Carnot batteries
From electricity storage to energy hubs

Vincent Lemort and co-workers

Thermodynamics Laboratory of the University of Liège

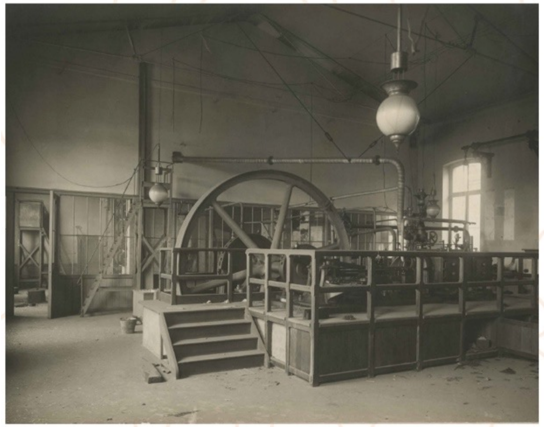
Rankine Memorial Lecture

Glasgow, October 28th 2025

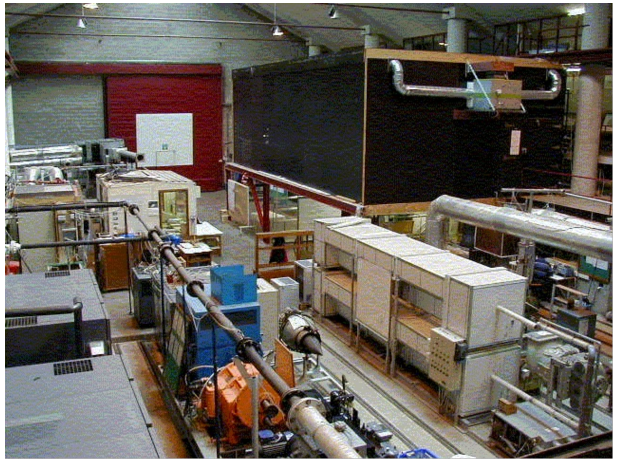
Introduction

Thermodynamics Laboratory of University of Liège

- Established in 1887 for investigating steam engines (with the support of Hirn)
- Aerospace and Mechanical Engineering Department
- Engineering School of University of Liège (est. 1817)
- 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

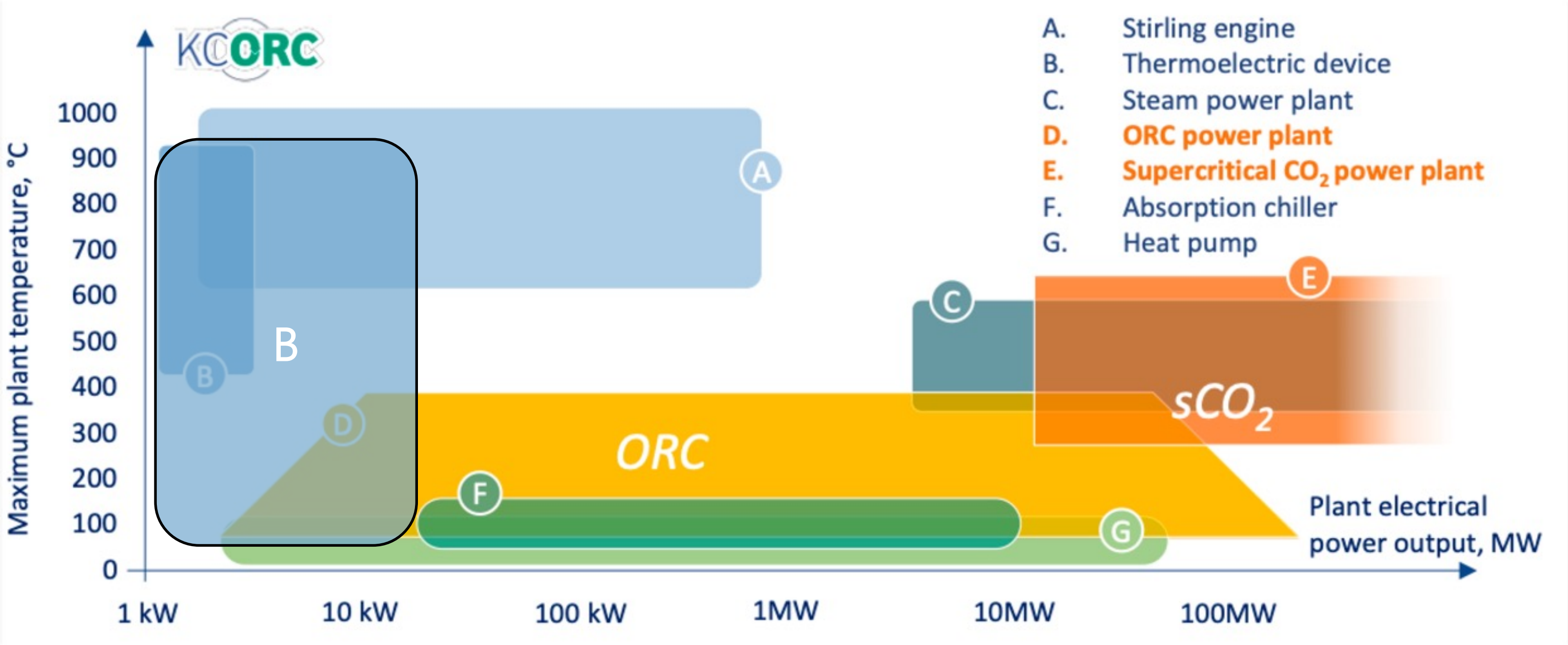
- Massive deployment of REs imposes stabilization constraints on the grid.
  - **Electric heat pumps + thermal storages** can offer services (self-consumption of local RE production; DSM; ancillary services for clusters of HPs),
  - **Distributed electricity storages** can also participate in DSM, ancillary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



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

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

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[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**.

Electricity $= f(t)$ →

(Waste or low-grade) Heat $= \boldsymbol{g(t)}$ →

Heat pumps + ORCs
(Conversions and storage of thermal and electrical energies)

= ENERGY HUB

→ **Electricity** $= \boldsymbol{f^*(t)}$

→ (Upgraded) Heat $= g^*(t)$

→ Cooling $= h^*(t)$

→ Hybridization of ORCs with heat pumps appears promising.

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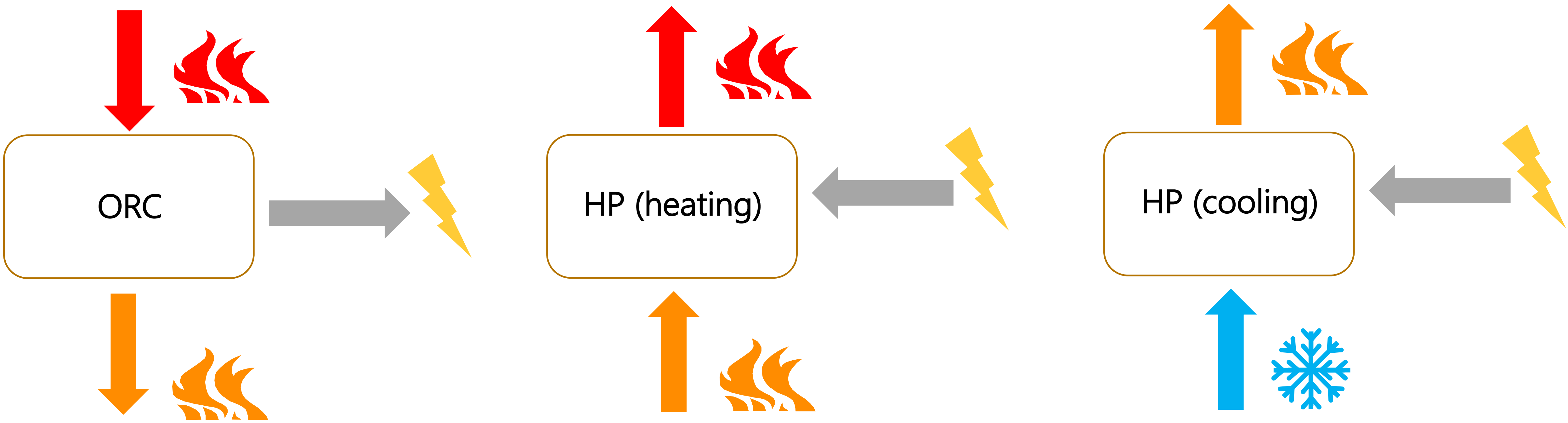
Introduction
Why hybridization?



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

→ Different ways to hybridize them, illustrated in this presentation.

Agenda of the presentation

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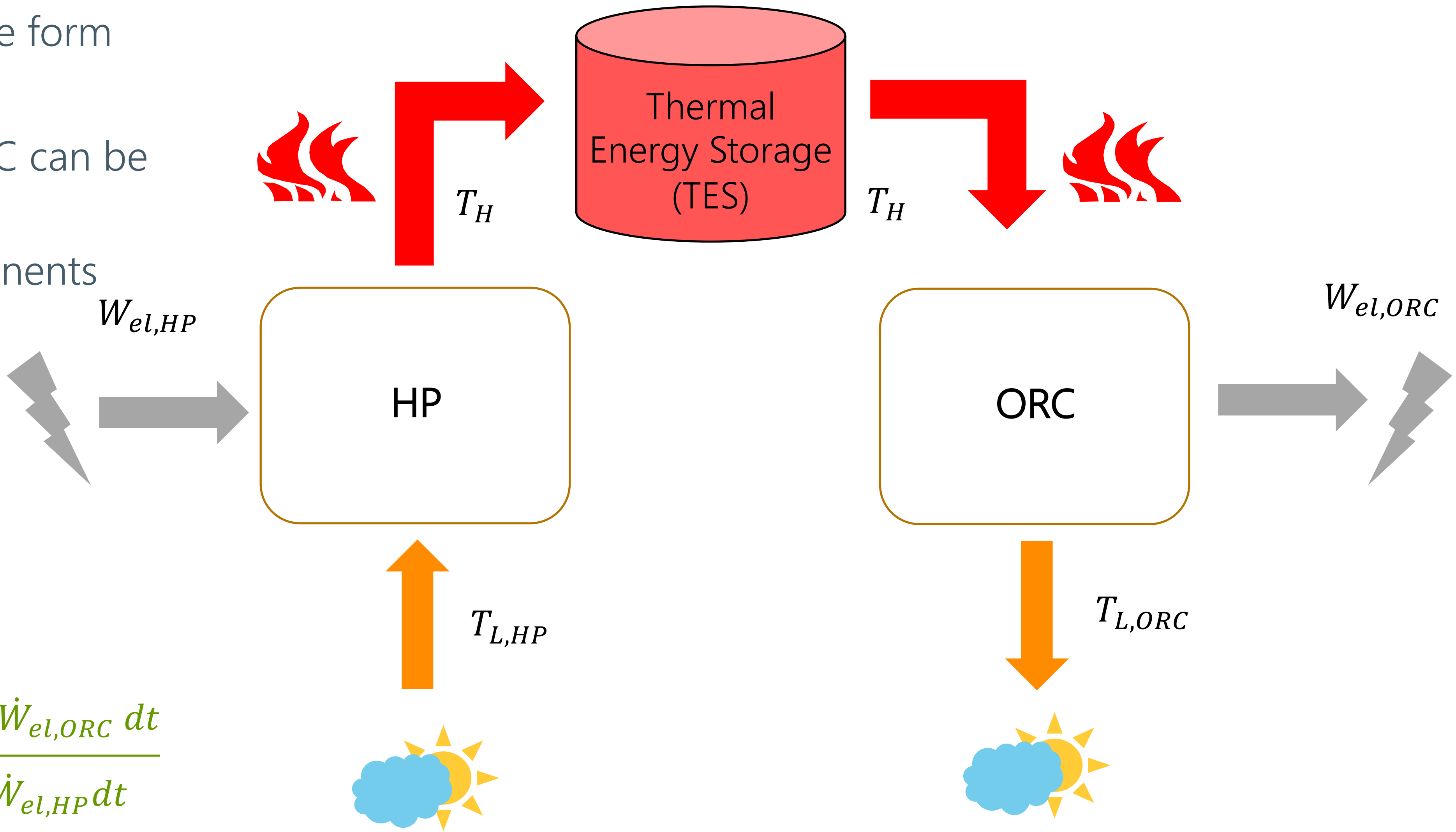
Carnot batteries
Working principle

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



Power-to-power efficiency :

$$\eta_{P2P} = \frac{W_{el,ORC}}{W_{el,HP}} = \frac{\int_{discharge} \dot{W}_{el,ORC}\, dt}{\int_{charge} \dot{W}_{el,HP} dt}$$

Carnot batteries

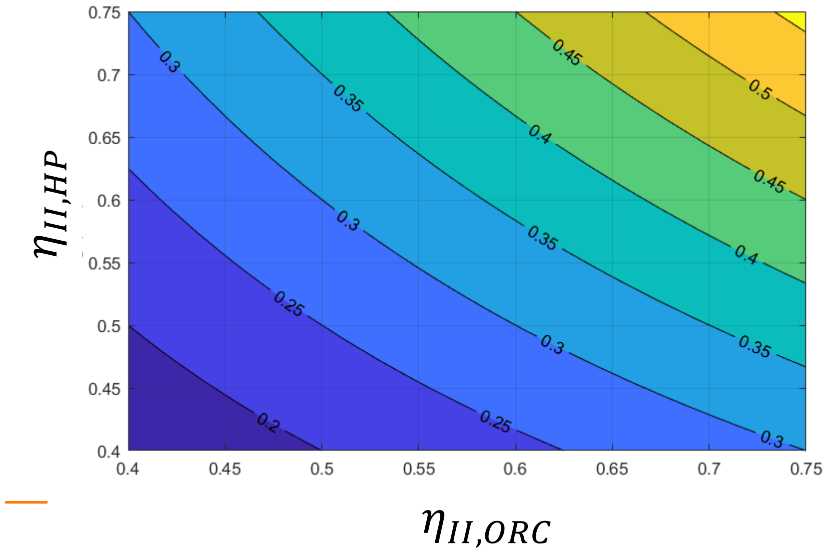
Performance

- 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



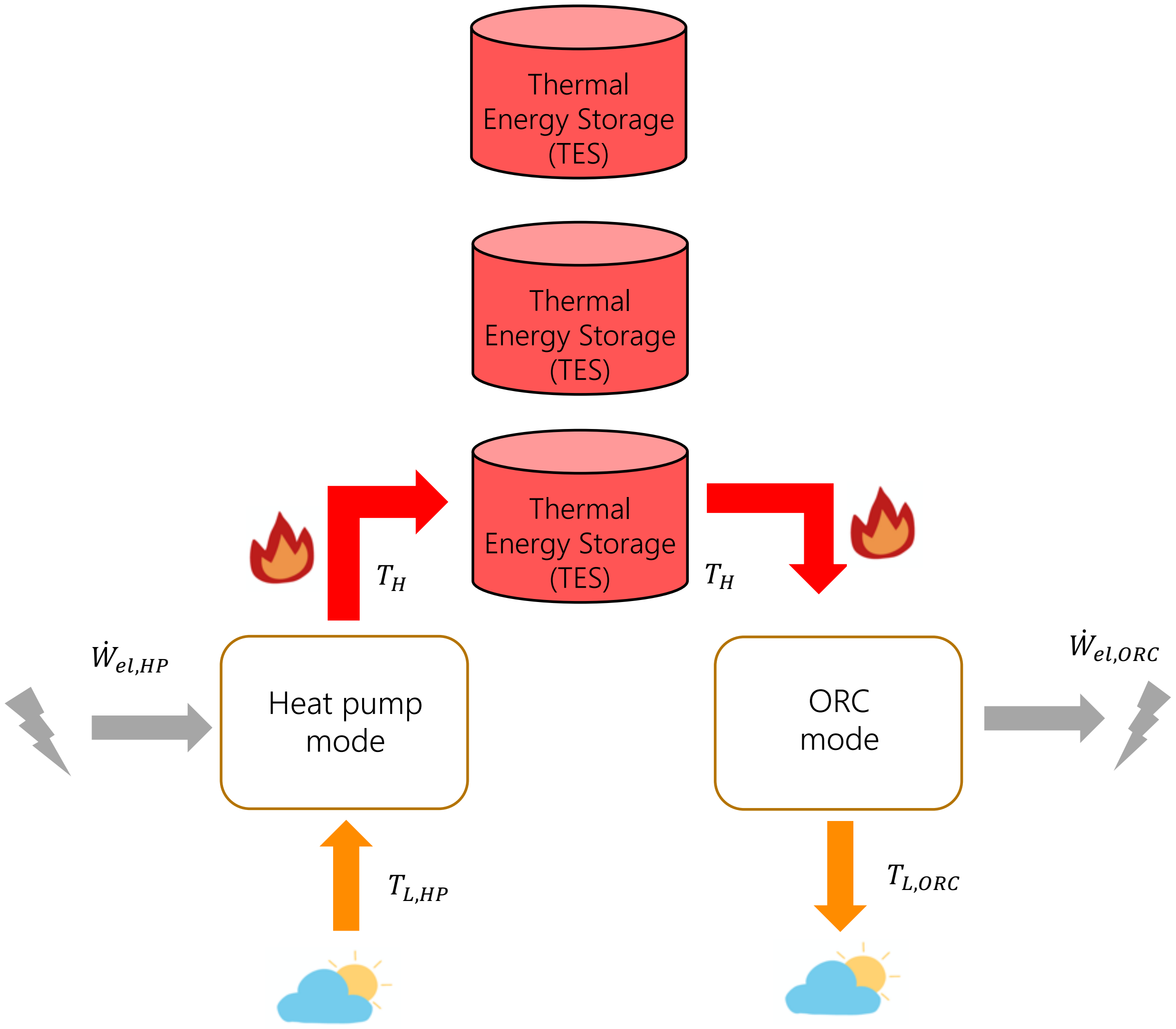
$$\eta_{P2P} = \eta_{II,HP}\ \eta_{II,ORC}\ (< 50\%\ and\ ca.\ 34\%\ *)$$

