ECHOGEN

Data Centers Coupled with Pumped Thermal Energy Storage System: Implementation and System Performance Evaluation

Ladislav Vesely, Jason Miller, Timothy Held, Robert Bernard

The International Supercritical CO2 Energy Technologies Symposium ● March 2 – 5, 2026 ● Pittsburgh, PA, USA

Introduction

- Potential use of energy storage system: Data centers
  - Rapidly growing development of AI applications = growing data centers capacity

- The data center consumption is only small portion of the overall energy demand:
  - Data center consumption – approx. 1.3 % (2022) of the total electrical consumption globally
    - The predicted growth in energy consumption
      - Between 2024 and 2030 - 15 % per year

- The data centers require base-load energy 24 hours / 7 days per week:
  - For cooling, servers, storage, network, and other operational infrastructure
  - Direct impact on the local electrical grid
    - Spatial concentration

Introduction

- Data centers:
  - Additional power generation systems or alternative energy systems
  - Cooling system = potential source of low-grade waste heat
    - The coolant temperatures up to 100 °C
      - Theoretical temperature – lab size
    - The heat removed can be utilized to improve system performance

- PTES can potentially use low-grade waste heat (i.e., bellow 150°C)
  - Proposed system

- ***NOTE:*** The same architecture of proposed PTES can be used for PTES coupled with a waste heat source stream (i.e., gas turbines exhaust stream, energy intensive industries, etc.) in the same range of temperature (10°C to 100°C).

Introduction – Data centers

The main types of data centers:

- **Hyperscale** - Owned and operated by companies
- **Enterprise** - Owned and operated by a single company for in-house use
- **Colocation** - Designed to provide available data center capability for rent

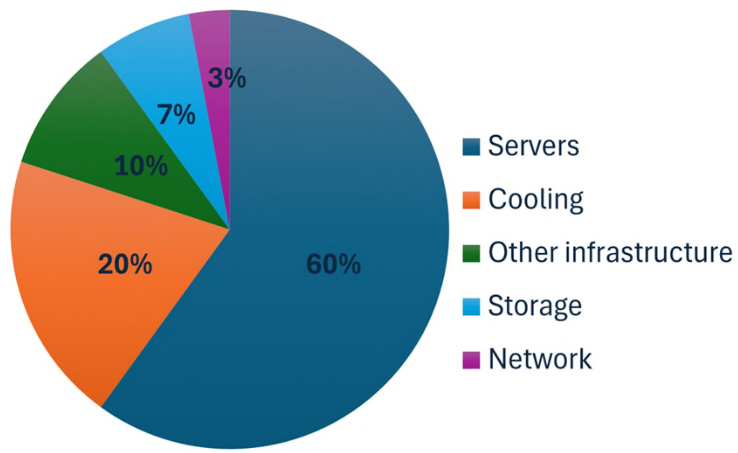
Cooling requirements:

- Enterprise - up to 30 % of the total electrical energy consumption
- Hyperscale - less than 20 % of the total electrical energy consumption

Cooling parameters:

- Typical max. cooling temperature – up to 50°C
  - Potential low-grid waste heat
- Temperature difference between inlet and outlet – approx. 10°C

Typical electrical energy consumption:

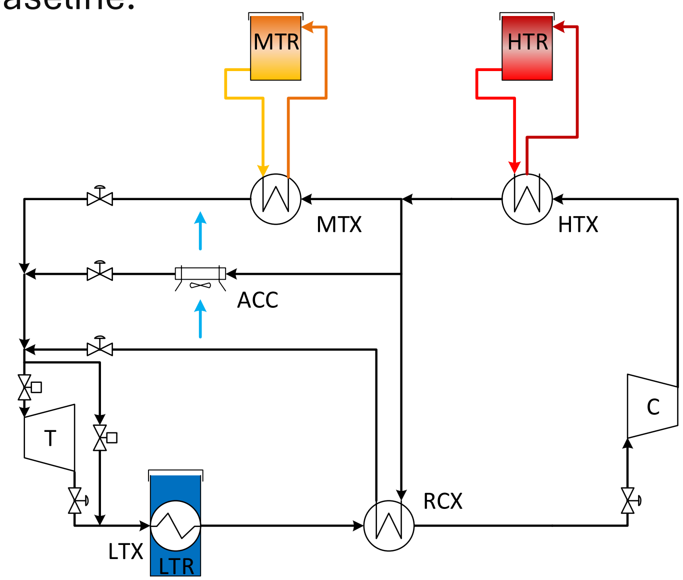


- The difference in the electrical energy consumption is dependent on the size and capacity of the data center

