A Systematic Comparison of Supercritical CO_2 Brayton Cycle Layouts for CSP with a Focus on Thermal Energy Storage Utilization

3rd European sCO_2 Conference

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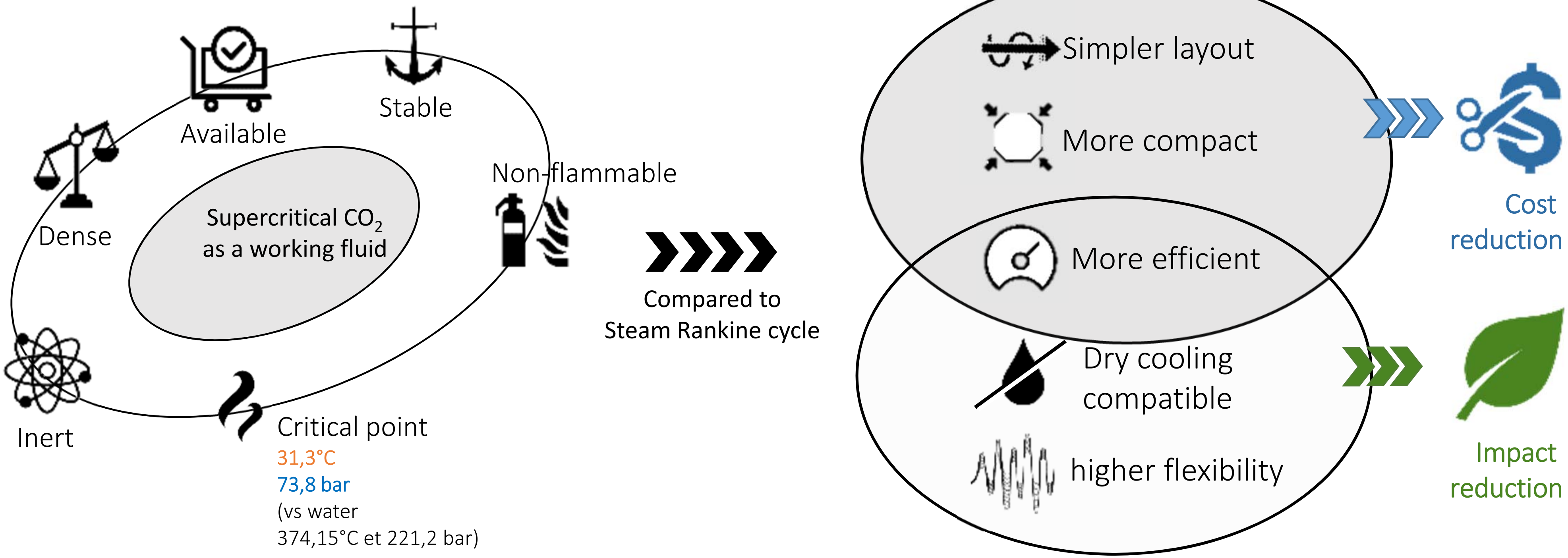
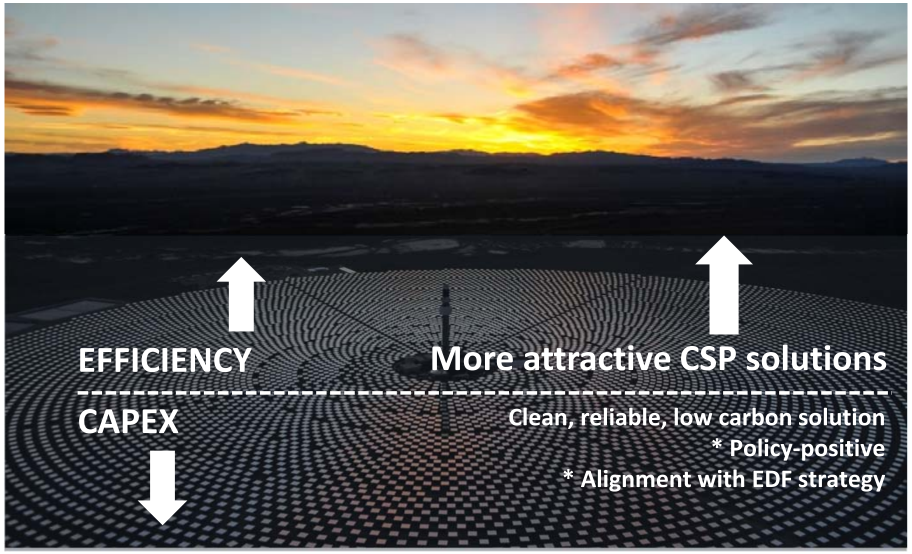
2019/09/19

