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Data Centers and Subsurface Thermal Energy Storage — Matching Data Center Cooling Needs with Recharging of Subsurface Thermal Energy Storage

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Data Centers and Subsurface Thermal Energy Storage – Matching Data Center Cooling Needs with Recharging of Subsurface Thermal Energy Storage

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ACRONYMS

Term/Acronym	Definition
ARPA-E	Advanced Research Projects Agency–Energy
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATES	Aquifer Thermal Energy Storage
CAPEX	Capital Expenditure
COP	Coefficient of Performance
CRAC	Computer Room Air Conditioning
CRAH	Computer Room Air Handler
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EOS	Equation of State
GTO	Geothermal Technologies Office
HPC	High Performance Computing
IAG	Industrial Advisory Group
IAPWS	International Association for the Properties of Water and Steam
INL	Idaho National Laboratory
IT	Information Technology
LBNL	Lawrence Berkeley National Laboratory
LCOC	Levelized Cost of Cooling
MOOSE	Multiphysics Objective Oriented Simulation Environment
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OCP	Open Compute Project
OPEX	Operating Expense
PDC	Percentage of Dry Cooler
RTES	Reservoir Thermal Energy Storage
TDS	Total Dissolved Solids
TEA	Techno-Economic Analysis
TES	Thermal Energy Storage
U.S.	United States

USGS	US Geological Survey

ABSTRACT

This multi-lab, DOE-funded project addresses the significant energy and water consumption and cost to cool information technology (IT) equipment in data centers by utilizing subsurface thermal energy storage systems, more specifically, reservoir thermal energy storage (RTES). The project was augmented by an industrial advisory group (IAG), including experts from both the data center and subsurface energy storage sectors, to provide feedback. A scenario-based method was applied to perform techno-economic feasibility analysis based on three types of data centers covering a range of sizes and in three geographical locations. The techno-economic analysis (TEA) was performed to compare RTES scenarios with commonly used or most competitive non-RTES cooling scenarios.

The main conclusions from the investigation are that all RTES systems studied are technically feasible and sustainable for at least a period of 20 years without major modifications of the RTES and IT cooling systems. Within the context of the assumptions made by this study, the key factor to make RTES for data center cooling economically feasible and attractive in the right location includes: 1) a shallow non-potable water-bearing geological formation with large transmissivity (thick and high permeability formation) to maximize storability and minimize the number and depth of wells needed; and 2) potential to use free (compressorless) or inexpensive cooling. Compressorless cooling can be provided by dry coolers in mild climates (although that is not the only option,) and inexpensive cooling can utilize compressor cooling when power costs are very low or negative (e.g., excessive renewable energy production).

Future studies should further consider using chillers for RTES cooling (in addition to dry coolers) when there is a significant grid value to do so (large difference between peak and off-peak power cost). Additionally, system optimization should be performed for a specific site to maximize the benefit of using RTES for cooling when deployed. Additional benefits, such as resiliency during high heat events, are often not captured in traditional TEA studies, and should be considered.

Keywords: reservoir thermal energy storage (RTES), thermal energy storage (TES), data center cooling, techno-economic analysis, chillers, compressorless cooling, liquid cooling

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. Introduction

1.1 Project Background

The project addresses the challenges of significant energy and water consumption cooling information technology (IT) equipment in data centers. Additionally, this data center work can be broadly applied to other industrial cooling and waste heat applications.

As the world has entered the digital revolution, the need for data processing and storage systems has grown exponentially. Many of the largest technology companies (such as Meta, Google, Amazon, Microsoft, and Apple) as well as cryptocurrency miners, High Performance Computing (HPC) and other intense users of information technology (IT) utilize a growing network of data centers to host, store, and analyze extensive datasets. The United States (U.S.) is the world leader in the number of data centers, with about 1/3 of the world's total (Daigle, 2021). These data centers have high power requirements – a 2016 report from Lawrence Berkley Laboratory noted that in 2014, U.S. data centers consumed about 70 billion kilowatt-hours (kWh) of electricity, representing more than 1.8% of all U.S. electricity use (Shehabi et al., 2016). While energy conservation efforts have significantly reduced the energy load for these systems, it is doubtful that such efforts can keep up with the growing demand for data centers (Masanet et al., 2020; Shehabi et al., 2018). One of the major energy requirements for data centers is the cooling needed to maintain optimal operating conditions for these systems. In fact, cooling is the second largest load, only surpassed by the IT equipment itself. Figure 1-1 shows the enterprise data center cooling demand by U.S. County, highlighting high cooling demand in northern Virginia (i.e., near Washington, D.C.) (Oh and Beckers, 2023). Recent shutdowns of tech giant data centers because of a failed cooling systems caused by record summertime temperatures (Vallance, 2022) highlight the challenges posed by climate change and data centers' energy consumption. Cooling of IT equipment in data centers is currently achieved using either air or liquid cooling (Coles et al., 2011; Shehabi et al., 2016). Water consumption in data center is driven by evaporative cooling (e.g., cooling towers) and is estimated to be on the order of 1.8 liters per kWh of data center site energy usage, which can lead to tens to hundreds of millions of gallons per year for large data centers (Shehabi et al., 2016). Such high usage rates are challenging to sustain given the scarcity of water in many regions of the country and world. In addition, data centers without cooling towers need additional electricity to drive air-cooled chillers and the U.S. power production uses significant water resources. For example, in 2020, an average of 11,857 gallons of water was used per MWh of electricity produced in the U.S. (Public Power, 2023).

The goal of this project is to investigate the potential of using reservoir thermal energy storage (RTES) for data center cooling for three types of data centers covering a range of sizes and in three different locations. The technical feasibility and techno-economic analysis are performed based on data from these three case studies.

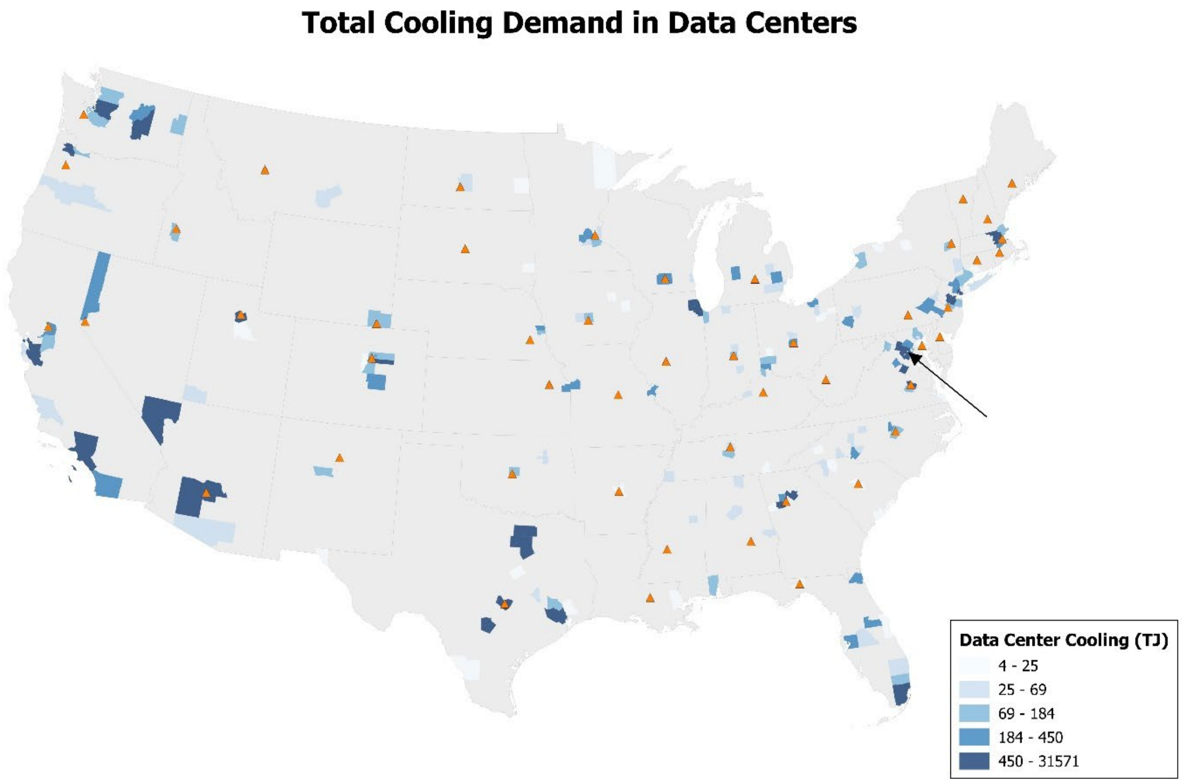


Figure 1-1. Co-location and enterprise data center cooling demand by U.S. County. The county where cooling demand is highest is highlighted with orange background and black arrow.

Figure credit: Oh and Beckers (2023).

Using subsurface porous media as a thermal "battery" to store cold thermal energy and later use it for data center cooling is not a new concept. Figure 1-2 shows a variety of thermal energy storage technologies that could be applied in a subsurface sedimentary basin. RTES is a type of long-term geological energy storage technology where thermal energy is stored in subsurface reservoirs. This is done through injecting the working fluid with a temperature different from the in-situ reservoir temperature into the reservoir. Two heat transfer processes are happening at the same time: (1) the injected fluid convectively transports heat into and through the pore space, (2) from where it is transferred by conduction into the solid grains of the reservoir. The total energy stored in the reservoir depends on the difference between the in-situ temperature and the injected fluid temperature. The partitioning of the stored energy between the rock (subscript r) and the water (subscript w) depends on porosity ϕ. Assuming thermal equilibrium between the water and the rock, the energy stored per unit volume at time t and a particular location, $\Delta E,$ can be calculated as $\Delta E_i(t) = \Delta \mathrm{T}(t) \cdot [\rho_r \cdot c_r \cdot (1-\phi) + \rho_w \cdot c_w \cdot \phi]$, where ρ is density, and c is heat capacity, with typical values being $\rho_r = 2650$ kg/m^3, $c_r = 1000$ J/(kg °C), ρ_w=1000 kg/m^3, and $c_w =$ 4184 J/(kg °C). $\Delta \mathrm{T}(t)$ is the temperature change at time t relative to the initial temperature. A larger porosity leads to more energy storage in the liquid, and vice versa.

Due to the large volume of reservoir rock permeated by the injected working fluid, the heat exchange between the fluid and rock grains is much more extensive and faster than achievable by other subsurface energy storage technologies, specifically borehole energy storage, where the heat exchange area between the working fluid and the storage formation is limited by the length and circumference of the borehole. Low permeability and low thermal conductivity of the formations above and below the reservoir are preferred to minimize vertical heat losses. Both heat and cold energy can be stored in and retrieved from porous reservoirs, as illustrated by Pepin et al. (2021) and others. The typical storage system includes a permeable formation for injecting fluid with low-permeable layers above and below to minimize hydraulic interaction, as well as one or more doublets of a cold and a hot well. The terms "hot well" and "cold well" refer to the relative temperature of the injected and extracted working fluid. They are not necessarily hot or cold per se. The thermal storage reservoirs used by RTES typically contain brackish or saline water (Burns et al., 2020; Pepin et al., 2021), whereas ATES reservoirs are usually located in shallow freshwater aquifers. In general, RTES involves deeper geological formation to avoid impacting the temperature of shallower drinking water aquifers. As a result, the native reservoir temperature could be higher, and the drilling cost of the wells could be higher compared to thermal energy storage in a shallower aquifer. The geological sites investigated in this project cover the ranges of depths from about 100 m to 800 m.

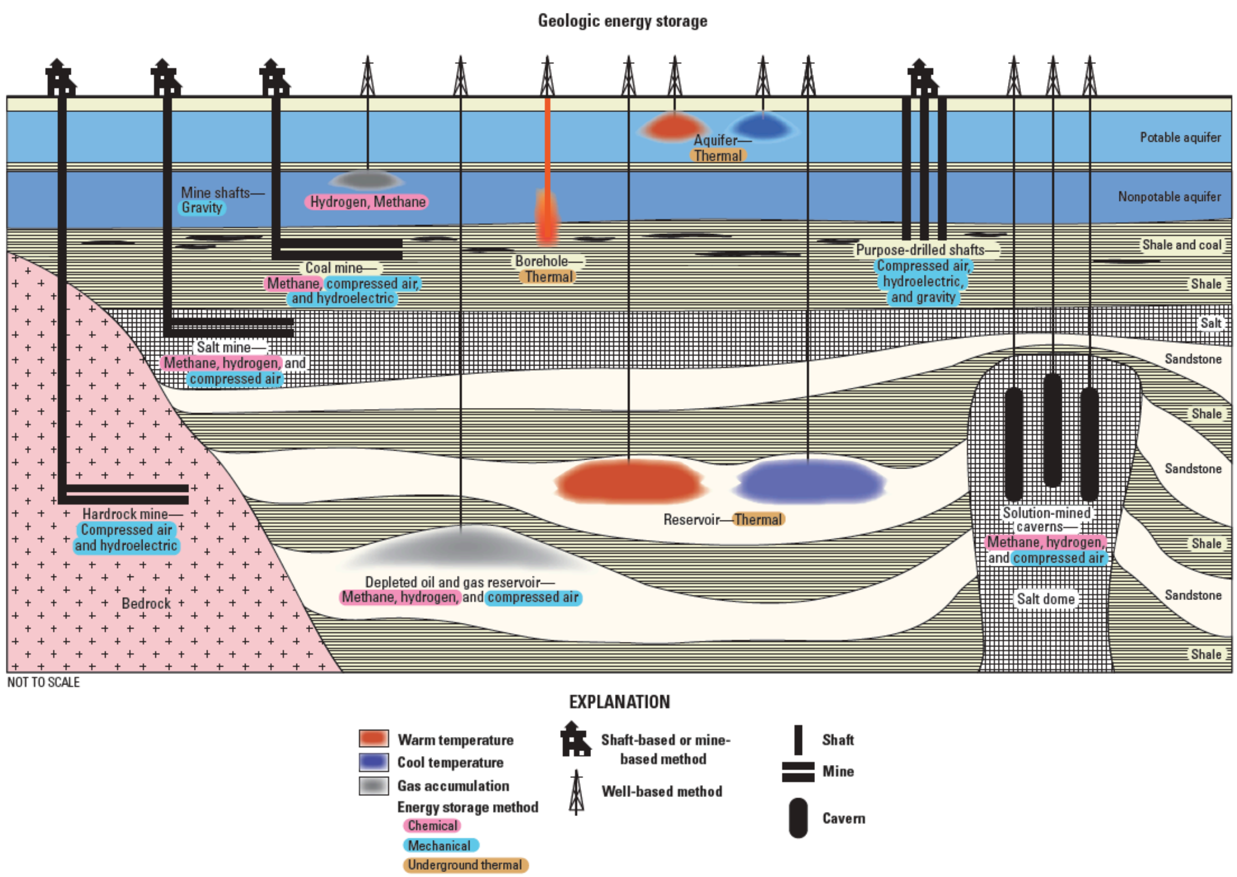


Figure 1-2. Examples of geological energy storage methods in a sedimentary basin.

Figure credit: Buursink et al., 2022.

Using subsurface aquifers for data center cooling has been previously implemented in other countries, such as the Netherlands (Poole, 2016). This is partially due to government encouragement, and the fact that most of the Netherlands's subsurface has uniquely favorable hydrogeological conditions (Drijver et al., 2019), i.e., shallow aquifers with near-surface groundwater table and good permeability. Yet, the techno-economics of using RTES for cooling needed further investigation.

Figure 1-3 (Buursink et al., 2022) shows where RTES, as a geological thermal storage method, sits and compares to the other energy storage methods in terms of the typical storage capacity and duration. Due to its weeks to years of storage duration, and tens of millions-to-trillions of BTU capacity, RTES is one of the energy storage solutions that can address the challenges of renewable energy intermittency as the US transitions to net-zero carbon. By storing inexpensive or free thermal energy produced when clean energy is abundant, and using it when clean energy is not available, RTES can help with peak load management and decarbonization goals. In addition, using RTES for cooling can avoid the water usage needed for evaporative cooling such as cooling towers. This not only provides more energy security and resilience (e.g., providing backup etc.), but also provides water resilience.

This project aligns with the U.S. Department of Energy's (DOE) goals to promote and support research and development priorities that improve the environmental sustainability of digital assets through decarbonization and reduced water consumption. The potential impact is significant. The information technology (IT) sector makes a large contribution to the US economy and continues to grow, producing highly innovative products and services, and creating high-paying jobs (Atkinson, 2022). For example, crypto-assets that rely on data center infrastructure have a total current global market capitalization of nearly $1 trillion (OSTP, 2022). In addition, reservoir cold storage capability will have many other potential applications beyond data centers, such as industrial decarbonization of food, manufacturing, and other processes with large cooling needs. RTES can be used to meet the cooling needs for campuses and regions with high-density cityscapes where traditional thermal energy storage (e.g., water tanks) is not feasible. Finally, IT load growth in data centers combined with increasing temperature extremes (e.g., the heat waves the world has been experiencing), pose a threat to the utility grid and normal operations of the IT industry. Demonstrating the economic viability of the proposed technology could have a large impact, including enhancing data center cooling and reducing strain on the electric grid during periods of peak demand.

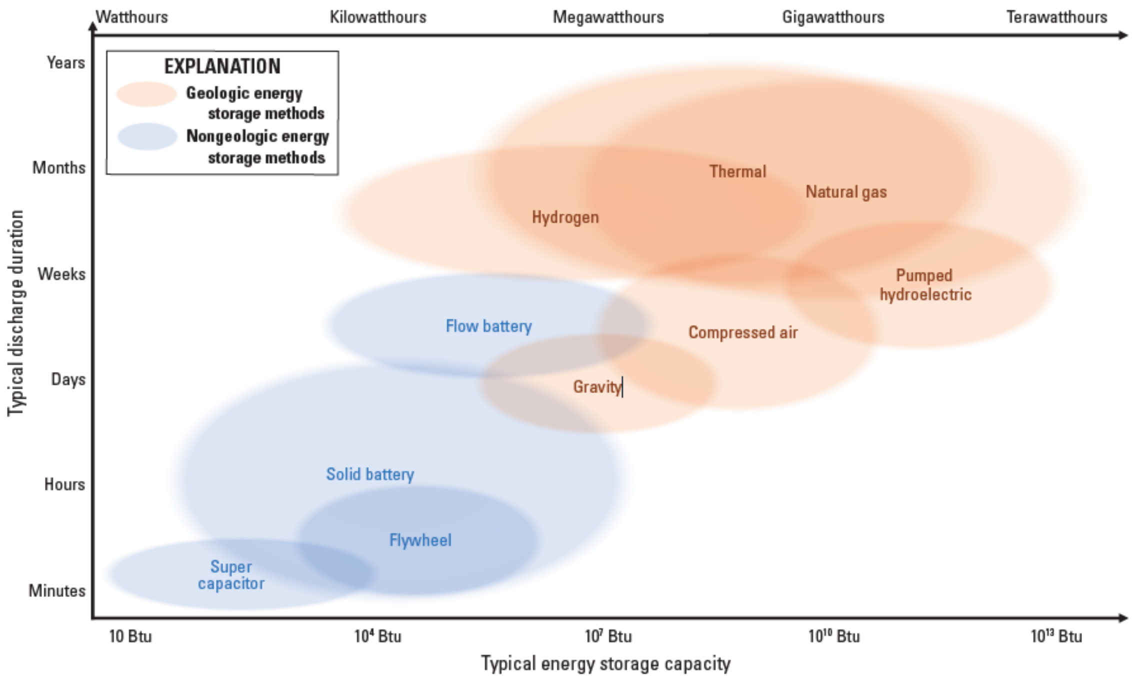


Figure 1-3. Typical storage capacity and duration for various geological and non-geological energy storage methods.

Figure credit: Buursink et al., 2022.

1.2 Project Objectives and Approach

The goal of the project is to perform high–level characterizations of reductions in energy use and water consumption for data center cooling using RTES, and to investigate the technical and economic feasibility of using RTES for data center cooling for three representative data centers case studies. A scenario-based evaluation is used. An industrial advisory group (IAG) including experts from both the data center industry and subsurface energy storage sectors was formed to provide feedback on the studied scenarios. Based on their feedback, three data center sizes are considered, each representing a different data center type (i.e., institutional, crypto mining and hyperscale). Three geological locations are selected as well to evaluate the techno-economic feasibility.

1.3 Conceptual RTES Cooling System Design

To make the storage system sustainable and economically attractive, the design of the system should:

- Maximize the use of the natural cooling capacity of ambient air
- Minimize the cooling applied to the RTES to no more than the cooling needed by the data centers.

Terminologies (e.g., dry coolers) related to data center cooling used in this report are defined and illustrated (when relevant) in Appendix A. The operational scheme to use RTES for data center cooling in this project is shown in Figure 1-4. The main components in this schematic are heat exchangers that separate various air and water loops, the cooling "plant" which is showing dry coolers but could be chillers, the RTES with doublets, and the option for heat recovery to provide external heating. As mentioned earlier, each doublet includes a cold well − used to inject cold fluid into the reservoir, and a hot well – used to re-inject the warm fluid after the water exits the data center. RTES heat exchangers are needed to separate the reservoir fluid which may contain elements that should not go through dry coolers or be used in the facility piping going to the data center.

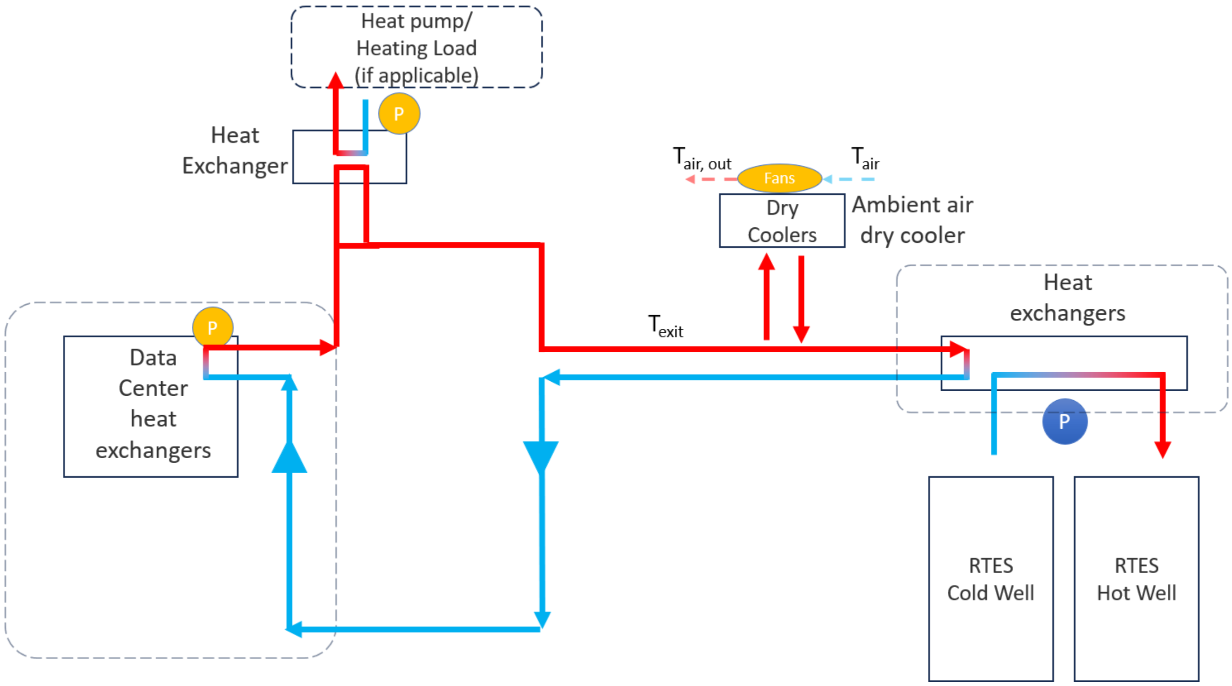


Figure 1-4. Schematics of an RTES system for data center cooling.

The system is assumed to operate in four modes depending on the ambient temperature (i.e., outside air):

1. When the ambient (outside air) temperature T_{air} is at a critical temperature T_{cri} (a system design parameter that depends on the required cooling temperature of a specific data center. Details how on this is determined will be discussed in later sections), i.e., $T_{air} = T_{cri}$, the dry cooler provides 100% cooling capacity needed for the data center.
2. When T_{air} is greater than or equal to the data center's cooling water exit temperature T_{exit}, i.e., $T_{air} \geq T_{exit}$, the dry cooler (see definition in Appendix A), can provide no cooling since it just rejects excess heat to atmosphere – a sensible heat transfer process, without other cooling mechanism involved. Instead, cooling is provided by the RTES and possibly chillers (either liquid or air cooled included in some scenarios).
3. When $T_{cri} < T_{air} < T_{exit}$, the dry cooler provides partial cooling (percentage is calculated based on a linear interpolation between the two temperature points (T_{cri} and T_{exit}), and the remaining cooling need is provided by the RTES or a chiller.

4. When $T_{air} < T_{cri}$, the dry cooler provides all the data center cooling needs, plus additional cooling for later use to be stored in the RTES, i.e., withdraws hot water from the hot well, cools it down using the surplus cooling capacity, and re-injects it into the cold well.

Energy storage is also a potential way to maximize grid value by charging the storage system during off-peak hours when the power (electricity) is abundant, negative or low cost (e.g., excess renewable power generation), and low carbon, and discharging the storage system when the power is more expensive, in greater demand, and perhaps carbon intensive. The main cooling technology used in this project to charge the storage reservoir is dry coolers to make use of the free cooling when ambient temperatures are low. Electrically driven chillers are another cooling technology that can be used to supplement dry coolers when the ambient temperatures are higher, or there is a desire for cooler storage temperatures. However, they have a much higher power consumption. One reason to use them is that low ambient temperatures over a course of a year may not be long enough for the dry coolers alone to deliver all the cooling needed to recharge the reservoir. Another may be that the operating hours of the dry coolers may include periods of high carbon intensity. Although the economic value/cost of using chillers in the RTES system will depend on the electricity price difference between peak- and off-peak hours, as well as the capital cost of chillers relative to the thermal well drilling cost, the cost might be further off-set by the carbon benefits from the difference in the carbon profile of the grid between the chillers' and dry coolers operations. The time of day difference in carbon intensity will grow as more but intermittent renewable energy is brought on line. TES essentially becomes a substitute for electric energy storage. Fair evaluation of chillers for charging RTES requires detailed knowledge of local power pricing structure, as well as the grid's carbon profile. Such an analysis was out of scope for this study but is recommended for the future. Shorter-term thermal energy storage including above ground TES combined with chillers is another option for grid responsive design and should be analyzed in future studies.

The rest of this report is organized based on the three main parts of the investigation:

- Data center cooling scenarios and evaluation
- Reservoir thermal energy storage evaluation and
- Techno-economic analysis

The final section provides conclusions and recommendations for further research.

2. Data Center Scenario and Evaluation

2.1 Overview

Various cooling options were provided to the IAG prior to and during the first IAG meeting. During the meeting, general characteristics (i.e., load range and cooling methods) of the three types of data centers were discussed. The industrial advisory group members provided the locations of greatest interest, information on existing industrial demonstrations, and other insights for deploying RTES systems for data center cooling.

In general, Figure 2-1 shows a representative configuration of how RTES will be incorporated with a data center. As briefly mentioned earlier, an RTES cooling system involves a number of doublets with each doublet including a hot well and a cold well. Water from the cold well will be supplied to serve the data center cooling needs. The return water will be injected into the hot well. Water stored in the hot well will be cooled (i.e., by cool ambient air) and returned back to the cold well.

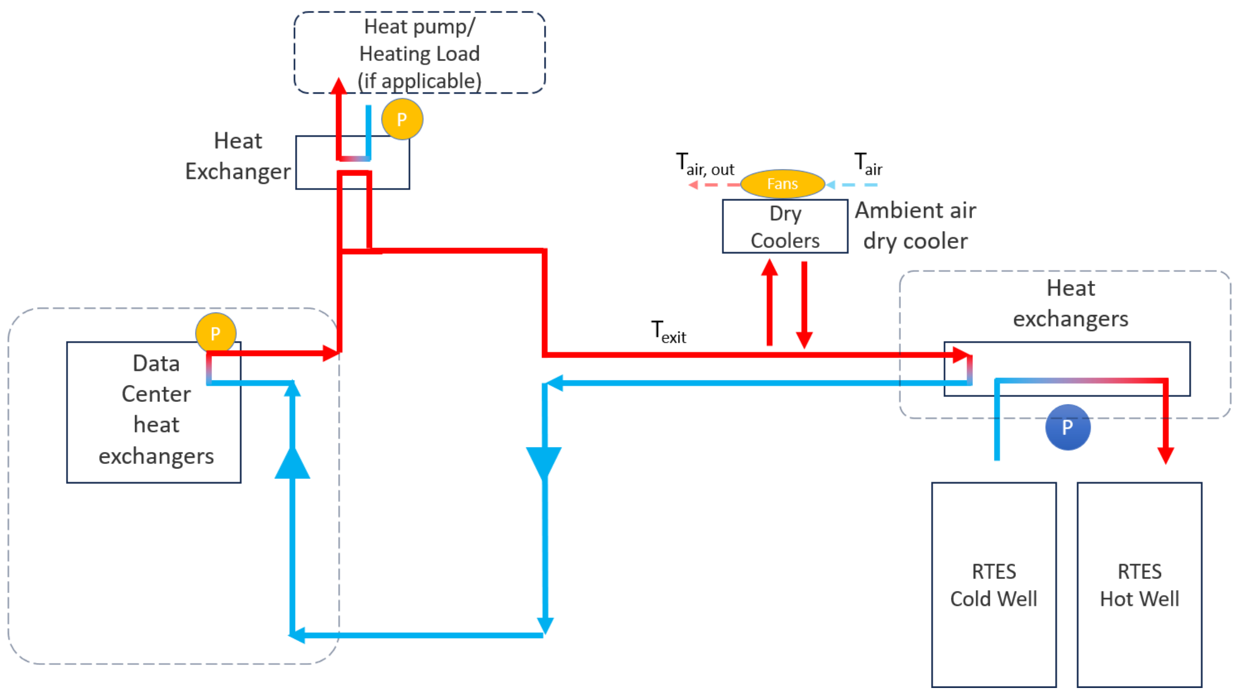


Figure 2-1. Schematic diagrams showing in general how the RTES will be used for the data center cooling.

