Numerical evaluation of high-temperature heat pump and thermal energy storage system for industrial processes

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Final Energy Consumption in World (2022)

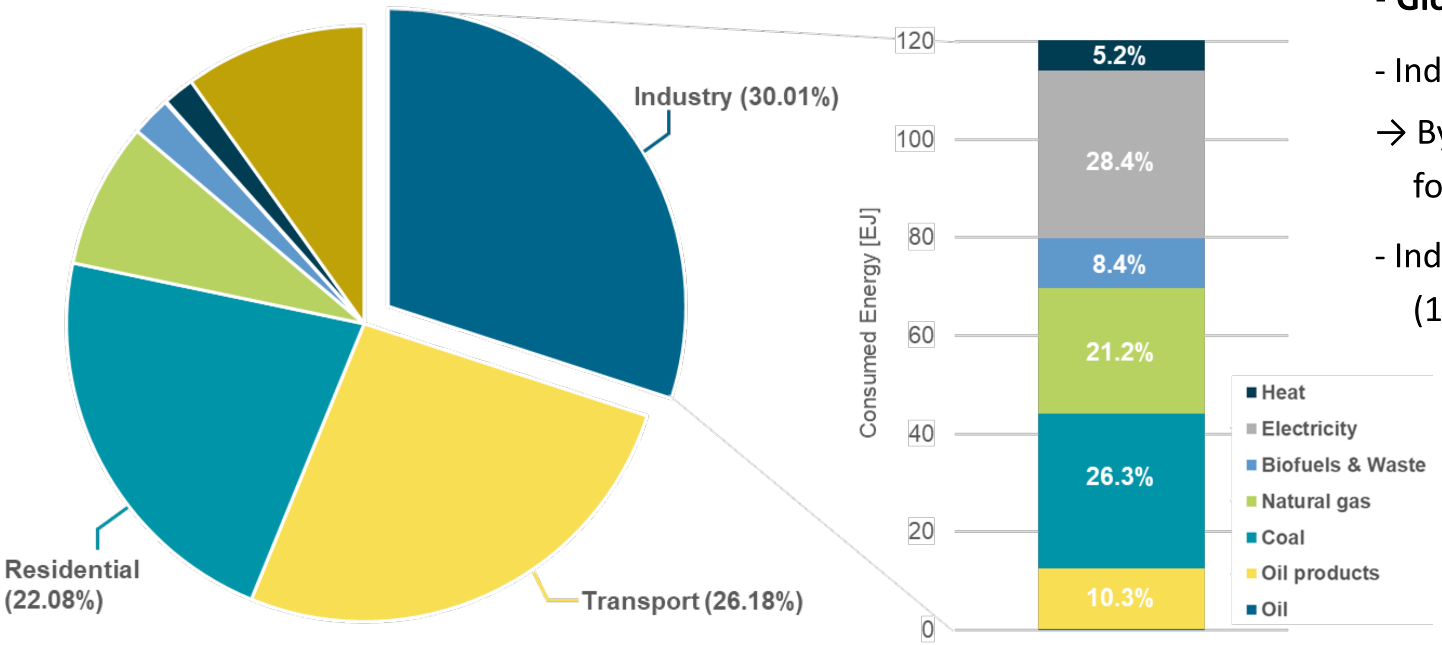


Fig. Total Energy consumption by sector & Energy carrier for industrial sector, World 2022 [IEA].

▪ **Global industrial energy consumption & greenhouse emission**

- Industrial process is the world's largest final energy consumer (120 EJ).

→ By considering electricity generated from fossil fuel, > 75% of energy used for industrial processes (> 90 EJ) comes from fossil fuels.

- Industrial processes emit 24% of the global greenhouse gas in 2019 (14 $GtCO_2eq$) with the exception of energy sector.

Electrification can be an effective option for reducing greenhouse gas emissions from the industry.