OUTLINE

Why using Supercritical CO_2 cycle for power generation?

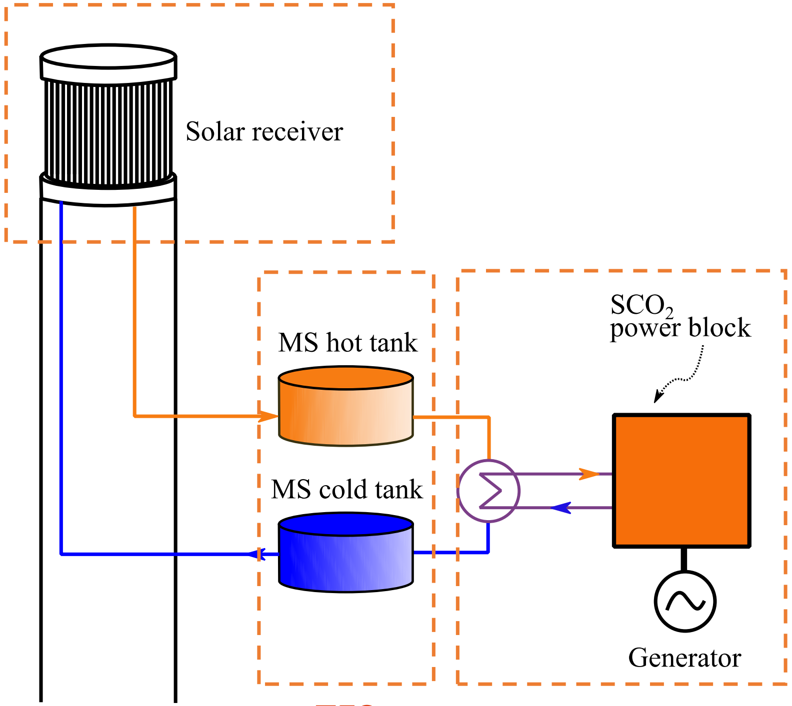


Supercritical CO_2 Cycle + CSP



- SCO_2, together with high temperature (> 500 ℃) molten salt CSP solutions, could achieve higher efficiency than steam solutions.
- The size of CSP plant is between 50MWe and 150MWe, which is suitable for the first industrial demonstration of cycle.
- Recompression cycle is taken for a preliminary cycle dynamics study, because this is the most studied layout with a good balance between complexity and efficiency.

Supercritical CO_2 Cycle + CSP



Consideration for the design of sCO2 cycle

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Minimize LCOE of the power plant

Related ↑

Cost performance of solar field and power block

Influence ↑

Important indicator

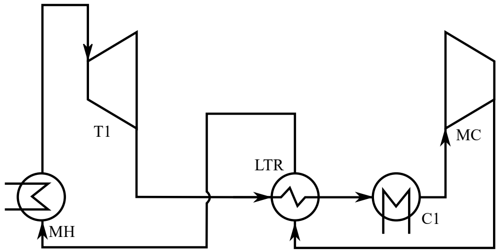
Potential of thermal energy storage (TES)