Based on lab expertise, literature reviews and input from the advisory group (poll results and discussion) and others, the following initial design values are assumed for data center characteristics and are used in this project as a starting point.

- A common temperature change (ΔT) of 10 °C will be used for all air and water streams being heated or cooled. This is the temperature drop across heat exchangers between the inlet and outlet.
- The RTES water temperature is assumed to be 3 °C colder than the Facility water temperature, which is the assumed water to water heat exchanger approach temperature.
- The approach temperature of water to air (facility "chilled" water cooling the data center supply air) and air to water (outside air-dry cooler cooling the facility water) heat exchangers is assumed to be 6 °C. In other words, ambient air fed to the dry cooler can only cool the water to 6 °C above the ambient temperature.
- Flow rate: cooling water flow rates are assumed for each data center size based on water heat capacity of 4.184 kJ/kg °C.

Based on the IAG inputs and the above assumptions, the following key characteristics were identified for each data center type (one location will be selected, listed in the order of preference) in Table 2-1. The cooling load is divided by the temperature change of 10 °C mentioned previously, then further divided by the heat capacity to determine the water flow rate for different data centers.

Table 2-1. Summary of the scale, location, and typical cooling methods for different data center types.

Data center type	Hyperscale	Crypto mining	Institutional
Scale (cooling load)	70 MW	30 MW	5 MW
Primary location	Virginia/ Maryland	Texas	Colorado
Secondary locations	Oregon/Washington; Wyoming	Georgia;New York	N/A
RTES water flow rate to meet the full cooling load	1,673 kg/s (26,099 gal/min)	717 kg/s (11,185 gal/min)	120 kg/s (1,864 gal/min)
Comments	Average of a large range of inputs, but will be scalable	Many are larger but wanted to have a good range of sizes in overall project	Representative of an HPC center on a campus, or an edge data center. Will be based on NREL's data center for this project

2.1.1 Heat Recovery

The power used by IT equipment (e.g., servers) in a data center is turned into heat that must be removed. Heat recovery (also referred to as heat reuse, or waste heat recovery) is defined as the beneficial use of any recovered heat from a data center. Data center heat can be transferred to a facility water loop that is used to pre-heat make-up air within a building or be a source of heat in a variety of industrial and commercial settings. Heat recovery can save money, reduce water usage (if cooling towers are part of the data center cooling system), and reduce carbon emissions through avoidance of carbon-intensive fuels used for heating. The essential hardware to transfer heat from the data center to a heating load is a heat exchanger along with associated piping to make the connections between the two locations. Heat pumps can be used to efficiently increase the temperature from the data center if heating load requires a higher temperature than can be produced by the data center. However, data centers still require cooling systems placed downstream in series of the heat recovery to guarantee data center operation year-round.

The Open Compute Project (OCP) Heat Reuse sub-project has a variety of resources, including white papers and guest presentations along with a global map of heat reuse projects (Open Compute Project, 2024).

2.1.2 Cooling Scenarios

The following sections (2.2-2.4) provides documentation of the scenarios developed for and analyzed in Sections 3 and 4. During the first IAG meeting, worksheets were shared with the IAG members. IAG members, from various data center companies, discussed and selected a common cooling scenario as the base case. Scenario #1 usually involves a more efficient scenario that industry leaders use. Other scenarios are either less commonly used or represent the ones that the IAG members think are more emerging in their fields including those using RTES or heat recovery and reuse. For each data center type, at least two scenarios involving the use of RTES were developed. These scenarios were later down selected. Sections 3 and 4, will discuss the down-selecting criteria and the corresponding analysis. The appendix provides a description of each potential component in these scenarios (the first column).

2.2 Initial Scenarios for Institutional Data Center, Colorado, 5 MW

- Base case: Tower-cooled chiller with tower side economizer (compressor based cooling with an evaporative cooling tower. Air-cooled HPC using computer room air handlers (CRAHs) (or in-row coolers) in the data center. Target supply air temperature of 27 °C with maximum of ASHRAE A1 (32 °C) air cooling. Chiller provides ASHRAE W17 (17 °C) chilled water. Actual use of chiller (if any) will depend on IT equipment specifications and ambient conditions.

- Scenario 1: A more efficient variation of the base case, based on the National Renewable Energy Laboratory's (NREL's) actual design – water-cooled data center with dry cooler (at low ambient temperatures) and cooling towers (no chillers at higher temperatures), and some low temperature heat recovery provided to campus heating systems. The data center/servers are primarily water-cooled (e.g., using rear door cooling and on-board cold plates). Note that rear door cooling is a heat exchanger affixed to the back (door) of a computer rack and hot air leaving the servers passes through the heat exchanger as it is cooled. On-board cold plates are liquid cooled heat exchangers affixed to the hot components of the server. The target air supply temperature to the servers is ASHRAE recommended (27 °C), with an allowable maximum of ASHRAE A1 (32 °C) for air cooling. Dry Cooler and Tower provide 21-24 °C, chilled water. This elevated temperature (between ASHRAE W17 and W27) allows for cooling without chillers. Recovered heat is available at ~34 °C.

- Scenario 2: First option using RTES and a dry cooler (no chiller or cooling tower). The target air supply temperature remains at the ASHRAE recommended (27 °C), with an allowable maximum of ASHRAE A1 (32 °C) for air cooling. The maximum RTES cooling supply water temperature is 18C. Recovered heat is available at ~34 °C.

- Scenario 3: Same as #2 with heat pump added to allow higher temperature heating (~70 ℃). Heat pump draws heat from the data center's hot return (~10 ℃ above supply) and elevates it to a more useful temperature for district/campus heating.

- Scenario 4: Same as #2 but with a second high temperature cooling loop likely utilizing immersion cooling to achieve ASHRAE W45. Note ARPA-E is targeting an even higher cooling temperature of 60 °C, but U.S. Industry advisors felt even W45 was aggressive. The other lower temperature data center cooling loop will operate at #2 conditions. The RTES cooling supply water temperature for the warm loop is 42 °C and the recovered heat will be available at ~55 °C.

Figure 2-2 below is the worksheet finalized at the IAG meeting and schematics of the corresponding scenarios. Any initial scenarios dropped during the geological modeling and TEA will be discussed in the corresponding sections.

Hyperscale Scenarios	**Base**	**1**	**2**	**3**	**4**
Heat Rejection Alternatives					
Dry water cooler (ext. fan coil)			X	X	X
Evaporative cooling tower		X			
Air cooled chiller	X				
Subsurface reservoir w ht exch			X	X	X
Heat recovery (e.g., district ht)					X
Plant Alternatives					
Air side economizer	X				
Evaporative mist or pad	X				
Indirect evaporative cooler					
Tower cooled chiller		X			
Water side economizer		X			
Air cooled chiller	X				
Refrigerant economizer					
Water to water heat pump					
Fan Coil Alternatives					
CRAH (underfloor air dist.)					
Central AH					
Fan Wall	X	X	X		
Liquid Cooling Alternatives					
In row fan coil					
Rear door heat exchanger				X	
On board (cold plate)				X	
Immersion					X
Cooling air supply temp (Class)					
Recommended (27 °C)	X		X	X	
Allowable: A1 (32 °C)	X		X	X	
A2 (35 °C)		X			
A3 (40 °C)					
A4 (45 °C)					X
Facility Water Supply Temp (Class)					
W17 (17 °C)	X		X	X	
W27 (27 °C)		X			
W32 (32 °C)					
W40 (40 °C)					X
W45 (45 °C)					

Figure 2-2. Example of the original worksheet used to develop initial scenarios for Institutional data center

2.3 Initial Scenarios for Crypto Mining Data Center, Texas, 30 MW

- Base case: Outside air-cooled data center/servers with evaporative cooling pad or mist assist on fan wall (often using internal miner/server fans). No chillers. Up to A3 (40 °C) ASHRAE air cooling temperature.

- Scenario 1: Immersion cooling with ASHRAE W40 "facility" cooling water provided by hybrid dry and wet (sprayed) cooler using mist or pad.

- Scenario 2: RTES with dry (only) cooler supplying W17 to fan & coil wall providing recommended 27 °C supply air to miners.

- Scenario 3: Same as #2 with a supply of W17 cooling water but using immersion cooling rather than fan/coil wall.

- Scenario 4: Same as #3 but using W27.

- Scenario 5: Same as #2 but with W45 to facilitate heat recovery.

Figure 2-3 below is the worksheet finalized at the IAG meeting and schematics of the corresponding scenarios. Any initial scenarios dropped during the geological modeling and TEA will be discussed in the corresponding sections.

Crypto scenarios	Base	1	2	3	4	5
Heat Rejection Alternatives						
Dry water cooler (ext. fan coil)		X (spr)	X	X	X	X
Evaporative cooling tower						
Air cooled chiller						
Subsurface reservoir w ht exch			X	X	X	X
Heat recovery (e.g., district ht)						X
Plant Alternatives						
Air side economizer	X					
Evaporative mist or pad	X					
Indirect evaporative cooler						
Tower cooled chiller						
Water side economizer						
Air cooled chiller						
Refrigerant economizer						
Water to water heat pump						
Fan Coil Alternatives	internal					
CRAH (underfloor air dist.)						
Central AH						
Fan Wall	X		X			
Liquid Cooling Alternatives						
In row fan coil						
Rear door heat exchanger						
On board (cold plate)						
Immersion		X		X	X	X
Cooling air supply temp (Class)						
A1 (32 °C)			X			
A2 (35 °C)						
A3 (40 °C)	X					
A4 (45 °C)						
Facility Water Supply Temp (Class)						
W17 (17 °C)			X	X		
W27 (27 °C)					X	
W32 (32 °C)						
W40 (40 °C)		X				
W45 (45 °C)						X

Figure 2-3 Example of the original worksheet used to develop initial scenarios for Crypto Mining data center

2.4 Initial Scenarios for Hyperscale Data Center, Northern Virginia, 70 MW

- Base case: Air-cooled data center/servers with air-cooled chiller and air side economizer with evaporative pads/mist. Fan wall air distribution. Target supply air temperature 27 °C with a maximum ASHRAE A1 (32 °C) cooling air temperature. Chiller provides ASHRAE W17 (17 °C) chilled water. Actual use of chiller (if any) depends on "A Class" and ambient conditions.

- Scenario 1: A more efficient variation of the base case. Tower-cooled chiller with tower/water side economizer supplying W27 chilled water to a fan wall. Target supply air may exceed ASHRAE recommended temperature (27 °C) depending on control sequence. For example, some hyperscale data centers control the air temperature above the ASHRAE recommended especially in the economizer mode (no chiller). Warmer A2 (35 °C) is the maximum supply air temperature. Warmer temperatures and evaporative cooling increase cooling plant efficiency and the number of "free" cooling hours.

- Scenario 2: First option using thermal energy storage that eliminates need for chiller and water evaporation. Target supply air temperature of 27 °C with maximum of A1 (32 °C) air cooling with W17 "chilled" water (provided by dry cooler and RTES) – little/no energy benefit for raising temperature unless using heat recovery. IT performance can be enhanced by lower temperature operation (need to quantify). Maximum RTES cooling supply water temperature: 14 °C.

- Scenario 3: First option using liquid cooling to the IT equipment (i.e., cold plates). Same heat rejection as #2 but no fan wall. Air-cooled components will use rear door heat exchangers (or equivalent). Same air and water temperatures (A1 and W17 unless aquifer warmer). Maximum RTES cooling supply water temperature: 14 °C.

- Scenario 4: Heat recovery option while still using RTES and dry cooler if required to balance loads. Immersion cooling to attain highest water temperature (W40 with heating water at least 55 °C). Maximum RTES cooling supply water temperature: 37 °C.

Figure 2-4 below is the worksheet finalized at the IAG meeting and schematics of the corresponding scenarios. Any initial scenarios dropped during the geological modeling and TEA will be discussed in the corresponding sections.

Institutional scenarios	Base	1	2	3	4
Heat Rejection Alternatives					
Dry water cooler (ext. fan coil)		X	X	X	X
Evaporative cooling tower	X	X			
Air cooled chiller					
Subsurface reservoir w ht exch			X	X	X
Heat recovery, e.g., district heat. (heat recovery temperature)		X(34 °C)	X(34 °C)	X(70 °C)	X(55 °C)
Plant Alternatives					
Air side economizer					
Evaporative mist or pad					
Indirect evaporative cooler					
Tower cooled chiller	X				
Water side economizer	X				
Air cooled chiller					
Refrigerant economizer					
Water to water heat pump				X	
Fan Coil Alternatives					
CRAH (underfloor air dist.)	X				
Central AH					
Fan Wall		X	X	X	X
Liquid Cooling Alternatives					
In row fan coil					
Rear door heat exchanger		X	X	X	X
On board (cold plate)		X	X	X	X
Immersion					X
Cooling air supply temp (Class)					
Recommended (27 °C)	X	X	X	X	X
Allowable: A1 (32 °C)	X	X	X	X	X
A2 (35 °C)					
A3 (40 °C)					
A4 (45 °C)					
Facility Water Supply Temp (Class)					2-loop
W17 (17 °C) (Temperature elevated for heat recovery)	X	X (21-24 °C)	X (21-24 °C)	X (21-24 °C)	X (21-24 °C)
W27 (27 °C)					
W32 (32 °C)					
W40 (40 °C)					
W45 (45 °C)					X

Figure 2-4. 3 Example of the original worksheet used to develop initial scenarios for Institutional data center.

2.5 Application Modes

Based on the characterizations in the previous sections (vetted by the IAG), modeling of the RTES systems and TEA proceeded. The hourly ambient temperature profiles of the primary locations for each data center type were extracted from EnergyPlus™. Three application modes were defined for the scenarios that involve RTES and dry coolers based on the ambient temperature profile, as shown in Figure 2-5.

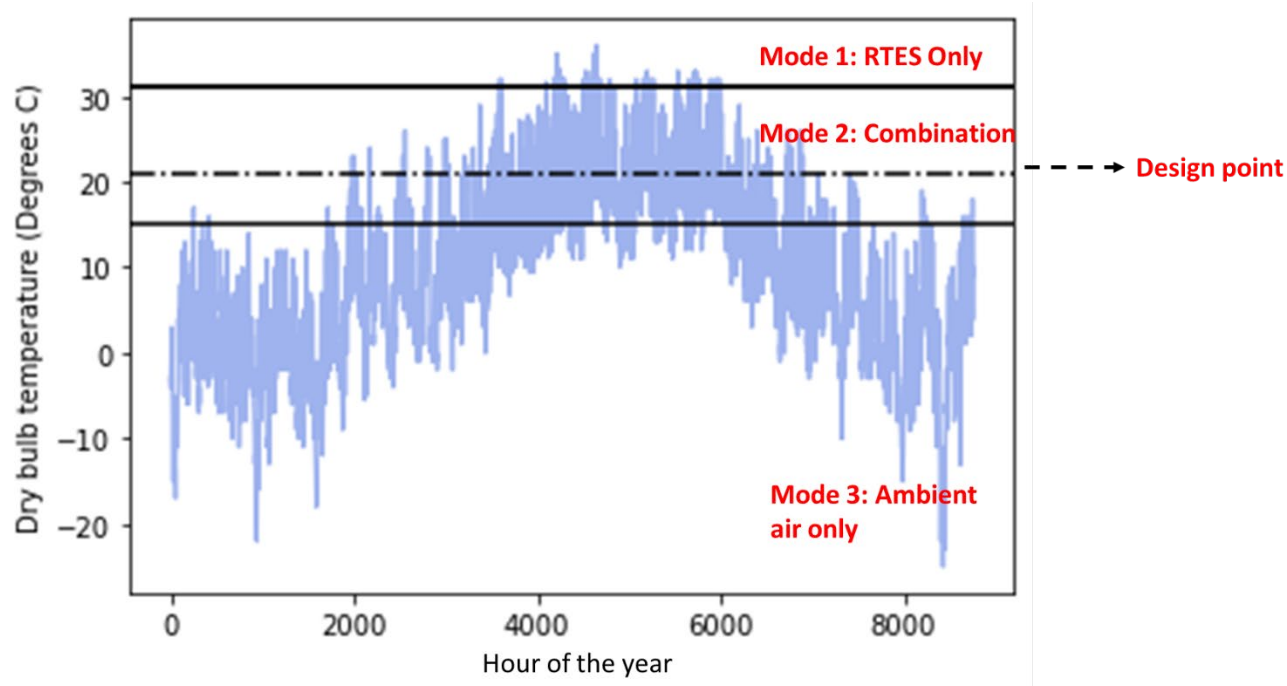


Figure 2-5. Definition of application modes based on ambient temperature. Using the initial scenario 2 for the institutional data center as an example.

The schematic illustrations of the modes and the design point are shown in Figures 2-7 to 2-10, which were based on Figure 2-6 that includes all the components for all modes. In this project, we assume the dry cooler and RTES are operated in series. The water is first cooled by the ambient air (dry cooler) and if the air isn't cool enough, the remaining cooling is provided to the data center facility cooling water via the RTES. Table 2-2 shows the summary of temperature parameters used in the diagrams.

Mode 1 RTES Only (Figure 2-7) is defined as when the ambient temperature is above the data center cooling water outlet temperature (T_3). In this mode, the dry cooler cannot provide any cooling to the data center (0% involvement), and all the data center cooling needs are satisfied by the RTES. In mode 1, the flow rate of the RTES and temperature of the RTES water from cold to hot well should match the initial design values for the initial scenarios described in Sections 2.1 - 2.4, unless otherwise specified in the following sections.

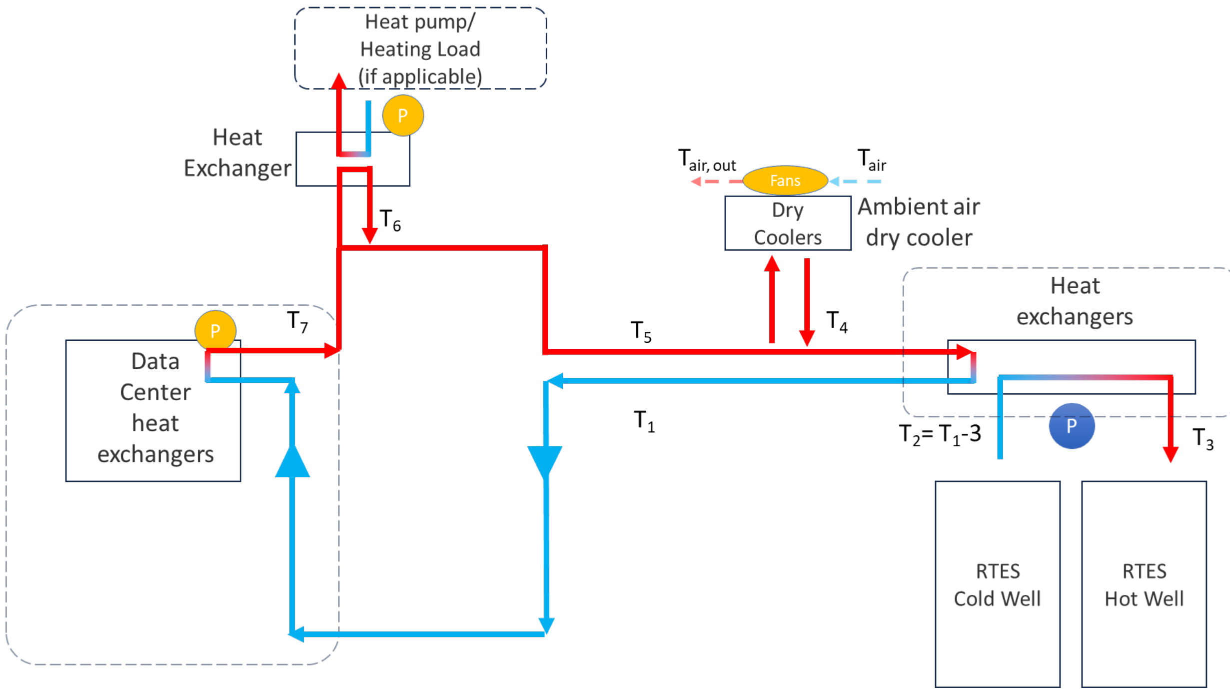


Figure 2-6. Schematic illustration of components included in this study. Symbol P stands for pumps (blue is for RETS pump).

Table 2-2. Summary of the temperature parameters used in the diagrams.

Temperature	Definition
T_1	Data center inlet water temperature
T_2	Cold well outlet temperature
T_3	Hot well inlet/outlet temperature
T_4	Dry cooler outlet/inlet temperature
T_5	Data center outlet/dry cooler inlet temperature
T_6	Heat pump outlet temperature (heat recovery only)
T_7	Data center outlet temperature Heat pump outlet temperature (heat recovery only)

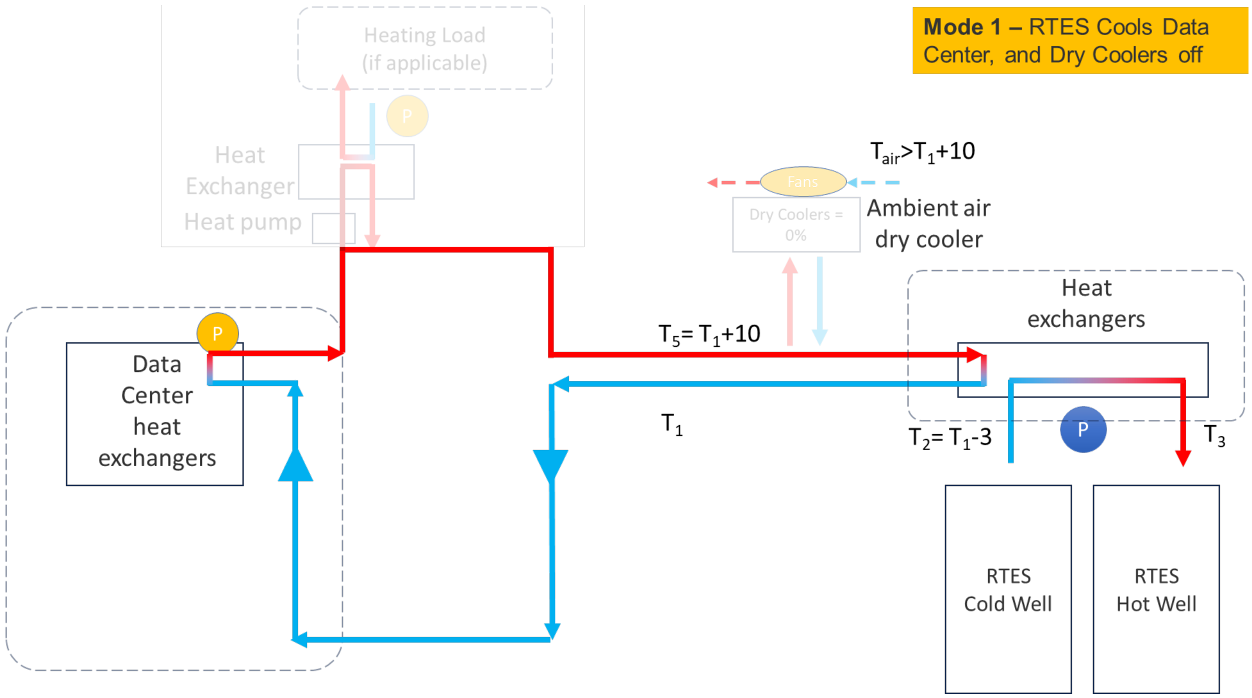


Figure 2-7. Schematic illustration of Mode 1 RTES Only.

Mode 2 Combination (Figure 2-8) is defined as when the ambient temperature is between the data center cooling water outlet temperature T_3 and 6 °C below the data center inlet temperature (T_1) (air-to-water heat exchange approach temperature). In this mode, the dry cooler can partially provide cooling to the data center (between 0% and 100% involvement), and all the data center cooling needs are satisfied by a combination of the dry cooler and the RTES. Note that in mode 2, the flow rate of the RTES and the temperatures of the RTES water from the cold to the hot well cannot both match the initial design value for the initial scenarios mentioned in Sections 2.1-2.4. Because both RTES and dry cooler are in partial use, and their responsible cooling loads vary dynamically with the ambient temperature. To reduce computational cost, we assume that the temperature at the RTES cold wells is at the initial design value (i.e., approach temperature minus 3°C), and the cooling provided by RTES is adjusted by changing the flow rate from the cold well to the hot well.

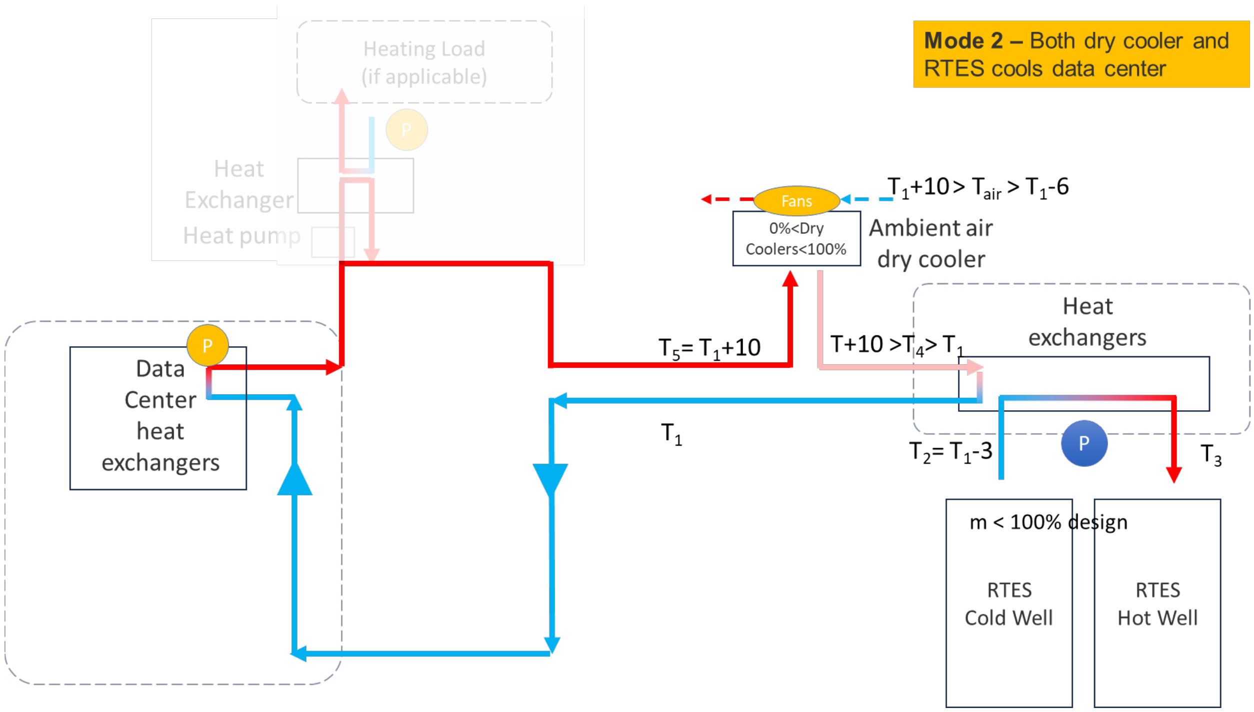


Figure 2-8. Schematic illustration of mode 2 combination.

The design point (Figure 2-9) is defined as when the ambient temperature is 6 °C (air-to-water heat exchange approach temperature) below the data center cooling water inlet temperature (T_1). In this mode, the dry cooler is assumed to provide all the cooling required by the data center (100% involvement), and there is no water flow from the RTES wells.

