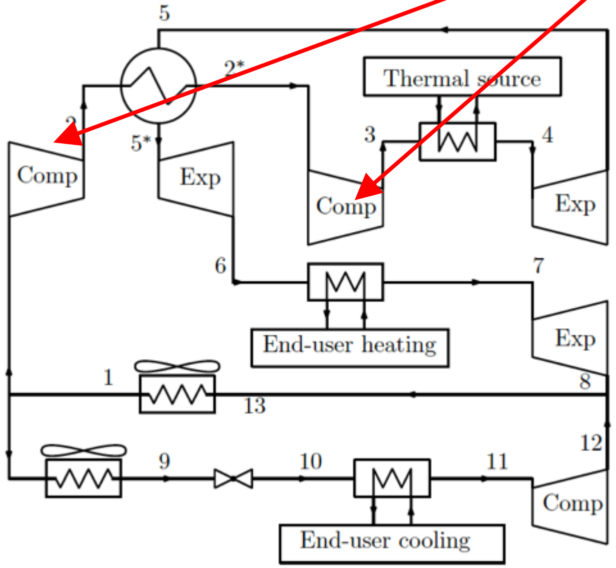
- Multigeneration of cooling, heat and electricity (CCHP) based on one single machine valorizing a low-grade heat source.

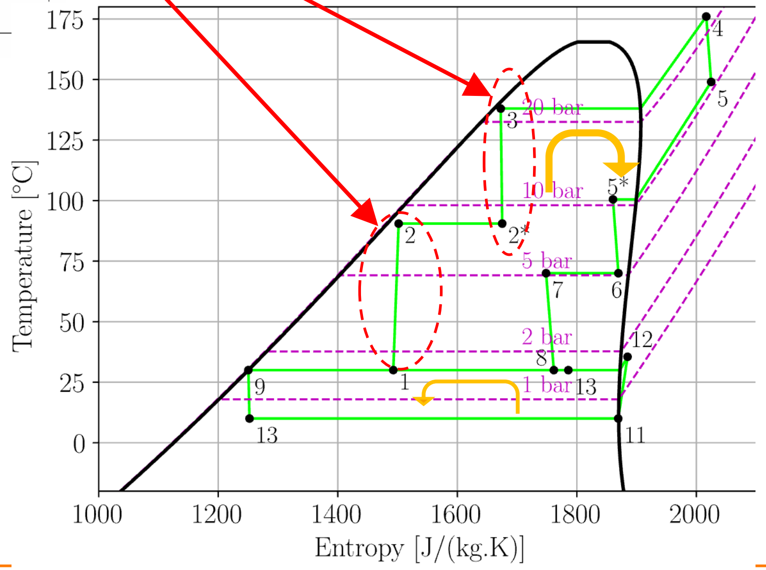
Research question

- 2-phase scroll compressor design

(2020-2026)





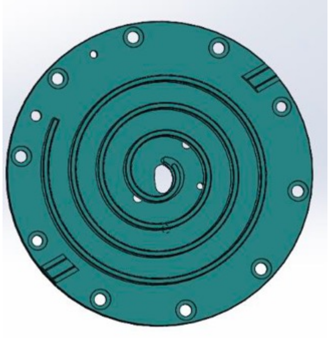


Power cycle

Heat pump cycle

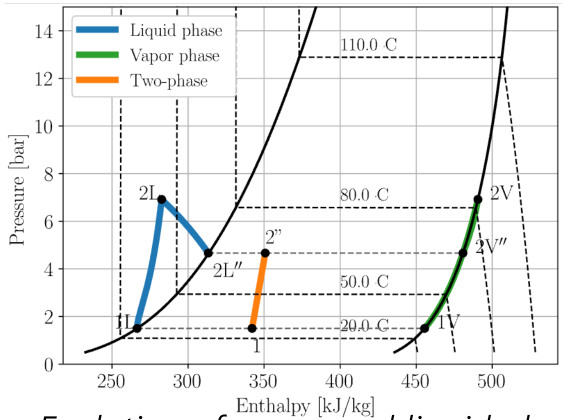
Regen-by-two: Next REnewable multi-GENeration technology enabled BY TWO-phase fluids machines.

Polygeneration systems
With heat pumps - ORCs

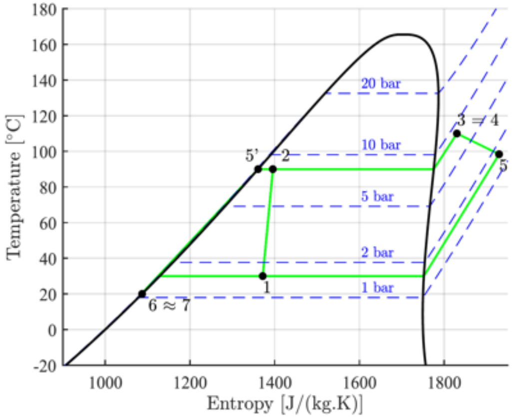


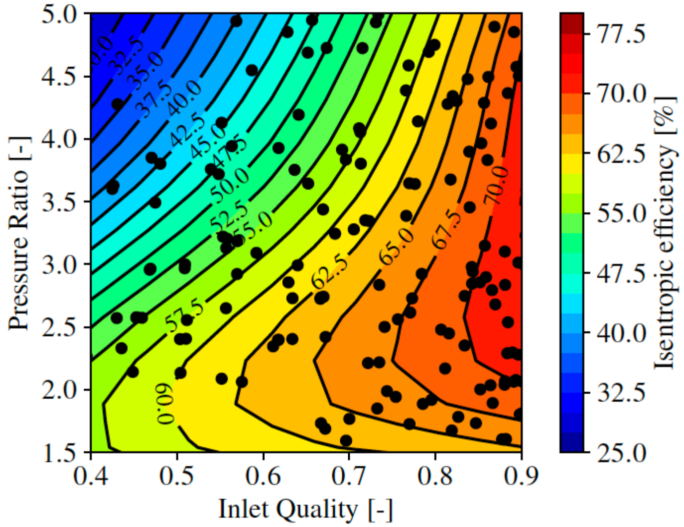
Prototype of 2-φ compressor

- **Challenges associated with compressor prototype** design:
  - Larger pressure losses in supply/discharge ports
  - Larger under-pressure losses with low quality
  - Two-phase + oil: liquid-phase viscosity lower vs pure oil (increase leakages)
  - Non-thermal equilibrium between phases yields unavoidable irreversibilities
- **Test bench** :
  - Difficulties to measure and control quality
  - Tests with **inlet quality** around **40%** have been achieved



Evolution of vapor and liquid phases during compression [1]



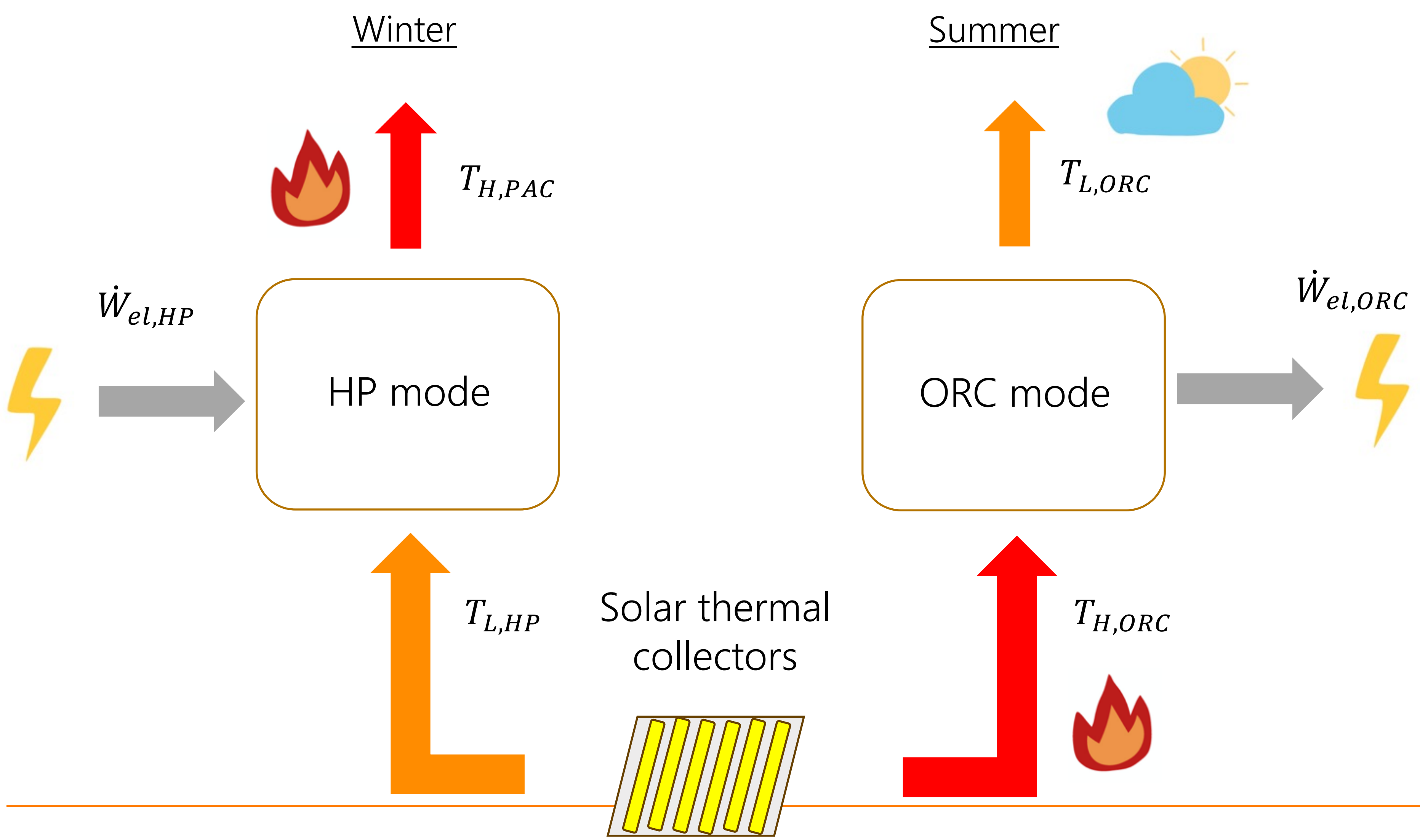


Measured isentropic effectiveness of retrofitted scroll compressor (2000 rpm, OCR=10%) [2]

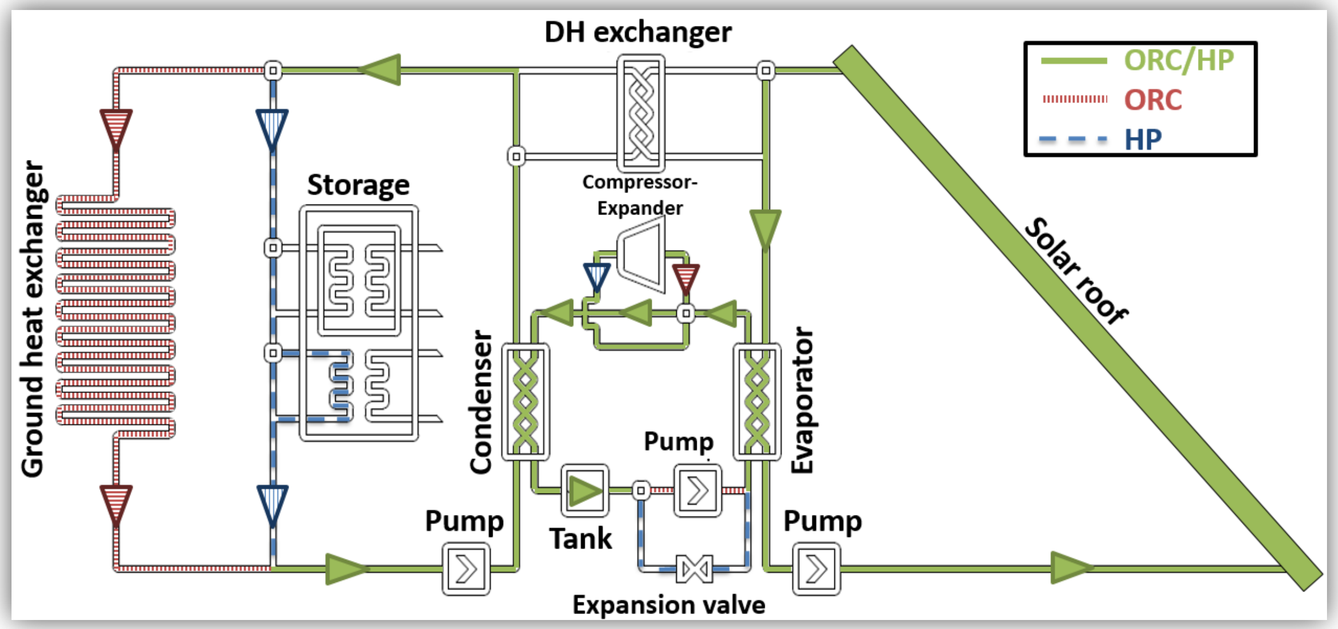
[1] Nicolas Leclercq and Vincent Lemort, A MATHEMATICAL MODEL FOR THE SIMULATION OF TWO-PHASE COMPRESSION IN THERMAL NON-EQUILIBRIUM, 1st Belgian Symposium of Thermodynamics, 16-18 December 2024, Liège, Belgium

[2] Leclercq et al., Experimental Study of a Retrofitted Scroll Compressor for operation with Two-phase Refrigerant Flows, paper submitted to IJR.

