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A Techno-Economic Model of a Data Center with Cold Underground Thermal Energy Storage

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ABSTRACT

The global expansion of data centers, driven by the increasing demand for data-intensive services such as artificial intelligence, is leading to a surge in electricity consumption and facility cooling requirements. The electricity consumption for data center cooling systems is second only to the electricity consumption of IT equipment, placing significant electrical loads on the power grid and increasing grid connection requirements. Cold underground thermal energy storage (Cold-UTES) is one solution for managing data center cooling loads. These systems leverage the natural thermal capacity of the earth (e.g., reservoirs, borehole thermal energy storage) by chilling the subsurface during off-peak hours and seasons and using the resource to provide cooling during peak periods. Cold-UTES systems can flexibly meet the cooling loads of data centers as needed, while reducing dependence on conventional, energy- or water-intensive cooling technologies. Cold-UTES has opportunities in scenarios where water usage must be minimized: Cold-UTES reduces water usage compared to evaporatively-cooled systems and reduces electricity consumption compared to dry air-cooled mechanical chillers. In this article, we describe data center cooling systems that include Cold-UTES. We develop technical models of these systems to illustrate the potential to manage cooling loads – and particularly to minimize energy consumption at times of peak grid stress (which often coincide with higher electricity prices).

1 INTRODUCTION

Data center development and demand for data intense services such as artificial intelligence and cloud computing are increasing rapidly (Shehabi, Smith, et al., 2024). Not only is the number of data centers growing, but their size is increasing, leading to an increase in electricity demand and consumption along with cooling requirements placed on the grid. Several challenges arise with this increase in electricity demand and cooling needs. First, the grid will see an increase in load as well as the need for efficient grid connections (Shehabi, Newkirk, et al., 2024). The increase in load must be met with a matching supply through challenging grid connections, which may stretch grid capacity and possibly cause blackouts. Demand charges also impact operator cost, prompting some mitigation efforts such as new rate classes for high energy users (Skidmore, 2025). Another challenge with increased data center deployment and size is the water usage and cooling requirements (Lei & Masanet, 2022). The IT equipment and buildings that house the data centers require specific temperatures that can be costly to maintain during the hottest parts of the year. Water usage is of vital concern for many cities surrounding and hosting data centers, since conventional cooling methods use large amounts of water.

Typically, evaporative cooling methods are used in data centers. These methods incorporate dry coolers and chillers with multiple loops to ensure the chips are kept at the correct temperature (Capozzoli & Primiceri, 2015; Cho et al., 2017; Evans, 2017; Gözcü et al., 2017; Lei & Masanet, 2022). The current cooling methods can be high in water usage and are generally dependent on the outside air temperature (Lei & Masanet, 2022). Dry cooling can reduce the water usage for cooling, but the ambient temperature impacts dry cooler and chiller efficiencies greatly. On top of this, high ambient temperatures generally correlate to high grid demand for air conditioning, adding further stress to the grid.

These challenges inform where innovation must grow in order to ensure a reliable and sustainable future for data centers and the grid (Cho et al., 2017). We propose using Cold Underground Thermal Energy Storage (Cold-UTES) to meet data center cooling demands. There is an opportunity for Cold-UTES to store cold energy when both the ambient temperature and grid demand are low, which can later be deployed at times of high temperature or high grid demand. Figure 1 shows a simple schematic of the Cold UTES system, where during the cool months cold

energy is stored in an underground system, and during the warmer months cold energy is extracted from the storage underground (Winick et al., 2025). Smoothing out peak loads and minimizing electricity cost and grid stress with this approach therefore requires storage on seasonal timescales. As seen in Figure 1, the Cold UTES system could offset the electrical cooling load during times of peak demand. The benefit of Cold-UTES is that it leverages the natural thermal capacity of the earth, via permeable reservoirs or borehole thermal energy storage. Cold-UTES can be particularly beneficial for data centers because they can meet inflexible cooling loads while also reducing dependence on conventional energy- or water-intensive cooling technologies.

