

# Hybridization of heat pumps and ORC power systems: some challenges and opportunities

Vincent Lemort and co-workers

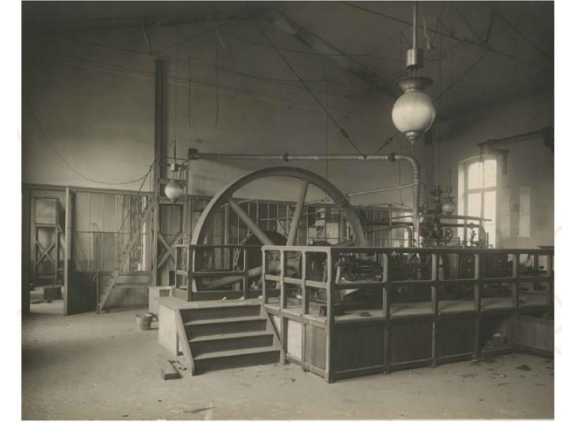
*Thermodynamics Laboratory of the University of Liège*

CERES Spring Meeting, London – City St George's University of London, March 12th 2025

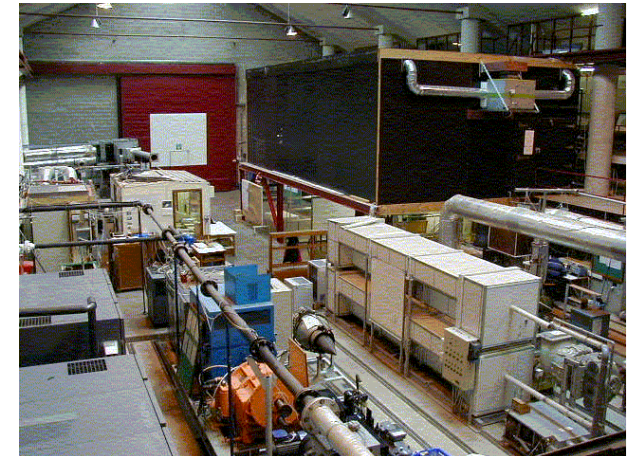
# Introduction

## *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



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

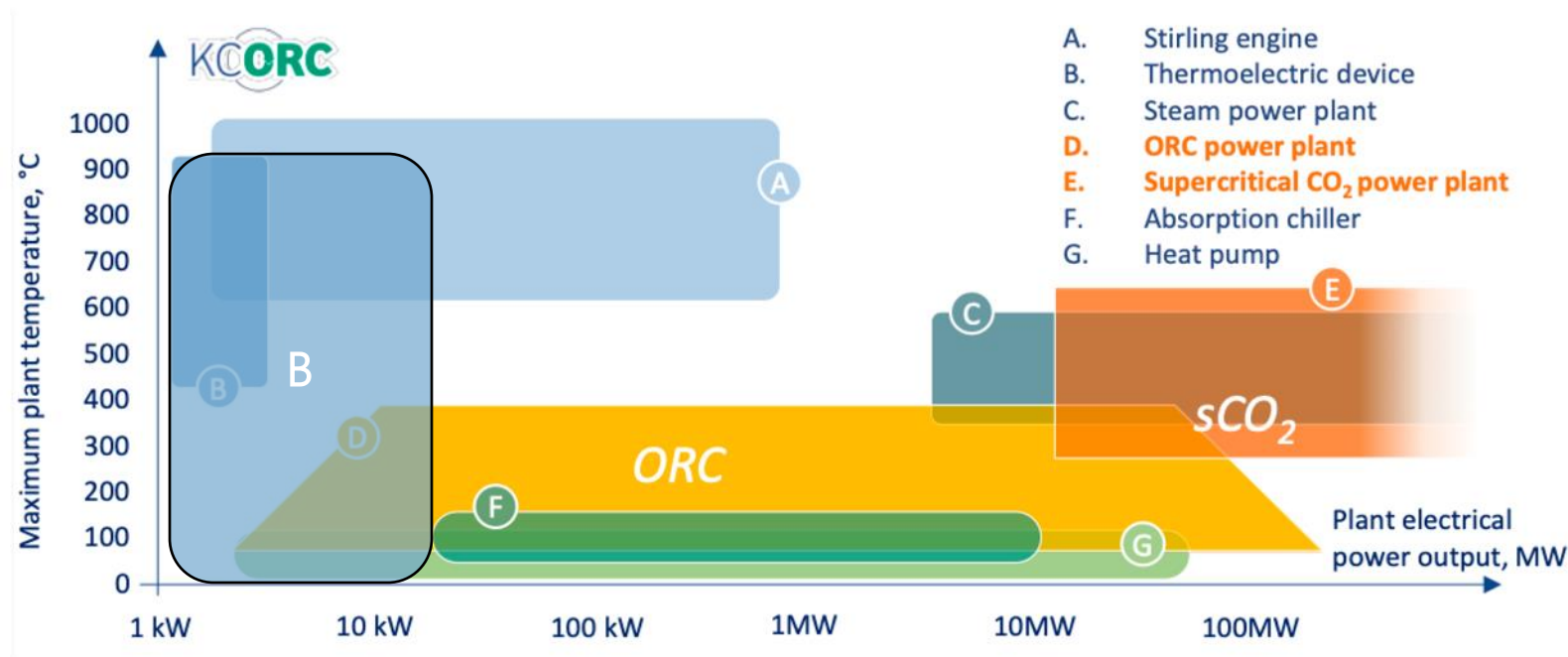
## *Context: cooling, heating and electrification*

- 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, arbitrage),
  - **Distributed electricity storages** can also participate in 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

# Introduction

## *Context: waste heat recovery*

- Very large potential of untapped thermal energy: EU28 countries rejected approx. 980 TWh/yr in 2015 [1]
- ORCs, sCO<sub>2</sub> cycle, vapor compression heat pumps and heat driven heat pump cover a large zone of the map
- Waste heat valorization by ORCs **does not produce CO<sub>2</sub>** and limits the demand of primary energy
- Local electricity production can cope with limitations of grid extension (especially if electrification of industry)

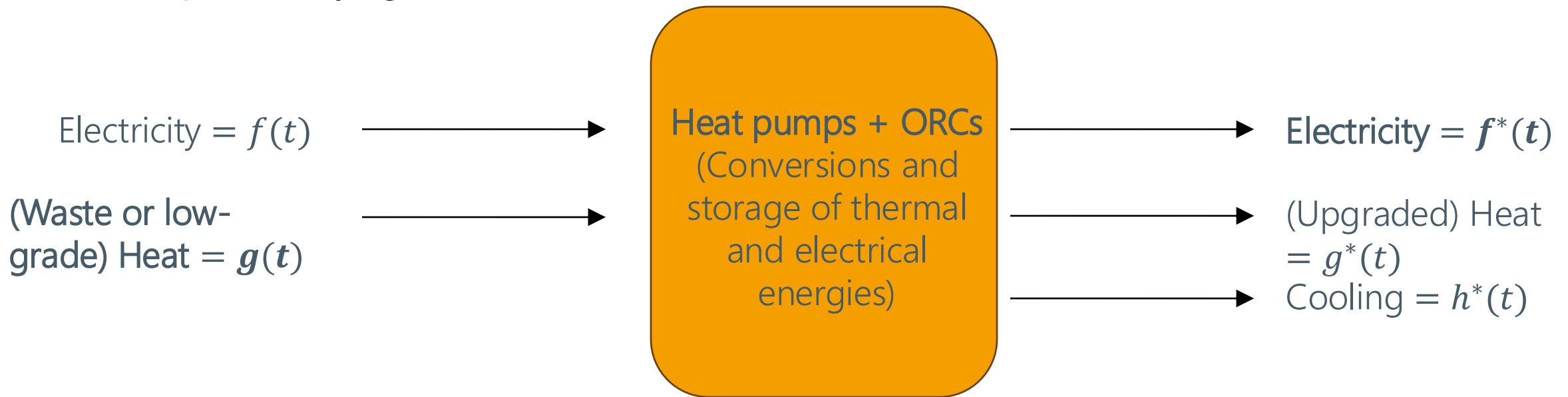


- But electricity production may be less an issue than electricity consumption and storage (PV, wind turbines)...

# 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**.



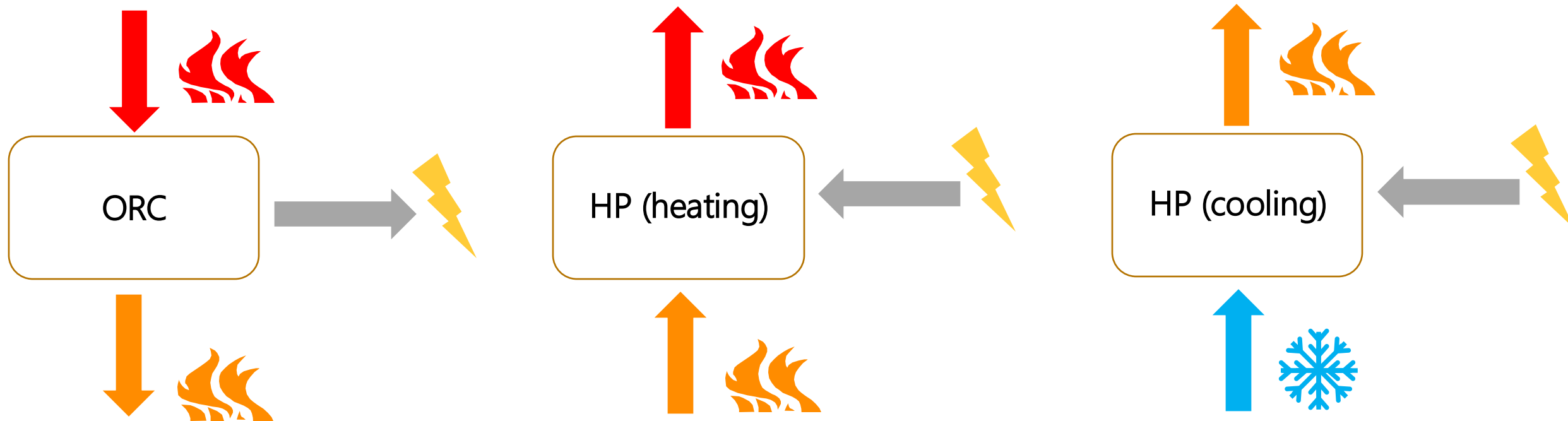
→ Hybridization of ORCs with heat pumps appears promising.

# Agenda of the presentation

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

# Hybridization

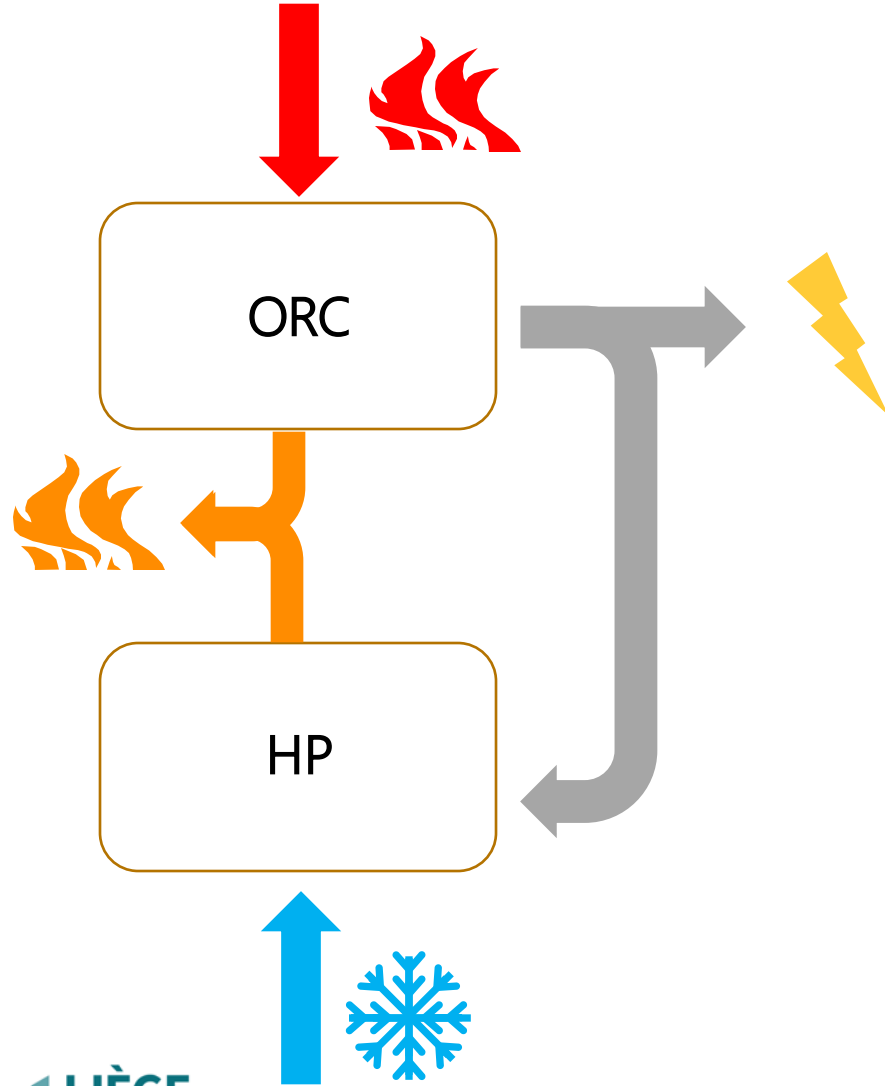
## *How?*



- ORCs and vapor compression HPs share many similar components and show similar temperatures regimes.
- Different ways to hybridize them.

