The 9th International Supercritical CO_2 Energy Technologies Symposium
March 2 - 5, 2026, Pittsburgh, PA
Paper 40

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

Ladislav Vesely
Echogen Power Systems
365 Water St, Akron, OH 44308

Timothy Held
Echogen Power Systems
365 Water St, Akron, OH 44308

Jason Miller
Echogen Power Systems
365 Water St, Akron, OH 44308

Robert Bernard
Echogen Power Systems
365 Water St, Akron, OH 44308

Bios

Ladislav Vesely works as a senior system engineer at Echogen Power Systems. He received his Ph.D. in 2018 from Czech Technical University where he investigated the effect of various mixtures on the performance of sCO_2 power cycles. Since receiving his Ph.D., his work has focused on sCO_2 cycles, energy storage, waste heat, CCS, and ORC systems.

Timothy Held is the Chief Technology Officer at Echogen Power Systems in Akron, Ohio, where he is responsible for development, maturation, and commercialization of supercritical CO_2 power cycles and energy storage systems. Prior to joining Echogen in 2008, Dr. Held was with GE Aviation for 13 years, where he held leadership positions in several combustor design and fuels technology teams. He received a BSAAE from Purdue University in 1987, and a Ph.D. in Mechanical and Aerospace Engineering from Princeton University in 1993. He has published several technical journal articles and book chapters and currently holds 50 U.S. patents.

Jason Miller is the Director of Engineering at Echogen Power Systems, where he leads multidisciplinary teams advancing sCO_2 power systems and thermal-energy technologies. He has over a decade of experience delivering DOE-funded programs, turbomachinery development efforts, and large-scale test initiatives. His work spans advanced heat-pump technologies, expander development, and next-generation energy-system modeling and testing. He earned his BSME in 2003 and pursued graduate studies at the University of Akron until 2008. He has published journal articles and holds multiple energy systems patents related to architecture and controls.

Robert Bernard is the Chief Commercial Officer at Echogen Power Systems, bringing 25 years of experience in business development, operations, and strategic growth within the power industry. In his current role, Robert leads sales, marketing, and business development efforts, driving the deployment of utility-scale Long Duration Energy Storage solutions powered by Echogen’s cutting-edge Pumped Thermal Energy Storage technology. Before joining Echogen, Robert held key leadership positions at Bloom Energy and Westinghouse Electric Company, where he played a pivotal role in advancing clean energy technologies and projects. During his tenure at Westinghouse, he led the Long Duration Energy Storage team, which ultimately laid the foundation for the company's current partnership with Echogen.

ABSTRACT

With increasing adoption of artificial intelligence (AI) comes a corresponding increase in energy demands of associated data centers. Data centers require a continuous heavy energy supply for operation and high cooling load requirements. Because of these demands, an additional power generation system (including nuclear, hydro, wind, or energy storage system) needs to be implemented into the design of data centers, which can have a direct impact on the cost and footprint of the facilities. Simultaneously, data center facilities can produce low-grade waste heat up to 100°C, with potential energy recovery via a power conversion system that can reduce energy consumption or have potential district heating applications. A pumped thermal energy storage (PTES) system based on a supercritical carbon dioxide (sCO_2) power system can utilize the low-grade waste heat from the data centers to improve the system-level energy efficiency. It can also balance energy costs by using energy that has been stored from the power grid during periods of low demand or from high production due to renewable energy generation systems. In this paper, a PTES system designed to provide energy to data centers and utilize the low-grade waste heat generated via cooling systems will be presented. The PTES system for data centers operates in two regimens (i.e., charging and generation cycle) and the thermal energy is stored in high- and low-temperature reservoirs. At the same time, the waste heat provided by the data centers is used to improve the PTES round trip efficiency (RTE) via the charging cycle. The PTES is designed to operate with the data center maximum cooling temperature up to 100°C and with ambient air-cooling temperature in range of -20°C to 40°C. The optimization results show that the PTES coupled with the data center cooling system can reach RTE of 80% and can provide required power to data centers.