Heating demands by industrial subsectors

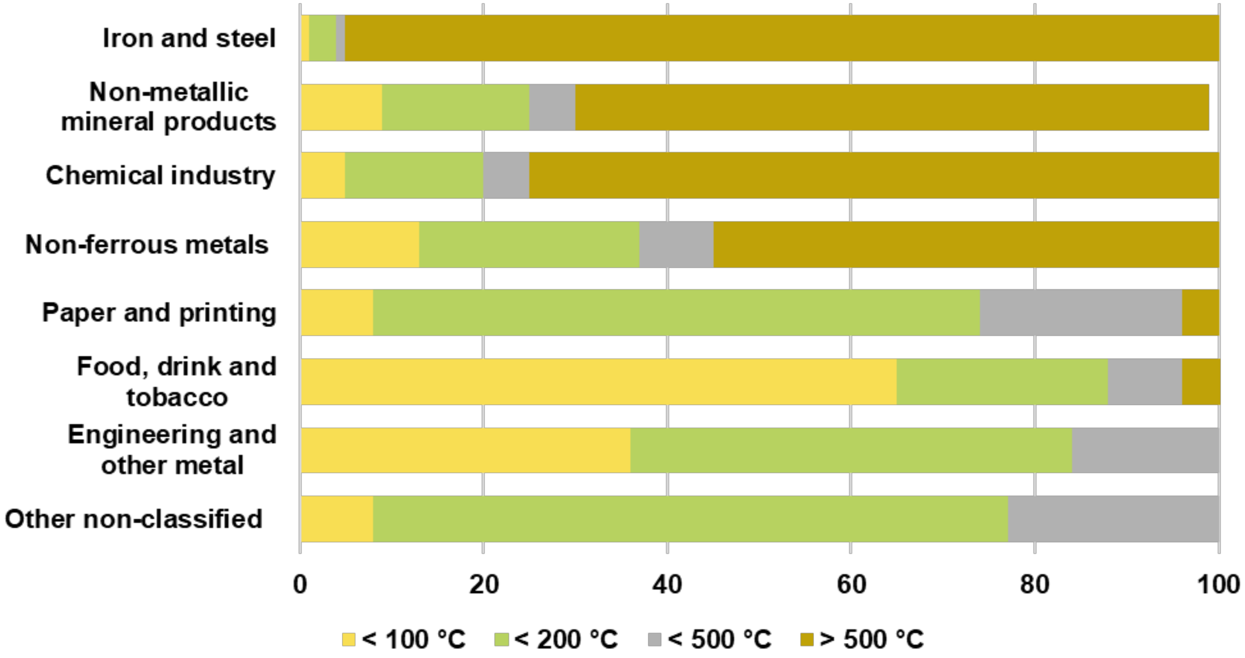


Fig. Temperature distribution by subsector [EU Commission 2016 (WP1)].

▪ **Temperature levels by industrial subsectors**

- Consumed temperature levels correlate with specific subsectors.

→ < 100°C: F&B, 100-500°C: Pulp & Printing, > 500°C: Iron & Steel.

- Process heat supplying methods and systems can be divided into 500°C.

→ < 500°C: Steam & Hot water, > 500°C: Industrial furnace.

▪ **High-Temperature Heat Pump (HTHP) for industrial processes**

- HTHP has high potential to efficiently recover waste heat from industrial process and upgrade it to higher temperature.

→ If zero-carbon electricity is used in the processes, the GHG emissions of the industrial site can be significantly reduced.

HTHP + TES systems

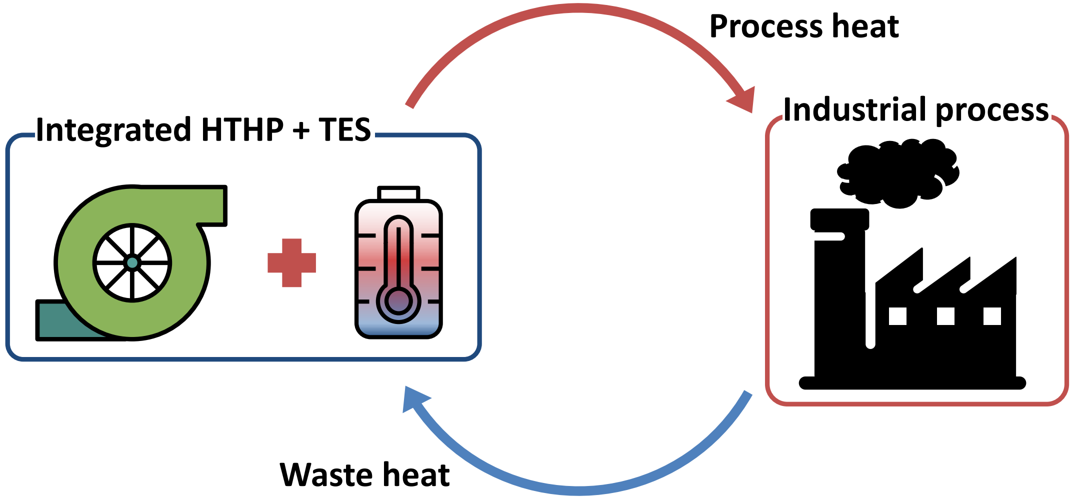


Fig. Image of working principle about HTHP + TES system.