# Hybridization

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



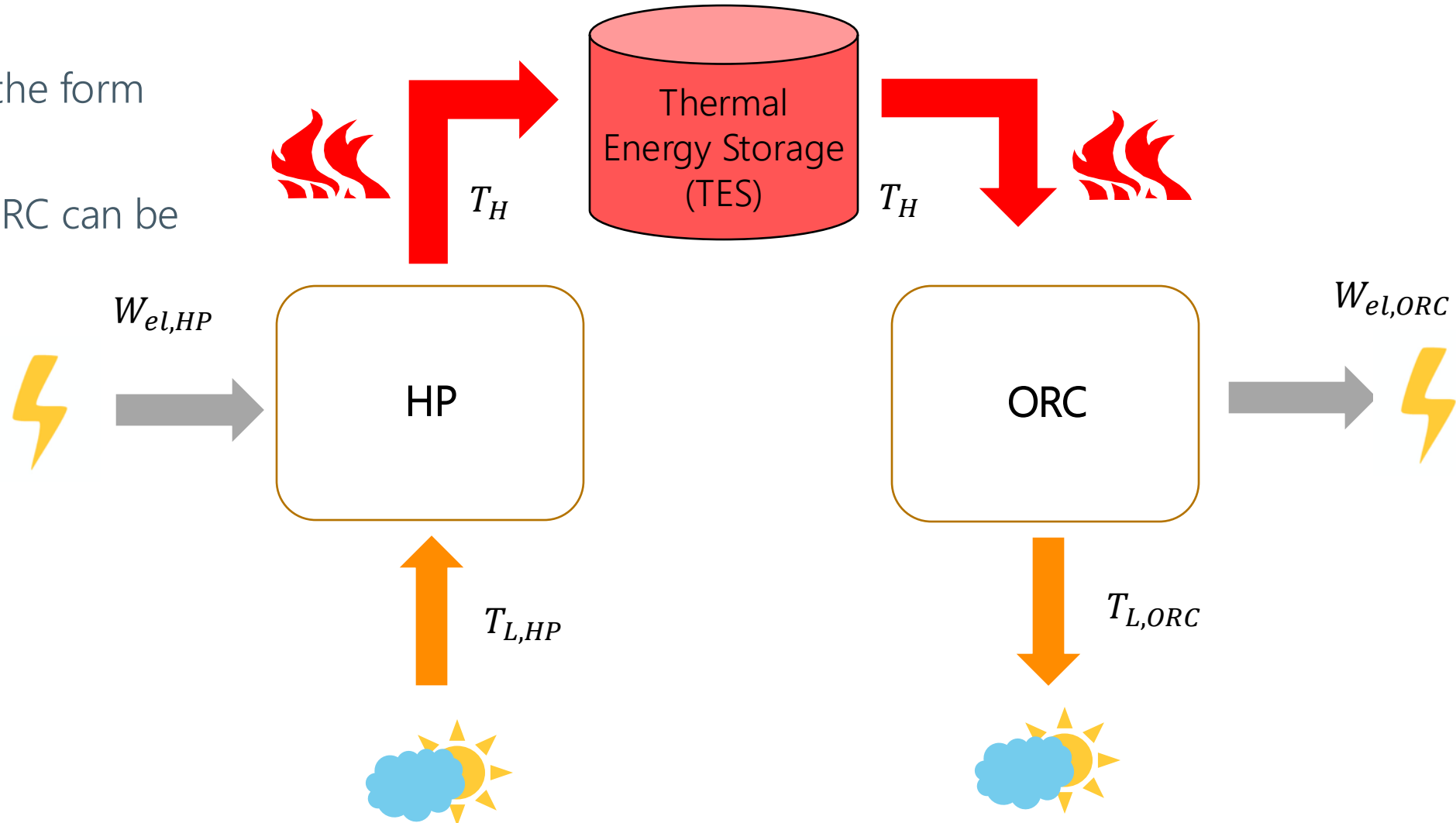
- Combined production of cooling, heat and electricity from a low-grade heat source (waste heat, solar energy...)



# 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

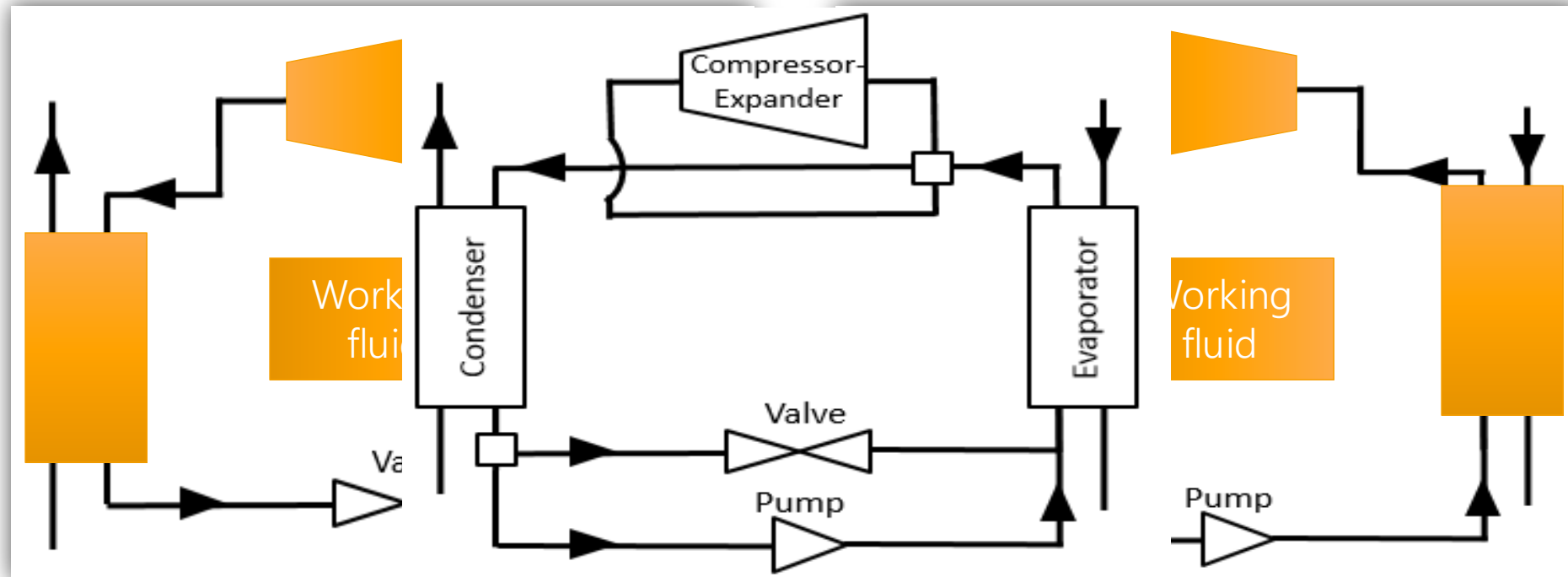


Power-to-power efficiency :

