Cycles de Rankine Organiques et batteries de Carnot

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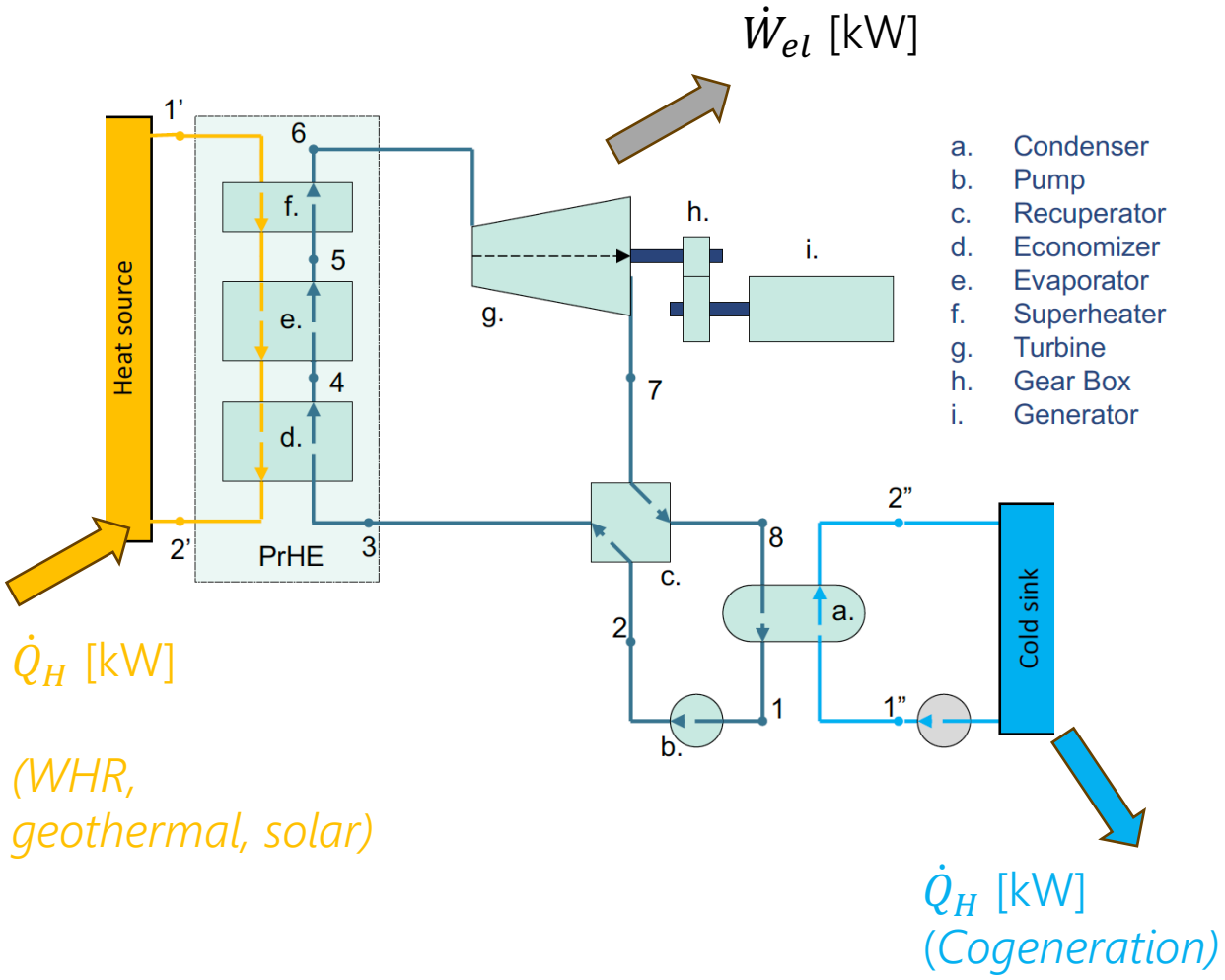
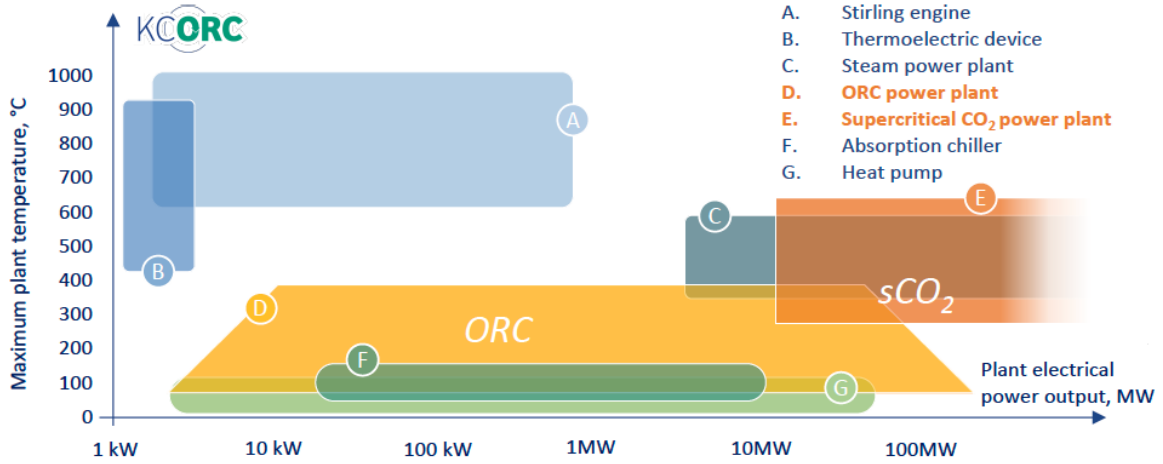
Valorisation de la chaleur fatale – Aperam Châtelet – 15 avril 2025