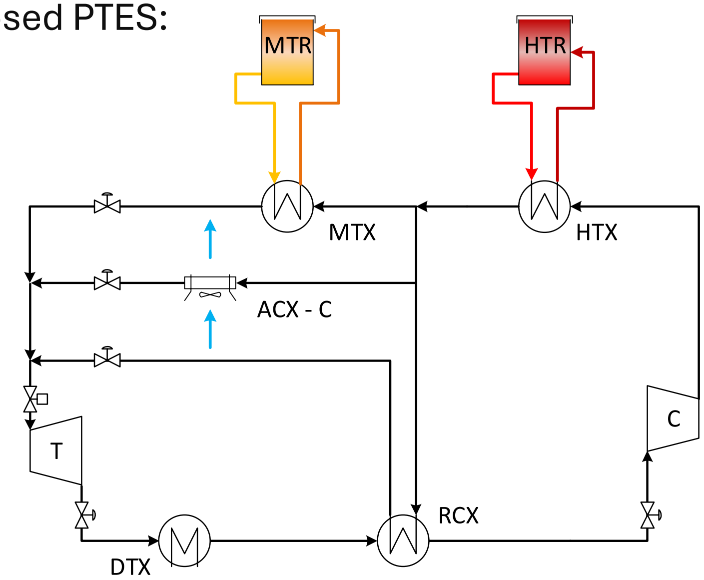
System description

PTES system description - CHG

Baseline:



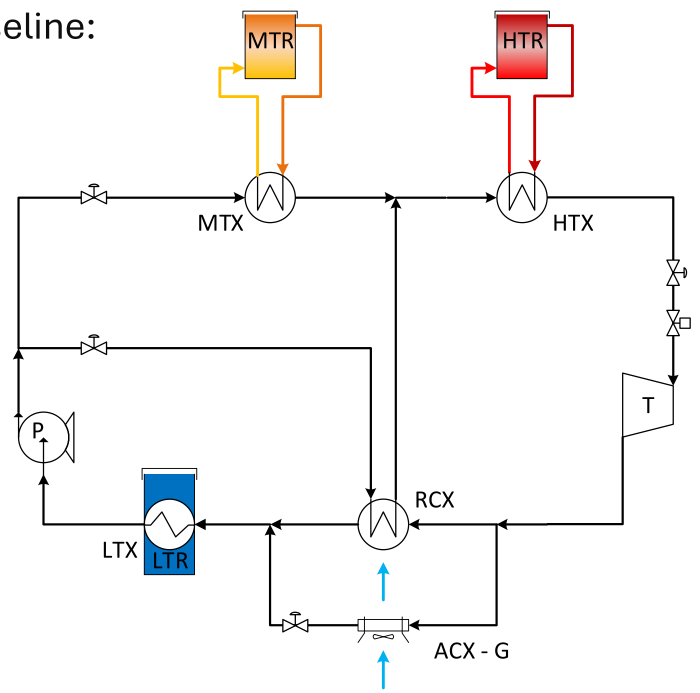
Proposed PTES:



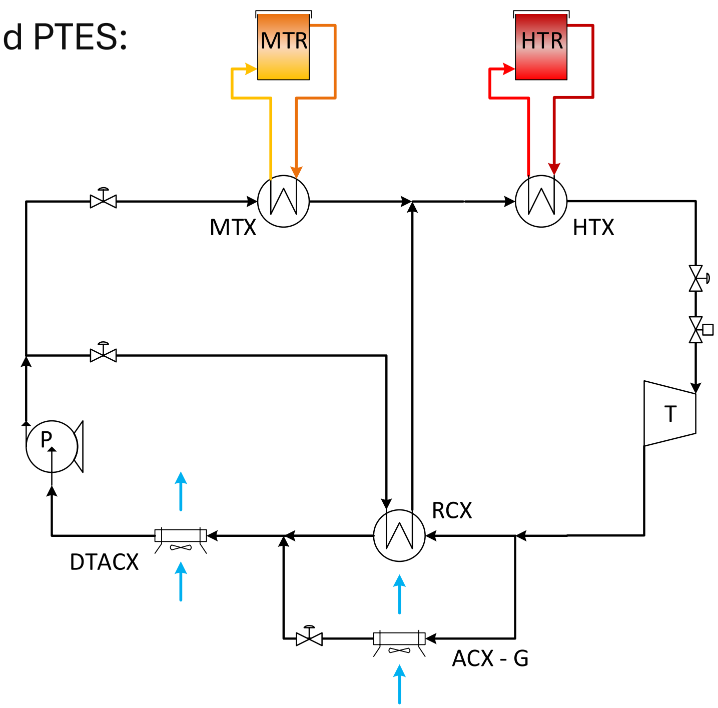
- HTX, MTX and RCX are common components for CHG and GEN cycles
- LTX – low-temperature reservoir (Baseline) = DTX – data center heat exchanger (Proposed PTES)

PTES system description - GEN

Baseline:



Proposed PTES:



- HTX, MTX and RCX are common components for CHG and GEN cycles
- LTX – low-temperature reservoir (Baseline) = DTACX – air-cooled heat exchanger (Proposed PTES)

System assumptions

Parameter	CHG	GEN	Unit
Load	100		MW
Max. system operating pressure	20 - 26		MPa
Min. system operating pressure	2.5		
Compressor / pump efficiency	90		%
Turbine efficiency	90		
Heat exchangers effectiveness	98		
Air-cooled heat exchanger effectiveness	98		
DTX inlet/outlet temperature difference	10	n/a	°C

- The PTES system was optimized via in-house code (MATLAB-based cycle model)

- Pressure drops and mechanical losses - not included
- Compressor motor efficiency - 98%
- Turbine gearbox and generator efficiency - 96%
- Ambient temperatures in range of -20°C to 40°C
- Waste heat / data center cooling system maximum temperature in range of 10°C to 100°C
- $\Psi_{h\text{-}m}$ ratio in range of 0.05 to 0.5
- MTX cold temperature in range of 50°C to 100°C

$$\Psi_{h-m} = \frac{Q_{MTR}}{Q_{MTR} + Q_{HTR}}$$

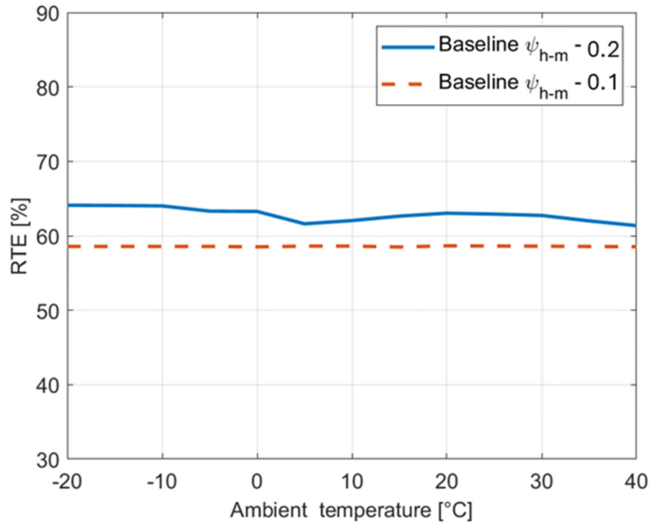
$$\Psi_{m-mh} = \frac{Q_{LTR}}{Q_{HTR}}$$