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

# Hybridization

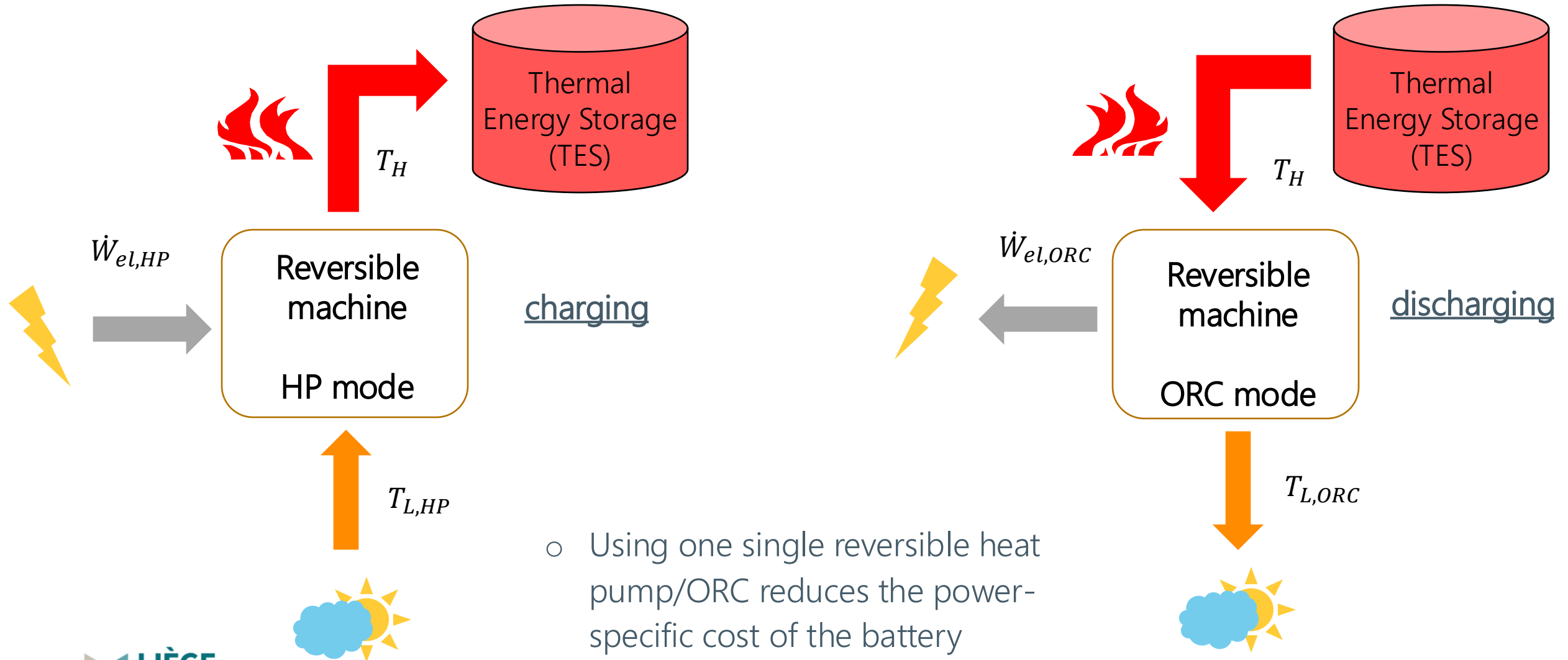
## *Reversible heat pump/ORC*



- Merging the ORC and HP into one single machine

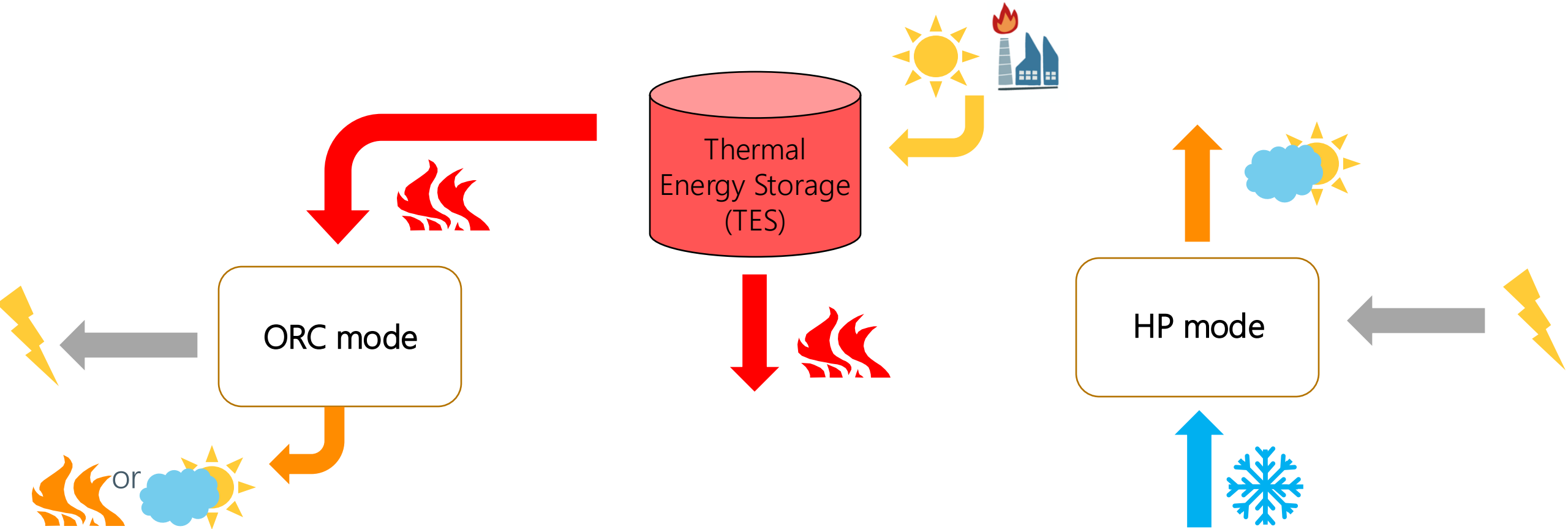
# Hybridization

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

# Agenda of the presentation

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

# Polygeneration systems

## *With heat pumps - ORCs*

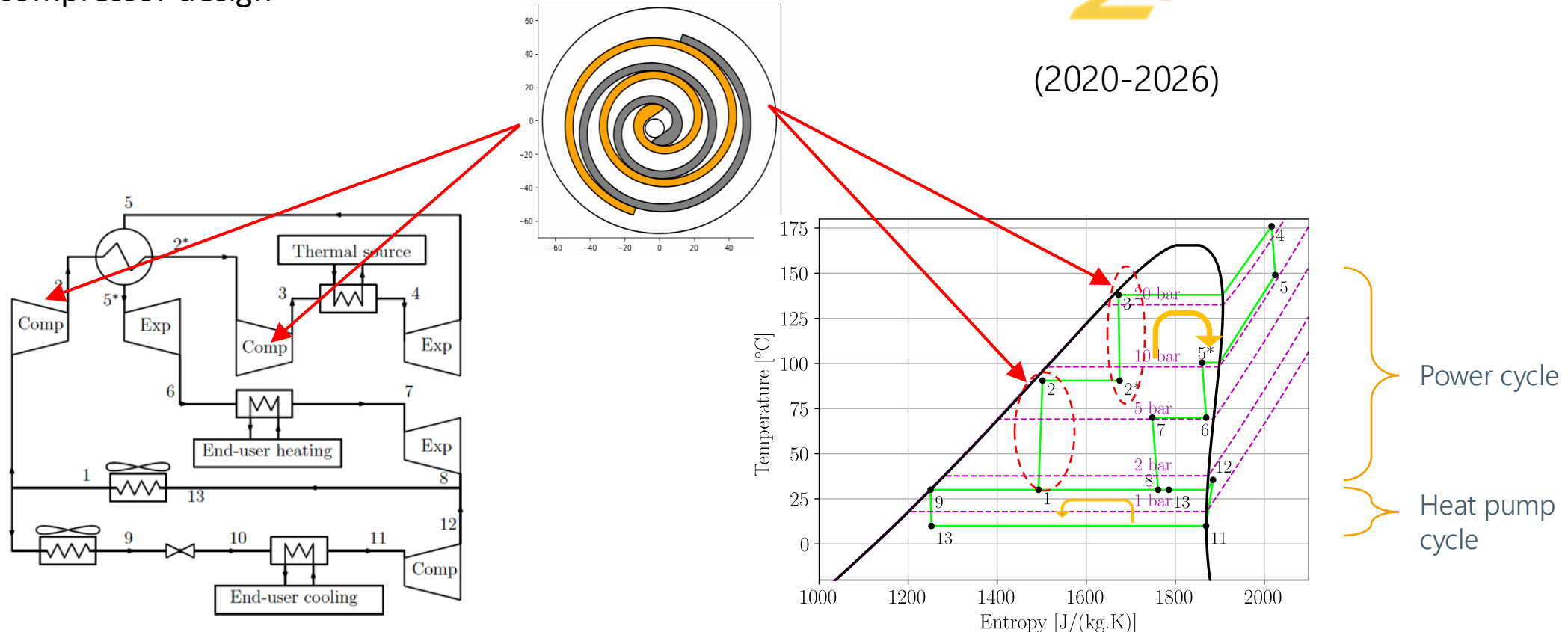
- Multigeneration of cooling, heat and electricity (CCHP) based on one single machine valorizing a low-grade heat source.

Research question

- 2-phase scroll compressor design



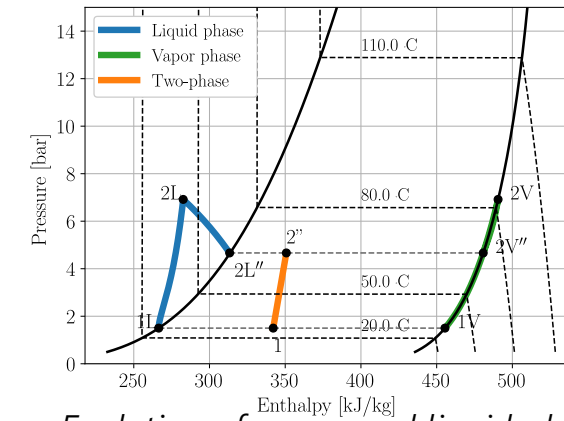
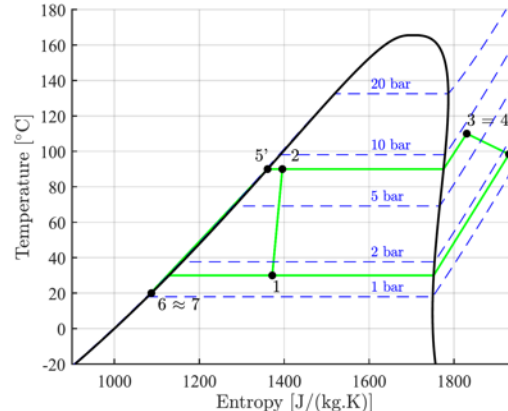
(2020-2026)



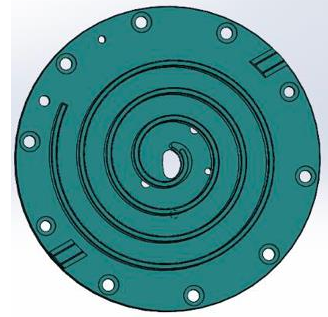
# Polygeneration systems

## *With heat pumps - ORCs*

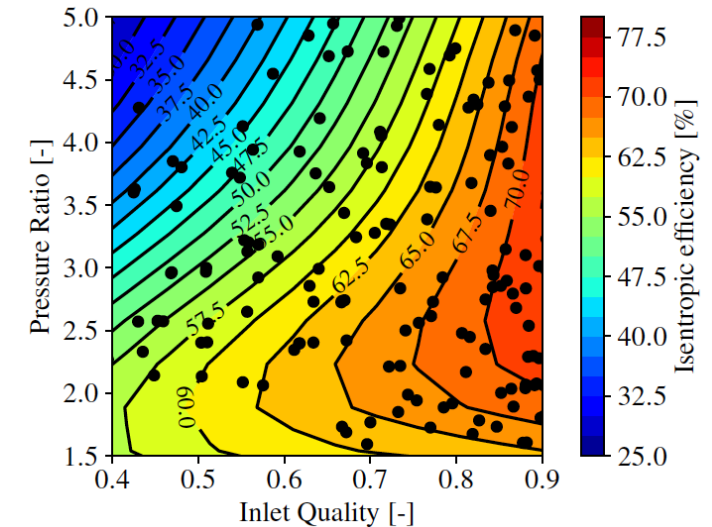
- **Challenges associated with compressor prototype design:**
  - Larger pressure losses in supply/discharge ports
  - Larger under-pressure losses with low quality
  - Two-phase + oil: liquid-phase viscosity lower vs pure oil (increase leakages)
  - Non-thermal equilibrium between phases yields unavoidable 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]



