

Potential of Thermally Integrated Pumped Thermal Energy Storage when integrated in industrial process

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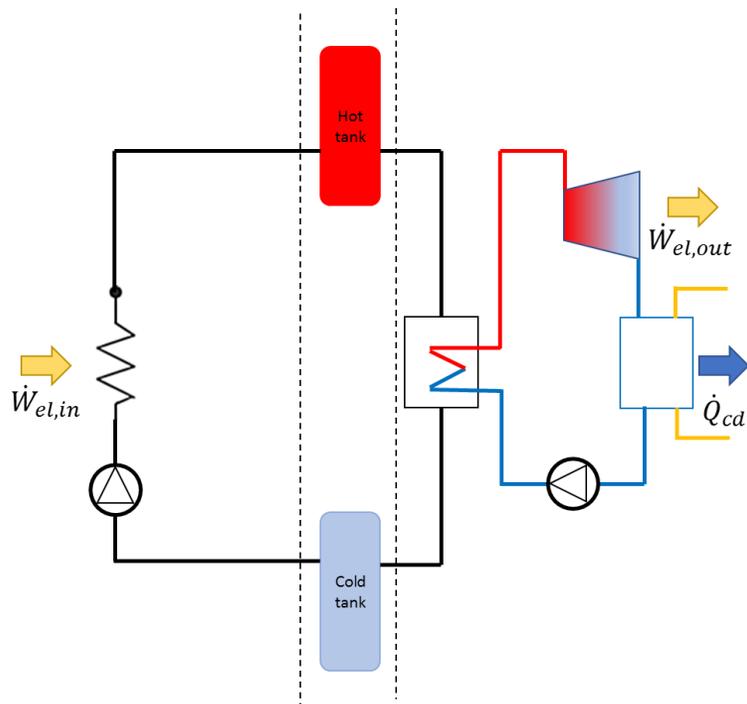
- Introduction
 - Carnot battery: concept
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 - Integration in industrial process
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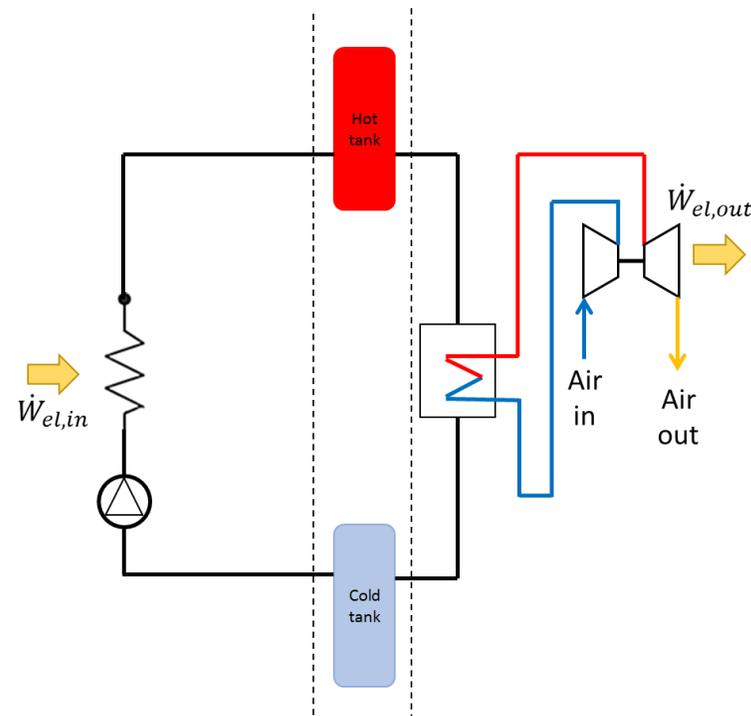
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Existing architectures: charging the storage with electrical resistance

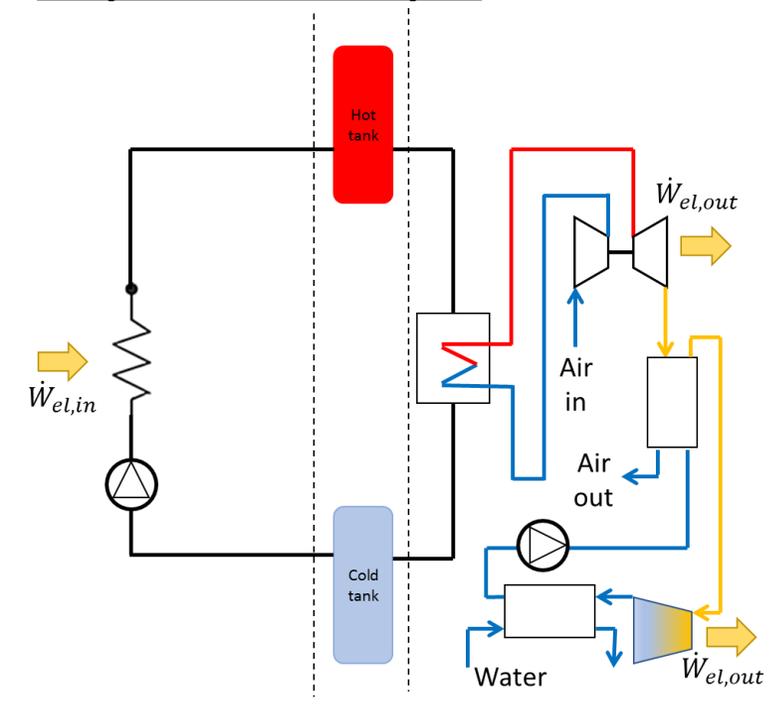
1. Electrical heater + Rankine cycle



2. Electrical heater + Brayton cycle

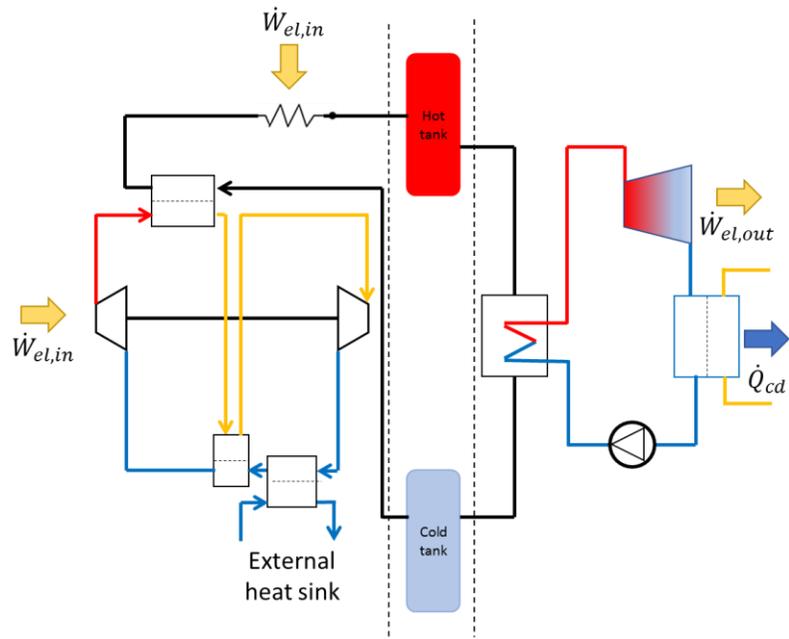


3. Electrical heater + Combined Brayton/Rankine cycle

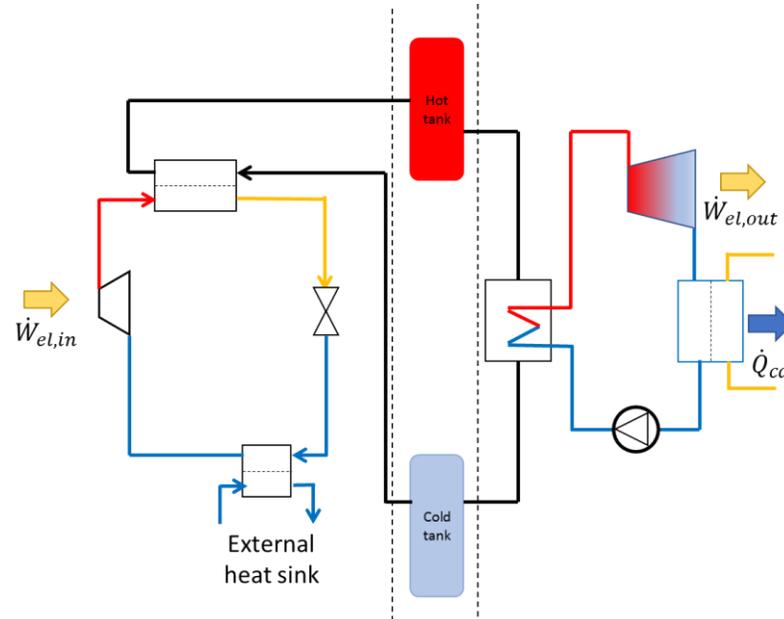


Existing architectures: charging the storage using a heat pump cycle

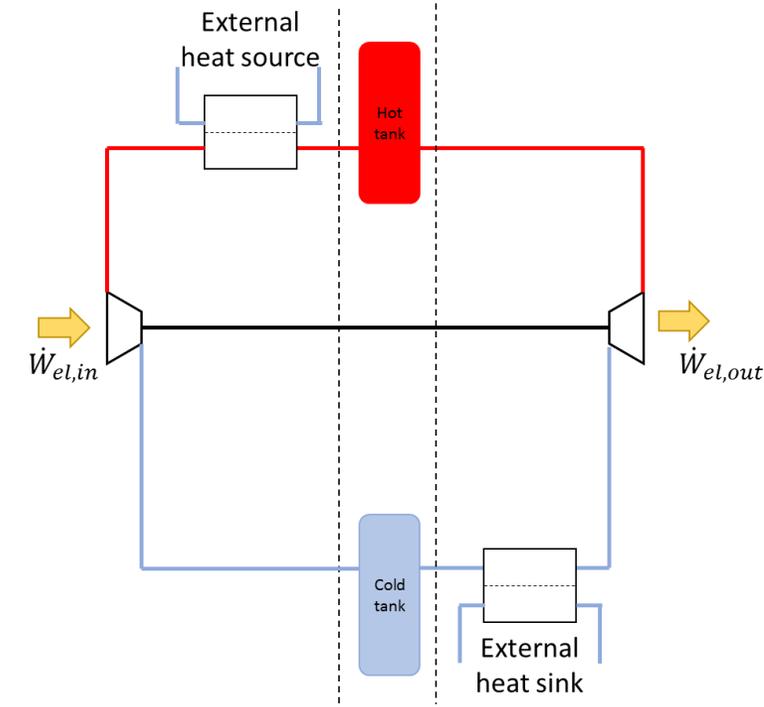
4. Reverse Brayton cycle + Rankine cycle



5. Vapor compression cycle + Rankine cycle



6. Reversible Brayton cycle



Possible architectures: Summary

System	Storage Temp [°C]	Round-trip Efficiency [%]	Compactness [kWh/m ³]	Estimated TRL
1. Electrical heater + Rankine cycle	400-600°C	[35-40]	4	9
2. Electrical heater + Brayton cycle	800-1400°C	[30-35]	-	5
3. Electrical heater + Combined Brayton/Rankine cycle	800-1400°C	[45-55]	-	5
4. Reverse Brayton cycle + Rankine cycle	500-600°C	[40-60]	-	5
5. Vapor compression cycle + Rankine cycle	100-200°C	[45-65]	[3-15]	7
6. Reversible Brayton cycle	-70-700°C	[52-65]	[10-30]	6

Possible architectures: Summary

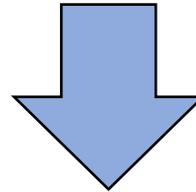
Carnot Battery

Advantages

- No site constraints
- Long life expectancies (20-30 years)
- Small environmental footprint

Disadvantages

- Low round-trip efficiency (30-65 %, to be compared with 65-85 % for the pumped-storage hydroelectricity)



Solution to increase the efficiency: the **Thermally Integrated Carnot Battery**

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The TI Carnot battery: a multi-sources energy concept

1. **Production and storage of high-grade (100-600°C) heat using a heat pump cycle**
2. **Possibility of high-grade (100-600°C) heat generation using the heat storage**
3. **Possibility of electricity generation using a heat-to-power cycle**