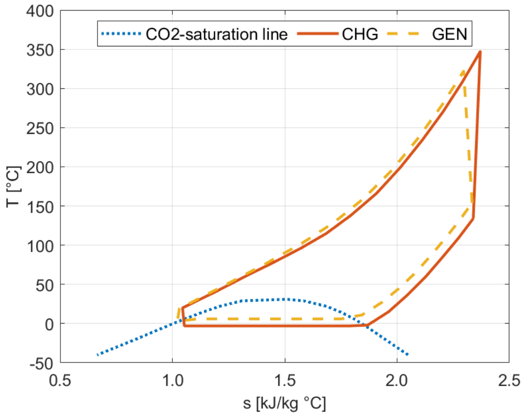
Note: Included only for baseline

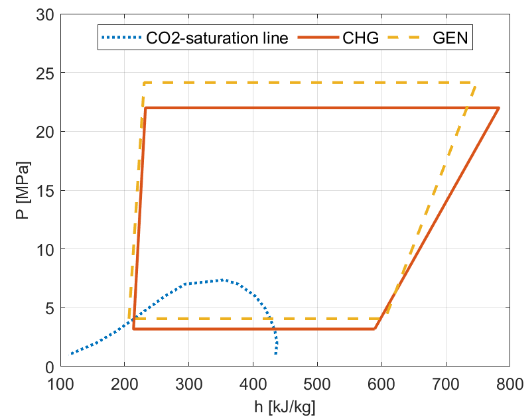
Results

Results - Baseline

- RTE around 58% ($\Psi_{h\text{-}m}$=0.1) or 62 to 64% ($\Psi_{h\text{-}m}$=0.2)
  - In full ambient range
- The MTX cold temperature is considered as low as 24°C







- The ACX-G load is almost negligible within the ambient range
- ACX-C load is very similar within the ambient range

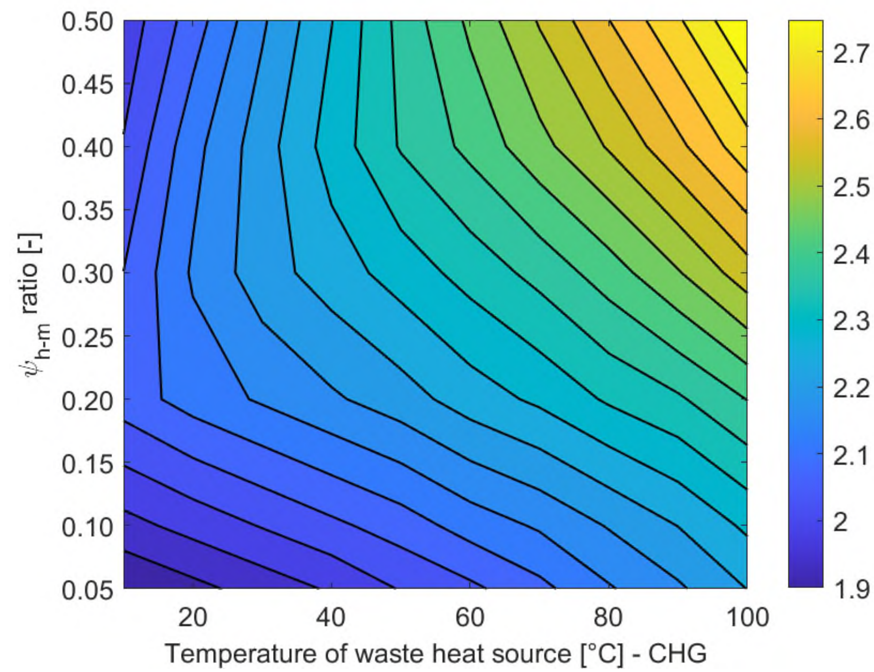
Results – proposed PTES (CHG)

Results

- Ambient temperature of 0°C
- MTX minimal storage temperature of 80°C

- The highest COP:
  - the highest waste heat temperature and Ψ_{h-m} ratio
  - Similar results with various ambient air temperatures.