Polygeneration systems
With reversible heat pump/ORC



Polygeneration systems
With reversible heat pump/ORC

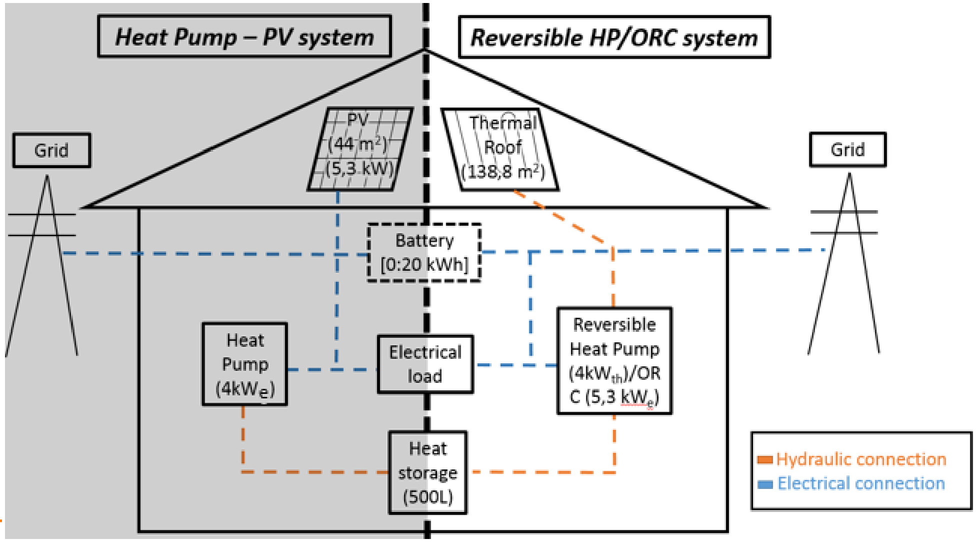


Eurostars Single HPA Unit
project (2015-2016)
coordinated by Innogie

Polygeneration systems
With reversible heat pump/ORC

- Prototype:
  - Sized to produce 4030 kWhe per year
  - COP of 4.21 (Tev = 21 °C / Tcd = 61 °C)
  - ORC efficientcy: 5,7 % (Texcd = 25 °C / Tsuev = 88 °C)

- Economical profitability not demonstrated versus PV + heat pumps (2016)

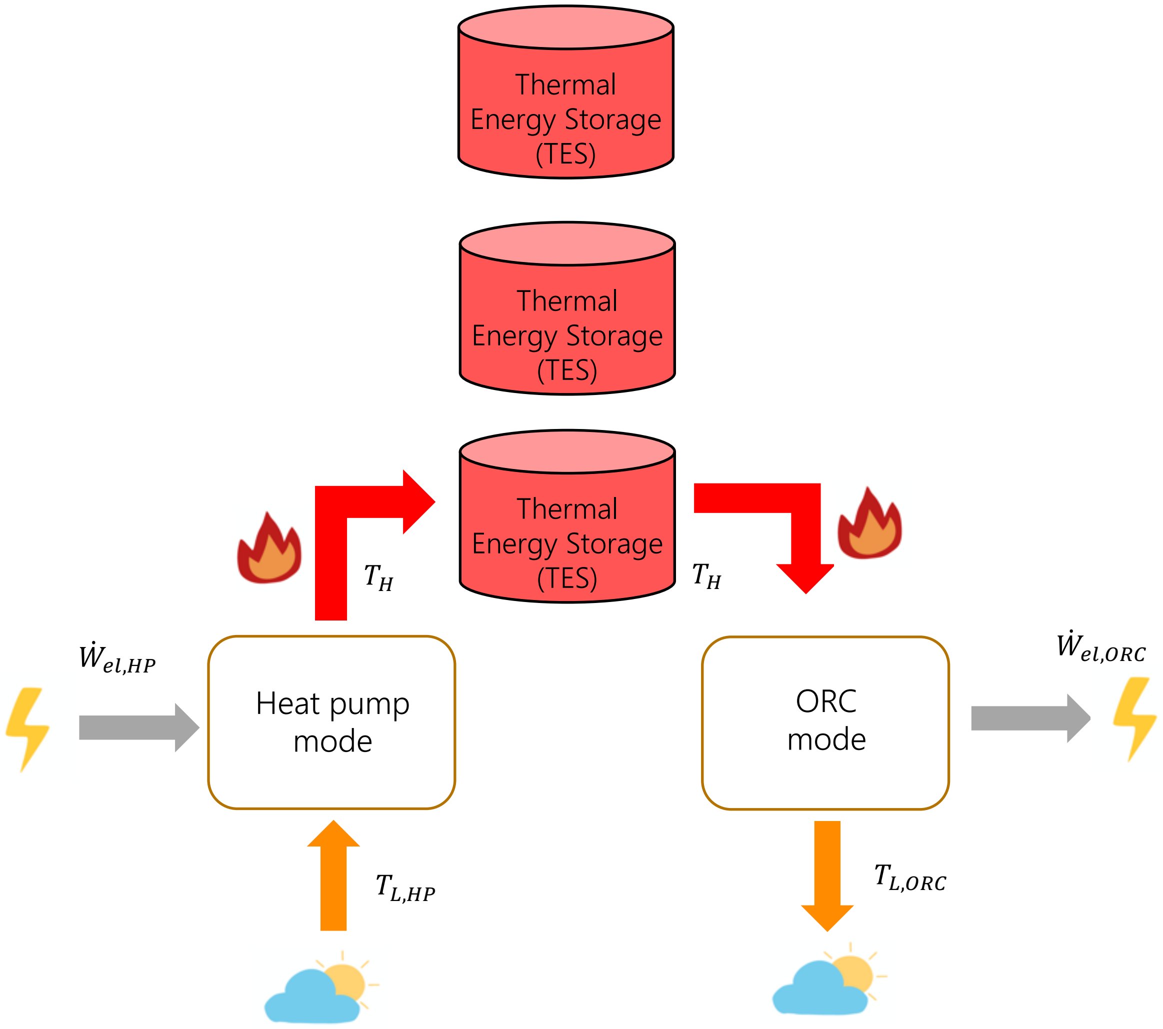


Agenda of the presentation

1. Introduction
2. Hybridization of heat pumps and ORCs
3. Polygeneration systems
4. **Carnot batteries (Store and not produce electricity)**
5. Conclusions

Carnot batteries
Working principle and advantages

- Long **lifespan** (no degradation of storage).
- Don't rely on rare and strategic **materials**. Limited environmental impact.
- No geographical dependence.
- **Modularity**: the capacity [kWh] can be increased by adding thermal storages (decreasing energy-specific cost)
- **Thermal storage** could be cheap (natural storages, pit storage).
- Can couple **heat and power sectors** (thermal integration).
- **Rankine-based** CB (versus Brayton): use off-the-shelf components, temperatures compatible with waste heat, building heating/cooling.



Round-trip effieincy: $\eta_{P2P} = \frac{\dot{W}_{el,ORC}}{\dot{W}_{el,HP}}$

Carnot batteries

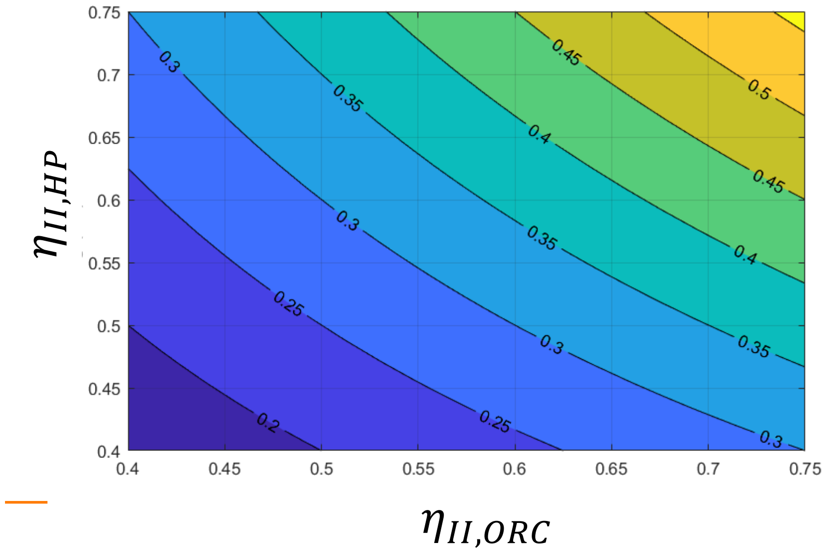
Performance

- The Power-to-Power efficiency is given by:

$$\eta_{P2P} = \frac{W_{el,ORC}}{W_{el,HP}} = (\eta_{sto})\ COP_{HP}\ \eta_{ORC}$$

$$= (\eta_{sto})\ \eta_{II,HP} \frac{T_H}{T_H - T_{L,HP}} \eta_{II,ORC} \left(1 - \frac{T_{L,ORC}}{T_H}\right)$$