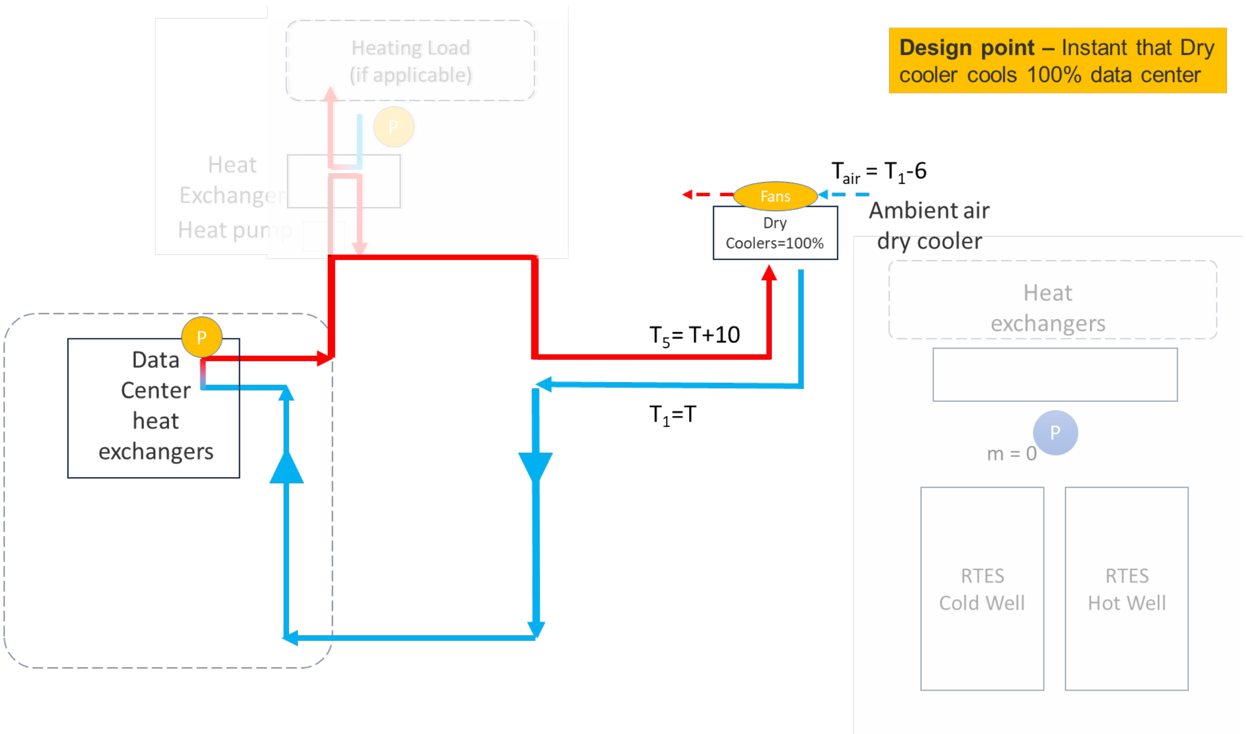


Figure 2-9. Schematic illustration of the design point.

Mode 3 Ambient Air Only (Figure 2-10) is defined as when the ambient temperature is at least 6 °C (air-to-water heat exchange approach temperature) below the data center cooling water inlet temperature (T_1). In this mode, the dry cooler can provide cooling to the data center with additional capacity to cool/charge the RTES (over 100% involvement). In mode 3, water flows from the hot RTES well to the cold RTES well. To not introduce additional wells and related cost, the water flow rate between the RTES wells does not exceed the initial design values for the initial scenarios described in Sections 2.1-2.4. The determination of flow rates and reinjected temperature will be described in the next chapter on the evaluation of RTES.

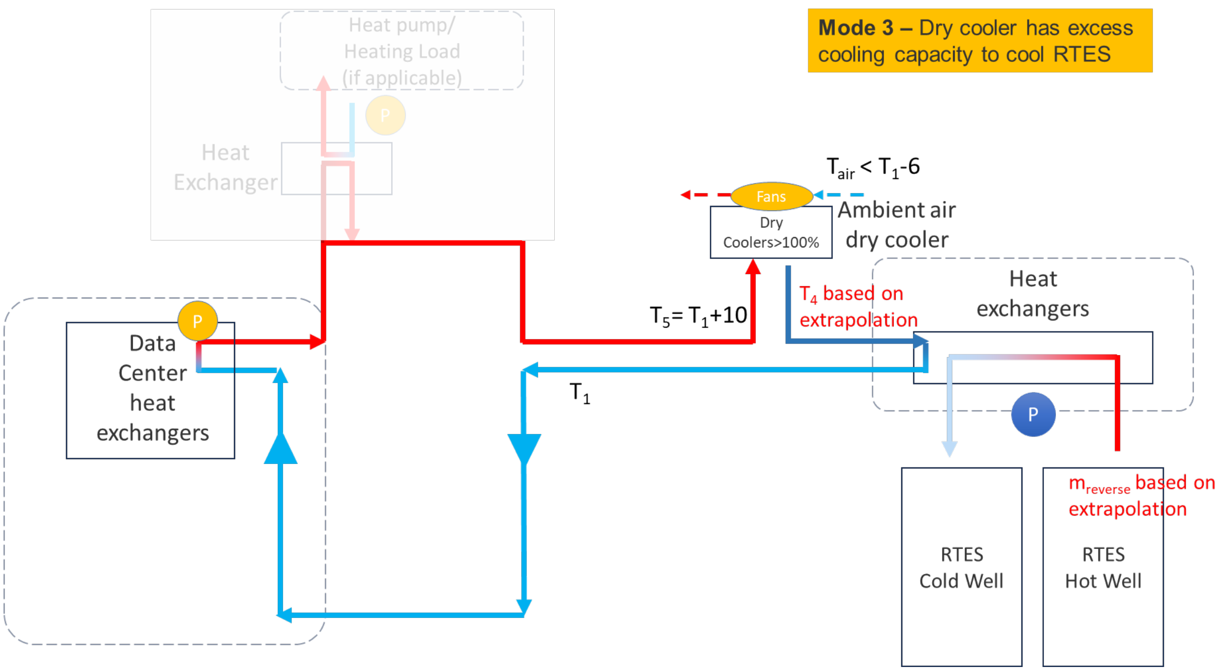


Figure 2-10. Schematic illustration of mode 3 Ambient Air Only.

In modes 2 and 3, the dry cooler percentage is determined from a linear relationship between the cut-off temperatures. The relationships for some representative scenarios are illustrated in Figure 2-11. Note that in mode 3, the extrapolation leads to a percentage exceeding 100%, meaning that it provides cooling to the RTES in addition to the data center. The initial conditions represent the target data center water inlet temperature minus the 6 °C water to air temperature for dry cooler to be in full capacity (100% involvement). End points represent when ambient air temperature equal to the data center outlet temperature, where the dry cooler cannot provide any cooling (0% involvement).

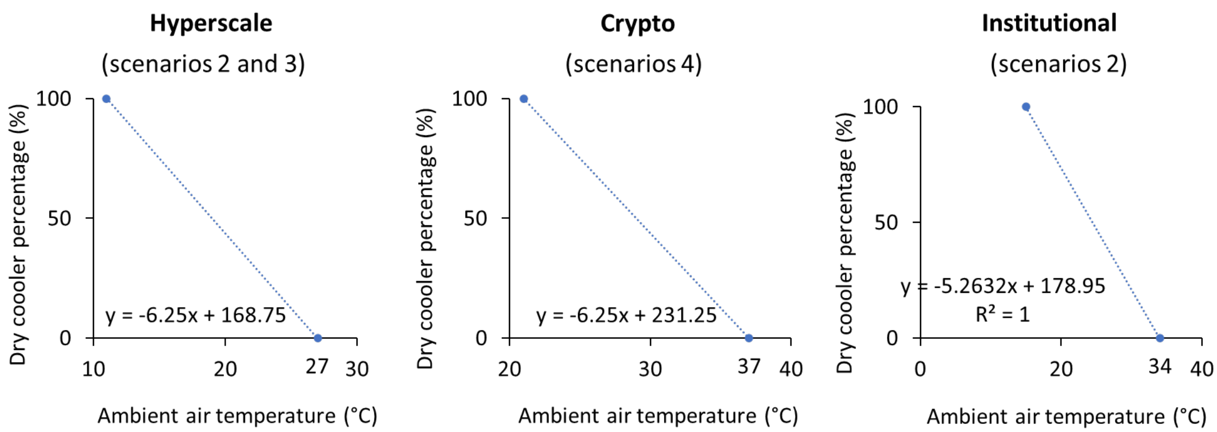


Figure 2-11. Representative relationship functions for dry cooler percentage in Schematic illustration of modes 2 and 3.

Furthermore, a linear relationship is used to determine the outlet water temperature from the dry cooler (T_4) based on the dry cooler percentage from Figure 2-11. The relationships for some representative scenarios are shown in Figure 2-12.

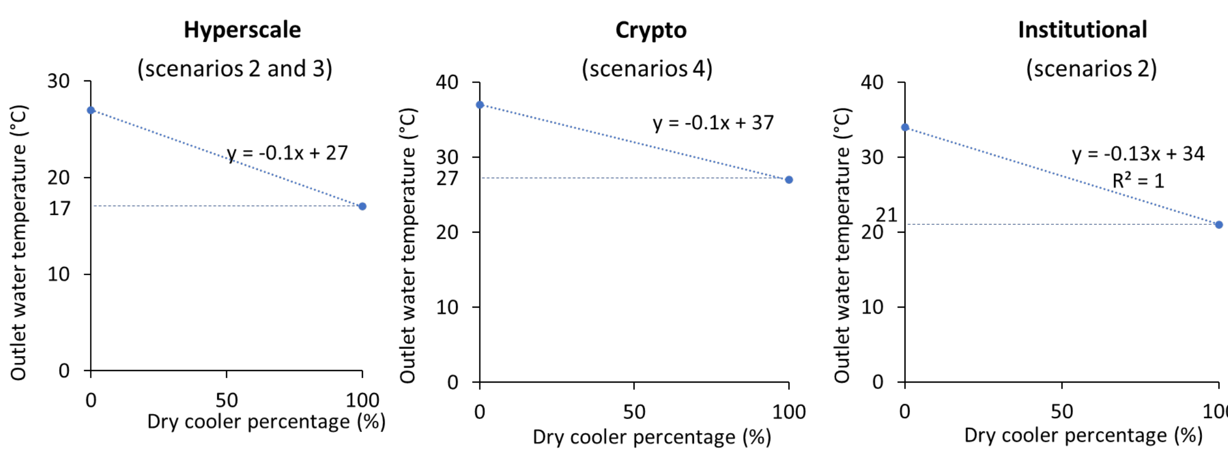


Figure 2-12. Representative relationship functions for dry cooler water outlet temperature in Schematic illustration of modes 2 and 3.

Note that under certain circumstances, the system might not be capable of satisfying all the assumptions on the temperature correlations between different streams, such as linear extrapolation and the various initial design values discussed in Section 2.1. Namely, in intermediate conditions in modes 2 and 3, the dry cooler outlet temperature (T_4) is calculated using linear extrapolation, which overwrites the 6 °C initial design approach for air-water heat exchange and 10 °C Δ T across water-water heat exchange. Also in mode 3 when ambient air temperature is just below T_1 – 6 °C, we assume that the dry cooler now can be used to cool the RTES, which deviates from the initial design values of the approach temperatures but is theoretically achievable. Recall that the initial design values and extrapolation are used to provide a high-level guidance on how the RTES, dry cooler, and chiller (later in Section 2.7) operate with respect to hourly temperature profile. The main purpose for applying these assumptions is to simplify the calculation between geological and TEA models, which are already complex by themselves. Thus, future studies are encouraged to study system and equipment designs, flow patterns, and temperature values for each stream to offer more detailed analyses for constructing RTES data center cooling projects.

2.6 Additional Potential Benefits and Improvements of RTES

Section 4 will discuss the economic performance (capital and operational cost that includes energy use) of using RTES for data centers. Beyond energy cost, there are other benefits of using RTES for cooling data centers.

2.6.1 Potential Water Savings

Evaporative-based cooling (e.g., cooling towers) involves water losses introduced by evaporation (W_e) and windage loss (W_w). By using dry coolers and storing the cool water in subsurface reservoirs, water loss due to evaporation can be eliminated. RTES could introduce significant water savings to the data center. Within the initial scenarios, the evaporative and windage losses are calculated using equations 2.1 and 2.2 below (equations 3.7.1 and 3.7.2 from Lei and Masanet, 2022; EPA, 2017):

$$W_e = \frac{Q}{H_v} \qquad (2.1)$$

$$W_w = \frac{\emptyset_{\%} \cdot Q}{C \cdot \Delta T} \qquad (2.2)$$

Where Q is the energy flow (kW), H_v is the latent heat of vaporization of water (kJ/kg), C is the specific heat of water ($kJ/kg \cdot$ °C), and ΔT is the temperature difference between cooling water supply and return, which is 10 °C in this case. The potentially reduced water loss for the initial scenarios that involve evaporative cooling are shown below in Table 2-3. Note that in this study we primarily evaluated the water loss for tower-based cooling. Future studies are recommended to evaluate the water saving benefits of RTES for air-based cooling that involves evaporation (i.e., mist pads).

Table 2-3. Potential water savings by RTES by not using evaporative cooling towers.

	Evaporation (Million L per year)	Windage (Million L per year)
Hyperscale scenario 1	920	5.0
Institutional Base	66	0.4
Institutional scenario 1	13	0.1

2.6.2 Performance enhancement

Another potential benefit of using RTES to cool data centers is enabling the IT equipment to increase clock speed while operating at lower temperatures. For example, crypto miners, on the IAG noted they tend to over-clock their devices for maximum profit. This can be reflected by comparing the potential operational temperatures of crypto mining with the RTES scenarios (4) with their representative operational temperatures using outside air cooling (device temperature 70-75 °C). Figure 2-13 shows the energy costs based on reported values of the energy requirement (i.e., kWh/hash) under different device temperature ranges. Note that hash is the function that generates encrypted data that is directly related to the transactions and profitability of crypto miners. The results show that based on performance of common crypto mining devices under various temperature ranges, RTES could potentially provide significant energy savings while offering the same performance by reducing the device's operating temperature. Note that beyond crypto mining, the potential performance enhancement by reducing operational temperatures is also relevant to other data centers (Jalili et al, 2021). Therefore, future studies relating to the degree of performance enhancement at various temperature reductions facilitated by employing RTES will be beneficial.

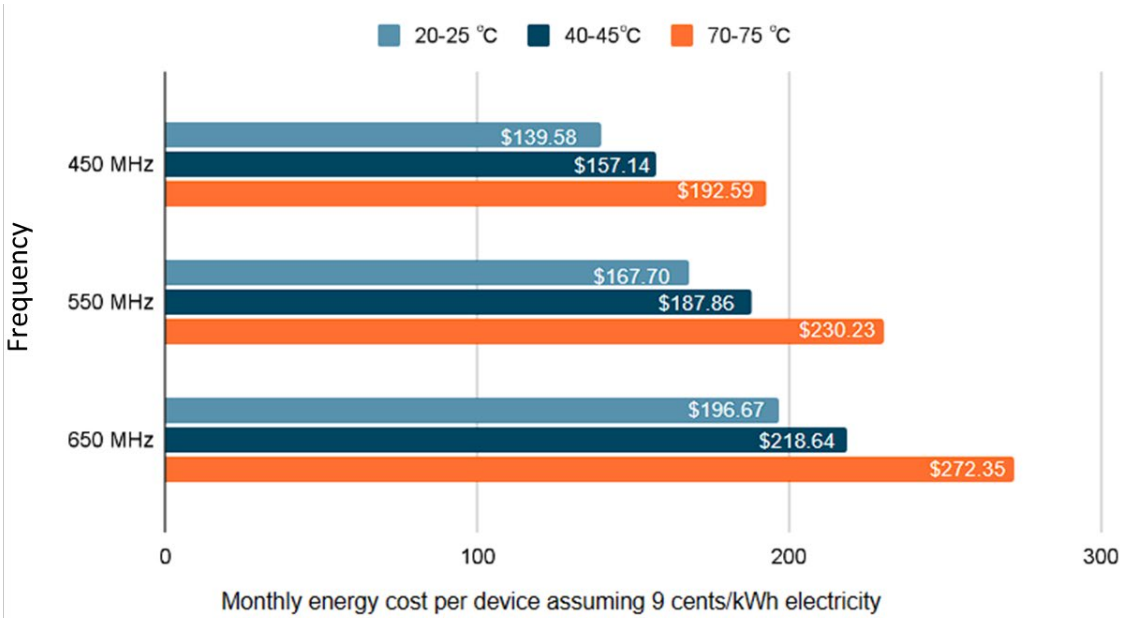


Figure 2-13. Estimated monthly energy costs of a representative crypto mining device under various temperatures based on performance data extracted from Braiins, 2023.

2.7 Combined Chiller and RTES Cooling for Cost Savings

Based on feedback from the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO), a hybrid option of using the combined cooling of chillers and an RTES system including ambient air-dry coolers was considered. Instead of relying solely on cooling the data center with an RTES system cooled by a dry cooler, this option of adding chillers would potentially provide the following advantages to the RTES.

1. A chiller can operate anytime and can cool to lower temperatures compared to a dry cooler. An "economizer" (including dry coolers) can still be used in conjunction with a chiller to provide "free" cooling when ambient conditions are cool (required by some energy codes). The economizer should be put in series with the chiller to precool the return chilled water. As computer densities increase, the need for lower temperature cooling may also increase, which will increase the demand for chillers.
2. The size of the RTES can be reduced. The size reduction depends on the number of hours the chiller is needed to cool the data center directly, and other factors requiring more careful modeling.
3. There are numerous advantages of thermal energy storage (TES) in cooling data centers, but current utilization is small. Thermal energy is stored in water tanks, ice, or other phase change materials and is typically "charged" with chillers. The capacity of data center TES systems can range from a few minutes to allow time for emergency generators to start up, to hours to allow for load shifting (chillers charge the storage when electricity prices are low, and the storage is discharged when prices are high). Furthermore, the carbon profile of low-priced electricity (when renewable power production exceeds the load) is generally very low and this is important to the IT industry whose leaders are seeking zero carbon operations. Conversely when prices are high, utilities typically depend on higher carbon fossil fuel peaking plants to meet the load. Hence TES is a win/win from a carbon standpoint. While TES for load shifting has been commercialized for decades, sales are low partially due to increased capital cost and the risk of constantly changing electrical rate structures (surpluses or shortages of electric capacity today could be gone tomorrow). Innovative financing and ownership models could potentially mitigate those risks and open up this market. Utilities could offer Megawatt Power Purchase Agreements (PPA) or Virtual Power Plants (VPP) and the data center industry would likely be receptive. Alternative financing of RTES is an area needing further research.
4. Many major data center owners are setting real-time zero carbon targets. This will very likely require energy storage. TES is generally less expensive than electric storage and contains no critical mineral components so this may drive a stronger market.
5. The benefits of using RTES for short-term storage (e.g., diurnal storage for load management) as an alternative to conventional above-ground TES need to be further studied. A major benefit of long-term RTES is the ability to use waterless "free" cooling and achieve lower operating temperatures than a typical economizer in real-time. Adding a chiller could allow even lower cooling water temperatures and could take advantage of

low power cost due to excess supply. This would be especially applicable if the excess power supply is available during warm afternoons when “free” cooling is less effective.

In this study, we select air-cooled over tower-cooled chiller because an air-cooled chiller has lower capital cost than a tower-cooled chiller. However air-cooled chillers are typically less efficient. If the hours of operation are low or occur during periods of very low electric prices, this disadvantage is mitigated.

Despite the above-mentioned advantages, using chillers in conjunction with RTES is considered “emerging” compared to the scenarios described in previous sections, especially for crypto mining operations because:

1. Data centers run much warmer than other buildings (the comfort range of IT equipment is wider than for humans) and dehumidification should not be needed. Therefore, cooling systems with lower capital cost and more efficient operation are generally preferred.
2. Typically, chillers add capital cost and operating costs. Best practice designs for data centers use free or natural cooling. In many cases outside air is used to directly cool IT equipment. That air may be supplemented with direct evaporation (pads or mist) in the supply air. Alternatively, water can be cooled via dry coolers or cooling towers to provide cooling water for fan walls, CRAHs, rear-door heat exchangers, on-board cold plates, and immersion cooling.
3. Very few purpose-built crypto mining data centers have chillers for primary cooling or backup. This is to minimize capital and operating costs. Compressor-less cooling is even being used by crypto miners in hot and humid climates such as Texas and Georgia. The base case has no chillers or other compressor-based cooling.
4. Some data centers, especially crypto miners, are moving from outside air cooling to liquid cooling, specifically immersion cooling. Liquid cooling is generally much more efficient than air cooling and can reduce the operating temperatures of the computer chips. The chips can then be overclocked to increase output. Capital cost is saved by reducing the number of mining machines (computers) needed for the same output. This cost savings covers the incremental cost of the immersion cooling. The non-conductive immersion fluid is cooled with water that in turn is typically cooled with dry coolers and no storage.
5. During very hot hours, the outside air, or in the case of immersion, the dry coolers are sprayed, providing an evaporative cooling assist (note that quantifying the amount of water used in this case would be beneficial for future studies). At extremely hot temperatures the mining equipment slows down and eventually stops. Crypto miners accept this penalty to save capital and operating costs, however, the penalty is much less with liquid immersion cooling. Hybrid cooling towers (operate dry or wet), or conventional cooling towers are also used for liquid cooling, but they are more common in mission critical data centers than in crypto mining operations.
6. One suggestion is to use chillers for charging RTES when there is a grid advantage to do so. The hypothesis is that energy prices are lowest when there is an excess of renewable power. It is possible to use chillers to charge the RTES during those hours. As a result of

increased hours for charging RTES, a colder RTES is created, leading to a reduced total flow rate, therefore, fewer number of wells are needed. The key here is to identify the hours with low power cost that do not overlap with low ambient temperatures (dry coolers are preferred over chillers with low ambient temperatures). Such an analysis will need detailed knowledge of electricity price structure, which could vary depending on locations. This is considered out of scope for the current study.

Specifically for this project, we evaluate the potential of using chillers to reduce the capital cost of the RTES system as a secondary cooling system, in case the RTES has a higher capital cost than the chiller. We also discuss the possibility of utilizing off peak power to run the chiller for cooling the data center as a key future research direction.

This concept was considered for the hyperscale data center scenario 3. To reduce computational complexity, the chiller is first assumed to provide all the cooling (no RTES). Note that the air chiller uses a compression-based cycle to reject heat, which is not shown in the diagrams to improve clarity. This concept has the following application modes:

1. Hot: Air-cooled chiller only
2. Medium: Dry coolers in series with chiller (economizer mode)
3. Cold: Dry coolers only (economizer mode)

In mode 1, when the ambient temperature is above the data center outlet water temperature (27 °C), the dry cooler cannot provide any cooling, and the air-cooled chiller supplies all the cooling needs of the data center, as shown in Figure 2-14.

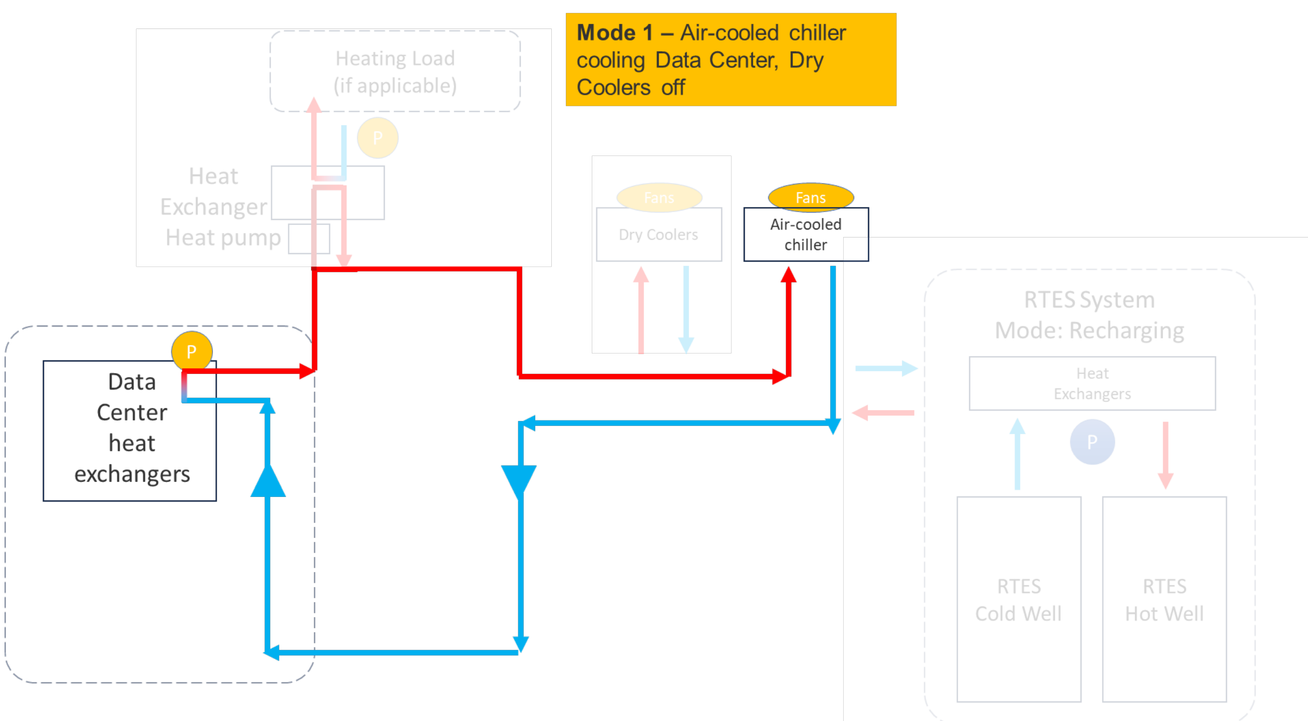


Figure 2-14. Schematic for mode 1 of the chiller scenario.

Mode 2 (Figure 2-15) denotes the conditions when the ambient temperature is below the data center outlet water temperature, but above the temperature required for the dry coolers to fully cool the data center on their own (11 °C). In this mode, both the dry cooler and the chiller provide cooling to the data center, and the dry cooler involvement is calculated using the same linear relationship as in Figure 2-12 for the hyperscale center.

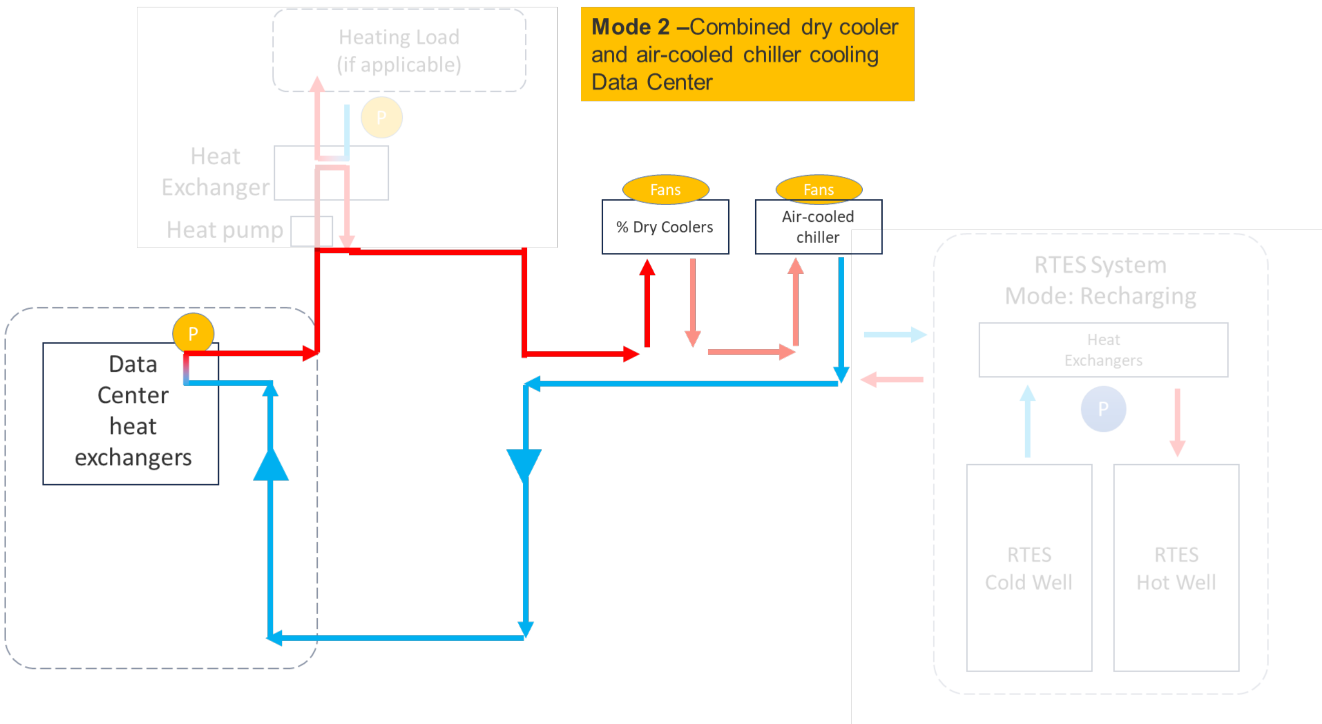


Figure 2-15. Schematic for mode 2 of the chiller scenario.

Mode 3 (Figure 2-16) denotes the conditions when the ambient temperature is below the temperature required to fully cool the data center with only the dry coolers (11 °C).