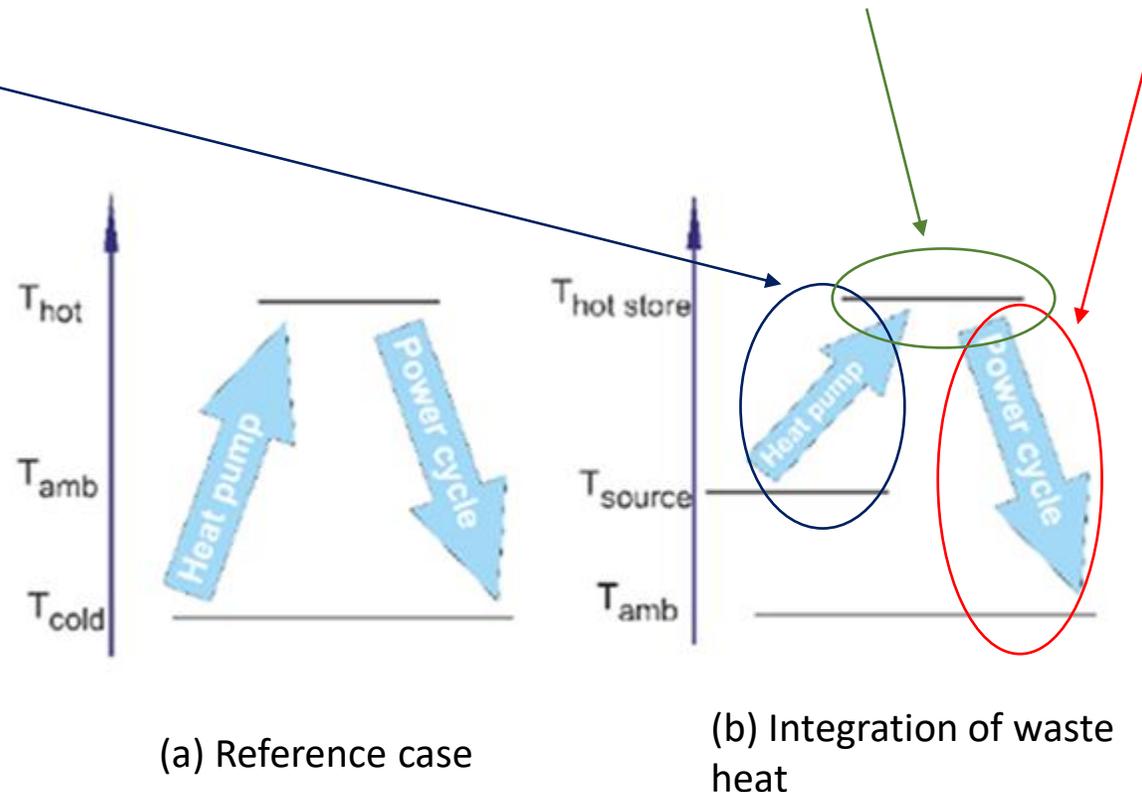


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The TI Carnot battery: integration in industrial process

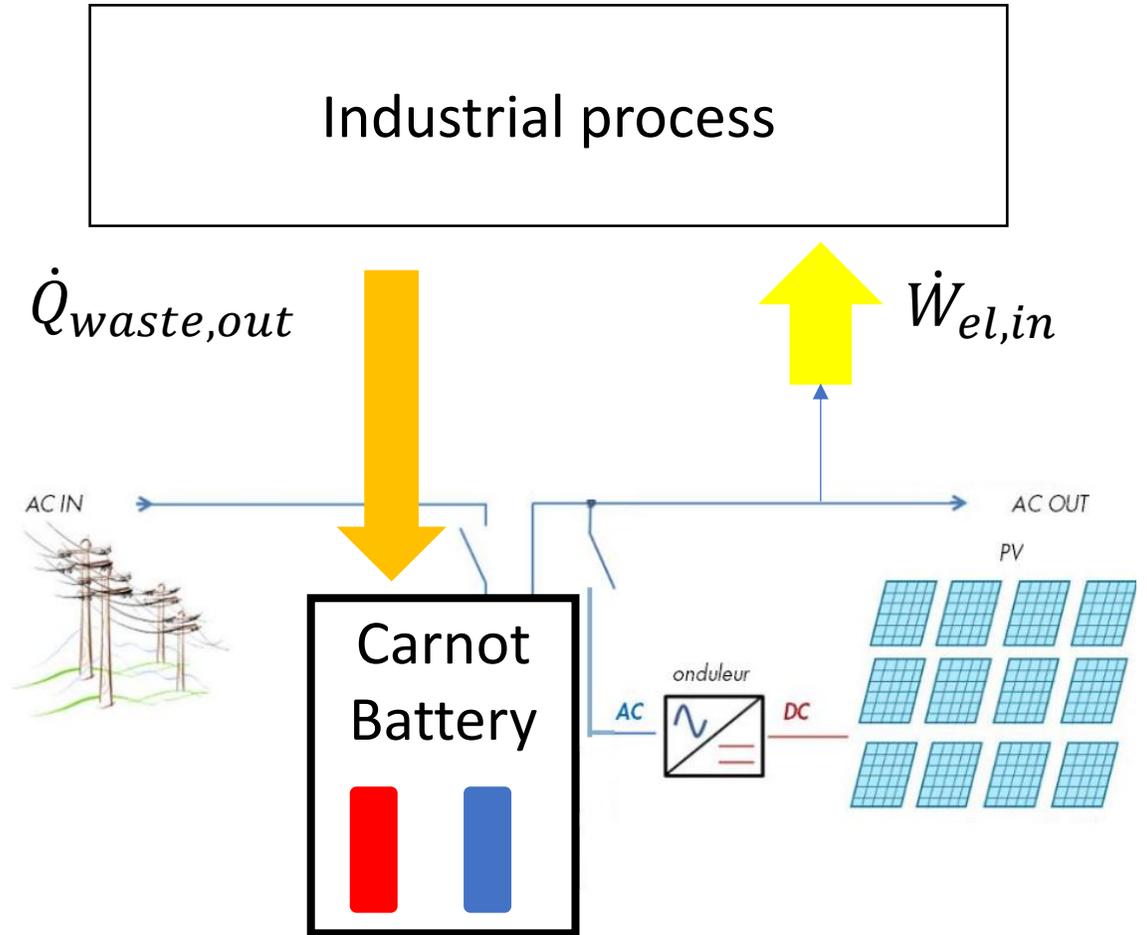
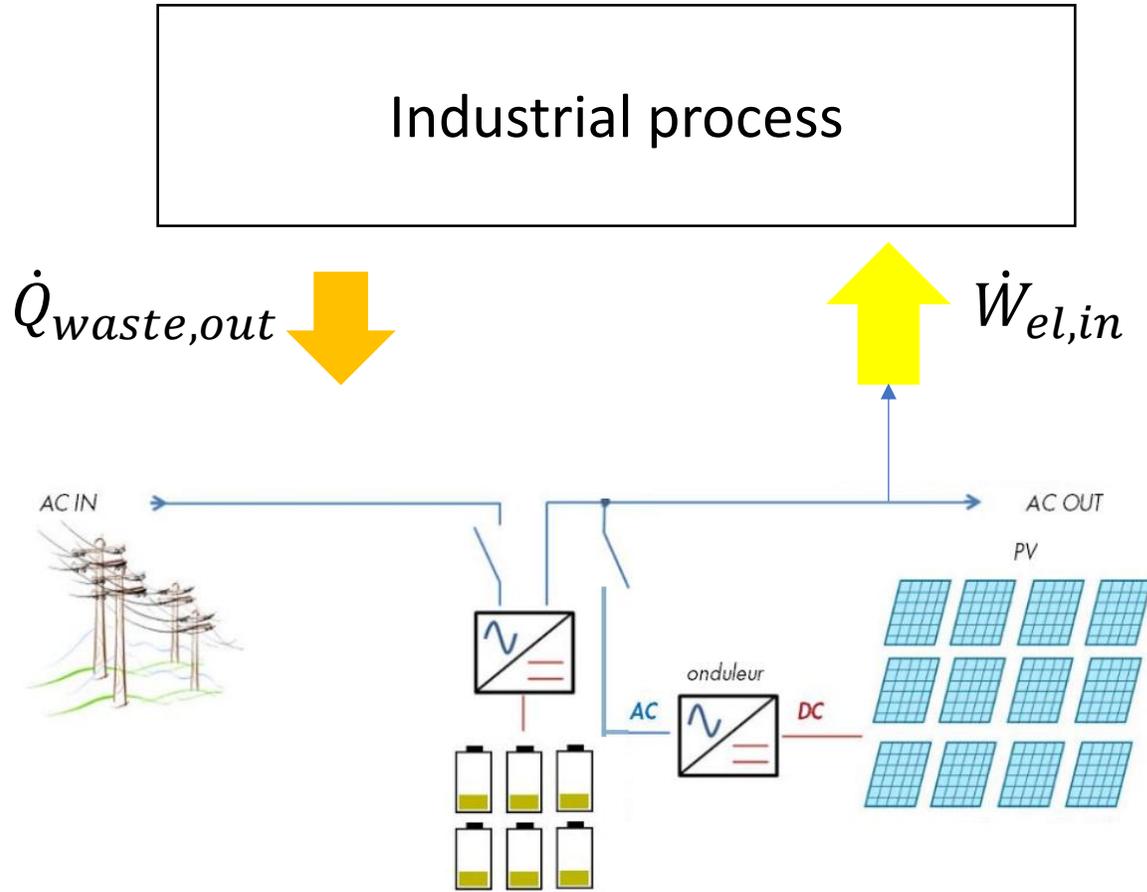
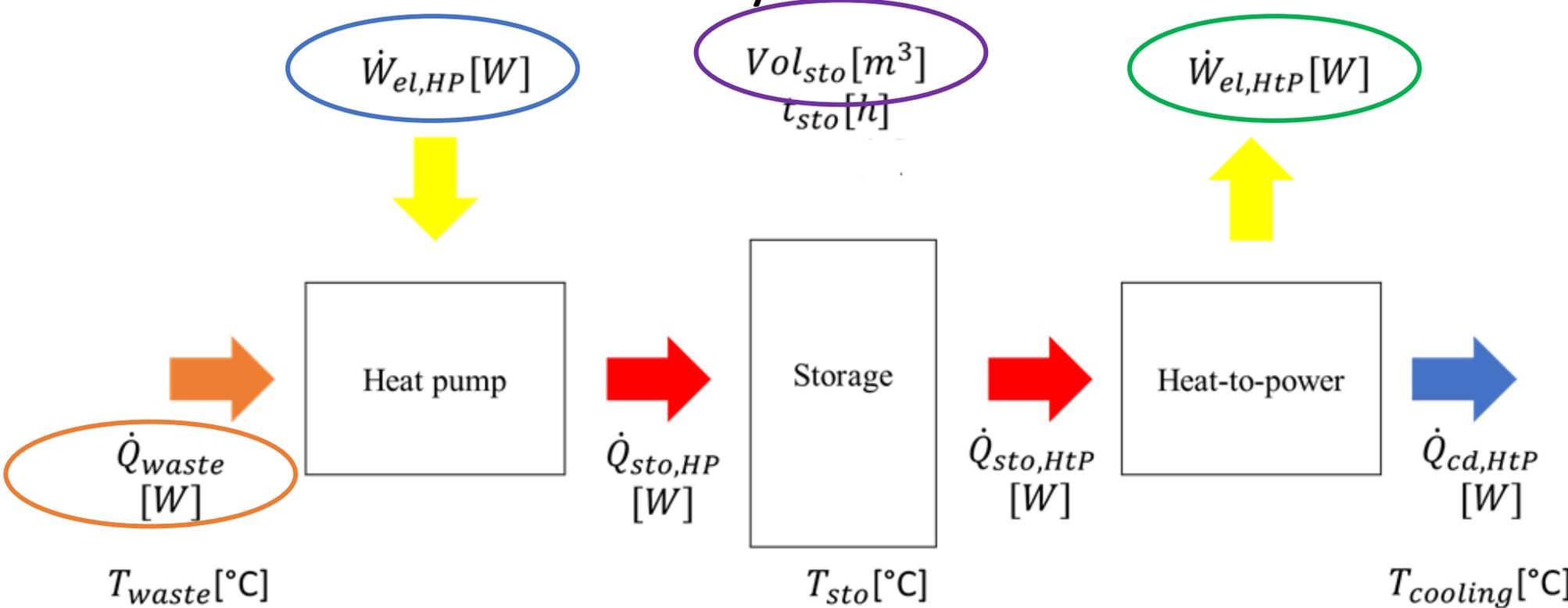