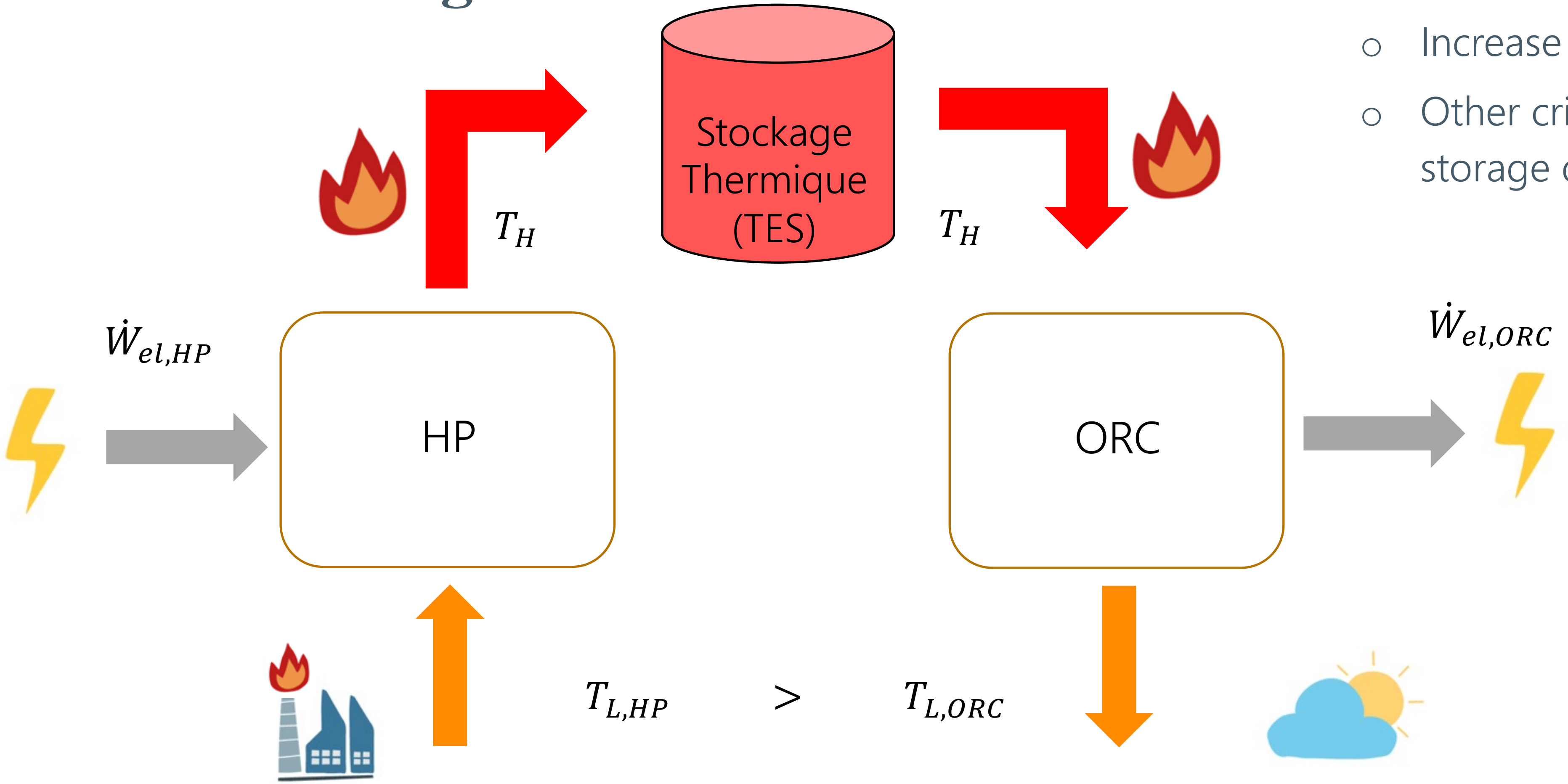
- If the heat source temperature of the HP is equal to the heat sink temperature of the ORC ($T_{L,HP} = T_{L,ORC}$), for instance ambient air, we get



$$\eta_{P2P} = \eta_{II,HP}\ \eta_{II,ORC}\ (< 50\%)$$

Carnot batteries

Thermal integration



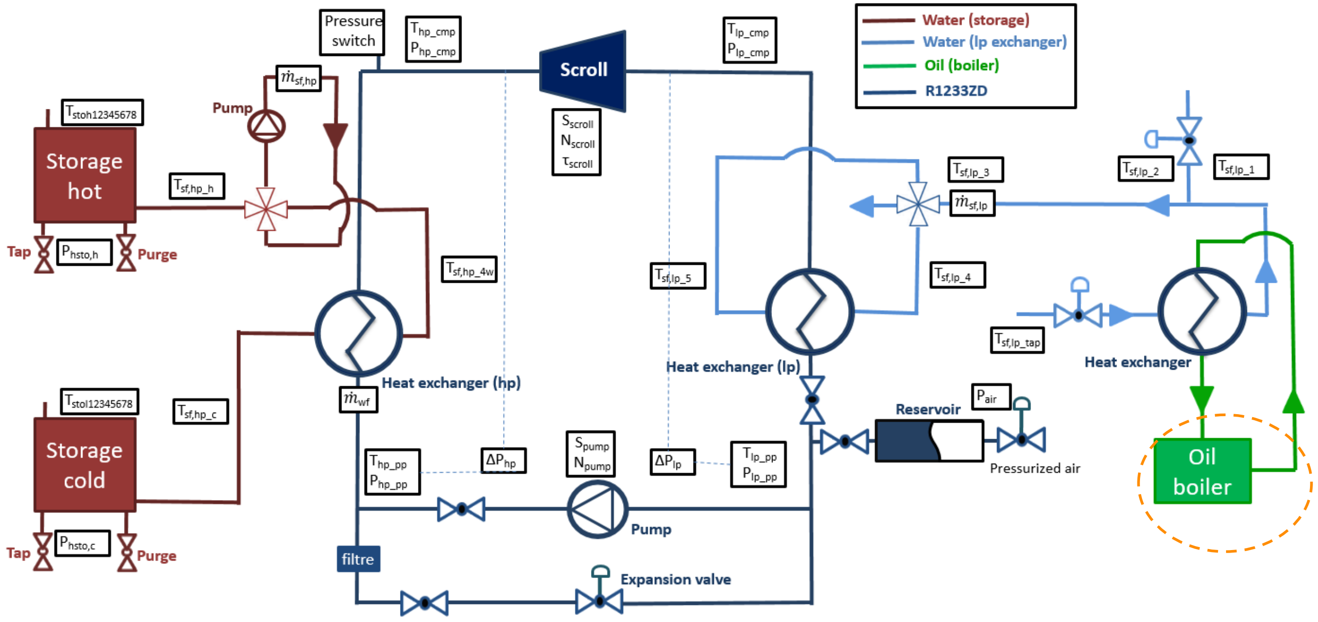
- Increase of power-to-power efficiency
- Other criteria: exergy efficiency, energy storage density

Valorization of waste heat

$$\eta_{P2P} = \eta_{II,HP} \frac{T_H}{T_H - T_{L,HP}} \eta_{II,ORC} \left(1 - \frac{T_{L,ORC}}{T_H}\right)$$

Carnot batteries

Thermal integration: prototype #1 (2018-2020)



To simulate waste heat

- R1233zd(E)
- Storage at ~90°C
- Thermal capacity of 10 kWhth, Discharge power close to 2 kWe
- Roundtrip efficiency of **72.5%** (ORC efficiency of 5% (lift: 49 K) and COP of HP of 14.4 (lift: 8 K)).

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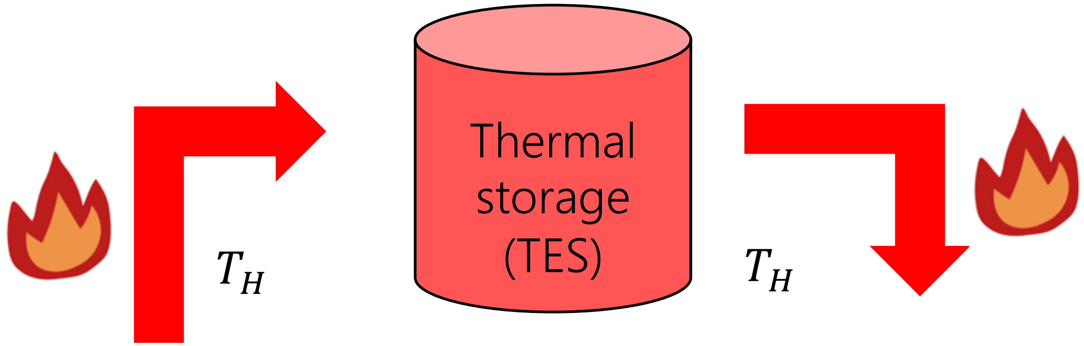
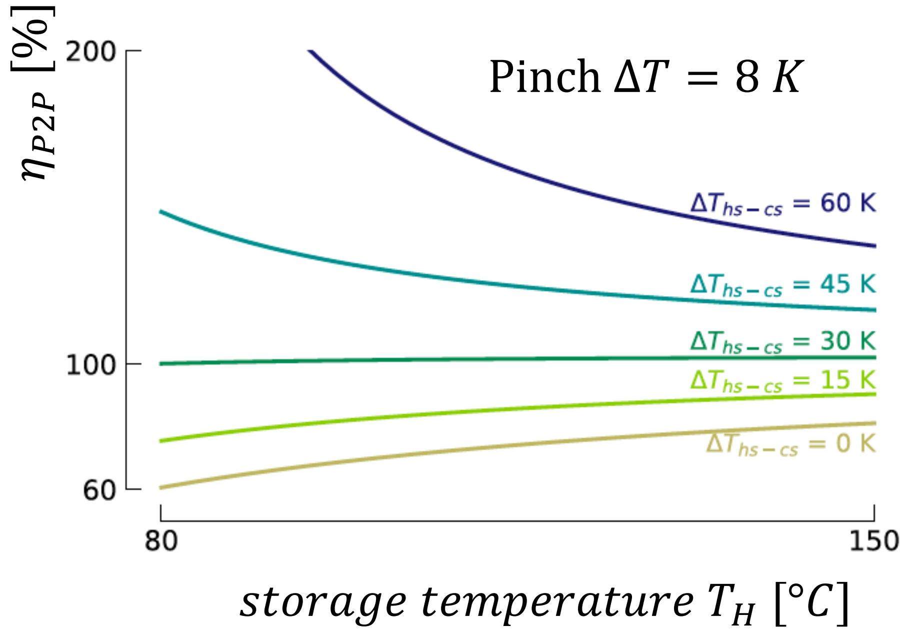
Thermal integration



What is the optimal temperature T_H of the thermal stroage?

Assuming the HP and ORC to be endoreversibe and if $\Delta T\ [K]$ is the temperature pinch point between the working fluid and source/sink:

$$\eta_{P2P} = \frac{T_H + \Delta T}{T_H - T_{L,HP} + 2\Delta T} \times \frac{T_H - T_{L,ORC} - 2\Delta T}{T_H - \Delta T}$$



$$\Delta T_{hs-cs} = T_{L,HP} - T_{L,ORC}$$

Waste heat *Ambient air*

For heat sources with temperatures 30 K higher than ambient temperatures, it is better to decrease the storage temperature

→HEX Pinch becomes more important for low ΔT_{hs-cs}

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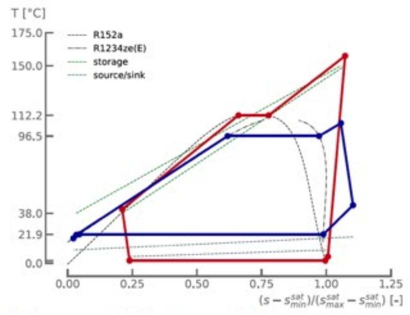
Source: Antoine Laterre et al., Extended mapping and systematic optimisation of the Carnot battery trilemma for sub-critical cycles with thermal integration, Energy, Volume 304, 2024

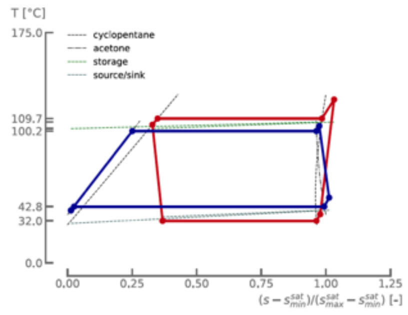
Carnot batteries

Thermal integration

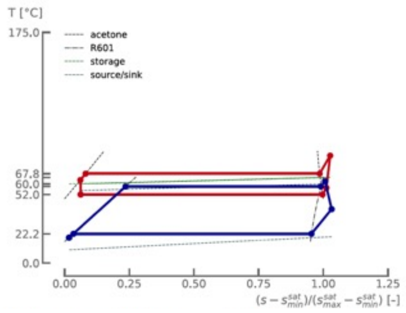
Exemple of optimisation



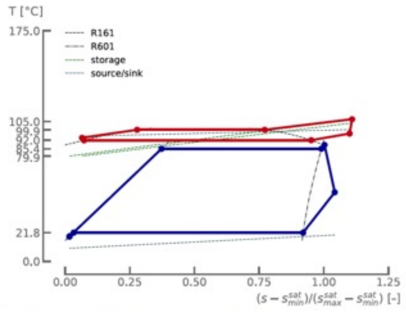
$T_{L,HP} = 10°C$ and $T_{L,ORC} = 10°C$