Organic Rankine Cycles
Working principle

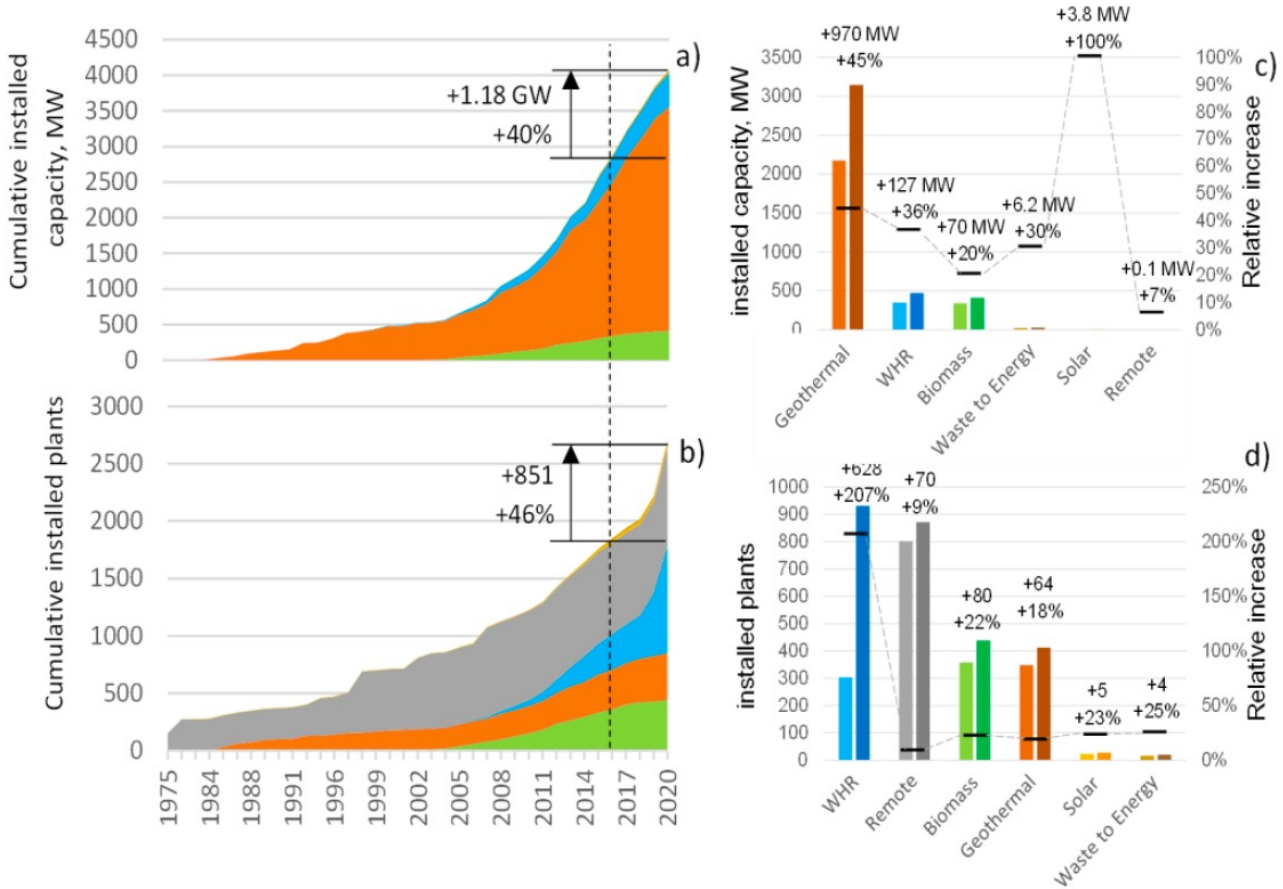


- Uses an **organic fluid** instead of water
- **Low normal boiling points**: well adapted to valorize low to medium temperature heat sources of limited capacity
- **External combustion** engines: can valorize many different heat sources
- Can be operated in **CHP** mode (turbine + condenser)
- Typical performance: efficiency of 5-24% (lower in CHP)



Source: Astolfi et al. (2025)

Organic Rankine Cycles
Evolution of the market



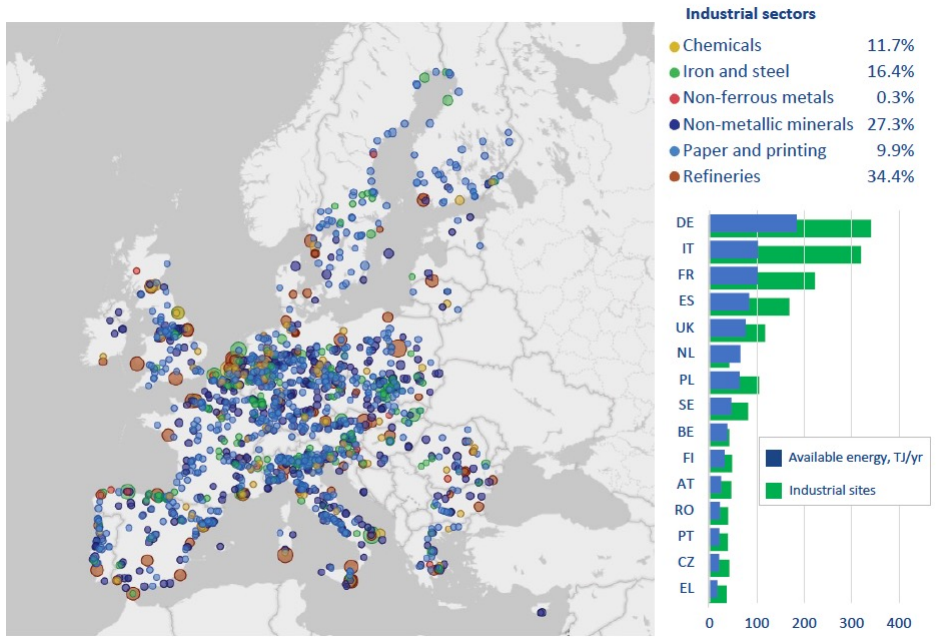
Source: Wieland et al. (2022)

- In 2022: **4.1 GWe** of ORC installed capacity
- Growing market for Waste Heat Recovery (WHR): **60% of new installations** and more than **double capacity** in last decade

	Any type		Waste-heat-to-power		% of Waste-heat-to-power	
	<2013	2013-2023	<2013	2013-2023	<2013	2013-2023
Number of units, world	1428	1849	110	1135	8%	61%
Number of units, EU	428	806	75	459	18%	57%
Capacity, world [MW_e]	1700	3250	165	377.1	10%	12%
Capacity, EU [MW_e]	353.4	284.8	41.7	92.3	12%	32%

Source: Astolfi et al. (2025)

Organic Rankine Cycles
Waste heat recovery market



European industrial sites with potential WHR. Adapted from (European Commission, 2021)

- Very **large potential of untapped thermal energy**: EU28 countries rejected approx. 980 TWh/yr in 2015 (Bianchi et al., 2019)

Country	Clinker	Container glass	Flat glass	Paper	Primary steel	Secondary steel	Chemicals	Food and beverages	Refinery	Total
Belgium	33.4	0	12.1	8.1	14.9	0.3	391.2	130.5	11.2	**602**
Denmark	9.5	0	0	1.9	0	0	26.1	54.5	2.6	**95**
France	85.5	36.9	12.1	32.5	32	0.7	453	427.3	20	**1100**
Germany	164.2	47.3	19.2	89.4	89.8	1.6	1367	486.4	32.6	**2298**
Italy	98.6	41.3	12.1	34.3	19.7	2.2	357.4	266	23.3	**855**
The Netherlands	13	0	0	11	20.6	0	666.8	193.5	19.8	**925**
United Kingdom	43.1	26.7	9.1	17.4	30.6	0.2	300.2	254.7	19.8	**702**
Total	**447.3**	**152.2**	**64.6**	**194.6**	**207.6**	**5**	**3562**	**1813**	**129.3**	**6577**