- Baseline:
  - Lower ambient air temperature increase COP
  - Higher ambient air temperature decrease COP
- Proposed PTES:
  - Ambient air temperature has limited effect on COP
  - Flow split between MTX, RCX and ACX-C
    - Most of the CO_2 flow is going via RCX and MTX
    - ACX-C flow is changing based on the Ψ_{h-m} ratio
      - Higher ratio requires lower ACX-C flow rate



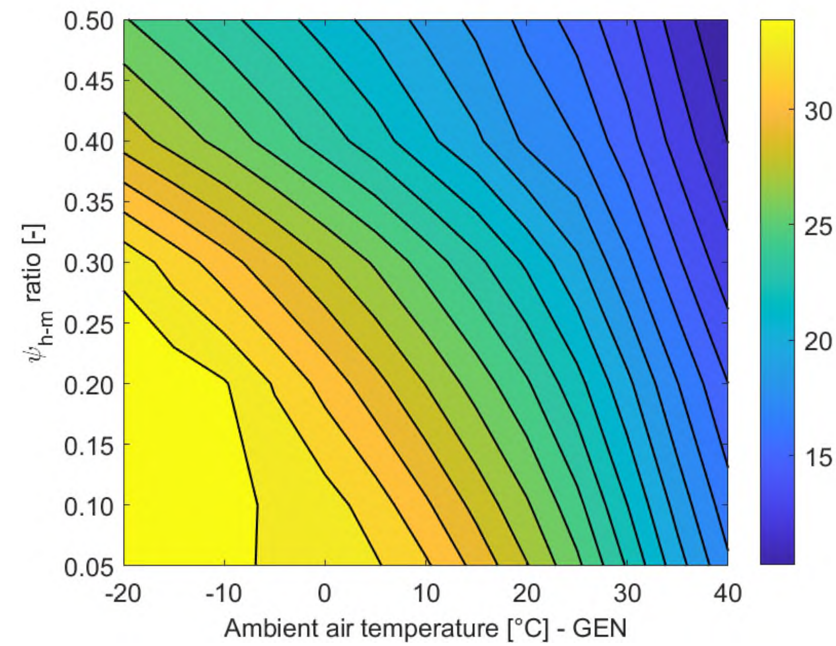
Results – proposed PTES (GEN)

Results

- Various ambient temperatures (-20°C to 40°C)
- $\Psi_{h\text{-}m}$ ratios (0.05 to 0.1)
- MTX minimal storage temperature of 80°C

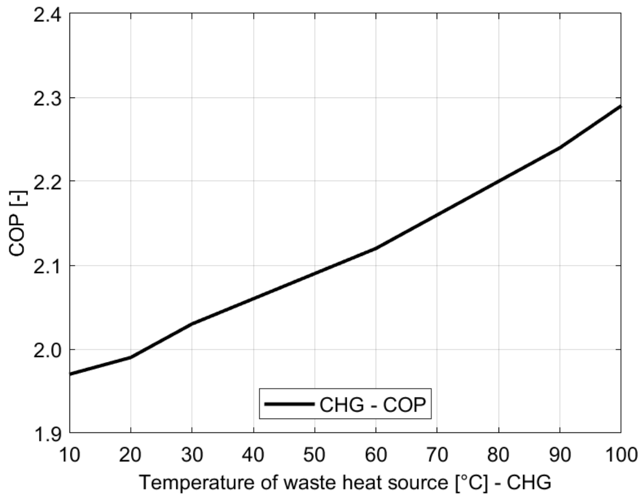
- The highest cycle efficiency is achieved for the lowest $\Psi_{h\text{-}m}$ ratio and ambient air temperature
  - Cycle efficiency can reach up to 35%
- ACX-G load is significantly smaller compared to the RCX load
  - To keep the MTX minimal storage temperature at design temperature
  - Most of the heat rejection is done via the DTACX.

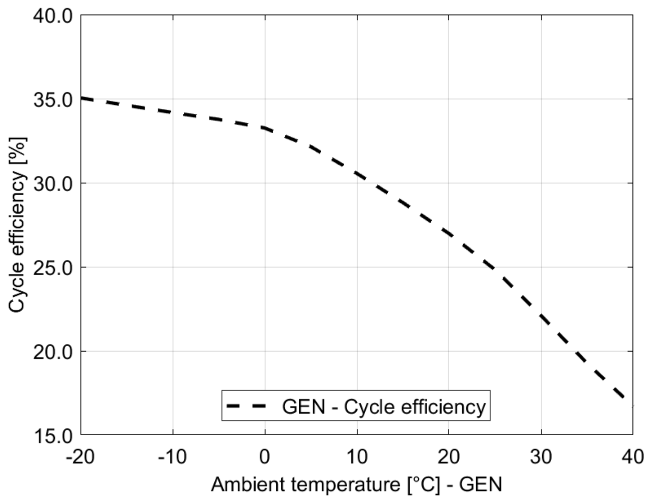
- *Note:* Air or water-based cooling system can be used to directly cool the data centers during GEN cycle