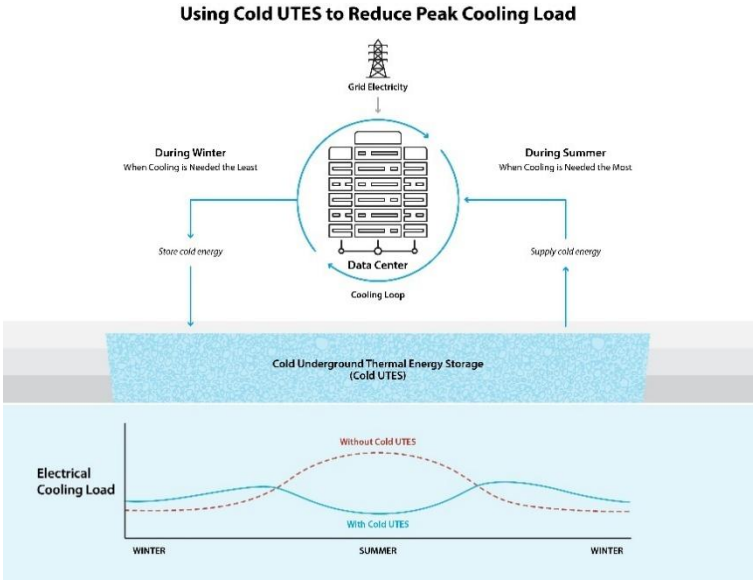


Figure 1: Schematic of the Cold-UTES system. The data center has its own cooling loop that interacts with the heat rejection loop. Cold energy is stored in the ground during the cool months of the year or during off-peak hours and extracted during warmer months during peak loads. The representative graph at the bottom shows the potential benefits of the Cold-UTES system.

Two main types of Cold-UTES are studied in this work: reservoir thermal energy storage (RTES), and borehole thermal energy storage (BTES). RTES utilizes reservoirs located in the earth's subsurface to exchange energy with the earth (Burns et al., 2020) while BTES uses boreholes drilled into the ground with pipes that then exchange energy with the ground. These systems are considered closed, creating benefits by reducing water usage. Recent studies investigate using RTES for data center cooling, finding RTES can reliably supply cooling to data centers via seasonal storage of cold water (Oh et al., 2025; Zhang et al., 2025). Many BTES systems have been investigated (Wang et al., 2024), however most studies discuss hot thermal storage rather than cold. One project demonstrated cold storage using BTES to show the potential sustainable infrastructure and energy savings (Hammock & Sullens, 2017).

In this paper we describe the technical models created for the Cold UTES system which demonstrate the potential for managing cooling loads and minimizing energy consumption at times of peak grid stress. We describe the path to estimating the conventional cooling of a data center, cooling with Cold-UTES, and the influence on electricity.

2 DATA CENTER COOLING SYSTEM

2.1 Conventional Cooling System

Figure 2 illustrates a data center that is cooled by a system comprising a dry cooler and chiller. The dry cooler and chiller are independently sized to provide all the required cooling for the data center. The amount of cooling provided by either component depends on the ambient temperature. This relationship can be seen in Figure 3, in which the cooling technology used, and the power consumed, is split into three distinct regions as a function of ambient temperature for a cooling demand of 100 MW_{th}. In this example, the dry cooler is characterized by a minimum approach temperature (Oh et al., 2025; Zhang et al., 2025) of 6°C (ΔT_{dry} in Figure 2) and the data center requires supply water at 21°C ($T_{DC,in}$ in Figure 2), thus, the dry cooler can provide all cooling only when ambient temperature is below 15°C. Above 28°C, however, there is an insufficient temperature difference between the cooling liquid and ambient air to drive effective heat transfer, so dry cooling becomes inefficient. At this point, the chiller provides all cooling, as seen in Figure 3.

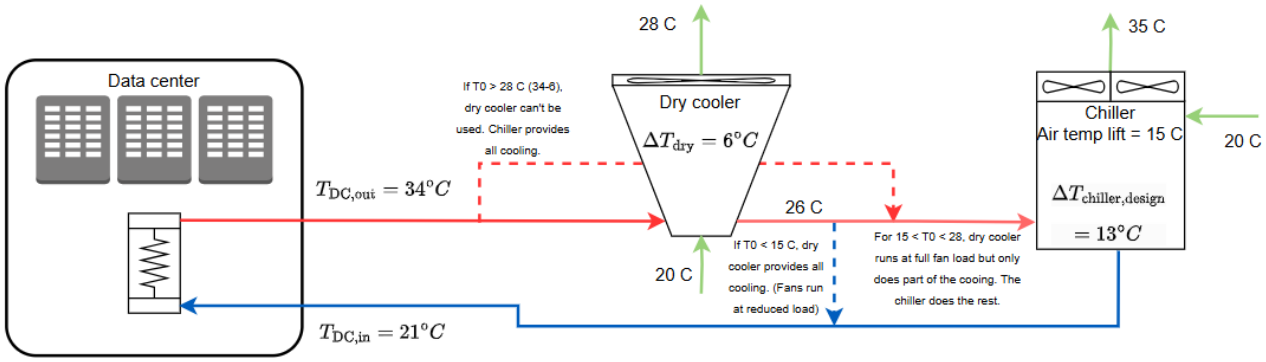


Figure 2: Schematic illustrating a data center cooled with a dry cooler and chiller.