▪ **Thermal Energy Storage (TES) system**

- TES systems are mainly used to overcome the mismatch between energy generation and demand (Temp., Location, or Power difference).

→ Sensible heat storage, Latent heat storage, Thermochemical storage.

- TES technology can improve the efficiency of heat pumps.

Object of this study

Performance Evaluation and Comparison of HTHP and Two Different TES Integrated Systems (SHS and TCES)

Modelling of HTHP

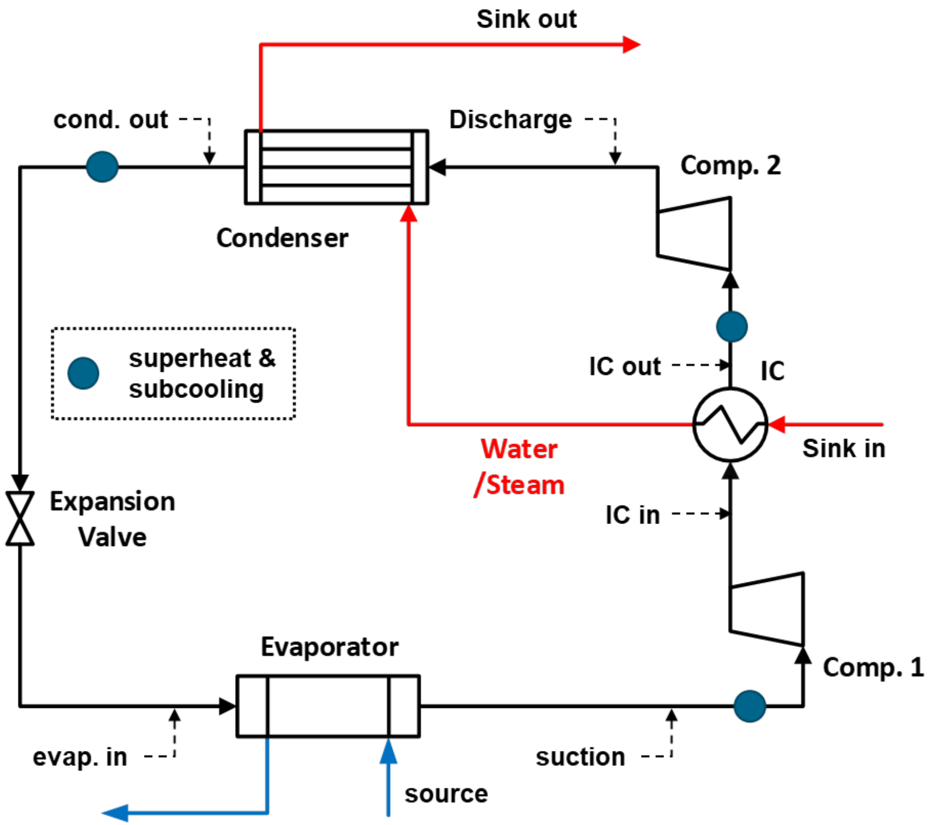


Fig. Schematic diagram of main HTHP cycle.

- **Modelling & Boundary conditions**

- Two-stage water vapor compression cycle with intercooling.

→ Both compressors have same pressure ratio.

- Boundary and operating conditions.

HTHP	Values	TES	Values
T_{evap}/T_{cond}	90°C/160°C (ΔT = 70 K)	$\dot{Q}_{sink}$	$\dot{Q}_{stor.}$ = 500 kW
η_{iso}/η_{mech}	0.78/0.95	τ_{stor}	8 hrs (28800 s)
$T_{source/sink\ in/sink\ out}$	110°C/25°C/200°C	P_{sink}	$P_{sink} = P_{cond}$
$T_{sup\ \&\ sub}$	10 K	m_{sink}	$m_{sink} = m_{stor\ \&\ dis}$

- Parameters of entire HTHP are determined based on Enthalpy/Entropy balance.