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The TI Carnot battery: Performance factors



$$\epsilon_{PtP} = \frac{\dot{W}_{el,HtP}}{\dot{W}_{el,HP}} [-]$$

Power-to-Power efficiency
Or round-trip efficiency

$$f_{waste} = \frac{\dot{W}_{el,HtP}}{\dot{Q}_{waste}} [-]$$

Waste heat ratio

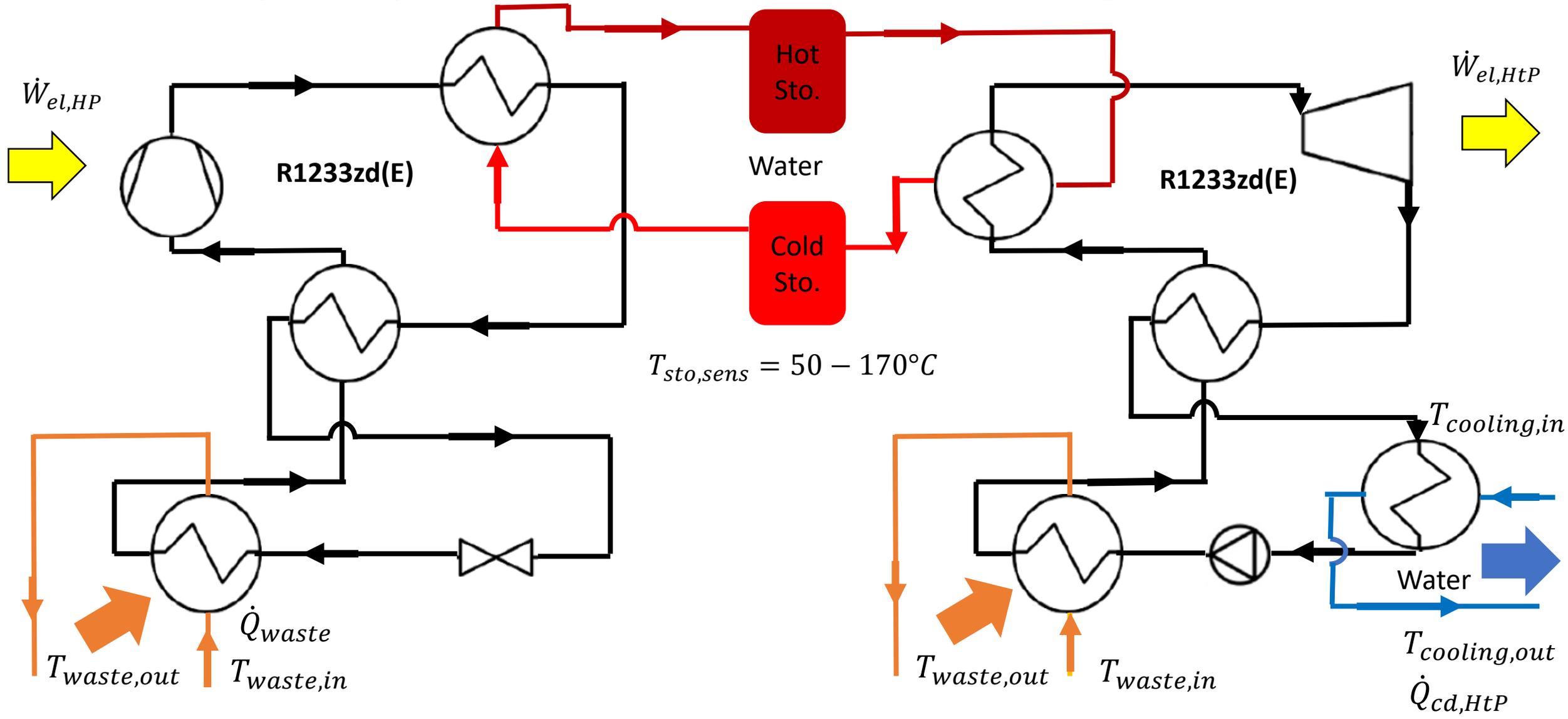
$$\gamma_{sto} = \frac{\dot{W}_{el,HtP}}{Vol_{sto}} [kW/m^3]$$

Compactness

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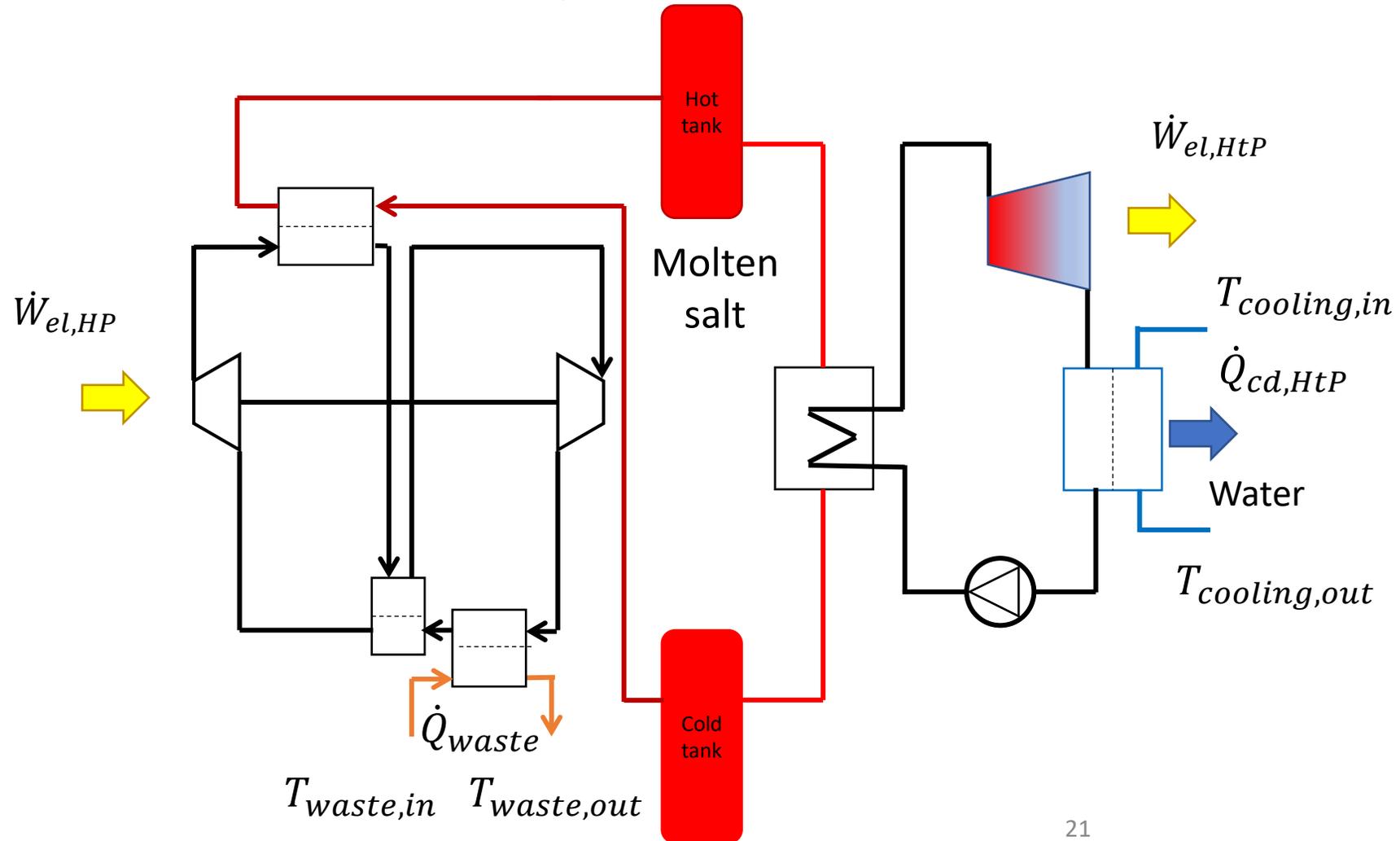
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Heat pump + ORC + sensible storage (1)



CO2 heat pump + Steam Rankine cycle (3)

$$T_{sto,sens} = 250 - 550^{\circ}\text{C}$$



Model Hypothesis

- **Steady-state** model, no dynamic and part-load operation not considered
- Constant **pinch-point** in the heat exchangers (**5 K**)
- Constant **isentropic efficiencies** for the compressors and the turbines (**85 %**)
- Constant **isentropic efficiency** of the pump: **60 %**
- **Cooling water** temperature range: **30-35°C**
- Constant **overheating** and **subcooling** in the heat pump and the ORC (**5 K**)
- Inlet **waste heat** temperature: between **50 and 90°C**
- **Storage temperature** limits:
 - **Water**: 60-170°C
 - **PCM**: 60-150°C
 - **Molten salt**: 250-550°C