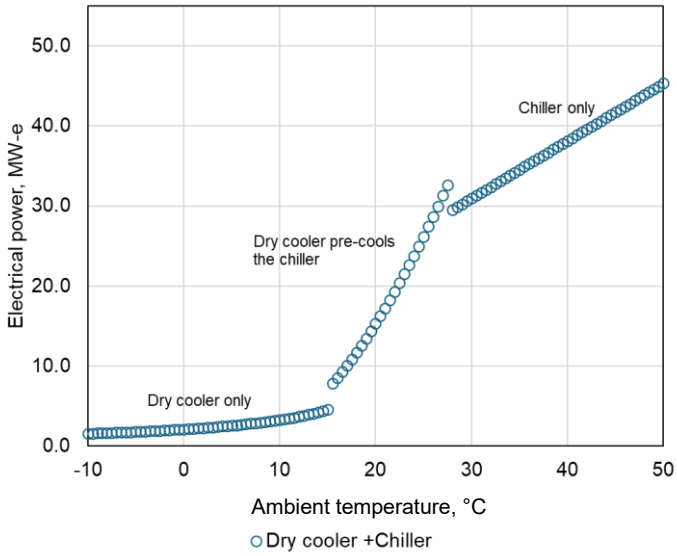


Figure 3: Electrical power input for a cooling system comprising a dry cooler and chiller. The data center cooling load is 100 MW_{th}.

2.2 Data Center Cooling with Cold-UTES

A schematic diagram illustrating how Cold-UTES can be connected to a data center cooling system is shown in Figure 4. In this example, RTES is the selected UTES system, but conceptually, BTES would operate in a similar way. RTES uses the existing fluid in the subsurface formation as the heat transfer fluid and an intermediate heat exchanger connects the RTES and data center cooling loops, preventing fouling in data center equipment. For this simplified analysis, we assume the geofluid has the same properties as water, and the system operates at its design point, meaning the RTES wells remain at a constant temperature. Under these assumptions, we can calculate the number of well pairs needed to deliver the desired cooling load.

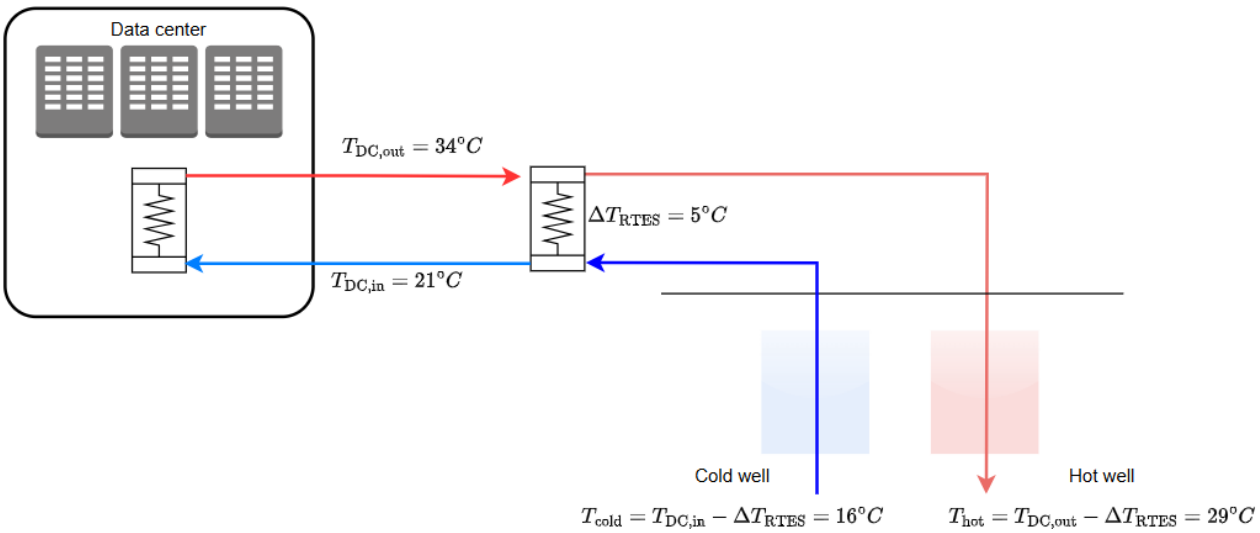


Figure 4: Schematic illustrating a RTES cooling a data center.