→ W_{comp}: 113.4 kW and COP: 4.4.

*Properties for Water/Steam: IAPWS-IF97.

Modeling of SHS system

- **Modeling of Sensible Heat Storage system**

- Concrete was considered as a SHS material.

→ Properties for 200°C are used (C_p, ρ, and so on).

- **Charge/Discharge operations**

- Charge: $T_{char.}$ is 190°C and the required amounts of concrete is obtained.

- Discharge: $T_{dis.}$ can be controlled by regulating the $\dot{m}_{\mathrm{air-dis}}$.

→ Due to P_{sink} = P_{cond}, phase shift in water/Steam depending on $T_{cycle\ out}$.

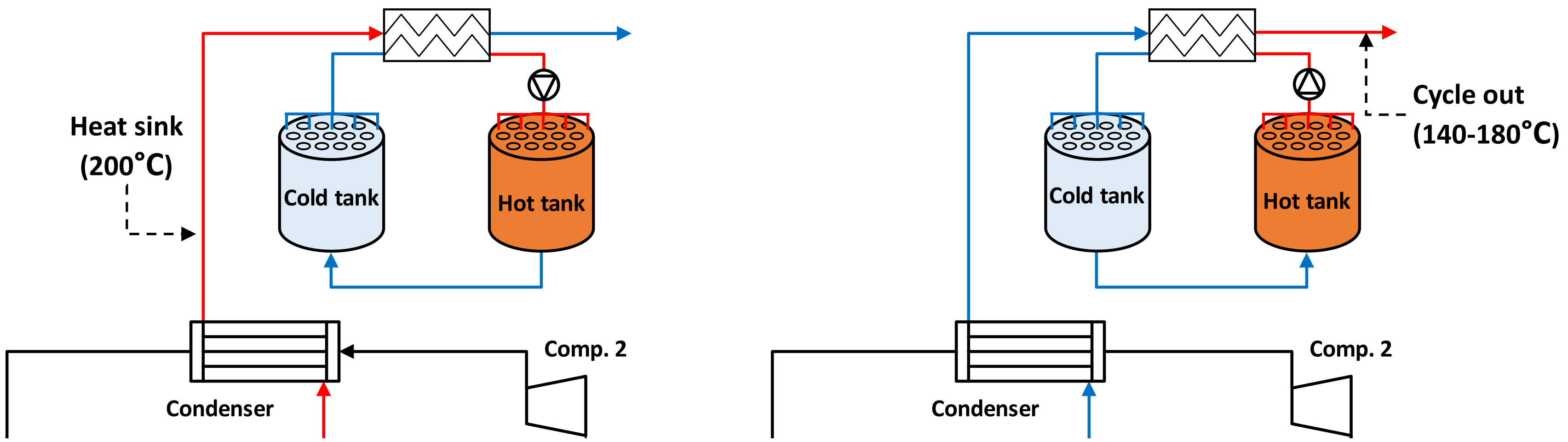


Fig. Image of pumped thermal energy storage: (left) Charge, (right) Discharge mode.