$T_{L,HP} = 40°C$ and $T_{L,ORC} = 30°C$



$T_{L,HP} = 60°C$ and $T_{L,ORC} = 10°C$



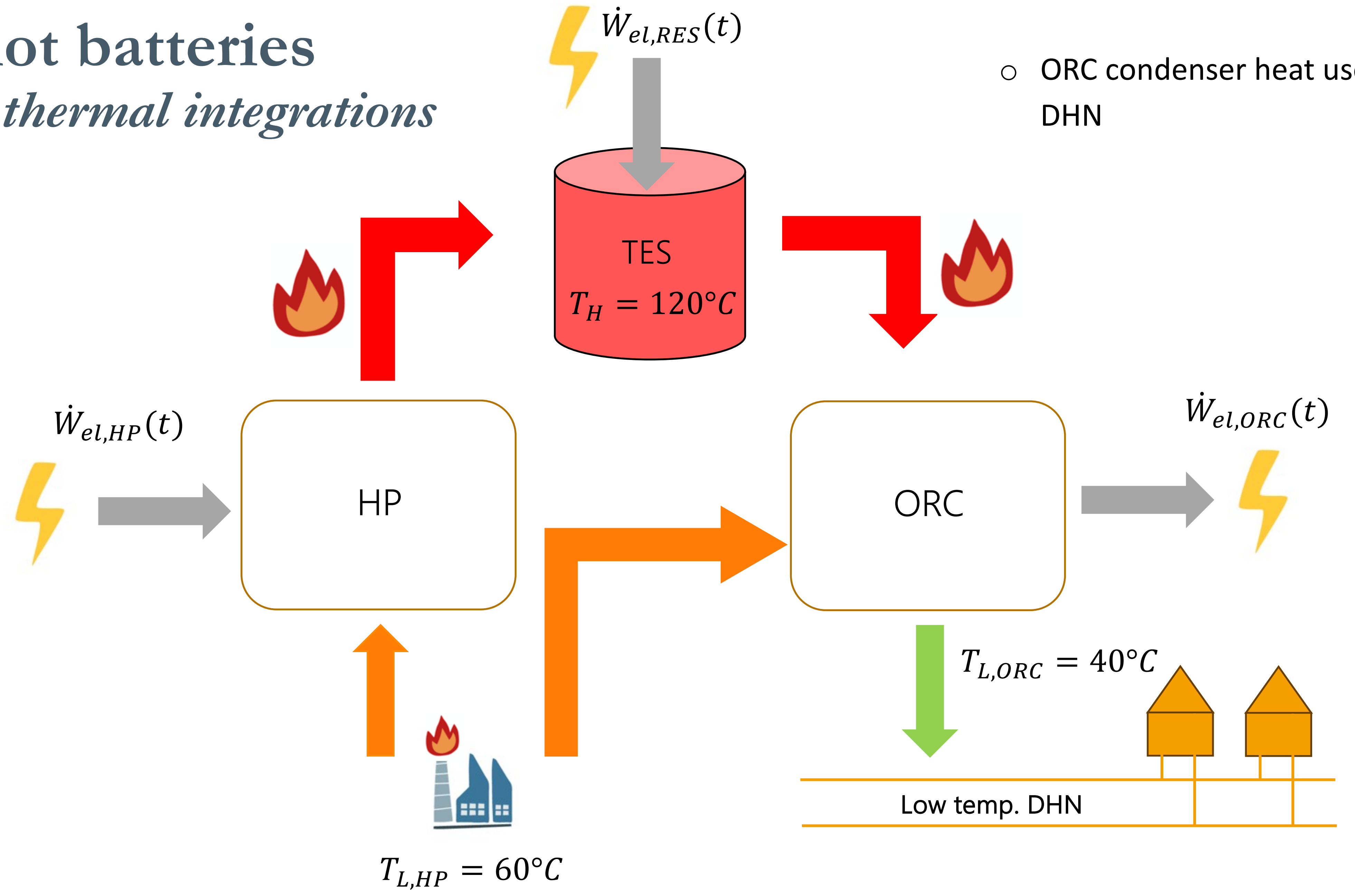
$T_{L,HP} = 100°C$ and $T_{L,ORC} = 10°C$

For high temperatures of the waste heat source, the heat pump cycle gets « flat » and degenerates into a waste heat recovery/thermal storage/ORC to produce electricity

Source: Antoine Laterre et al., Extended mapping and systematic optimisation of the Carnot battery trilemma for sub-critical cycles with thermal integration, Energy, Volume 304, 2024

Carnot batteries
Other thermal integrations

- ORC condenser heat used in a DHN



Carnot batteries

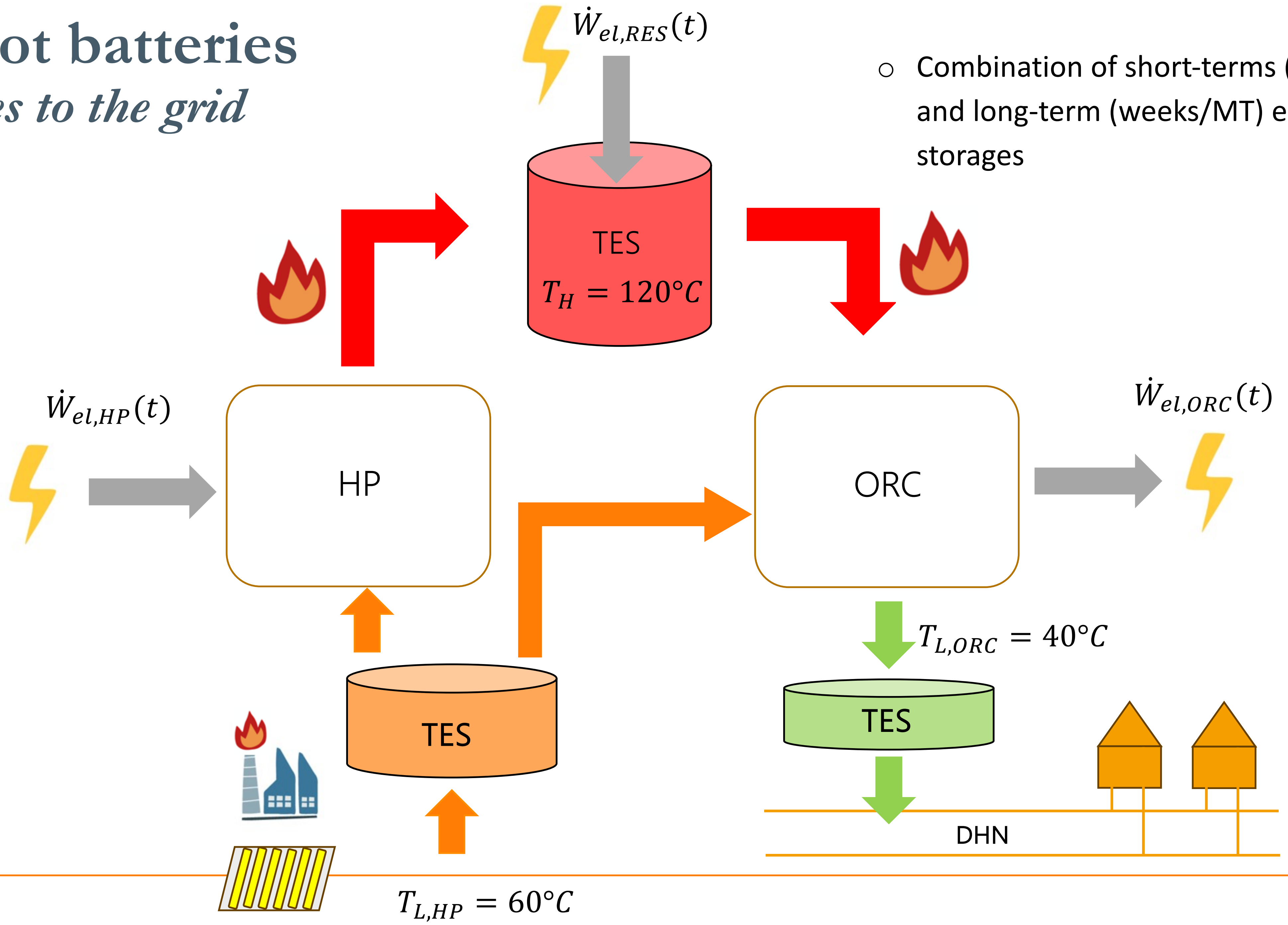
Services to the grid

- Not competitive with batteries for storage durations lower than 2 hours => adapted to longer storage durations.
- Still a lot of pending questions :
  - What are the most suitable **storage durations** (hours, days, weeks, months)?
  - What are the cost-effective storage **capacities**? The storage capacity [kWh] is function of the size of the thermal storage (for constant size of machines [kW]): use of natural reservoir vs artificial reservoir.
  - What are the optimal charging and discharging times? Carnot batteries can work with **contrasted charging and discharging powers.**
  - What is the **dynamics** of such systems (ramp-up time)?
    - ✓ Thermal and mechanical inertia
    - ✓ Coupling with fast-reacting electric resistances? ORC pre-heating?
    - ✓ mFRR (tertiary reserves, reaction < 15 minutes), DAM?

Carnot batteries

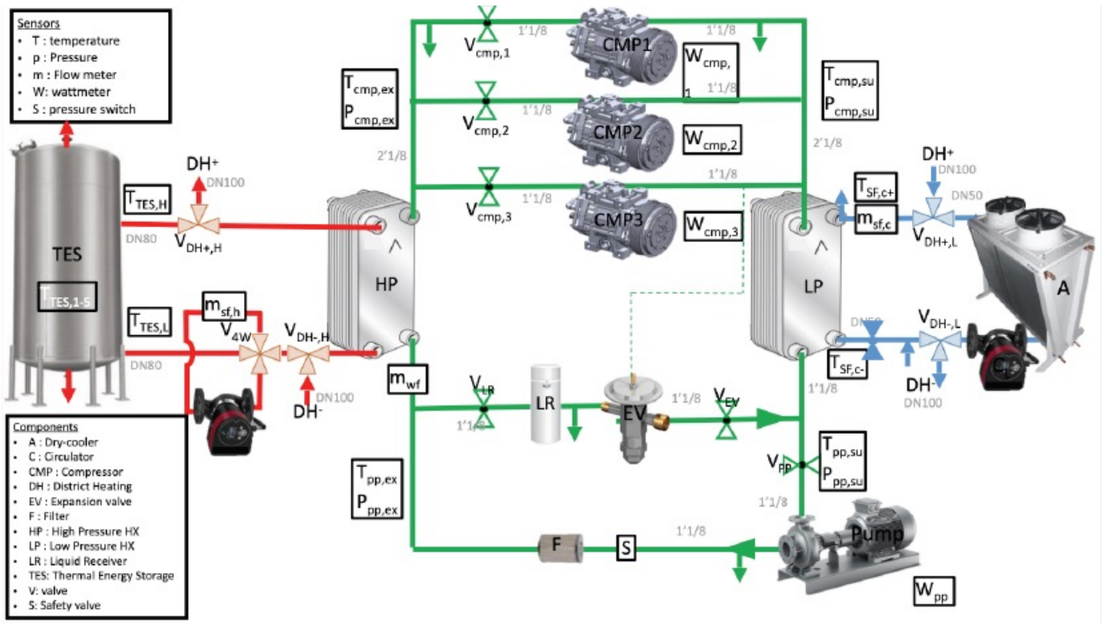
Services to the grid

- Combination of short-terms (days/HT) and long-term (weeks/MT) energy storages



Carnot batteries

Services to the grid: prototype #2



- 8.1 m³ single water tank (thermocline)
- 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%
- Investigate **machine dynamics** + possibility of **active charge management**