2.3 Charging a Cold-UTES

The Cold-UTES can be charged using the conventional data center cooling system, a dry cooler and a chiller, described in Section 2.1. The ambient temperature determines whether the dry cooler or chiller (or combination) is used to charge the Cold-UTES. A schematic illustrating how Cold-UTES is charged is shown in Figure 5. The operation is designed such that the data center cooling load is always satisfied, and any possible excess cold energy is used to charge the UTES. Figure 6 shows the electrical power consumption for a data center with a 100 MW_{th} using different cooling system components, as determined by the ambient temperature. In addition to the fan and chiller work, the power consumption includes the electricity consumed in the pumps that move fluid through the UTES wells or boreholes. For BTES systems this is simply found by considering the pressure drop in a pipe with a u-bend using the Darcy-Weisbach equation and assuming turbulent flow. For RTES, the reservoir impedance is estimated to be 0.05 GPa/(s/m^3) and this is multiplied by the volumetric flow rate to find the pressure drop per well-pair.

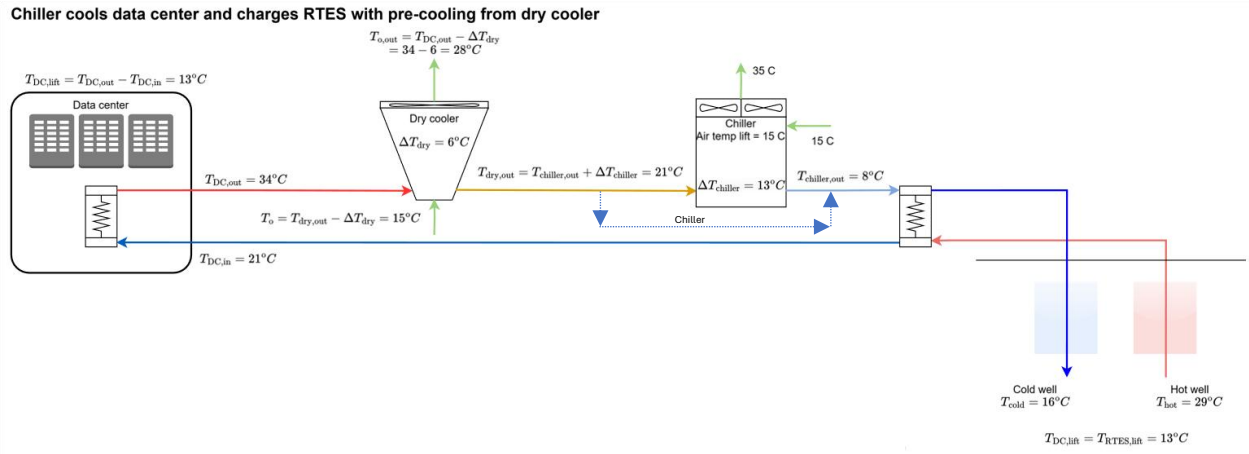


Figure 5: A schematic where pre-cooling is provided by the dry cooler and supplemental cooling is provided by the chiller. This arrangement always provides the design cooling to the data center. When it is cool enough, it can provide the design cooling to the RTES. When temperatures increase, it can provide partial cooling to the RTES (reduced mass flow at the design temperature). At higher temperatures, it operates without RTES as in Figure 2.