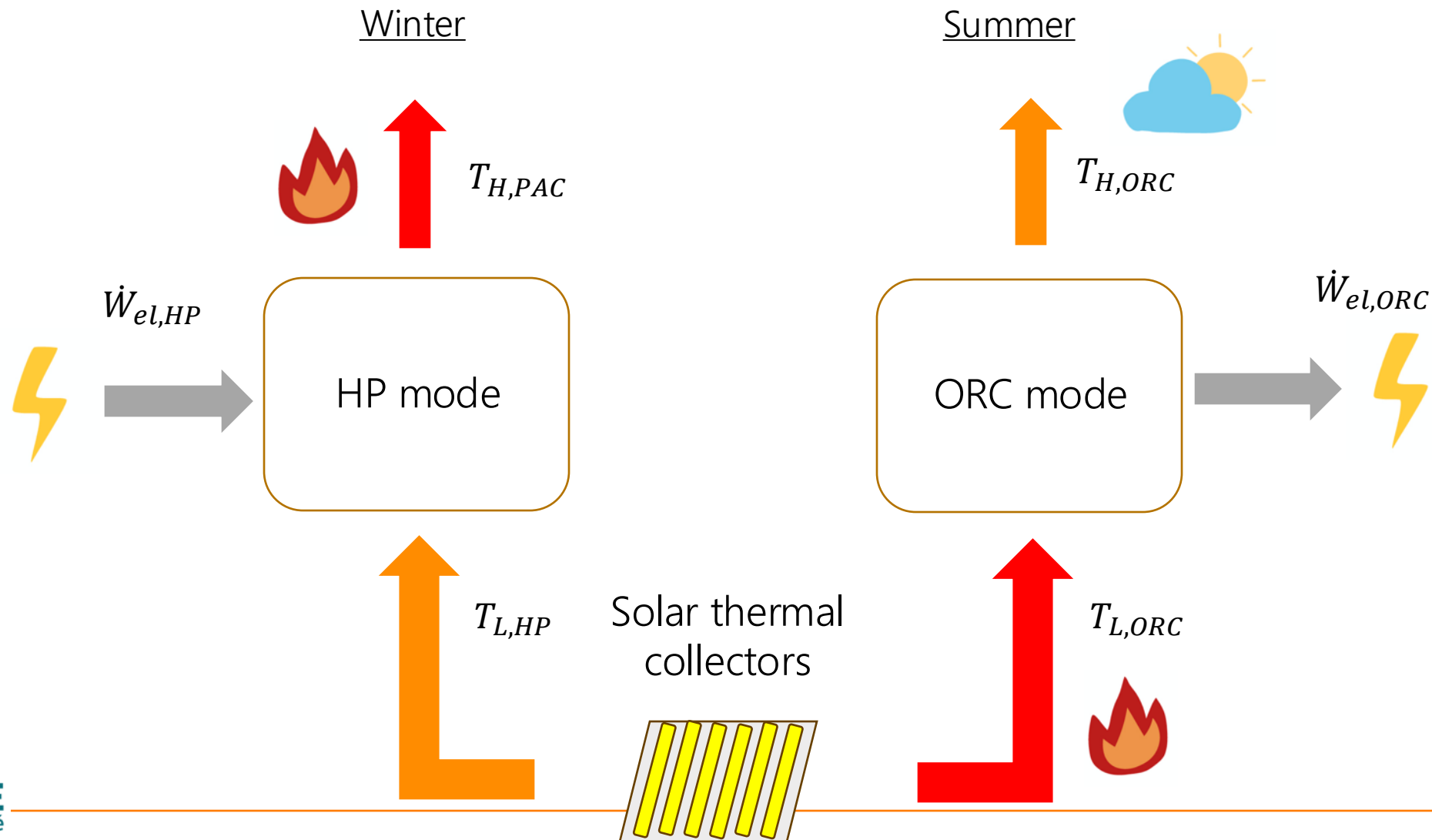
Prototype of 2- $\phi$  compressor



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

# Polygeneration systems

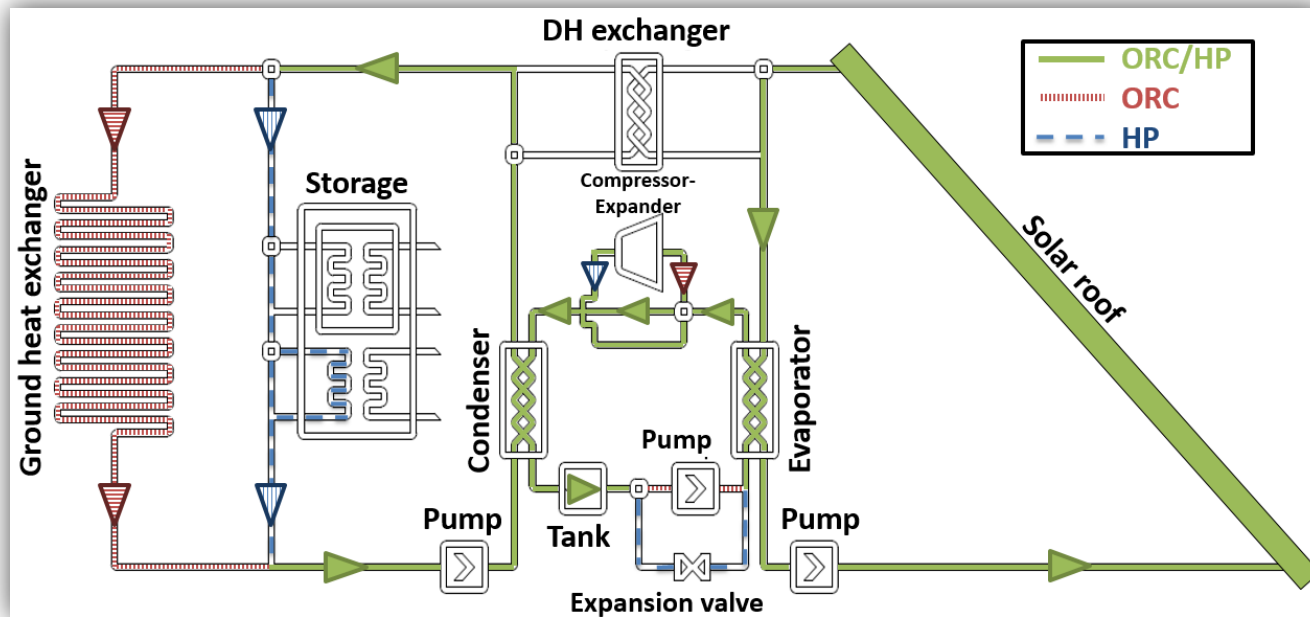
## *With reversible heat pump/ORC*





# Polygeneration systems

## *With reversible heat pump/ORC*



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

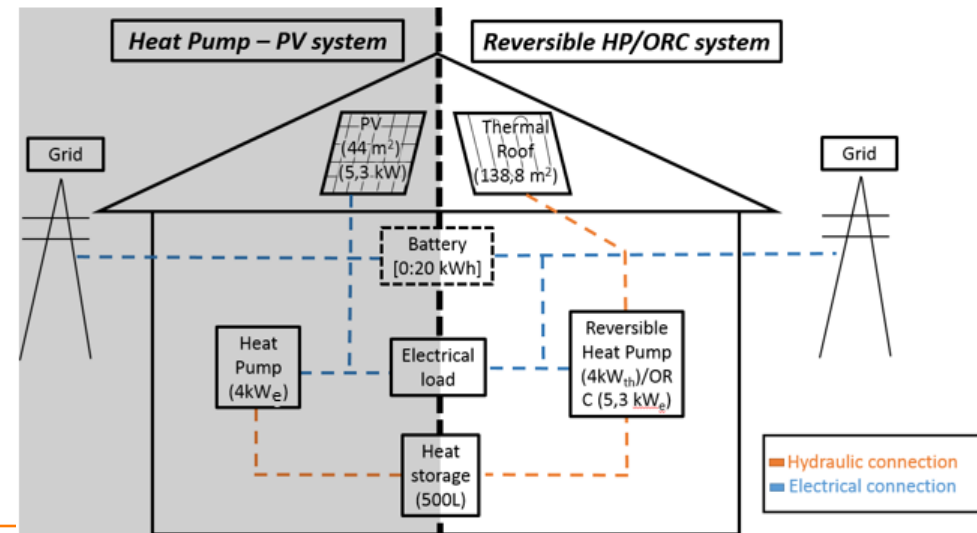
# Polygeneration systems

## *With reversible heat pump/ORC*



- Prototype:
  - Sized to produce 4030 kWh per year
  - COP of 4.21 ( $T_{ev} = 21\text{ °C}$  /  $T_{cd} = 61\text{ °C}$ )
  - ORC efficiency: 5,7 % ( $T_{excd} = 25\text{ °C}$  /  $T_{suev} = 88\text{ °C}$ )

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



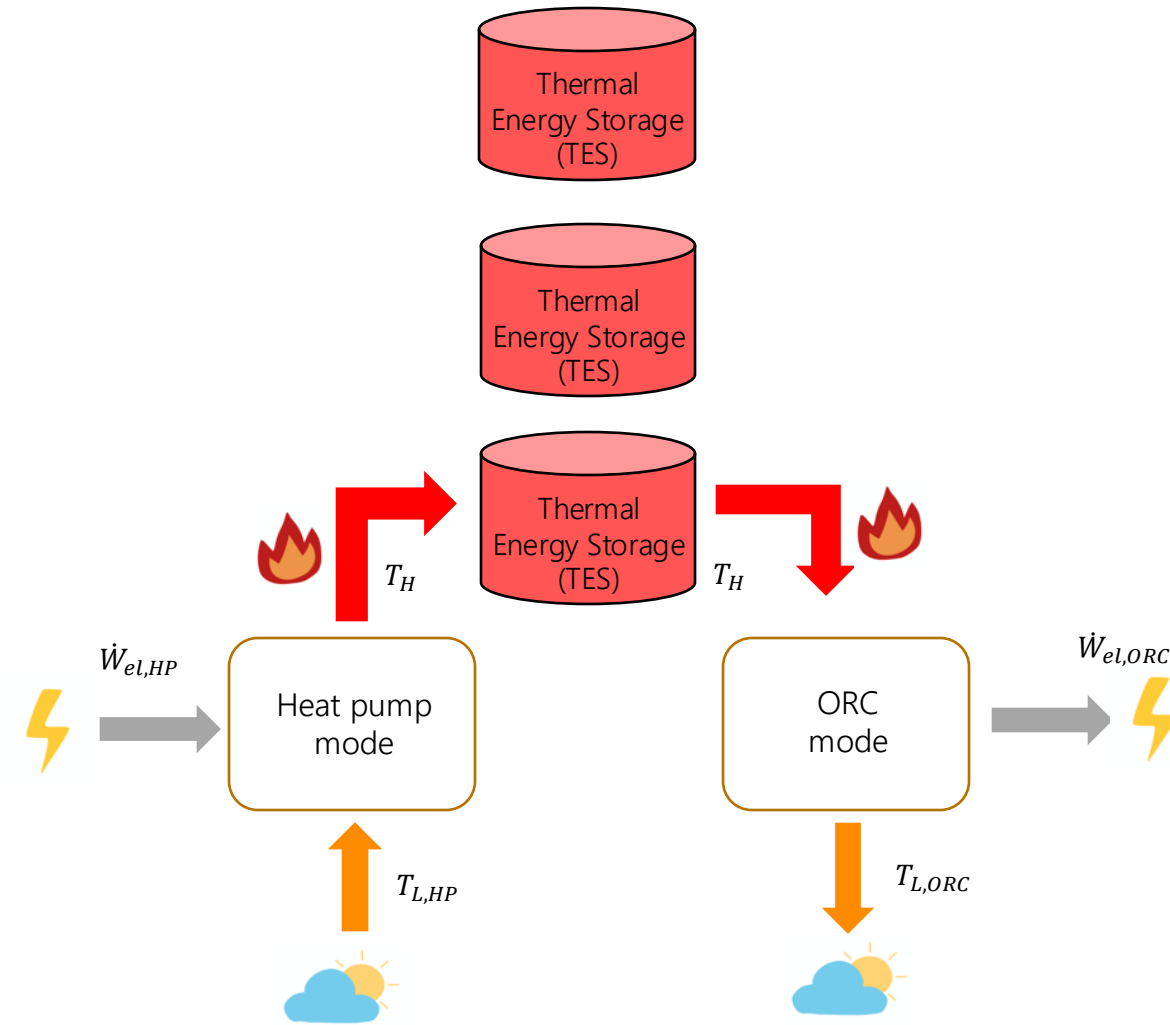
# Agenda of the presentation

1. Introduction
2. Hybridization of heat pumps and ORCs
3. Polygeneration systems
- 4. Carnot batteries**
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, heating/cooling.



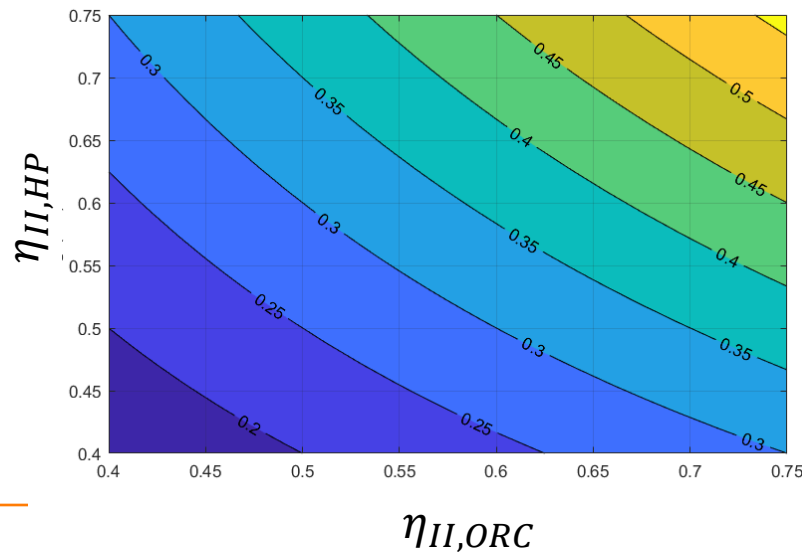
# Carnot batteries

## Performance

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

$$\begin{aligned}\eta_{P2P} &= \frac{W_{el,ORC}}{W_{el,HP}} = (\eta_{sto}) COP_{HP} \eta_{ORC} \\ &= (\eta_{sto}) \eta_{II,HP} \frac{T_H}{T_H - T_{L,HP}} \eta_{II,ORC} \left( 1 - \frac{T_{L,ORC}}{T_H} \right)\end{aligned}$$