*Systems operating with volumetric machines with TES at 120°C (Laterre, 2025)

Carnot batteries

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 (~ 1 EUR/kWh)).
- 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

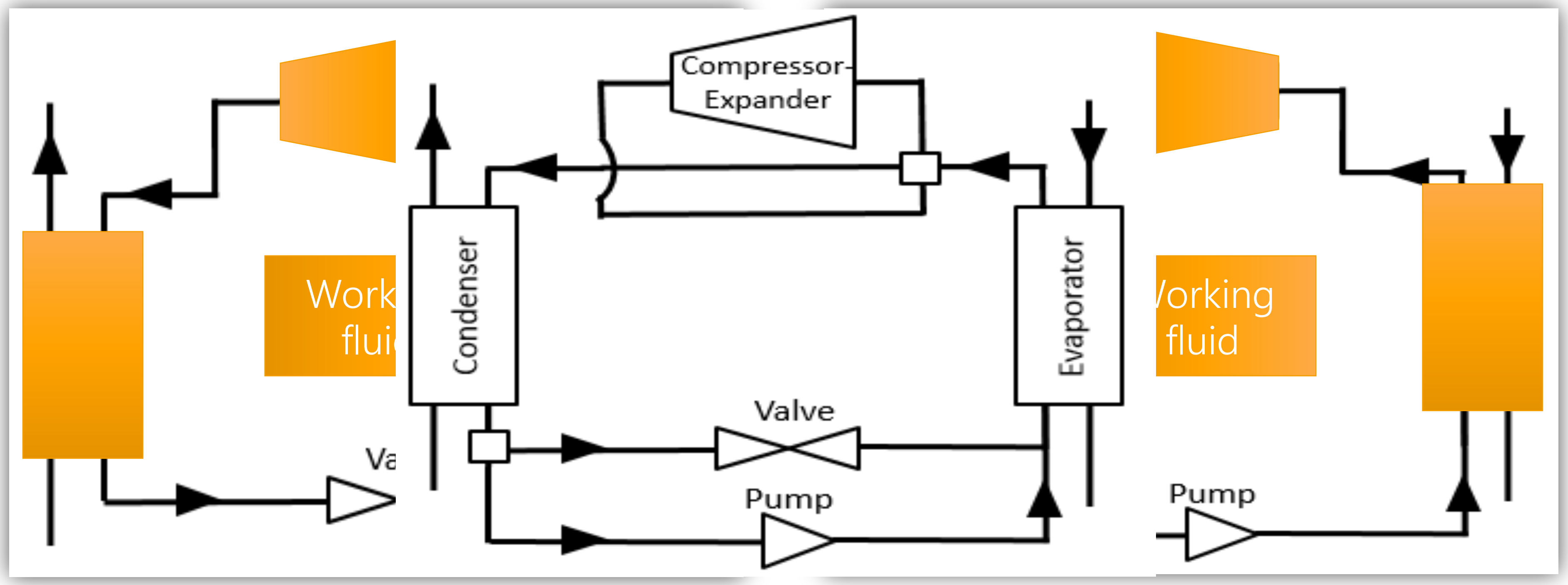
Services to the electricity grid

- 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

Reversible heat pump/ORC

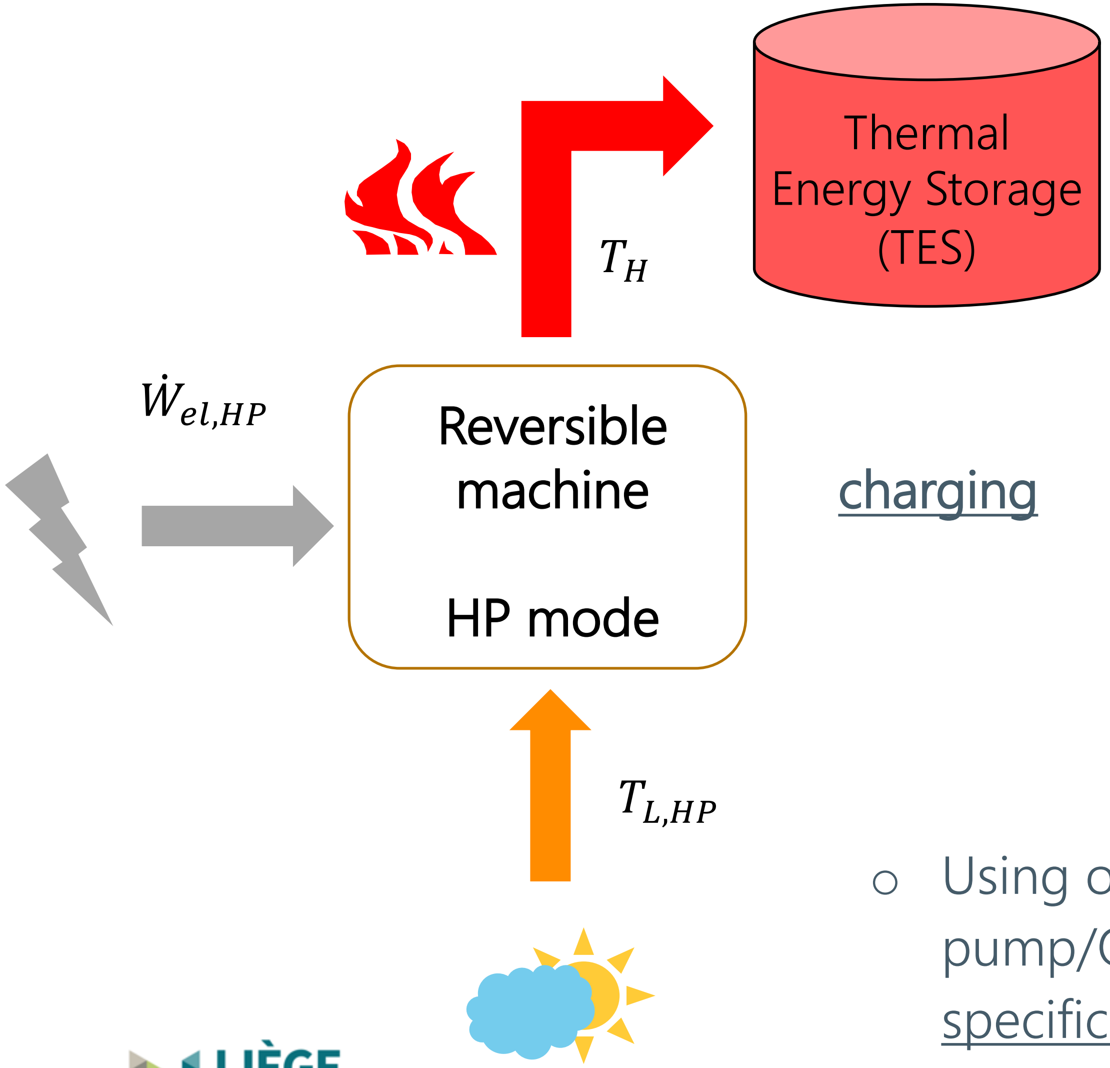
Heat pump (HP) → ORC → Reversible HP/ORC

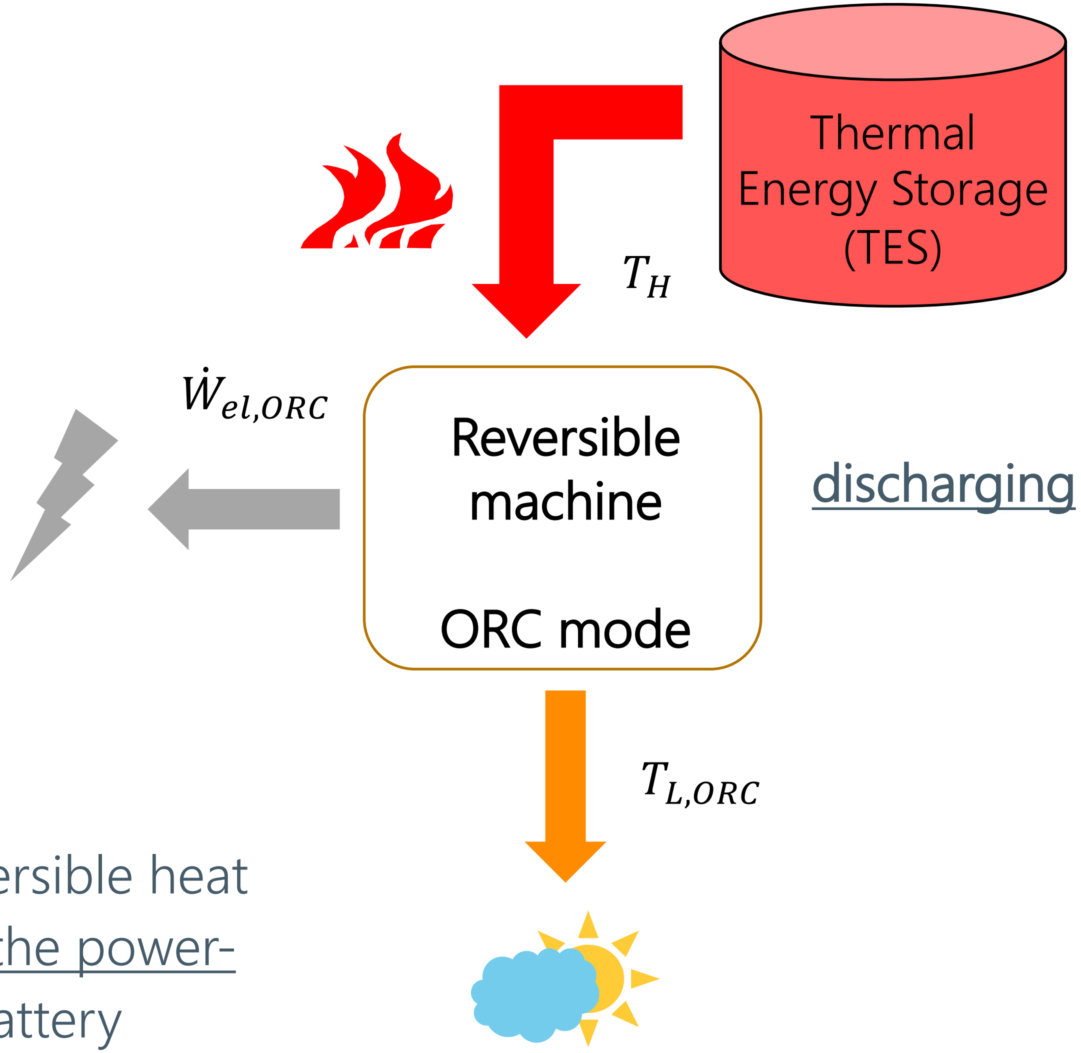


- Merging the ORC and HP (at least the working fluid circuit) into one single machine

Carnot batteries

Reversible heat pump/ORC





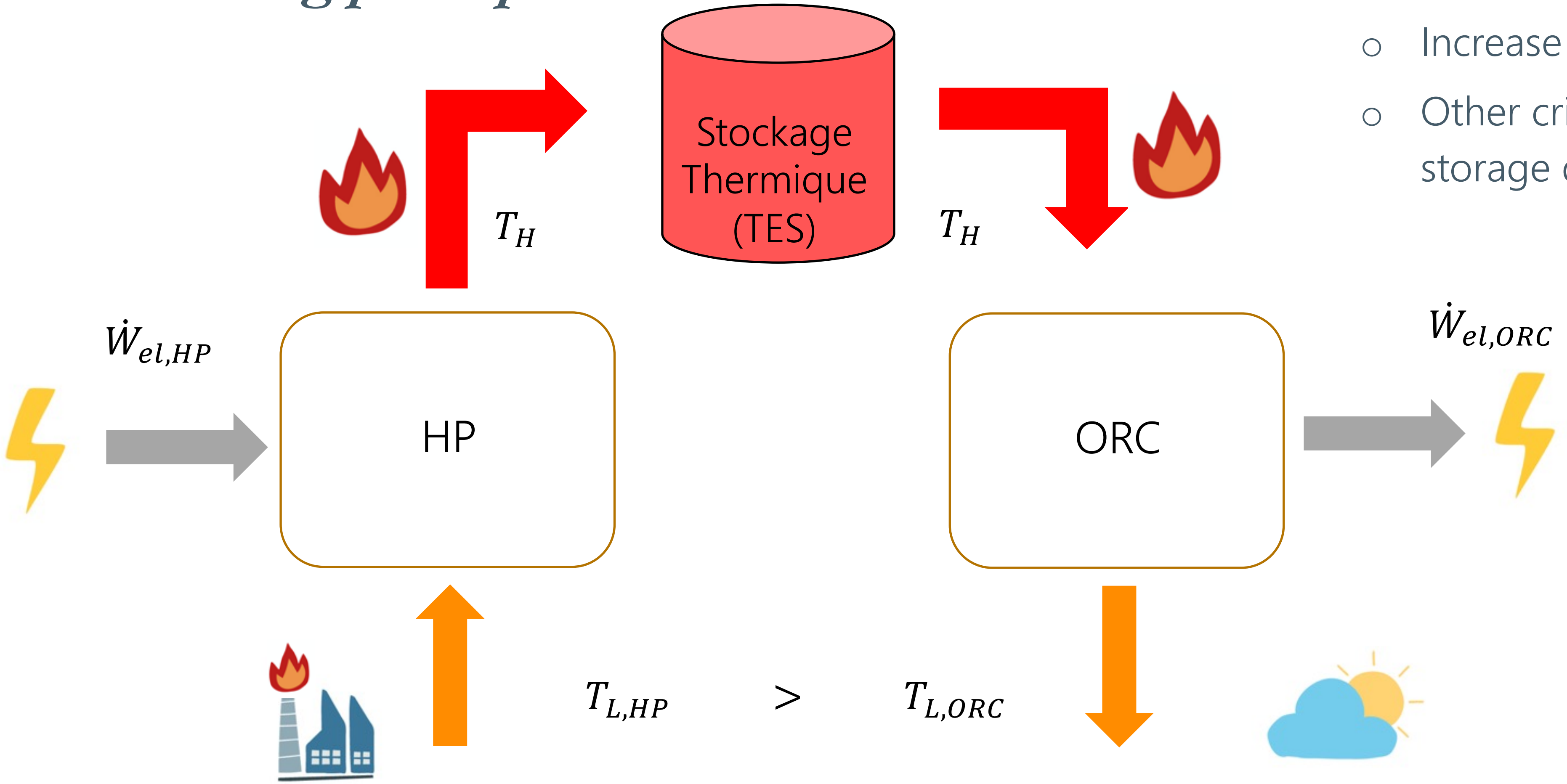
- Using one single reversible heat pump/ORC reduces the power-specific cost of the battery

Agenda of the presentation

1. Introduction
2. Carnot battery for electricity storage
3. **Thermally-integrated Carnot batteries**
   - Boosting the performance of a geothermal power plant
   - Valorization of the heat of a DHN
4. From Carnot batteries to energy hubs
   - Use of flooded mines as underground thermal energy storage
5. Conclusions

Thermally integrated Carnot batteries (TI-CB)