INTRODUCTION

Energy storage systems play a more significant role with increased energy demand requirements which do not correspond with potential energy generation availability, especially with fast-growing data centers and AI applications. In 2024, the energy demand increased by 2.2% and the electricity demand increased by 4.3% [1]. In 2022, data center consumption was around 1.3% of the total electrical consumption [2]. Compared to other industries/end-users (e.g., electrical vehicles, energy-intensive industries, etc.), the data centers are only a small portion of the overall energy demand at this moment. One of the main challenges of the data centers is their impact on the local electrical grid due to spatial concentration [2]. The data centers require large amounts of energy for cooling as well as for servers, storage, network, and other operational infrastructure. The typical energy consumption for a data center is shown in Figure 1 [3].

Energy consumption may vary based on the type of data centers. For example, a data center run by companies for their own use requires more than 20% for the cooling, and hyperscale data centers operated by companies such as Google, Amazon, Microsoft or Meta, might require less than 20% for the cooling [3]. The predicted growth in energy consumption for data centers between 2024 and 2030 is around 15% per year [3]. Due to this forecast, alternative energy systems such as pumped thermal energy storage (PTES) systems are necessary for sustainable data center operation.

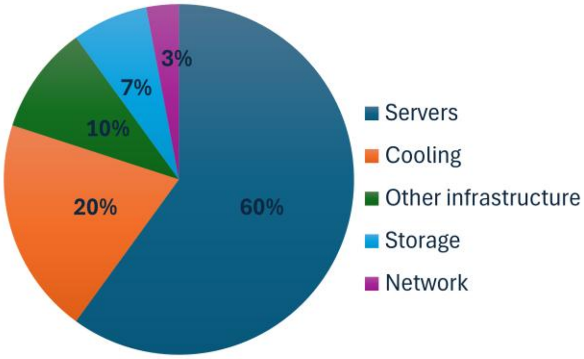

Figure 1: Data center energy consumption.

The PTES can provide low-cost energy and reduce potential risk on the electrical grid [4]. The PTES system can operate with a wide range of available and required load, ambient conditions, and thermal storage mediums and corresponding temperatures [5]. Additionally, the PTES system can potentially use low-grade waste heat, which is generated by the cooling system of the data center [6,7]. This can reduce required energy consumption (see Figure 1) compared to other cooling technologies used for the data center cooling, and can have a positive effect on the PTES performance (RTE) and overall system size. To utilize the low-grade waste heat requires several modifications of the PTES. The waste heat recovery will remove one of the storage reservoirs (low-temperature reservoir). However, the additional heat can increase the coefficient of performance (COP) of the charging cycle which has a direct impact on the system round trip efficiency (RTE). On the other side, the higher temperature of the waste heat compared to low temperature reservoir affects the operation temperature of the medium temperature reservoir and recuperative heat exchanger.

In this paper, a study to evaluate potential design of a data center coupled with a PTES system is investigated. The proposed system will provide required energy to the data center as well as remove necessary waste heat from the data center cooling system to reduce data center energy consumption and improve the PTES system performance. The study focuses on a wide range of ambient conditions and temperature ranges of the waste heat between 100 and 10ºC.

SYSTEM DESCRIPTION

The proposed PTES system operates in two regimes, i.e., generating (GEN) and charging (CHG) regimes, that reflect the cycle layouts' configuration. In the charging regime, the CHG cycle operates to store the thermal energy in storage reservoirs by converting the electricity available in the electrical grid. Additionally, the CHG cycle is designed to receive heat from the data center cooling system via a waste heat recovery heat exchanger. The heat received from the data center has a potentially positive effect on the CHG cycle coefficient of performance (COP) compared to CHG without waste heat recovery option. In the generating regime, the GEN cycle operates to converge the stored thermal energy into the electricity to support either the electrical grid demand or the data center demand. Compared to the CHG cycle, the GEN cycle is not designed to utilize the waste heat generated by the data center's cooling system.