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Results

System 1

Heat pump + ORC + water sensible storage

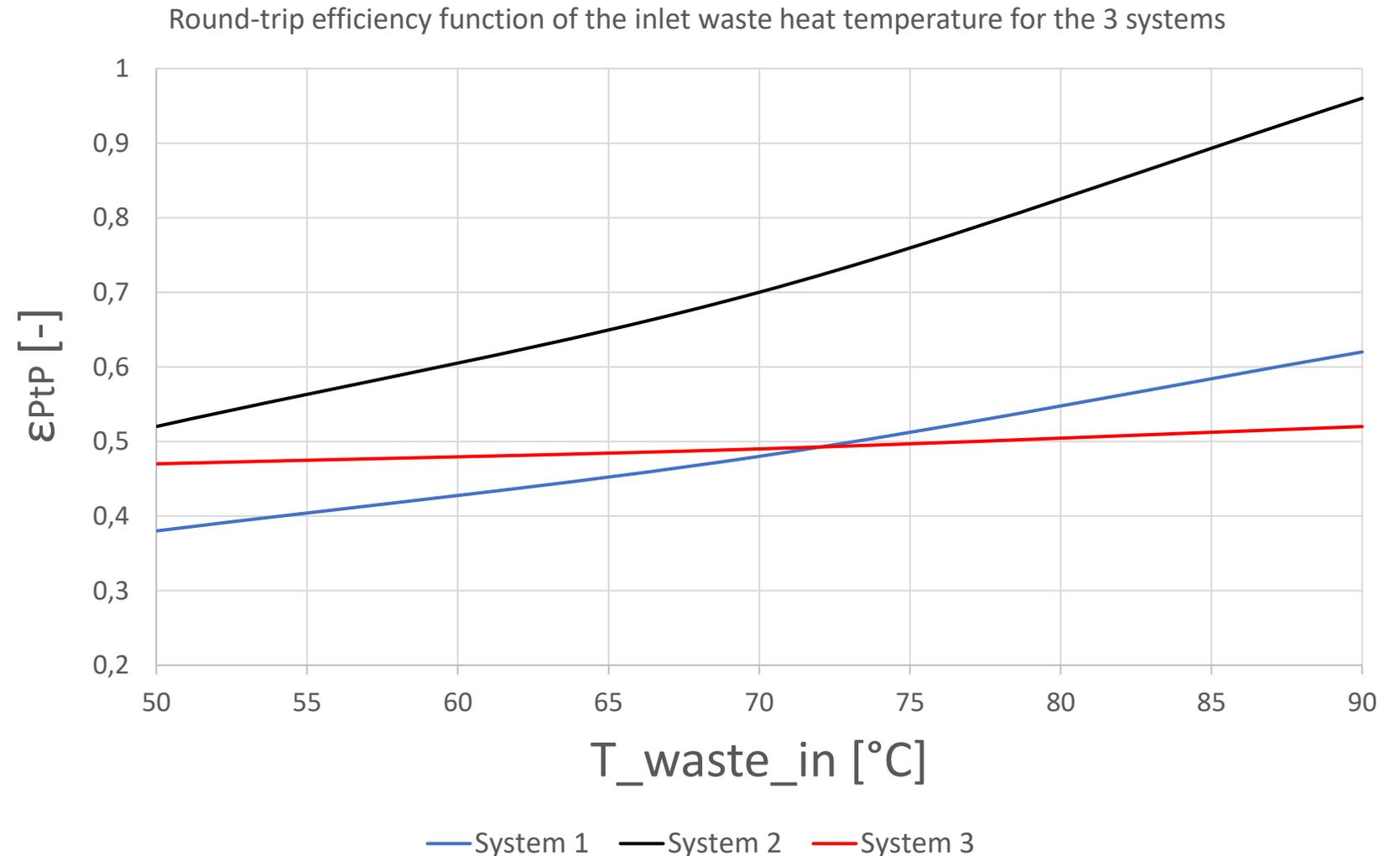
System 2

Heat pump + ORC + PCM latent storage

System 3

CO₂ heat pump + Steam Rankine cycle + sensible molten salt storage

Round-trip efficiency vs inlet waste heat temperature



Results

$$f_{waste} = \frac{\dot{W}_{el,HtP}}{\dot{Q}_{waste}} [-]$$

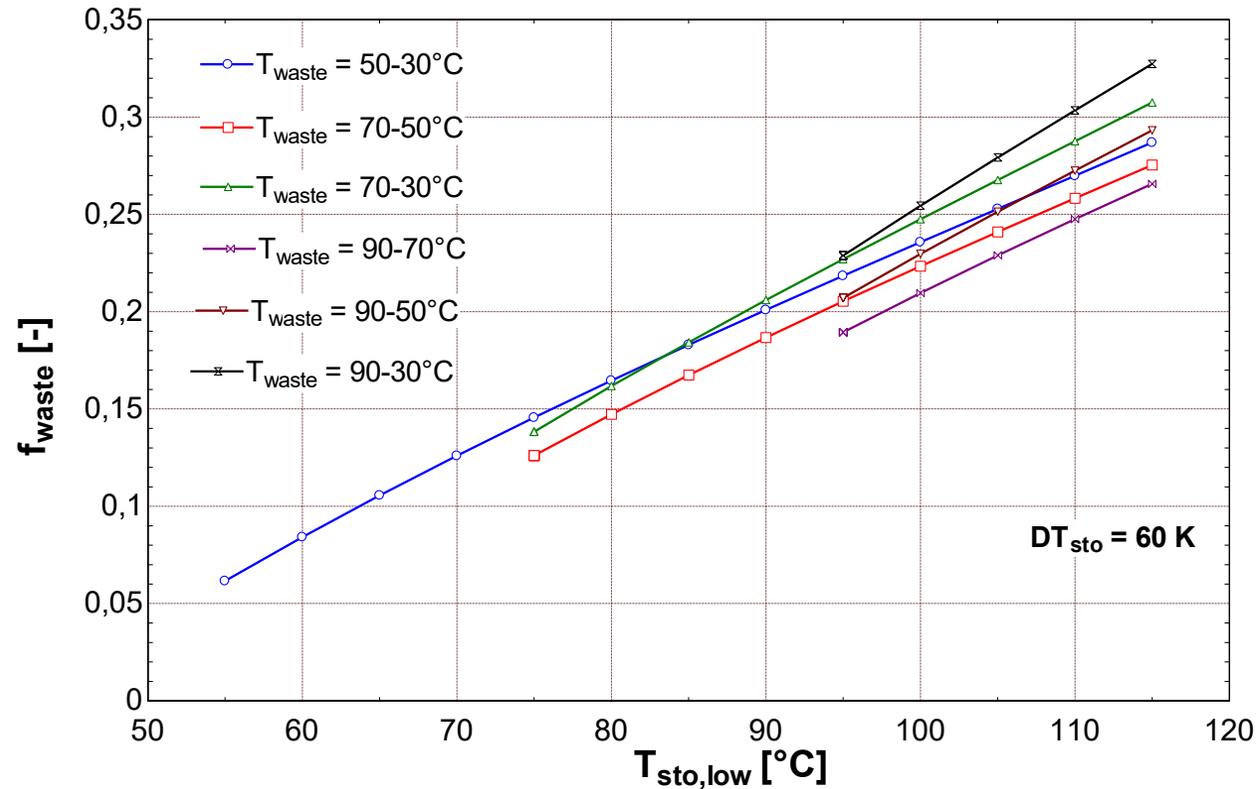
Waste heat ratio

System 1

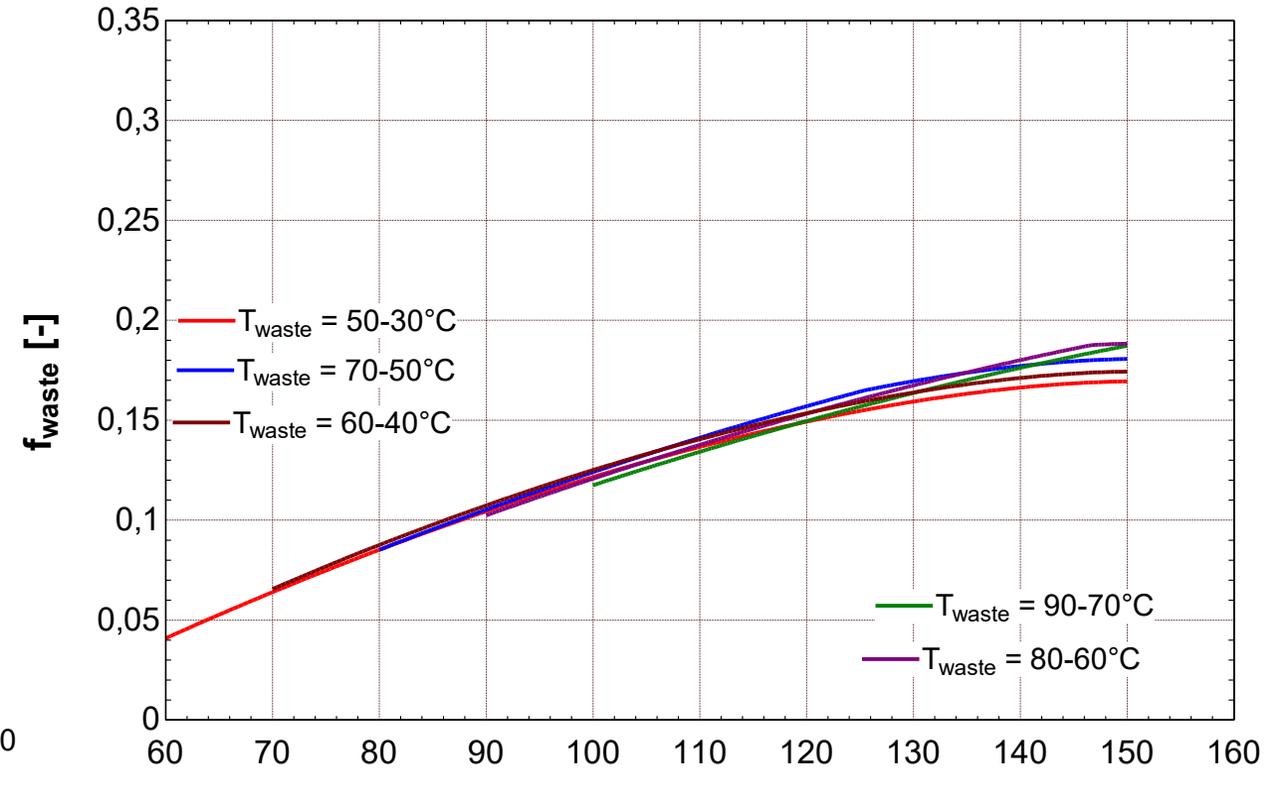
System 2

Heat pump + ORC + water sensible storage

Heat pump + ORC + PCM latent storage



Low storage temperature



Latent storage temperature

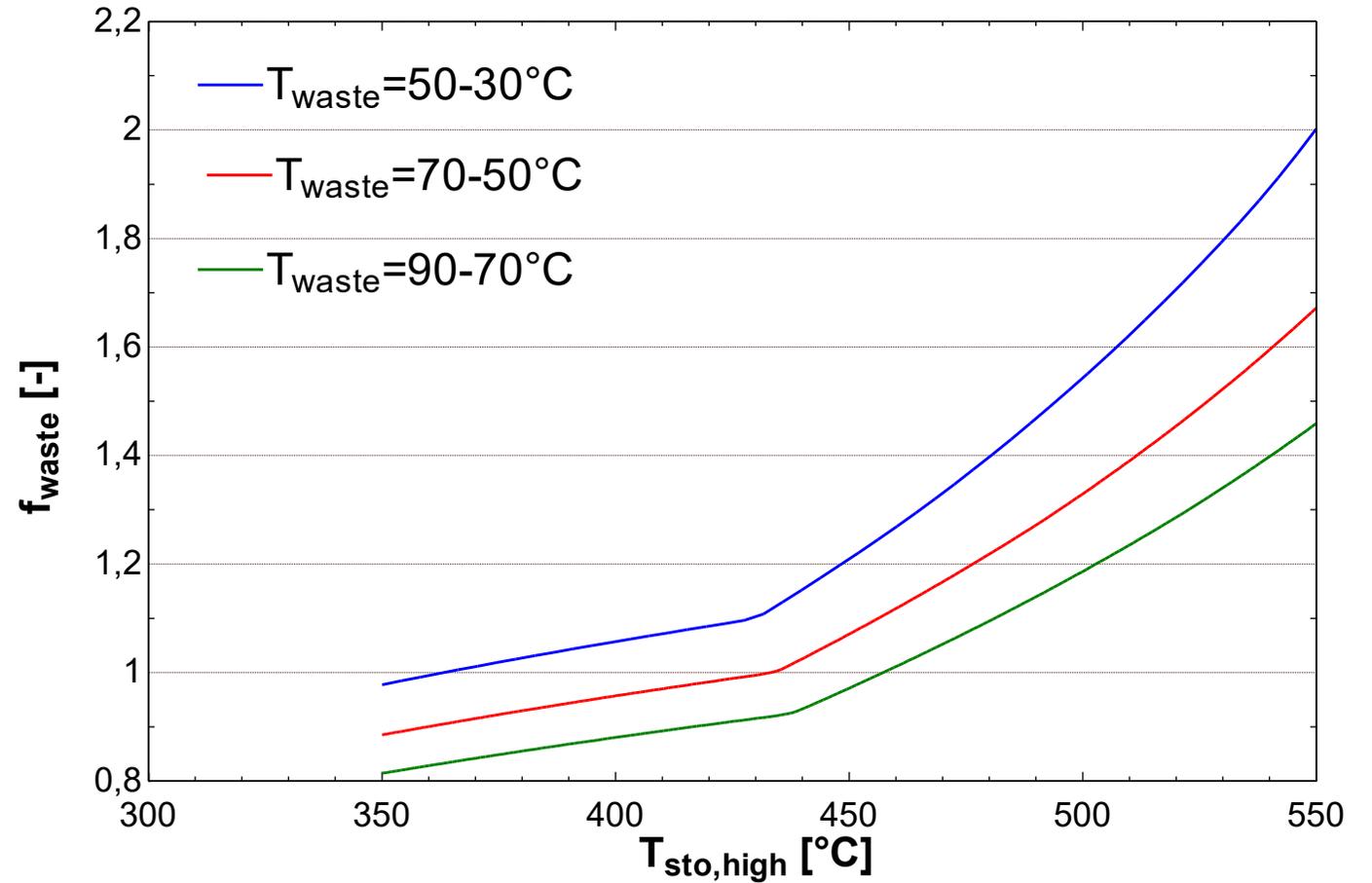
Results

$$f_{waste} = \frac{\dot{W}_{el,HtP}}{\dot{Q}_{waste}} [-]$$

Waste heat ratio

System 3

CO₂ heat pump + Steam Rankine cycle + sensible molten salt storage



High storage temperature

Results

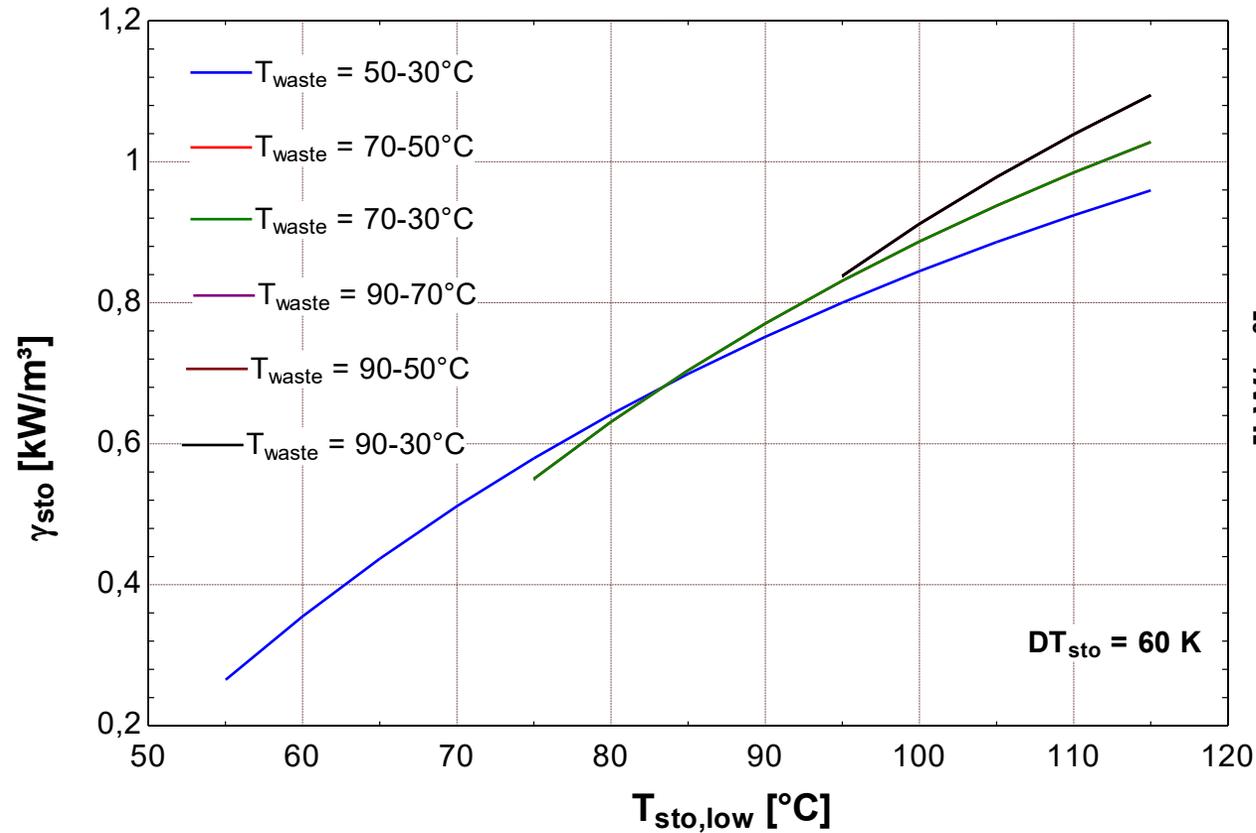
$$\gamma_{sto} = \frac{\dot{W}_{el,HtP}}{Vol_{sto}} \text{ [kW/m}^3\text{]}$$