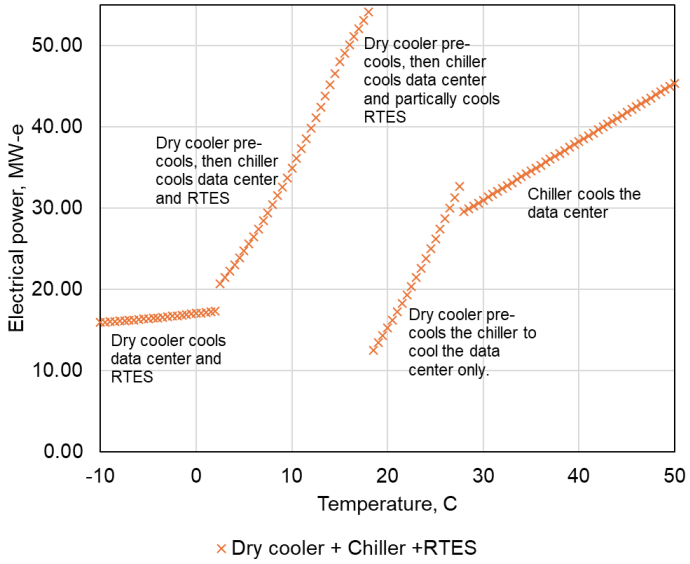


Figure 6: Electrical power input for a cooling system comprising a dry cooler and chiller which also charge the RTES. The data center cooling load is 100 MW_{th}.

3 REDUCING ELECTRICITY USE DURING PEAK HOURS

Integrating a Cold-UTES into a data center cooling system achieves two objectives: eliminate water usage from data center cooling systems and reduce the electricity consumption associated with the cooling load, particularly during peak hours. Reducing electricity consumption during peak hours has several important consequences. First, during peak hours, electrical grid components can be overloaded, which increases the risk of failures and outages. In addition, electricity prices increase during peak hours, which increases operational costs for the data center owner. And finally, some electricity markets have demand charges; whereby additional fees are levied on electricity users depending on their electricity usage during peak hours (which are typically determined after-the-fact). Managing data center electricity usage by the flexible dispatch of cold thermal energy therefore provides value to the grid and to the data center owner.

A simple techno-economic model is implemented here to illustrate these benefits. For each hour of the year, the data center may be cooled by either the conventional cooling system or by discharging the UTES. The UTES must also be charged at some point during the year. Therefore, at each hour of the year, a decision must be made about whether to charge or discharge the UTES.

3.1 Dispatch Approach

Figure 7 overlays the electricity load profiles of Figure 3 and Figure 6, along with the electricity consumption when discharging UTES. This figure shows that charging the RTES consumes more power than cooling only the data center. Thus, RTES should only be charged at times of lowest grid demand/price. Figure 7 also shows that discharging the RTES to meet the entire cooling load uses less power than the conventional cooling system at temperatures above 20°C since the mechanical chiller is not used.

A simple dispatch approach compares the electricity price against the cooling electrical load of each cooling option at the ambient temperature in each hour of the year. Figure 8 shows the distribution of projected 2030 electricity prices in Virginia and Arizona from the Cambium 2024 Mid-Case Scenarios. Both distributions show very large increases in electricity price for the highest few percentiles. This price spike represents the few high stress periods in which extreme energy demand and low supply intersect alongside low transmission and storage availability, requiring expensive marginal peaking plants to come online. To minimize costs, electricity consumption is minimized during the highest 25% of electricity prices by choosing the cooling mode with the lowest power usage. This means discharging the UTES if ambient temperature is higher than 20°C, otherwise using the dry coolers. We then calculate the total cold thermal energy that must be dispatched from the Cold-UTES during this 25% highest price hours and determine the cold energy that must be added to the cold reservoir by considering the thermal recovery efficiency (assumed to be 80%). The Cold-UTES is charged during the coldest possible hours of the year until the required cold energy has been stored. This simple dispatch approach does not provide a mathematically optimal solution, but it still provides an optimistic view of the benefit that Cold-UTES could provide due to having perfect foresight.