Working principle



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

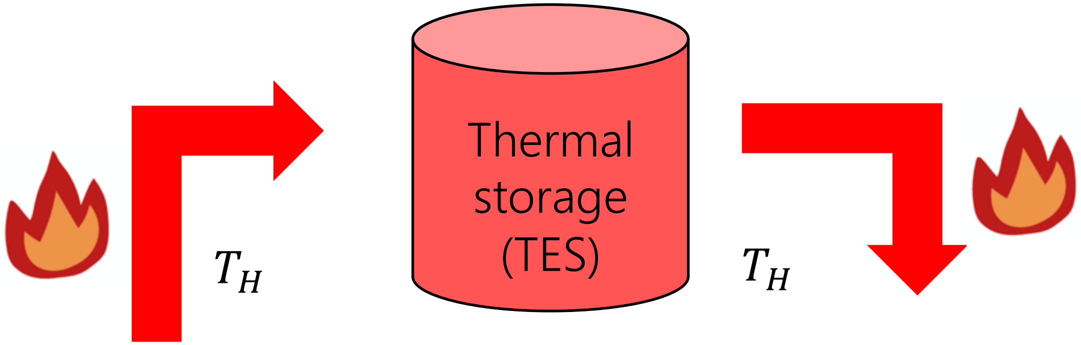
Valorization of waste heat

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

TI-Carnot batteries

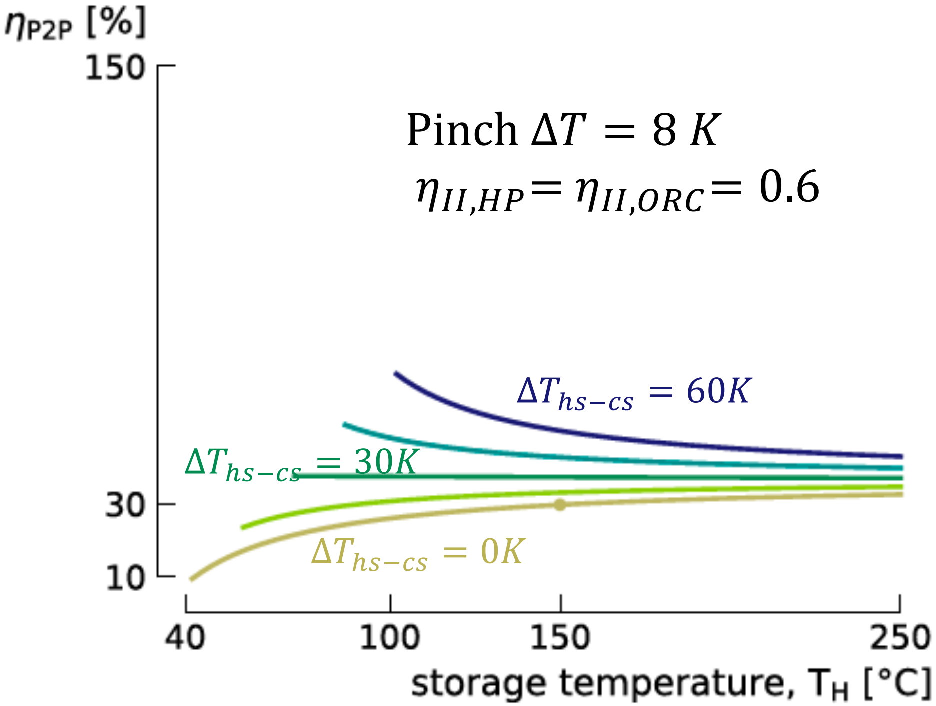
Storage temperature

What is the optimal temperature T_H of the thermal storage?



Introducing both the internal (η_{II}) and external irreversibilities (ΔT [K]) :

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



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

Waste heat *Ambient air*

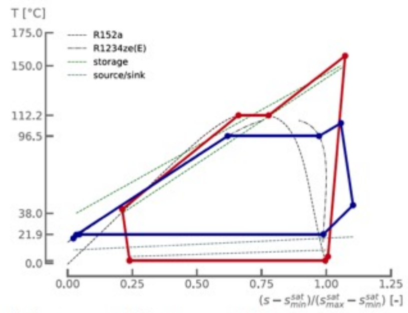
For heat sources with temperatures 30 K higher than ambient temperatures, it is better to decrease the storage temperature

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

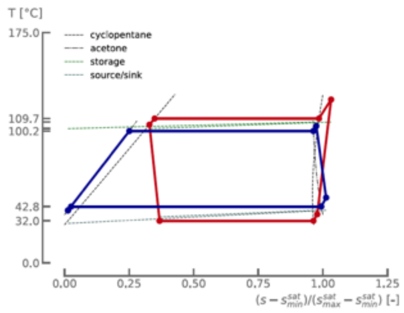
TI-Carnot batteries

Storage temperature

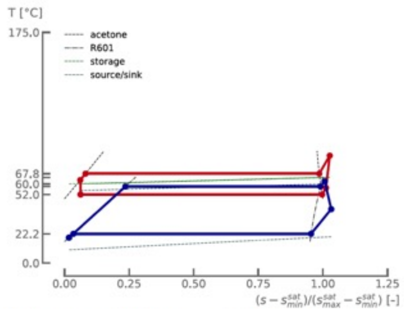
Exemple of optimisation



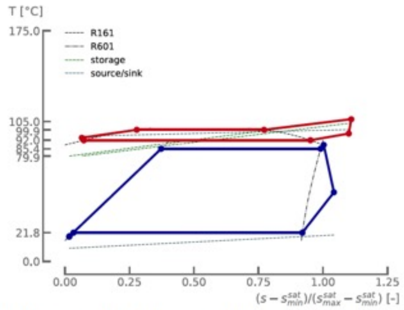
$T_{L,HP} = 10°C \ and \ T_{L,ORC} = 10°C$



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



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



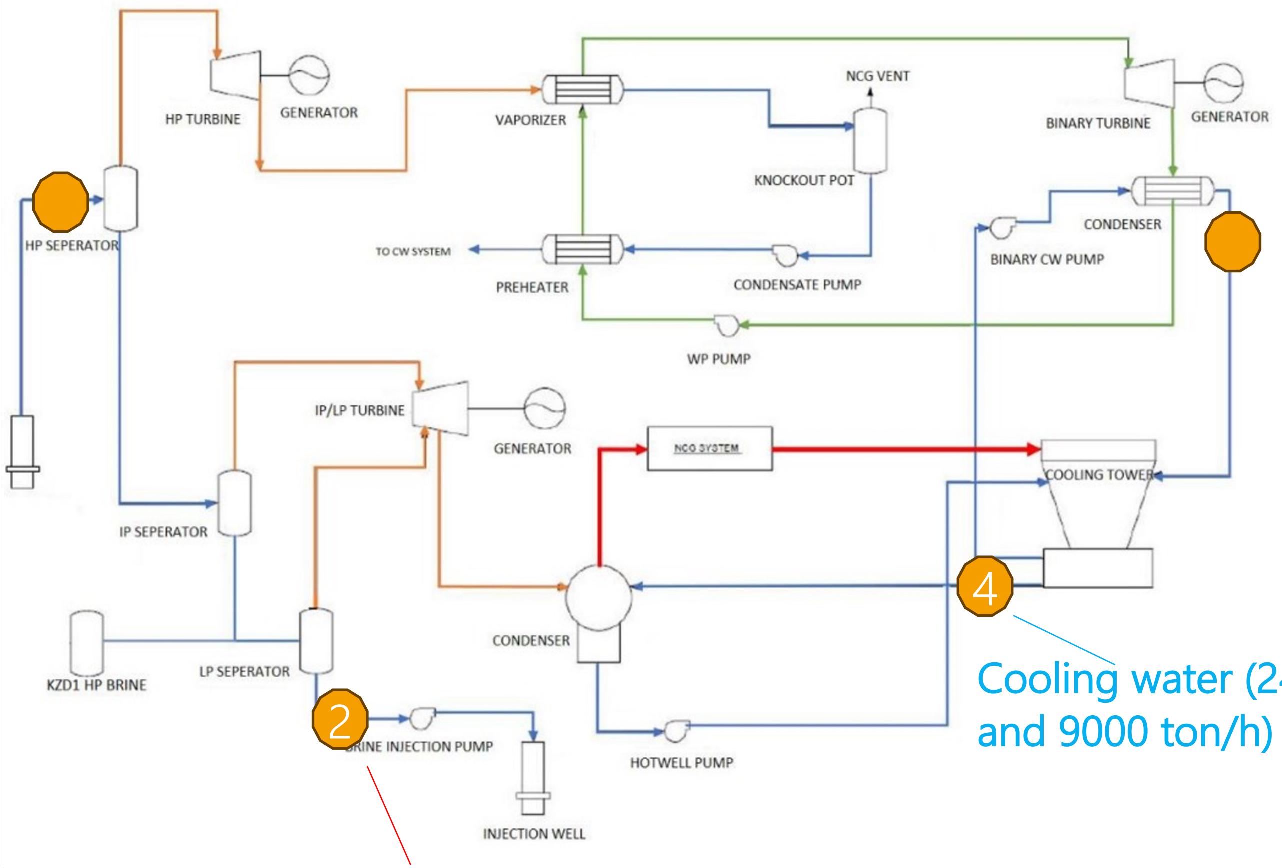
$T_{L,HP} = 100°C \ and \ T_{L,ORC} = 10°C$

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

TI-Carnot batteries

Integration with a geothermal power plant



Cooling water (24.1°C and 9000 ton/h)

Geothermal brine reinjected (113.1°C and 3088.6 ton/h)

- Kizildere II geothermal power plant has an installed capacity of 80 MWe and operates using a triple flash and binary combined cycle technology
- Works as a baseload at 50 MWe
- Should evolve towards baseload+flexible additional power
- Flexible additional power by means of Carnot batteries (TI-CB)

Source: Alfani et al., Integration of an Electro-Thermal Energy Storage (ETES) System in a Geothermal Power Plant, European Geothermal Congress, 2025

TI-Carnot batteries

Integration with a geothermal power plant

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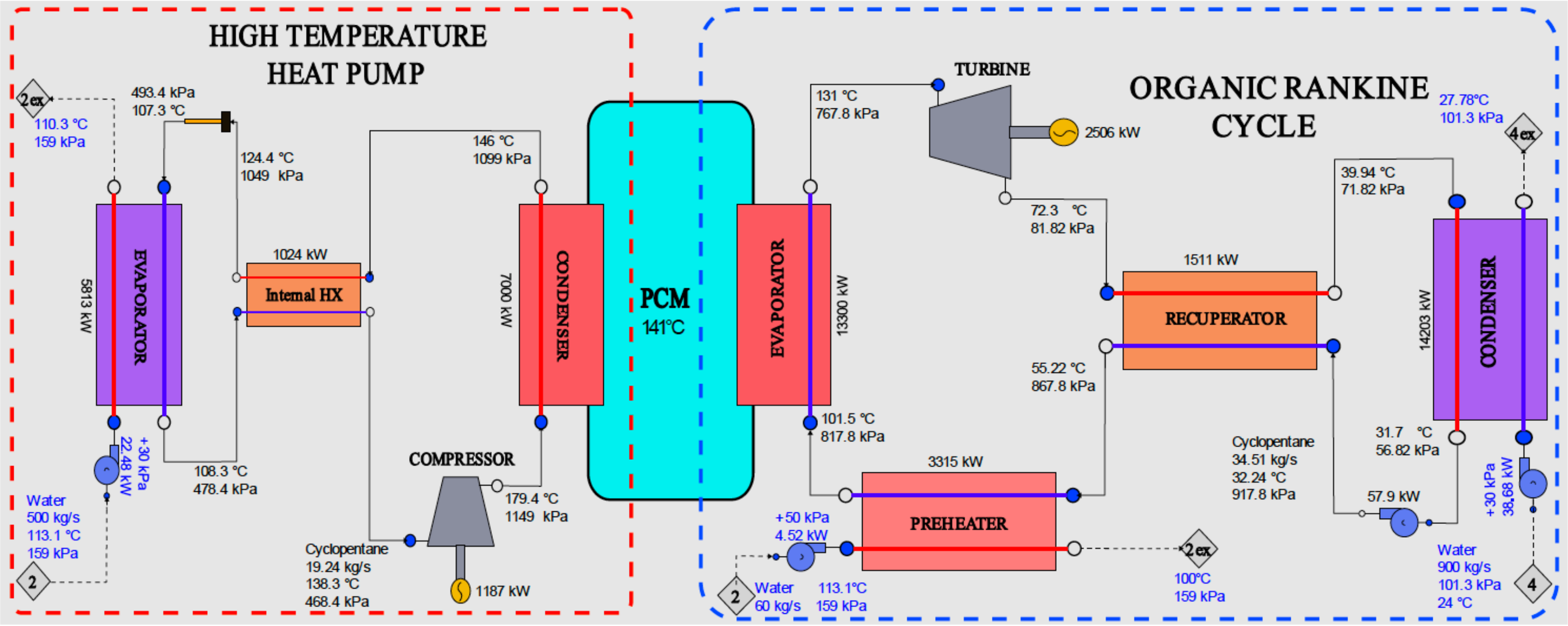

4-hour charging

2-hour discharging

- HP heat source and ORC pre-heat : geothermal brine (point 2)
- ORC heat sink: plant cooling water loop (point 4 oversized)
- **PCM TES with integrated hex**
- $\eta_{P2P} = \dfrac{\int_{2h} \dot{W}_{ORC}\, dt}{\int_{4h} \dot{W}_{HP}\, dt} \approx 90\%$

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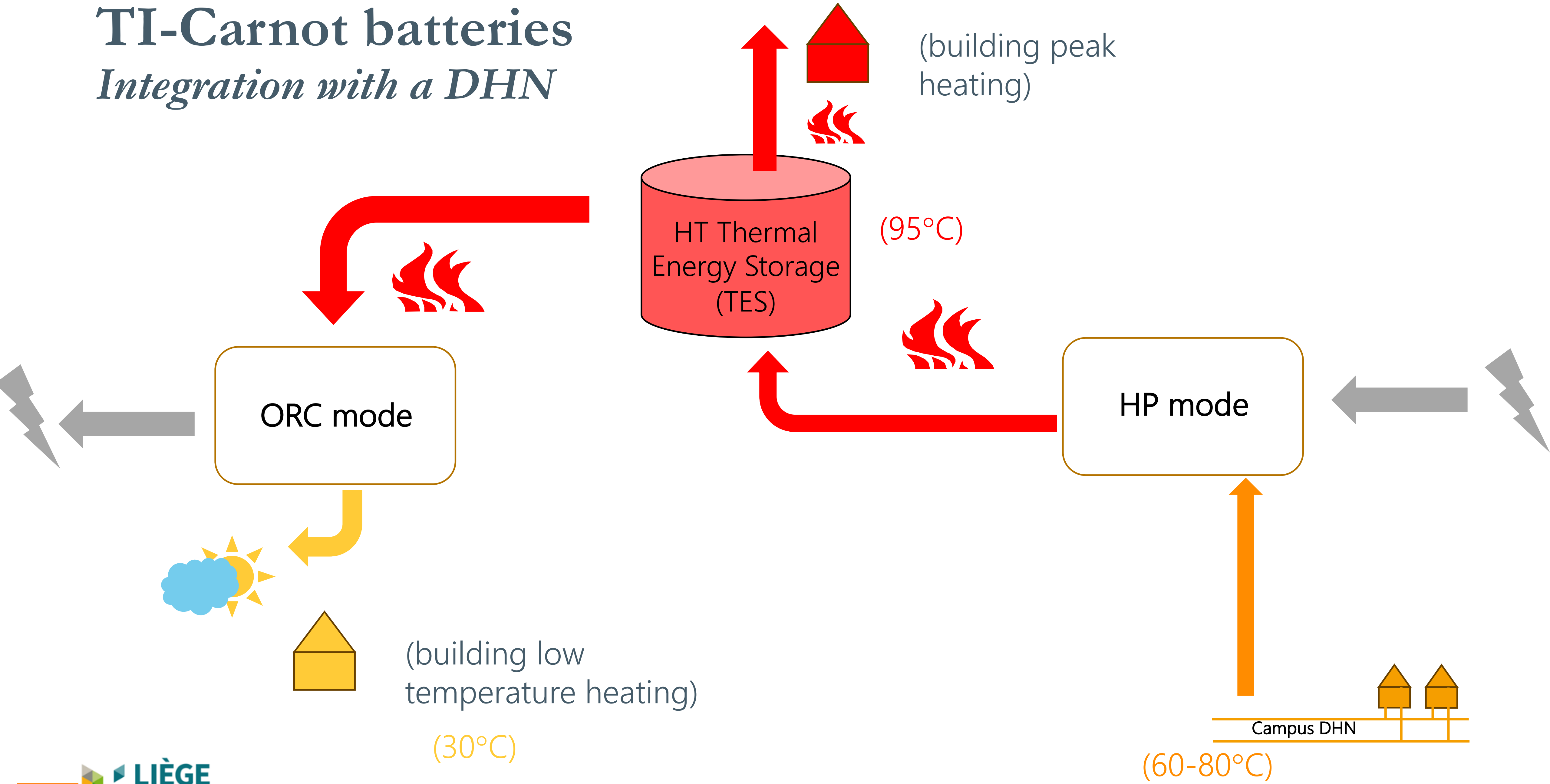
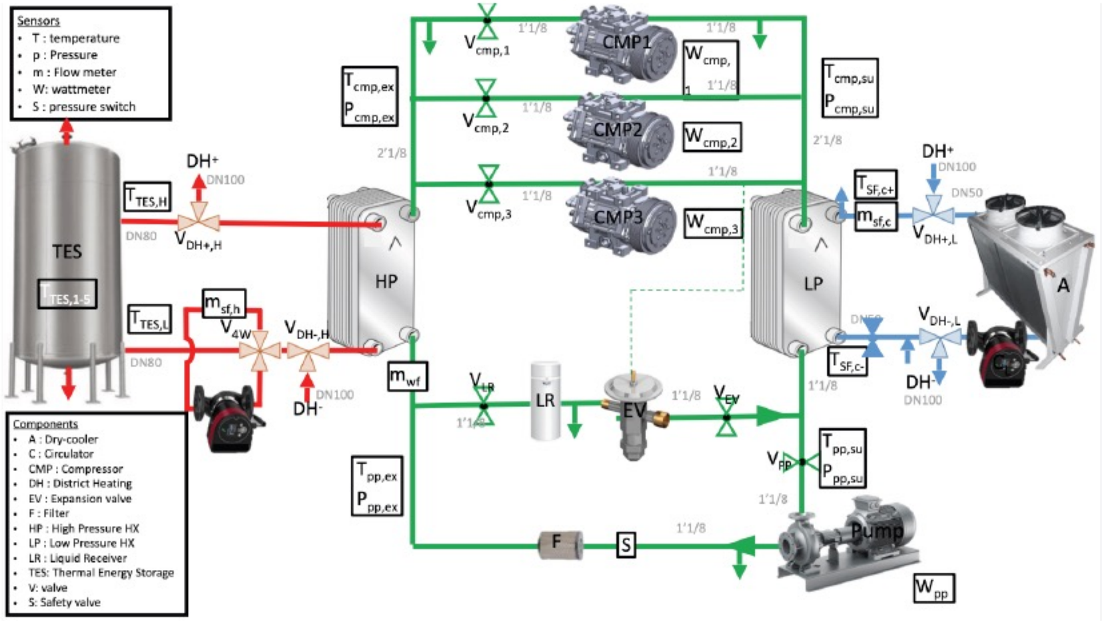
TI-Carnot batteries