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Carnot batteries

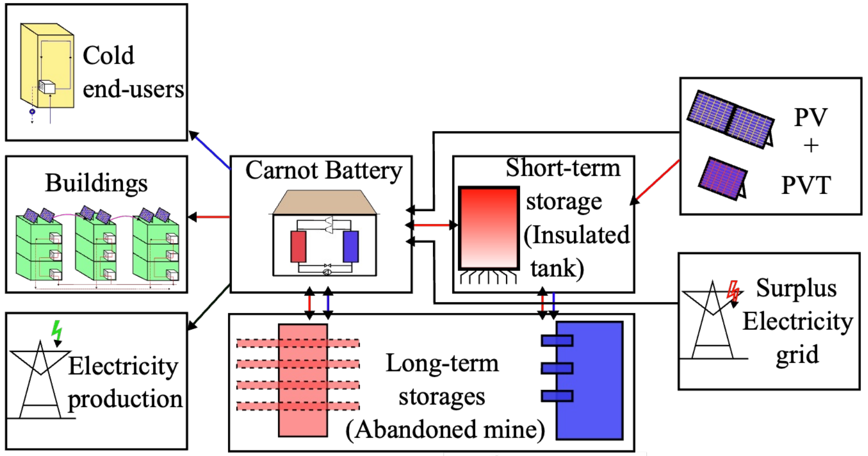
Underground thermal energy storage

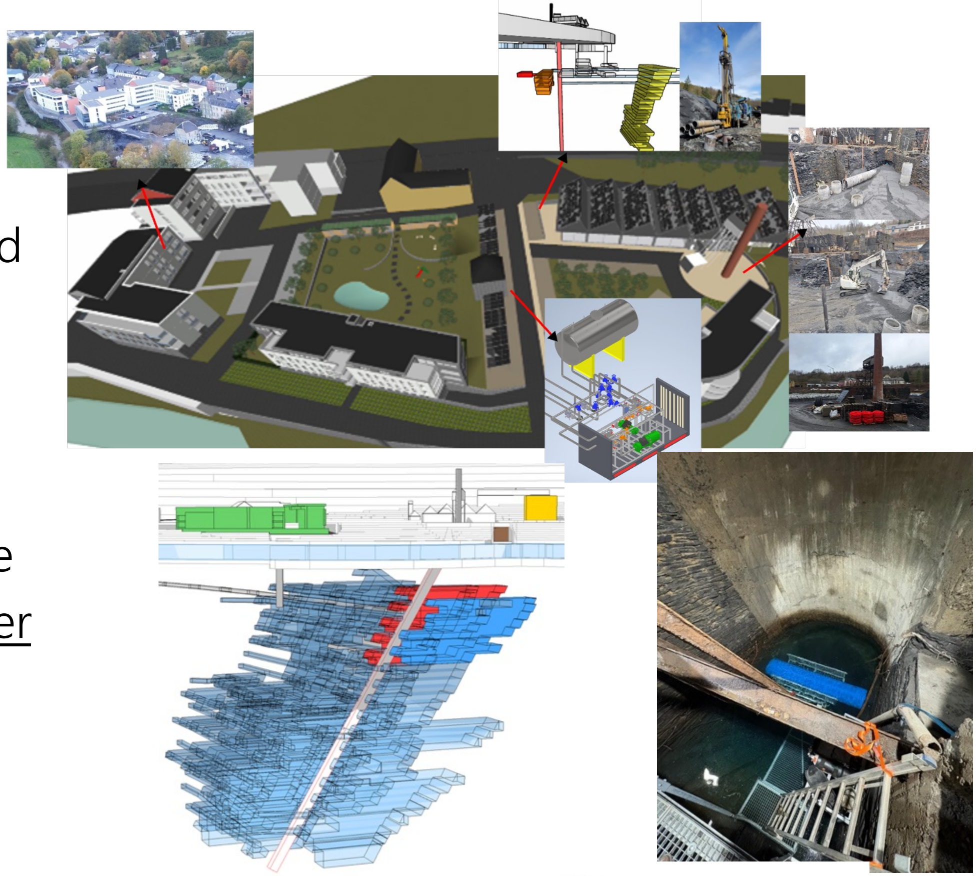
- Slate mines in the South of Belgium
- Abandoned since the 90s
- Flooded with 500,000 m^3 of water = massive storage
- Residential buildings (50 apartments) with heating/cooling demands
- Local electricity production: 70 kWe photovoltaic (PV) system and a 140 kWth photovoltaic-thermal (PT) collector installation

Heat and cold storage

⇒ for covering heating/cooling **demands in buildings**: to increase **self-consumption** of local electricity production (water-to-water heat pump)

⇒ for local and grid **electricity storage** (Carnot battery)





Carnot batteries

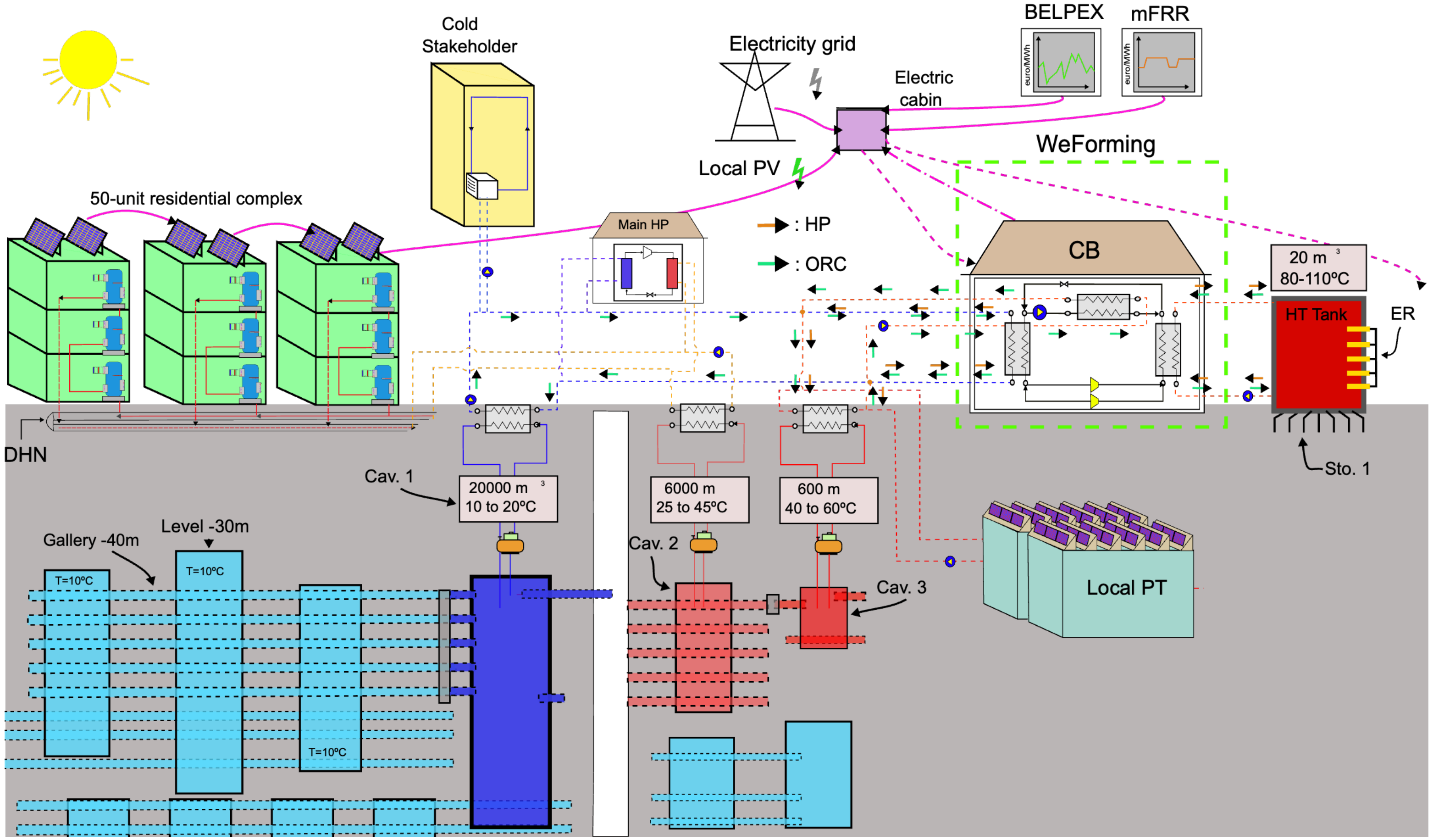
Underground thermal energy storage

TI-Carnot battery

- 20 m³ overground tank at 80-110°C (difficulty to find a submersible pump).
- 600 m³ underground chamber at 40-60°C : PVT or **industrial waste heat** (40-60°C).
- 20000 m³ underground chamber at 10-20°C : produced by main heat pump and natural generation.

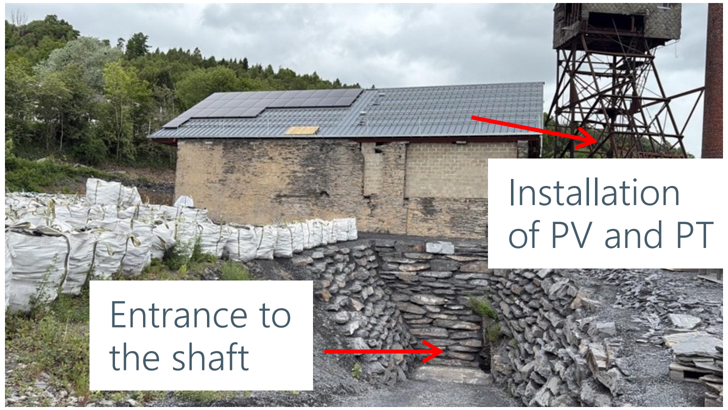
C/H demands

- 6000 m³ underground chamber at 25-45°C : produced by main heat pump.