Results – proposed PTES

- COP values for different waste heat source temperature (10°C to 100°C) and ambient temperature equal to 0°C
- Cycle efficiency values for different ambient temperature (-20°C to 40°C)
- $\Psi_{h\text{-}m}$ ratios equal to 0.1

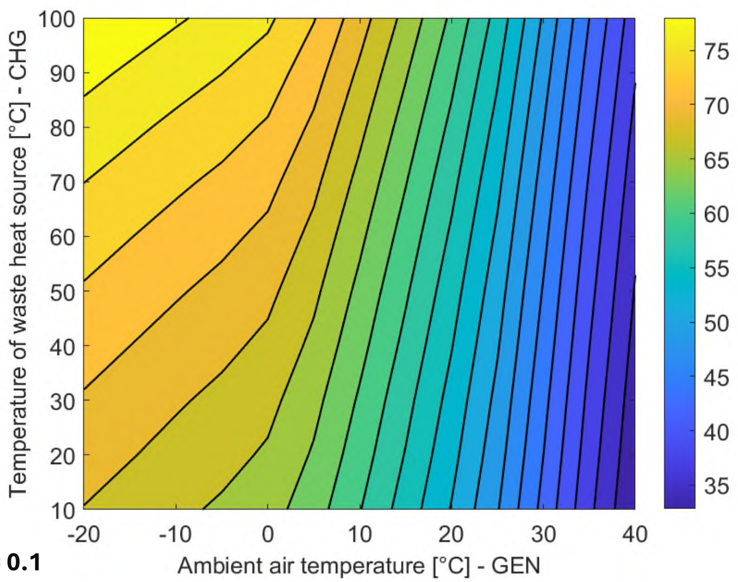




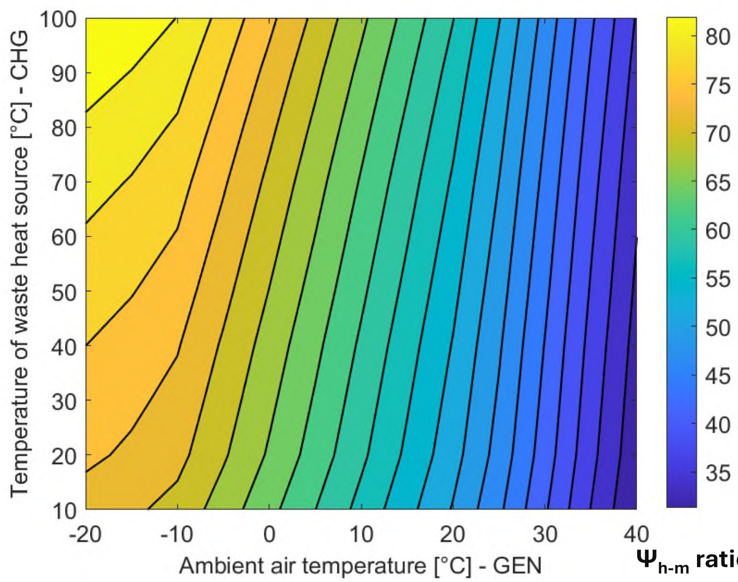
- COP in range of 1.97 to 2.3 ($\Psi_{h\text{-}m}$ = 0.1), and 2.1 to 2.4 ($\Psi_{h\text{-}m}$ = 0.2)
  - Higher $\Psi_{h\text{-}m}$ ratio (up to 0.2) has a positive effect on COP
- Cycle efficiency in range of 16.7 to 35 % ($\Psi_{h\text{-}m}$ = 0.1), and 15 to 35.1 % ($\Psi_{h\text{-}m}$ = 0.2)
  - Higher $\Psi_{h\text{-}m}$ ratio slightly reduces the cycle efficiency

Results – proposed PTES (RTE)