Integration with a DHN



TI-Carnot batteries

Integration with a DHN : Prototype #2 (2021-)

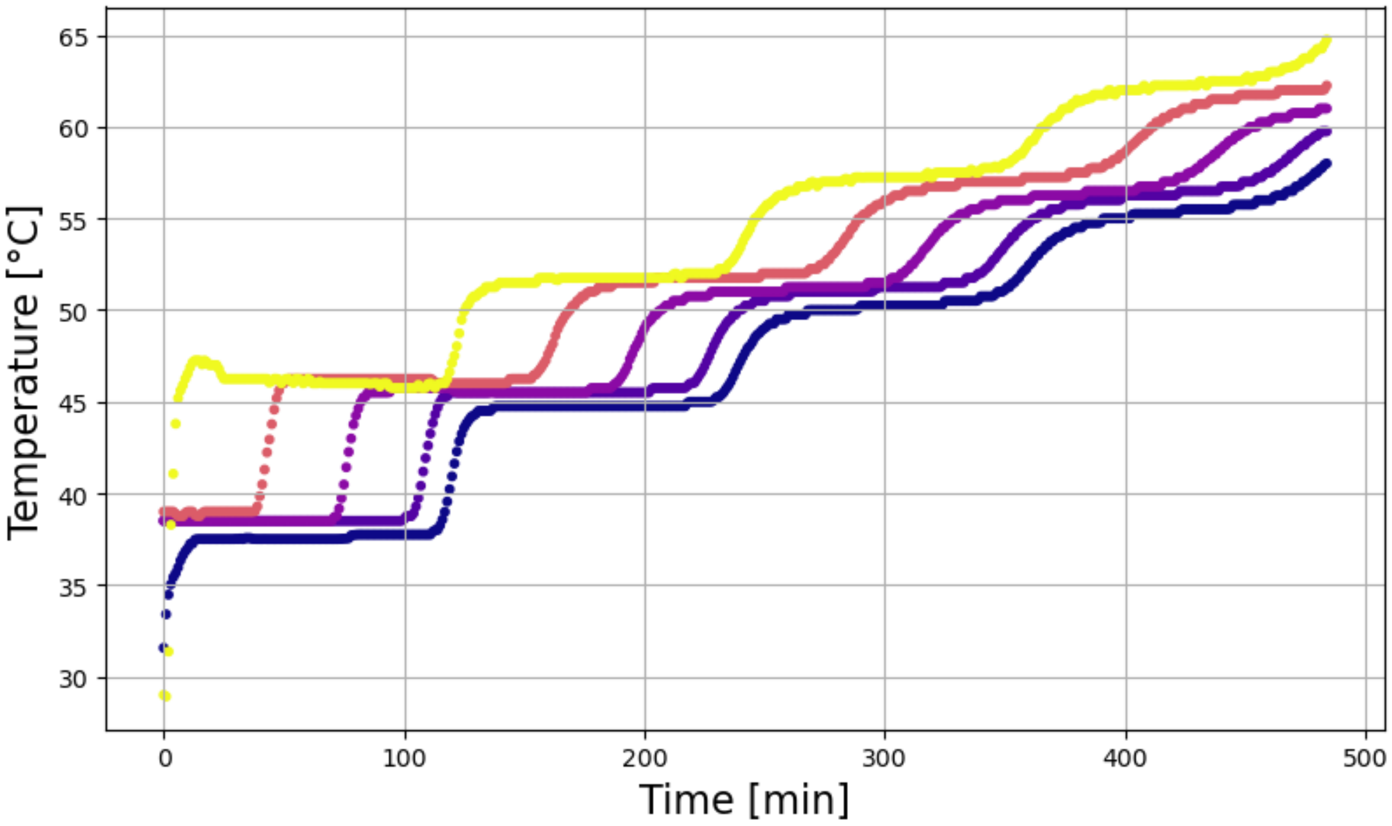


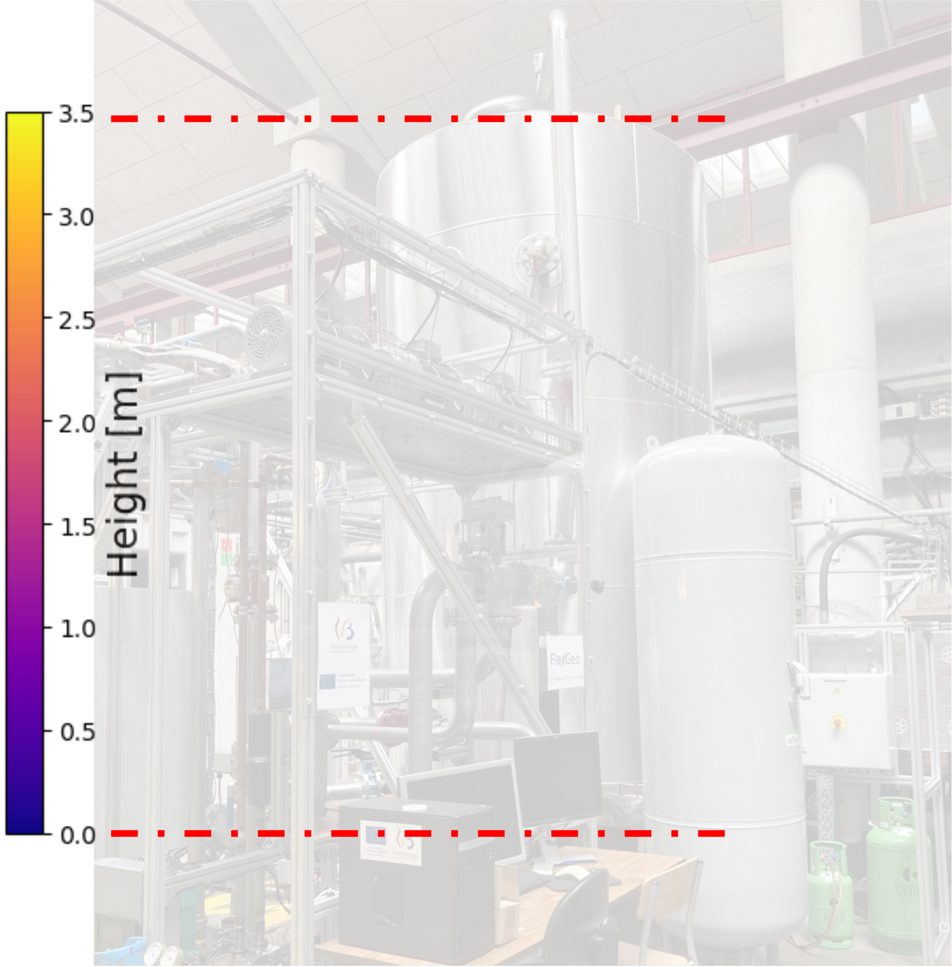
- 8.1 m^3 single water tank (thermocline), 130 kWh$_{th}$
- HP: nominal electrical consumption of 10.7 kW$_e$ and a COP of 7.69
- ORC: nominal electrical production is 5.6 kW$_e$ with the efficiency is 5.5%
- Investigate **machine dynamics** + possibility of **active charge management**

TI-Carnot batteries

Integration with a DHN : Prototype #2 (2021-)

First results on the thermocline storage





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4. **From Carnot batteries to energy hubs**
   - Use of flooded mines as underground thermal energy storage
5. Conclusions

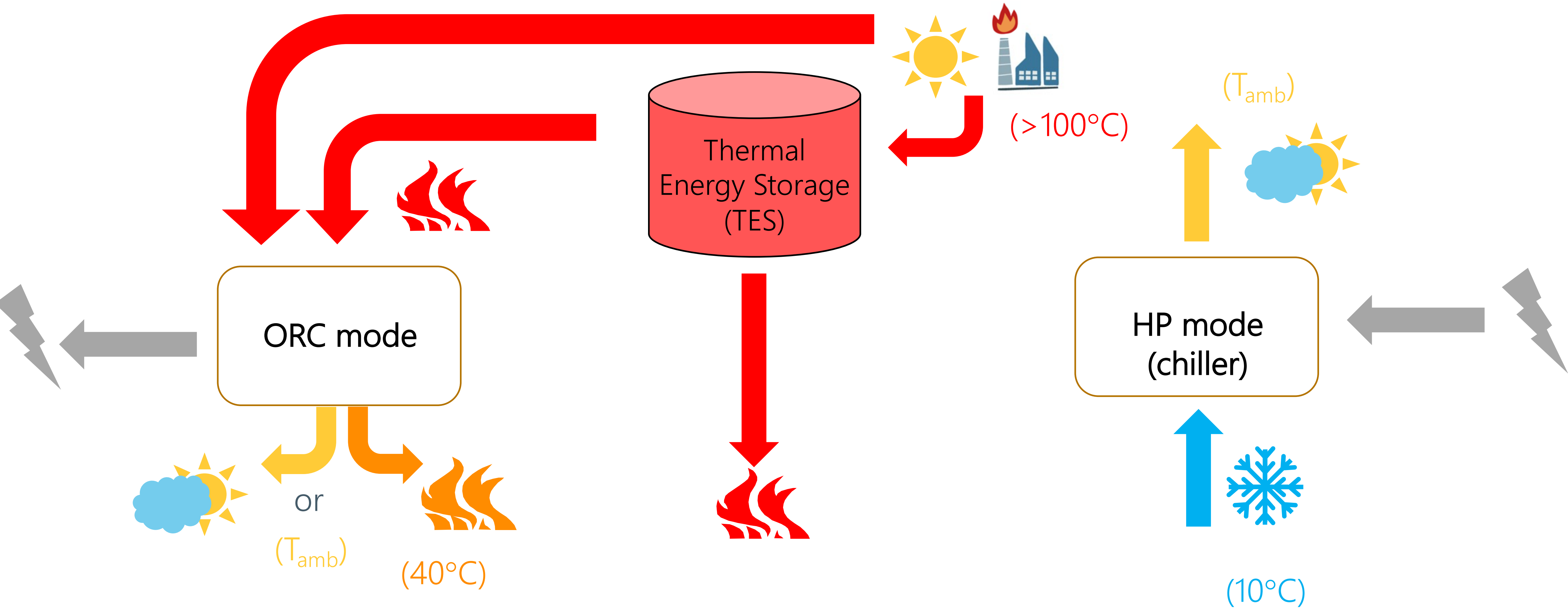
Energy hubs with reversible heat pump/ORC

- Power-to-power efficiency of Carnot batteries is not expected to exceed 40%
- For waste heat temperature over 80°C, maximizing power-to-power efficiency yields a "degenerated" CB.
- Carnot batteries, as other electricity storage, yield a profit if
  - **They prevent curtailment** (better to store whatever efficiency)
  - They increase **self-consumption** (especially if zero feed-in tariff)
  - They can make **energy arbitrage** (dynamic retail tariff)

- Carnot batteries can compete with other electricity storage techniques if
  - The power-specific cost of the machine can be reduced (**increase reversible feature**)
  - **Massive and cheap thermal energy storage** are used (CB can show low energy-specific cost)
  - Carnot battery can offer **other services** than electricity storage: heat or cold production
  - They limit the environmental impact (natural fluids)

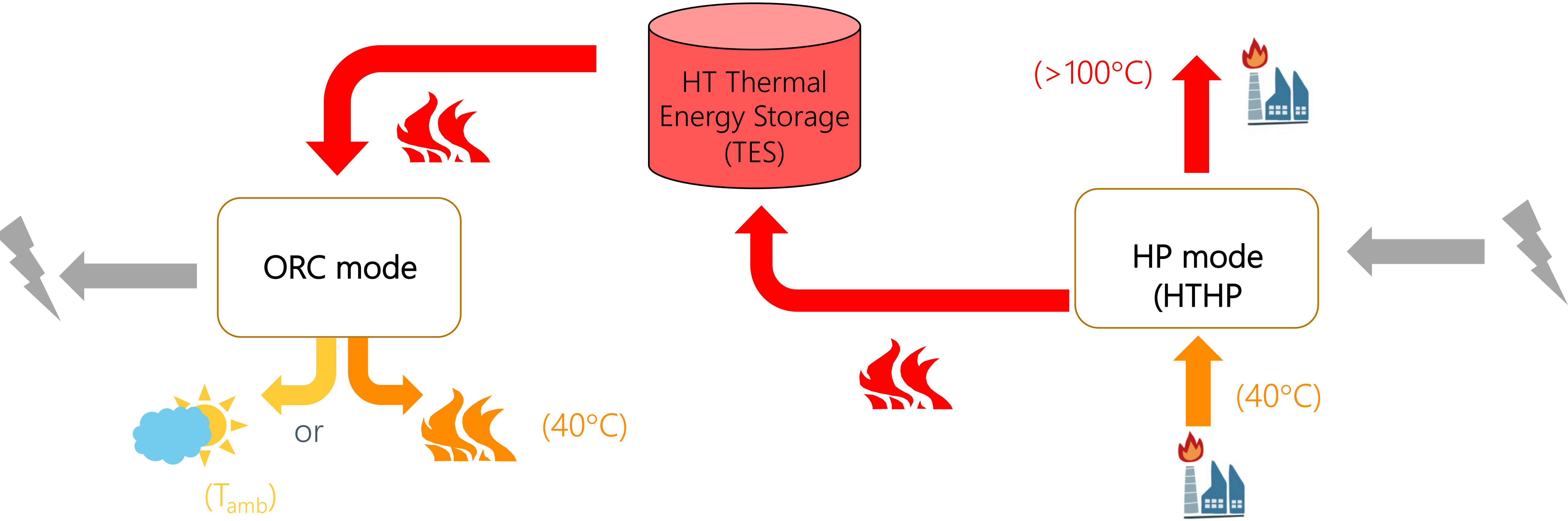
Energy hubs with reversible heat pump/ORC