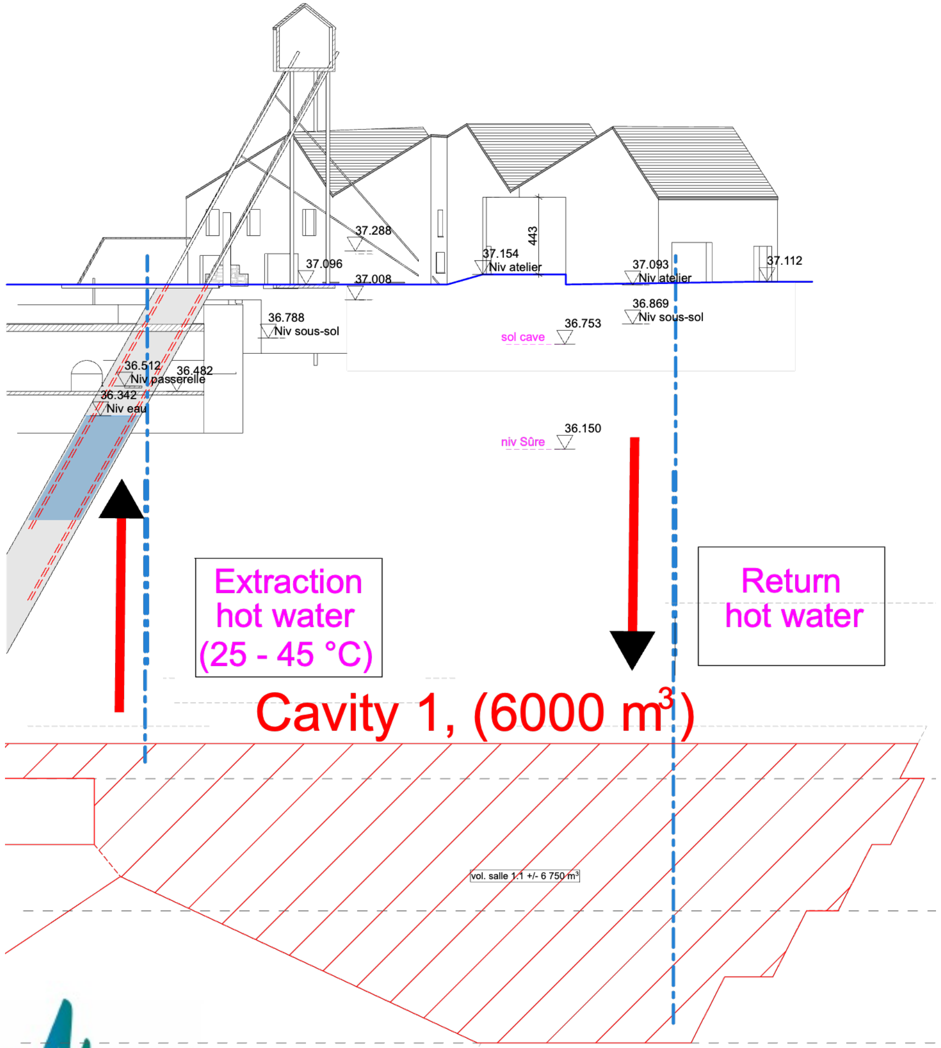
Carnot batteries

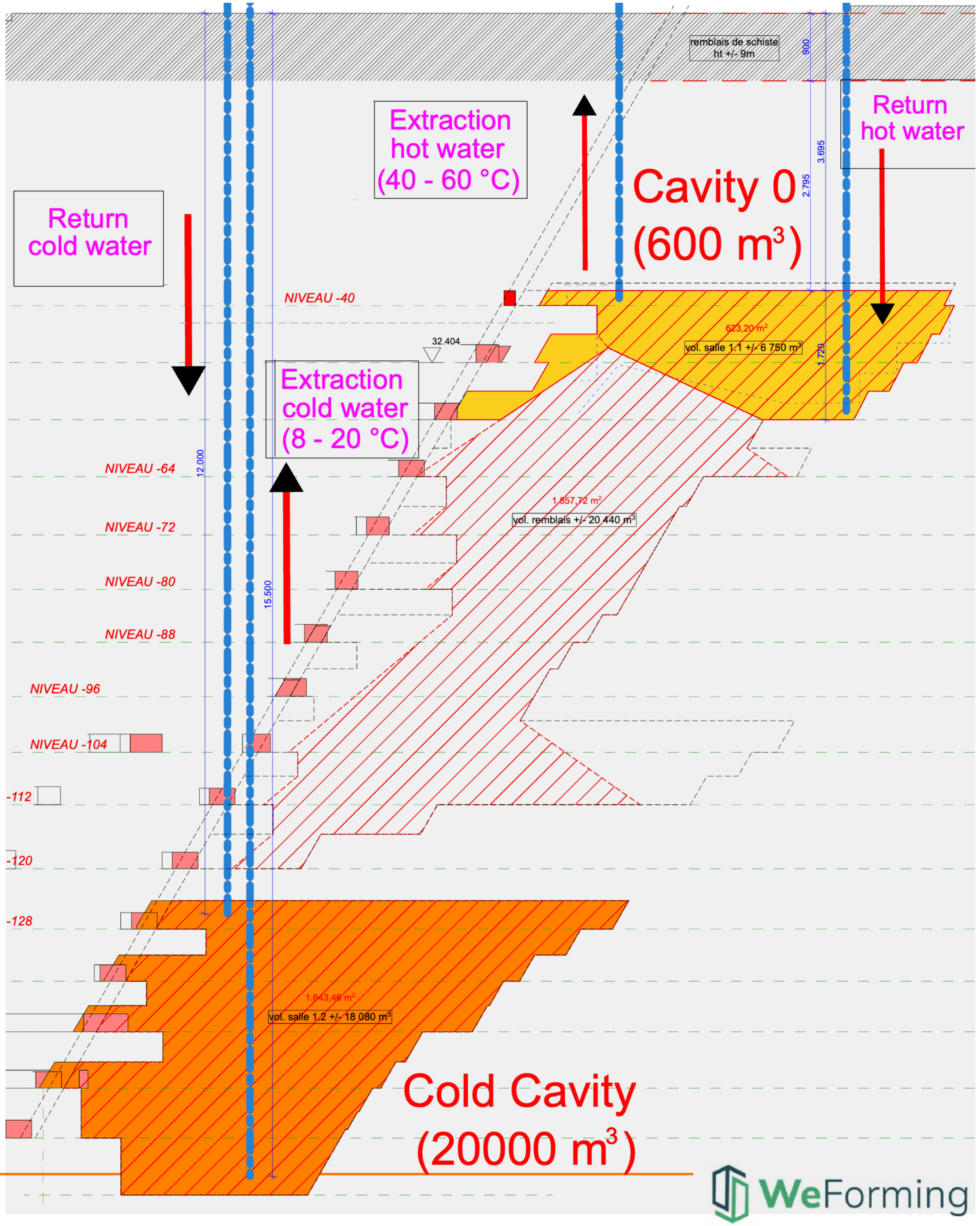
Underground thermal energy storage (UTES)



Carnot batteries

UTES





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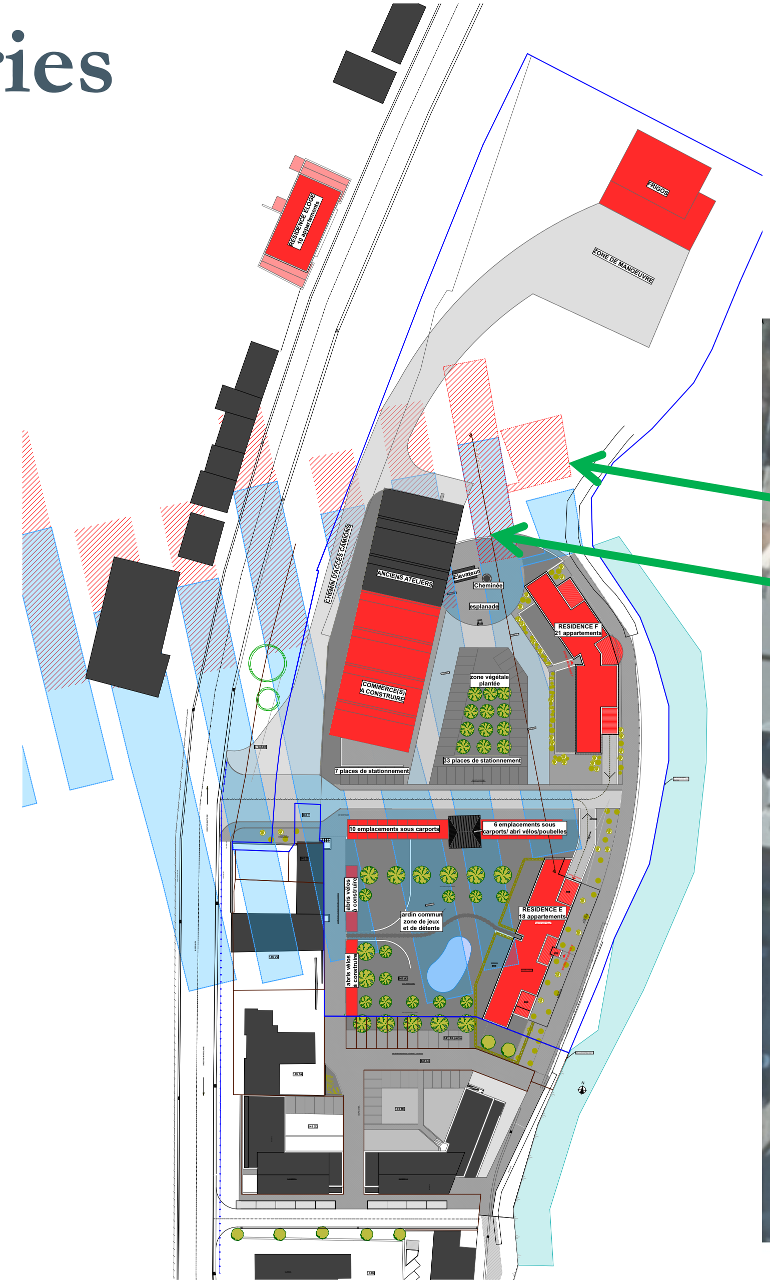
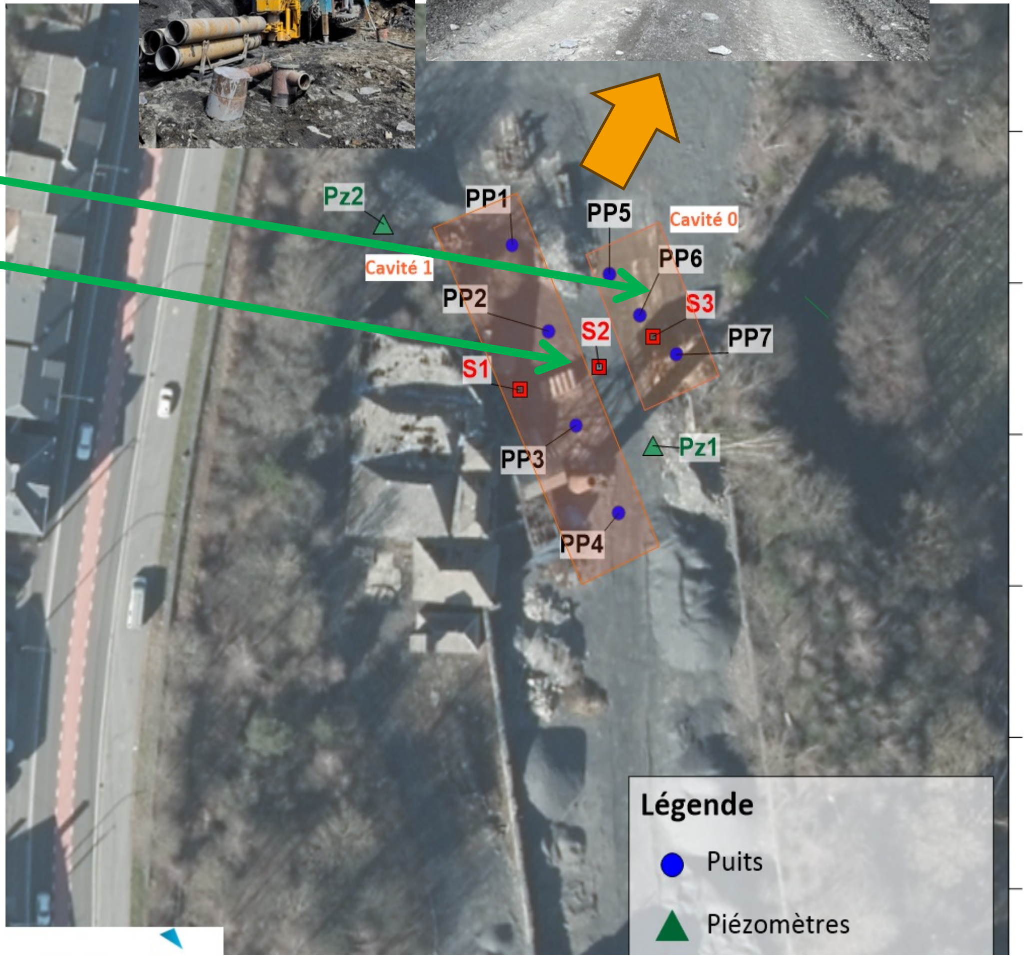
Carnot batteries