Performance of SHS system

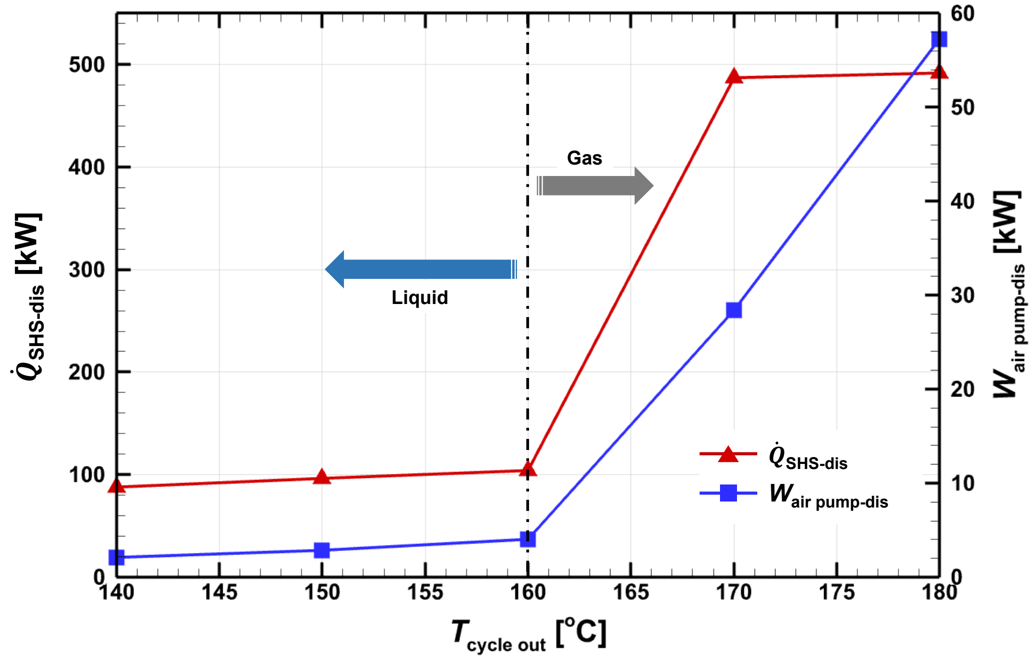


Fig. Changing of $\dot{Q}_{\mathrm{SHS-dis}}$ and $W_{\mathrm{air\ pump-dis}}$.

- **Specification of SHS system**

- Required amount of concrete for SHS system.

→ m_{concrete}: 96,647 kg, V_{concrete} = 43.0 m^3.

- Corresponded $\dot{m}_{\mathrm{air}}$ and $W_{\mathrm{air\ pump}}$ are changed for each operation.

→ Charge: $\dot{m}_{\mathrm{air}}$ = 2.82 kg, $W_{\mathrm{air\ pump}}$ = 3.5 kW.

→ Discharge: $\dot{m}_{\mathrm{air}}$ = 1.66-45.89 kg, $W_{\mathrm{air\ pump}}$ = 2.1-57.3 kW.

Modeling of TCES system

- **Modeling of Thermochemical Energy Storage system**

- Strontium bromide and Water system ($SrBr_2/H_2O$).

→ $SrBr_2$ (s) + H_2O (g) ↔ $SrBr_2 \cdot H_2O$ (s), ΔH_{SrBr2} = 71.98 kJ/mole.

→ H_2O (g) ↔ H_2O (l), ΔH_{H2O} = 40.65 kJ/mole.

- Packed bed reactor system is adopted.

- **Charge/Discharge operations**

- Charge: $SrBr_2 \cdot H_2O$ is decomposed at 190°C.

- Discharge: Waste heat from industrial processes is assumed at 110°C.

→ Discharge performance has been estimated by using equilibrium pressure.

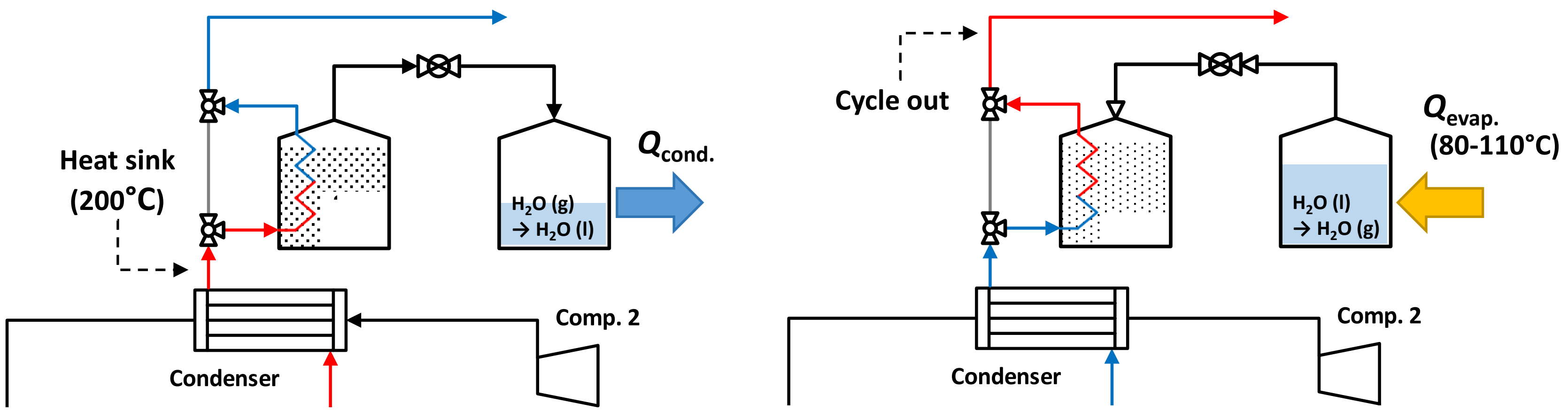


Fig. Image of thermochemical energy storage system: (left) Charge mode, (right) Discharge mode.