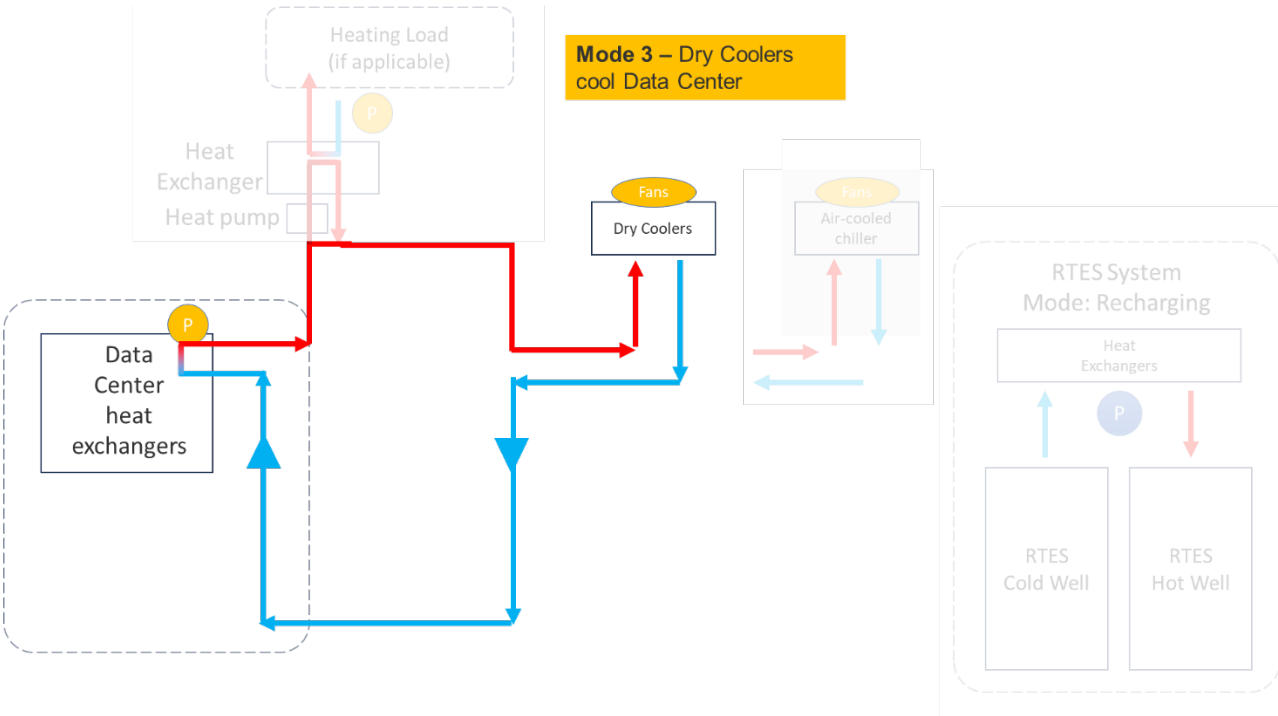


Figure 2-16. Schematic for mode 3 of the chiller scenario.

Based on the chiller scenario and its three modes, the contributions of RTES were modelled by adjusting the percentage of RTES contribution (as a function of RTES size) between the original hyperscale scenario 3 and the chiller scenario. To elaborate, instead of modelling all the potential scenarios of RTES + dry cooler + chiller, we model separately the operating cost of two scenarios, RTES + dry cooler and chiller + dry cooler. The cost of the intermediate scenarios (various sizes of RTES) will be calculated by the weighted average of the two scenarios using the percent RTES contribution. For example, 40% of RTES contribution means that RTES + dry cooler is used 40% of the time, and chiller + dry cooler is used for 60% of the time. The details of how they are distributed throughout the year are not in the scope of this analysis and require further research. The coefficient of performance (COP) of the chiller, is estimated using a linear relationship between a representative range of 2.4 - 3.06 (Yu et al, 2014) using the lower cut off temperature of mode 2 (11.0 °C) and the maximum temperature of Virginia (37.5 °C). Note that the COP value determines the theoretical mechanical energy consumption required by the chiller with respect to the cooling load it provides. This chiller energy consumption will be combined with its capital cost for comparison with RTES energy consumption and capital cost under various electricity costs. In this simplified analysis, we assume constant $/kWh based on the maximum and minimum hourly electricity cost at the target location. Note that the two scenarios have large variances of capital cost and operational cost (e.g. depending on the geographical region, electricity price, or uncertainties in cost performance models in TEA), the optimum RTES size and contribution could be determined in the future, as shown in Figure 2-17. Based on the above schematics and relationships, modeling of the chiller scenario will be discussed in Section 4.

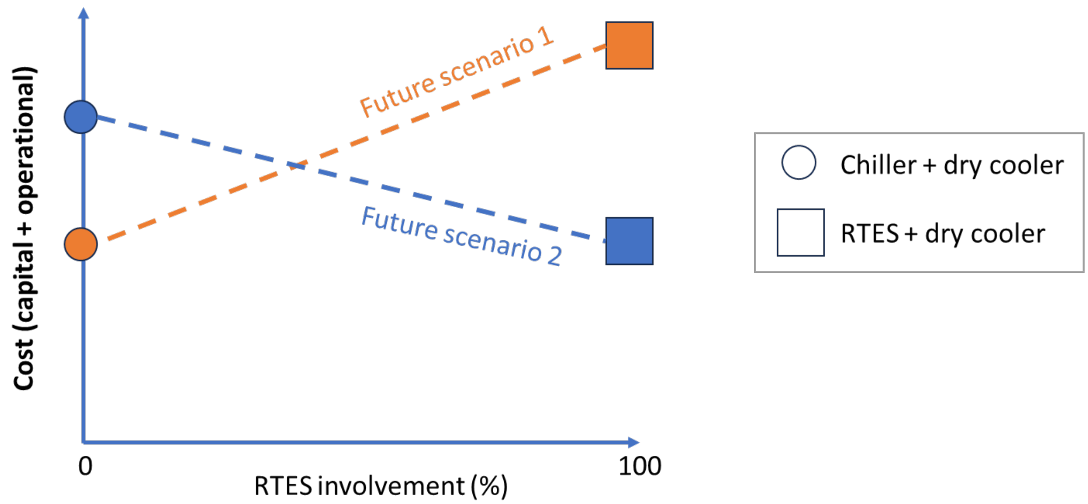


Figure 2-17. Illustration of the hypothesis for determining the optimum RTES size based on results from the chiller scenario (left) and the original hyperscale scenario 3 (right) when RTES has higher capital cost, but lower operational cost than a chiller.

Future studies should investigate the potential of using air-cooled chillers to cool/charge the RTES when the grid electricity price is low and/or clean and there is available chiller capacity. The chiller could be oversized relative to the data center cooling load or run when the data center is being cooled with the dry coolers. Other types of chillers such as water/liquid-based chillers could also be explored. Therefore, beyond the characterization discussed above, future detailed studies in load optimization for RTES end-users are recommended to evaluate the full potential benefits including decarbonization and energy cost savings of an RTES system coupled with a chiller plant. As we consider moving from long-term (seasonal) thermal energy storage to shorter term storage for grid optimization, conventional TES would need to be considered as an option. Some electric rate structures have had large time-of-day differences as well as large peak demand charges for many years. TES, including water, ice, and other phase change materials have been developed and commercialized for buildings including data centers. TES can also provide greater resilience and reduce water consumption. The relative benefits (and costs) of hybrid RTES versus aboveground TES need to be evaluated. Finally, other geological energy storage options could also be investigated.

2.8 Conclusion and Discussion

In this project, three types of data centers were chosen to evaluate their use of RTES-based cooling. They included institutional, crypto mining, and hyperscale. For each data center type, their representative characteristics (i.e., scales, locations) and key assumptions (i.e., water temperature differences, approach temperatures) were determined based on literature review and inputs from the IAG. Various cooling scenarios, including base cases, alternative high-efficiency cooling scenarios, and RTES-based cooling scenarios, were characterized for down-selection and evaluation during the RTES and techno-economics analyses. Feedback from the IAG showed interest toward RTES technology in general, but concern regarding its economic performance, which indicated the importance of TEA in Section 4. For cooling scenarios that involve RTES and dry coolers, application modes were defined using the hourly ambient temperatures. These temperatures govern how much cooling is provided by the RTES and dry coolers in each mode.

High-level energy consumptions of the key cooling components (i.e., chillers, fans, cooling tower) in non-RTES scenarios were estimated to benchmark with the RTES performance. Energy and carbon savings are estimated in the techno-economic analyses. Other potential benefits of RTES were discussed at a high-level, including 1) water saving from evaporation and windage loss caused by the cooling towers, and 2) computer performance enhancements by operating at lower temperatures. An additional scenario involving both a chiller and RTES system for hyperscale data center cooling was also characterized. Recommendations for future studies include more detailed modeling using real-world operational data for various data centers, and more robust operational pattern design involving load optimization to maximize the potential benefits of hybrid RTES systems to users and grid operators.

3. Reservoir Thermal Energy Storage Evaluation

3.1 Golden Colorado for Institutional Data Centers

3.1.1 Site Description and Selection

The Denver Basin Group is a set of alternating alluvial sandstones, shales, and conglomerates with ages ranging from the upper Cretaceous through the Eocene. These formations of the Denver Basin extend eastward from the Front Range of northeastern Colorado toward Nebraska and Kansas, and northward including the southeastern corner of Wyoming. Detailed geologic and hydrogeologic studies have been carried out by the United States Geological Survey (USGS), Colorado Geological Survey, the Colorado Department of Natural Resources, and many others to characterize the hydrogeology of this region (Paschke, 2011, Dechesne et al., 2011, Musgrove et al., 2014, Raynolds et al., 2001). The Denver Basin hosts four main aquifer systems (Dawson, Denver, Arapahoe, Fox Hills-Laramie) that provide groundwater resources in the region (Musgrove et al., 2014).

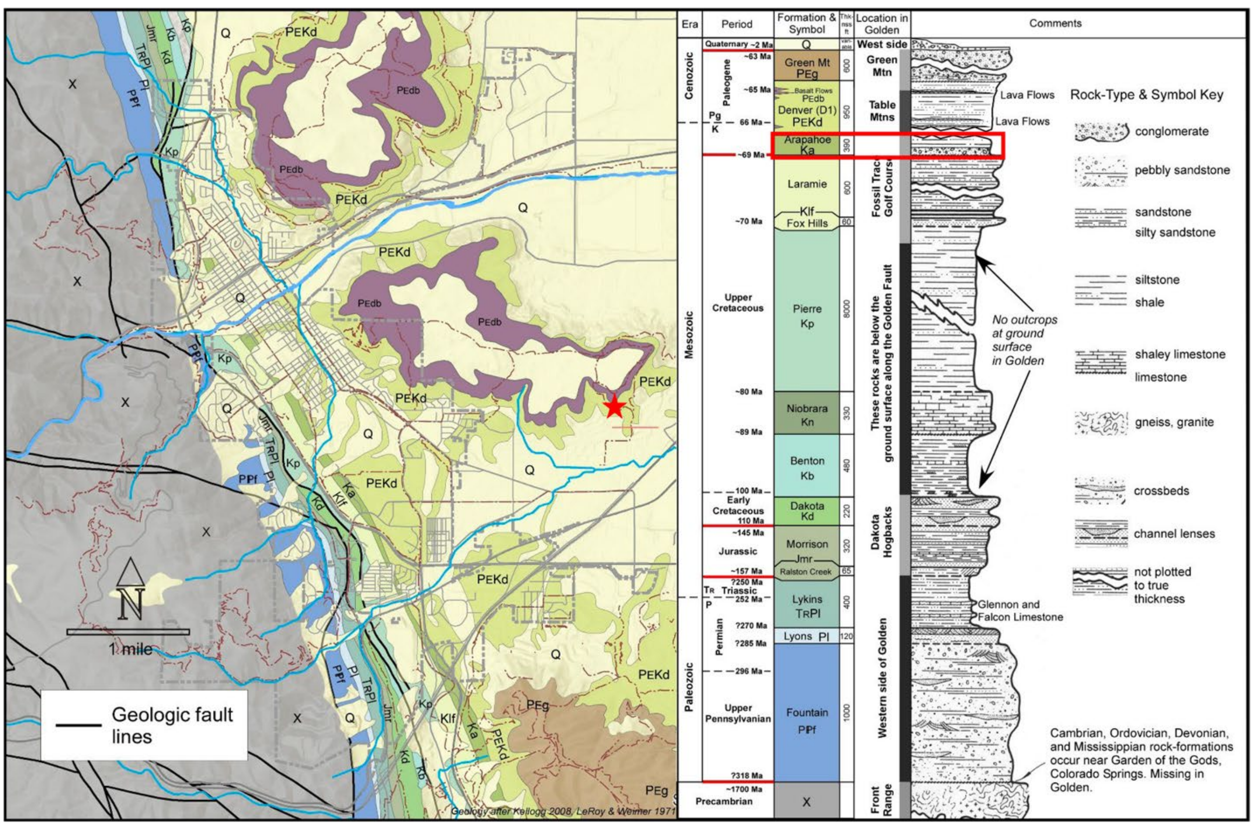


Figure 3-1: Geologic map (left) and geologic column of the Golden area (right) with the Arapahoe Conglomerate highlighted in red. Note the red star indicating the location of NREL and the HPC Data Center. (modified after Anderson and Haseman, 2022).

The Arapahoe aquifer is hosted in the basal Arapahoe Conglomerate of the Denver Basin Group (Figure 3-1). The conglomerate is thickest near the Front Range (~100 m) and thins eastward toward the center of the basin. It is capped by confining units (shales and siltstones) of the D1 sequence and underlain by low permeability shales and siltstones of the Cretaceous Laramie Formation (Dechesne et al., 2011). The Arapahoe Conglomerate was chosen as the test target for the institutional data center RTES modeling with the High-Performance Computing (HPC) Data Center at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. The thickness of the formation is estimated to be roughly 350 ft (107 m) near Golden at a depth ranging from 558-886 ft (170-270 m) below ground surface (bgs) (Dechesne et al., 2011). Median hydraulic conductivity is estimated to be 1.8 ft/day (0.55 m/day) (Musgrove et al., 2014) and porosity is 34% (Raynolds et al., 2001). The variability of grain sizes within the Arapahoe will likely lead to heterogeneous horizontal permeability while continuous confining units above and below provide sufficient sealing for the system.

3.1.2 Reservoir Model Description

With the geological information provided in the previous section, we first built two reservoir models in 3D, one with layered hydraulic properties and the other one with homogenous hydraulic properties, to investigate their impact on RTES cooling performance. As shown in Figure 3-2, a one doublet system is simulated with half of the domain due to symmetry. The two 3D models have aquifer, caprock, and base-rock thicknesses of 105 m, 15 m, and 30 m, respectively. The modeling domain has a size of 2000 m × 1000 m to avoid any boundary effects. A no-flux (undrained) boundary condition was applied to the top, bottom, and symmetrical surfaces, while the rest of the sides were applied a Dirichlet (constant pressure) boundary condition with an initial reservoir temperature of 16.5°C and an initial hydrostatic pore pressure (linearly increase with depth) assuming the water table is at the surface. The doublet has a distance of 160 m between wells. The modeling results in Figure 3-2 show the heat plume distribution when cold water is extracted from the cold well to cool down the data center. The heated fluid is then injected back into the formation via the hot well. Table 3-1 lists all thermal-hydrogeological properties used for the 3D model simulation of the homogeneous case. For the layered case, we assigned the permeability of each layer with different values and their weighted sum (via layer thickness) is the same as the value listed in Table 3-1.

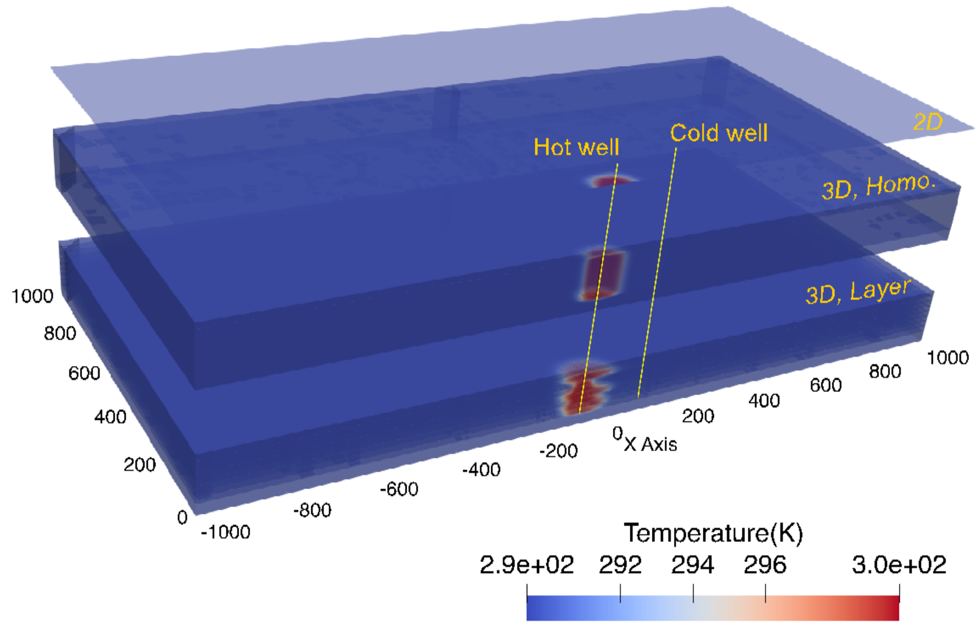


Figure 3-2: Reservoir models (3D layered model, 3D homogenous model, and 2D model) used to reduce the uncertainty on hydraulic properties across the depth of the targeted Arapahoe aquifer and to reduce the computational cost. Note these models are stacked together for comparison.

Table 3-1: Thermo-hydro-geological parameters of the Denver Basin formations collected from literature.

Parameter	Caprock Shale Beds	Arapahoe	Basal Shale Beds	Source
Permeability (m^2)	1e-18	6.5e-13	1e-18	Musgrove et al. 2014
Porosity (%)	1	34*	1	*Raynolds et al. 2001; Rice et al. 2021
Thermal Conductivity (W/m/K)	1.1	2.5**	1.1	Ochsner 2014; Rice et al. 2021; **Generic value
Specific Heat Capacity (J/kgK)	1000	920*	1000	*Typical values
Grain Density (kg/m^3)	2500	2650*	2500	*Typical values
Thickness (m)	15	105	100	Dechesne et al. 2011 Cross section A-A'; Musgrove et al. 2014
Formation Depth (m)	155-170	170-275	275-375	Dechesne et al. 2011 Cross section A-A'
Temperature (°C)	16.5	16.5	16.5	Musgrove et al. 2014; Rice et al. 2021

With these two models, we performed seasonal RTES operation for two years, in which cold water is extracted from the cold well in the summer to cool down the data center at a rate of 60 kg/s and reinjects the hot fluid with elevated temperature of $\Delta T = 10°C$ into the hot well during the summer season. During the winter, the hot fluid is extracted back from the hot well and cooled down and recharged back to the cold well for RTES sustainability. In this simplified sensitivity analysis, the RTES is at rest without any operation for the spring and fall seasons. We used the PorousFlow module (Wilkins et al., 2021) in the Multiphysics Objective Oriented Simulation Environment (MOOSE) (Permann et al., 2020) to solve the coupled mass conservation and energy conservation governing equations. For the equation of state of fluid properties, we adopted the International

Association for the Properties of Water and Steam-Industrial Formulation 1997 (IAPWS-IF97) in this work. Figure 3-3 shows the simulated results on pore pressure at the bottom of the two wells and the average temperature of the fluid within the two wells. For the two 3D models, we also investigated the impact of the vertical-horizontal permeability ratio ($\frac{\kappa_v}{\kappa_h}$.) All 3D models yield almost identical results for the four monitored values, even though the heat plumes are clearly different between the homogenous case and the layered case as shown in Figure 3-2.

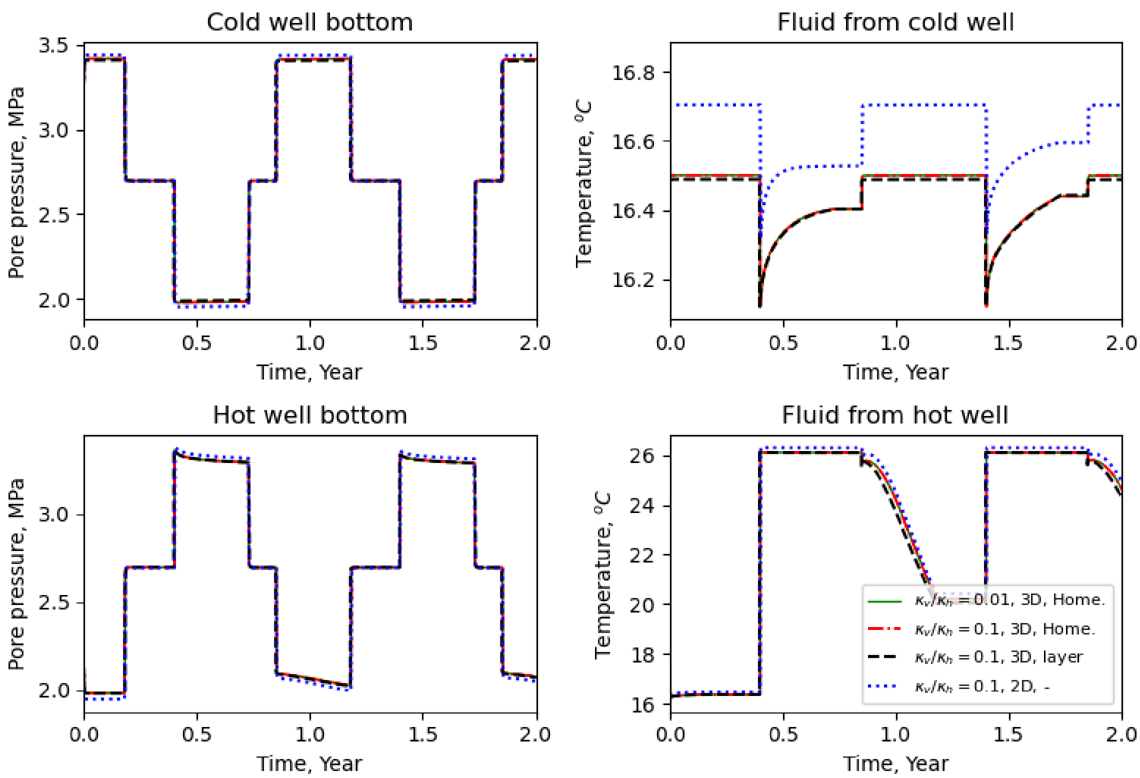


Figure 3-3. Parametric study to quantify the influence of 3D homogenous versus layered domain, vertical/horizontal permeability ratio, and 3D versus 2D model on RTES performance.

The above parametric study justifies that the homogenous assumption is valid for RTES techno-economic analysis (TEA). However, the homogenous case is still computationally expensive considering the hourly rate change based on ambient temperature conditions. We further reduced the computational model to a 2D model assuming axial symmetry in the aquifer section and ignoring the heat conduction loss in the cap and base rocks. With the 2D model, we simulated the same operation with scaled injection rate, and the results are compared with the 3D case results shown in Figure 3-3. There is a close match between the two cases observed except the fluid temperature at the cold well, which has a 0.2 ℃ difference between the 2D and 3D cases. This minor difference does not impact the TEA and therefore we used 2D models for the rest of the simulations.

3.1.3 Simulation Scenarios

As described in Section 2, among the four scenarios of cooling design for the 5MW institutional data center, scenario-2 and scenario-3 utilize both RTES and dry coolers. Figure 3-4 shows the fluid temperature at the inlet and outlet as well as its flow rate. T_1 and T_7 denote fluid temperature at the inlet and outlet of the data center. These values match with the current operational temperatures for the NREL data center. With ΔT=13°C, we can calculate a flow rate of 92 kg/s is needed to cool the data center with a capacity of 5MW. Note this temperature difference was adjusted to match the actual operating conditions at the NREL data center, which differs from the calculated 120 kg/s flow rate with the general assumption of ΔT=10°C in Section 2. For scenario-2, no heat is recovered and the fluid at T_5=34°C is sent to heat exchanger. In the simulation, the fluid temperature from the RTES cold well is fixed as its initial reservoir temperature T_{in}=16.5°C, and we fix the fluid in the hot well at T_{out}=29.5°C. The 13°C temperature difference requires a 92 kg/s fluid injection/extraction rate of RTES to satisfy the cooling need. The temperature out of the data center (before entering heat exchanger) is T_7=34°C. For scenario-3, an assumed constant 25% of the available heat is recovered throughout the year, or 50% is recovered for half of the year during the winter. Heat is recovered after the fluid is heated to T_7=34°C from cooling down the data center. This heat recovery reduces the fluid temperature from T_7=34°C to T_5=30.75°C and T_5=27.5°C for the constant and seasonal heat recovery, respectively. To satisfy the cooling needs with 92 kg/s of flow and a ΔT=9.75/6.5°C for the two heat recovery cases, a 69/46 kg/s injection/extraction flow rate is needed from the RTES side using a fixed ΔT=T_{out}-T_{in} =13°C between the hot and cold wells. Note the above flow rate calculation assumes that the data center is fully cooled by the RTES system. The flow rate between the cold and hot wells will change when the dry cooler is used to cool down the data center or to recharge cold into the RTES system.

The dry cooler operates according to ambient temperature. For the institutional data center located at Golden, Colorado, the maximum ambient temperature is T_{max}=34°C, above which the dry cooler will not cool. We also choose the minimum limiting temperature T_{min}=10°C, at which the dry cooler can provide all 5MW cooling needed for the data center. For any ambient temperatures, the percentage of dry cooler (PDC) contributing to the data center cooling is linearly interpolated via equation 3.1:

$$\text{PDC}=100\times(34-T_{air})/(34-10) \qquad (3.1)$$

With the above assumptions and the recorded hourly ambient temperature profile, we calculated the dry cooler utilization percentage as shown in the top plot of Figure 3-5. As described in the previous section, for PDC>100%, the dry cooler provides all cooling needs for the data center, and the extra cooling provides cold recharge to the RTES system. For PDC<100%, the dry cooler and RTES work together to satisfy the cooling needs of data center.

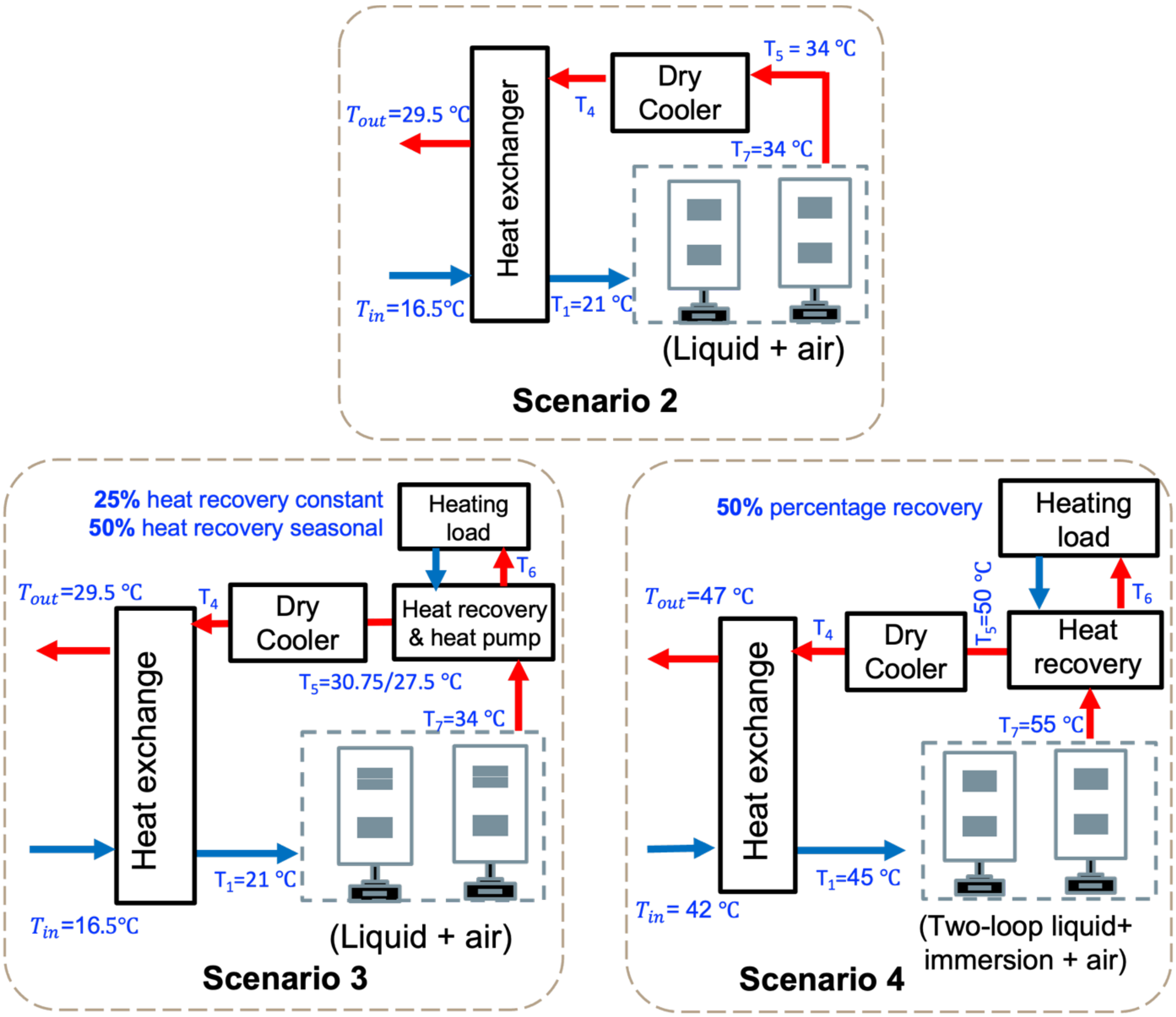


Figure 3-4. Institutional data center cooling design assuming that RTES provides all cooling demands. Note the base scenario-1 is the current cooling method used by NREL campus without RTES. The difference between scenario 2 & 3 is heat recovery. For scenario-4, higher heat recovery is achieved due to the high operation temperature.