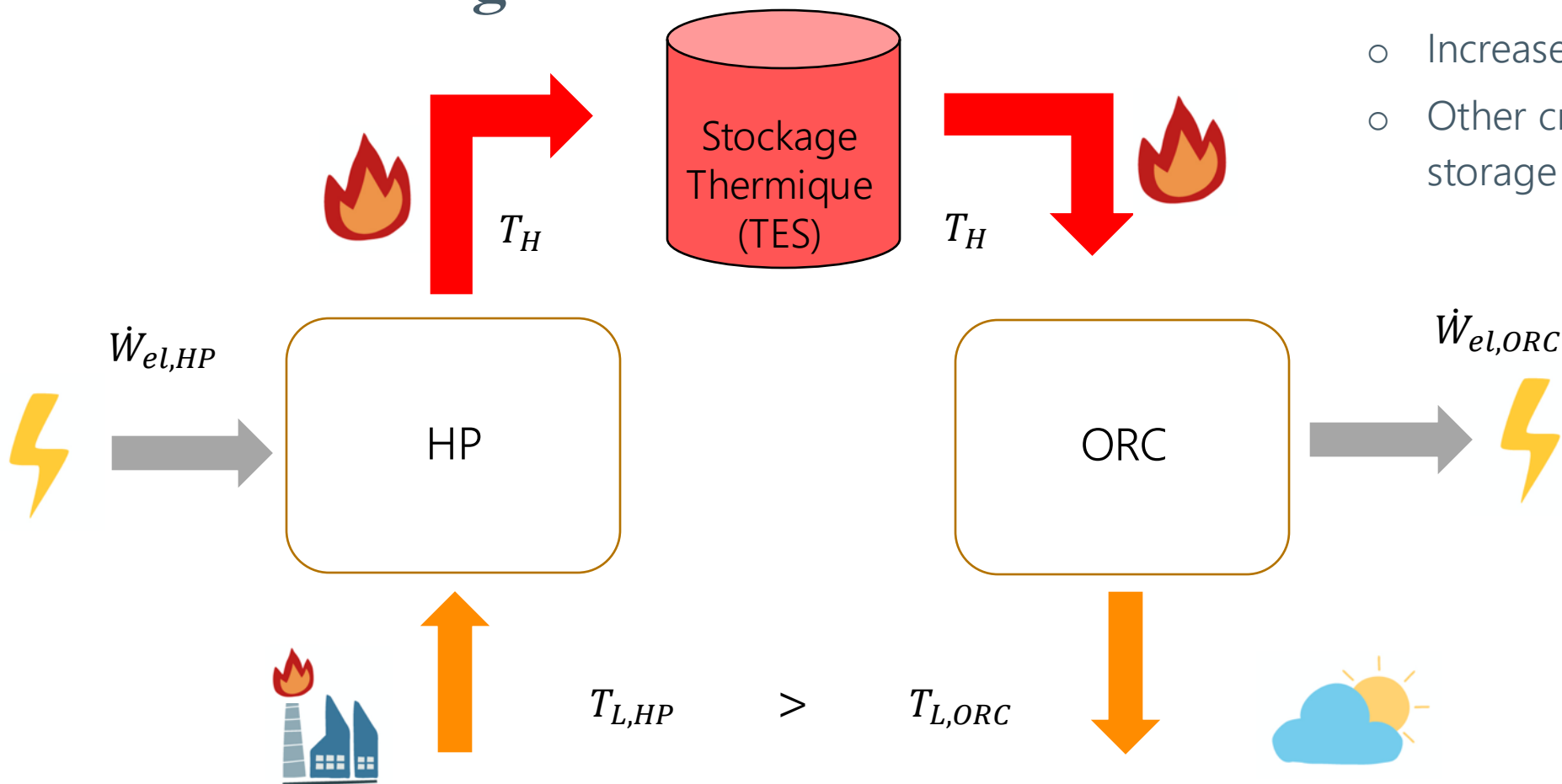
- If the heat source temperature of the HP is equal to the heat sink temperature of the ORC ( $T_{L,HP} = T_{L,ORC}$ ), for instance ambient air, we get



$$\eta_{P2P} = \eta_{II,HP} \eta_{II,ORC}$$

# Carnot batteries

## *Thermal integration*



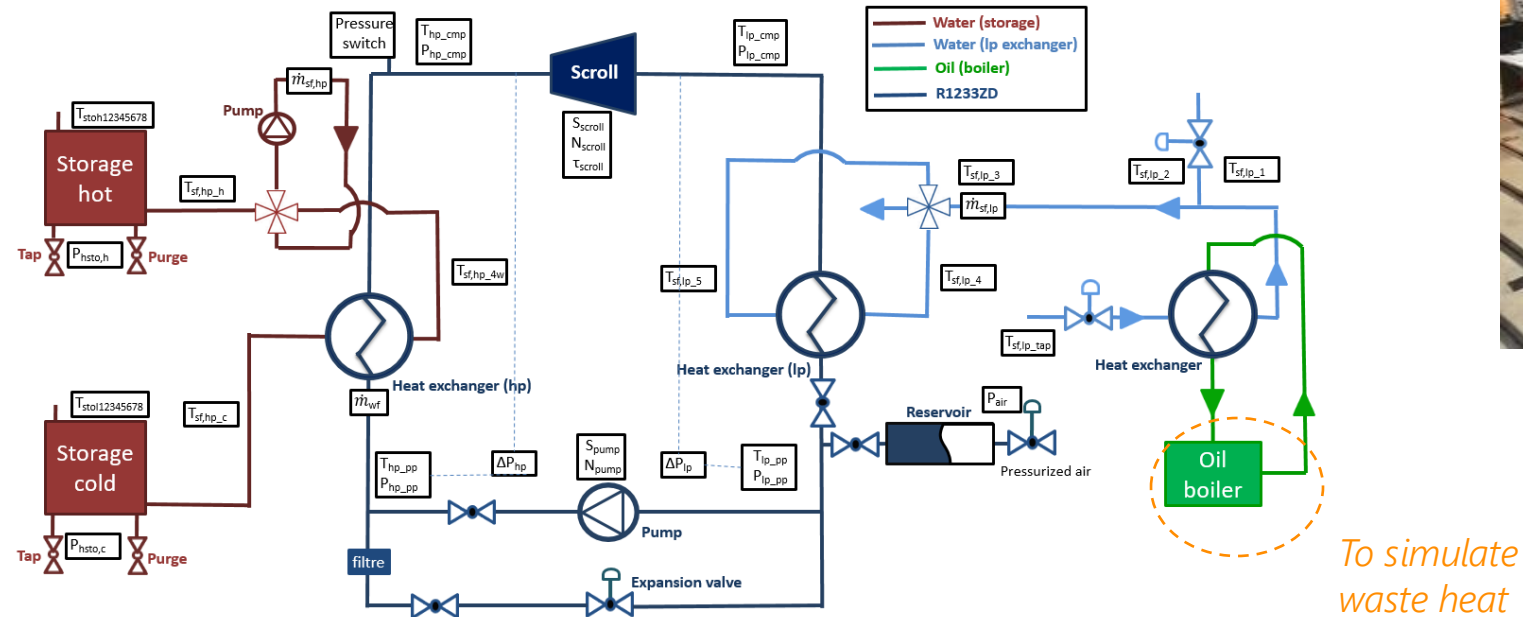
- Increase of power-to-power efficiency
- Other criteria: exergy efficiency, energy storage density

*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

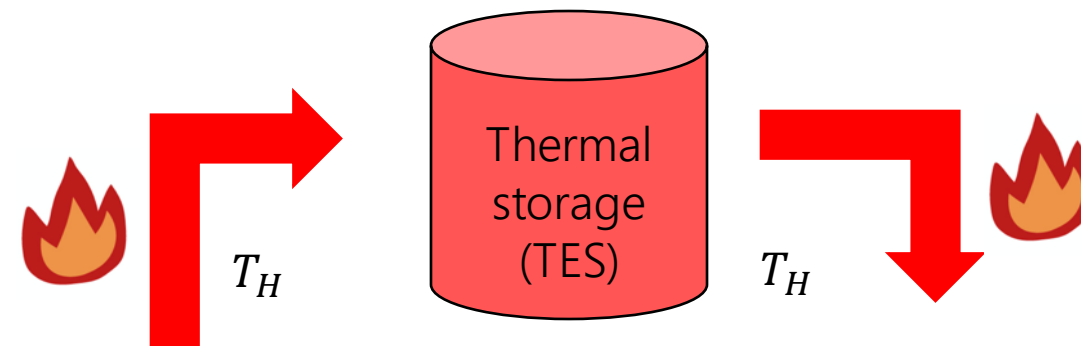
## *Thermal integration: prototype #1 (2018-2020)*



- R1233zd(E)
- Storage at  $\sim 90^{\circ}\text{C}$
- Thermal capacity of 10 kWh<sub>th</sub>, Discharge power close to 2 kW<sub>e</sub>
- Roundtrip efficiency of **72.5%** (ORC efficiency of 5% (lift: 49 K) and COP of HP of 14.4 (lift: 8 K)).

# Carnot batteries

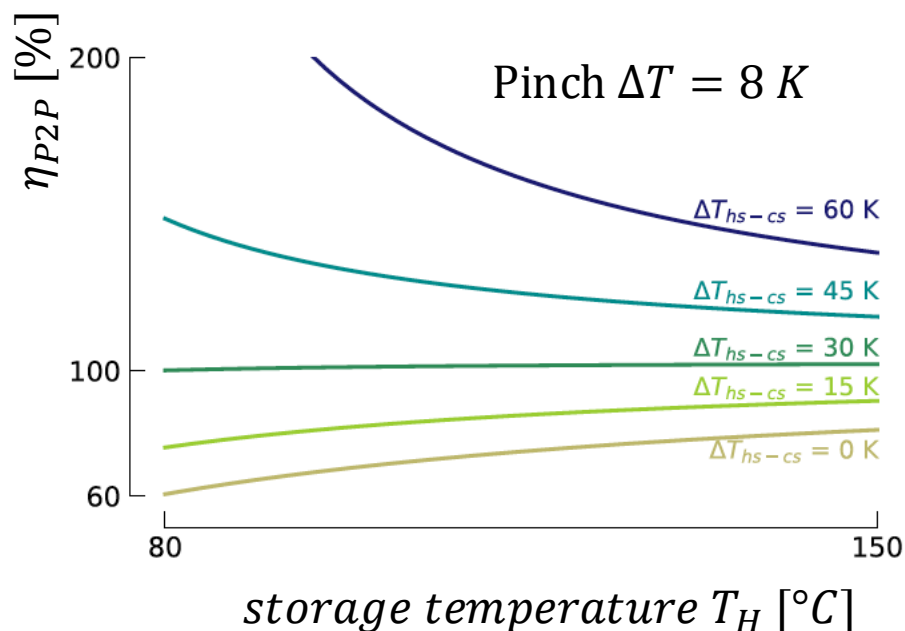
## *Thermal integration*



What is the optimal temperature  $T_H$  of the thermal storage?