Potential of ORC installation (in MWe) (de Beer et al., 2017)

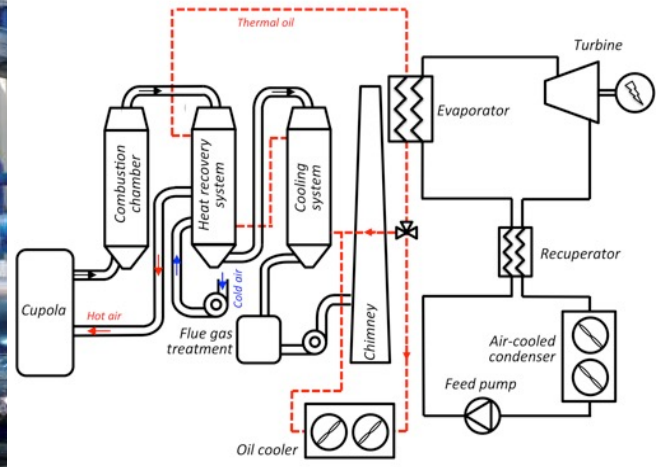
- In 2016: more than 40 ORC plants for WHR in Europe (**26 MWe**): Cement, glass, iron and steel (Cruz et al., 2021)

⇒ **Potential still not fully covered**

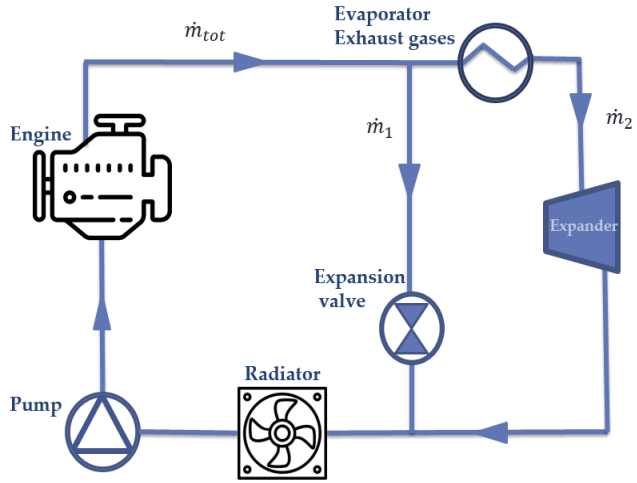
- according to KCORC, **150 TWhe/year** could be generated from European industry waste heat =20 millions homes = 19 x 1 GWe nuclear (Astolfi et al. 2025)

WHR Organic Rankine Cycles
Strengths/opportunities

- **Mature technology**. Already business models for iron and steel, cement, glass, non-ferrous metals, (petro-)chemicals industries, engines
- **Available products** on the market: European manufacturers propose modules of 20 kWe-20 MWe.
- ORC operation is **autonomous** (no skilled operators on site) + low maintenance
- ORC module can adapt to **varying heat sources**
- **WHR does not produce CO_2**, decentralized, dispatchable
- Could decrease dependency of Europe on imported fuels
- Condenser dry-cooling is possible (**no water consumption**)
- Local electricity production can cope with **limitations of grid extension** (especially if electrification of industry)



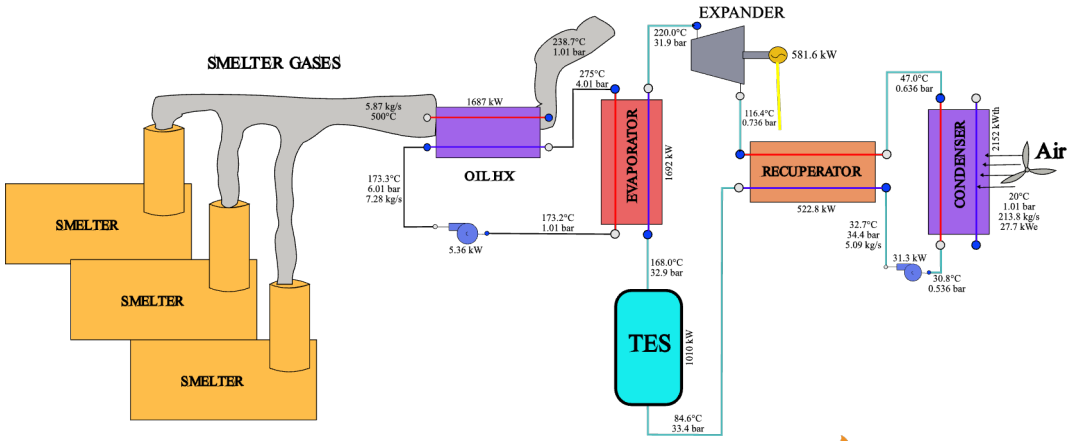
Source: Enertime



Heat recovery on engines

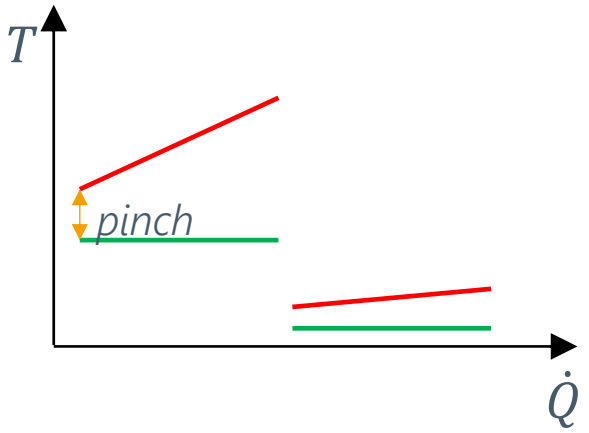
Organic Rankine Cycles
R&D opportunities

- Heat from highly **intermittent processes**:
  - ✓ develop innovative **thermal energy storages**
  - ✓ advanced **control** (also useful for FDD and predictive maintenance)



Source: Janod et al., 2025

- **Low temperature** waste heat: large HEX to limit t° pinch (cost, pressure drop!) + large heat source flow (rate pressure drop!)