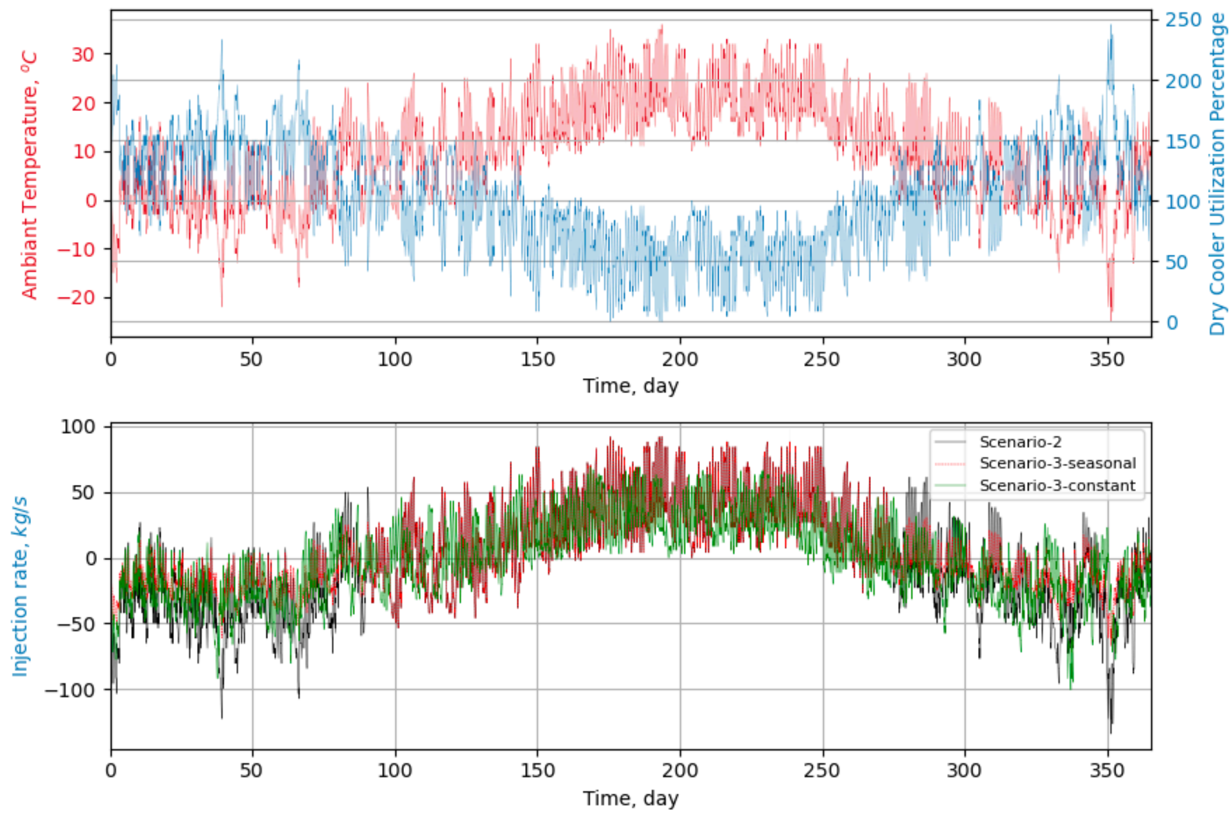


Figure 3-5. The upper plot is the ambient temperature through the year at Golden, Colorado with the calculated dry cooler utilization percentage assuming a cut-off temperature of 34 ℃. The lower plot is the calculated fluid injection/extraction rates at the cold well for scenario-2 and scenario-3 with 25% constant heat recovery throughout the full year (denoted as scenario-3-constant) and 50% seasonal heat recovery for a half year (denoted as scenario-3-seasonal).

Using the dry cooler utilization percentage described above, we can determine the fluid temperature after passing through the dry cooler as:

Scenario-2	T_4=-0.13*PDC+34,
Scenario-3-constant	T_4=-0.0975*PDC+30.75
Scenario-3-seasonal	T_4=-0.065*PDC+27.5 during the heating season and the same as scenario-2 during the cooling season.

These equations assume that at PDC=100%, the working fluid can be cooled down to T_1=21℃ and the RTES will be turned off.

The water temperature leaving the dry cooler (T_4) drives the RTES flow rate (Q) according to the ratio of temperature differences between the two sides of dry cooler with respect to the data center inlet temperature (T_1):

Scenario-2 $Q=92\times(T_4-T_1)/(T_7-T_1)$

Scenario-3-constant $Q=69\times(T_4-T_1)/(T_7-T_1)$

Scenario-3-seasonal $Q=46\times(T_4-T_1)/(T_7-T_1)$ with heat recovery (heating season) and the same as scenario-2 without heat recovery (cooling season)

The 92/69/46 kg/s for all three scenarios is the calculated flow rate when RTES provides all the needed cooling, while T_7 = 34/30.75/27.5°C corresponding 0%, 25%, and 50% of heat recovery as shown in Figure 3-4. When Q>0, the RTES works with the dry cooler and together they cool the data center. When Q<0, the extra cooling capacity of the dry cooler recharges the RTES by extracting hot fluid from the hot well, cooling it down, and reinjecting it into the cold well (the flow direction is reversed). The bottom plot of Figure 3-5 shows the hourly flow rate for all three scenarios for a whole year. Note all the temperatures are designed so that the approximate amount of fluid moved from the cold well to the hot well for cooling the data center is the same as the amount of fluid moved from the hot well to the cold well for RTES recharge, thus ensuring sustainability of the RTES system.

Figure 3-4 also shows the temperatures and flow rates at the inlet and outlet of each system component for scenario-4. With ASHRAE W45 used as the data center cooling fluid temperature, a constant 50% heat recovery is assumed throughout the year. Following $\Delta T=10$°C as discussed in the previous section, 120 kg/s flow rate is needed to satisfy the 5MW cooling need. With this design, the outlet temperature from the heat exchange is T_{out}=47°C, which is higher than the maximum ambient temperature in Golden Colorado. Therefore, energy-efficient dry coolers can satisfy the 2.5MW cooling load (i.e., after heat recovery) throughout the year negating the need for an RTES system. Consequently, RTES deployment in this scenario is considered non-beneficial and the subsequent analysis (including the TEA analysis in Section 4) was not developed.

3.1.4 Simulation Results

The maximum injection rate calculated in Figure 3-5 for scenario-2 is 134 kg/s when the ambient temperature is extremely low, and the dry cooler is used to cool down data center and recharge the RTES. For scenario-3-seasonal, the maximum rate is 92 kg/s at which the ambient temperature exceeds 34°C and RTES is used to cool down the data center. For these two cases, the large amount of injection will create fractures in the targeted formation given the in-situ conditions of stress (i.e., assuming the minimum principal stress is the overburden stress) and permeability. As a result, we have to use two doublets to reduce the wellbore pressure for scenario-2 and scenario-3-seasonal. For scenario-3-constant, one doublet is enough as the maximum injection rate is 75 kg/s. The distance between the wells of the doublet is kept the same as 160 m as the 3D cases. The distance between the two doublet is 500 m, which can be further reduced from the simulation results. Figure 3-6 shows the simulated pore pressure and temperature distributions for the two doublets and one doublet scenarios at a typical time. Note the mesh close to wells was extensively refined to better reflect the sharp gradient of pore pressure and the temperature. The maximum and minimum pressure wells will switch when the injection and extraction is reversed, and the size of heat fluid plume dynamics change according to the injection plan.

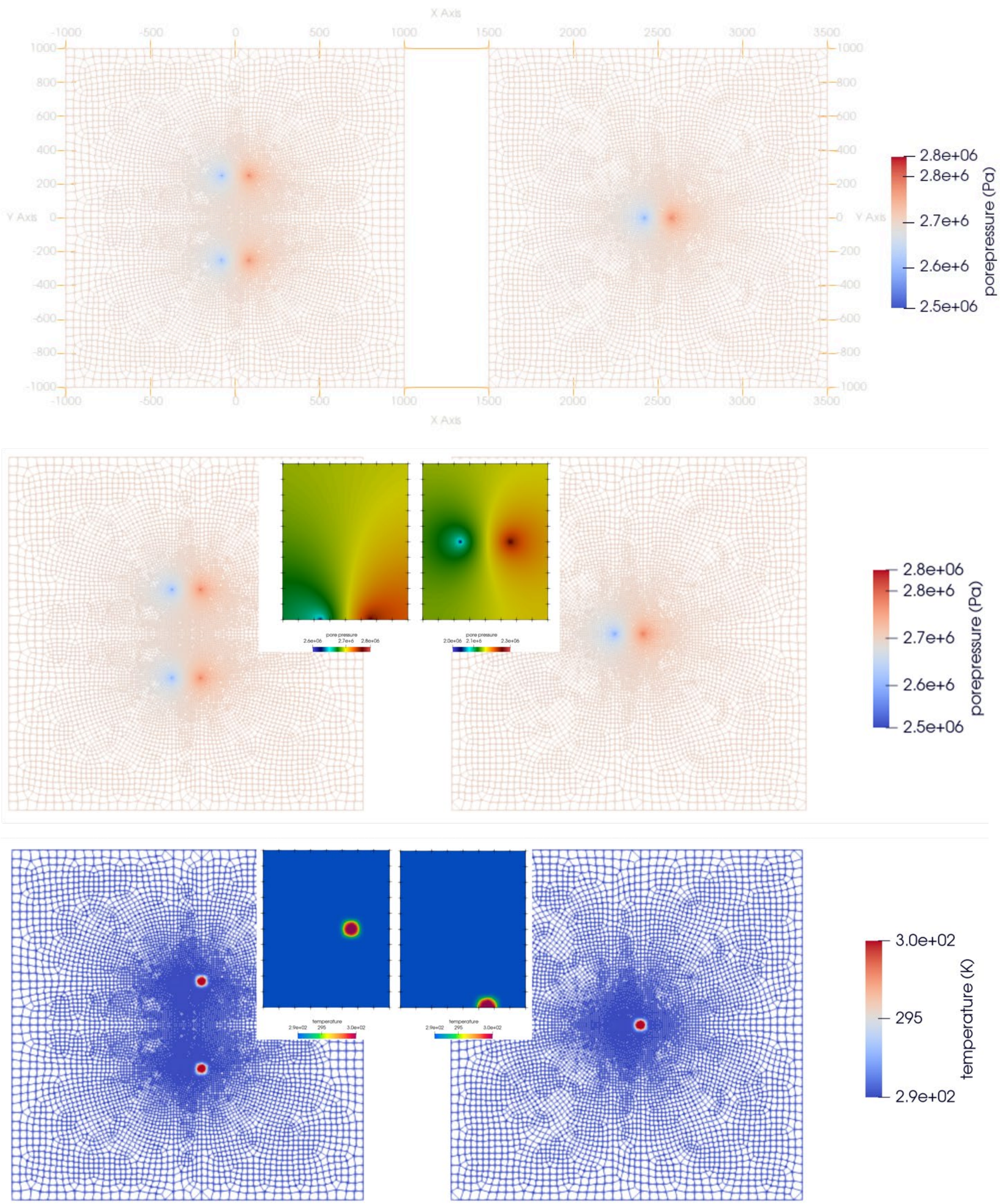


Figure 3-6. Predicted pore pressure distribution (top) and temperature distribution (bottom) for the scenario-2 with two doublets (left) and for scenario-3-constant with one doublet (right).

Figure 3-7 shows the predicted pressure evolution at the two wells across 20 years of operation for both scenarios. The maximum pressure difference between the cold and hot wells is about 2MPa for scenario-2 and 0.2 MPa for scenario-3. Figure 3-8 shows the fluid temperature extracted or injected into the two wells. Due to heat conduction, the fluid extracted from hot well is not fixed as 29.5 ℃, but the difference to 29.5 ℃ is decreasing with operational time. This temperature drop indicates that not all the extra capacity of the dry cooler is used to recharge the RTES, and the injection/extraction rate can be further increased. However, we can see the constant temperature from the cold well, indicating the cooling capacity of the RTES is maintained throughout the operation time. Figure 3-9 shows the calculated cooling capacity from RTES for 20 years of operation. The patterns of all scenarios are similar to each other, although the maximum values are different due to operational differences.

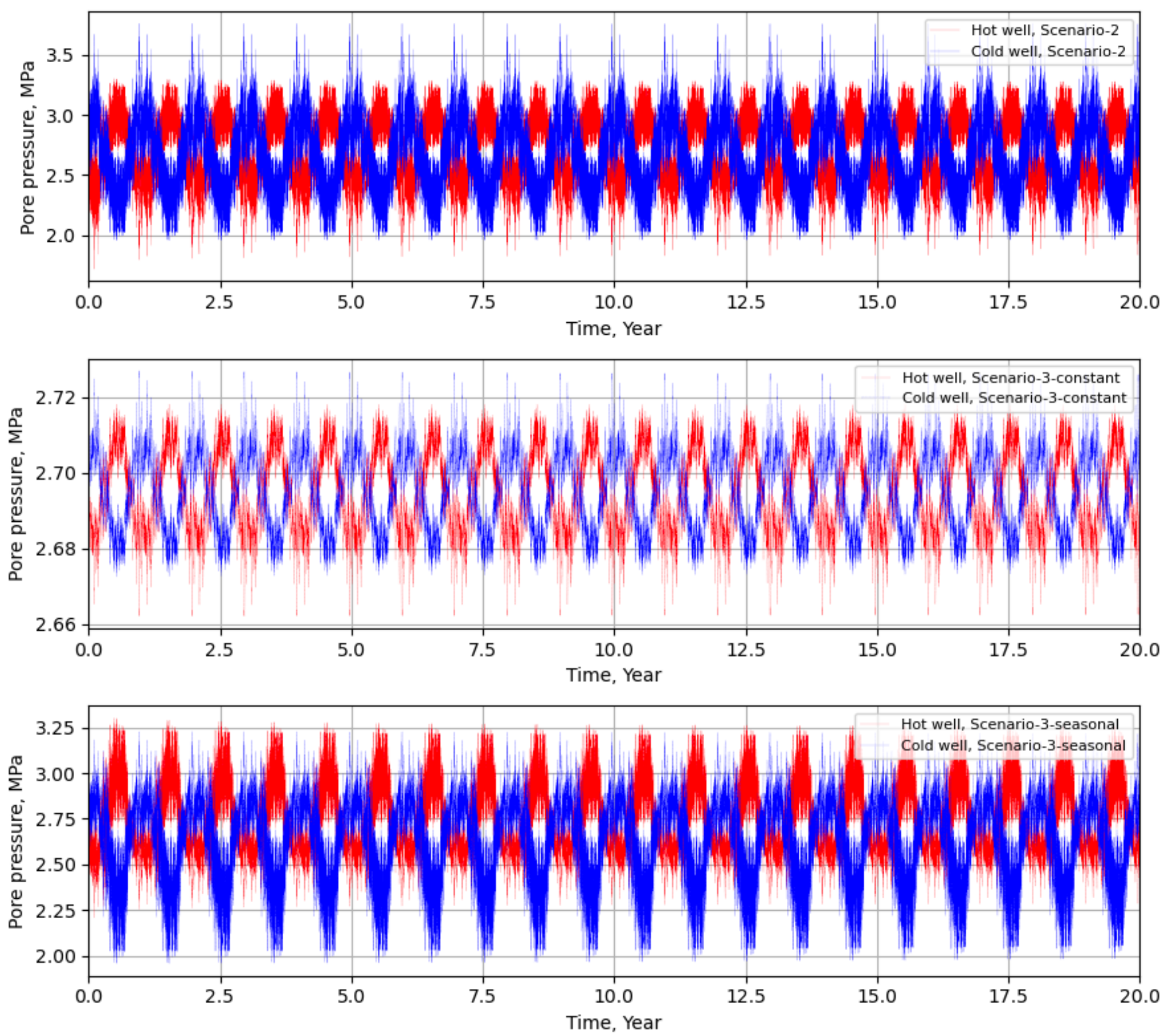


Figure 3-7. Predicted pore pressure evolution at the hot and cold wells for all simulated scenarios.

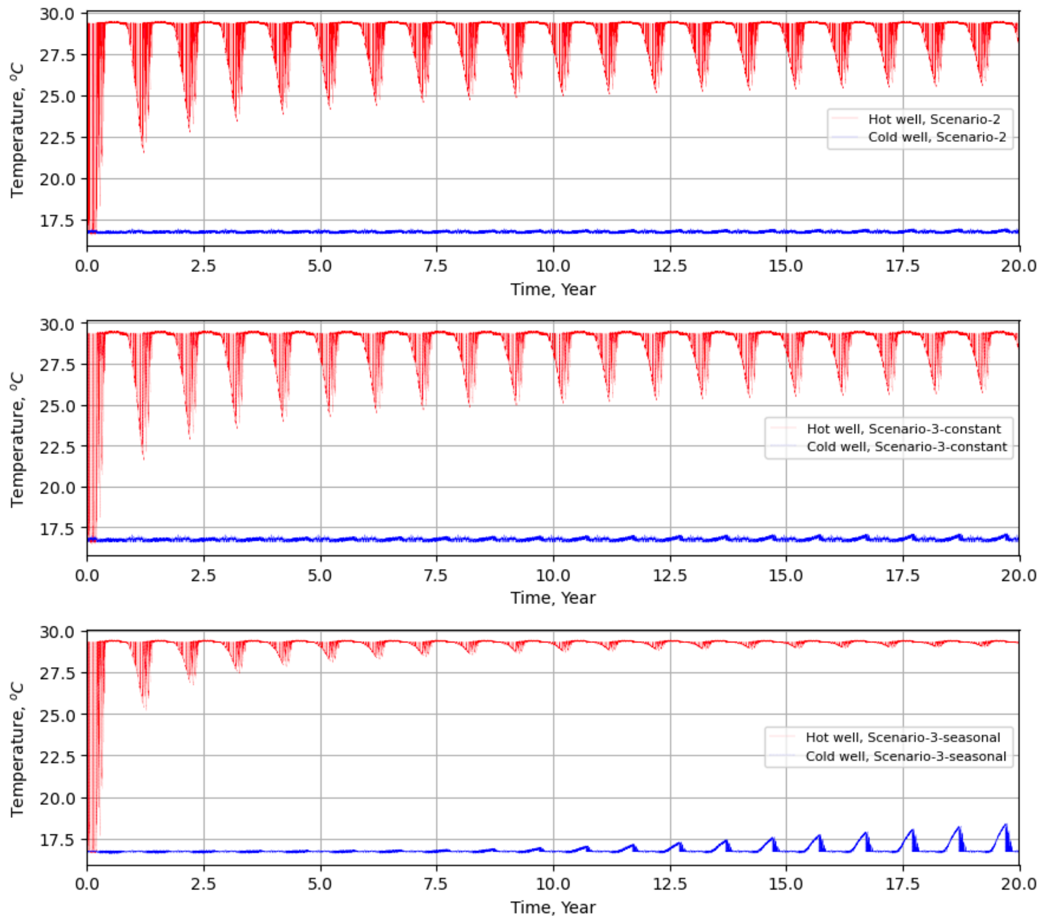


Figure 3-8. Predicted fluid temperature evolution from hot and cold wells for all simulated scenarios.

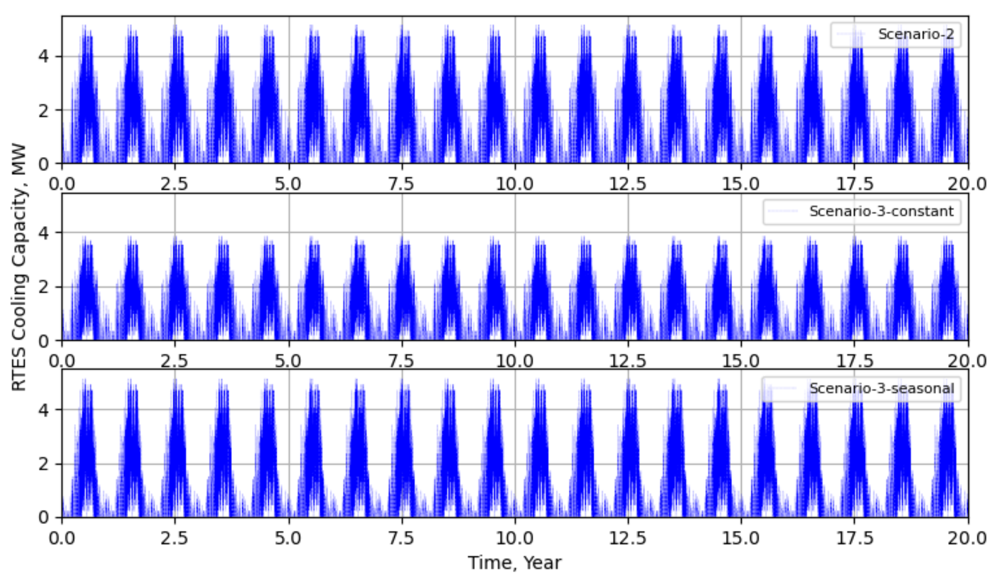


Figure 3-9. RTES provided cooling capacity throughout 20 years of operation.

3.1.5 Conclusion and Discussion

1. A simplified 2D simulation is capable of reproducing pore pressure in the wells at a specific depth and the fluid temperature extracted from the wells as compared to the 3D simulations. This enabled rapid 2D simulation with hourly injection rates and temperature change.
2. The combination of dry coolers and RTES can satisfy 5MW data center cooling needs located at Golden, Colorado with the consideration of ambient temperature change throughout the year. The aquifer's hydraulic parameters and the maximum injection/extraction rates require 1 or 2 doublets of RTES for the cooling needs depending on the required flow rate.
3. Given the existing in-situ temperature of the targeted aquifer is 16.5℃ and the maximum ambient temperature is 34 ℃, scenario-4 with W47 (47℃ facility cooling water) does not need the involvement of RTES for data center cooling and was dropped from consideration based on there being no economic benefit.
4. The cooling needs from RTES change with direct heat recovery from the data center (i.e., 25% heat recovery throughout the year, or 50% heat recovery half of the year during the winter in scenario 3). Heat recovery to satisfy the campus heating needs reduces the RTES cooling needs, and consequently reduces the maximum injection rates and the number of doublets needed.

3.2 Crypto Mining Data Center at Houston, Texas

3.2.1 Site Selection and Description

The sediments of the Gulf Coast aquifer in Texas were deposited under a fluvial-deltaic to shallow-marine environments during the Miocene to the Pleistocene. Although stratigraphic classification of the Gulf Coast aquifer in Texas is controversial, Baker's (1978) classification has received widespread acceptance, which classified the Gulf Coast aquifer into five hydrostratigraphic units: (1) the Catahoula Confining System, (2) the Jasper aquifer, (3) the Burkeville Confining System, (4) the Evangeline aquifer, and (5) the Chicot aquifer, from the oldest to the youngest. Figure 3-10 shows the cross-section stratigraphy underlying the Houston Area (Chowdhury and Turco, 2006; Campbell et al., 2018).

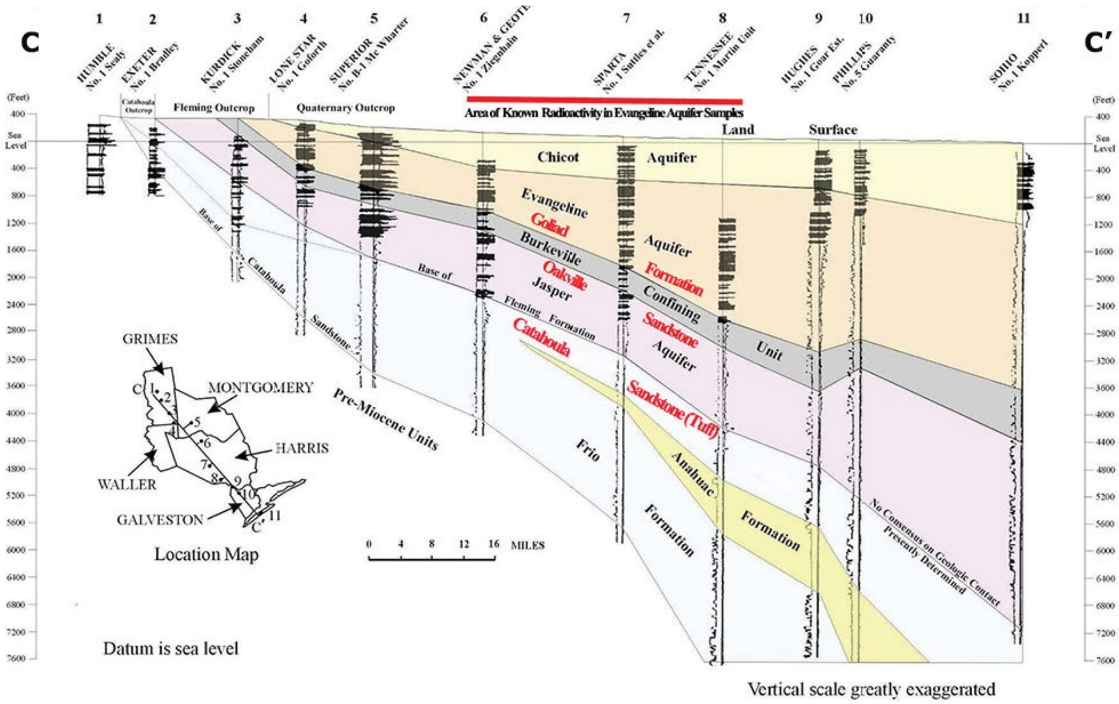


Figure 3-10. Cross-section of the stratigraphy underlying the Houston area.

Figure credit: Chowdhury and Turco (2006); Campbell et al. (2018).

In this project, the Oakville sandstone is used to investigate RTES potential for data center cooling due to the following reasons:

1. The Evangeline and Chicot aquifers currently provide 14 percent of the City's water supply (Houston Public Works, 2023). To avoid thermal alteration of chemical species and potential permitting issues, these two aquifers are excluded as energy storage reservoirs.

2. The Burkeville Confining System is predominantly composed of silt and clay beds. The hydraulic properties are not suitable as a storage reservoir.

3. The Oakville sandstone/Jasper aquifer is considered a good candidate as a storage unit. Chowdhury and Mace (2007) provided the range of the hydraulic conductivity of the aquifer to be 0.1 – 1.0 ft/d (3.5e-14 to 3.5e-13 m^2 in terms of permeability). This translates to a logarithm-averaged value of 0.5 ft/d (1.76e-13 m^2) (Nicot et al., 2010). In addition, the Jasper aquifer is not used as a drinking water aquifer due to the fact that total dissolved solids (TDS) in the Oakville are generally in the brackish range (>1,000 mg/L). The Burkeville Confining unit acts as a separating unit, preventing interaction between the Jasper aquifer and drinking water aquifers.

4. Theoretically, the Frio Formation can also be a potential candidate for thermal energy storage reservoirs. The Frio Formation has been considered as a potential CO_2 storage reservoir (Hovorka, 2005), which demonstrates it has reasonable permeability and porosity as a storage reservoir. Deeper reservoirs (i.e., depth greater than 800m) are

usually preferred for CO_2 storage so that CO_2 is stored in the form of supercritical CO_2 under reservoir conditions. However, contrary to CO_2 storage, RTES in deep reservoirs do not have advantages compared to shallow ones due to the much higher drilling costs for the wells, as well as higher pumping cost. If RTES is used for cold storage, higher native reservoir temperatures in deeper formation also makes it less desirable.

Based on the above reasoning, the Oakville sandstone reservoir is used to investigate the RTES potential for hyperscale data center cooling. The properties are summarized in Table 3-2.

An average reservoir porosity is used based on a porosity-depth function (Kelly et al., 2018). The thermal conductivity of the rock is estimated based on the average heat flow (about 55 mW/m^2) (Blackwell et al., 2011) in the area and its average geothermal gradient (21°C/km) (Forrest et al., 2005).