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

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



$$\Delta T_{hs-cs} = \underbrace{T_{L,HP}}_{\text{Waste heat}} - \underbrace{T_{L,ORC}}_{\text{Ambient air}}$$

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

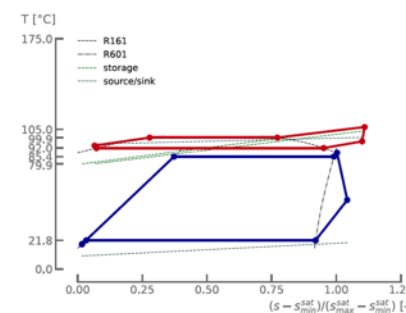
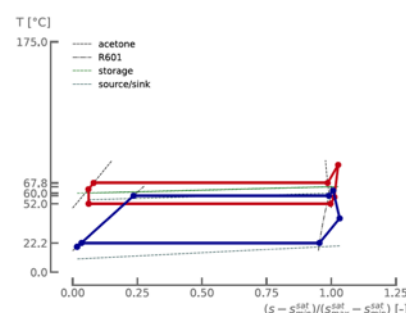
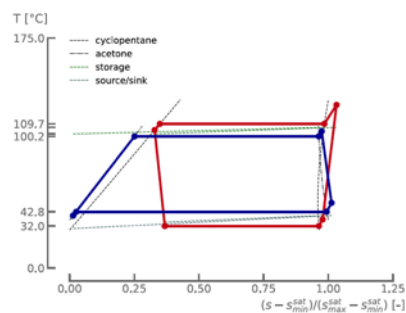
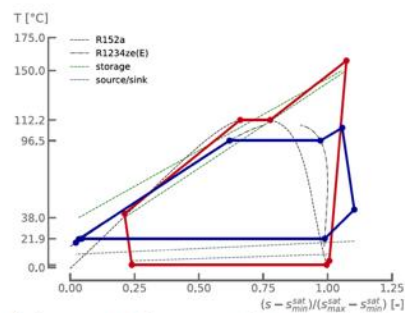
→ HEX Pinch becomes more important for low  $\Delta T_{hs-cs}$



# Carnot batteries

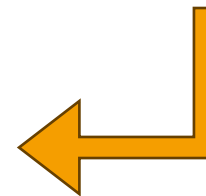
## *Thermal integration*

Exemple of optimisation



$T_{L,HP} = 10^{\circ}\text{C}$  and  $T_{L,ORC} = 10^{\circ}\text{C}$      $T_{L,HP} = 40^{\circ}\text{C}$  and  $T_{L,ORC} = 30^{\circ}\text{C}$      $T_{L,HP} = 60^{\circ}\text{C}$  and  $T_{L,ORC} = 10^{\circ}\text{C}$      $T_{L,HP} = 100^{\circ}\text{C}$  and  $T_{L,ORC} = 10^{\circ}\text{C}$

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

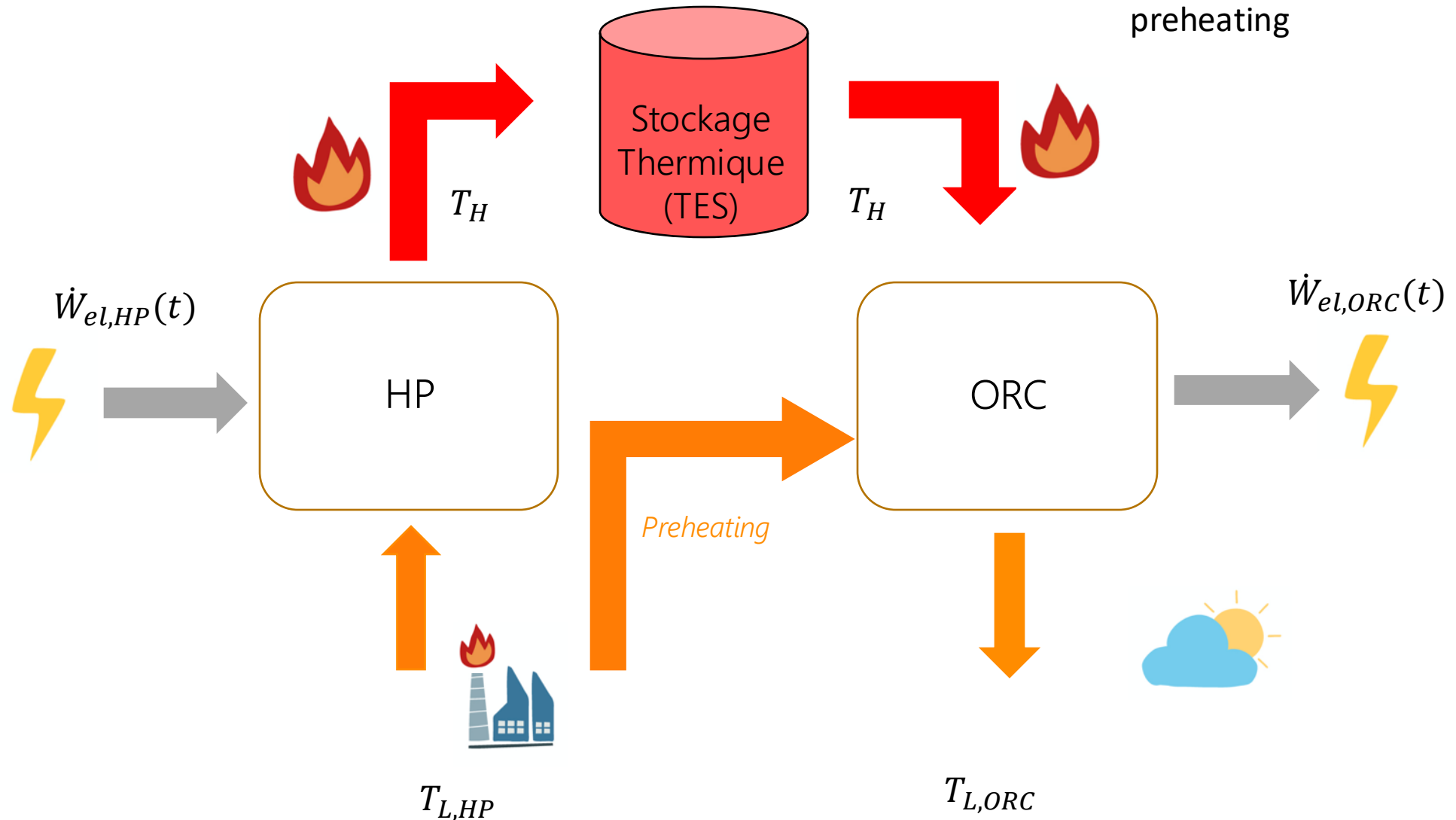


Source: Antoine Laterre et al., Extended mapping and systematic optimisation of the Carnot battery trilemma for sub-critical cycles with thermal integration, Energy, Volume 304, 2024