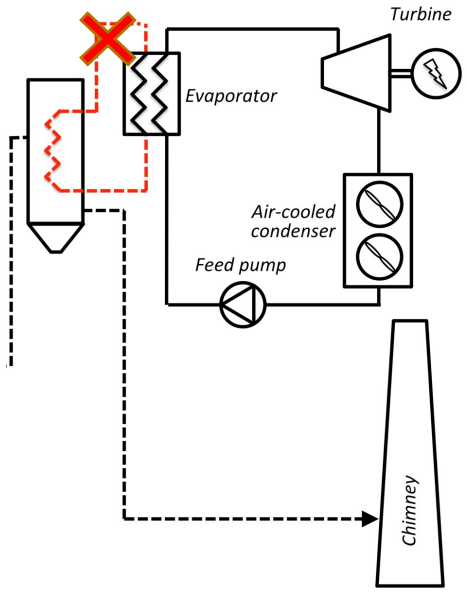


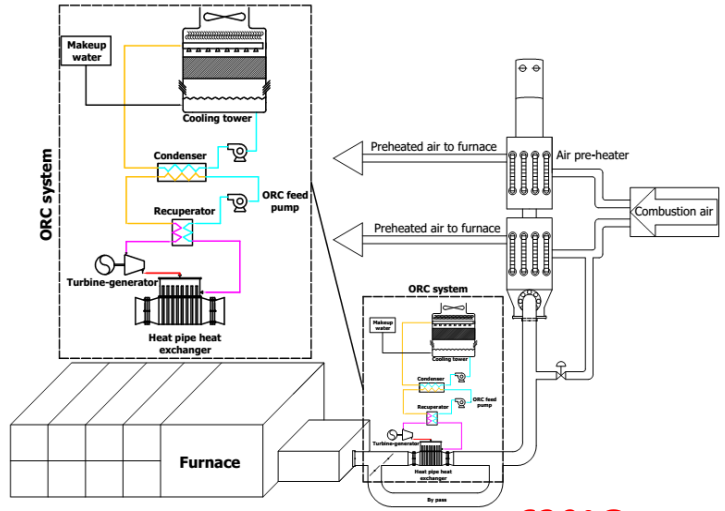
Organic Rankine Cycles
R&D opportunities

- Develop **direct vaporization solutions**: better performance, reduction of cost, but less controllability, hot spots, more difficult to store heat… or **heat pipes**

- Use of **natural fluids**: pentane, sCO2 (flammability, high pressure, charge limitation/control)

- **Small scale systems cost**: standardization, simplified design, …

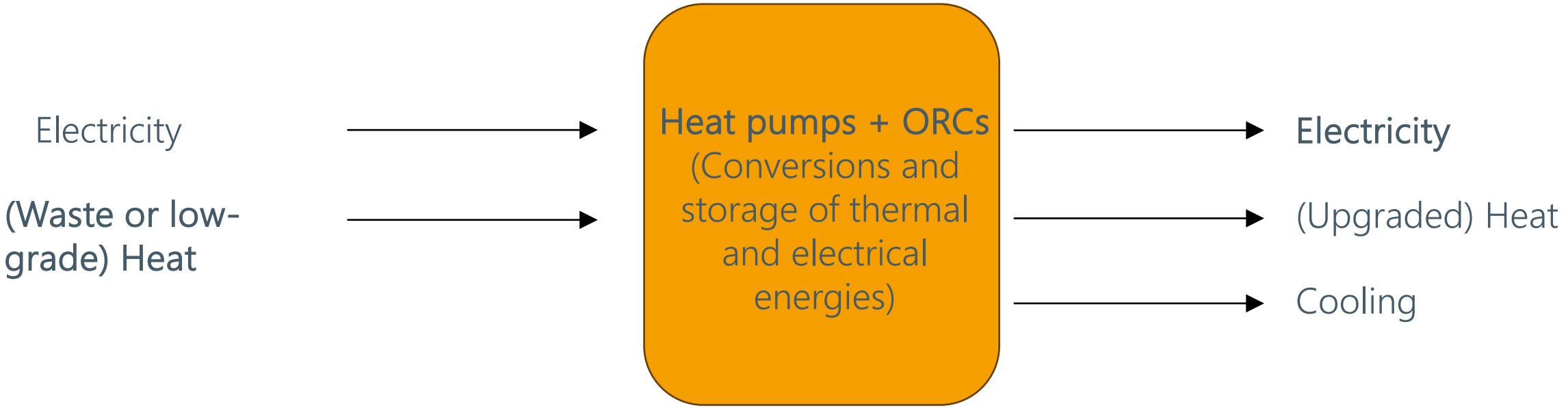




Projet ORCAL (Le et al., 2017)

Hybridization with other conversion technologies

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**.