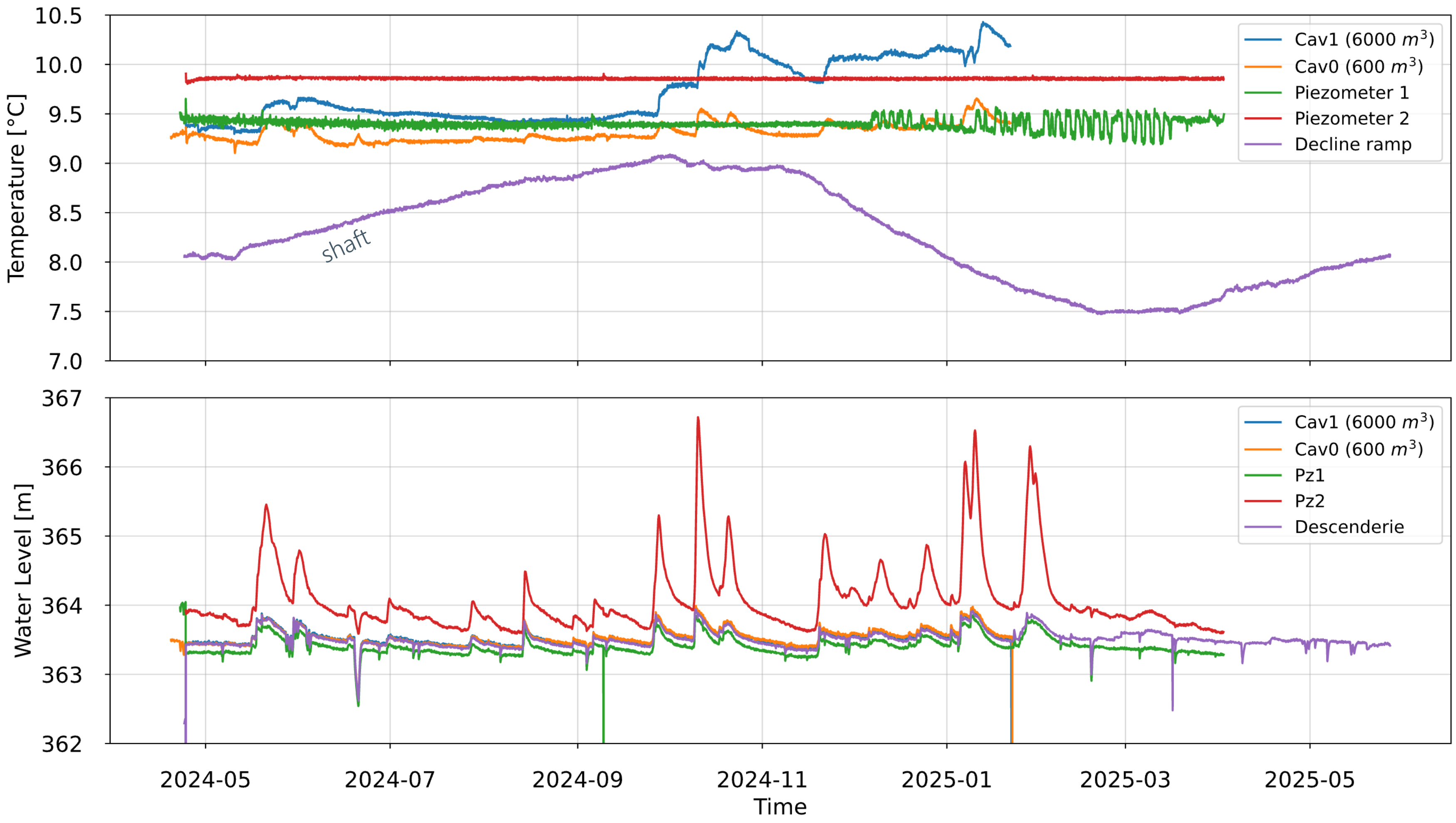
UTES





Carnot batteries
UTES

- Temperature and piezometer sensors in the chambers 0 (600 m3) and 1 (6000 m3). *Ready and data for almost one year*
- There is no large variation in the temperature. Larger in the decline ramp, which (7.5 – 9) ✓
- The water level remains almost fixed with the exception of the Piezometer 2, which oscillates a maximum of 2 meters ✓



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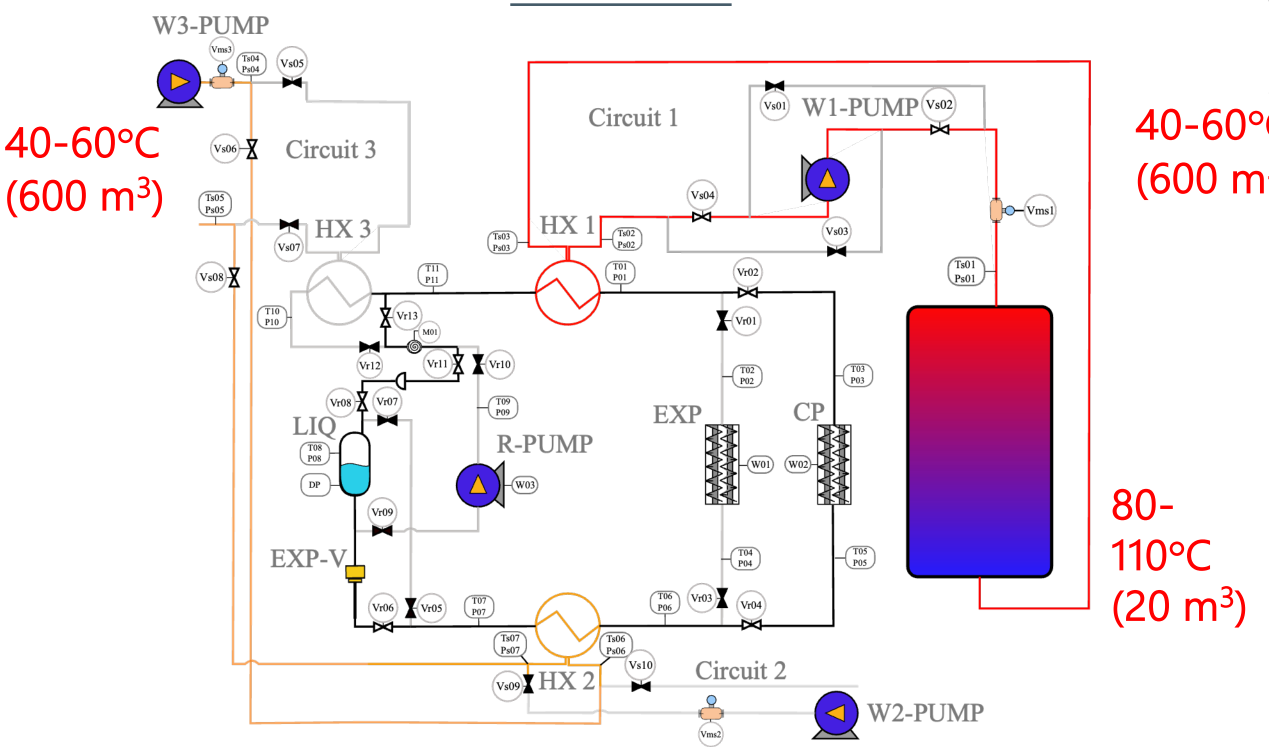
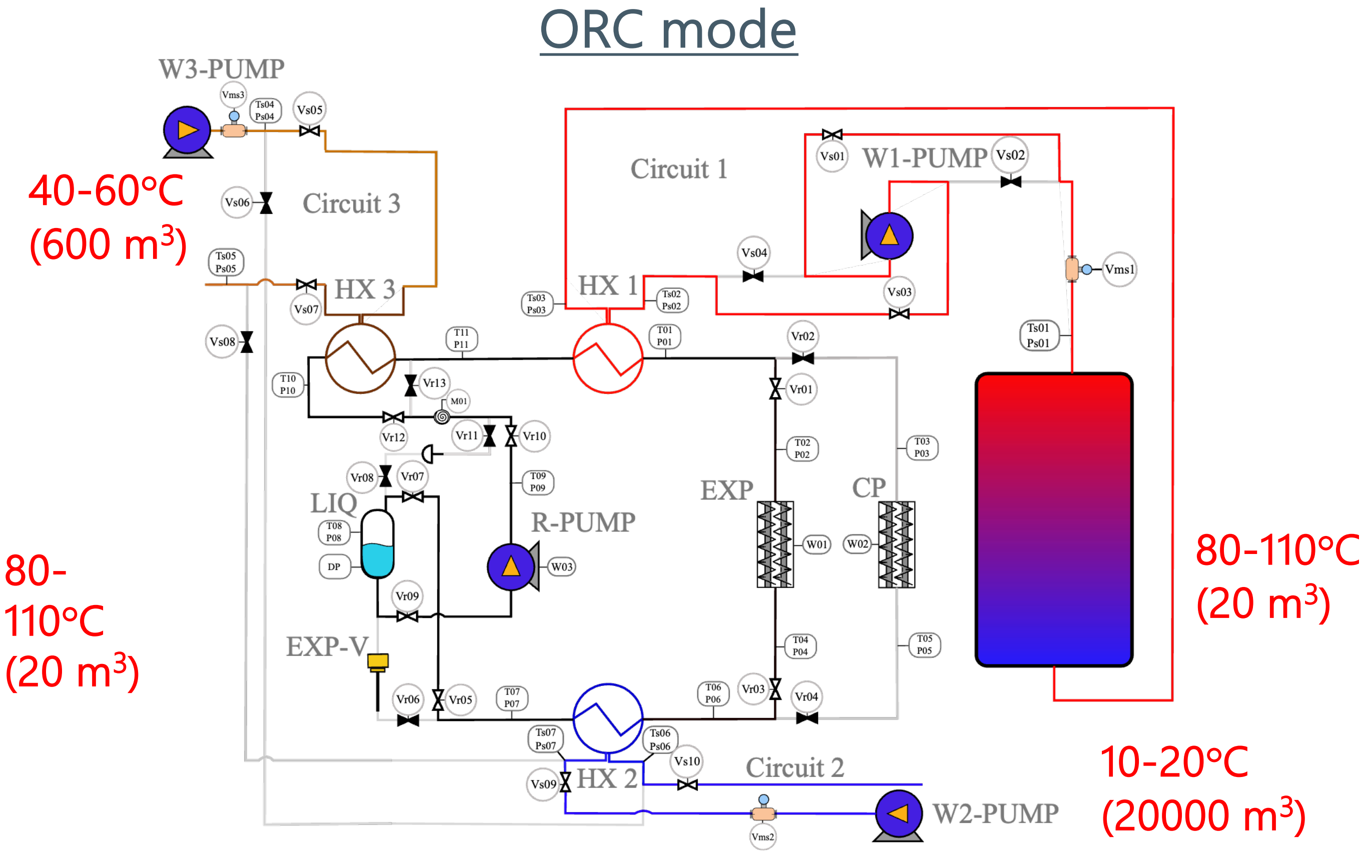
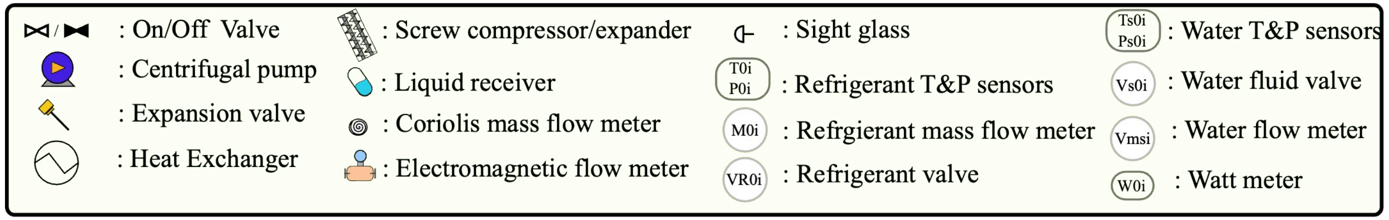
Carnot batteries

Underground thermal energy storage : prototype #3





- Semi-reversible: dedicated compressor and expander. All other components are shared
- R1233zd(e)