Table 3-2. Oakville storage reservoir properties for cooling data centers in Houston area

Depth (m)	Reservoir thickness (m)	Permeability (m^2)	Porosity (%)	Thermal conductivity (W/m·K)	Initial reservoir temperature (°C)
800	~ 200	1.8e-13	23	2.6	37

3.2.2 Reservoir Model Description

The EOS 1 module of iTOUGH2 (Finsterle, 2004) is used to model the storage reservoirs both in Texas and Virginia. The TOUGH family code is a suite of numerical simulators for non-isothermal flows of multicomponent, multiphase fluids in multi-dimensional porous and fractured media (LBL, 2024a). The Equation of State module (EOS) – EOS1 was specifically developed for geothermal applications, and it has been widely applied in both geothermal energy and subsurface energy storage industries. iTOUGH2 is a computer program that provides inverse modeling capabilities for the TOUGH codes. It is used in this project due to some enhancements (LBL, 2024b) to incorporate time-varying injection temperatures and rates (see details later in the section).

As mentioned earlier, an RTES system contains one or more doublets. The operation of the RTES will induce pressure change, which should be less than the maximum pressure a formation can withstand without incurring geo-mechanical damage. If the storage reservoir is managed with a balanced mass (the total amount of injected liquid is about the same as withdrawn liquid) over the long term, ground deformation should not be a concern. Therefore, the number of doublets is determined by the minimum number that can satisfy the maximum flow rate needed for data center cooling while assuring the maximum pressure increase is below the fracturing pressure. Without going into detailed geo-mechanical modeling, the maximum pressure increase allowed to avoid fracturing is about 4.6MPa at 800 m depth in the Gulf Coast region (calculation is based on Figure 2.5.19, fracture gradient vs. depth at Gulf Coast, Lyons et al., 2016).

The system is dominated by horizontal flow for two reasons: the wells are in pairs (one injector and one producer), and the vertical hydraulic conductivity in an aquifer is primarily controlled by low-permeability lenses. As a result, a one-vertical layer, 2D model only containing the storage reservoir is sufficient without site specific information. Heat exchange between the storage formation and upper/lower geological formations can be modeled using a semi-analytical heat solution (Pruess et. al., 2003).

Due to the assumed size of the data center (30MW), it is estimated that a large number of doublets (~ 9) is needed. For simplicity, these doublets are assumed to be aligned along one (horizontal) direction as shown in Figure 3-11. In addition, at this stage of the analysis without incorporating system optimization based on detailed geological information, the spacing between the cold wells is assumed to be 100 m and the distance between hot and cold wells is 200 m. The hot/cold wells should be spaced to avoid thermal interference. The choice of the spacing is not only affected by the longest injection/withdrawal duration and the injection rate, but also the distance among doublets. Although the flow is locally radial around the wells, the behavior of the flow between the cold/hot wells is linear on a large scale. Figure 3-11 shows the model domain. Due to symmetry, only one doublet is modelled. In this case, the heat (cold) loss at the 1st and 9th doublets to the sides is ignored. As shown in Figure 3-11, a finer mesh is used to capture thermal change in the reservoir, while bigger elements are used on the side for pressure propagation.

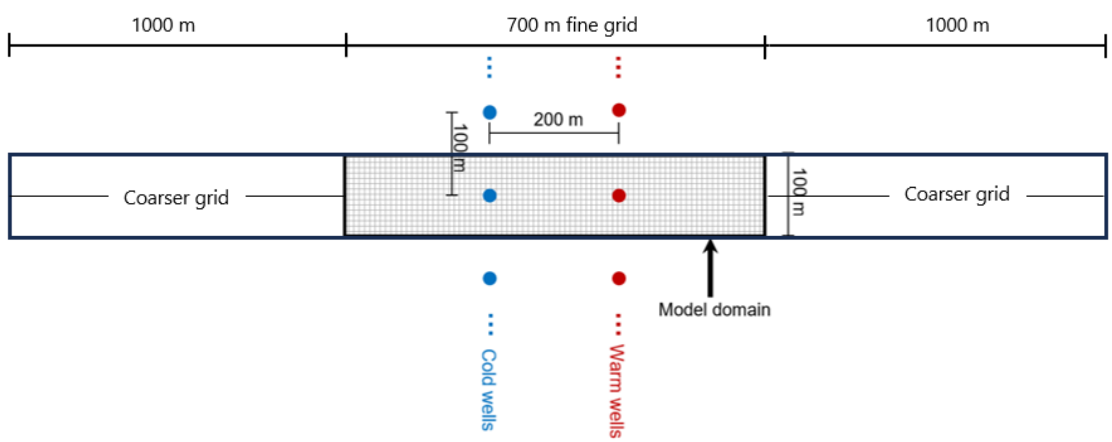


Figure 3-11. Model setup for the RTES considered in Texas.

3.2.3 Simulation Scenarios

Figure 3-12 shows the typical meteorological temperature (hourly) in Houston over a calendar year (Vignola et al, 2013). It is used as the weather condition for the crypto-mining data center scenarios. Four crypto-mining data center scenarios outlined in Section 2 involve RTES cooling: scenarios 2, 3, 4 and 5. The difference between Scenarios 2 and 3 is in the details of if fan wall or liquid cooling is used inside the data centers, i.e. there is no difference in terms of RTES operation (simulation. Therefore, only Scenario 3 (or 2), 4 and 5 are considered here, as shown in Figure 3-13.

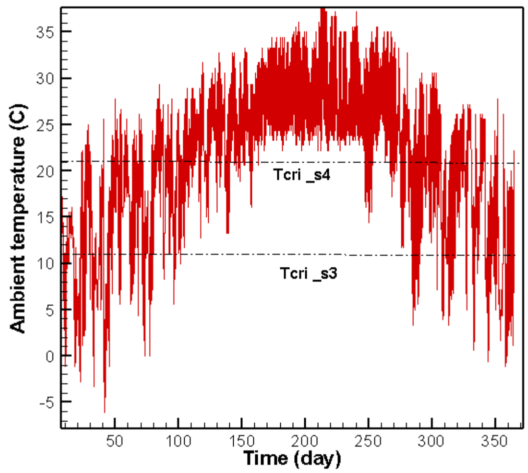


Figure 3-12. Typical meteorological temperature in the Houston area (EnergyPlus b). Two lines marked as T_{cri}_s3 and T_{cri}_s4 are the critical temperatures above which RTES will be used for cooling in scenarios 3 and 4.

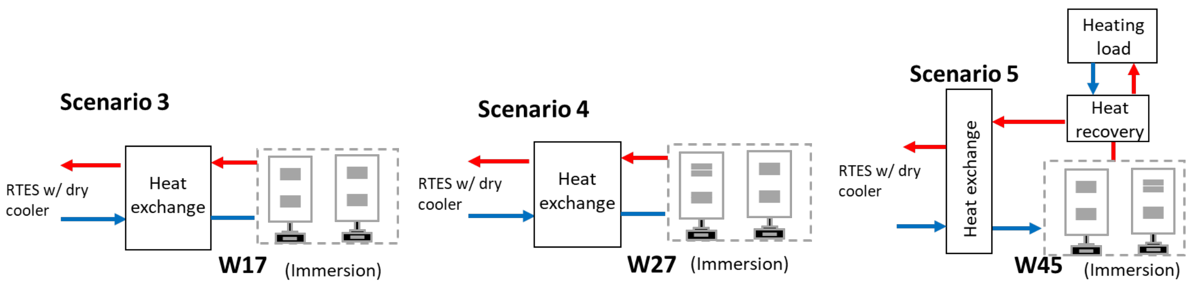


Figure 3-13. Data center cooling scenarios that involve RTES.

A brief description of the three scenarios follows:

- Scenario 3

The data center cooling temperature for scenario 3 is W17 (17°C). For a dry cooler to provide 100% of the cooling needed, the ambient temperature (T_{air}) has to be 6°C lower than the designed facility inlet liquid temperature. This means that RTES is needed whenever T_{air} >11°C (indicated by dotted line marked as T_{cri} _s3), which is about 85% of the year. In this case, the RTES can only be recharged (cooled) for about 15% of the year if no other cooling methods are involved. This will result in additional wells for recharge purposes, which makes the scenario unattractive. Therefore, it was not pursued further.

- Scenario 4

The data center cooling temperature of scenario 4 is W27 (27°C), indicating T_{cri}=21°C (T_{cri} _s4). In this case, the RTES can be recharged 45% of the time, and the dry cooler can provide partial cooling most of the remaining time of the year. As a result, the number of doublets is determined by the maximum flow rate satisfying the data center cooling need, instead of the maximum flow rate to recharge the reservoir for maintaining a sustainable storage reservoir. The hourly cooling capacity of dry coolers is calculated based on ambient temperatures (details see Section 2), from which hourly flow rates from the cold well of the RTES can be determined (based on ambient temperatures). In this case, based on the fracture pressure discussed earlier, nine doublets are needed to satisfy annual data center cooling.

- Scenario 5

For scenario 5, with WT=45°C, the resulting T_{cri}=39°C. With ambient temperatures below 39°C, the dry coolers alone would be sufficient for data center cooling. No RTES is needed unless heat recovery becomes the objective in this scenario. As heat recovery is not the main interest for using RTES for crypto-mining data center cooling, this scenario will not be considered further (both here and in the TEA section).

Based on the above discussion, the RTES simulations are done for Scenario 4.

3.2.4 Simulation Results

- Pre-cooling period

The initial reservoir temperature is about 37°C. The cold well temperature needs to be lowered to 24°C or below for it to be used for data center cooling with WT=27°C (i.e., with a ~3°C approach temperature through the heat exchanger). Pre-cooling of the reservoir is needed. There are options for reservoir pre-cooling. In this case, it is assumed that it will be done through withdrawing warm (37°C) liquid from the hot well, cooling it down using the dry cooler, and re-injecting it into the cold well when the ambient temperature allows. As discussed in Section 2.5 this is assumed when ambient temperature is less than 21°C to charge the RTES with injected water at 24 °C or less during the normal operation period. During the pre-cooling period, one could choose a higher temperature limit to take advantage of partial cooling and potential mixing with lower temperature liquid in the reservoir. Here, the reinjection temperature is capped at 28°C. Figure 3-14 shows the temperature at the cold well during the 2-year pre-cooling period. The low temperature in the initial period indicates it is within the wintertime (January 1st is day 1). Notice when the well is at 28°C, it is either because 28°C water is injected at the time, or the well is shut-in due to the high ambient temperature.

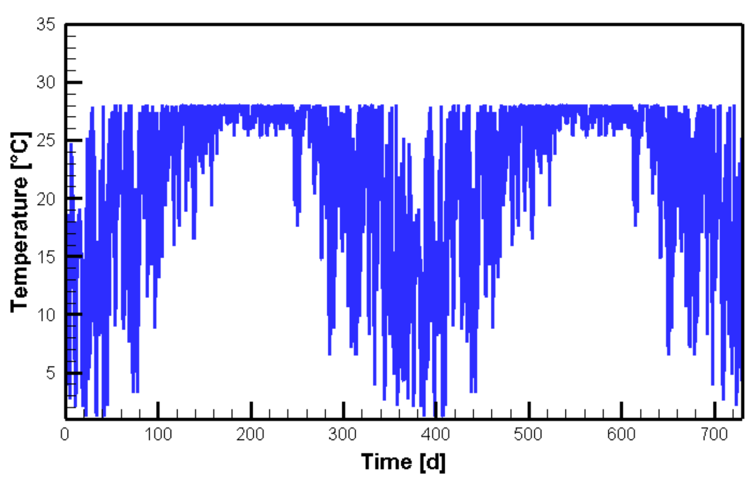


Figure 3-14. Temperature at the cold well during the pre-cooling period.

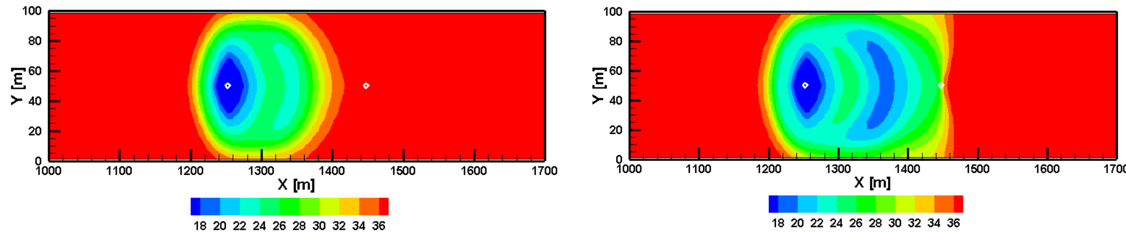


Figure 3-15. Temperature distribution at the end of 1 year (left) and 2 years (right). The white dots indicate well locations, cold well to the left and hot well to the right.

Figure 3-15 shows the temperature distribution after 1 and 2 years, respectively. The distribution of temperatures clearly shows the injected temperature patterns. The non-monotonic temperature plume between the two wells is caused by the change in the injected temperature, which following a seasonal change. It also shows there is no temperature breakthrough from the cold well to the hot well at the end of the first year, but the cold liquid front gets to the hot well at the end of the second year. If this becomes a concern for a specific site, one could reduce the second year's pre-cooling, or make the cold and hot wells further away (or larger distance among the doublets). However, the hot well getting cold is not a concern here as the goal for this scenario is to store cold only without heat recovery. When RTES is in operation, the cycle is every year, and the injection rate will be less, so hot water will not arrive to the cold well within a yearly cycle.

- RTES operational period

As discussed in Section 2, the hourly percentage of dry cooler capacity (PDC) can be calculated based on the data center cooling approach temperature, the ambient temperature, and the exit temperature T_{exit} from the data center at that time. If all nine doublets are in operation and all data center cooling needs are provided by RTES, the flow rate per doublet Q can be calculated as 717 kg/s divided by 9, i.e., Q=Qmax=80 kg/s. When PDC is less than 100%, the rest of the cooling (1-PDC) is provided by RTES, i.e., Q=Qmax*(1-PDC). When PDC>100%, excess dry cooler capacity is used to cool liquid withdrawn from the hot well, which is then re-injected into the reservoir through cold well. The reinjection temperature is controlled to be 22°C when the ambient temperature allows, and the reinjection flow rate is calculated based on the excess dry cooler capacity. The reason to keep the injected temperature a little lower than required (24°C) is that the liquid temperature could change with the pressure change due to the Joule Tompson effect. When pressure lowers and liquid temperature could go up a little but still maintains at or below 24°C. The lower than 22°C temperature happens when PDC exceeds 200%, instead of allowing flow rate exceeding the maximum flow rate, the injected water temperature is lowered for fully taking advantage of the dry coolers capacity.

Figure 3-16 show the pressures and temperatures for the 20 years of operation, with the first year enlarged. The maximum pressure (12MPa) is about 0.6MPa less than the allowed maximum pressure (12.6MPa), indicating that if one doublet is out of service, the flow rate needed from that doublet can be made up from others without creating formation damage. The cold well temperature mostly fluctuates between 22°C and 24°C but could occasionally go as low as 20°C in winter.

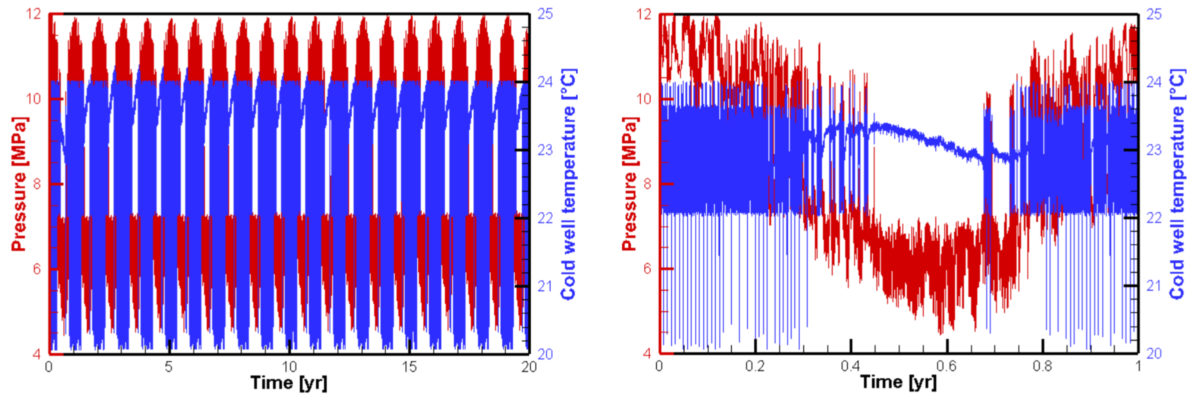
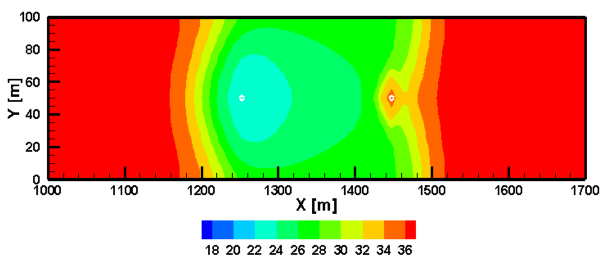
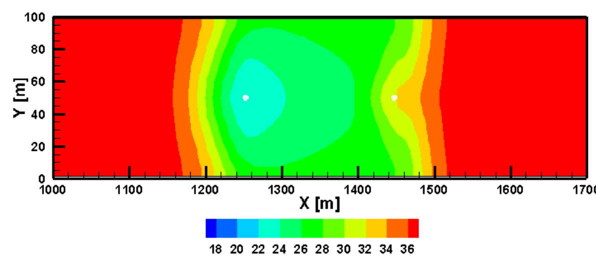


Figure 3-16. Pressures and temperatures at the cold well for 20 years (left) and an enlarged view for the first year (right) of RTES operation.

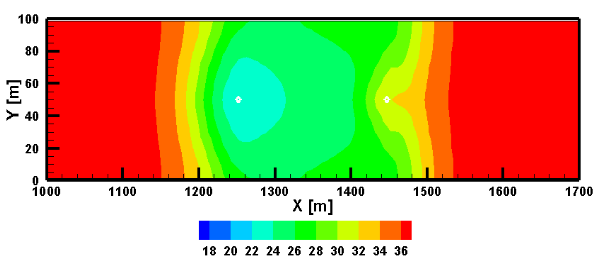
Figure 3-17 shows the temperature distributions at a few points in time. The distribution in summer shows clearly the warm plume from the hot well injection. The injection temperature at the hot well is 34°C (24°C plus 10°C), still lower than initial reservoir temperature of 37°C. In general, the reservoir temperature is getting a little colder over time, which can be observed based on the temperature plumes at the end of 10 and 20 years. The change from 10 years to 20 years is not significant, indicating the reservoir can sustain much longer than 20 years under the simulated conditions).



(a) 9.5 years (summer)



(b) the end of 10 years (winter)



(c) the end of 20 years (winter)

Figure 3-17. Temperature distributions at a few times.

3.2.5 Conclusion and Discussion

The conclusions based on the above simulations include:

1. The analyses and simulations performed show that using RTES and dry coolers (waterless and non-compressor-based cooling) for cooling a 30 MW crypto mining data center operated at 27°C facility cooling water (W27) with a climate similar to Texas is technically feasible under the modeled conditions. For the formation properties used, nine doublets are needed for meeting the 30MW cooling need.
2. In Texas, it is more feasible to use RTES for cooling W27 data centers than W17 data centers when using only dry coolers for RTES recharge because of the relatively warm climate and the relatively high reservoir temperatures. The conclusion would be different for a different climate and/or initial storage reservoir temperature. Crypto miners using immersion cooling in Texas already use dry coolers and no compressor-based cooling. The advantage to them of RTES is lower and more constant cooling water temperatures. This allows them to increase the clock speed even more than just going to immersion cooling, and for more hours per year (higher productivity).
3. With high reservoir temperatures, pre-cooling is needed to cool down the reservoir for its initial usage. For the current system design (only dry coolers are engaged without other cooling methods), a 2-year cold water precooling is needed (only happens when the ambient temperature allows).
4. Taking advantage of the dry coolers partial cooling capacity when $T_{cri} < T_{air} < T_{exit}$ can reduce the cooling need from the RTES, and therefore, the total flow needed from RTES.
5. Over the 20-year operation period, the maximum pressure increase is less than the fracture pressure. With the current system design, it is possible for one doublet to be taken out of service for maintenance, while the flow rate needed from that doublet can be made up from others without creating formation damage.
6. Although the input from the model is based on the average property of the Oakville sandstones/Jasper aquifer and climate conditions in Houston, Texas, the optimum design of a system (number of doublets, well distance etc.) at a specific site needs to be made based on site-specific conditions, supported by uncertainty analysis.

There are a lot of uncertainties for the designed system. A number of modeling decisions are made for this generic model. The potential impact is discussed below:

1. Model domain: in this study, a simplification is made for the generic model that the layout of the nine doublets is structured. In the current design the nine doublets are aligned. Other potential designs (e.g., five-spot design) will be considered in the future. Due to symmetry, only one doublet needs to be modeled. The distance between pairs is chosen so that the total footprint is not too big, but big enough so storage volume can be guaranteed. In reality, this choice, which will depend on the geological features of a site, and other site-specific properties, could have some impact on formation pressure

change and thermal plume distribution. A smaller distance among doublets will result in a smaller thermal plume, smaller thermal loss to formation, and less piping, but a potential larger pressure increase. The optimal locations of doublets should be determined using a site-specific model, which may have an impact on the number of doublets, and therefore, the economics. However, this simple model with the current typical design is considered sufficient at this stage. The potential impact on the number of doublets will be considered in the techno-economic analysis in Section 4.

2. Spacing between the cold and hot wells within a doublet: the optimum distance between the two wells within a doublet is based on avoiding thermal breakthrough from the hot well to the cold well within a charge-recharge cycle (in this case, one year), but being as short as possible to reduce the pressure change due to well operations.

3. Other uncertain properties include formation thickness, hydraulic properties (permeability, porosity), formation heterogeneity, and formation thermal properties (thermal diffusivity, initial temperature). These will have different degrees of impact on the system design and should be included when site-specific information becomes available.

Without site-specific information, a detailed sensitivity/uncertainly analysis for specific variables was not performed. Instead, the effects will be combined into the potential required number of doublets. A sensitivity analysis with a different number of doublets will be performed in the techno-economic analysis. However, once a site is selected, optimization (under uncertainty) should be performed to minimize the number and cost of the doublets.

3.3 Hyperscale Data Center in Virginia/Maryland Area

3.3.1 Site Description and Selection

The Potomac Formation/Group is a Cretaceous sandstone that is present in the Mid-Atlantic Coastal Plain from New Jersey to North Carolina. It consists of interbedded fluvial sediments with coarse and fine-grained intervals. The coarse-grained intervals form a groundwater aquifer that is a primary source of groundwater in the Coastal Plain of Virginia (McFarland, 2013). Detailed mapping and hydraulic testing of this unit has been conducted by the USGS in collaboration with the Virginia Department of Environmental Quality to characterize this aquifer. Regional structures, such as the Salisbury embayment near the Virginia-Maryland border, the Norfolk arch in east-central Virginia, the Chesapeake Bay impact crater at the southern end of Chesapeake Bay, and the Albemarle embayment in northeastern North Carolina, impact the thickness and nature of the sediments. A single thick aquifer of coarse-grained sediments occurs in the Norfolk arch, and several smaller aquifer intervals, which can be divided into upper, middle, and lower units, that deepen and thicken to the east, occur in the Salisbury and Albemarle embayment to the north and south (Figure 3-18).

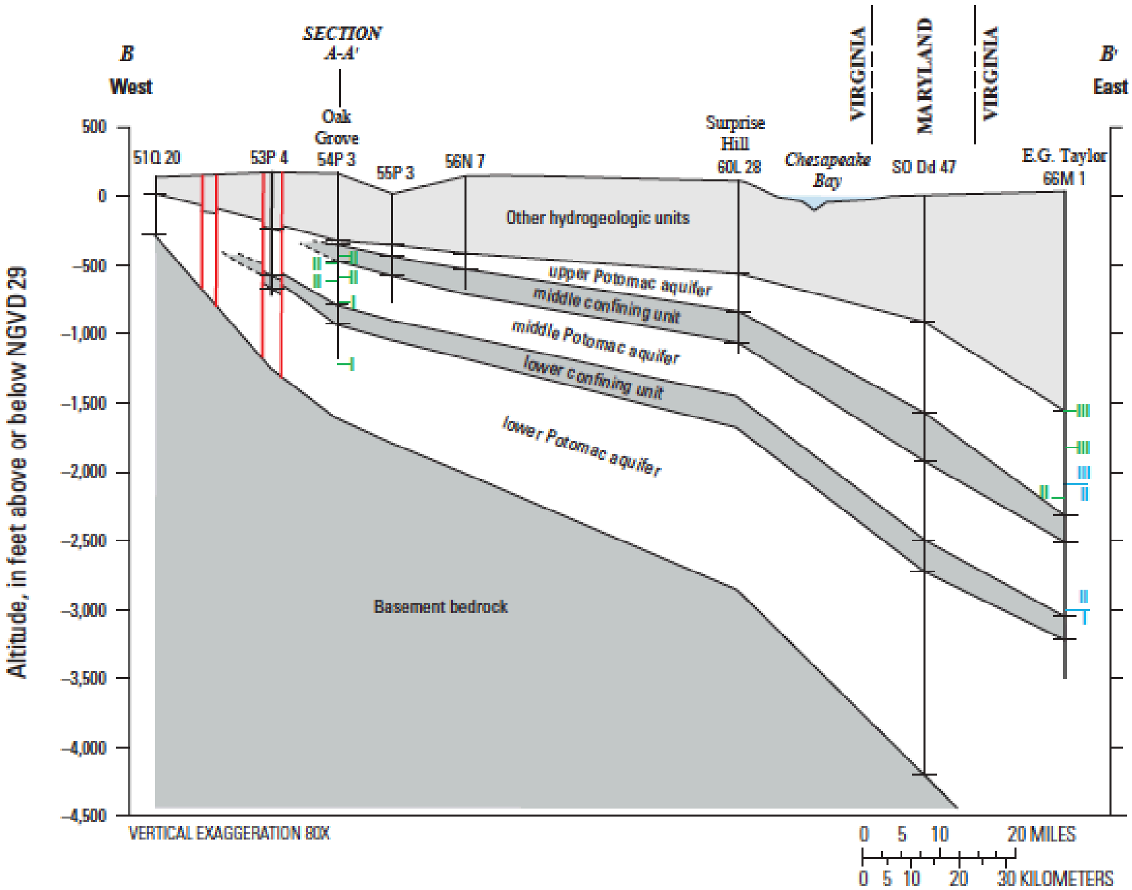


Figure 3-18. Hydrogeologic section of the Potomac Aquifer in northern Virginia in an E-W transect just south of the Potomac River within the Salisbury embayment.

Figure credit: McFarland, 2013

The aquifer is capped by a confining layer that is regionally extensive (Roth et al., 2012), and is underlain by a crystalline basement. Estimated transmissivity values obtained from aquifer tests in the Northern Neck area of northern Virginia range from >3,000 (3.2e-3m^2/s) to 6,000 (6.4e-3 m^2/s) and >6,000 to 10,000 ft^2/day (Figure 27 from McFarland, 2013). Corresponding hydraulic conductivity values for this region vary from >50-100 (1.8-3.5e-4 m/s) to >100-300 ft/day (3.5e-4-1.1e-3 m/s) (Figure 29 from McFarland, 2013). For the area of interest (northern Virginia near DC), two wells of interest that characterize the Potomac aquifer are 54P3 (Oak Grove) and 60L28 (Surprise Hill); McFarland (2013) summarized information on these wells. For the well pair 60L28 and 60L29 by Surprise Hill, differences in water level elevations were observed, resulting in a mean calculated vertical hydraulic gradient of -0.392 (a negative number indicates an upward gradient). The presence of fine-grained interbeds leads to small vertical hydraulic conductivities ranging from 0.0000019 to 0.000081 ft/day (Roth et al., 2012). Based on the cross section in Figure 3-18, 1, the lower Potomac aquifer at Oak Grove, VA would have a reservoir depth ranging from ~1000 to ~1800 feet (~300 to 550 m) and a thickness of ~800 ft (~250 m), and at Surprise Hill, VA (further to the east), it would have a reservoir depth ranging from ~1500 to ~3000 ft (~455 to ~ 914 m) and a reservoir thickness of ~1500 ft (~455 m).

Due to its capacity for storage, the deeper portions (>800 m) of the Potomac aquifer have been proposed as a potential target for CO_2 sequestration (Roth et al., 2012; Miller et al., 2017). Porosity values for the lower Potomac aquifer unit are on the order of 20% (Miller et al., 2017); these values will likely be higher for the shallower and less compacted upper and middle Potomac aquifers.

The properties of the lower Potomac aquifer are used to explore the RTES for cooling hyperscale data center in the area. The modelled depth of thickness of the formation is based on the above information, and maps of depth (GCCC, 2021a) and thickness (GCCC, 2021b) in the area. The value of permeability is estimated based on an estimated value from Smith (1999), and ranges provided by McFarland (attachment 2 from McFarland, 2013). The thermal properties are taken from Diment and Werre (1964). The initial reservoir temperature 18.7°C is estimated based on surface average temperature of 12.7°C (Figure 3-19) and a heat flow of 46.9 m·W/m^2 and vertical thermal conductivity of 3.3 W/m·K (Diment and Werre, 1964). The properties are summarized in Table 3-3.

Table 3-3. Storage reservoir properties for cooling hyperscale data centers in northern Virginia near DC.