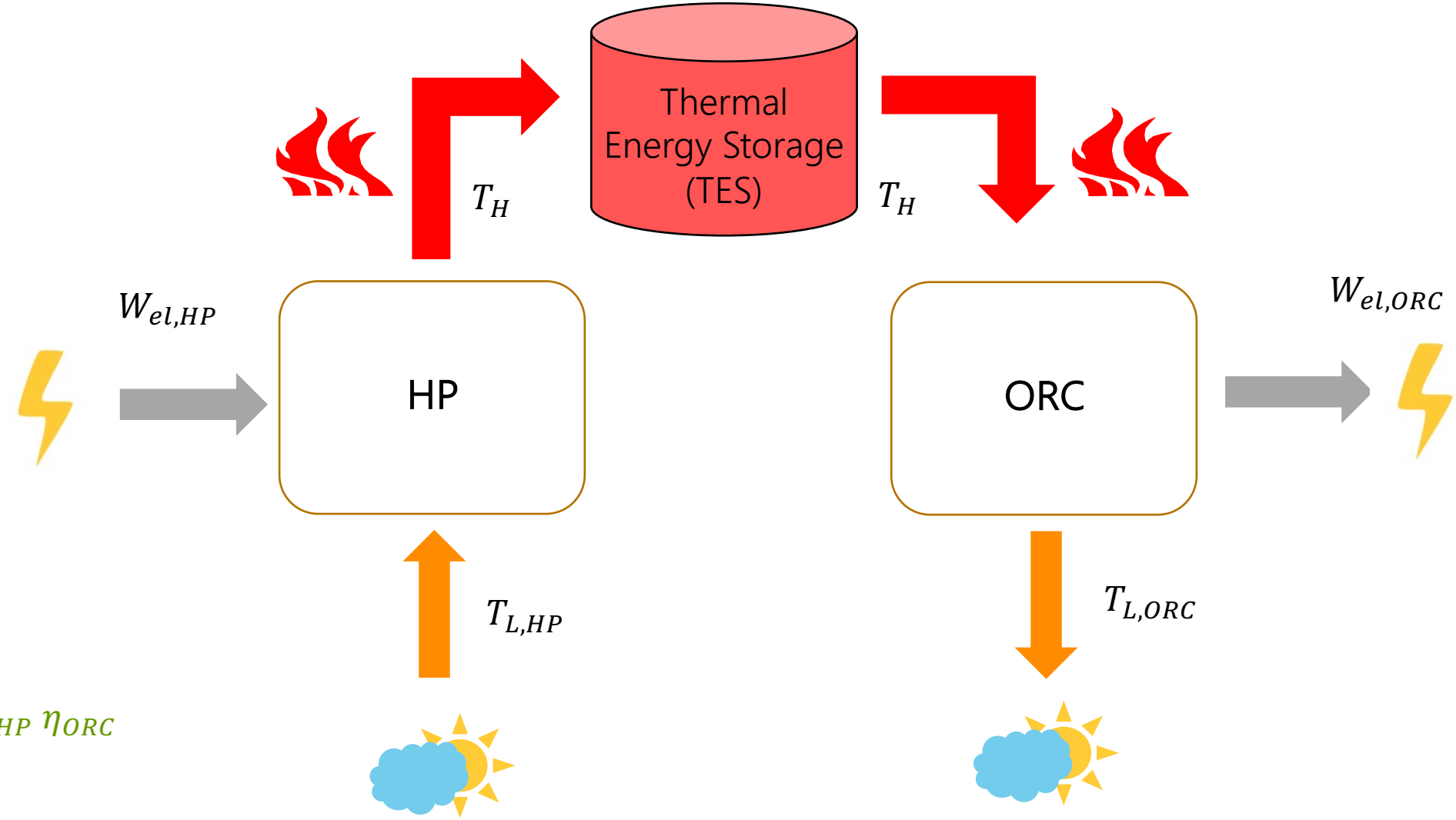


→ Hybridization of ORCs with heat pumps appears promising.

Carnot batteries

Coupling of heat pump/ORC/storage

- Electricity is stored in the form of thermal exergy
- The heat pump and ORC can be a unique invertible machine

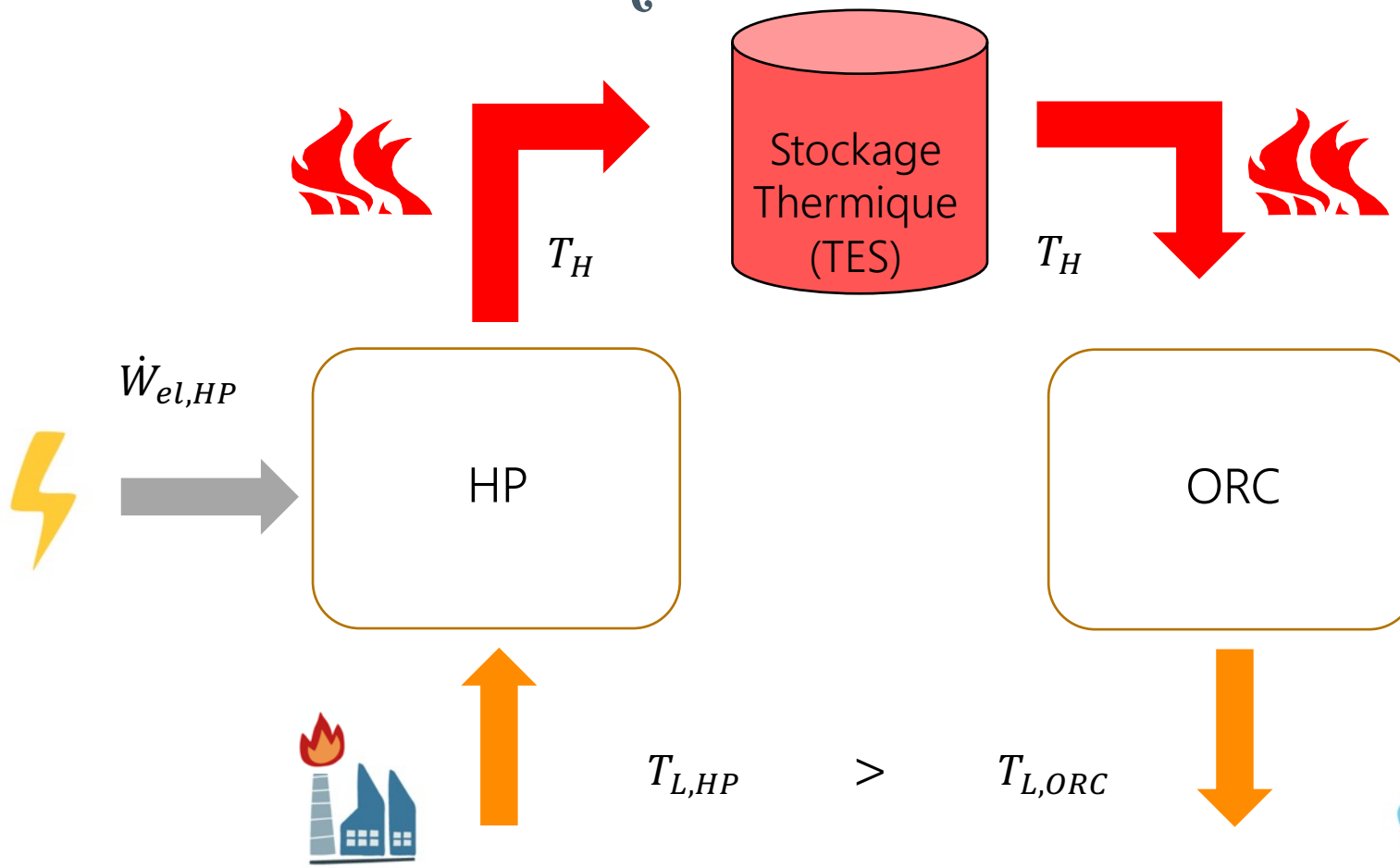


Power-to-power efficiency :

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

Carnot batteries

Waste heat valorization



- WHR valorization: increase of power-to-power efficiency
- Other criteria: exergy efficiency, energy storage density

- For $T_{L,HP} - T_{L,ORC} \gtrsim 30\ K$, Carnot batteries "degenerate" into a storage + ORC conversion system