- GEN and CHG cycle best operation points are for the opposite Ψ_{h-m} ratios
  - Direct impact on the system
- RTE varies based on the ambient air and waste heat temperature, and Ψ_{h-m} ratio
  - The highest RTE - the highest waste heat temperature and the lowest ambient air temperature



Ψ_{h-m} ratio = 0.1



Ψ_{h-m} ratio = 0.2

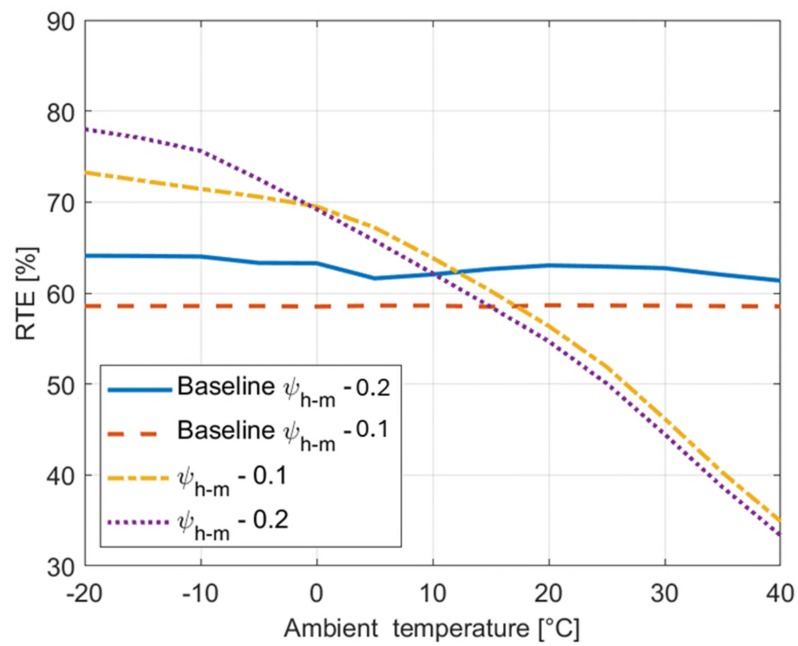
- The results are for ambient air temperature in range of -20°C to 40°C in the GEN cycle and for 0°C in the CHG cycle

Results – comparison

Proposed PTES:

- The system with $\Psi_{h\text{-}m}$ equal to 0.1:
  - RTE in range of 80.3 % to 32.8 %
- The systems with $\Psi_{h\text{-}m}$ ratio equal to 0.2
  - RTE in the range of 82.5 % to 31.3 %

- WHR has a positive effect on the COP and RTE
  - The effect is sensitive to:
    - Ambient air temperature
    - $\Psi_{h\text{-}m}$ ratio
    - Corresponding CO2 flow split between MTX, ACX-C, and RCX



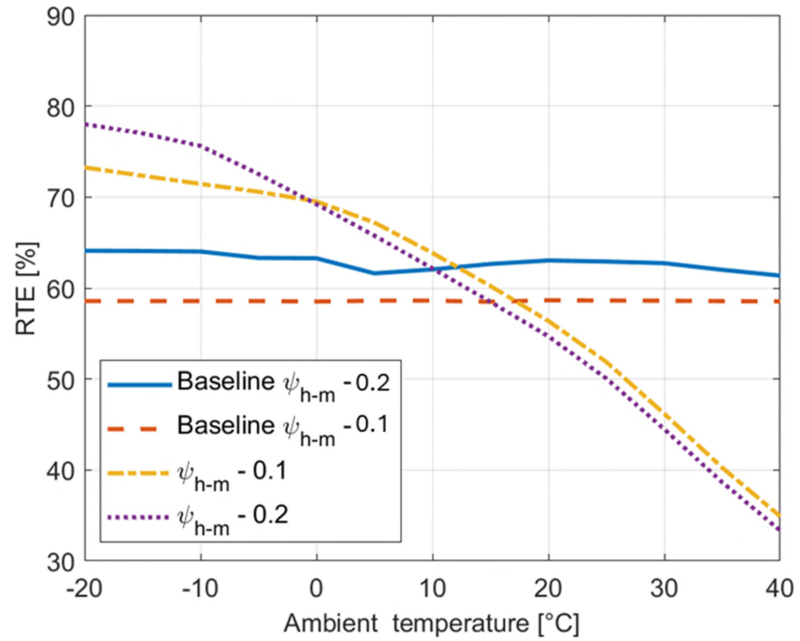
- Waste heat source temperature equal to 50°C
  - Typical max. cooling temperature