Compactness

System 1

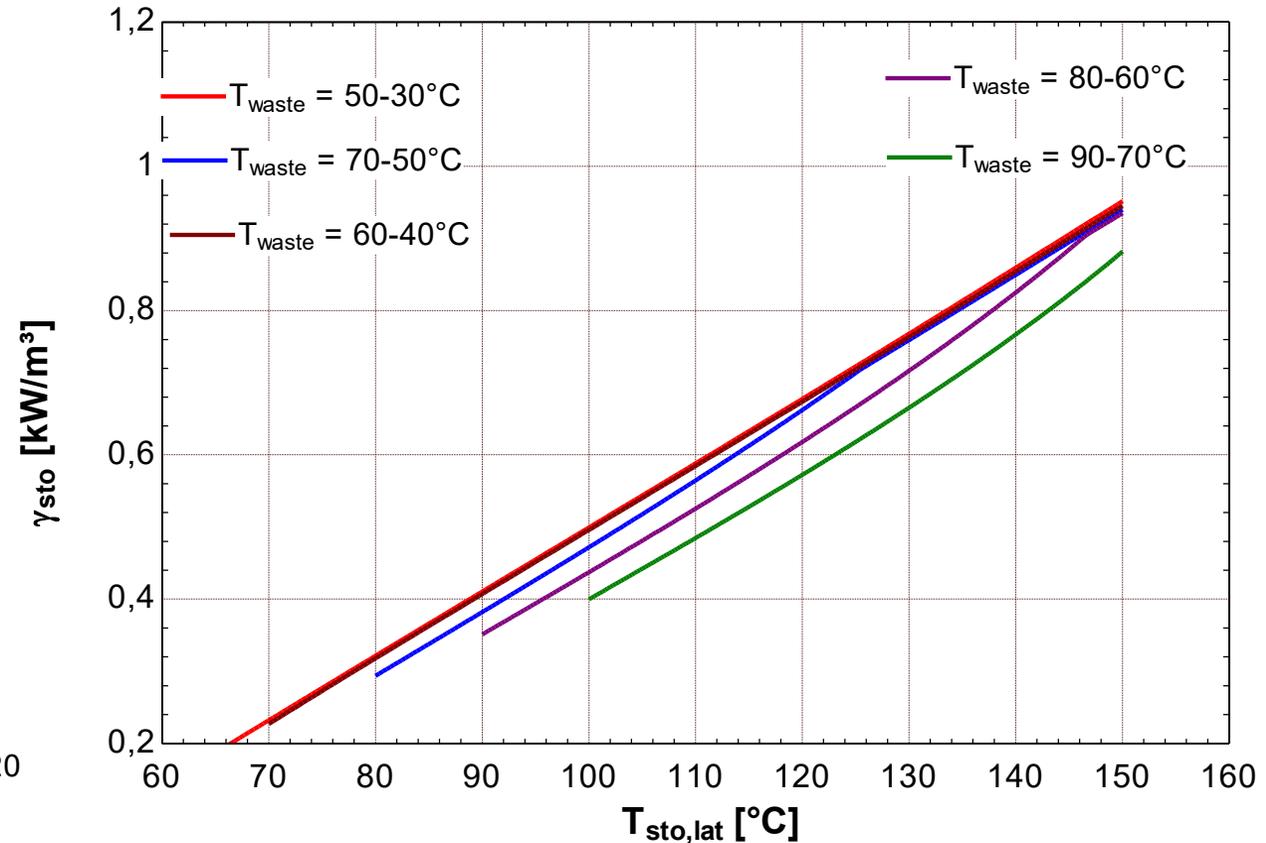
System 2

Heat pump + ORC + water sensible storage



Low storage temperature

Heat pump + ORC + PCM latent storage



Latent storage temperature

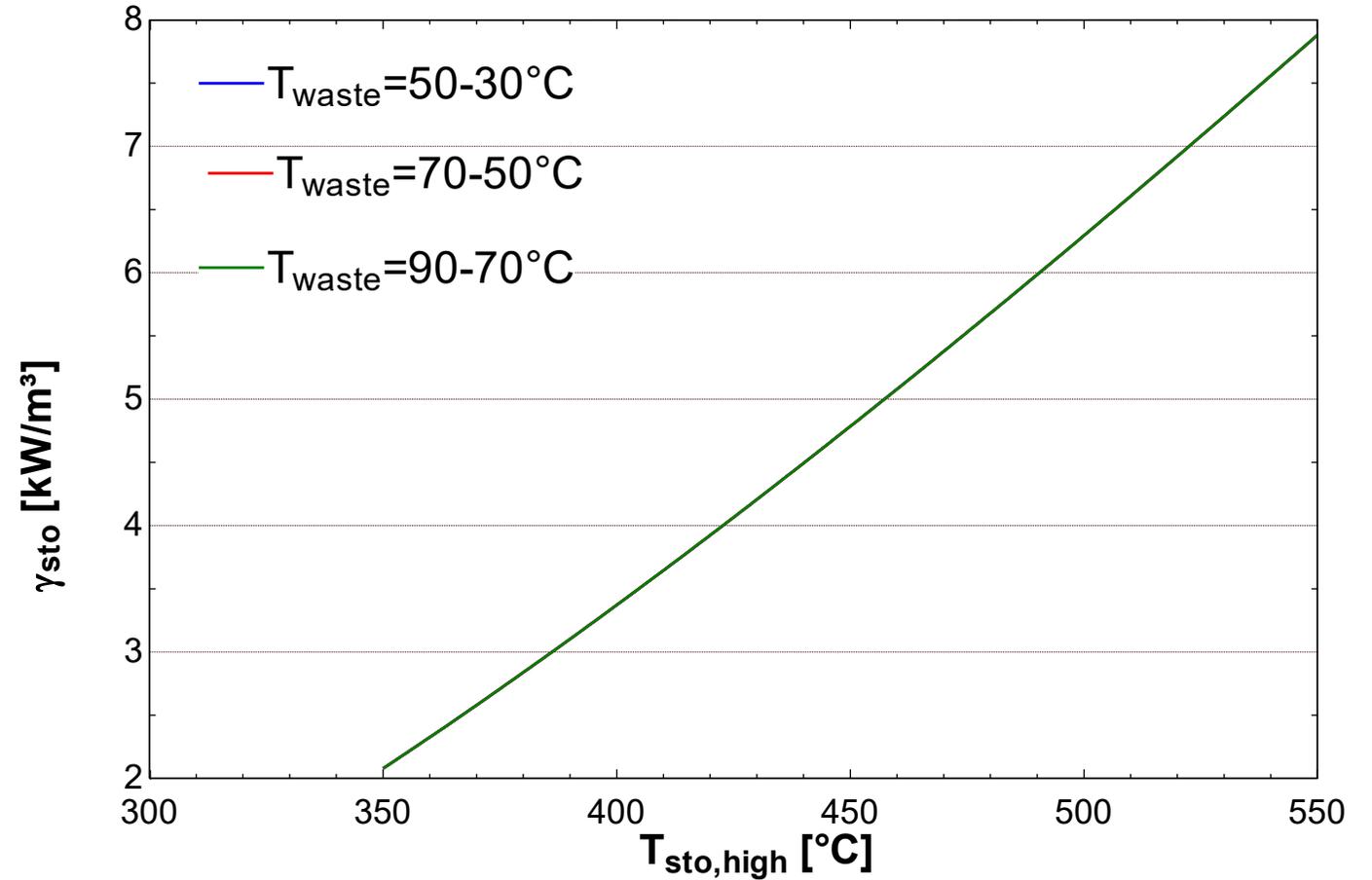
Results

$$\gamma_{sto} = \frac{\dot{W}_{el,HtP}}{Vol_{sto}} \text{ [kW/m}^3\text{]}$$

Compactness

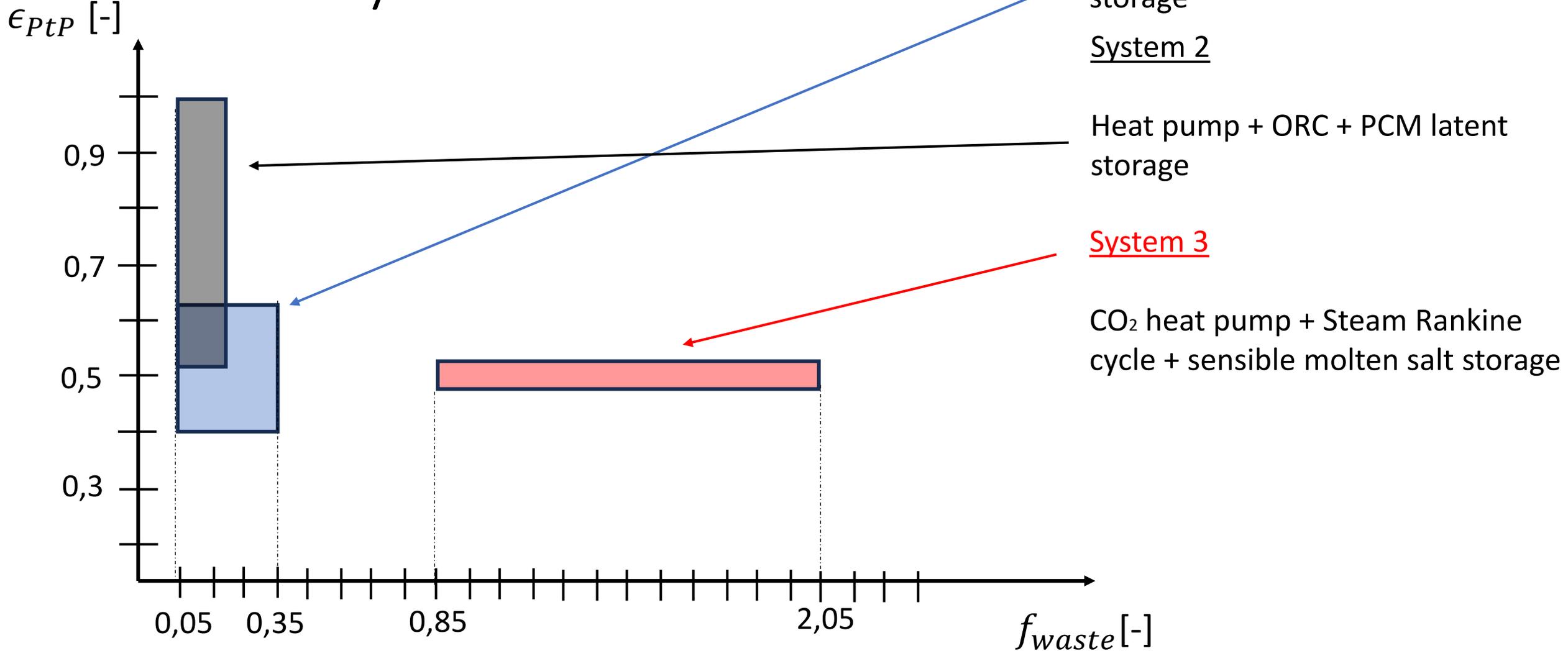
System 3

CO₂ heat pump + Steam Rankine cycle + sensible molten salt storage



High storage temperature

Summary



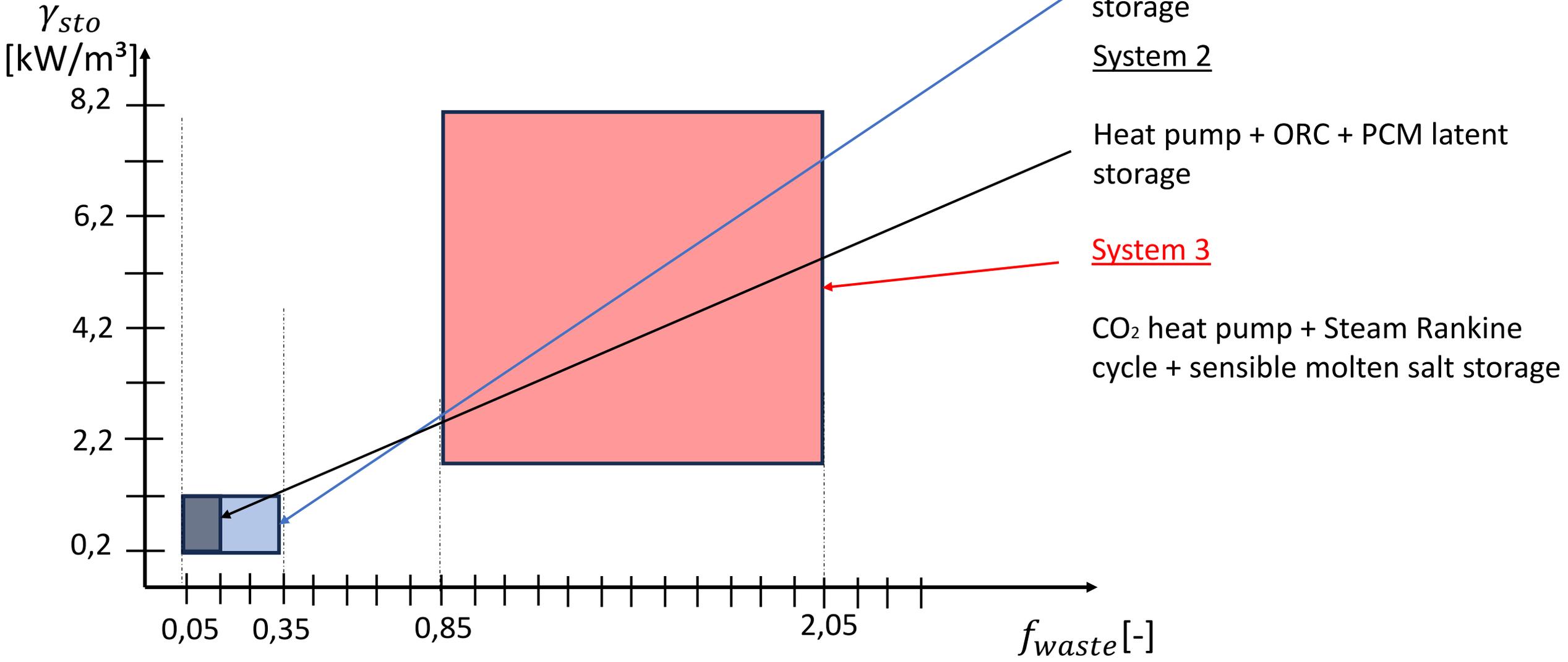


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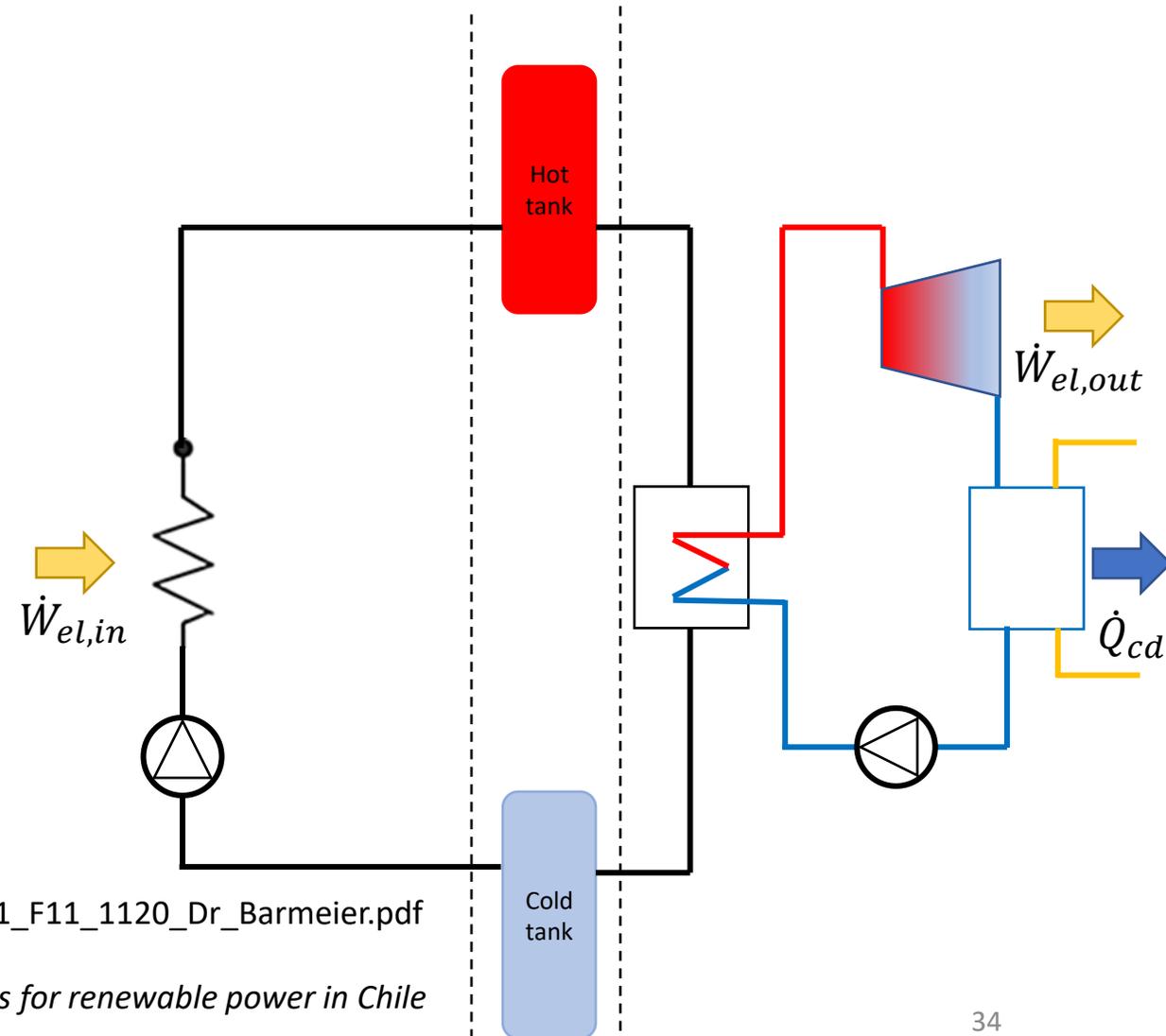
Conclusion

- The Heat pump + ORC + water sensible storage system is interesting for low waste heat ratio industrial processes with potential high efficiency.
- The Heat pump + ORC + PCM latent storage is also interesting for low waste heat ratio industrial processes with potential higher efficiency. The limiting parameter for now is the PCM price.
- The CO₂ heat pump + Steam Rankine cycle + sensible molten salt storage system can be used for high waste heat ratio industrial processes with efficiency around 50 %. The system is also much more compact. The use of waste heat in that case can be discussed due to the low variation of round-trip efficiency with waste heat temperature.
- Other architectures must be added to fill-in the gap between $f_{waste} = 0,3$ and $f_{waste} = 0,9$

Electrical heater + Rankine cycle

1. Electrical heater + Rankine cycle

- Electrical heater for charging
- Steam Rankine cycle for discharging
- Typical storage temperature: 500 – 800°C