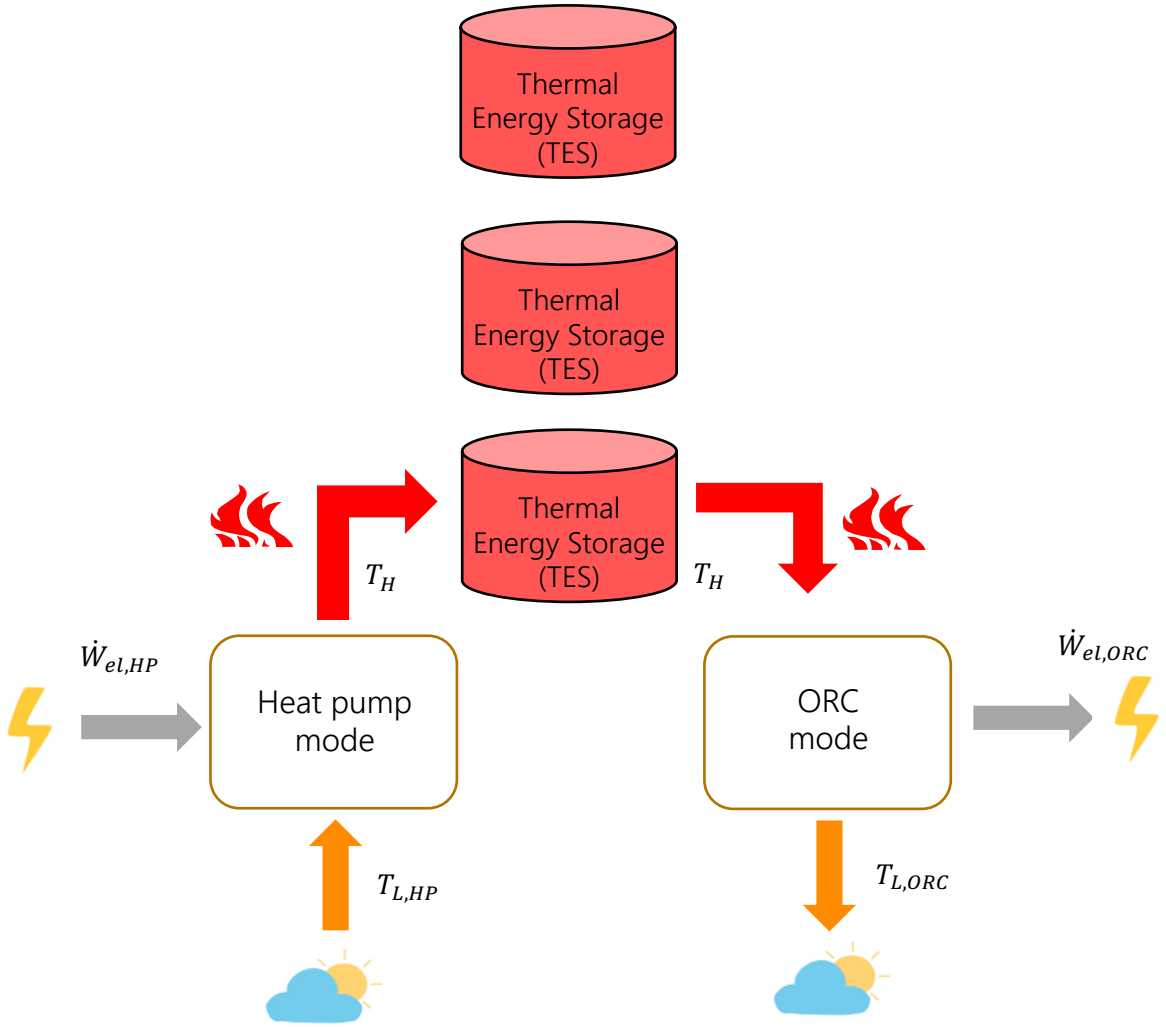
Valorization of waste heat

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

Carnot batteries

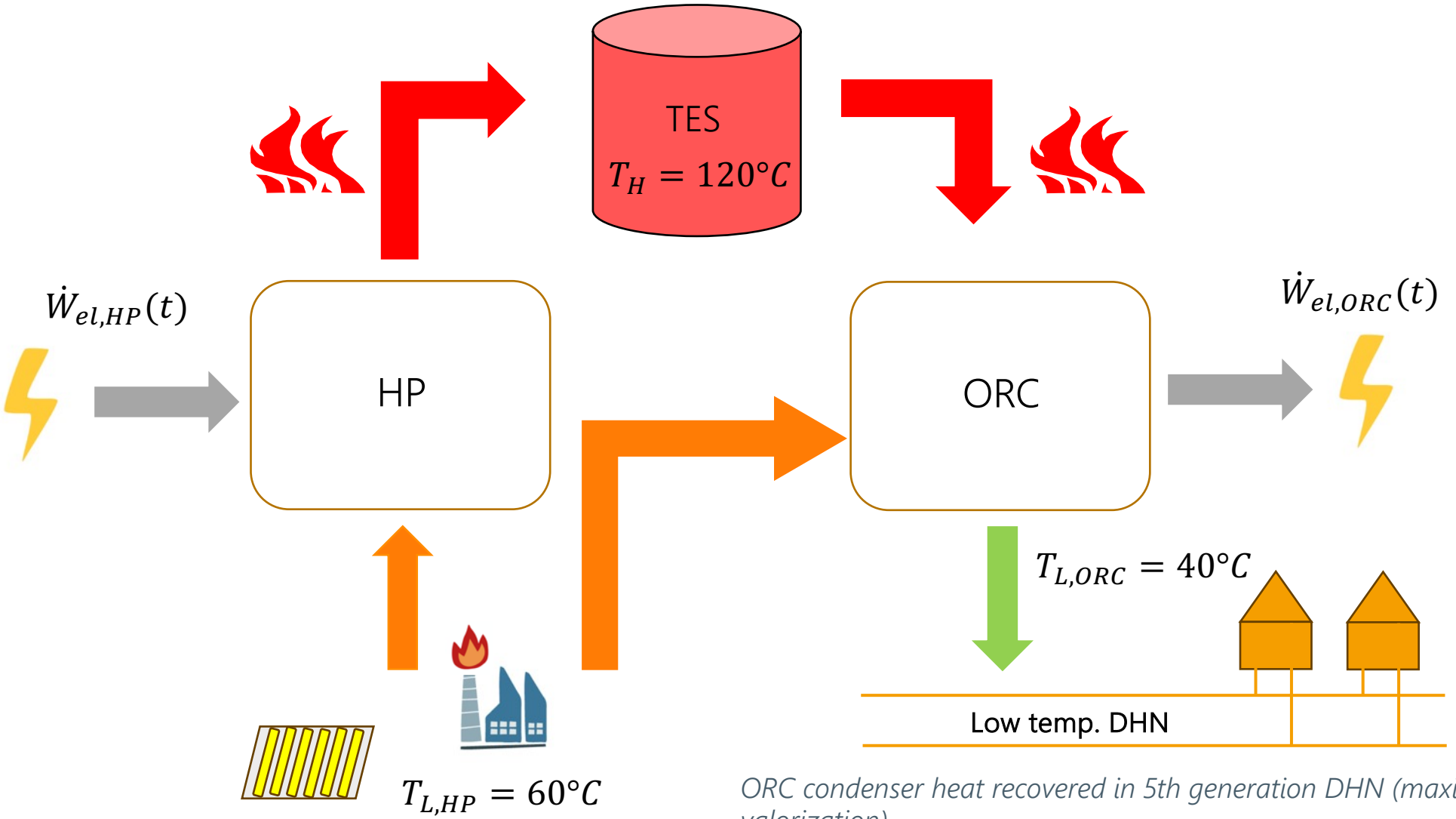
Working principle and advantages

- 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

Heat and power sector coupling

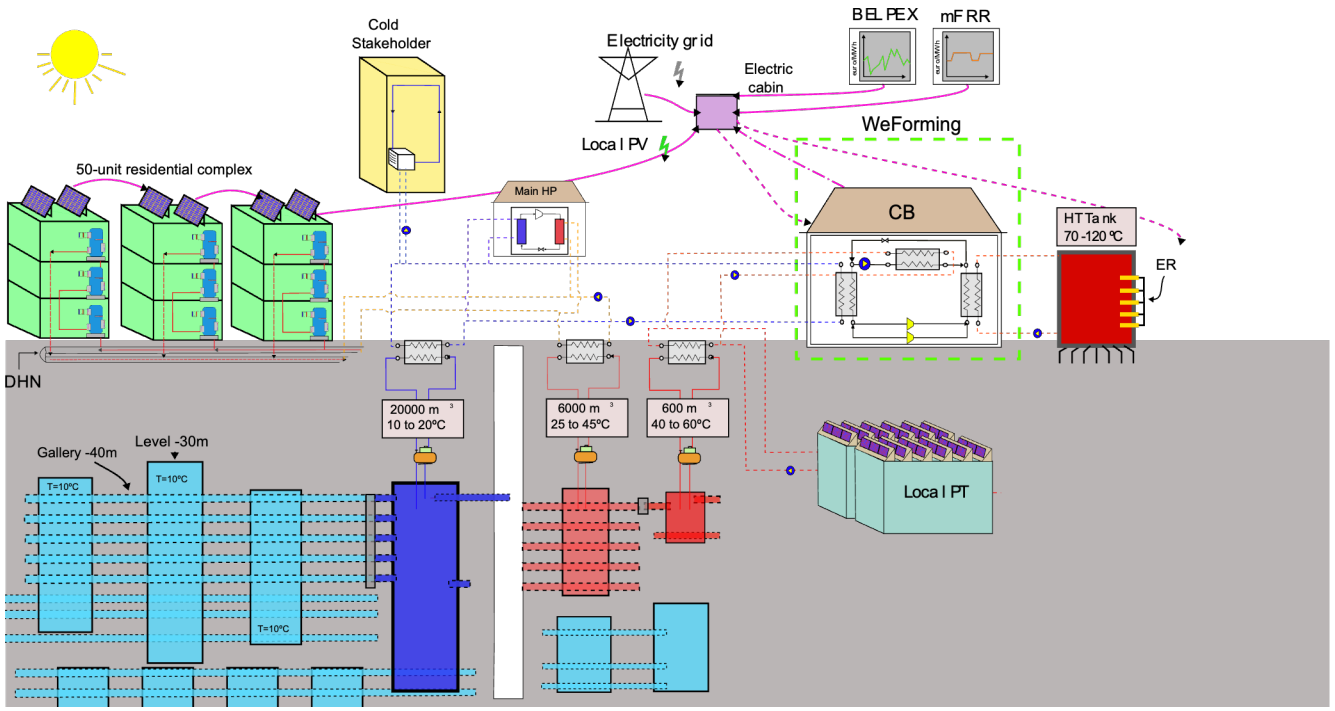


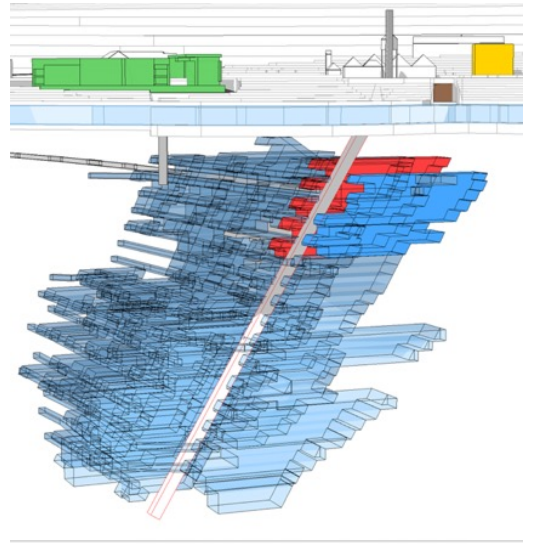
ORC condenser heat recovered in 5th generation DHN (maximal energy valorization)