# Carnot batteries

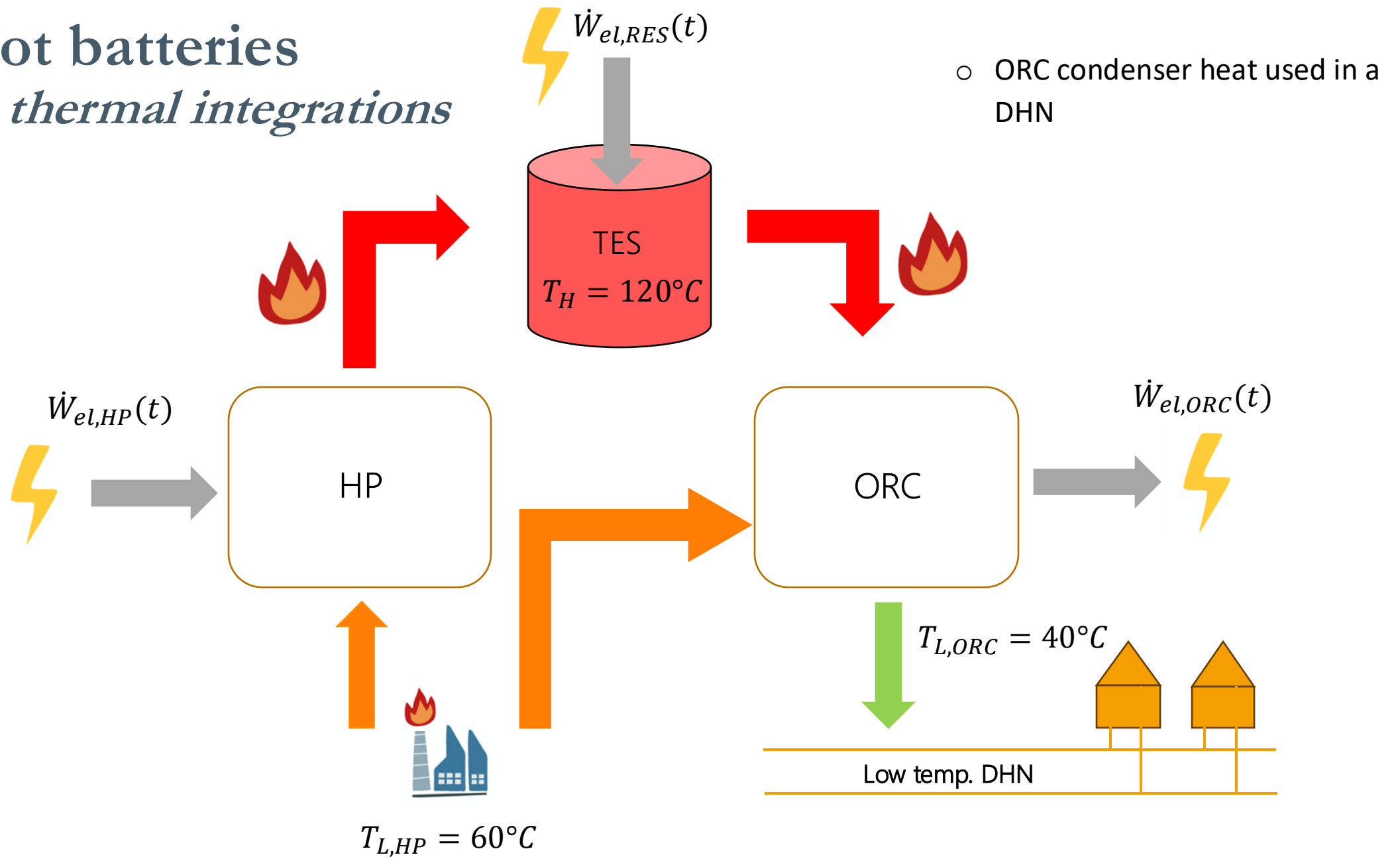
## *Other thermal integrations*

- Waste heat can be used during discharge (ORC) for liquid preheating



# Carnot batteries

## *Other thermal integrations*



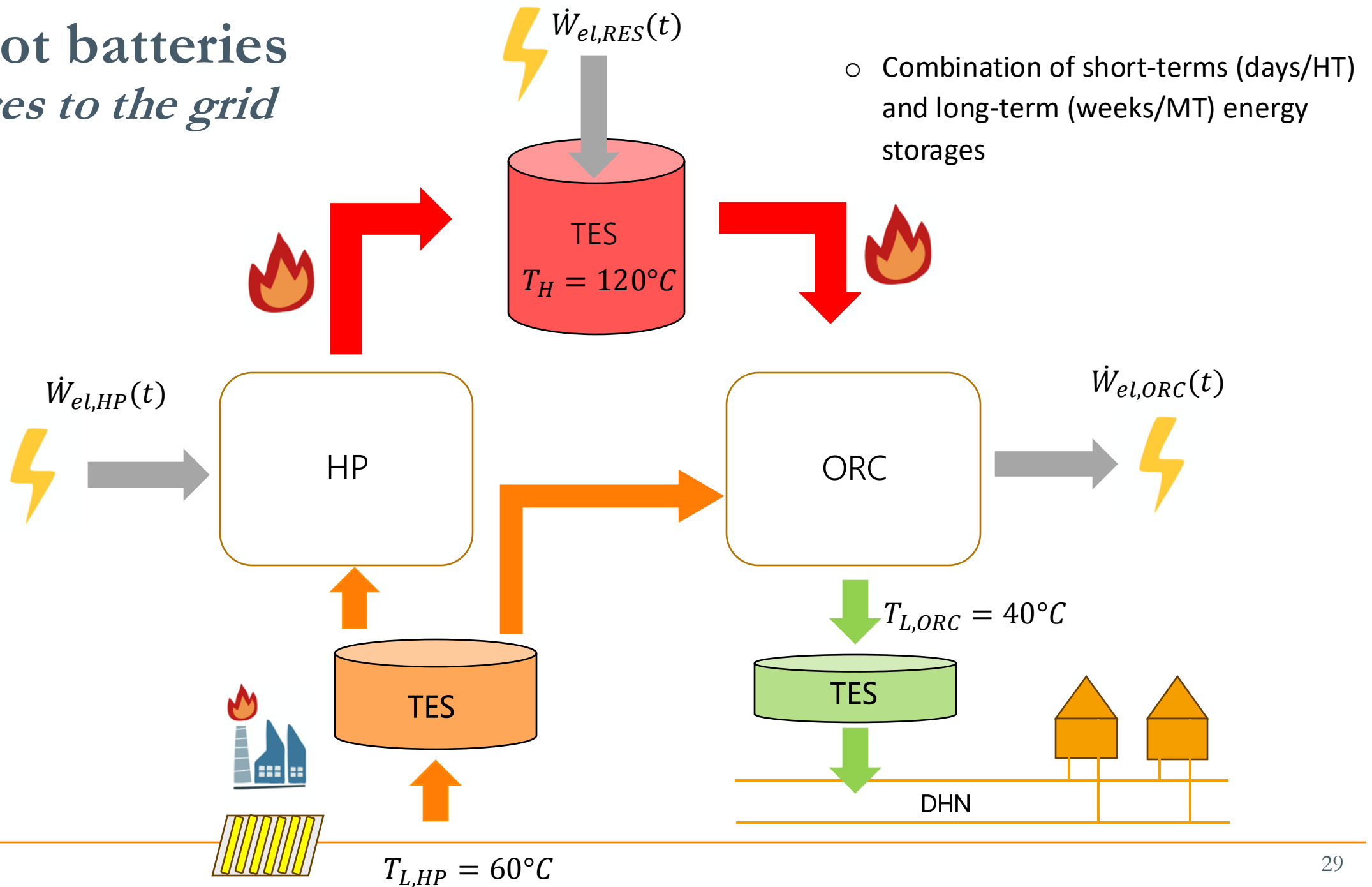
# Carnot batteries

## *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** (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, DAM?

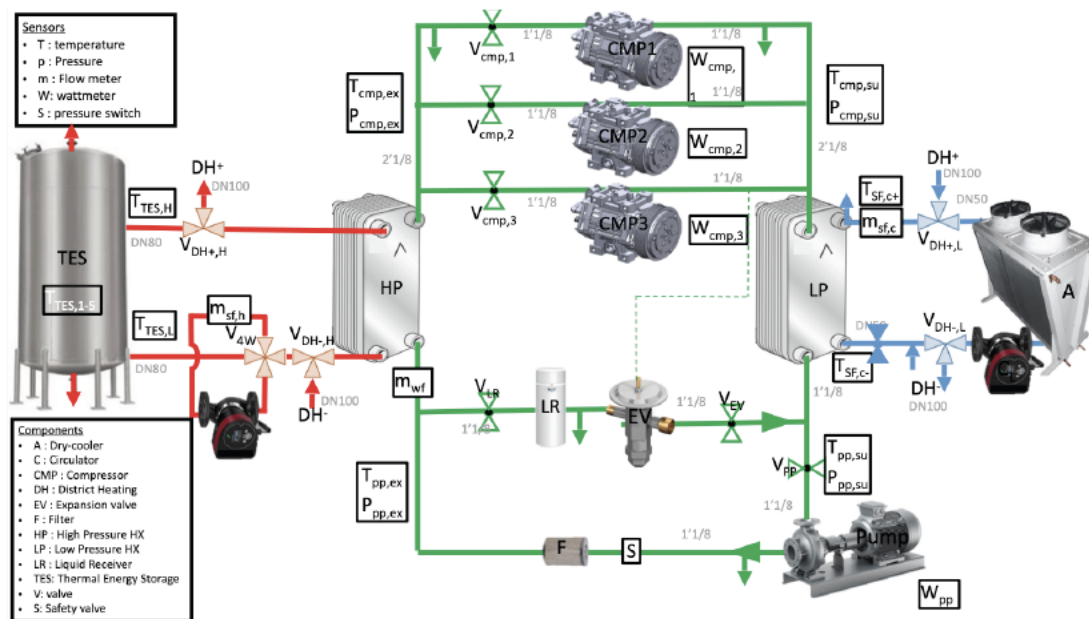
# Carnot batteries

## *Services to the grid*



# Carnot batteries

## *Services to the grid: prototype #2*

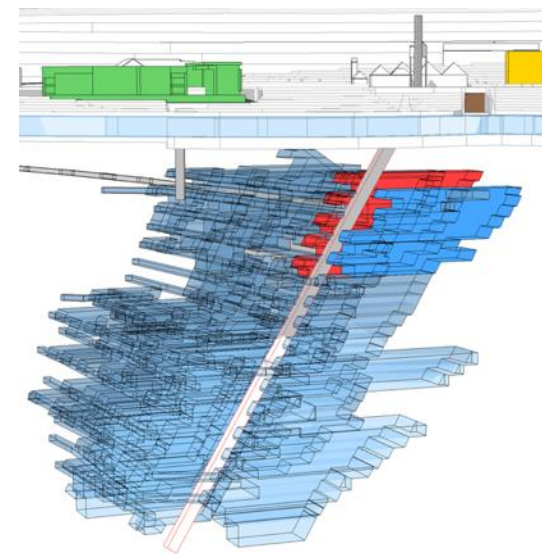
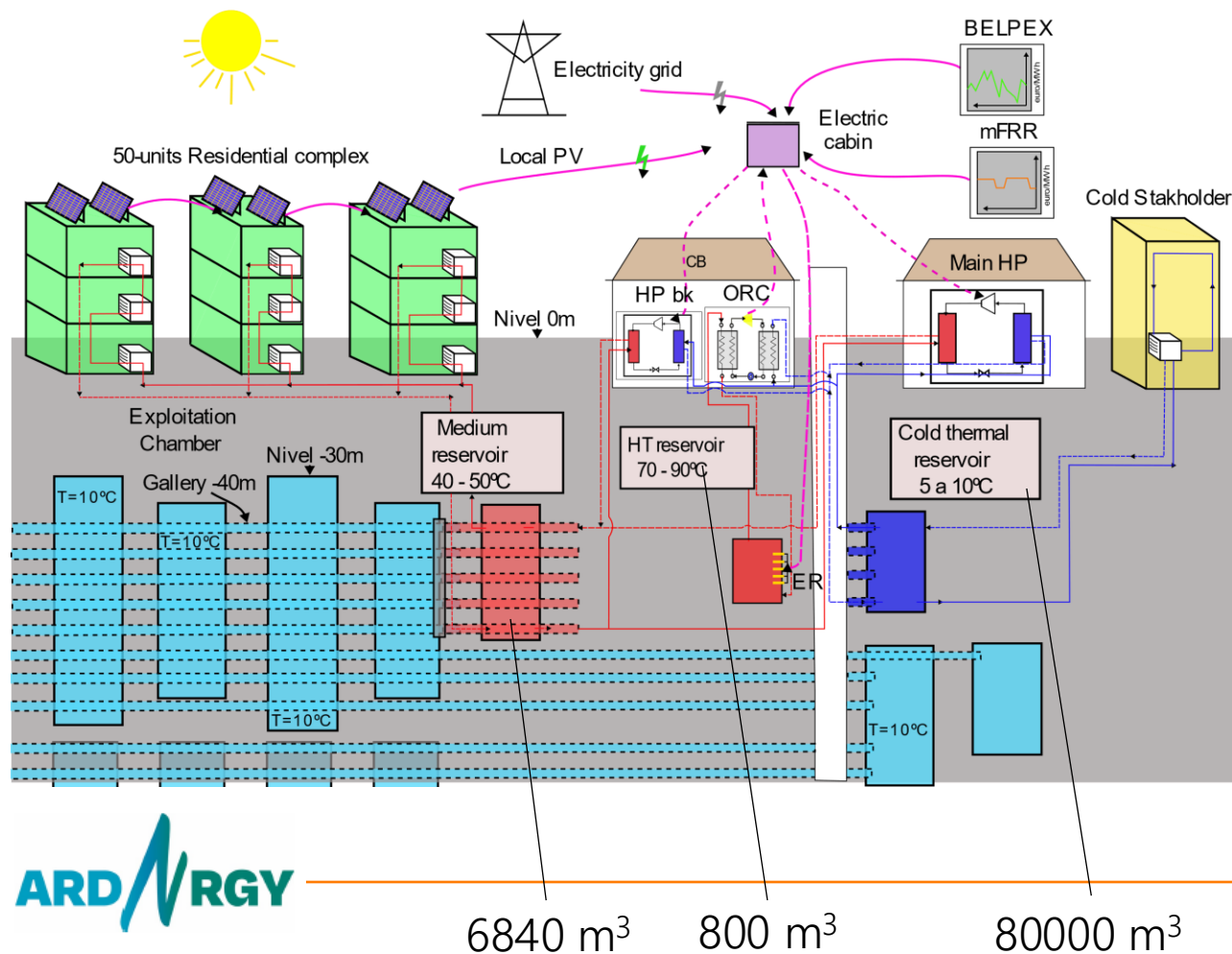


- 8.1 m<sup>3</sup> single water tank (thermocline)
- HP: nominal electrical consumption of 10.7 kWe and a COP of 7.69
- ORC: nominal electrical production is 5.6 kWe with the efficiency is 5.5%
- Investigate **machine dynamics** + possibility of **active charge management**

# Carnot batteries

## *Underground thermal energy storage*

- Use of abandoned flooded mines as massive thermal energy storage.

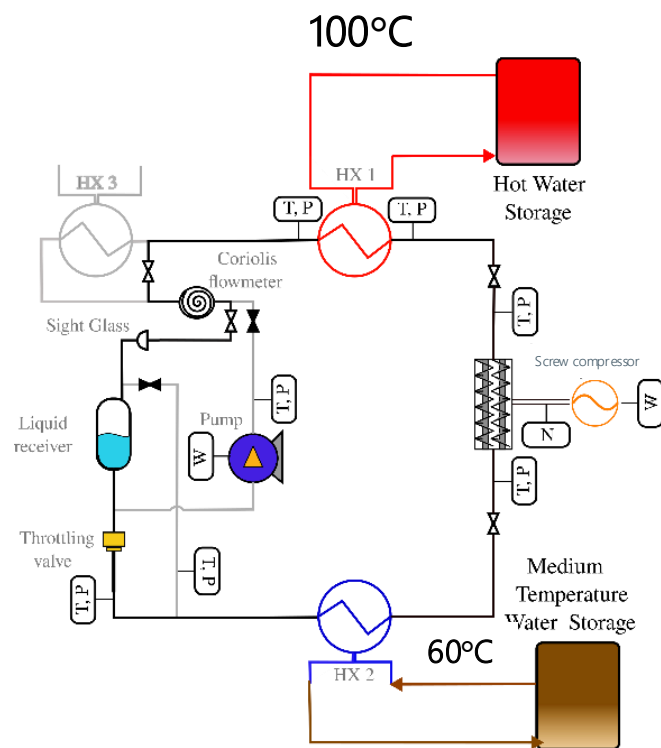


- Prototype under construction.
  - 3 chambers at different temperature (10-50-60°C) + 1 HT chamber overground (90°C)
  - A Carnot battery (50 kW<sub>e</sub> ORC/ORC + ER+ solar panels) + main HP
- Simulation:
  - Main HP produces MT (50°C) and LT water (10°C):
    - large self-consumption of PV (>95%) because of HP
    - 77% of heat demand covered by the mine
    - Need of a cold consumer
  - Carnot battery (10-60-100°C): play on Belpex market + balancing services (mFRR).