Each cycle consists of its own set of design point parameters, namely mass flow, temperature, and pressure based on the cycle layout configurations, system operating load, and available waste heat load or cooling load. Both cycles share the main components such as HTX and MTX (the interfaces between cycle working medium and reservoirs working/storage medium) and recuperated heat exchanger. Other components are specific for each cycle. The CHG and GEN cycle configurations are shown in Figure 2. The PTES system optimized in this study was designed based on the baseline PTES system without waste heat recovery utilization. The difference between the PTES for data center applications and the baseline PTES is in the DTX and DTACX, which are replaced by low temperature reservoir in the baseline PTES configuration.

Charging cycle

The CHG cycle consists of a turbine (T), compressor (C), air-cooled heat exchanger (ACX-C), recuperative heat exchanger (RCX), high and medium temperature reservoirs heat exchangers (HTX and MTX), and data center heat recovery heat exchanger (DTX). As was mentioned above, the HTX, MTX and RCX are common for CHG and GEN. The ACX-C is a cycle-specific heat exchanger that serves to reject excess heat in each cycle to maintain thermal balance between the reservoirs. In the CHG cycle, ACX-C operates on the high-pressure side of the system. The DTX is a cycle-specific heat exchanger that is used to transfer heat from the data center cooling system into the CHG working medium (CO_2). The CHG configuration is shown in Figure 2 (left side).

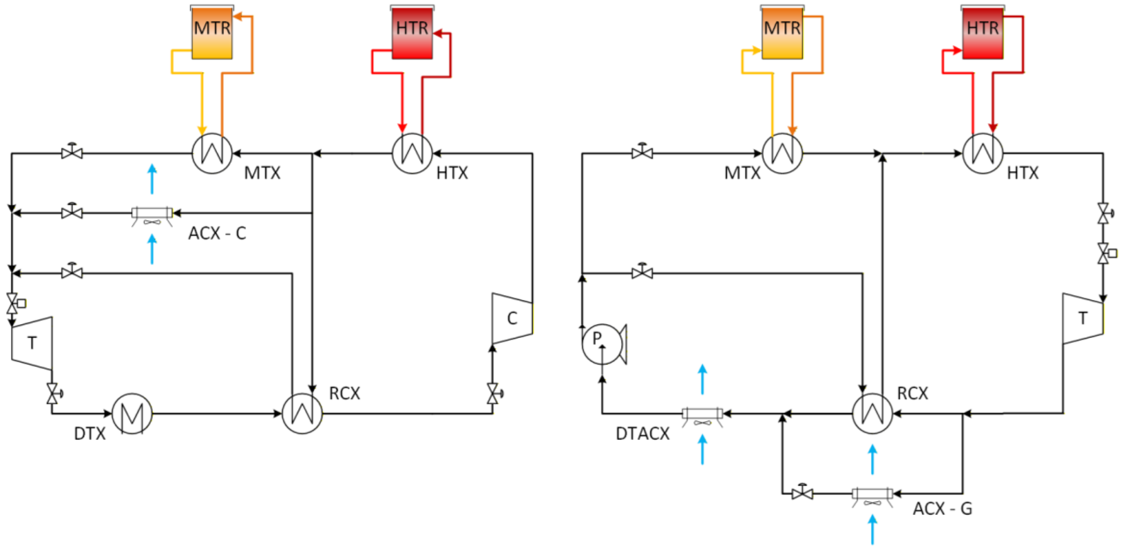

Figure 2: CHG (left side) and GEN (right side) Cycle Configuration.

Generating cycle

Similar to the CHG cycle, the GEN cycle consists of common components such as CHG cycle, the recuperative heat exchanger (RCX), high, and medium temperature reservoirs heat exchangers (HTX and MTX). Additionally, the GEN cycle consists of a generating turbine (T), pump (C), and two air-cooled heat exchangers (i.e., ACX-G and DTACX). The ACX is a cycle-specific heat exchanger that serves to reject excess heat in each cycle to maintain thermal balance between the reservoirs. Compared to the CHG cycle, the ACX-G operates on low-pressure side of the system. Because of non-waste heat recovery during the GEN cycle, DTX is replaced with an additional air-cooled heat exchanger (DTACX), that is used to reject additional heat required for the system operation. The GEN configuration is shown in Figure 2 (right side).