Carnot batteries

Underground thermal energy storage

- Use of abandonned flooded mines as massive thermal energy storage (Martelange, Be).



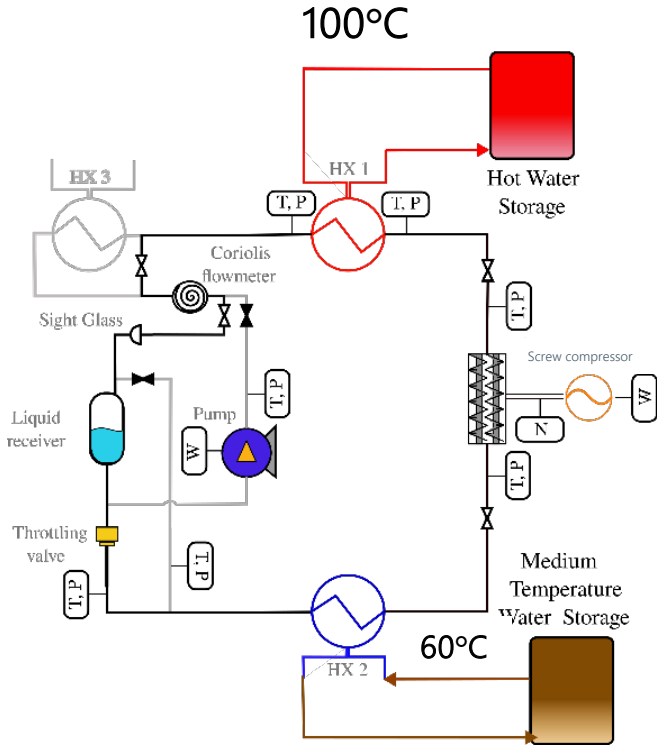


- Photovoltaic-Thermal solar collectors as WHR.
- 30-65 kWe in ORC mode, 80-120°C high temperature, 10-40°C low temperature, net efficiency around 7%.
- 200-700 kWth in HP mode, 80-120°C high temperature, 30-70°C low temperature, COP between 3 and 6.
- R1233zd(e) as working fluid.