Depth (m)	Reservoir thickness (m)	Permeability (m^2)	Porosity (%)	Thermal conductivity (horizontal) (W/m·K)	Initial reservoir temperature (°C)
425	~ 250	1.0e-12	20	3.7	18.7

3.3.2 Reservoir Model Description

As mentioned earlier, iTOUGH-EOS1 is used for reservoir modeling for this site. The total required flow rate has been provided as 1200 kg/s. The number of doublets is determined by the fracture pressure. Fracture pressure (P_f) can be calculated using equation 3.2 (Lyons, et al., 2016):

$$\frac{P_f}{d} = \left(\frac{\sigma_{ob}}{d} - \frac{P_p}{d}\right)\frac{\gamma}{1-\gamma} + \frac{P_p}{d} \tag{3.2}$$

Where, γ is Poisson's ratio; σ_{ob} is the overburden stress; P_p is pore pressure, estimated from hydrostatic pressure; and d is the depth.

The overburden stress gradient ($\frac{\sigma_{ob}}{d}$) is estimated using the overburden material weight (equation 3.3), assuming uniform vertical properties:

$$\sigma_{ob} = (1-\phi)\rho_r + \phi\rho_l \tag{3.3}$$

Where, ϕ is the porosity, ρ_r and ρ_l are densities of rock (assuming to be 2650 kg/m^3 for rock, and 1000 kg/m^3 for pore liquid).

Using a Poisson's ratio of 0.3, the maximum pressure increase allowed to avoid fracturing is about 2.7MPa at a depth of 425 m. Compared to the storage reservoir at Texas, the fracture pressure gradient ($\frac{P_f}{d}$) is higher in this case, but due to a shallower formation, the actual fracture pressure at the reservoir depth is lower.

The reservoir model used is similar to the one shown in Figure 3-11, except a larger flow rate per well is expected due to the higher formation transmissivity. Therefore, 200 m is used for the distance between the doublets (Y direction in Figure 3-11). Using this design, six doublets are needed to meet the data center cooling requirements and ensure that the maximum pressure increase is below the fracture pressure. This smaller number of wells compared to Texas is due to the higher permeability and larger reservoir thickness.

3.3.3 Simulation Scenarios

Figure 3-19 shows the typical hourly meteorological temperature in Virginia over a calendar year (Vignola et al, 2013). It is used as the weather condition for the hyperscale data center scenarios. Among the initially proposed cooling scenarios, three of them involve RTES (Figure 3-20):

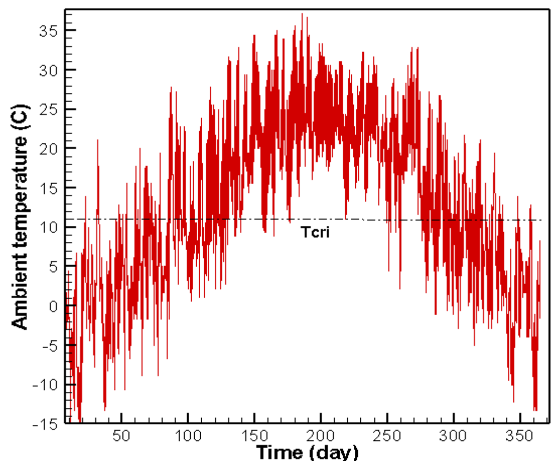


Figure 3-19. Typical meteorological temperature in the Virginia area Error! Bookmark not defined.. The line marked as T_{cri} indicates the critical temperatures above which RTES will be used for cooling in scenarios 2 and 3.

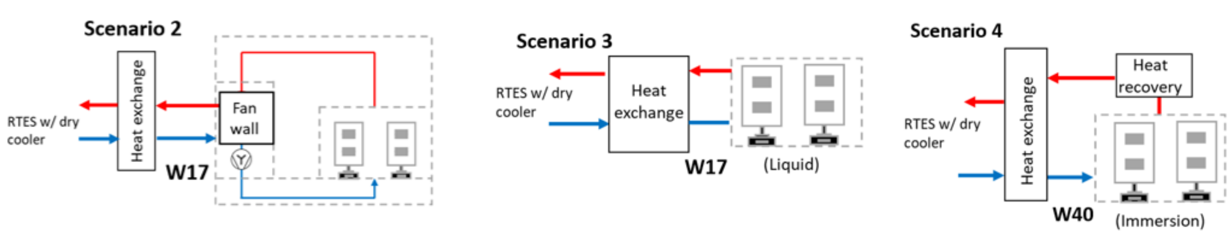


Figure 3-20. Data center cooling scenarios that involve RTES.

- Scenario 2 and 3

The difference between scenarios 2 and 3 lies in how the IT units are cooled within the data center. The liquid cooling in Scenario 3 will result in much lower data center operating temperatures than the air-cooled servers in Scenario 2. This will allow for higher density cooling and higher computer productivity (via overclocking). In terms of RTES temperatures and operations, these two are assumed to be identical. Therefore, they are considered together here but will be separated in TEA (Section 4). T_{cri} is about the median temperature on the annual temperature curve. The scenarios should be continued for the modelling effort.

- Scenario 4

The data center facility cooling temperature is W40 (40°C) in this scenario to allow for heat recovery. Similar to scenario 5 for crypto-mining data centers in Texas, RTES is not needed unless the heating load is more than 70 MW (highly unlikely), in which case the RTES could be used for storing low grade heat. Again, the focus is to evaluate cooling options and cold storage, while heat recovery is considered as a by-product. In this case, the need for RTES is nil and the scenario is unattractive. Therefore, it was not pursued further.

- Scenario involving air-cooled chillers

The potential to utilize chillers was considered and was discussed in Section 2. The method can make use of the RTES modeling results from Scenario2/3 and does not require additional reservoir modeling. The results and implications will be further discussed in Section 4.

3.3.4 Simulation Results

- Pre-cooling period

The initial reservoir temperature is about 18.7°C. The cold well temperature needs to be lowered to 14°C or below. The energy needed to lower the reservoir temperature to the required temperature per unit volume is much less compared to the Texas RTES (from 37°C to 24°C). The ambient temperature is also much lower compared to Texas weather. As a result, one cold season of pre-cooling is sufficient. The temperature at the cold well is shown in Figure 3-21. The ceiling of 14°C at the cold well indicates the injected fluid temperature is kept below or at 14°C.

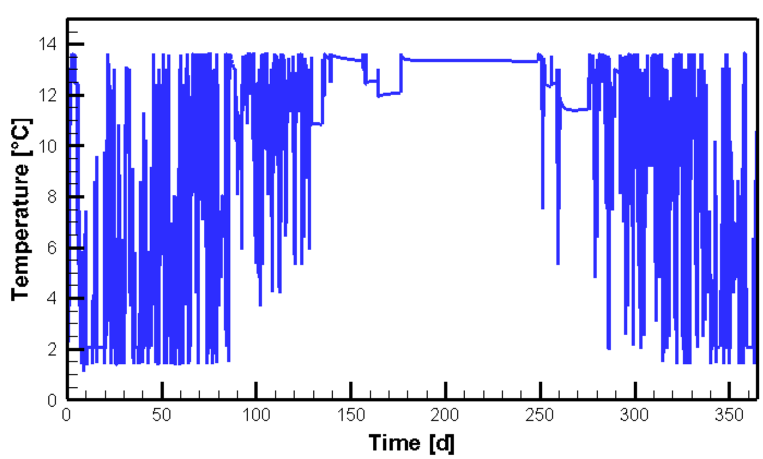


Figure 3-21. Cold well temperature for the hyperscale data center in Virginia/DC area.

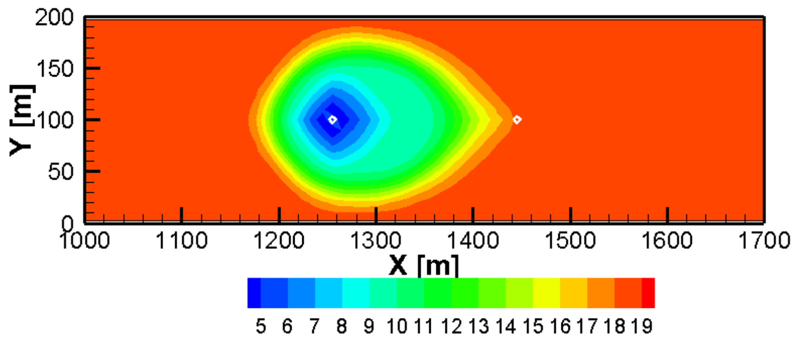


Figure 3-22. Temperature distribution at the end of 1 year pre-cooling period. The white dots indicate well locations, cold well to the left and hot well to the right.

Figure 3-22 shows the temperature distribution after a 1-year pre-cooling period. The temperature distribution clearly shows the injected temperature patterns. It also shows the cold temperature front arrived at the hot well at the end of the first year. Similar to the Texas scenario, the cold front arriving at the hot well is not a concern as the goal for this scenario is to store cold only without heat recovery. When the RTES is in operation, the actual injected/withdrawn fluid to keep the reservoir sustainable will be less due to the partial cooling provided by the dry cooler when the ambient temperature is between 11°C and 27°C. Thermal breakthrough will not be a concern over the life of the RTES operation, Figure 3-24 shows the thermal plume at the end of 10 and 20 years of reservoir operation.

- RTES operational period

As discussed in Section 2, the hourly percentage of dry cooler capacity (PDC) can be calculated based on the data center facility water temperature, the ambient air temperature, and the facility water exit temperature (T_{exit}) from the data center at any given time (Figures 2-10 and 2-11). If all six doublets are in operation and all data center cooling needs are met entirely by the RTES system, the flow rate per doublet Q can be calculated as 1673 kg/s divided by 6, i.e., Q=Qmax=279 kg/s. Notice this large rate is only possible because of the large formation transmissivity (a thick formation with a high permeability). At that point the PDC is 0%. When the PDC is less than 100%, the rest of the cooling (1-PDC) is provided by the RTES, i.e., Q=Qmax*(1-PDC). When the PDC>100%, the excess dry cooler capacity is used to cool liquid withdrawn from the hot well, which then is re-injected into the reservoir through cold well. The reinjection temperature is 13°C most of the time, and the reinjection flow rate is calculated based on the additional dry cooler capacity. The reason to keep the injected temperature a little lower than required (14°C) is that liquid temperature could change with pressure change due to the Joule Tompson effect. When the pressure decreases the liquid temperature could go up a little but still remain at or below 14°C.

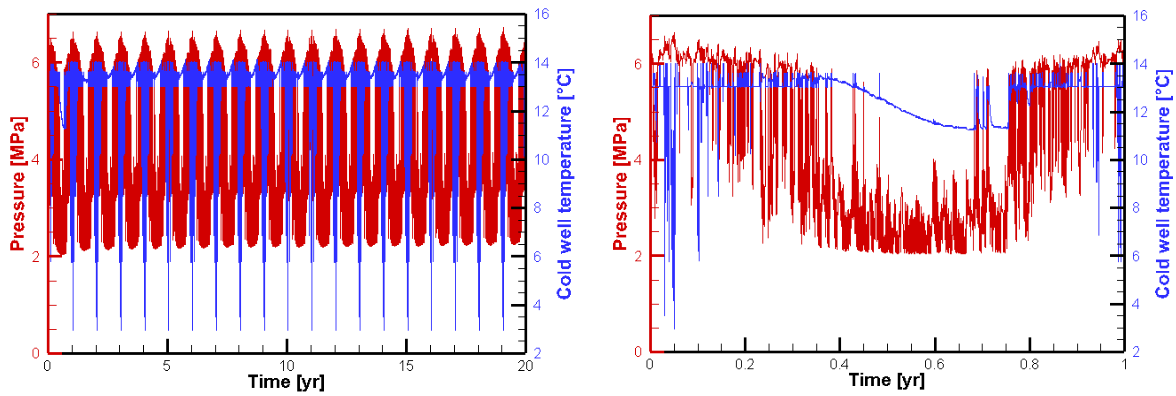


Figure 3-23. Pressures and temperatures at the cold well for 20 years (left) and an enlarged view for the first year (right) of RTES operation.

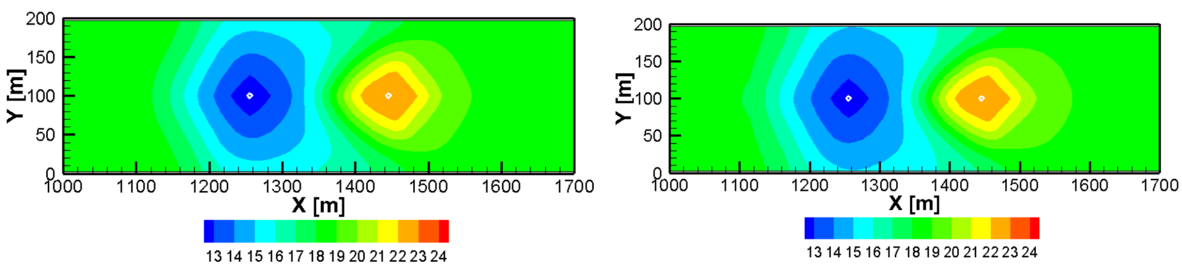


Figure 3-24. Temperature distributions at the end of 10 (left) and 20 (right) years.

Figure 3-23 shows the pressures and temperatures for the 20 years of operation, with the first year enlarged. The maximum pressure (6.5MPa) is about 0.5MPa less than the allowed maximum pressure (7MPa), indicating if one doublet is out of service, the flow rate needed from that doublet can be made up from others without creating formation damage. The temperature mostly fluctuates between 13°C and 14°C but could occasionally go as low as 3°C in winter.

Figure 3-24 shows the temperature distributions at the end of 10 and 20 years of system operation. The distribution shows the water temperature is slightly lower than 24°C at the hot well, which is the injection temperature after the cold well water has been heated by the warm water from the data center via the heat exchanger. The temperature is not exactly 24°C because of the elevated pressure at the injection well and the Joule-Tompson effect of water (Zhang, et al., 2018). There is not much change between the thermal plumes at the end of 10 and 20 years, indicating the reservoir can sustain much longer than 20 years under the simulated conditions. This is based on the assumption that the future annual temperatures are similar to what is used in the simulation, i.e., effects of change in climate and data center operation are not considered here.

3.3.5 Conclusion and Discussion

The conclusions from the reservoir model for investigating RTES for cooling hyperscale data centers include:

1. The analysis/simulations performed shows that using RTES for cooling a 70 MW hyperscale data center operated at 17°C in DC/Virginia area is technically feasible. RTES simulations only dry coolers as the primary method for cooling reservoir fluid.

It is possible that the air cooler chiller will bring additional benefits. This will be estimated in the TEA Section as the reservoir simulation will stay the same. For the geological formation explored, six wells are needed for meeting the 70MW cooling need. The small number of wells (compared to the Texas case) is due to the high permeability and large thickness of the lower Potomac aquifer.

2. Due to a much colder climate in Virginia/DC than in Texas, it is possible to use RTES for cooling W17 data centers. The reservoir considered in this case is 425 meters deep, with an initial reservoir temperature of about 18.7°C.
3. Pre-cooling is needed to cool down the reservoir for its initial usage. Based on the system design, a 1-year cold water recharge (only happens when the ambient temperature allows) is needed.
4. Taking advantage of the dry coolers partial cooling capacity when $T_{cri} < T_{air} < T_{exit}$ can reduce the cooling need from the RTES, and therefore, the total flow needed from the RTES. The advantage of using an air-cooled chiller will be discussed in the TEA.
5. The hydraulic properties of the formation used for the RTES modeling was taken from the properties of the lower Potomac aquifer documented in the literature. Over the 20-year operation period, the maximum pressure increase is less than the fracture pressure. With the current system design and formation properties used, it is possible for one doublet to be taken out of service for maintenance, while the flow rate needed from that doublet can be made up from others without creating formation damage. While the evaluation most likely needs to be adjusted based on site-specific information, the pressure increase may be approximated based on formation transmissivity (formation thickness times permeability) and the number of wells can be determined accordingly.
6. The thermal properties are from generic descriptions of the area. Again, site-specific conditions with uncertainty analysis are needed for evaluation of a specific project.

Most uncertainty in the analysis was discussed in the analysis for the crypto-mining data center, therefore, will not be repeated here. Although system optimization is out of scope in this study, for the hyperscale data center, we explored an alternative layout of doublets. A layout similar to Figure 3-11 with the same distance (100 m) among the doublets is investigated. Because of less space for pressure propagation, 8 doublets are needed and the distance between the cold well and hot well needs to be larger (for example, 250 m) to avoid thermal breakthroughs between the two wells. However, the total flow that needs to be withdrawn from the hot well, cooled, and reinjected back into the cold well to maintain a sustainable reservoir is less due to less energy loss. In general, this is a trade-off. If the doublets are closer, more doublets are needed to keep the maximum pressure less than the fracture pressure due to the potential pressure interference among the doublets. But the heat loss to the sides is reduced, and the flow needed from the hot well to the cold well is less. Again, this illustrates optimization that could be considered for a specific site. For this study, the effects from natural uncertainties and decision uncertainties are lumped together and considered in the potential number of wells required. In this case, a six well scenario is the base case for the TEA. Additional numbers of doublets are considered in the TEA sensitivity analysis.

3.4 RTES Evaluation Conclusions

Three models were built to investigate the technical performance of RTES for the three types of data centers (at three locations). While the models are built with assumptions and uncertainties, the analysis demonstrated the importance of finding the “right” type of storage reservoir: a thicker reservoir with high porosity for storage capacity, a good formation permeability to increase the injectivity and minimize the total number of wells, a shallower reservoir for an initial colder reservoir and reduced drilling cost (demonstrated in the next Section). The analysis is based on generic descriptions of the appropriate reservoir formation properties at the three locations. Some of the results can be scaled when information is different (e.g., pressure difference between the cold and hot wells can be scaled based on transmissivity for the same well layout). In-depth analysis using site-specific information and optimization should be applied to evaluate the performance of actual systems.

In the current study, only dry coolers are used to provide cooling for the reservoirs. Reservoir discharge and charge periods and rates are based on ambient temperatures. Future studies could consider adding chillers to take advantage of lower off-peak power prices, and potentially increase the charging periods and decrease the storage temperatures, yielding smaller RTES systems.

4. Techno-Economic Analysis

4.1 Introduction

The levelized cost of energy production (e.g., electricity, heating, cooling) is defined as a ratio of the system capital and operational costs to energy production over its lifetime. The levelized costs have been analyzed as an economic metric in the literature to compare the cost effectiveness of a system to those of different systems and production scenarios. In this section, levelized cost of cooling (LCOC) of the data center cooling systems connected to the RTES were evaluated and compared to the LCOC of base scenarios where the cooling demand is supplied by typical cooling systems without the RTES (e.g., chillers or dry coolers).

$$LCOC = \frac{C_{cap} + \sum_{t=1}^{LT} \frac{C_{O\&M,t}}{(1+d)^t}}{\sum_{t=1}^{LT} \frac{E_t}{(1+d)^t}} \tag{4.1}$$

where C_{cap} = total upfront capital investment, $C_{O\&M}$ = average annual O&M cost, d = real discount rate, LT = system lifetime, E = average annual cooling production. In this study, 5% discount rate and 20-year lifetime were assumed for the LCOC calculations.

4.2 System Components Considered in LCOC Estimations

Even though various data center cooling scenarios were initially proposed in Sections 2.2 to 2.4 with different heat rejection alternatives, plant alternatives, and data center room cooling alternatives including liquid cooling in the IT equipment, the techno-economic analysis mainly focuses on heat rejection alternatives. These alternatives include dry coolers, evaporative cooling towers, chillers, and RTES along with necessary components, such as pumps, to compare the LCOC of RTES-based cooling systems to the LCOC of non-RTES scenarios while simplifying the cooling alternatives within data centers (e.g., computer room air conditioning [CRAC], computer room air handlers [CRAH], and immersion cooling). The intent of these LCOC comparisons of RTES and non-RTES scenarios is to highlight the techno-economic benefits and disadvantages of RTES cooling systems.

Key components of the RTES-based data center cooling systems considered in capital (CAPEX) and operation and maintenance cost (O&M or OPEX) estimations were borehole drilling (i.e., RTES), circulating pumps, distribution piping, heat exchangers, and dry coolers. Non-RTES cooling systems included dry coolers, air-cooled chillers, and/or evaporative cooling towers (Figures 2-6 to Figure 2-9). Table 4-1 summarizes the system components and design parameters for the different scenarios in three different data center types. This study assumed that one pump system (multiple pumps, N+1) is needed to circulate the water in each of the RTES doublet wells and the data center circulating loop. Similarly, it was assumed that one heat exchanger system (multiple heat exchangers, N+1) is needed between the RTES and distribution piping due to the quality of water throughout the RTES (e.g., to avoid pipe scaling), while assuming the water circulated throughout the closed loops of the data center, dry cooler, and/or chiller has minimum scaling potential and no heat exchanger was assumed. The evaporative cooling tower in 5 MW and 70 MW non-RTES scenarios was designed with heat exchangers (and additional circulating pumps at the cooling tower side). The heat recovery scenario in the 5 MW data center was simplified with 100 m additional piping, assuming that 50% of the 5 MW thermal load can be recovered for direct-use heating applications in nearby buildings during winter (6 months). The number of system components, such as the circulating pump, in Table 4-1 and system schematics (Section 2) does not refer to one big component. The actual number of the components will vary depending on the specific designs for the desired capacity, such as 30 MW cooling load. It is also important to note that this study assumes all the components may not be operated continuously, and any of the components (N+1) can be isolated and serviced anytime when the system is not being operated at 100% capacity.

Table 4-1. Data center cooling system components and design parameters.

	70 MW Data Center			30 MW Data Center		5 MW Data Center		
	Cooling Tower	Chiller and Dry Cooler	RTES	Dry Cooler	RTES	Cooling Tower	RTES (No Heat Recovery)	RTES & Heat Recovery
Scenario in Section 2	Simplified Scenario 1	Modified Base	Simplified Scenario 2	Scenario 1	Scenario 4	Simplified Scenario 1	Simplified Scenario 2	Simplified Scenario 2
Supply Water	21 to 24 °C	17 °C	17 °C	40 °C	27 °C	21 to 24 °C		
Well Depth	N/A	N/A	425 m	N/A	800 m	N/A	275 m	275 m
[1]Number of Doublets	N/A	N/A	6	N/A	9	N/A	2	2
[2]Number of Circulating Pumps	2	1	7	1	10	2	3	3
[2]Number of Heat Exchangers	1	0	1	0	1	1	1	1
[3]Electricity Rate	Peak: ¢11.1/kWh Off-peak: ¢7.1/kWh			Peak: ¢10.8/kWh Off-peak: ¢6.8/kWh		Peak: ¢13.5/kWh Off-peak: ¢9.5/kWh		
[2]Number of Non-RTES Cooling System								
Dry Cooler Systems	N/A	1	1	1	1	N/A	1	1
Evaporative Cooling Tower	1	N/A	N/A	N/A	N/A	1	N/A	N/A
Air-Cooled Chiller	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A

[1]Note: Doublet system consists of injection and production wells (i.e., the number of wells = the number of doublets multiplied by 2).

[2]Note: The number of components implies the whole system at each location for the desired capacity and will be split into many modular subcomponents in an N+X configuration for specific designs (e.g., 20 dry coolers for 30 MW load instead of one big dry cooler).

[3]Note: Average electricity rates in VA (70 MW), TX (30 MW), and CO (5 MW) obtained from State Energy Profile Data in the U.S. Energy Information Administration for commercial sector were incorporated with +$0.2/kWh for peak rate and -$0.2/kWh for off-peak rate.

4.3 Useful Cooling Delivered

As summarized in Table 4-1, the RTES cooling systems in the three data centers consisted of the RTES and the dry cooler. During the RTES recharging periods, as described in Section 2 and 3 (e.g., Figure 2-5), the dry cooler can solely supply the 70 MW, 30 MW, or 5 MW data center cooling load, while also charging the RTES at the same time (Mode 3). During the RTES operation periods (Mode 1 or Mode 2), the RTES combined with the dry cooler (Mode 2) supplies the given data center cooling loads. It is only during certain hot periods (i.e., during the summer) that the dry cooler cannot be used for any cooling (i.e., Mode 1).

For the non-RTES scenarios, the 70 MW, 30 MW, and 5 MW data center cooling loads were supplied by evaporative cooling towers or a combination of dry coolers and chillers (70 MW data center), dry coolers (30 MW data center), and evaporative cooling towers (5 MW data center), respectively. In the cooling tower-based non-RTES scenario for the 70 MW data center, the cooling tower supplied 100% of the cooling load with 21 °C to 24 °C supply water temperature. For the 70 MW data center non-RTES cooling scenario with chillers (combined with dry coolers), the dry cooler had a higher priority than the chillers when applicable because of the comparative advantage of dry coolers (i.e., lower electricity consumption for operating mechanical fans in dry cooler versus higher electricity consumption for a refrigeration cycle in the chiller). Specifically, the dry cooler was operated when the ambient temperature was lower than 11 °C (W17 minus 6 °C air-to-water approach temperature) in Mode 3 for full 70 MW cooling load without the chiller operation, or the dry cooler partially supplied the cooling load with the chiller when the ambient temperature was between 11 °C and 27 °C in Mode 2. That is, chiller operations were minimized for optimal operational costs in the chiller-based non-RTES scenario for the 70 MW data center. For the 30 MW data center non-RTES cooling scenario, the dry cooler always supplied 100% of the cooling load with W40 by increasing flow rates when the ambient temperature ranged between 34 °C and 39.4 °C, which is the highest average ambient temperature in Houston, Texas. For the 5 MW data center, non-RTES scenario, the evaporative cooling tower supplied 100% of the cooling load with supply water of 21 °C to 24 °C temperature. The useful cooling delivered was calculated using Equation 4.2.

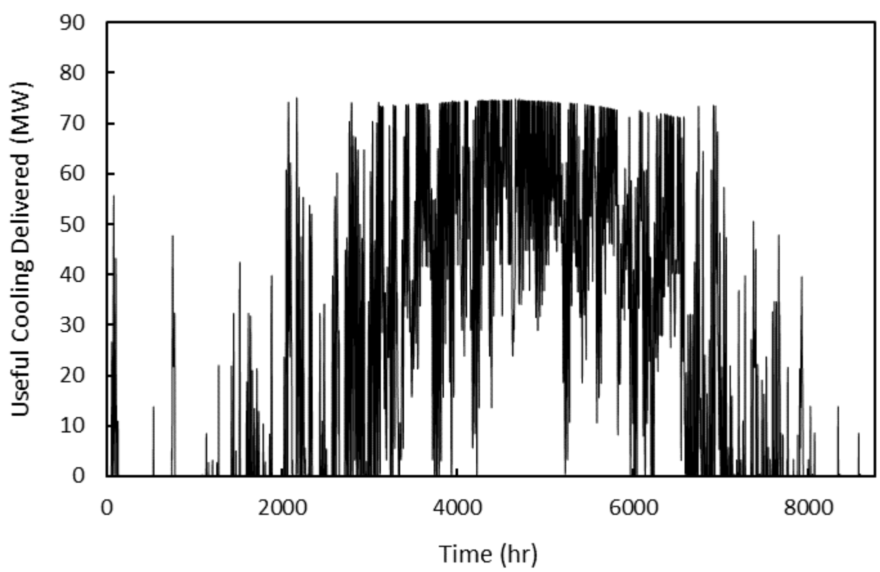
$$Q = m \times C_p \times \Delta T \tag{4.2}$$

where Q = useful cooling delivered (W), m = mass flow rate (kg/s), C_p= specific heat (J/kg·K), which was 4,184.4 J/kg·K for water and 1,005 J/kg·K for air, ΔT = difference in temperatures at injection and production wells (°C). The flow rates and temperature difference were obtained from the RTES modeling demonstrated in the previous "Reservoir Thermal Energy Storage Evaluation" section. Depending on the various flow rates and delta temperature, the RTES cooling production varied (Figure 4-1), and annual average cooling productions were used in the LCOC calculations (Table 4-2). This study assumed that there was no RTES cooling production in the RTES scenarios during the RTES pre-cooling periods–the first 2 years for the Texas 30 MW data center and the first year for the Virginia 70 MW data center–while operational costs for the RTES pre-cooling were included.