Results – comparison

Comparison:

- The proposed PTES can achieve higher RTE:
    - Full range of waste heat temperatures
    - Ambient air temperatures below 10 °C
    - $\Psi_{h\text{-}m}$ ratios (0.1 and 0.2)
- The baseline PTES performs better for higher ambient air temperatures:
    - Above 10 °C
- RTE drop for higher ambient temperature between can be reduced:
    - Higher waste heat source temperatures

Note: Similar trends in RTE can also be observed for the different waste heat source temperatures.

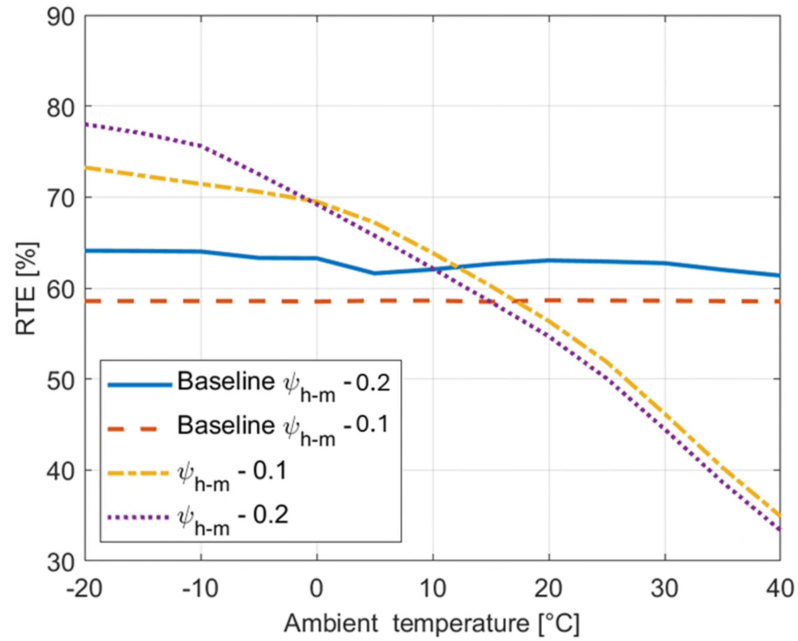


- Waste heat source temperature equal to 50°C
    - Typical max. cooling temperature

Results – comparison

Comparison:

- The potential disadvantages in RTE:
  - Can be eliminated via charging and discharging regime
  - Charging during the daytime
    - The ambient air temperature has a negligible effect on the COP
  - Discharging during the nighttime
    - Potential positive effect of lower ambient air temperature
  - ***Note***: the cost of electricity is the main parameter to decide when to charge the PTES system
- Another option:
  - Alternative cooling system
    - Water received from large water reservoirs (i.e., rivers, lakes, ocean, etc.)



- Waste heat source temperature equal to 50°C
  - Typical max. cooling temperature

Conclusion

Conclusion

- sCO_2-based PTES for data center applications utilizing low-grade waste heat from the data centers cooling systems had been designed and optimized

- PTES can operate with RTE close to 85 % (80 % - case with WHR temperature - 50°C)
  - With ambient air temperatures around -20°C
- The waste heat can improve COP for the cold days (10°C to -20°C) compared to baseline PTES
  - RTE rapidly drops with increasing ambient air temperature - RTE around 30 % for hot days (40°C)
- The improvement in the RTE for the higher ambient air temperatures
  - Additional flow split distribution between ACX-C, RCX, MTX and off-design pressures

- ***Note:*** The proposed architecture of sCO_2-based PTES coupled with waste heat source can be used for any source of waste heat (i.e., gas turbines, energy intensive industries, etc.)

Thank you for your attention.

Ladislav Vesely
lvesely@echogen.com