Influence ↓

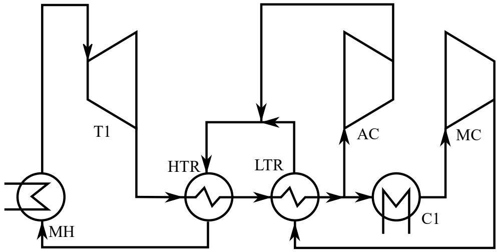
Cost of thermal energy storage (TES)

sCO_2 cycles

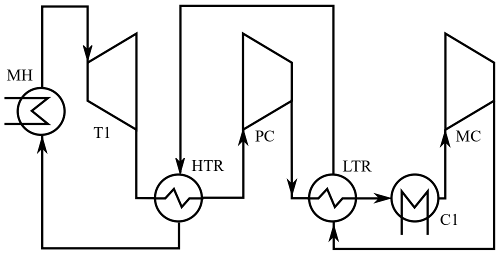
Regenerative cycle (RG)



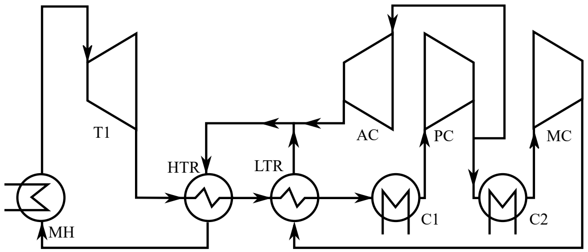
Recompression cycles (RC)



4 fundamental sCO_2 cycles



Precompression cycle (PC)



Partial cooling cycle (PartC)

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3 cycle characteristics

- Intercooling (IC)
- Preheating (PH)
- Reheating (RH)

16 sCO_2 cycles studied

Modeling

- A zero-dimension model based on energy balance equation
- Model including turbine, compressor and heat exchangers
- Three indicators of cycle performance
  - cycle efficiency η
  - TES utilization ratio τ
  - specific power output w

$$\eta = \frac{\sum W_{turbine} - \sum W_{compressor}}{\sum Q_{in}} \qquad w = \frac{P \cdot t_{storage}}{m_{storage}} \qquad \tau = \frac{T_{upper}^{MS} - T_{lower}^{MS}}{T_{\max}^{MS} - T_{\min}^{MS}}$$

Parameters	Unit	Value
Maximum molten salt temperature, T_{max}^{MS}	°C	565
Minimum molten salt temperature, T_{min}^{MS}	°C	290
Maximum pressure, p_{max}	MPa	25
Main compressor inlet temperature, T_{MCI}	°C	35
Pre-compressor inlet temperature, T_{PCI}	°C	35
Compressor isentropic efficiency, η_{cmp}	%	89
Turbine isentropic efficiency, η_{tb}	%	93
Molten salt/CO_2 heat exchanger minimum internal pinch, $\Delta T_{min}^{MS/CO2}$	°C	5
CO_2/CO_2 heat exchanger minimum internal pinch, $\Delta T_{min}^{CO2/CO2}$	°C	5
Molten salt /CO_2 heat exchanger pressure drop (CO_2 side), $\Delta p^{MS/CO2}$	MPa	0.1
CO_2 /CO_2 heat exchanger pressure drop, $\Delta p^{CO2/CO2}$	MPa	0.1

Optimization of the cycle

Objective of optimization

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Maximize (specific output power)

At given TES utilization ratio

By changing

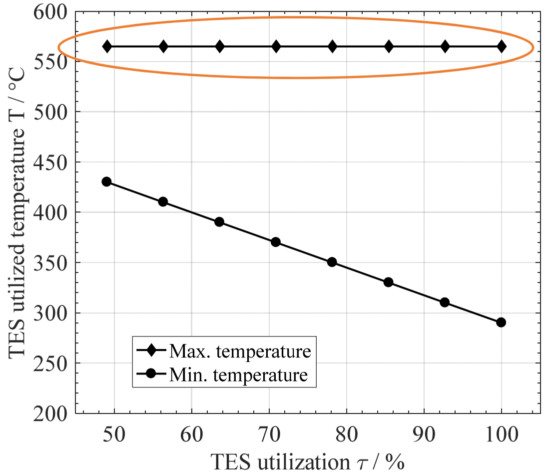
- sCO_2 mass flow rate
- Molten salt outlet temperature and TIT
- Cycle highest pressure
- Other parameters according to cycle characteristics