=> Molten salt or packed-bed stones
- Application: conversion of fossil fuel power plants
- Typical efficiency: 40 %
- Manufacturers: Siemens Gamesa⁽³⁾, RWE⁽⁴⁾, E2S power⁽⁵⁾



(3) https://windenergetage.de/wp-content/uploads/sites/2/2017/11/26WT0811_F11_1120_Dr_Barmeier.pdf

(4) German Aerospace Center. 2020.

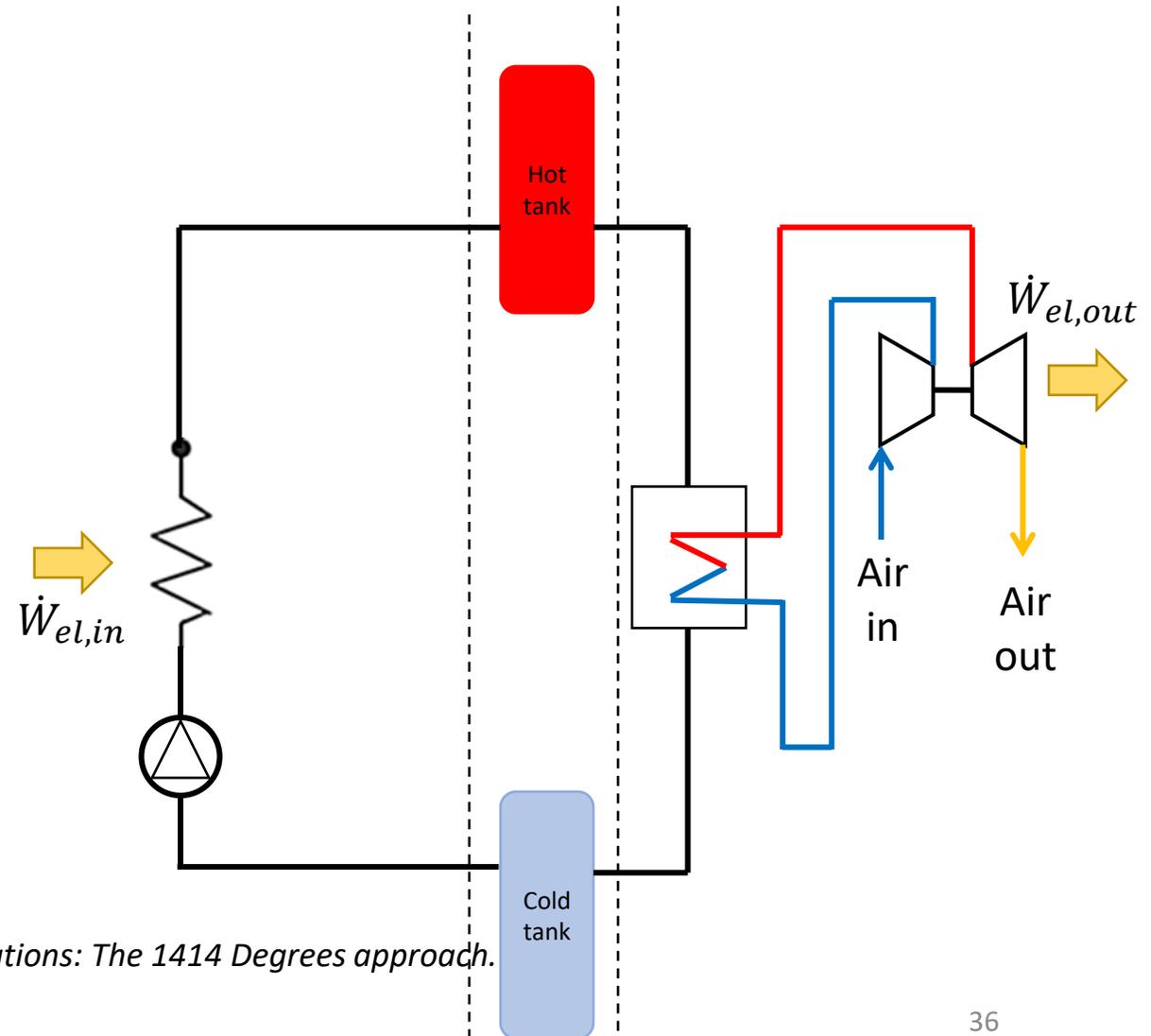
Repurposing of existing coal-fired power plants into Thermal Storage Plants for renewable power in Chile

(5) <http://e2s-power.com/>

Electrical heater + Brayton cycle

2. Electrical heater + Brayton cycle

- Electrical heater for charging
- Brayton cycle for discharging
- Typical storage temperature: 800 – 1400°C
=> packed-bed stones, sand or melted metal alloy
- Typical efficiency: 35-40 %
- Manufacturers: 247Solar⁽⁶⁾, 1414Degrees⁽⁷⁾, Peregrine Turbine Technologies⁽⁸⁾



(6) <https://247solar.com/sustainable-solar-solutions-products/heatstore/>

(7) Parham, J., Vrettos, P., Levinson, N. 2021.

Commercialisation of ultra-high temperature energy storage applications: The 1414 Degrees approach.

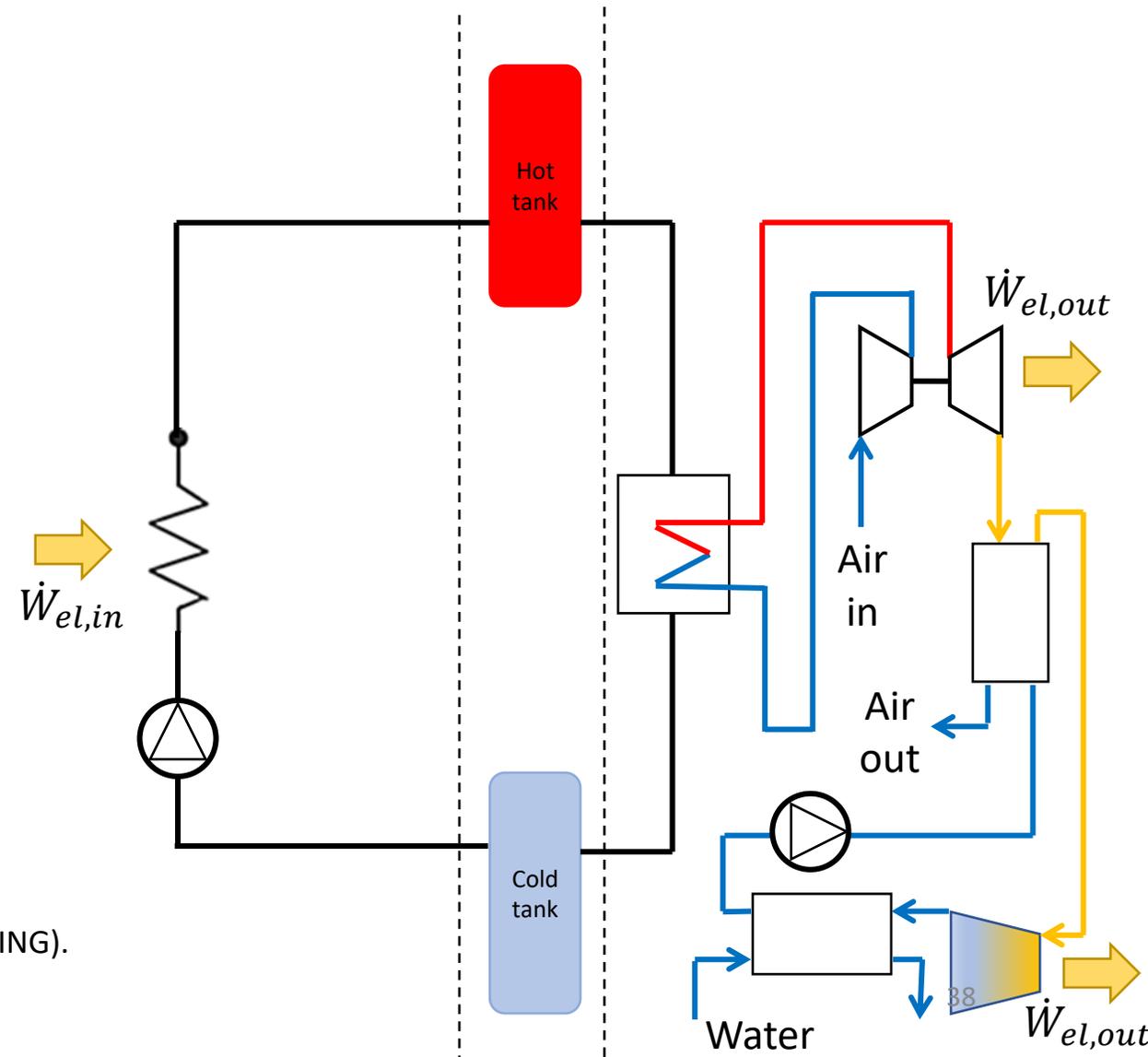
(8) <https://www.peregrineturbine.com/technology/>

Electrical heater + Combined Brayton/Rankine cycle

3. Electrical heater + Combined Brayton/Rankine cycle

- Electrical heater for charging
- Combined Brayton/Steam Rankine cycle for discharging
- Typical storage temperature: 800 – 1400°C
=> packed-bed stones
- Typical efficiency: 45 - 55 %
- Manufacturer: Project ENDURING (consortium General Electric, Colorado School of Mines, Purdue University, Allied Mineral Products Inc)⁽⁹⁾