System assumptions

In this paper, a case study of a potential PTES system designed to provide energy to data centers and utilize the low-grade waste heat generated via cooling systems has been investigated. To design and optimize the PTES system for the data center applications, several assumptions and boundary conditions need to be established. The assumptions and boundary conditions are listed in Table 1.

Table 1: Case study assumptions and boundary conditions.

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 pressure drops and mechanical losses are not included in the simulations. The compressor motor efficiency is around 98%; turbine gearbox and generator efficiency are around 96%. Both cycles are considered to operate at a range of ambient temperatures (-20°C to 40°C). The waste heat / data center cooling system is considered to achieve maximum temperature in range of 10°C to 100°C. To be able to utilize the available waste heat, additional assumptions / limitations have been considered. Those assumptions are that the $\Psi_{h\text{-}m}$ ratio is considered to be in range of 0.05 to 0.5, and the MTX cold temperature to be in range of 50°C to 100°C. The $\Psi_{h\text{-}m}$ ratio is ratio between medium temperature reservoir load and sum of medium-temperature reservoir and high-temperature reservoir loads (Equation 1), and it defines the potential storage load in the system between the reservoirs.

$$\Psi_{h-m} = \frac{Q_{MTR}}{Q_{MTR}+Q_{HTR}} \tag{1}$$

$$\Psi_{m-mh} = \frac{Q_{LTR}}{Q_{HTR}} \tag{2}$$

Similar assumptions are used for the baseline PTES system. The main difference is due to low temperature reservoir which adds additional reservoir ratio ($\Psi_{h\text{-}c}$). The $\Psi_{h\text{-}c}$ ratio is ratio between the low temperature reservoir load and high temperature reservoir load (Equation 2). The MTX cold temperature is not limited, and is to be considered as low as 24°C. The P-h and T-s diagrams of GEN and CHG baseline system is shown in Figure 3. Note: the results in Figure 3 are for ambient temperature 0°C, $\Psi_{h\text{-}c}$ 1.3, and $\Psi_{h\text{-}m}$ ratio 0.1.

The PTES system was optimized via in-house code (MATLAB-based cycle model), which was developed and has been used for various ongoing projects related to PTES and waste heat recovery systems [8,9].

RESULTS AND DISCUSSION

The first step of the study is to optimize the baseline PTES, which will be used as a baseline and system comparison for the PTES coupled with data center. The baseline PTES system has been optimized with $\Psi_{h\text{-}m}$ ratio of 0.1 and 0.2 and ambient temperature in range of -20°C to 40°C. The results are shown in Figure 4. According to the results the baseline PTES system can operate with RTE around 58% ($\Psi_{h\text{-}m}$=0.1) or 62 to 64% ($\Psi_{h\text{-}m}$=0.2) in the full ambient range.