With constraints of

- MS temperature range (290 - 565°C)
- Maximum of cycle pressure
- 5 °C pinch of heat exchanger

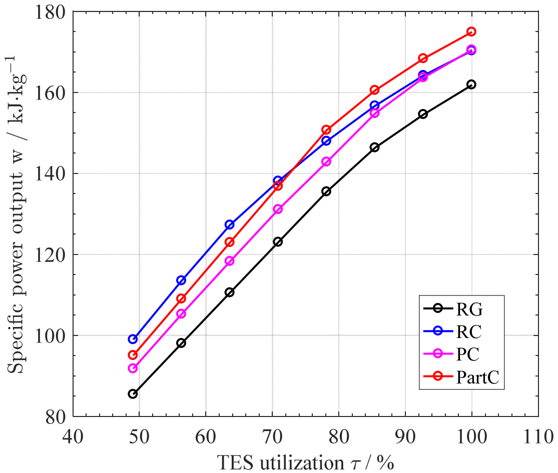
Effect of TES utilization ratio for fundamental cycles

1



Maximum molten salt temperature is always equal to 565°C

2



Specific power output increases with TES utilization ratio

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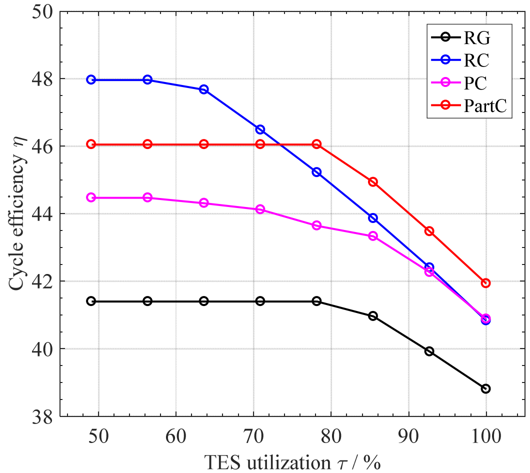

Average T_{MS} increases with the decrease of TES utilization ratio

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Rise of TIT

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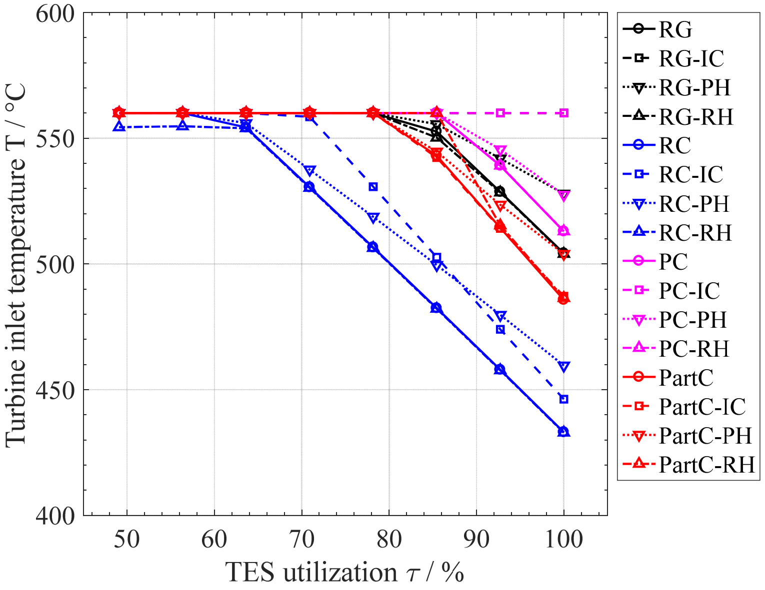
Rise of cycle efficiency