Thermochemical Energy Storage ($SrBr_2/H_2O$)

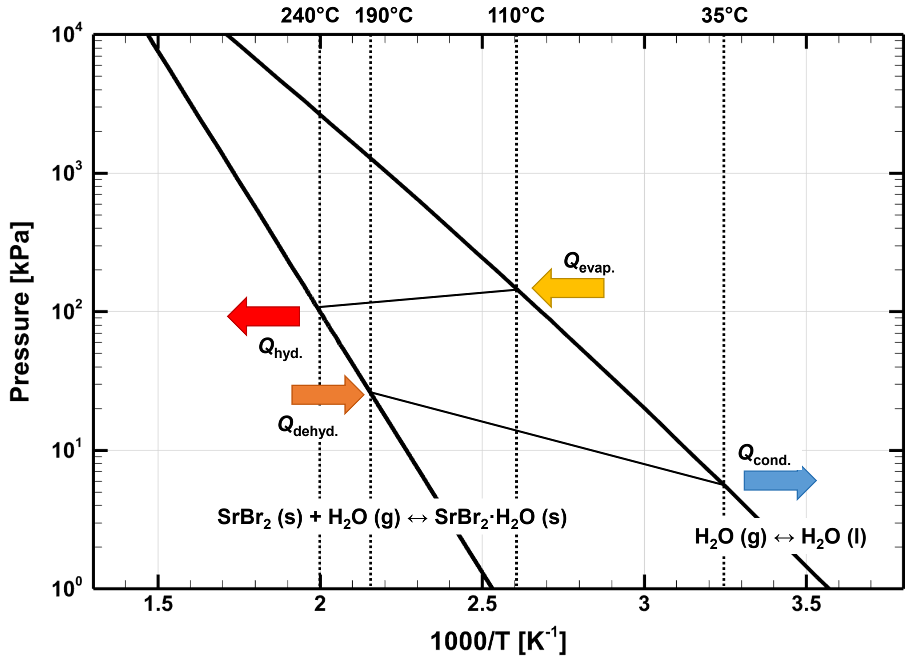


Fig. Van't Hoff diagram of $SrBr_2{\cdot}H_2O$ solid-gas reaction.

- **$SrBr_2/H_2O$ working pair for TCES system**

- Van't Hoff equation for a reversible solid-gas reaction ($SrBr_2{\cdot}H_2O$).

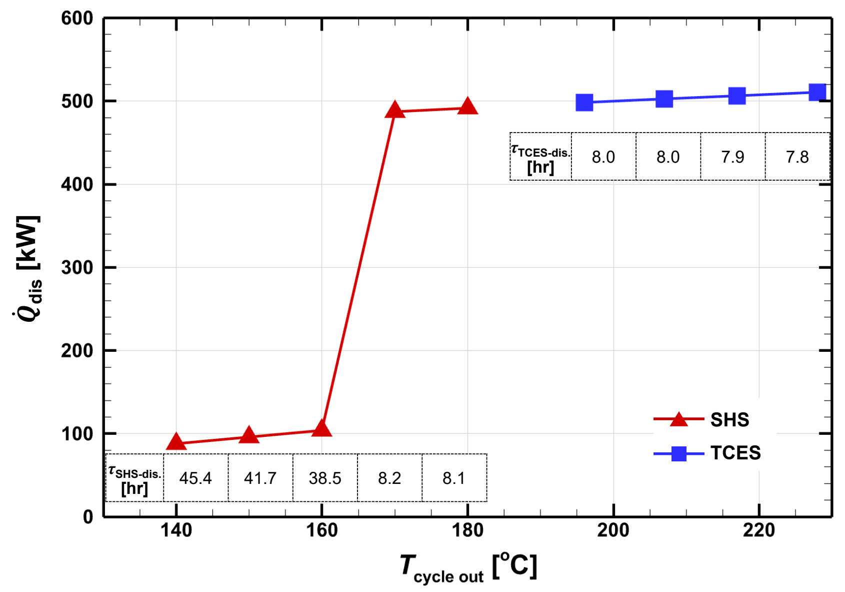
$$\ln K_{\mathrm{eq}}(T,P) = \ln\left(\frac{P}{P^0}\right) = \frac{\Delta G}{\mathrm{RT}} = -\frac{\Delta H}{\mathrm{RT}} + \frac{\Delta S}{R}$$

- Water-vapor saturation table is used for water/steam line.