Cooling and direct electricity production



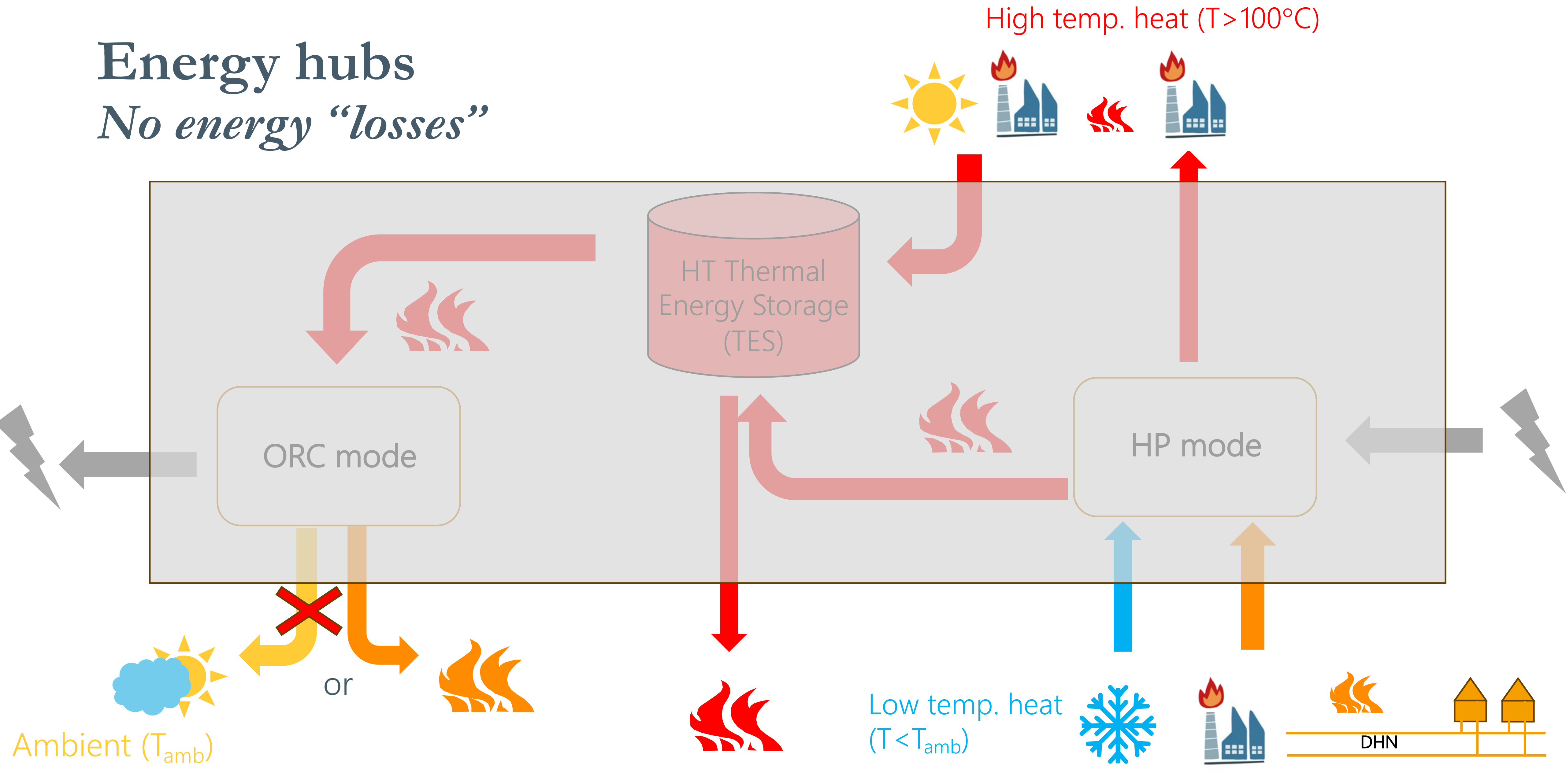
Energy hubs with reversible heat pump/ORC

Industrial HT heat production



Energy hubs

No energy "losses"



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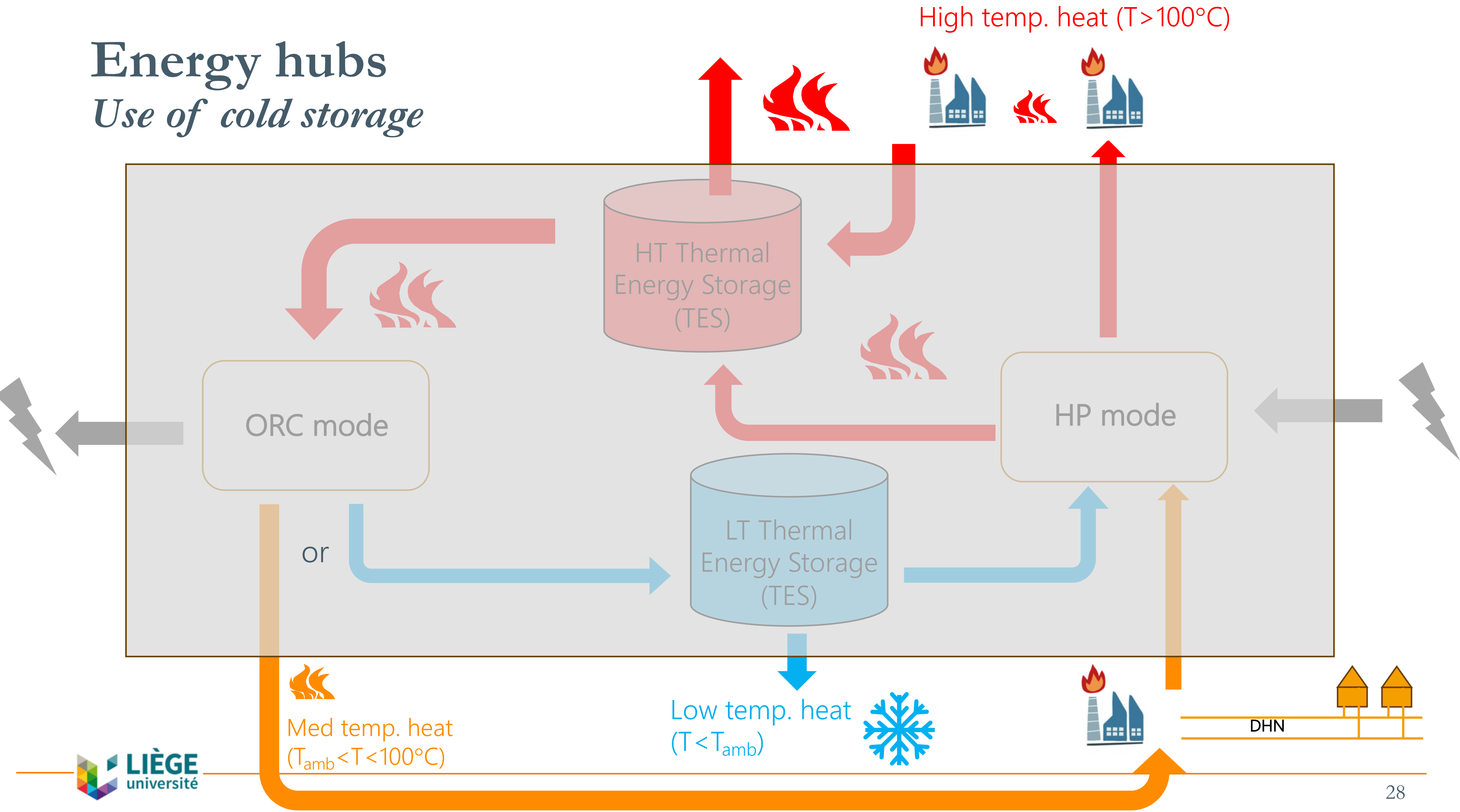
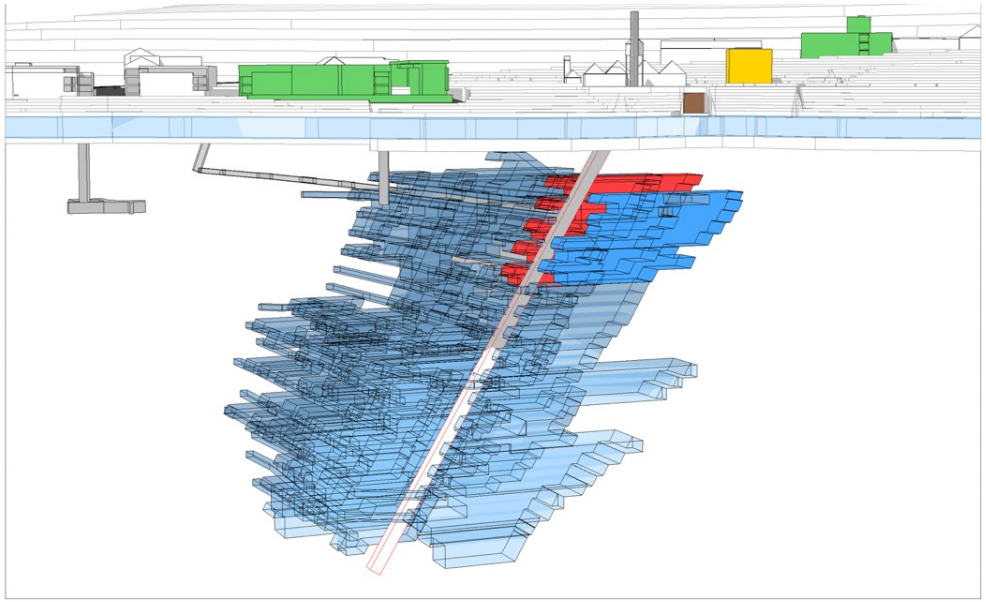
Energy hubs

Use of cold storage



Energy hubs
Flooded mines as UTES

- 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)

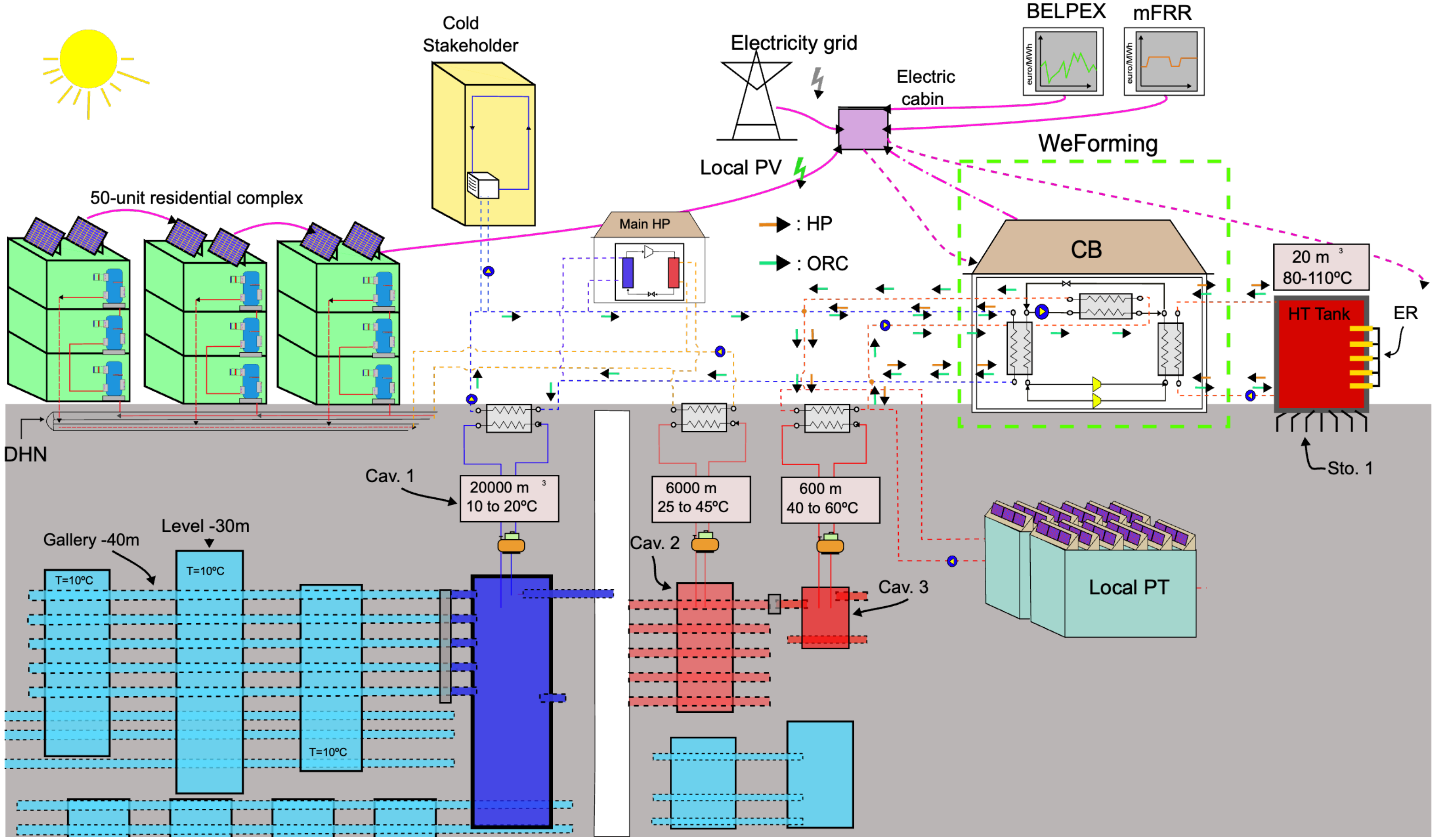
Energy hubs

Flooded mines as UTES: architecture of the energy system

TI-Carnot battery

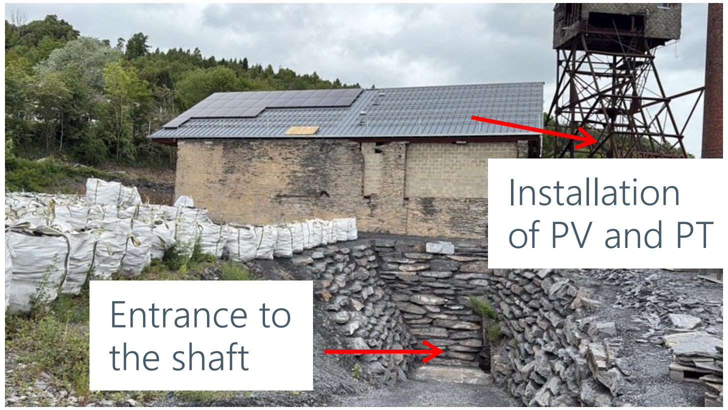
C/H demands

- 20 m^3 overground tank at 80-110°C (difficulty to find a submersible pump).
- 600 m^3 underground chamber at 40-60°C : PVT or **industrial waste heat** (40-60°C).
- 20000 m^3 underground chamber at 10-20°C : produced by main heat pump; natural generation.
- 6000 m^3 underground chamber at 25-45°C : produced by main heat pump.