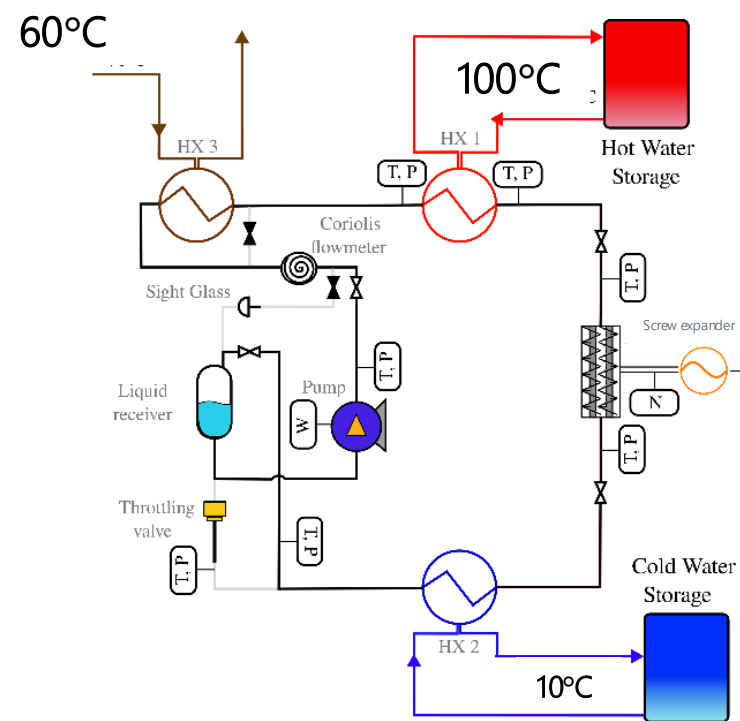
# Carnot batteries

## *Underground thermal energy storage : prototype #3*

- 50 kWe (ORC) + 400 kWth (HP) + solar panels to produce water at 60°C (~ waste heat)
- R1233zd(E)
- Dedicated screw compressor and screw expander (single reversible machine to be tested after)



Heat pump mode

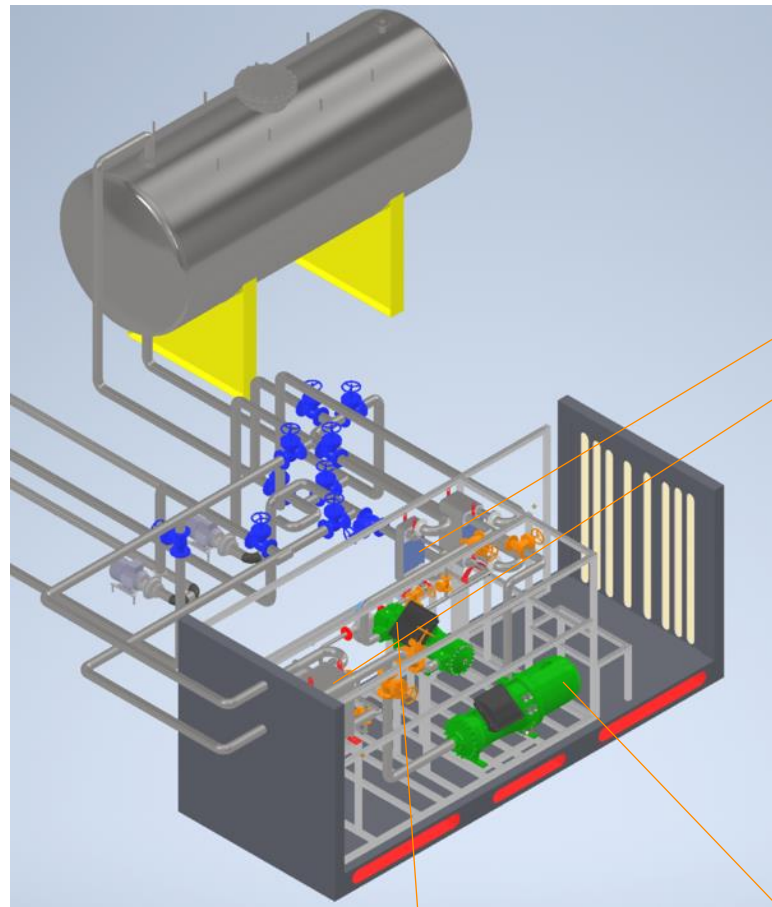


ORC mode



# Carnot batteries

## *Underground thermal energy storage : prototype #3*



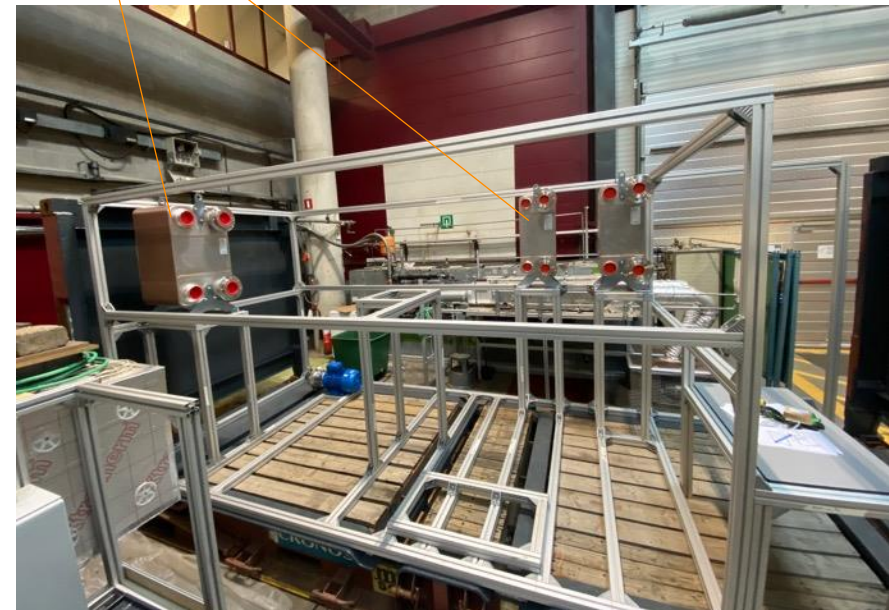
Assembly has just started

HX3 (preheater)

HX2 (low-P HEX)

Expander

Compressor



# Carnot batteries

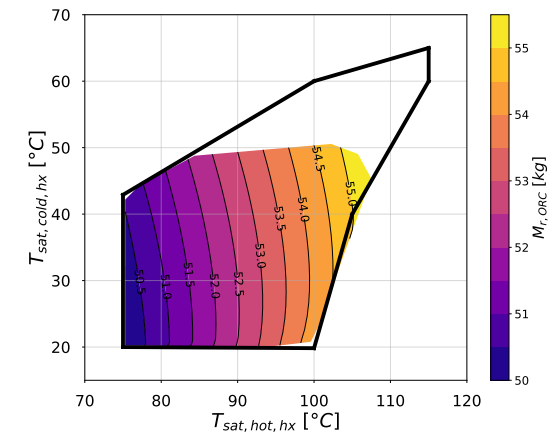
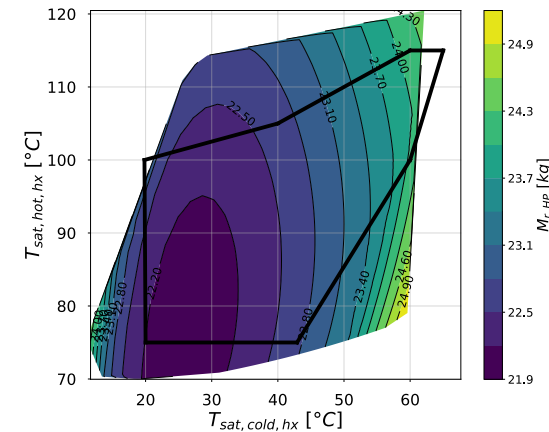
## *Underground thermal energy storage: prototype #3*

Some technical challenges:

- Refrigerant charge

- Larger charge in ORC than HP because of large liquid preheating zone
- 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

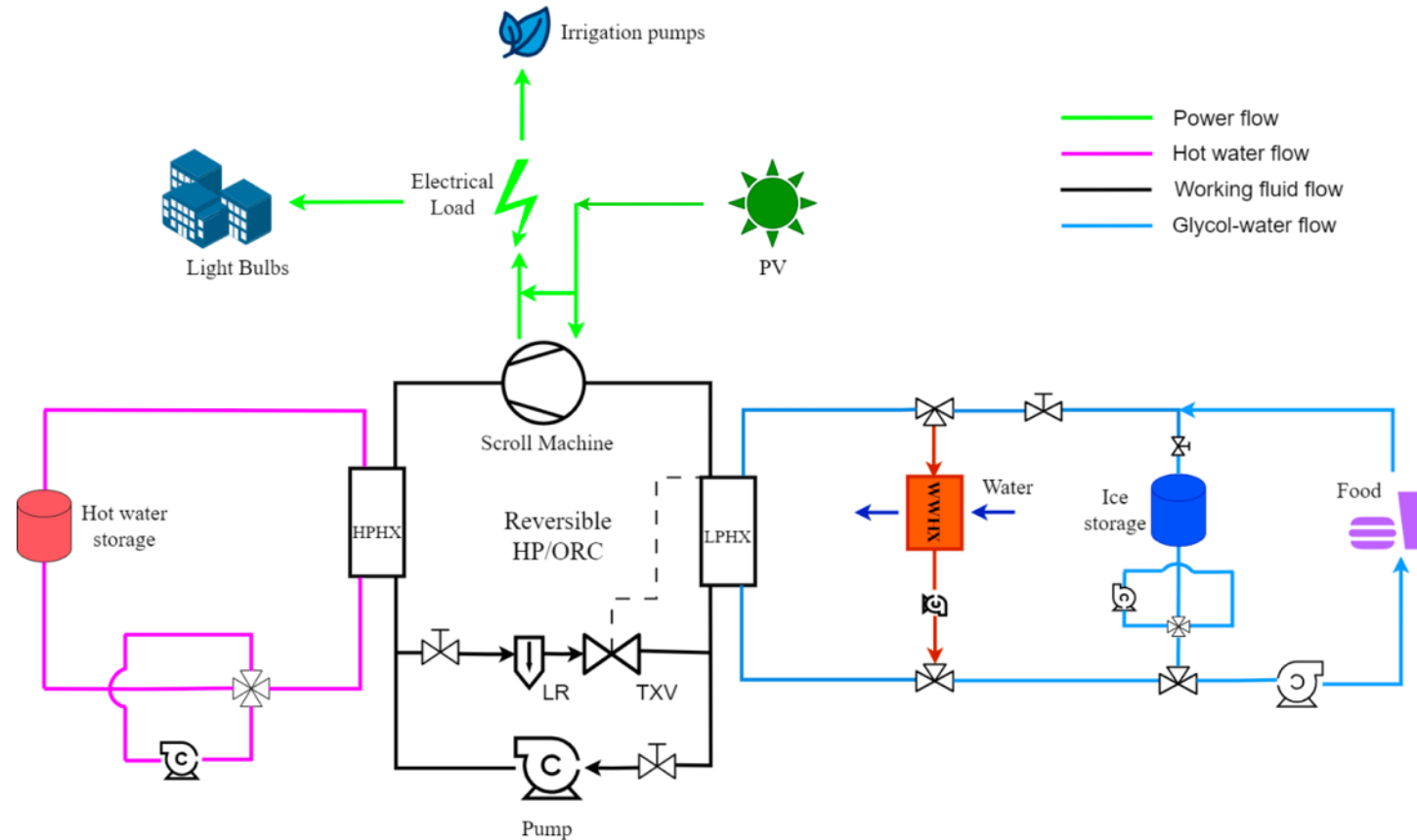
- Lubricating oil: OCR much larger for the expander mode than compressor → Oil management when switching from modes.



# 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.

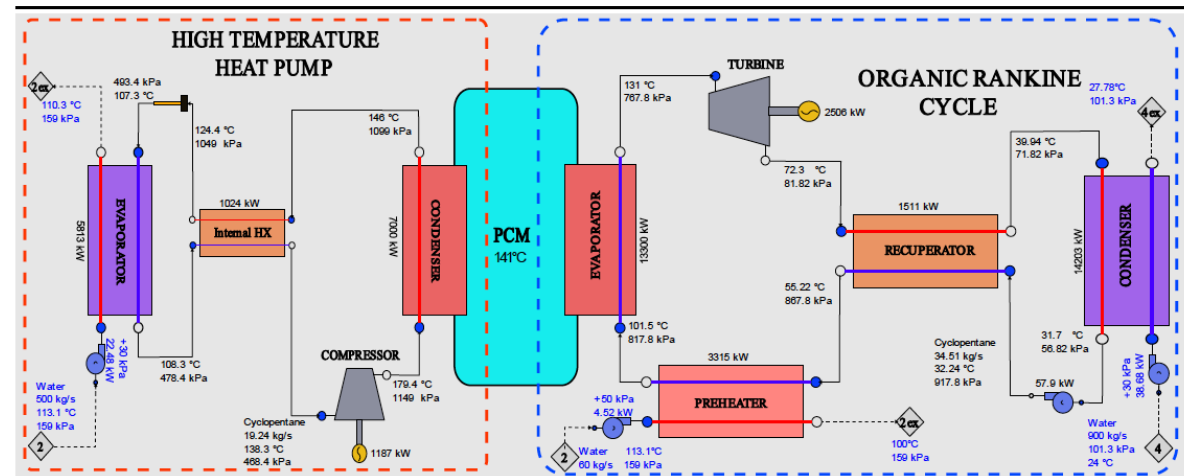
# Conclusions

- In the context of energy transition and sector couplings, 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 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

# Conclusions

## ○ Perspectives:

- ✓ Transcritical CO<sub>2</sub> 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)

# Many thanks for your attention!

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