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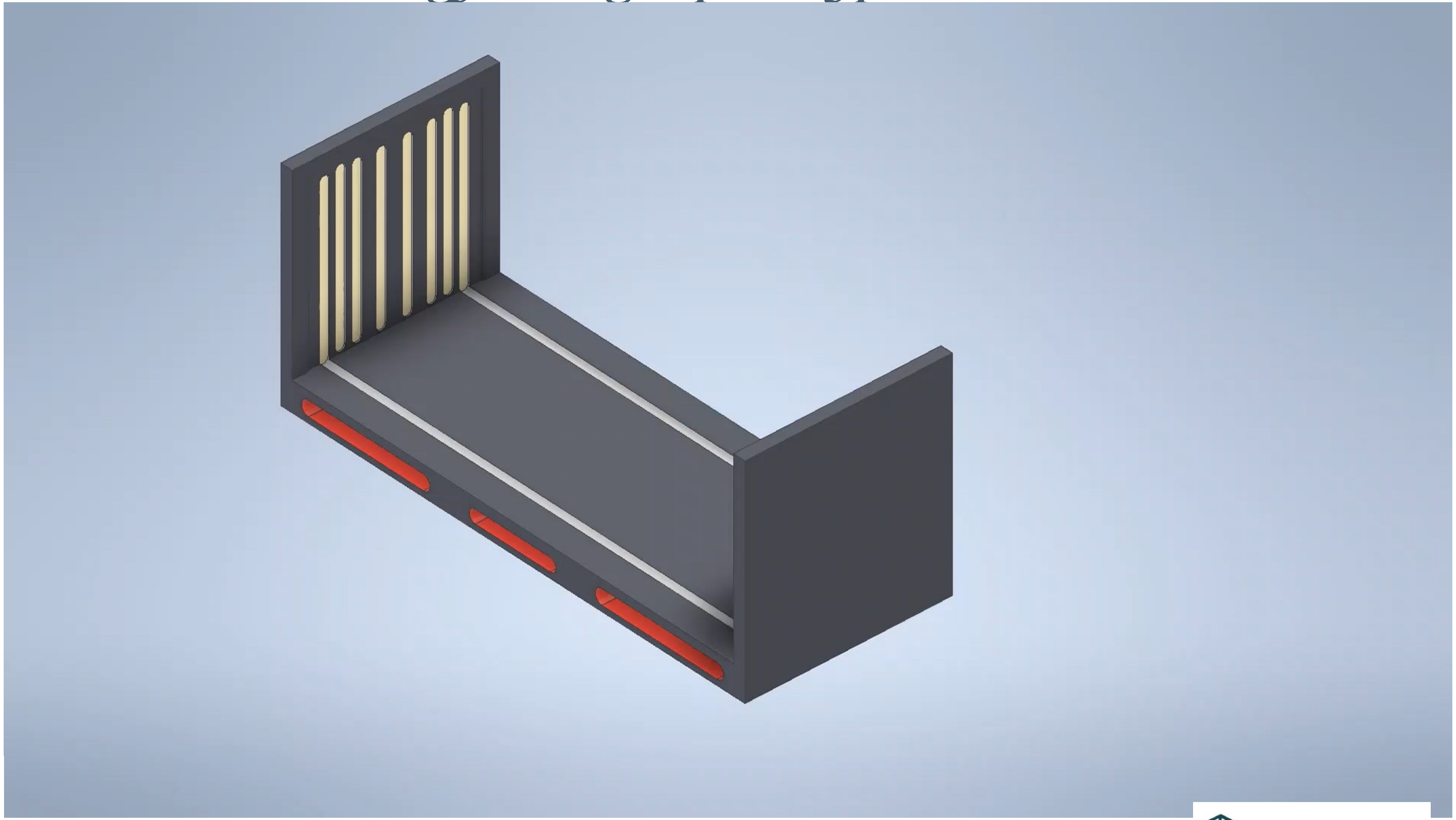
Carnot batteries

Underground thermal energy storage : prototype #3



Carnot batteries

Underground thermal energy storage : prototype #3



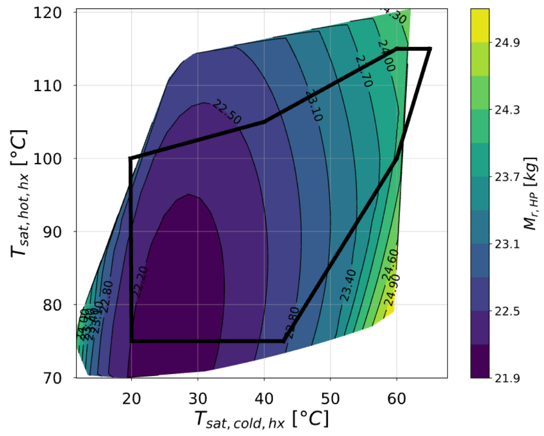
Carnot batteries

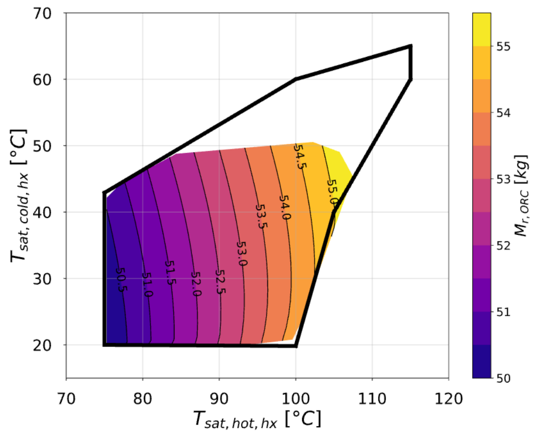
Underground thermal energy storage: prototype #3

Some technical challenges:

- **Refrigerant charge**
  - Larger charge in ORC than HP because of large liquid preheating zone and larger density
  - Correct refrigerant charge is important for safe, stable and efficient operation of the machine
  - Charge management solutions:
    - Inline liquid receiver able to work in both modes
    - Parallel branch with LR to charge/discharge the loop

- **Lubricating oil**: OCR much larger for the expander mode than compressor → Oil management when switching from modes.

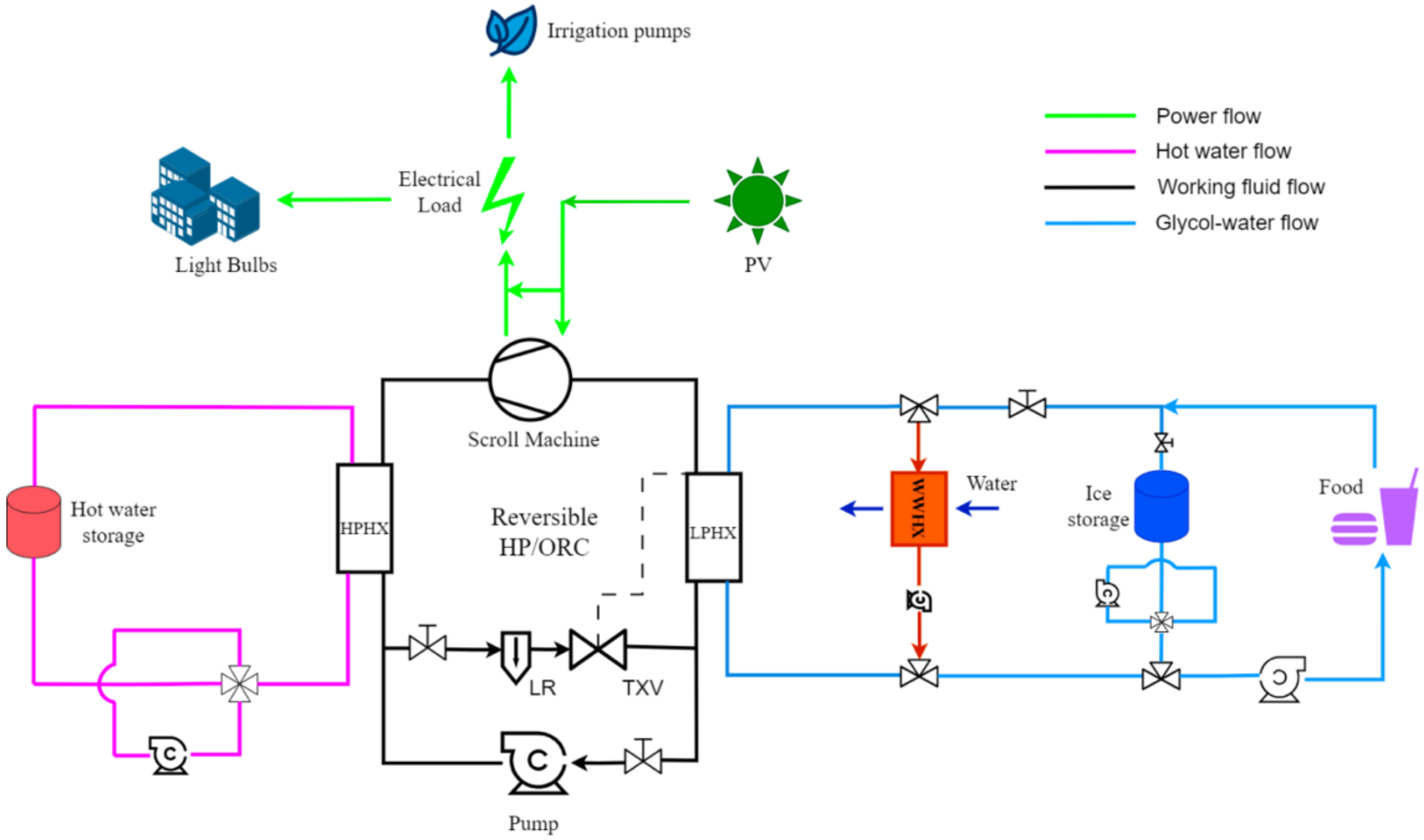




Carnot batteries

Isolated grid and other coupling with heat sector

- Ice thermal storage can be used for covering **cooling** demand: case study of an off-grid Nigerian farm



Source: B. Guo and V. Lemort. « Designing of an off-grid reversible heat pump/organic rankine cycle system for electricity and cooling demands of a nigerian family farm. » In *37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. ECOS2024, 2024.

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LEAP-RE REPTES

Conclusions

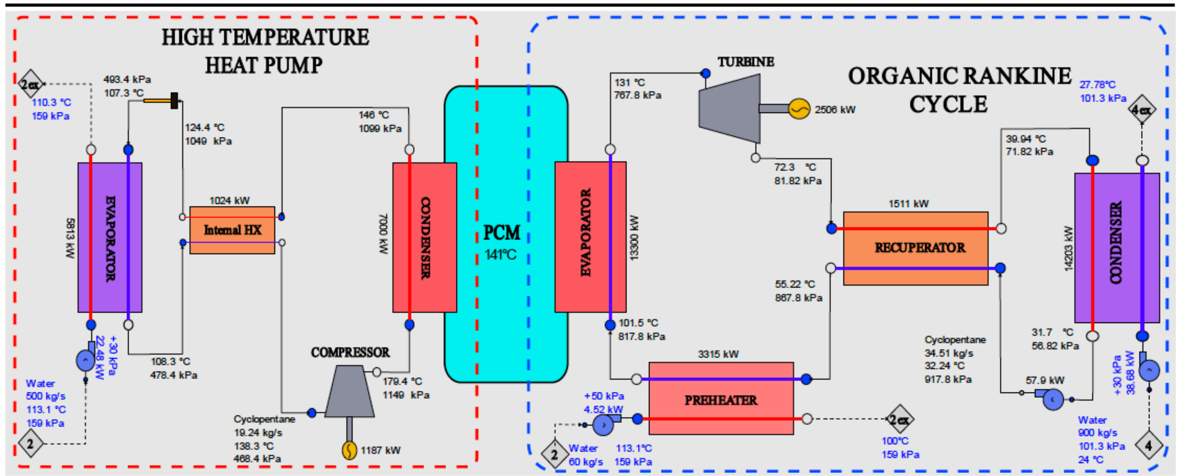
- In the context of energy transition and sectors coupling, versatile machines with multi-functionalities: **storing/producing (upgraded) heat/cold/electricity** valorizing **waste heat** could play a role

  ⇒ **Hybridization** of ORCs with heat pumps and thermal storages offers many possibilities
- There are numerous hybridization possibilities (**polygeneration** systems, **Carnot batteries**,...)
- Unlocking various **technical constraints** opens avenues to very original designs that meet energy needs:
  - ✓ Reversibility (invertibility) of components
  - ✓ Impact of temperature pinch points when considering low-temperature lift systems
  - ✓ Lubricating oil and charge management for multimodal machines
  - ✓ Irreversibilities associated with two-phase compression
  - ✓ Advanced control taking advantage of dynamics of systems

- The paradigm of Carnot battery is moving from an electric battery to a multi-energy storage system => New performance indicators needed for benchmark with currently available technologies (CCHP)

Conclusions

- Perspectives:
  - ✓ Transcritical CO_2 Carnot batteries coupled with LT ice storage and HT sensible storage
  - ✓ Direct coupling of ORC/HP with PCM storage



Integration of a carnot battery in Geothermal power plant [1]

- Economical aspects:
  - ✓ Solar heat driven systems compete with massively-produced PV panels → other assets should be considered
  - ✓ Carnot batteries still need to find their market (vs batteries) and become competitive (increase performance and decrease specific-power cost)

[1] Cendoya et al. CARNOT BATTERY INTEGRATION IN A GEOTHERMAL POWER PLANT: STUDY CASE OF ZORLU ENERJI, 1st Belgian Symposium of Thermodynamics, 16-18 December 2024, Liège, Belgium

Many thanks for your attention!

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