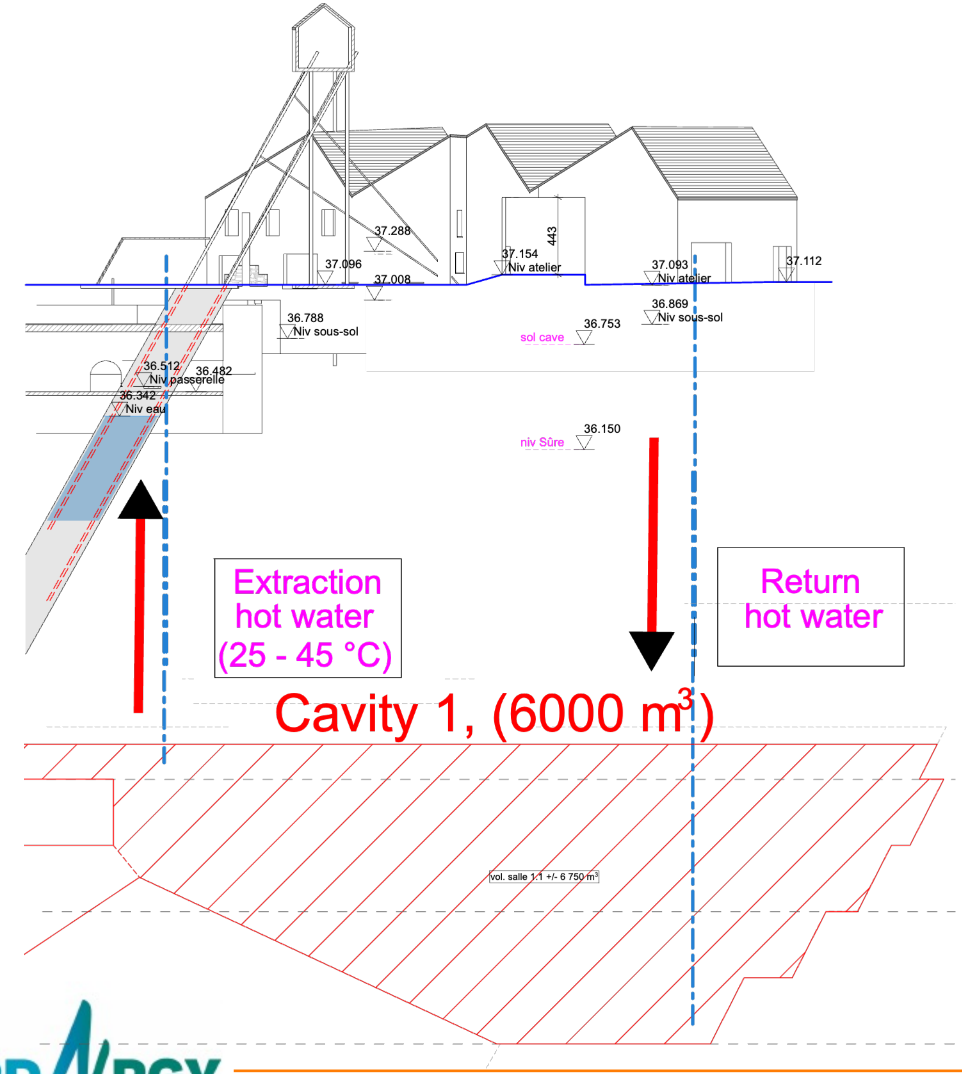
Energy hubs

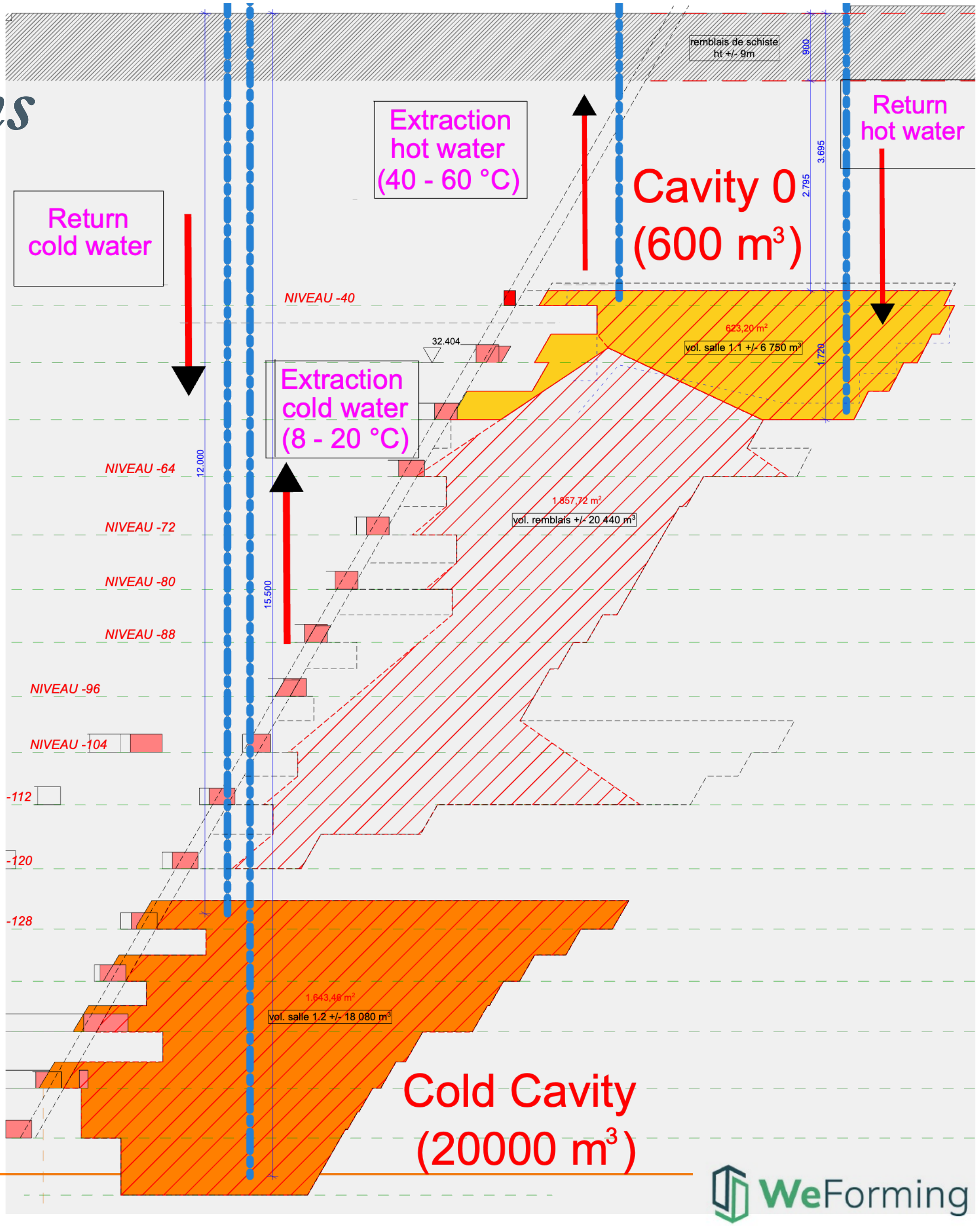
UTES: overground constructions



Energy hubs

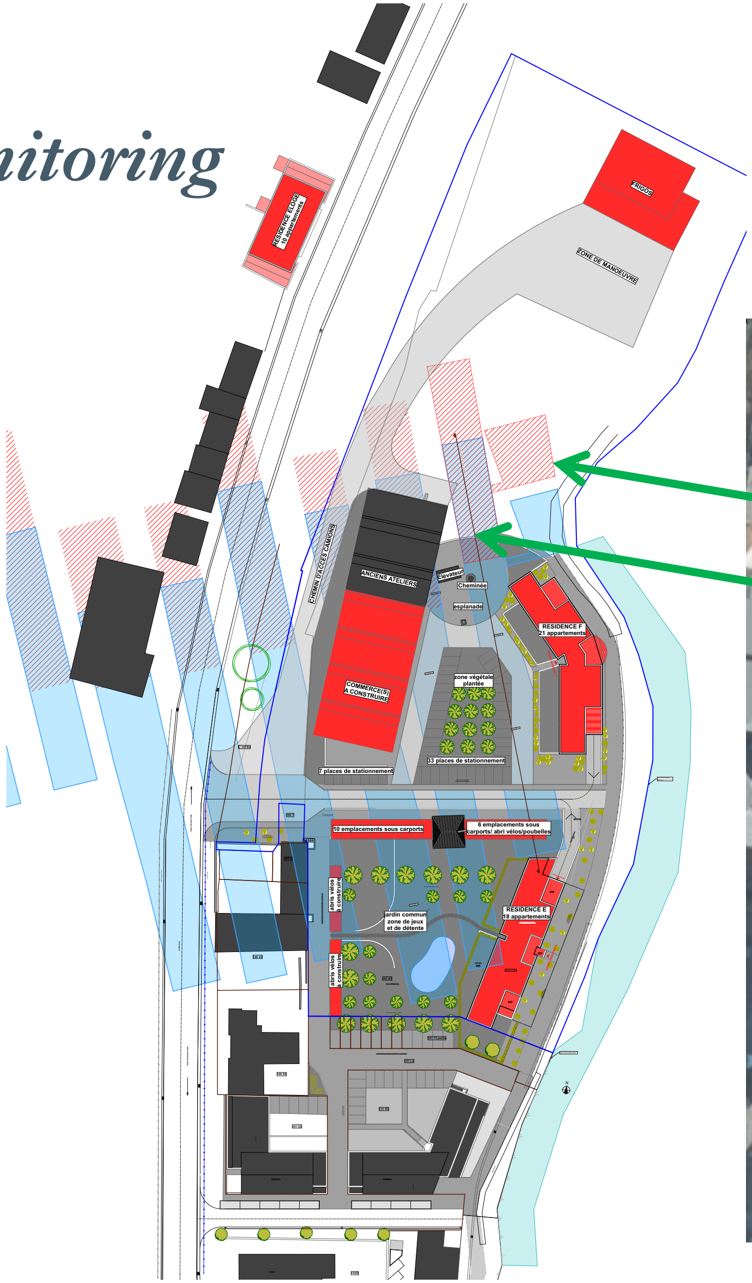
UTES: underground constructions

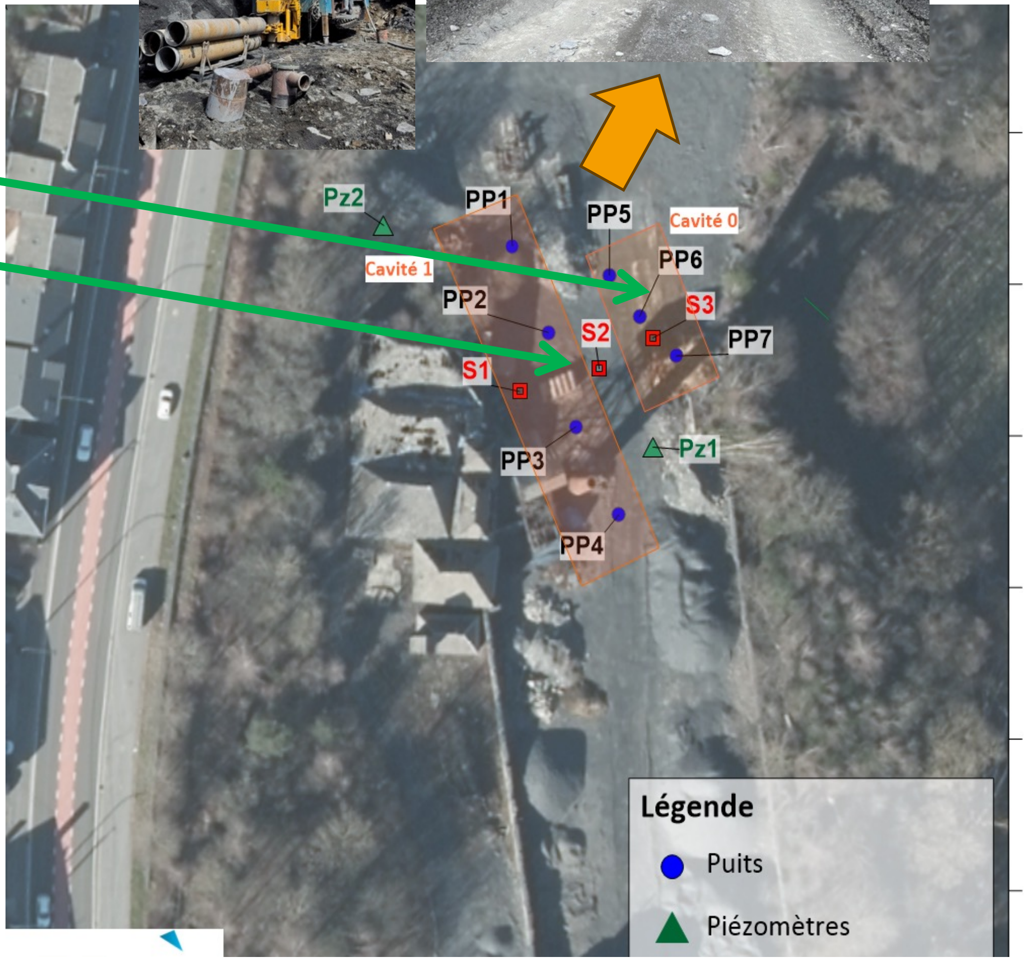




Energy hubs

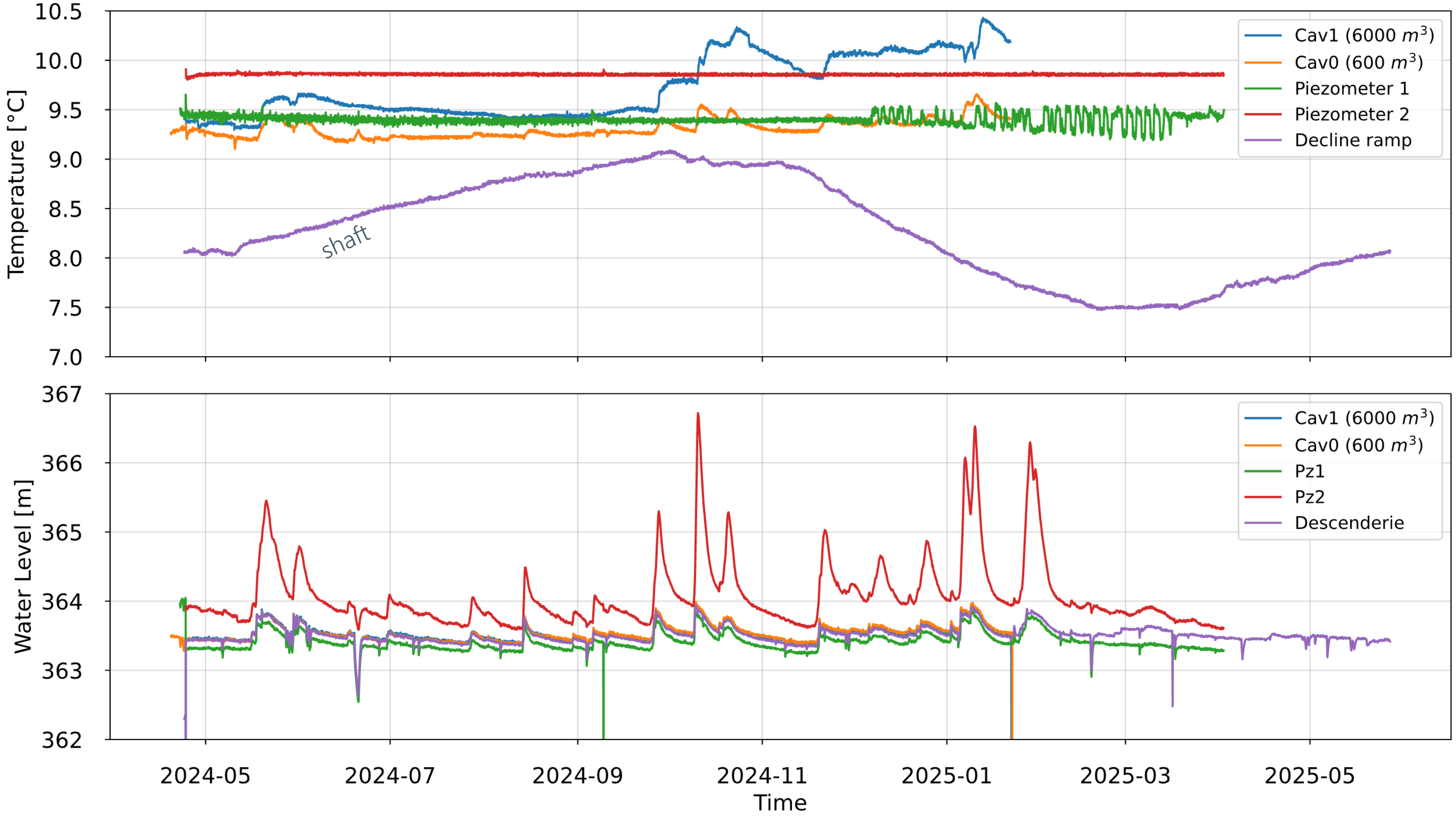
Underground monitoring





Energy hubs
Underground monitoring

- 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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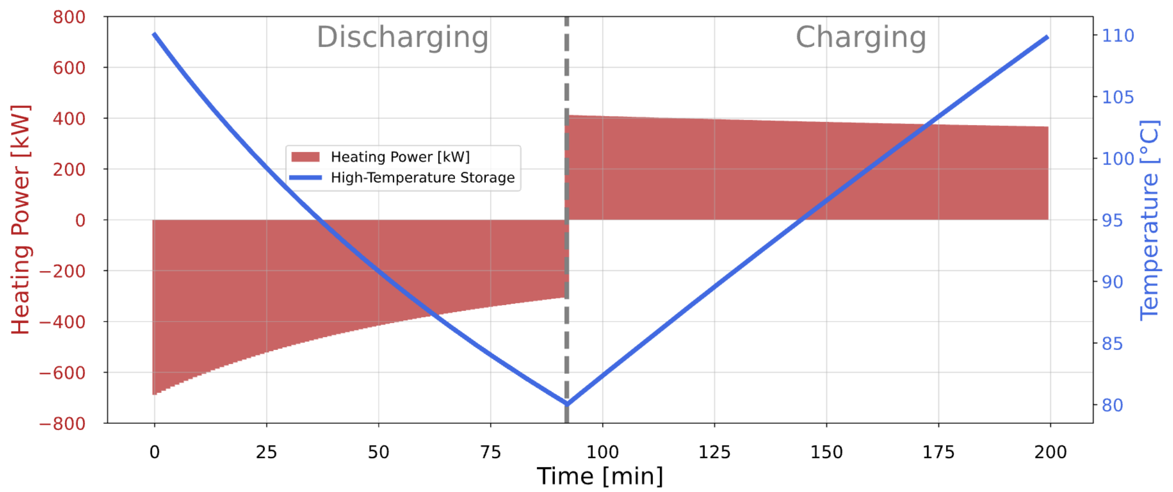
Energy hubs