Effect of TES utilization ratio on TIT



For high TES utilization level, TIT does not reach its upper limit to have the best cycle efficiency

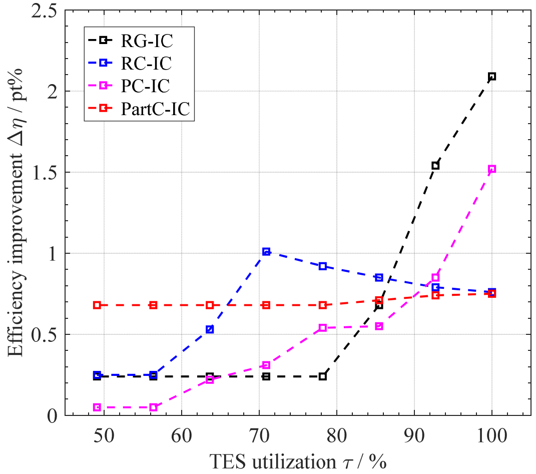
To keep both high TIT and TES utilization ratio

Simple RG	Full optimization	Partial optimization
TIT (°C)	504.23	560 (fixed)
Pressure Ratio	3.06	3.58
P_{min} (bar)	81.74	**69.75**
Efficiency	38.8	31.3

Higher efficiency

Effect of TES utilization ratio on cycle efficiency for cycle characteristics

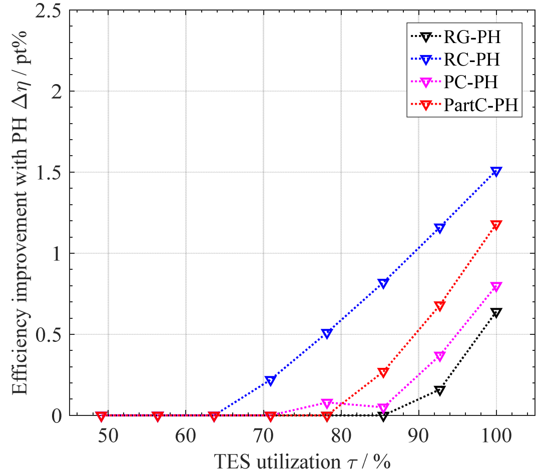
1 Intercooling



IC helps increase the cycle efficiency especially at high TES utilization ratio

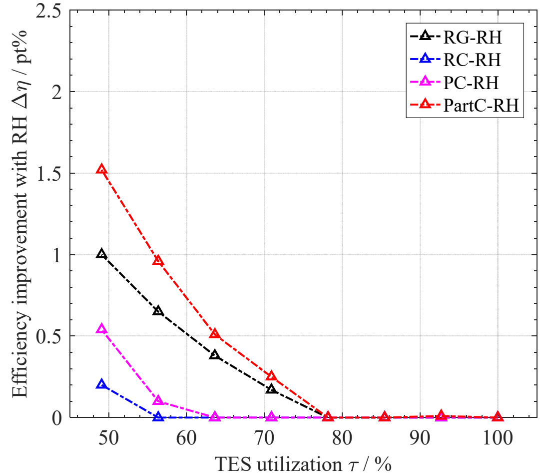
More evident improvement for RG and PC cycles