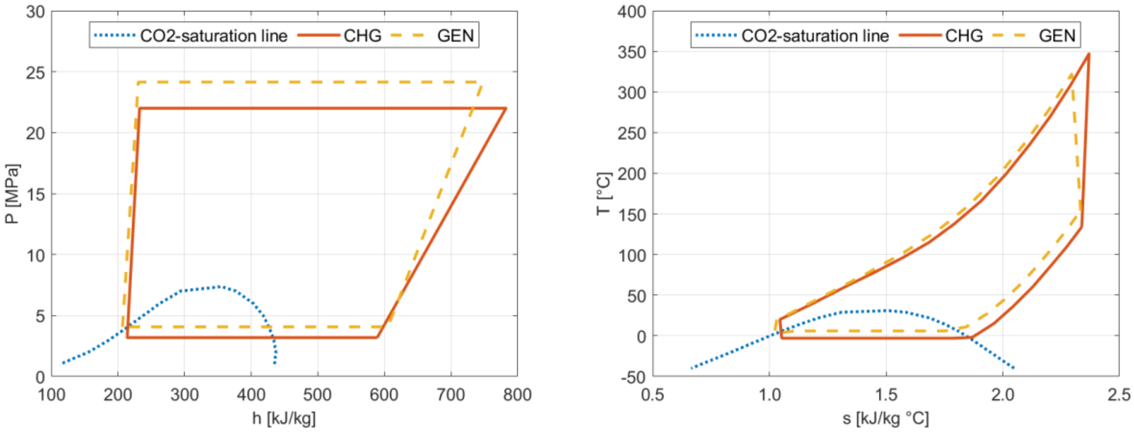

Figure 3: P-h and T-s diagrams of GEN and CHG baseline system.

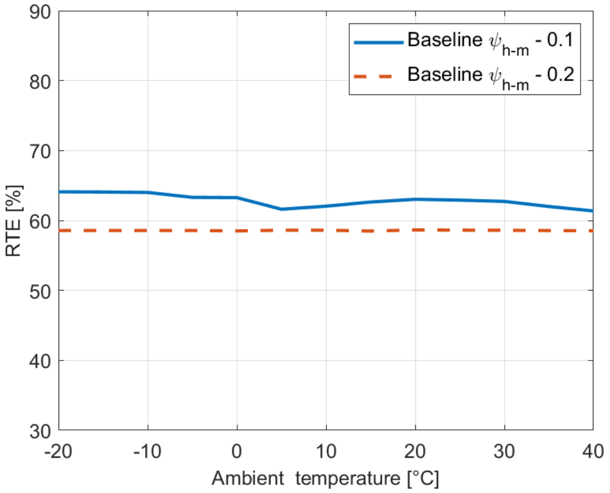

Figure 4: RTE results for baseline PTES system.

The proposed PTES system for the data center application has been optimized based on the assumptions listed in Table 1. The CHG and GEN cycle were optimized together to keep the same operation parameters between CHG and GEN, that might be affected by the ambient temperature or / and waste heat temperature from the data center. As was mentioned, the CHG cycle is operated with waste heat, which is transferred into the system via DTX on the low-pressure side of the CHG cycle. Because of this, the working medium temperature increases on the inlet to the low-pressure RCX, which has an impact on the high-pressure RCX outlet and simultaneously has an effect on the ACX-C and MTX parameters. Due to this, the MTX cold storage medium temperature increases from 24°C up to the new design temperature.

Based on the optimization results, the highest COP is achieved for the MTX cold temperature in range of 60ºC to 80°C. Like the CHG cycle, the higher MTX temperature has an impact on the

GEN cycle performance. According to the results, the highest cycle efficiency is achieved for MTX temperature in range of 80°C to 90°C. Hence, the MTX cold temperature based on the optimization results was selected to be approximately 80°C. This temperature is used for all simulation results listed in this paper.

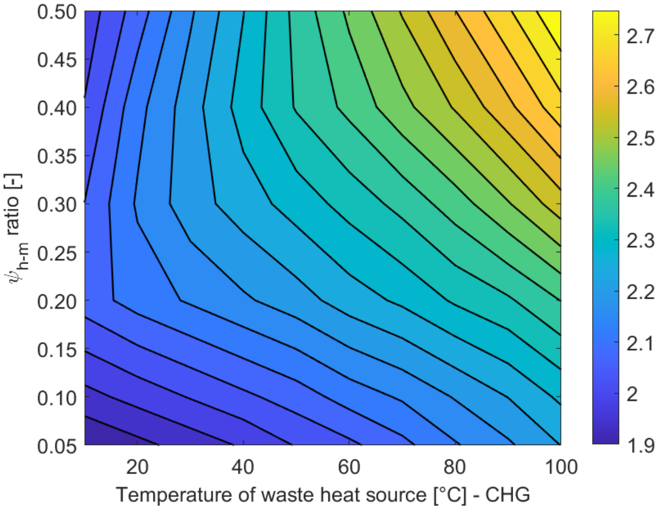

Figure 5: COP distribution for various waste heat source temperatures and $\Psi_{h\text{-}m}$ ratios.