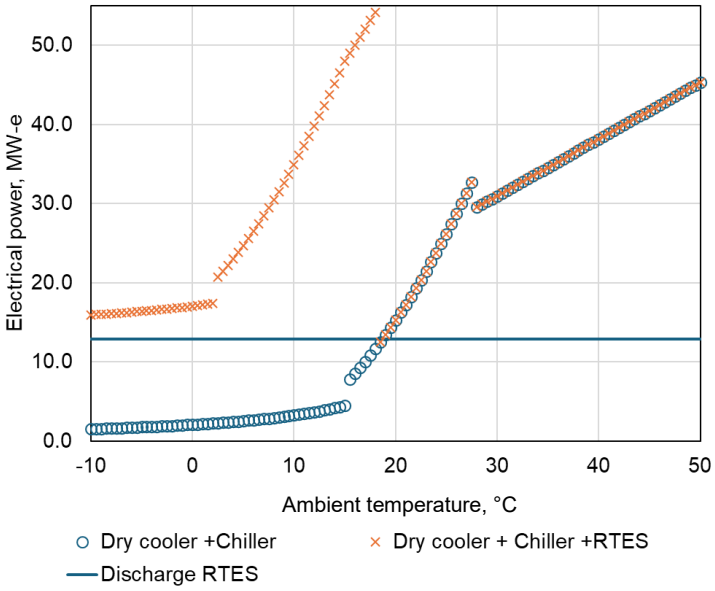


Figure 7: Comparison of electrical loads of cooling with and without an RTES. The power consumption of discharging the RTES is also shown.

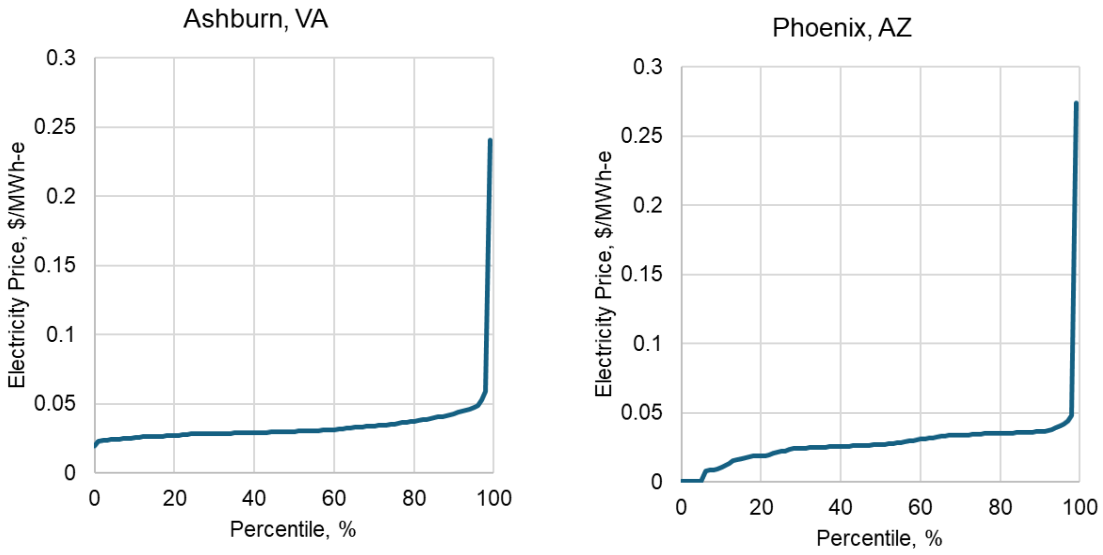


Figure 8: Distribution of electricity prices in Virginia and Arizona. Data obtained from Cambium 2024 Mid-Case Scenarios representing 2030 electricity prices.

3.2 Electricity Consumption Reduction

Incorporating Cold-UTES to data center cooling systems reduces the total electricity required for cooling when compared to conventional cooling, as seen in Figure 9. Results for both RTES and BTES are shown for locations in Virginia and Arizona. By charging the Cold-UTES mainly during cold hours and discharging during relatively hot periods, the system operates at a relatively high Coefficient of Performance (COP) compared to what a mechanical chiller could achieve if it operated during those hot hours. This difference is more pronounced in Virginia than in Arizona where average ambient temperatures are lower, which increases cooling efficiency. Additionally, Cold-UTES significantly decreases electricity consumption in peak hours (i.e. the 25% highest priced hours). This reduction is more substantial for BTES systems because they have lower pumping losses than RTES.

The cost of electricity for cooling also decreases significantly with the addition of a Cold-UTES system because the highest electricity prices are avoided. These reductions are seen in Figure 10, and highlight the value in having a dispatchable, seasonal storage option to avoid outlying electricity prices throughout the year.