2 Preheating



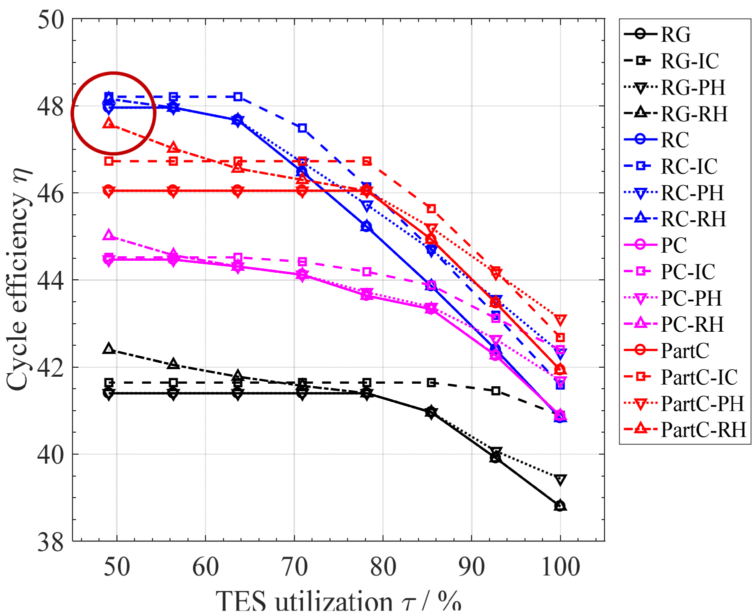
PH improves cycle efficiency only for high TES utilization ratio

3 Reheating



RH improves cycle efficiency only for low TES utilization ratio

Effect of TES utilization ratio on cycle efficiency



TES utilization ratio	Cycle with highest efficiency
100% – 93%	PartC-PH
93% - 75%	PartC-IC
75% - 49%	RC-IC
< 49%	RC-RH

RC starts to dominate at 50% TES utilization ratio

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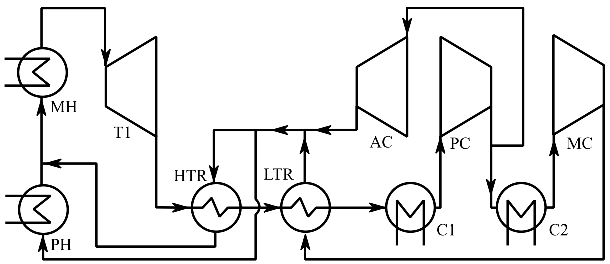
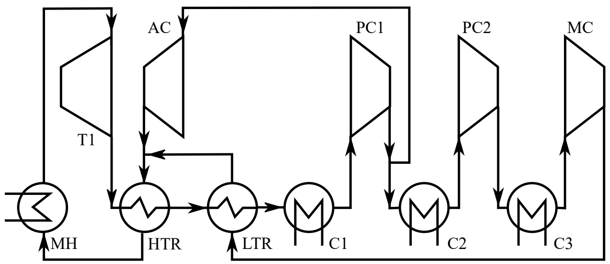
Two times molten salt and bigger storage tank needed compared with 100% TES utilization ratio

Effect of TES utilization ratio on cycle efficiency (2)

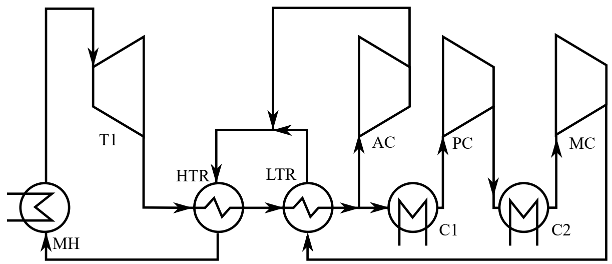
Cycle configuration	PartC - PH	PartC - IC	RC - IC
TES utilization ratio (%)	100	85.45	63.64
Cycle efficiency	43.11	45.64	48.21
TIT (°C)	503.98	542.3	560
Cycle minimum pressure (MPa)	63.57	53.77	80.06
Specific power output (kJ/kg MS)	179.78	163.02	128.66



PartC - PH



PartC - IC



RC - IC

Conclusions

- Effect of TES utilization ratio for CSP with sCO_2 power cycles
    - It is favorable to use higher-temperature molten salt
    - Lower TES utilization ratio helps reach higher cycle efficiency but will reduce specific power output
    - For high TES utilization ratio, it is not always optimal for TIT to reach its upper limit
    - Cycle with highest efficiency at different TES utilization ratio was listed
- TES utilization is an important factor when integrating sCO_2 with CSP
- Perspectives
    - Study on higher molten salt temperature
    - More complex combination of cycle characteristics


Questions?
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