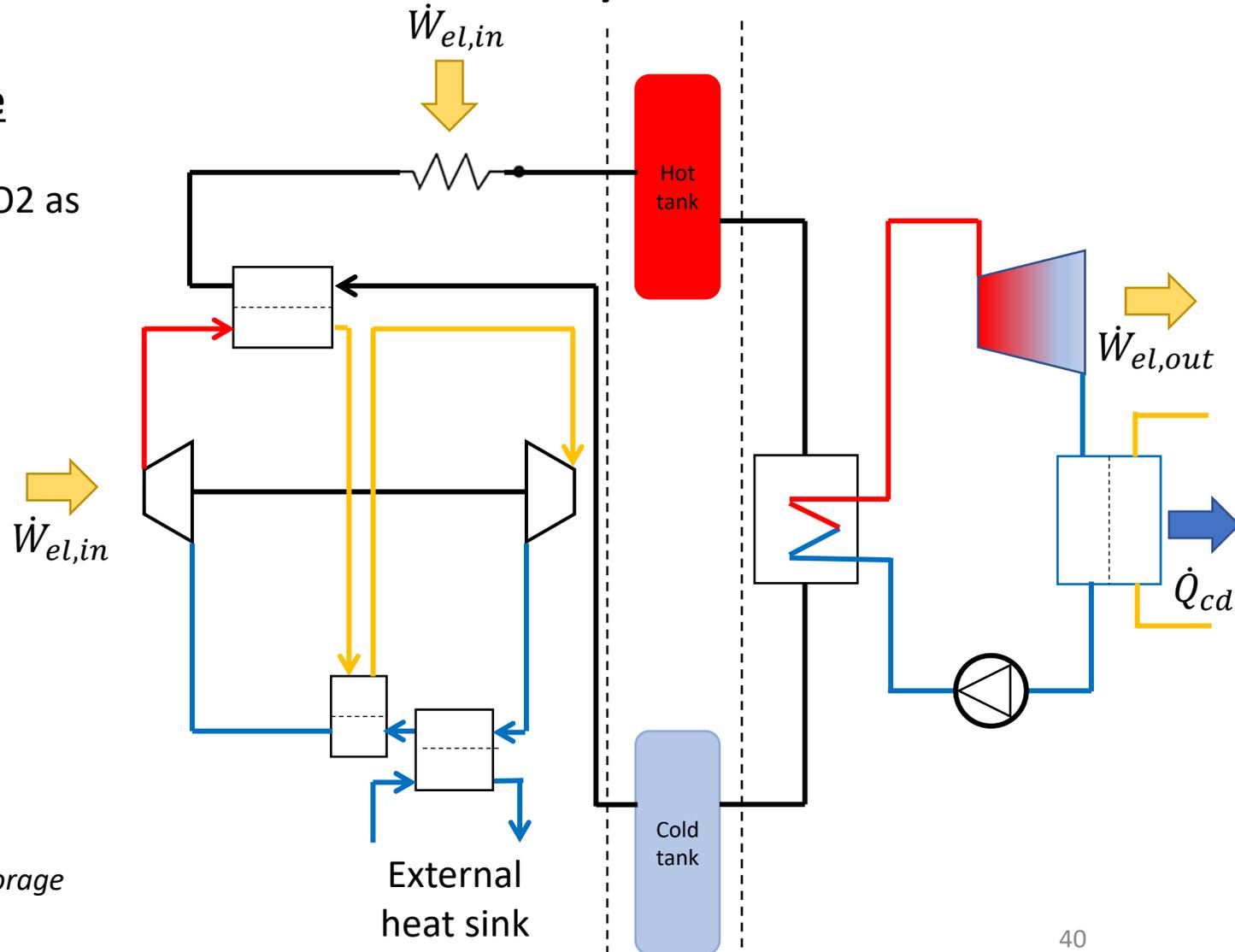
(9) Ma Z., Hofer D., Tallman J., Zhang R., Lambert M.M. 2021.
Economic Long-Duration Electricity Storage Using Low-Cost Thermal Energy Storage and a High-Efficiency Power Cycle (ENDURING).



Reverse Brayton cycle + Rankine cycle

4. Reverse Brayton cycle + Rankine cycle

- Reverse Brayton cycle for charging using CO₂ as working fluid
- Steam Rankine cycle for discharging
- Typical storage temperature: 500-600 °C
=> Molten salt
- Efficiency: 42-62 %
- Manufacturers: GE Renewable Energy ⁽¹⁰⁾

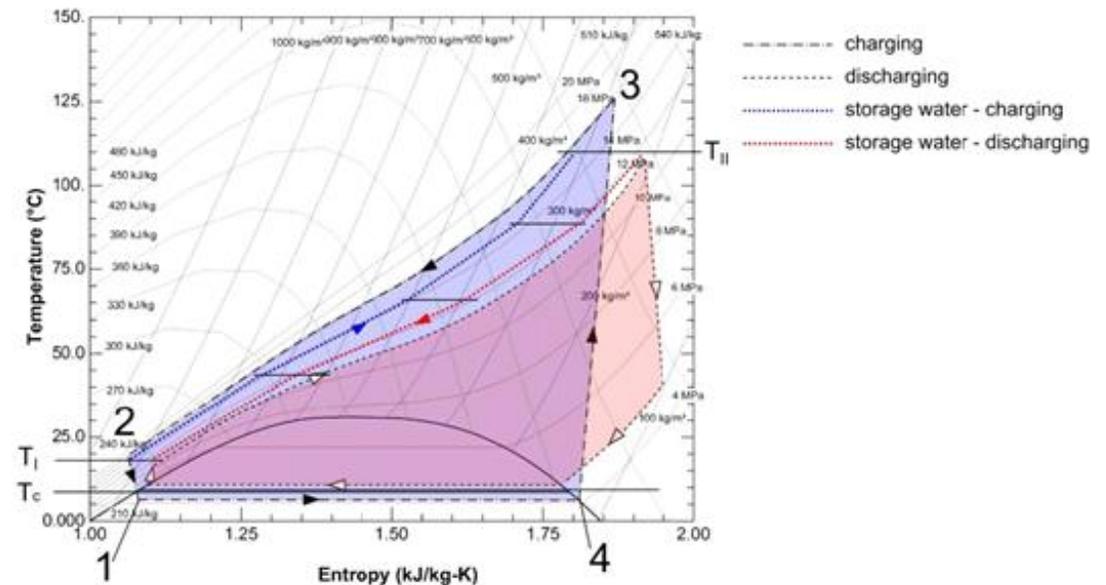
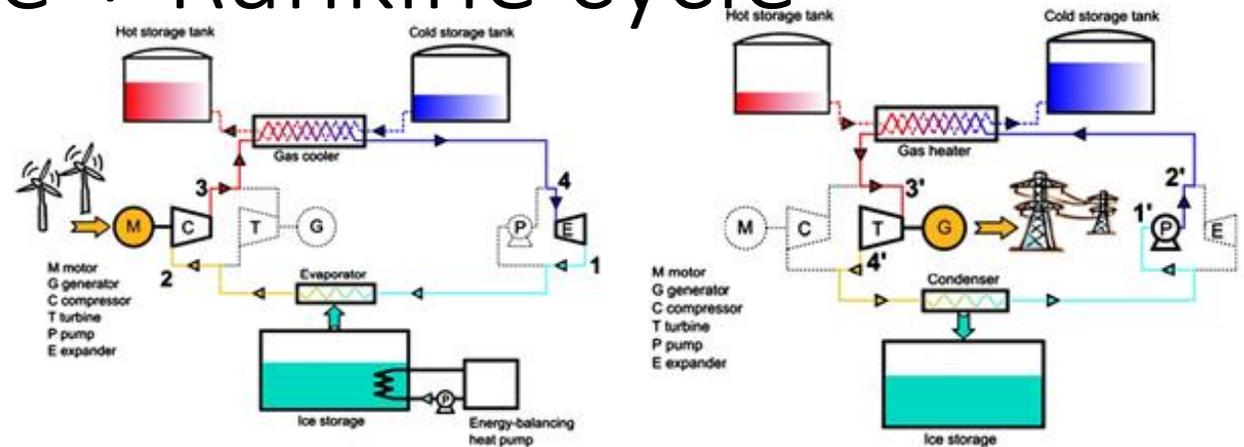


(10) Aga V., Conte E., Carroni R., Burcker B., Ramond M. 2016
*Supercritical CO₂-Based Heat Pump Cycle for Electrical Energy Storage
for Utility Scale Dispatchable Renewable Energy Power Plants.*

Reverse Brayton cycle + Rankine cycle

4. a. transcritical CO₂

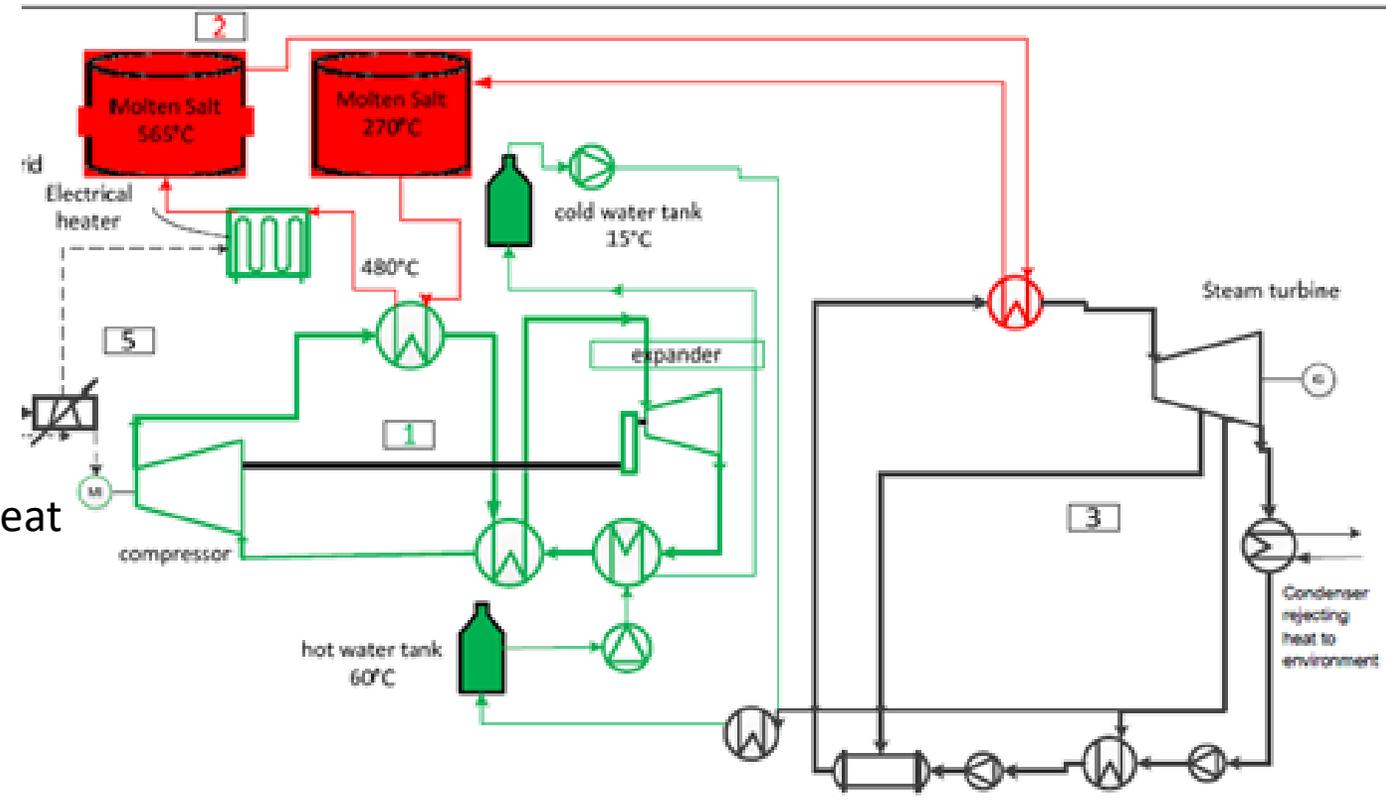
- One hot water storage at 120°C
- One cold water storage and one ice storage
- Maximum CO₂ pressure: 160 bar
- Advantages
 - Simple storages (Water tanks)
 - Low output compressor temperature (130°C)
- Drawbacks/technical challenge
 - Low round-trip efficiency: 40-50 %
 - Integration of low temperature waste heat impossible
- TRL: 4