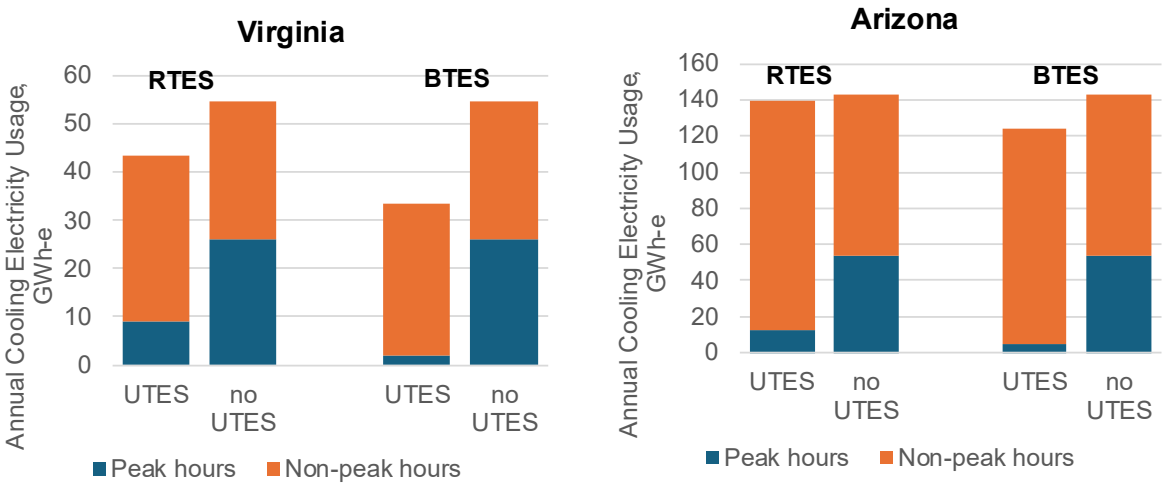


Figure 9: Electricity consumption due to cooling data centers in Virginia and Arizona with and without Cold-UTES in RTES and BTES configurations.

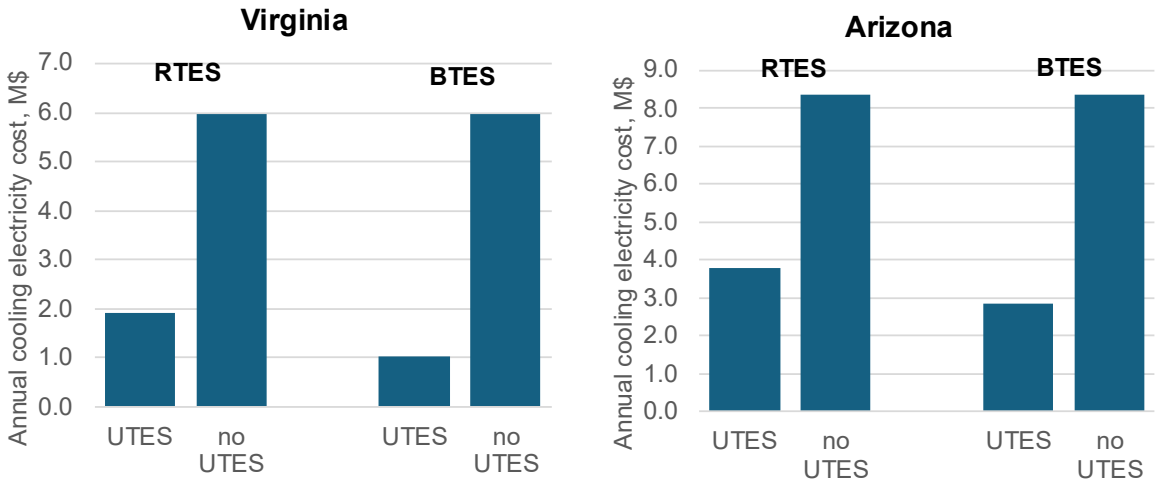


Figure 10: Electricity cost due to cooling data centers in Virginia and Arizona with and without Cold-UTES in RTES and BTES configurations.

4 CONCLUSIONS

In this study, we explored the integration of Cold-UTES into data center cooling systems with two primary objectives: eliminating water use in cooling systems and reducing electricity consumption, particularly during peak-demand hours. A simple data center cooling strategy was developed based on ambient conditions and for example data center fluid temperatures, using Cold-UTES. In addition, a flexible dispatch strategy was proposed to shift cooling loads away from peak electricity price periods by strategically charging and discharging the UTES throughout the year. The UTES-based cooling system provided significant benefits by reducing electricity consumption during high-cost, peak-demand hours. This resulted in meaningful reductions in operating costs, especially in electricity markets with steep time-of-use pricing or demand charges. Even with low recovery efficiencies, Cold-UTES can substantially lower annual cooling-related electricity expenditures. Future work will focus on refining cooling system configurations, developing more accurate models of key components, and evaluating economic trade-offs through detailed cost-benefit analyses.