- **Discharge performance of TCES system**

$T_{evap.}$ [°C]	$T_{hyd.}$ [°C]	$\tau_{dis.}$ [hrs]	$\dot{Q}_{TCES-dis.}$ [kW]
80	206	8.03	498
90	217	7.96	502
100	227	7.90	506
110	238	7.80	510

Comparisons (SHS & TCES)



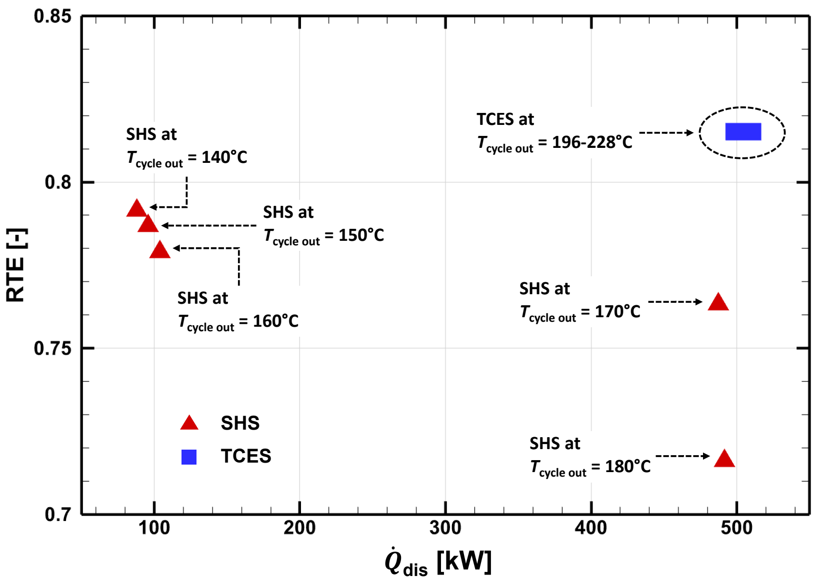


Fig. Results of comparison: (left) $\dot{Q}_{\text{dis}}$ and τ_{dis}in function of the $T_{\text{cycle out}}$, (right) RTE according to $\dot{Q}_{\text{dis}}$.

- **Comparison of both TES systems**

- TCES has higher $T_{\text{cycle out}}$ and $\dot{Q}_{\text{dis.}}$than SHS.

- Round Trip Efficiency (RTE) of TES systems.

→ Air pump power consumption affects RTE difference (SHS: 0.72-0.79, TCES: ~0.82).

$$\eta_{\text{RT}} = \frac{\left(\dot{Q}_{\text{cycle out}} - Po_{\text{pump dis}}\right) \times \tau_{\text{dis}}}{\left(\dot{Q}_{\text{sink}} + W_{\text{comp.}} + Po_{\text{pump char}}\right) \times \tau_{\text{stor.}}}$$

Conclusions

- **Comparison of both TES systems**

- TCES system has the advantage of being compact in size.

→ High energy density of thermochemical reaction results in compact system.

- TCES system can supply a higher temperature than it was stored.

Table. Specifications of TES systems.

	SHS	TCES	Note
Material	Concrete	$SrBr_2 \cdot H_2O$ ($SrBr_2$)	TCES/SHS
Weight	96,647	53,101 (49,500)	0.55 (0.51)
Volume	43.0	13.6 (11.7)	0.32 (0.27)

- **Future works**

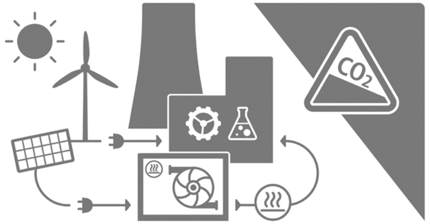
- Investigating the effects of different temperature conditions.

- Develop the transient simulation model for HTHP-TES system.

- Practical economic analysis of HTHP-TES system.

- Pilot plant test of HTHP-TCES system for industrial application.

An effective HTHP + TES system can decarbonize industrial processes



THANK YOU FOR YOUR ATTENTION