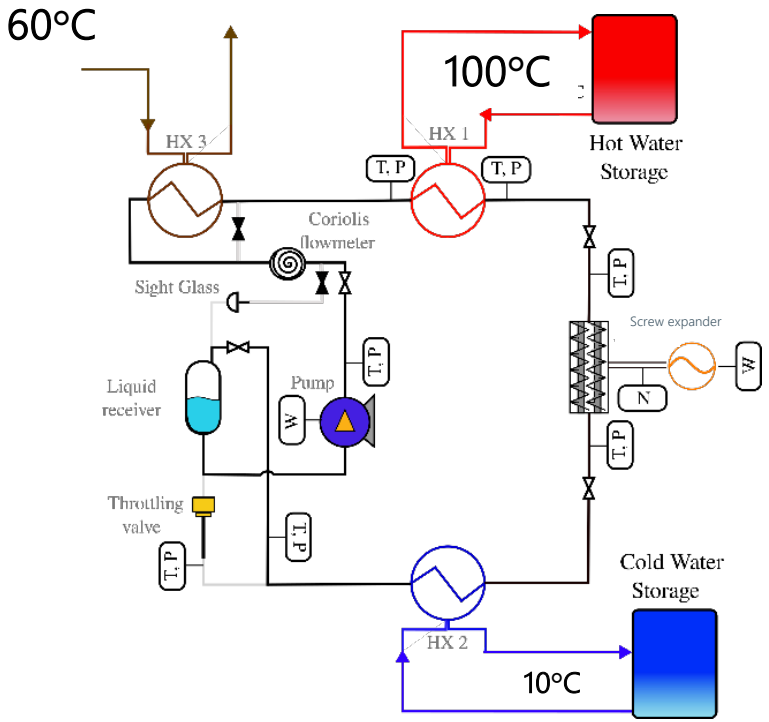
Carnot batteries

Underground thermal energy storage : prototype #3

- Semi-reversible machine with dedicated compressor and expander.



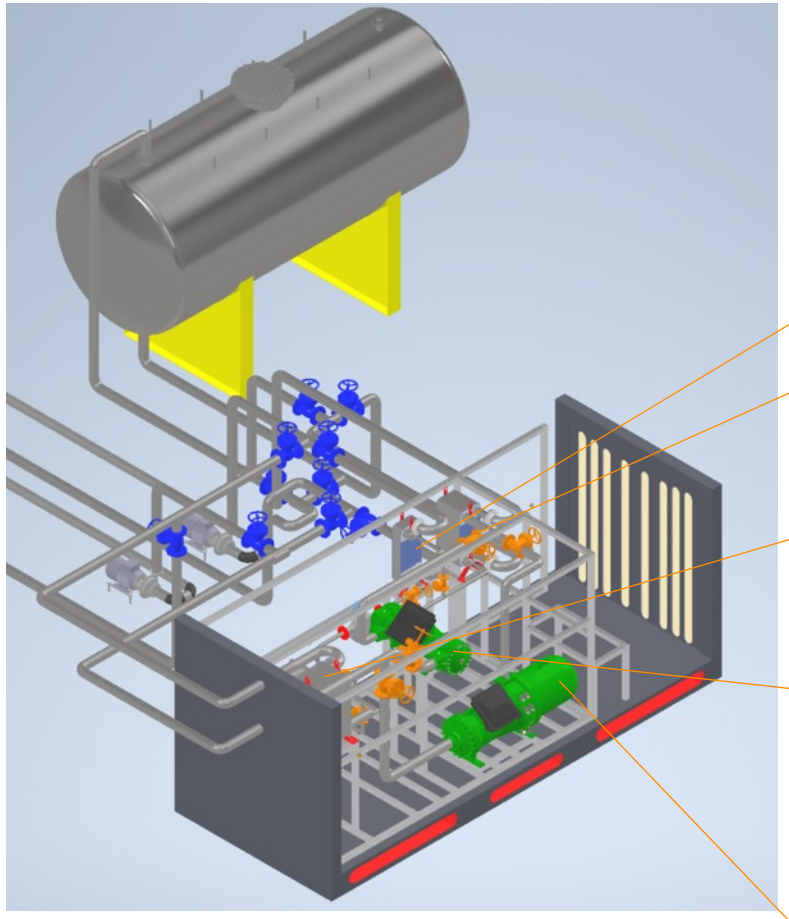
Heat pump mode



ORC mode

Carnot batteries

Underground thermal energy storage : prototype #3



Assembly has just started

HX3 (preheater)

HX1 (high-P HEX)

HX2 (low-P HEX)

Expander

Compressor

Conclusions

- **ORC** is a **mature technology** for waste heat recovery in the temperature range of **100-500°C** with thermal capacities magnitude from **1 kWth to 100 MWth**.
- Potential of untapped thermal energy is very large: **150 TWhe/year in EU27** could be produced with ORC.
- ORC power production in existing industrial sites (no "Not-in-my-backyard" difficulties).
- No CO_2 emission, autonomous system, no need for cooling towers, rather flexible with transient waste heat, CHP mode possible.
- Eases the electrification of industry, reduces dependency on fossil fuels, increases competitiveness of industry (energy accounts for a large part of production cost).
- ORC = complementary technology to **Heat Pumps** (upgrade of lower temperature heat)

- **Carnot batteries** is an interesting option for WHR + electricity storage (for waste heat temperature typically lower than 60°C)
- Power-to-power efficiency of around **35-45%** but requires **fewer strategic resources** than electrochemical storage and can offer services to the grid.

Merci beaucoup pour votre attention!

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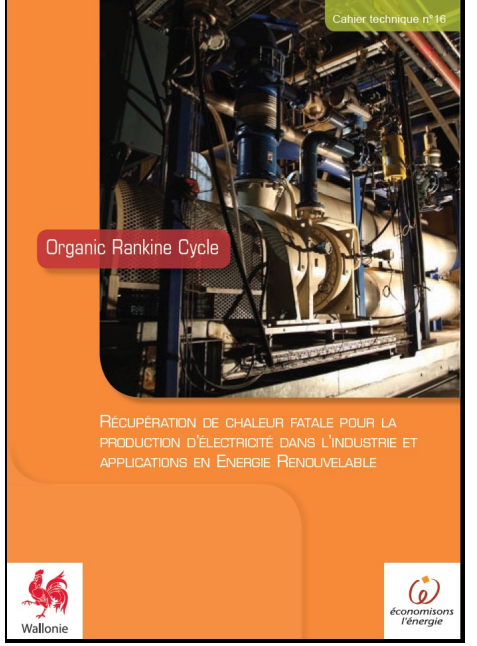

2014

Thermal Energy Harvesting

The Path to Tapping into a Large CO_2-free European Power Source

Version 2.0

2025

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