Reverse Brayton cycle + Rankine cycle

4. b. supercritical CO₂

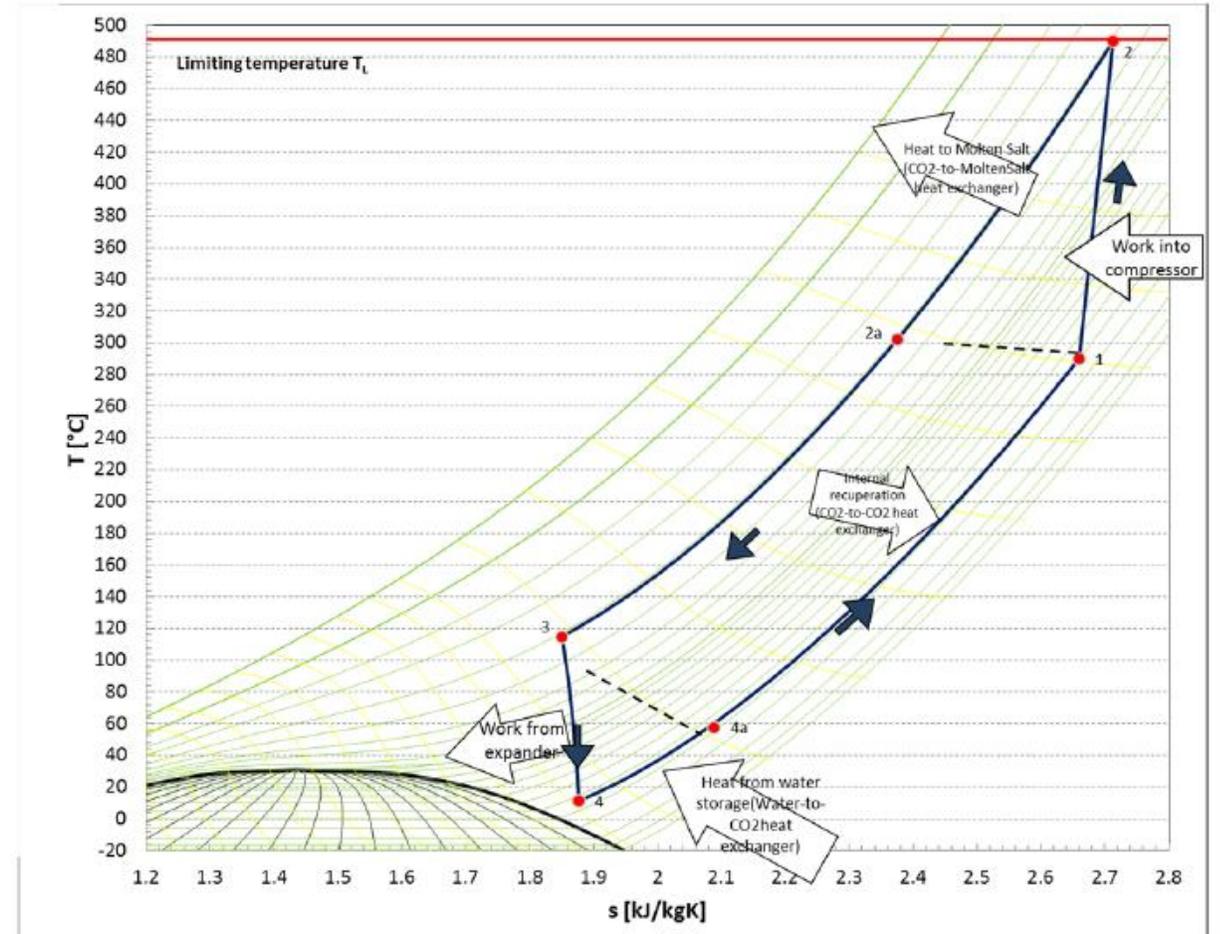
- Two high temperature molten salt storages
- Two cold temperature water storages
- Advantages
 - Relatively low temperature storage temperature (500-600°C)
 - Higher efficiency expected (62 %)
 - Integration of low temperature waste heat is possible
- TRL: 2



Reverse Brayton cycle + Rankine cycle

4. b. supercritical CO₂

- Min/max pressure: 40/140 bar
- Min/max temp: 10-480°C
- Drawbacks/technical challenge
 - High temperature and pressure at the compressor exhaust (>140 bar and >400°C)
 - High efficiencies of compressor and expander are necessary to reach high round trip efficiency
 - Combined high temperature, pressure and power (> 50 MW) compressors are not available
 - Problem of corrosion at high temperature (500°C)
 - The design of the heat exchangers is difficult: high pressure, high temperature, low pressure drop constraint

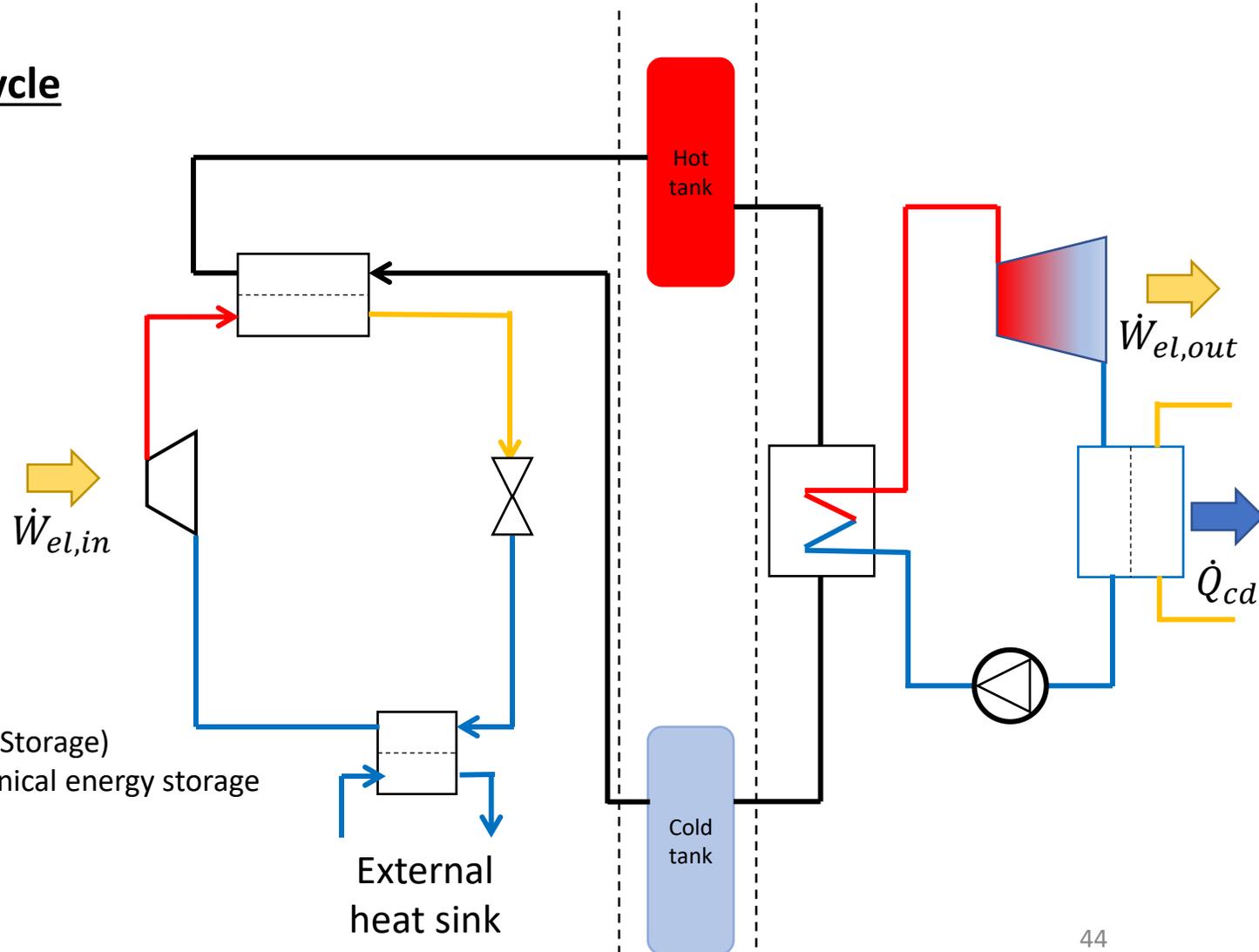


(10) Aga V., Conte E., Carroni R., Burcker B., Ramond M. 2016
Supercritical CO₂-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants.

Vapor compression cycle + Rankine cycle

5. Vapor compression cycle + Rankine cycle

- Vapour compression cycle for charging
- Rankine cycle for discharging
- Typical storage temperature: 300 - 400 °C
=> Molten salt
- Efficiency: 25 - 70 %
- Manufacturers: Project CHESTER (consortium)⁽¹¹⁾, Climeon⁽¹²⁾, Future Bay⁽¹³⁾
- TRL: 3



(11) W.D Steinmann. 2014. The CHEST (Compressed Heat Energy Storage) concept for facility scale thermo mechanical energy storage

(12) Karthaus J. 2020 *Power production and electricity storage, utilizing 80-120°C hot water.*

(13) <https://futurebay.uk.com/>

Reversible Brayton cycle

6. Reversible Brayton cycle

- Brayton cycle for charging and discharging
- Typical storage temperature: 500 °C hot storage and -160°C cold storage
- Typical efficiency: 50 - 70 %
- Manufacturers: Isentropic⁽¹⁴⁾ Malta⁽¹⁵⁾, Stiesdal⁽¹⁶⁾, Echogen⁽¹⁷⁾, MAN/ABB⁽¹⁸⁾, Enolcon⁽¹⁹⁾, WindTP⁽²⁰⁾

(14) White A., Parks G., Markides C. N. 2013.

Thermodynamic analysis of pumped thermal electricity storage

(15) www.sandia.gov/ess-ssl/wp-content/uploads/2021/LDES/Ben_Bollinger.pdf

(16) <https://www.stiesdal.com/storage/the-gridscale-technology-explained/>

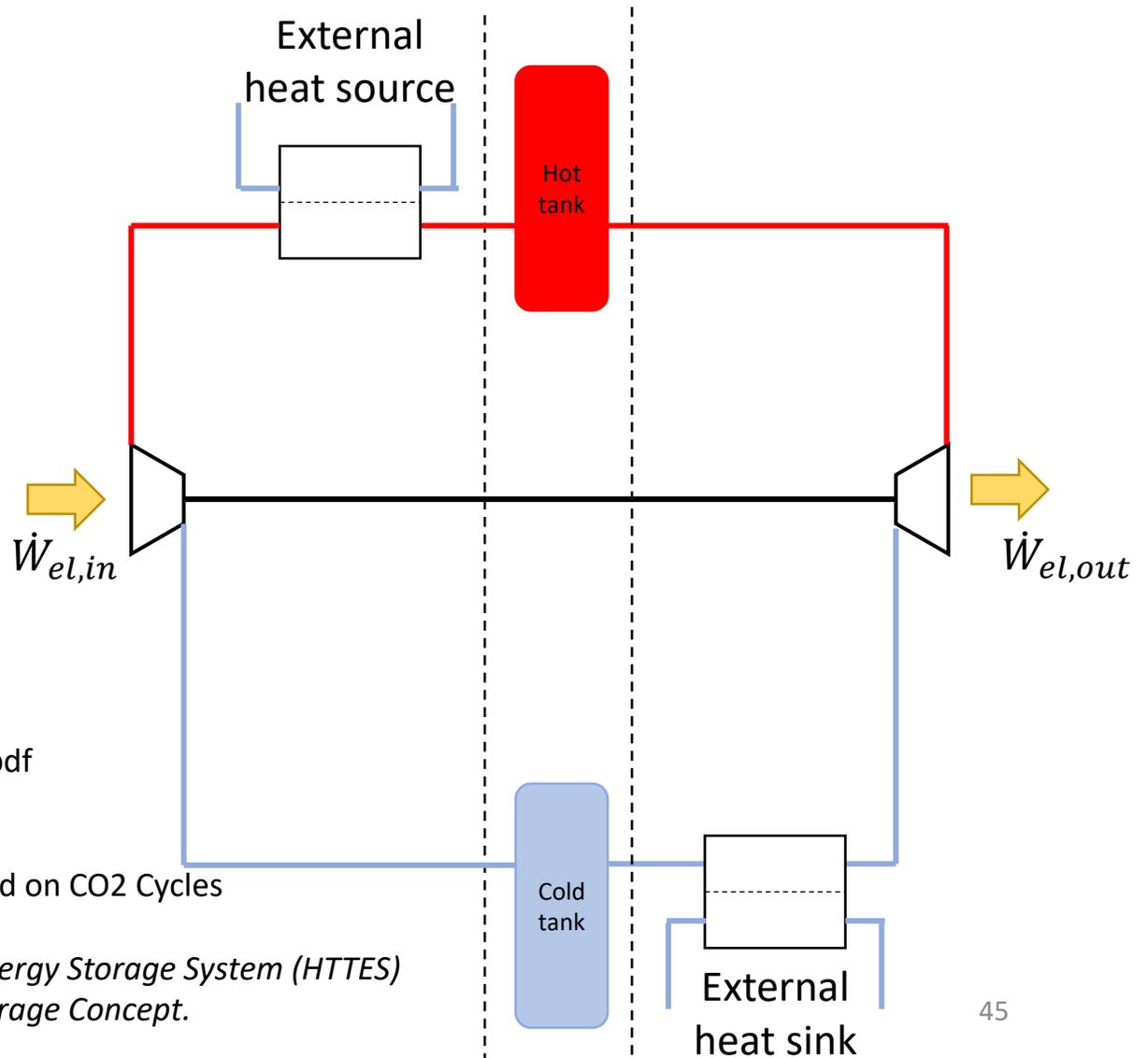
(17) <https://www.echogen.com/energy-storage/>

(18) Jacquemoud E. 2021. Electro-Thermal Energy Storage System (ETES) Based on CO₂ Cycles

(19) Schneider, G.; Maier, H.; Häcker, J.; Siegele, S. 2021.

*Electricity Storage with a Solid Bed High Temperature Thermal Energy Storage System (HTTES)
A Methodical Approach to Improve the Pumped Thermal Grid Storage Concept.*

(20) <https://www.wind-tp.com/>



Reversible Brayton cycle

6. Reversible Brayton cycle

- Proposed working fluid: Argon
- Advantages
 - Relatively low temperature storage temperature (500-600°C)
 - High efficiency expected (60 %)
- Drawbacks/technical challenge
 - High compressor and expander efficiencies necessary to reach high roundtrip efficiency

- TRL: 5