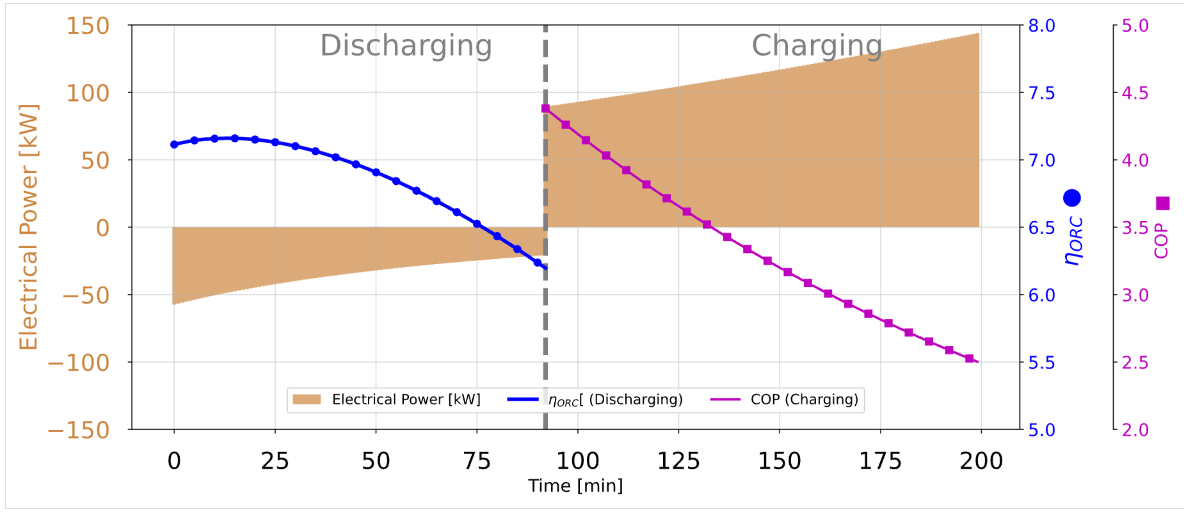
Simulation of charging/discharging

- overground 20 m³ hot storage:
  - SOC=100% at 110°C
  - SOC=0% at 80°C
- No modeling of the stratification (fully mixed)
- ORC efficiency: 7.12% to 6.20%
- Heat pump COP: 4.38 to 2.50
- $\eta_{P2P} = \frac{\int_{\tau_{ini}}^{\tau_{dis}} E_{net,ORC}\, d\tau}{\int_{\tau_{dis}}^{\tau_{char}} E_{net,HP}\, d\tau} = 22.64\%.$
- Includes the consumption of **auxiliaries**
- Could be increased by integrating larger-grade waste heat or decreasing the storage temperature (CB "degenerates", large volumes for storing the same electricity, consider LCOS)

93 minutes

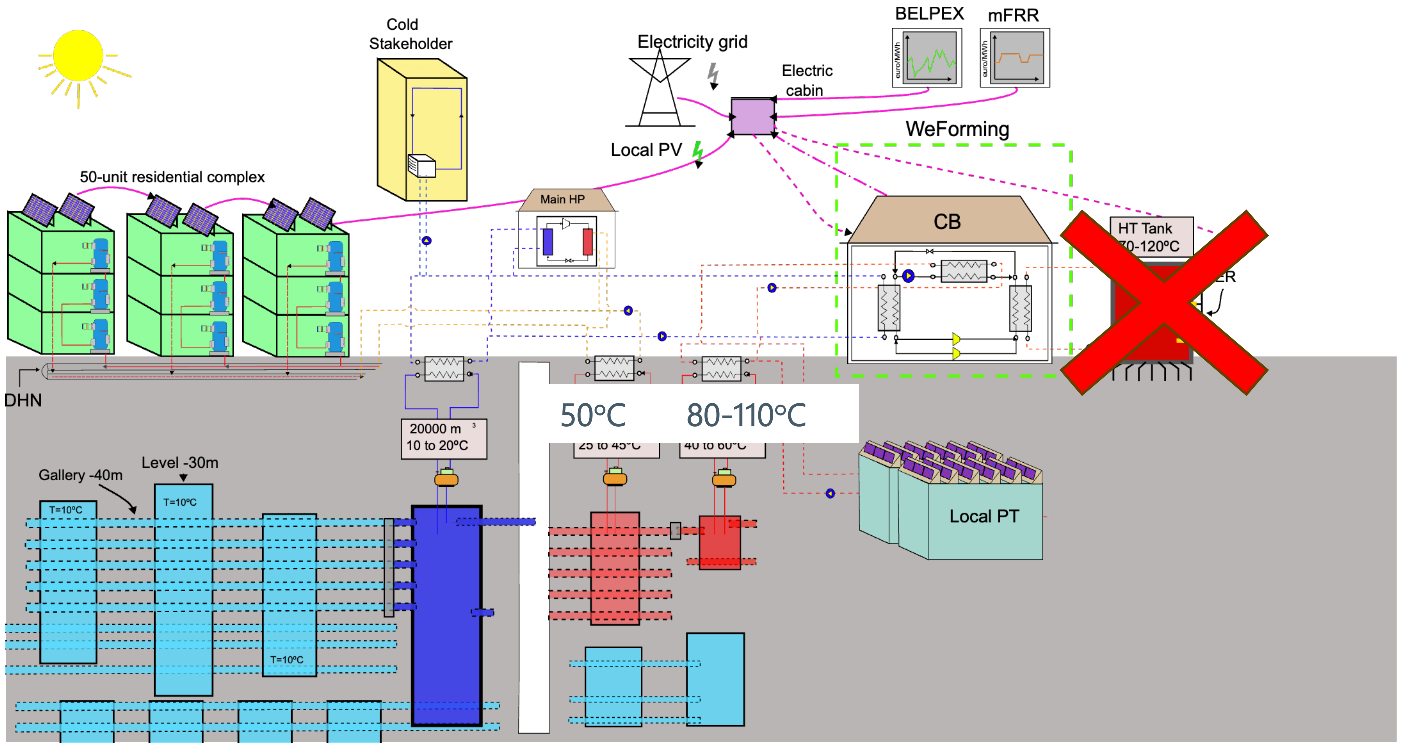
108 minutes





Energy hubs
Simulation of performance

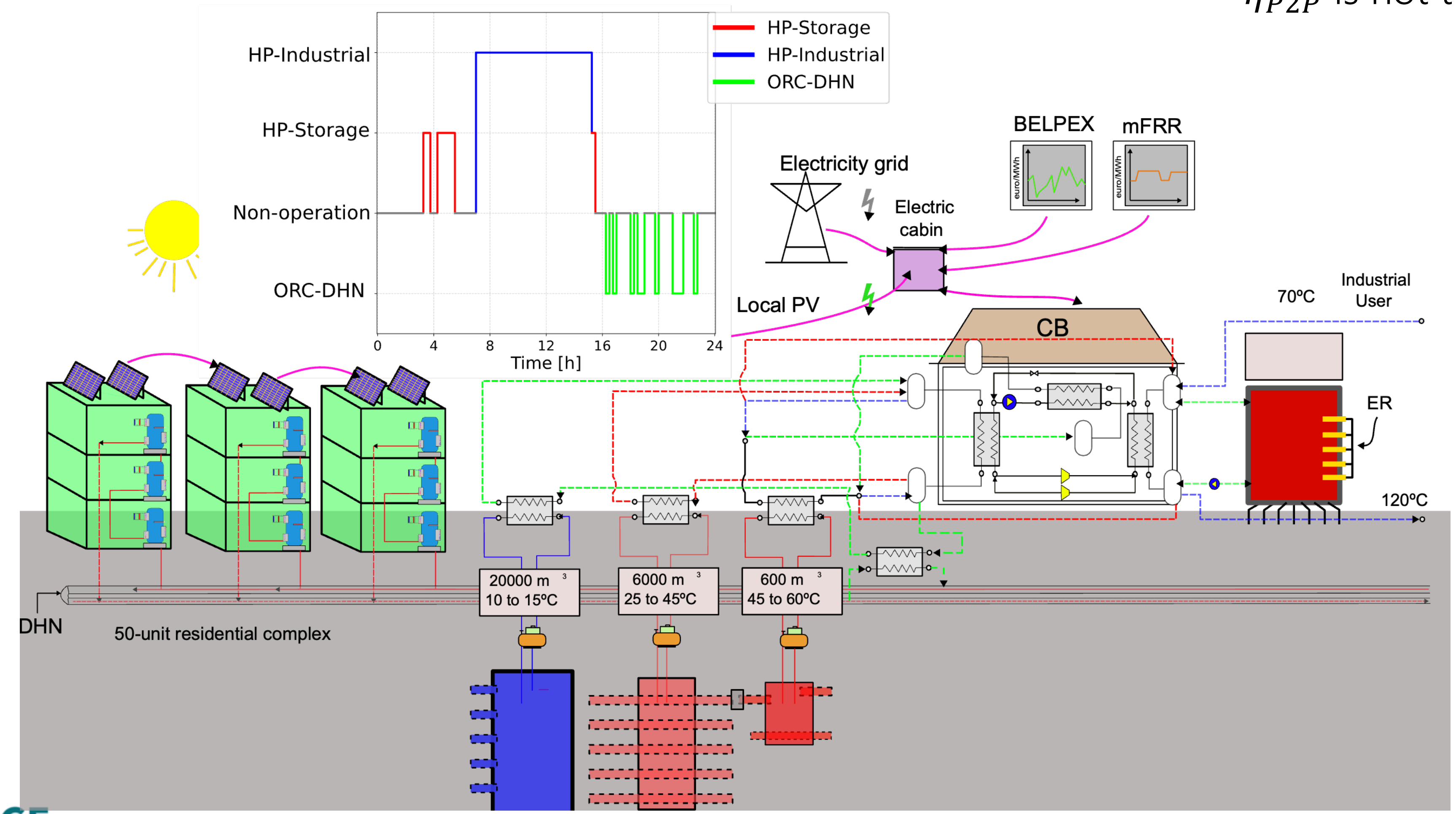
- Storing higher temp heat in the 600 m^3 chamber
- discharging and charging times of 46.5 and 54.2 hours, respectively, with a RTE of 24.34%.
- need specific pump.



Energy hubs

Simulation of performance

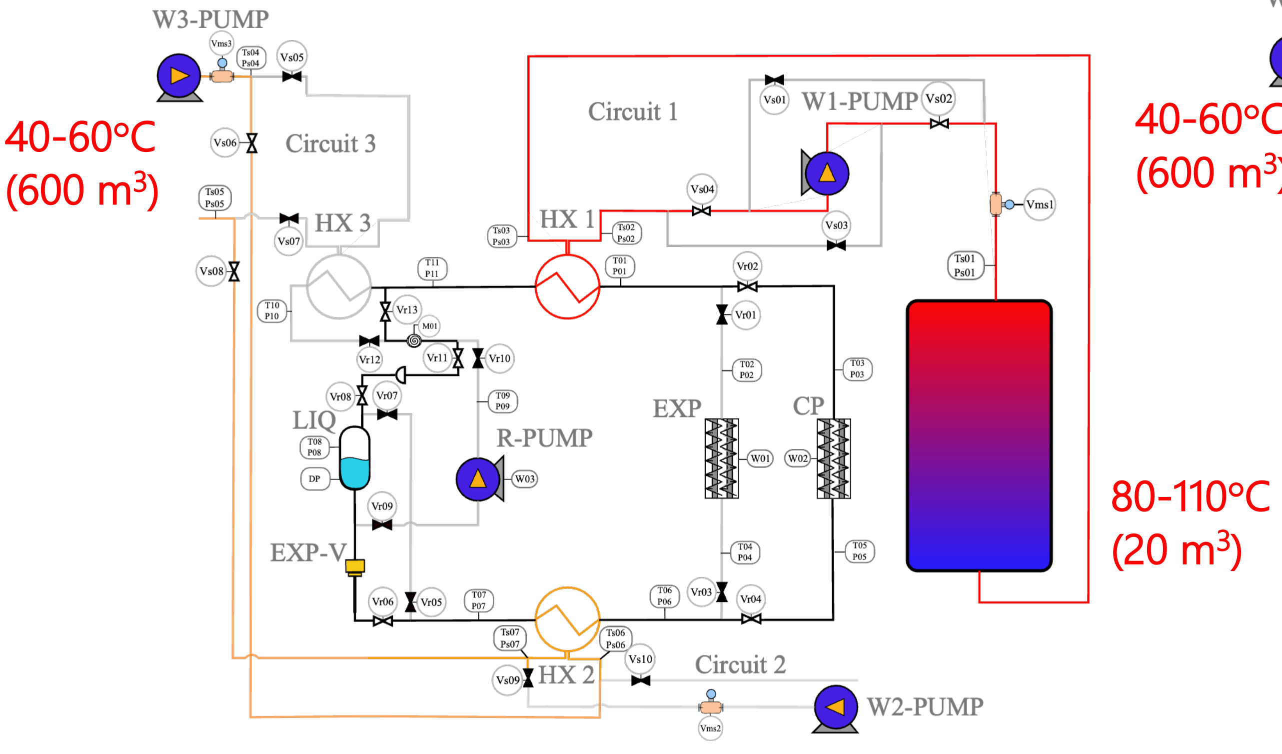
- If the system provides heating to an industrial process or cooling/heating to buildings, the η_{P2P} is not the good KPI.