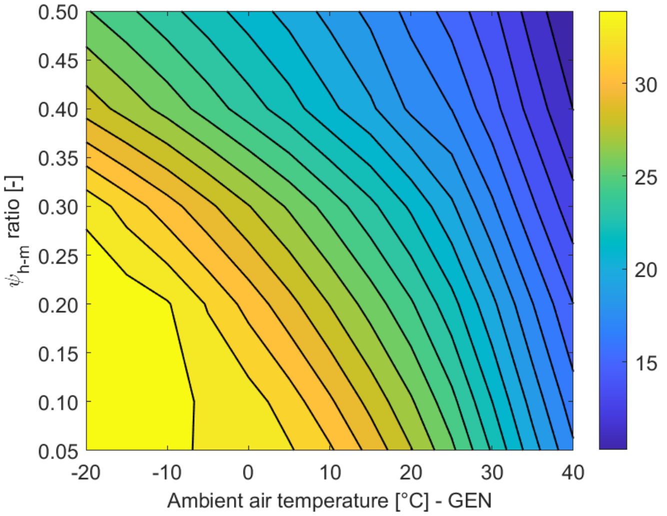

Figure 6: Cycle efficiency distribution for various ambient temperatures and $\Psi_{h\text{-}m}$ ratios.

The results for the CHG cycle are listed in Figure 5. The results listed in the figure are for the ambient temperature of 0°C. According to the results, the COP is in the range of 1.8 to 2.8 for selected waste heat temperatures and $\Psi_{h\text{-}m}$ ratios. The highest COP is achieved for the highest waste heat temperature and $\Psi_{h\text{-}m}$ ratio. Similar results can be seen for cases with various ambient temperatures in range of -20°C to 40°C. However, the ambient temperature has limited effect on CHG performance due to the flow split between MTX, RCX and ACX-C (see Figure 2), and the effect of ambient temperature on the COP is insignificant. Most of the flow is going via RCX and MTX. The ACX-C flow is changing based on the $\Psi_{h\text{-}m}$ ratio, i.e., higher ratio requires lower ACX-C flow rate.

Similar to CHG cycle results, the GEN cycle results are listed in Figure 6. The GEN cycle operates with various ambient temperatures (-20°C to 40°C) and Ψ_{h-m} ratios (0.05 to 0.1). Within those ranges, the cycle efficiency can reach up to 35%, according to the results. The highest cycle efficiency is achieved for the lowest Ψ_{h-c} ratio and ambient temperature. Based on the results, the ACX-G load is significantly smaller compared to the RCX load to keep the MTX cold temperature at design temperature (i.e., 80°C). Most of the heat rejection is done via the DTACX heat exchanger. The results also showed that GEN and CHG cycle best operation points are for the opposite Ψ_{h-m} ratios, this has direct impact on the system design point and overall system RTE. The RTE varies based on the ambient and waste heat temperature, and the Ψ_{h-m}. Because of this, the two most promising cases (i.e., Ψ_{h-m} = 0.1 and 0.2) are selected as potential design operation ranges of the PTES coupled with the data center applications.