REFERENCES

Burns, E. R., Bershaw, J., Williams, C. F., Wells, R., Uddenberg, M., Scanlon, D., Cladouhos, T., & van Houten, B. (2020). Using saline or brackish aquifers as reservoirs for thermal energy storage, with example calculations

for direct-use heating in the Portland Basin, Oregon, USA. *Geothermics*, *88*, 101877. https://doi.org/10.1016/j.geothermics.2020.101877

Capozzoli, A., & Primiceri, G. (2015). Cooling Systems in Data Centers: State of Art and Emerging Technologies. *Energy Procedia*, *83*, 484–493. https://doi.org/10.1016/j.egypro.2015.12.168

Cho, K., Chang, H., Jung, Y., & Yoon, Y. (2017). Economic analysis of data center cooling strategies. *Sustainable Cities and Society*, *31*, 234–243. https://doi.org/10.1016/j.scs.2017.03.008

Evans, T. (2017). *The different technologies for cooling data centers* (White Paper 59). Schneider Electric. https://www.se.com/us/en/download/document/SPD_VAVR-5UDTU5_EN/

Gözcü, O., Özada, B., Carfi, M. U., & Erden, H. S. (2017). *Worldwide energy analysis of major free cooling methods for data centers*. 968–976. https://doi.org/10.1109/ITHERM.2017.7992592

Hammock, C. W., & Sullens, S. (2017). *Coupling Geothermal Heat Pumps with Underground Seasonal Thermal Energy Storage* (EW-201135). https://apps.dtic.mil/sti/citations/AD1034826

Lei, N., & Masanet, E. (2022). Climate- and technology-specific PUE and WUE estimations for U.S. data centers using a hybrid statistical and thermodynamics-based approach. *Resources, Conservation and Recycling*, *182*, 106323. https://doi.org/10.1016/j.resconrec.2022.106323

Oh, H., Jin, W., Peng, P., Winick, J. A., Sickinger, D., Sartor, D., Zhang, Y., Beckers, K., Kitz, K., Acero-Allard, D., Atkinson, T. A., & Dobson, P. (2025). Techno-economic performance of reservoir thermal energy storage for data center cooling system. *Applied Energy*, *391*, 125858. https://doi.org/10.1016/j.apenergy.2025.125858

Shehabi, A., Newkirk, A., Smith, S. J., Hubbard, A., Lei, N., Siddik, M. A. B., Holecek, B., Koomey, J., Masanet, E., & Sartor, D. (2024). *2024 United States Data Center Energy Usage Report*. https://doi.org/10.71468/P1WC7Q

Shehabi, A., Smith, S., Hubbard, Newkirk, A., Lei, N., Siddik, M. A. B., Holecek, B., Koomey, J., Masanet, E., & Sartor, D. (2024). *2024 United States Data Center Energy Usage Report* (LBNL-2001637). Lawrence Berkley National Lab. https://escholarship.org/uc/item/32d6m0d1

Skidmore, Z. (2025, May 2). *Dominion sees no slow down in Northern Virginia data center demand, proposes new electricity rates for large load customers*. Data Center Dynamics. https://www.datacenterdynamics.com/en/news/dominion-reports-high-data-center-demand-in-northern-virginia-proposes-new-electricty-rates-for-large-load-customers/

Wang, X., Zhang, H., Cui, L., Wang, J., Lee, C., Zhu, X., & Dong, Y. (2024). Borehole thermal energy storage for building heating application: A review. *Renewable and Sustainable Energy Reviews*, *203*, 114772. https://doi.org/10.1016/j.rser.2024.114772

Winick, J., Zhu, G., Kitz, K., & Adams, A. (2025, February 10). Reducing Data Center Peak Cooling Demand and Energy Costs with Underground Thermal Energy Storage (UTES). *PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering*. 50th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Zhang, Y., Peng, P., Oh, H., Jin, W., Winick, J., Sickinger, D., Atkinson, T., Sartor, D., Lei, N., Sauter, I., & Dobson, P. F. (2025). Addressing Data Center Cooling Needs Through the Use of Reservoir Thermal Energy Storage Systems. *Journal of Clean Energy and Energy Storage*, *02*, 2550002. https://doi.org/10.1142/S2811034X25500029