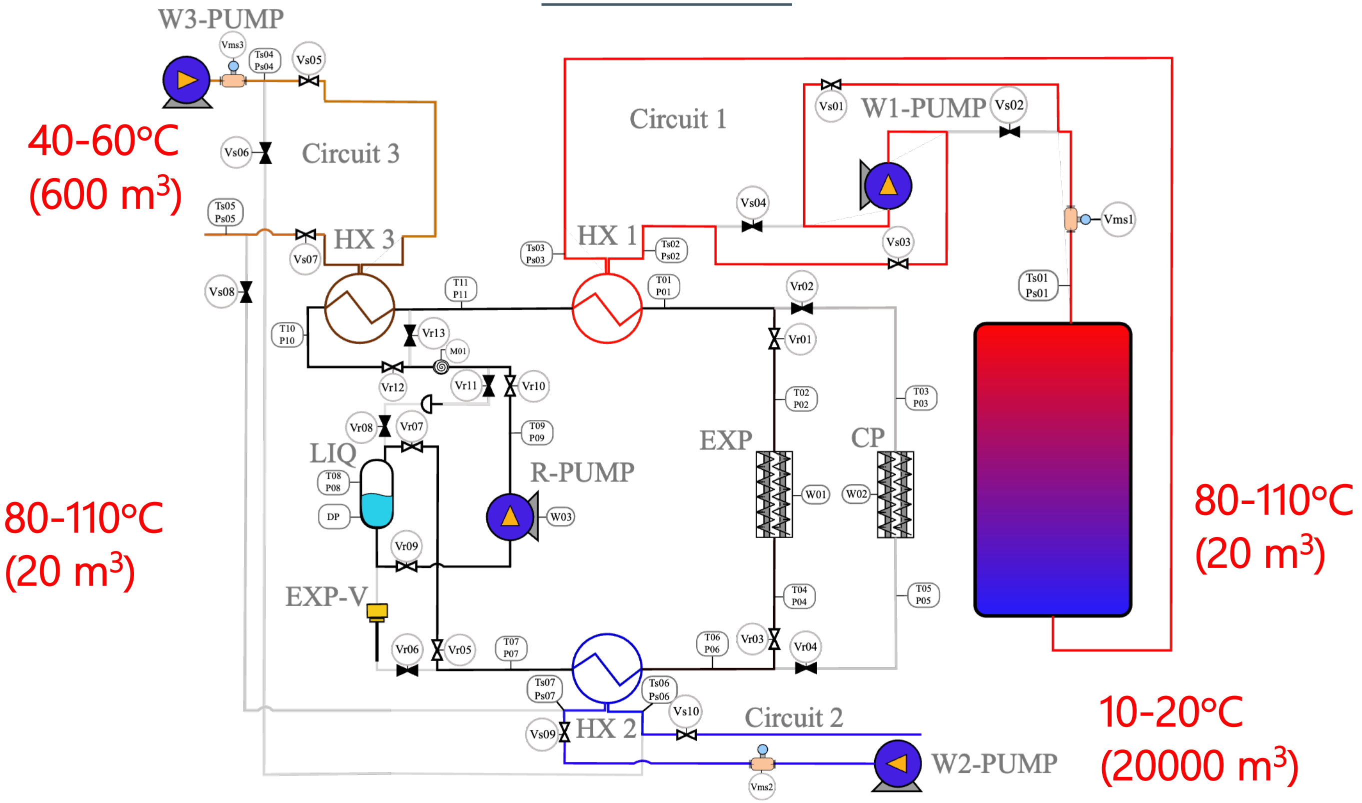
Energy hubs

Semi-reversible HP/ORC module

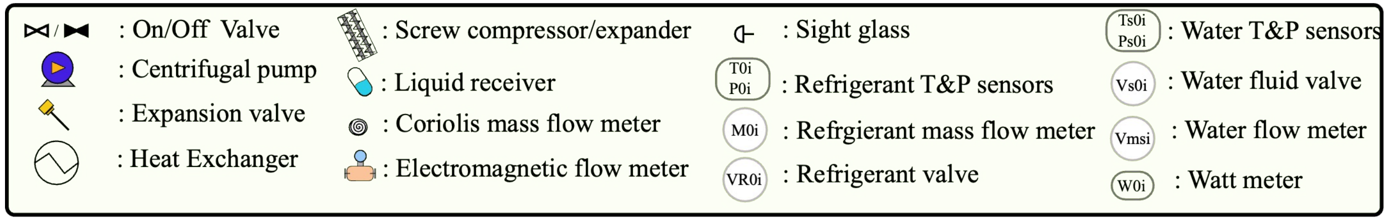
HP mode



ORC mode



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



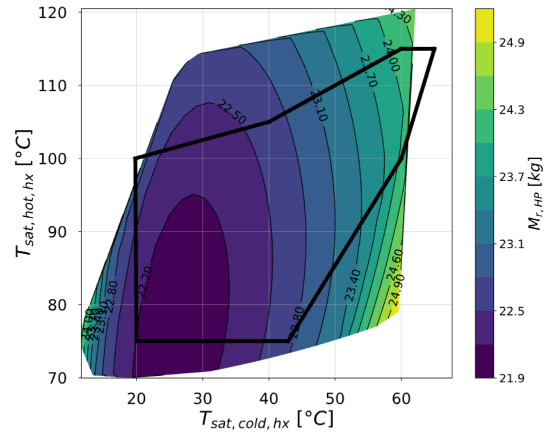
Energy hubs

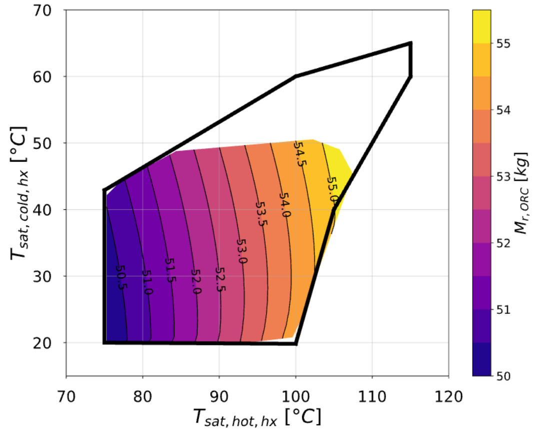
Semi-reversible HP/ORC module : Model-based design

Some technical challenges:

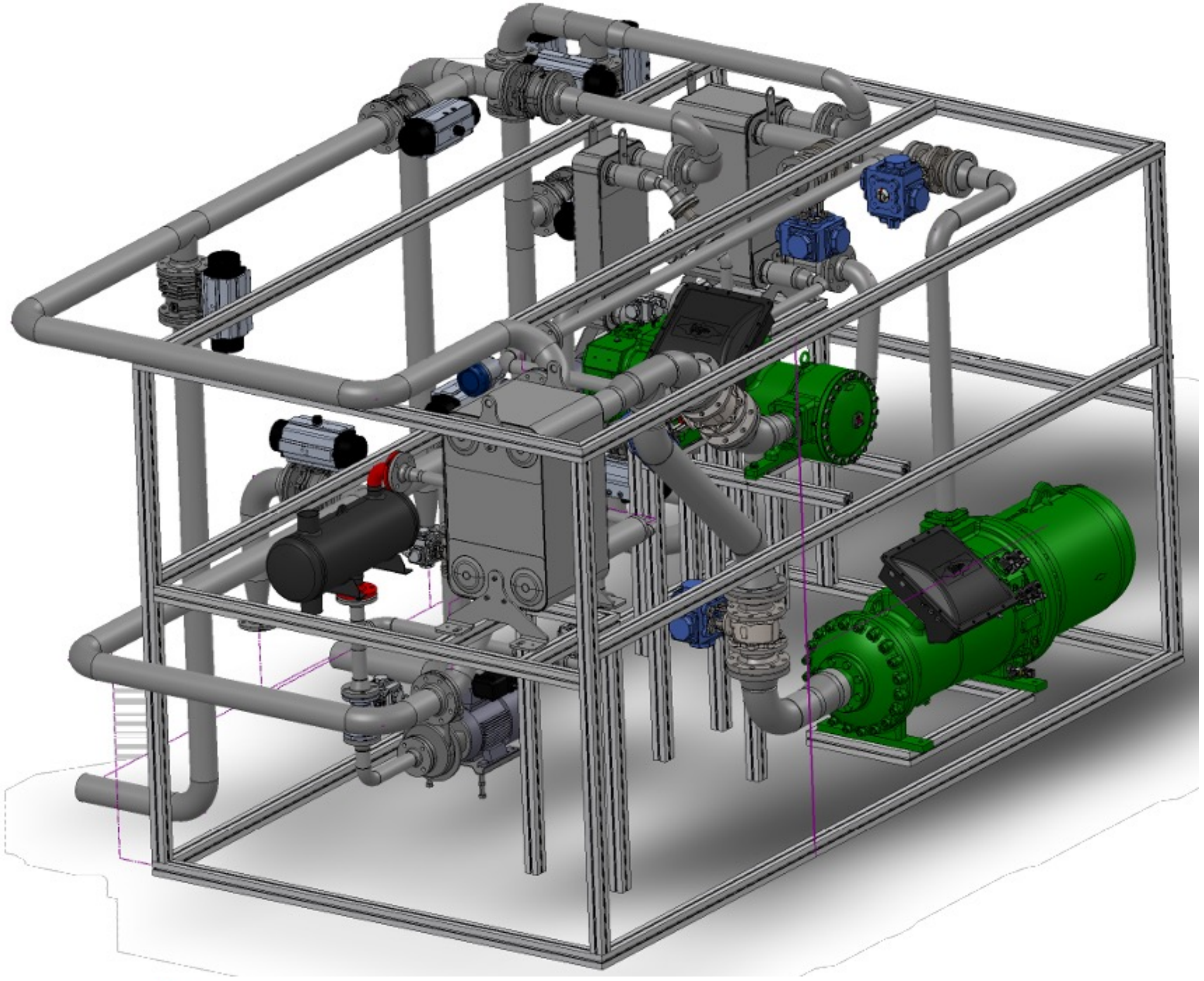
- **Refrigerant charge**
  - Larger charge in ORC than HP because of large liquid preheating zone and larger density
  - Correct refrigerant charge is important for safe, stable and efficient operation of the machine
  - Charge management solutions:
    - Inline liquid receiver able to work in both modes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

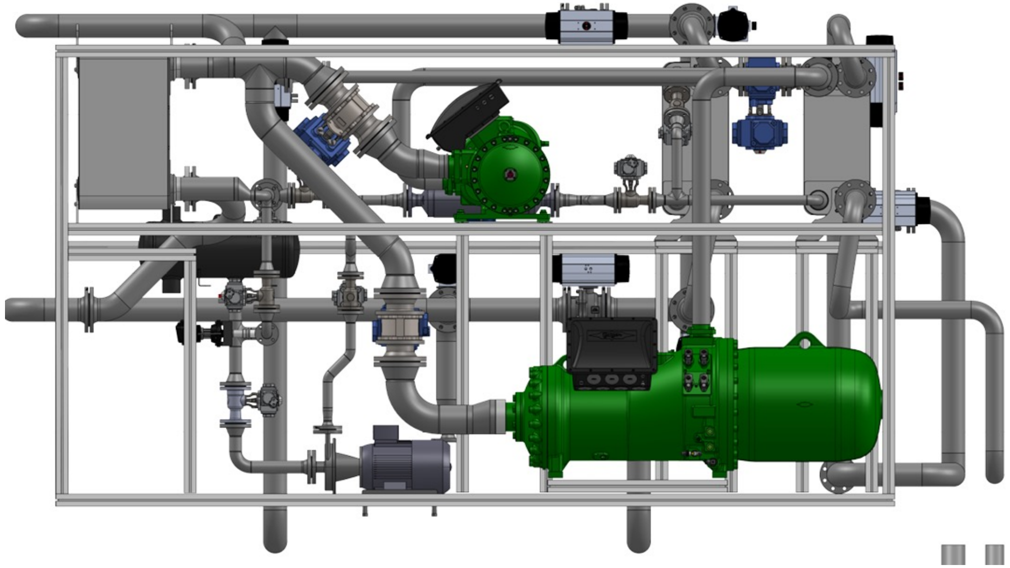
- **Lubricating oil**: OCR much larger for the expander mode than compressor → Oil management when switching from modes.

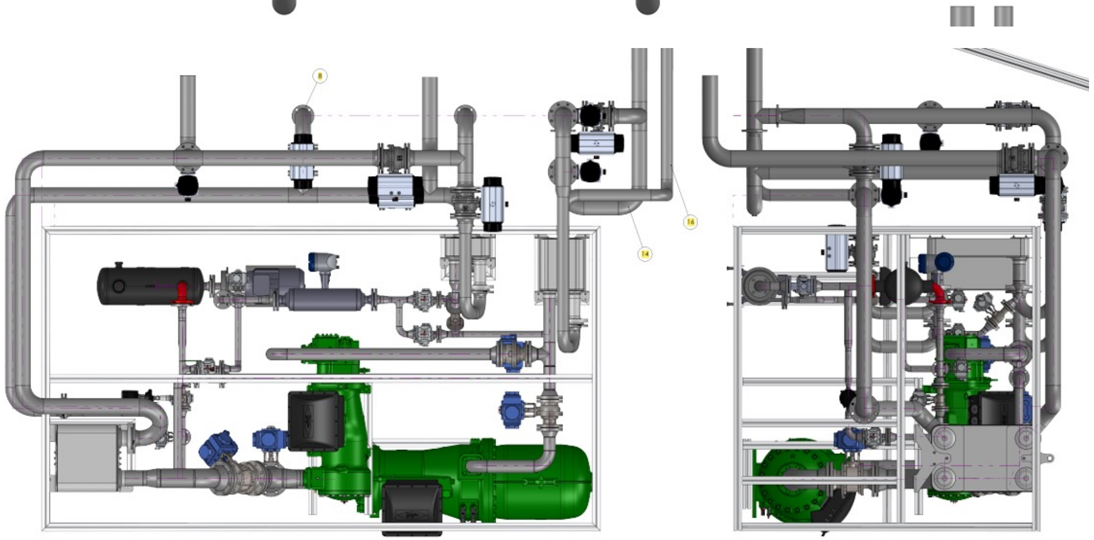




Energy hubs
Prototype #3 (2024 –)







ARDNRGY

WeForming

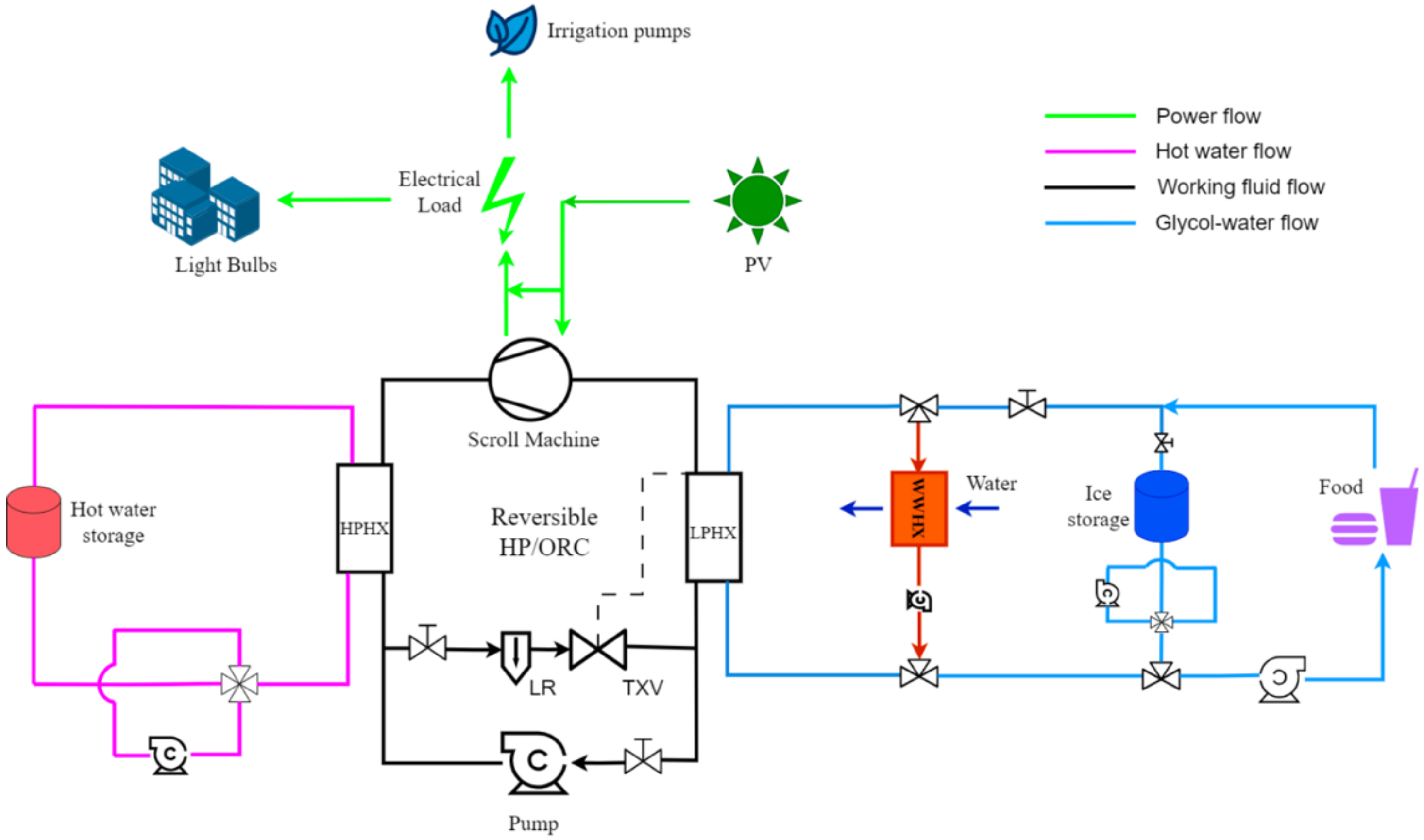
Energy hubs

Prototype #3 (2024 –)

Energy hubs

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.

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 significant role
  - ⇒ **Hybridization** of ORCs with heat pumps and thermal storages offers many possibilities
- **Carnot batteries** is an interesting concept of hybridization.

- Unlocking various **technical constraints** opens avenues to very original CB designs that meet energy needs:
  - ✓ Reversibility (invertibility) of components
  - ✓ Low temperature pinch points when considering low-temperature lift systems (LT WHR)
  - ✓ Lubricating oil and charge management for multimodal machines
  - ✓ Advanced control taking advantage of dynamics of systems to answer market signals
  - ✓ Limiting consumption of auxiliaries (+ optimization of water glides)

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Conclusions

- Carnot batteries show high power-specific cost (in [EUR/kWe]) **but low energy-specific cost** (in [EUR/kWhe]) because of TES => cannot easily compete with daily storage => more adapted to **longer duration storage**
- Probably their main advantage over batteries is the **absence of rare materials (and natural fluids, f.i. CO_2)**
- For sensible storage: **trade-off between compactness and $\boldsymbol{\eta_{P2P}}$** (large temperature spread on storage allows for storing more energy but COP and $\eta_{ORC}\downarrow$)
- Offering other services than purely electricity storage makes the Carnot Battery the backbone of an **Energy Hub** (multi-energy storage system), offering
  - ✓ Electricity storage
  - ✓ Waste heat to electricity conversion
  - ✓ Cold production
  - ✓ High temperature industrial heat production
  - ⇒ Other KPI indicators than the power-to-power ("round trip") efficiency to be considered
  - ⇒ Control will become of paramount importance

Many thanks for your attention!

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