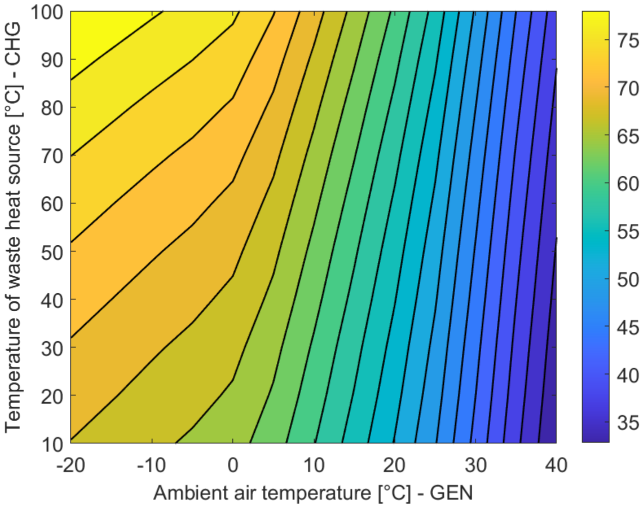

Figure 7: RTE distribution for various ambient, and waste heat source temperatures (Ψ_{h-m} = 0.1).

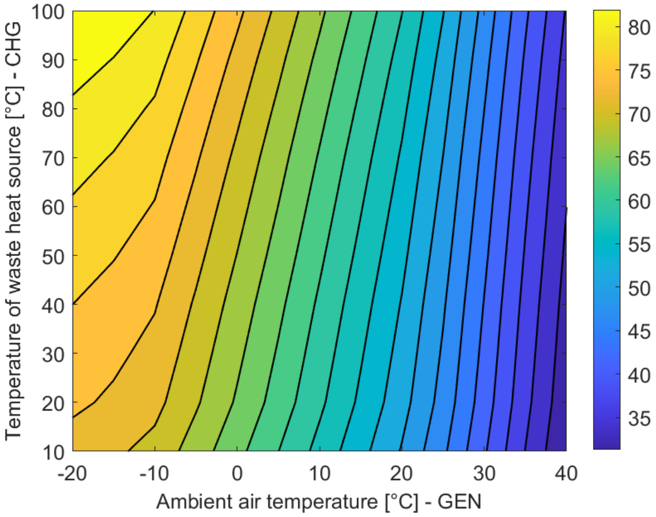

Figure 8: RTE distribution for various ambient, and waste heat source temperatures (Ψ_{h-m} = 0.2).

The RTE results for the Ψ_{h-m} ratio equal to 0.1 are shown in Figure 7, and results for the Ψ_{h-m} ratio equal to 0.2 are shown in Figure 8. The results are for ambient temperature in the range of -20°C to 40°C in the GEN cycle and for 0°C in the CHG cycle. As was mentioned above, the effect of the ambient temperature on the CHG cycle is insignificant. Because of this, the effect of the CHG ambient temperature on the overall RTE is insignificant as well.

The results show very similar trends for both cases; the PTES system can operate in the selected ambient and waste heat temperature ranges with the RTE up to 85%. According to the results listed in Figure 7 and Figure 8, the RTE is very sensitive to the ambient temperature as well as the waste heat source temperature. The lower ambient temperatures have a positive effect on the RTE. With increasing ambient temperature, the RTE is decreasing, especially for the highest ambient temperatures. The drop in the RTE for the hot day temperatures is very similar for both cases. The difference between the cases starts with ambient temperature below 0°C. The higher RTE can be achieved with higher $\Psi_{h\text{-}m}$ ratio, see Figure 8.

In comparison with the baseline PTES system, the PTES system coupled with data center applications achieved higher RTE for full range of waste heat temperatures and ambient temperatures below 10°C. The baseline PTES system performs better for higher ambient temperatures. However, the difference in RTE can be reduced with higher waste heat source temperatures. The comparison between the baseline PTES and the PTES coupled with data center applications is shown in Figure 9. The comparison listed in Figure 9 is for the waste heat source temperature equal to 50°C, which can be assumed as typical cooling temperature for typical data centers. Similar trends can also be observed for the different waste heat source temperatures.

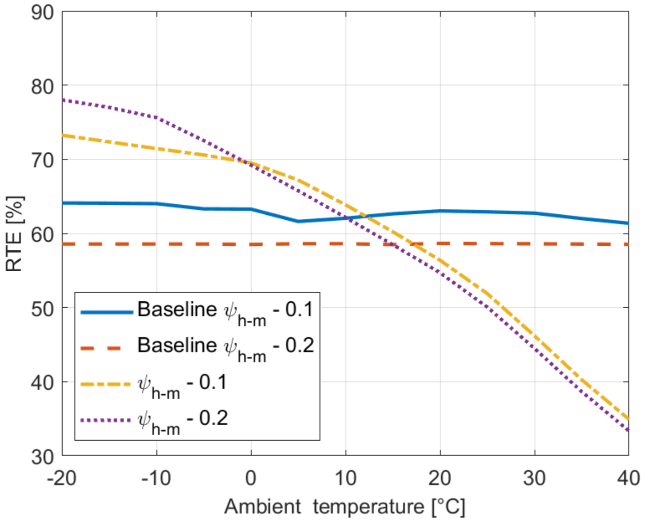

Figure 9: RTE comparison between the baseline and data center PTES with waste heat source temperature of 50°C.

CONCLUSION

In this study, a PTES system for data center applications utilizing waste heat from the data centers had been designed and optimized based on the assumptions listed in Table 1, and compared with baseline PTES system without waste heat utilization. The results showed that the PTES system can operate with RTE close to 80% with ambient temperatures around -20°C and the waste heat can improve the system performance for cold days compared to baseline PTES. On the other side, the RTE rapidly drops with increasing ambient temperature and can reach RTE around 30% (40°C). The effect of the ambient temperature on the CHG performance is insignificant. Because of the negligible affect of ambient temperature on CHG cycle performance, the system is able to charge during the day, when there is already available electricity from renewables, and then generate at night, when the temperatures drop and the available electricity is already reduced. This system can provide low-cost electrical power for the data center, while providing efficient cooling during high ambient temperatures.

The improvement in the RTE for the higher ambient temperatures can be potentially achieved with additional flow split distribution between ACX-C, RCX, and MTX as well as maximum and minimum operation pressures and temperatures. Additionally, CAPEX and OPEX will affect the design operation point as well, which includes the ongoing and future work in this study.

REFERENCES

[1] IEA (2025), Global Energy Review 2025, IEA, Paris https://www.iea.org/reports/global-energy-review-2025, License: CC BY 4.0.

[2] IEA (2024), World Energy Outlook 2024, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2024, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A).

[3] IEA (2025), Energy and AI, IEA, Paris https://www.iea.org/reports/energy-and-ai, Licence: CC BY 4.0.

[4] Sumit S., Mehdi M., Pumped thermal energy storage: A review, International Journal of Heat and Mass Transfer, Volume 213, 2023, 124286, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2023.124286.

[5] McTigue, Joshua, and Neises, Ty. Off-design operation and performance of pumped thermal energy storage. United States: N. p., 2024. Web. doi:10.1016/j.est.2024.113355.

[6] Ahmed A. Alkrush, Mohamed S. Salem, O. Abdelrehim, A.A. Hegazi, Data centers cooling: A critical review of techniques, challenges, and energy saving solutions, International Journal of Refrigeration, Volume 160, 2024, Pages 246-262, ISSN 0140-7007, https://doi.org/10.1016/j.ijrefrig.2024.02.007.

[7] Khosrow Ebrahimi, Gerard F. Jones, Amy S. Fleischer, A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities, Renewable and Sustainable Energy Reviews, Volume 31, 2014, Pages 622-638, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2013.12.007.

[8] Held, Timothy J, Miller, Jason, Mallinak, Jason, Avadhanula, Vamshi and Magyar, Luke. “Supercritical CO2-based pumped thermal energy storage (PTES).” Turbo Expo: Power for Land, Sea, and Air: pp. GT2024–129211. 2024. American Society of Mechanical Engineers, London.

[9] Held, Timothy J. “A high-temperature, dual rail heat pump cycle for high performance at high temperature lift and range.” U.S. Utility Application 17/974,913. Echogen Power Systems. 2022.