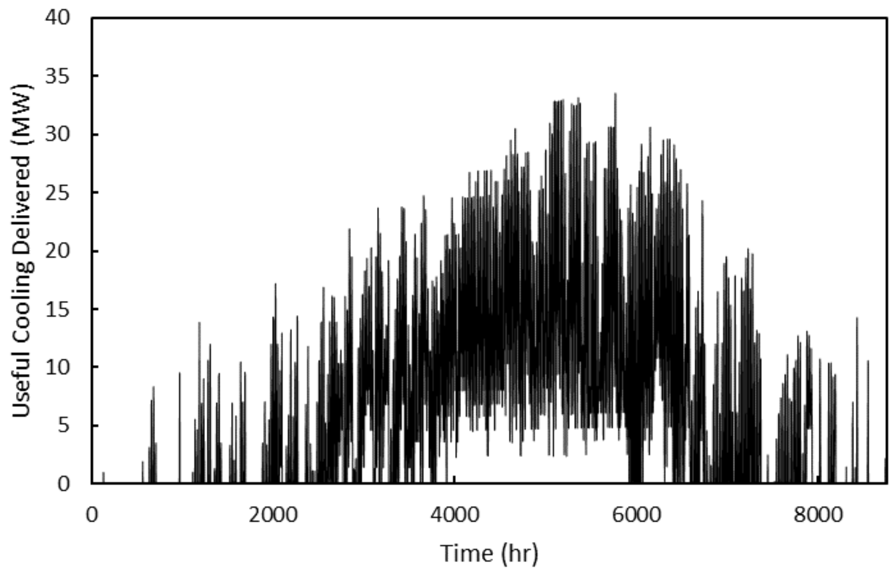
Table 4-2. Cooling productions of different cooling systems

Component	Annual Average Cooling Production (MW)							
	70 MW Data Center			30 MW Data Center		5 MW Data Center		
	Cooling Tower	Chiller & Dry Cooler	RTES	Non-RTES	RTES	Non-RTES	RTES	RTES & Heat Recovery
RTES	N/A	N/A	42.1	N/A	10.8	N/A	2	[1]1.7
Dry Cooler	N/A	30.5	27.9	30	19.2	N/A	3	3
Evaporative Cooling Tower	70	N/A	N/A	N/A	N/A	5	N/A	N/A
Air-Cooled Chiller	N/A	39.5	N/A	N/A	N/A	N/A	N/A	N/A

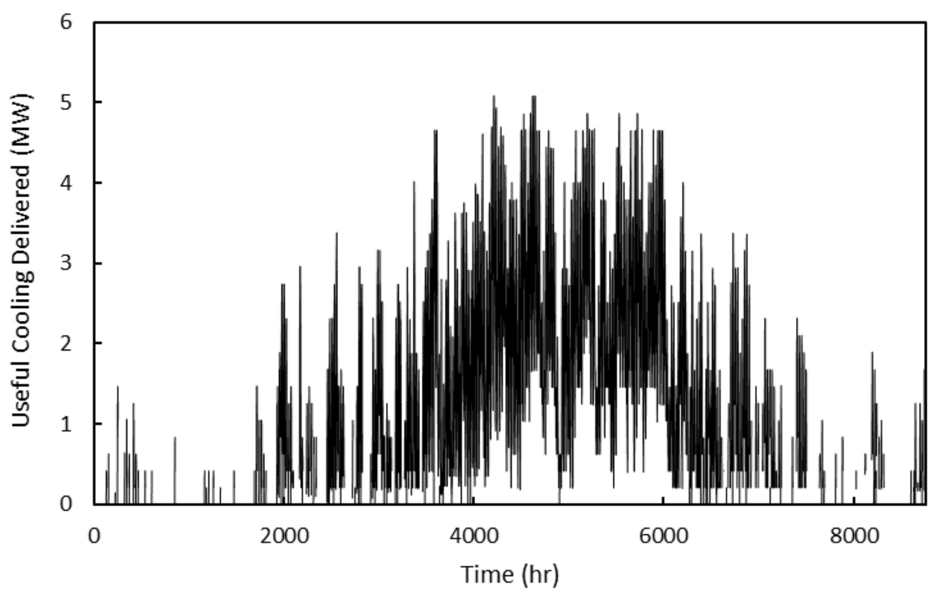
[1]Note: 0.3 MW was recovered during winter season (50% heat recovery during winter)



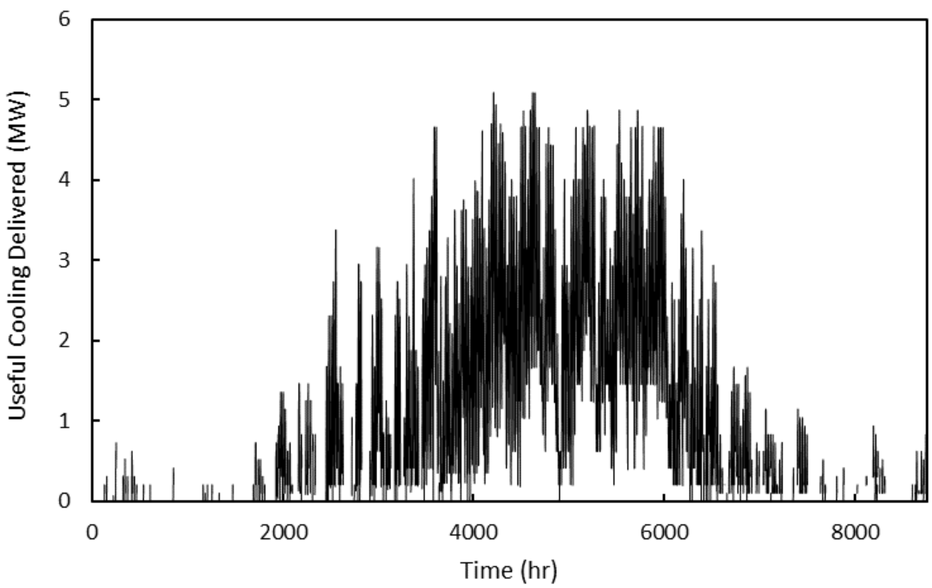
(a)


Useful Cooling Delivered (MW)
Time (hr)
0
5
10
15
20
25
30
35
40
0
2000
4000
6000
8000

(b)


Useful Cooling Delivered (MW)
Time (hr)
0
1
2
3
4
5
6
0
2000
4000
6000
8000

(c)



(d)

Figure 4-1. Useful cooling delivered from RTES to: (a) 70 MW hyperscale data center, (b) 30 MW crypto mining Texas data center, (c) 5 MW institutional data center, and (d) 5 MW institutional data center with 50% heat recovery during winter.

4.4 Capital and Operational Costs of Key Components

4.4.1 Drilling Cost

While the drilling cost for geothermal wells at a depth below 1 km has been extensively investigated in the literature (e.g., Lowry et al. 2017), there are limited resources on drilling costs for shallow wells which might be significantly different. In this study, the drilling cost was estimated using a cost of $300/m ($91.4/ft) in Virginia (70 MW data center) and $200/m ($61/ft) in Texas and Colorado, representing typical regional drilling cost in the shallow subsurface (e.g., depth less than 1 km). The drilling costs were obtained by interviewing and surveying regional drilling companies.

4.4.2 Distribution Pipe

As summarized in Table 4-3, lengths of distribution piping system in the data centers were assumed as 500 m (additional 100 m at the cooling tower side in 70 MW and 5 MW and additional 100 m at heat recovery side in 5 MW), and similarly those between the RTES field and data center were assumed as 500 m. In the RTES scenarios, connection pipes between RTES doublets for each of cold and hot wells were also considered with 200 m between doublets in 70 MW and 5 MW data centers and 100 m between doublets in 30 MW data center (find example in Figure 3-11). The pipe diameter was assumed as 106.7 cm (42 in.) for 70 MW data center, 76.2 cm (30 in.) for 30 MW data center, and 25.4 cm (10 in.) for 5 MW data center in terms of flow rates in the three data centers. HDPE piping The piping cost was estimated using the cost correlations ($/m) in Figure 4-

2, originally derived for piping including expansion loop at 300 ft intervals, a check valve and butterfly valve, one tee, pipe supports, and insulation (Mines 2016).

Table 4-3 Distribution pipe configurations and capital cost.

	70 MW			30 MW		5 MW		
	Cooling Tower	Chiller & Dry Cooler	RTES	Non-RTES	RTES	Cooling Tower	RTES	RTES & Heat Recovery
Diameter (cm)	106.7			76.2		25.4		
RTES Connection & Distribution Piping								
Length (m)	-	-	[1]2,500	-	[1]2,100	-	[1]900	[1]900
Cost	-	-	$9.4M	-	$5.2M	-	$0.94M	$0.94M
Piping in Data Centers								
Length (m)	600	500	500	500	500	600	500	600
[2]Cost	$1.6M	$1.4M	$1.4M	$0.98M	$0.98M	$0.45M	$0.38M	$0.45M
Total CAPEX	$1.6M	$1.4M	$10.8M	$0.98M	$6.2M	$0.45M	$1.31M	$1.39M

[1]Note: 70 MW: 500 m (between RTES and data center) + 200 m (between doublets) × 10 connecting pipes for each of cold and hot wells; 30 MW: 500 m (between RTES and data center) + 100 m (between doublets) × 16 connecting pipes for each of cold and hot wells; 5 MW: 500 m (between RTES and data center) + 200 m (between doublets) × 2 connecting pipes for each of cold and hot wells

[2]Note: Data center piping cost was estimated based on the estimate for the NREL data center piping costs (e.g., $750/m)

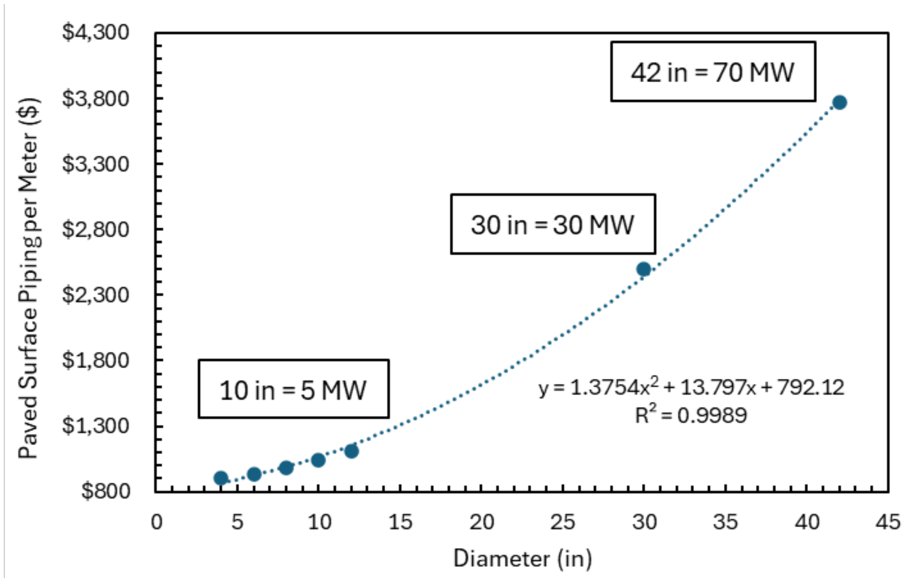


Figure 4-2. Cost estimation for paved surface HDPE piping: 70 MW = $3,775/m, 30 MW = $2,499/m, and 5 MW = $1,040/m

4.4.3 Circulating Pump Cost

CAPEX of the pump used to circulate water through a loop between the main cooling equipment (e.g., RTES, dry cooler) and data center was estimated with a cost of $1,000/pump power (kWe), which is a typical market price, while those of the pumps used to circulate water through RTES was estimated using an empirical cost correlation (Equation 4.3). As Equation 4.3 was originally derived for production pump and driver in a single geothermal production well (Mines 2016), the calculated CAPEX of the RTES pumps were multiplied by 2 to size for doublet systems. The pump replacement cost was also calculated using the first and third terms ($\$1750 \times (pump\ hp)^{0.7} \times PPI_{pump}$for the RTES circulating pump, while the same data center circulating pump cost was assumed for the replacement cost, assuming the pump and driver are replaced every 15 years.

$$CAPEX_{pump} = \$1750 \times (pump\ hp)^{0.7} + \$5750 \times (pump\ hp)^{0.2} \times PPI_{pump} \qquad (4.3)$$

$$Pump\ Power = flow\ rate/fluid\ density \times pressure\ drop \times pump\ efficiency \qquad (4.4)$$

where pump hp = pump power in horsepower unit, PPI_{pump}= producer price index to adjust cost to the year for which the estimation is being performed, which was 1.47. The pump power can be calculated using Equation 4.4. Flow rate and pressure drop used to calculate the power of a pump in the RTES systems were given from the RTES modeling results, and fluid density and pump efficiency were assumed as 997 kg/m3 and 80%, respectively. On the other hand, the pump power on the data center side was estimated using Equation 4.5 with the flow rates of 1,673 kg/s (70 MW data center), 717 kg/s (30 MW data center), and 120 kg/s (5 MW data center) and the pipe lengths and diameters summarized in Table 4-3. The Darcy friction factor used to calculate the frictional pressure drop was solved using Darcy-Weisbach equation.

$$\frac{\Delta P}{L} = f_D \times \frac{\rho}{2} \times \frac{v^2}{D_H} \quad (4.5)$$

where L = pipe length (m), f_D = Darcy friction factor, ρ = fluid density (kg/m^3), v = mean flow velocity (m/s), D_H = pipe hydraulic diameter (m). Then, pumping power was calculated using Equation 4.6 (Table 4-4).

$$Pump\ Power = \rho \times \frac{\rho}{2} \times \frac{v^2}{D_H} \quad (4.6)$$

The estimated pump power was also multiplied by the operation hours to convert the unit from kW to kWh and then incorporated with the two regional electricity rates summarized in Table 4-1 for peak and off-peak assumed as 7:00 to 19:00 and 19:00 to 7:00, respectively, to calculate the pump OPEX.

Table 4-4. Pump capital and operational costs.

	70 MW Hyperscale			30 MW Crypto		5 MW Institutional		
	Cooling Tower	Chiller & Dry Cooler	RTES	Non-RTES	RTES	Non-RTES	RTES	RTES & Heat Recovery
Power Consumption (GWh/yr)	0.22	0.18	41.5	0.08	18.9	0.14	0.6	0.43
CAPEX	$25k	$21k	$3.2M	$9k	$3.4M	$16k	$0.12M	$0.11M
Average OPEX	$20k	$17k	$3.7M	$7k	$1.8M	$16k	$69k	$49k

4.4.4 Heat Exchanger

A plate and frame heat exchanger were designed for the heat exchange 1) between the RTES and the data center facility circulating loop in RTES scenarios and 2) between the evaporative cooling towers and the facility circulating loop in non-RTES scenarios. As discussed earlier, this study assumes that water circulated through dry coolers can be circulated without heat exchangers in the data center facility circulating loop with minimum scaling potential. The heat exchanger costs were estimated using a cost correlation of $140/gpm, which is used in practices.

Table 4-5. Plate heat exchanger design parameters and costs.

	70 MW Data Center	30 MW Data Center	5 MW Data Center
Flow Rate (kg/s)	1,673	717	120
CAPEX	$3.7M	$1.6M	$0.27M

4.4.5 Dry Cooler

As summarized in Table 4-1, a dry cooler was designed for the chiller and dry cooler scenario in 70 MW, non-RTES dry cooler scenario in 30 MW, and any of the RTES scenarios in the three data centers. The dry coolers will supply data center cooling when the ambient temperature is within a range from the supply temperature (e.g., W40) plus 10 °C data center delta temperature to the supply temperature minus the air-to-water approach temperature of 6 °C in Mode 2 (partial operation), or the ambient temperature is lower than the supply temperature minus 6 °C air-to-water approach temperature in Mode 3 (full operation). In addition to the data center cooling, in RTES scenarios, the dry cooler supplies cooling to the RTES for pre-cooling and recharging. All of the 70 MW, 30 MW, or 5 MW data center cooling load is supplied by the dry cooler during the RTES recharging periods (e.g., winter season). The RTES modeling results were used to calculate the cooling required by the dry cooler for:

1. RTES pre-cooling = energy flow from hot well to cold well during the pre-cooling period (designed in terms of the regional ambient temperature and the initial subsurface reservoir temperature)
2. Data center during RTES cooling periods in Mode 2 = the given cooling loads of 70 MW, 30 MW, or 5 MW minus the RTES cooling supply
3. RTES recharging (winter season) in Mode 3 = energy flow from hot well to cold well during the recharging period

The dry cooler's electricity consumption for these cooling loads was estimated and used in CAPEX and OPEX calculations. As the first step, air flow rates through the dry cooler were estimated using Equation 4.2 to meet the desired cooling loads (i.e., the three cases listed above). This was done for each of the three data center cases (70 MW, 30 MW, and 5 MW). The air flow rates varied depending on the ambient air temperature. When supplying the data center cooling loads during the RTES recharging period in Mode 3, the air flow rates were constant to not over-produce cooling (the ambient temperature is low enough during winter), while the rest of available cooling capacity of the dry cooler was used to recharge the RTES. To partially supply data center cooling in Mode 2, the variable air flow rates were calculated using Equation 4.2 with the information on the ambient air temperature and desired cooling load where the RTES is not contributing. The dry cooler was sized in the CAPEX calculations to satisfy the peak demand during the winter season, combining the given data center cooling load (e.g., 30 MW) and RTES recharging load (e.g., 19.7 MW in 30 MW RTES), while the OPEX estimations were based on the average electricity consumption of the dry cooler. To estimate the electricity consumption, the estimated air flow rates were incorporated into an empirical correlation of 0.25 kW per kg/s of the air flow (Augustine 2009). The CAPEX was estimated using a cost correlation of $664.81/kW (Moser et al. 2014). In addition to the CAPEX calculations based on the fan power, similar to the plate and frame heat exchanger design, the dry cooler CAPEX was estimated using a cost correlation of $200/ton. The two regional electricity rates in Table 4-1 were incorporated with the average dry cooler power consumption kWh to estimate the dry cooler OPEX.

Table 4-6. Annual dry cooler electricity consumption and costs.

	70 MW Data Center		30 MW Data Center		5 MW Data Center	
	Chiller & Dry Cooler	RTES	Dry Cooler	RTES	RTES	RTES & Heat Recovery
Cooling for RTES Pre-Cooling (per year)						
Electricity Consumption (kWe)	N/A	1,746.2 (avg) 2,081.4 (peak)	N/A	860 (avg) 1,118 (peak)	N/A	N/A
[1]OPEX	N/A	$0.61M	N/A	$0.46M	N/A	N/A
Total Annual Dry Cooler Energy Consumption and Costs						
Peak Electrical Load (kWe)	2,902	3,708.8	1,332.6	1,330.2	214	214
Annual Electrical Load Total (GWh/yr)	16.3	14.2 (6.78 for pre-cooling)	2.98	6.6 (5.24 for pre-cooling)	0.96	0.98

[2]CAPEX	$1.9M	$2.47M	$0.89M	$0.88M	$0.14M	$0.14M
OPEX	$1.6M	$1.3M	$0.27M	$0.58M	$0.11M	$0.11M

1Note: Operational costs for pre-cooling in RTES scenarios are excluded here but included in the system LCOC calculations.

2Note: Capital costs were calculated with peak load in each scenario.

4.4.6 Evaporative Cooling Tower

An evaporative cooling tower was designed for the non-RTES scenarios in the 70 MW and 5 MW data centers. Actual monitored data was available from NREL's data center, and the cooling tower supplied 2.61 MW cooling load on average. The assumed design, including the cooling load, tower fan power, and pump power and flow rate, was proportioned for the 5 MW institutional and 70 MW hyperscale data center cooling loads (Table 4-7). The CAPEX was estimated using a cost correlation of $300/ton.

Table 4-7. Evaporative cooling tower electricity consumption and costs.

	NREL Data Center (Reference)	5 MW Institutional	70 MW Hyperscale
IT Load (MW)	2.61	5	70
Fan Power (kW)	16.25	31.2	436.6
CAPEX	N/A	$0.43M	$5.97M
Annual Average OPEX	N/A	$31k	$0.44M

4.4.7 Air-Cooled Chiller

An air-cooled chiller was designed for data center cooling in the non-RTES base case of the 70 MW data center when the ambient temperature is higher than 27 °C (Mode 1) or when the ambient temperature ranged between 27 °C and 11 °C (Mode 2) with the dry cooler. The capital cost was estimated using the peak electricity consumption and a cost correlation of $800/ton. Table 4-8 summarizes the electricity consumption and costs of the chiller in Mode 1 and Mode 2.

Table 4-8. Air-cooled chiller electricity consumption and costs.

	Mode 1 (Full Operation)	Mode 2 (Partial Operation)
Electricity Consumption (MWe)	27.1 (avg) 29.2 (peak)	12.5 (avg) 26 (peak)
CAPEX by Capacity	$15.9M	
OPEX	$1.69M (688 hrs/yr)	$4.75M (4,193 hrs/yr)

4.5 Levelized Cost of Cooling of Data Center Cooling Systems

Table 4-9 summarizes initial capital and annual operational costs of non-RTES and RTES cooling systems in the three data centers, as well as annual average power consumption (MWe). The initial capital costs (CAPEX) for both RTES-based and non-RTES-based cooling systems took a similar proportion in the system cost total, incorporating CAPEX and lifetime OPEX (calculated using annual OPEX and 5% discount rate).

The LCOC of the data center cooling systems was calculated using Equation 4.1 for a 20-year lifetime. For the 70 MW data center, the chiller-based scenario showed higher LCOC than the RTES scenario ($15.5/MWh vs. $11.9/MWh) mainly because of higher capital and operational costs of the chiller. Specifically, the CAPEX of the chiller took a significantly higher proportion of the total cost of the non-RTES system (12.5%) than the proportion of drilling cost in the total cost of the RTES system (1.6%). Furthermore, the annual operating cost of the chiller-based cooling system ($8.1 million) was higher than that of RTES-based cooling system ($5.2 million). Note that even though annual average power consumption in the chiller-based cooling system (MWe) was significantly higher than that consumed for any other components in any scenarios, the operational cost of the 70 MW non-RTES scenario was optimized with minimum chiller operation hours (MWh) as briefly discussed in Section 4.3. If the chiller-based cooling system incorporates a side economizer, which has been commonly incorporated with the chillers, the chiller-based scenario will provide the cooling more economically Nonetheless, it is important to note that the higher power consumption of the chiller implies that the lifetime operational cost and LCOC of non-RTES scenario in 70 MW data center can be significantly affected by the regional electricity rates anytime later.

In contrast, the LCOC of the RTES scenarios for the 30 MW and 5 MW data centers was higher than those of non-RTES scenarios due to the higher CAPEX and OPEX of the RTES systems. In particular, the higher number of RTES wells (18 wells) and relatively deeper depth (800 m) for the 30 MW data center resulted in high drilling and RTES pumping costs that were not needed in the non-RTES scenario, in addition to the higher capital cost for the heat exchanger and piping. Furthermore, there were additional costs for the 2-year RTES pre-cooling for the 30 MW data center and dry cooler operations for RTES recharging during winter seasons, which were not included in the non-RTES scenarios. However, the non-RTES scenario for the 30 MW crypto-mining data center in Texas has a much higher approach temperature, leading to less efficient operation. The trade-off between the loss of efficiency and cost is out of scope here but should be studied in addition to a comprehensive evaluation of environmental and social benefits of RTES-based cooling systems in the future (e.g., water savings).

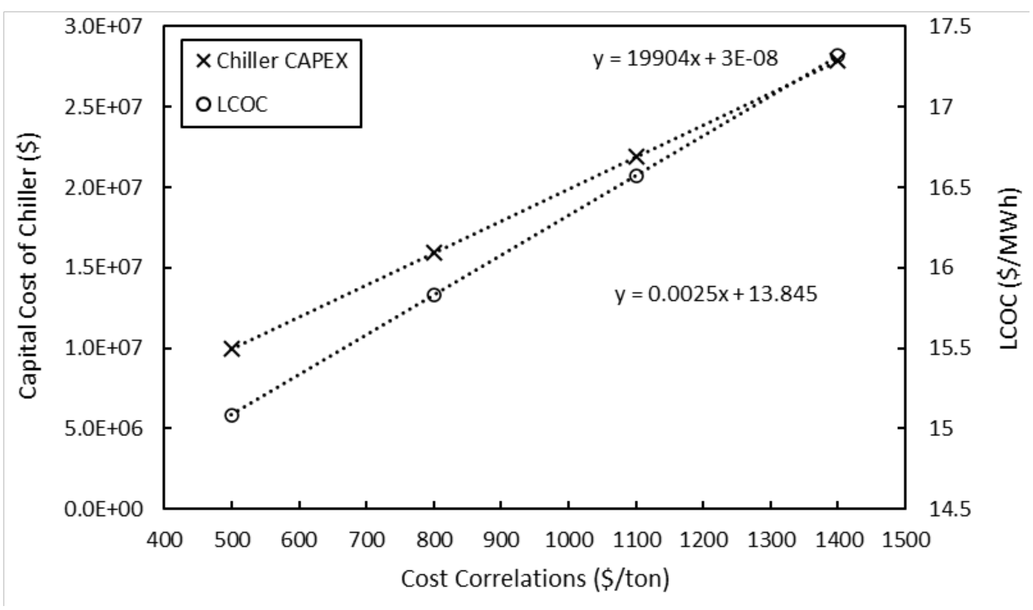
Table 4-9. Capital and operation costs of data center cooling system.

	70 MW Data Center			30 MW Data Center		5 MW Data Center		
	Cooling Tower	Chiller and Dry Cooler	RTES	Dry Cooler	RTES	Cooling Tower	RTES (No Heat Recovery)	RTES & Heat Recovery
Capital Cost								
Drilling	N/A	N/A	$1.5M	N/A	$2.9M	N/A	$0.22M	$0.22M
Piping	$1.6M	$1.4M	$10.8M	$0.98M	$6.2M	$0.45M	$1.31M	$1.39M
Circulating Pump	$25k	$21k	$3.2M	$9k	$1.7M	$16k	$0.12M	$0.11M
[1]Heat Exchanger	$3.7M	N/A	$3.7M	N/A	$0.87M	$0.27M	$0.27M	$0.27M
Dry Cooler	N/A	$1.93M	$2.47M	$0.89M	$0.88M	N/A	$0.14M	$0.14M
Air-Cooled Chiller	N/A	$15.9M	N/A	N/A	N/A	N/A	N/A	N/A
Cooling Tower	$5.97M	N/A	N/A	N/A	N/A	$0.43M	N/A	N/A
Total	$11.3M	$19.2M	$21.7M	$1.5M	$14.3M	$1.2M	$2.1M	$2.1M
Annual Operational Cost								
Circulating Pump	$20k	$17k	$3.7M	$7k	$1.7M	$16k	$91k	$71k
Dry Cooler	N/A	$1.6M	$1.3M	$0.27M	$0.58M	N/A	$0.11M	$0.11M
Air-Cooled Chiller	N/A	$6.4M	N/A	N/A	N/A	N/A	N/A	N/A
Evaporative Cooling Tower	$0.44M	N/A	N/A	N/A	N/A	$31k	N/A	N/A
Total	$0.46M	$8.1M	$5M	$0.28M	$2.3M	$47k	$0.2M	$0.18M
Levelized Cost of Cooling								
LCOC ($/MWh)	2.2	15.5	11.9	1.3	14.8	3.1	7.7	7.2

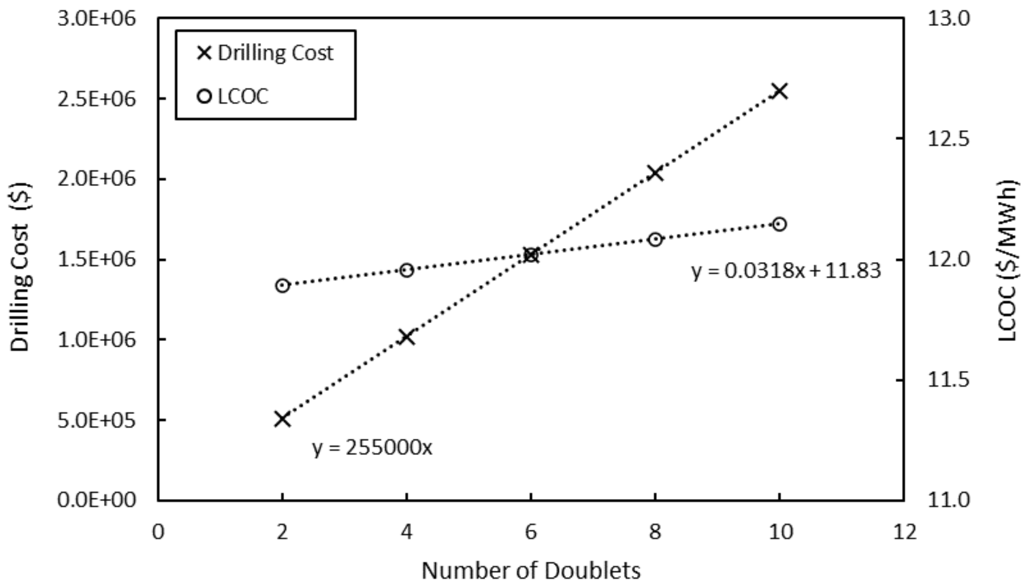
4.6 Sensitivity Analysis

As summarized in Table 4-9, the highest LCOC was estimated with the chiller-based cooling system in the 70 MW data center, and the RTES-based cooling systems showed relatively higher LCOC in the 30 MW and 5 MW data centers. However, the chiller cost (i.e., \$800/ton) for the non-RTES 70 MW data center can vary depending on the design details and the system size. Similarly, the number of RTES wells currently designed for all case studies may be insufficient or excessive relative to site-specific geological conditions. A sensitivity analysis was thus conducted to address the uncertainties of chiller costs and the number of wells. As presented in Figure 4-4(a), the CAPEX of the chiller ranged from \$9.95 million to \$28 million with cost correlations of \$500/ton to \$1,400/ton, and the corresponding LCOC ranged from \$15.1/MWh (with \$500/ton) to \$17.3/MWh (with \$1,400/ton). Similarly, the number of RTES wells affected the LCOC in terms of both drilling and RTES pumping costs:

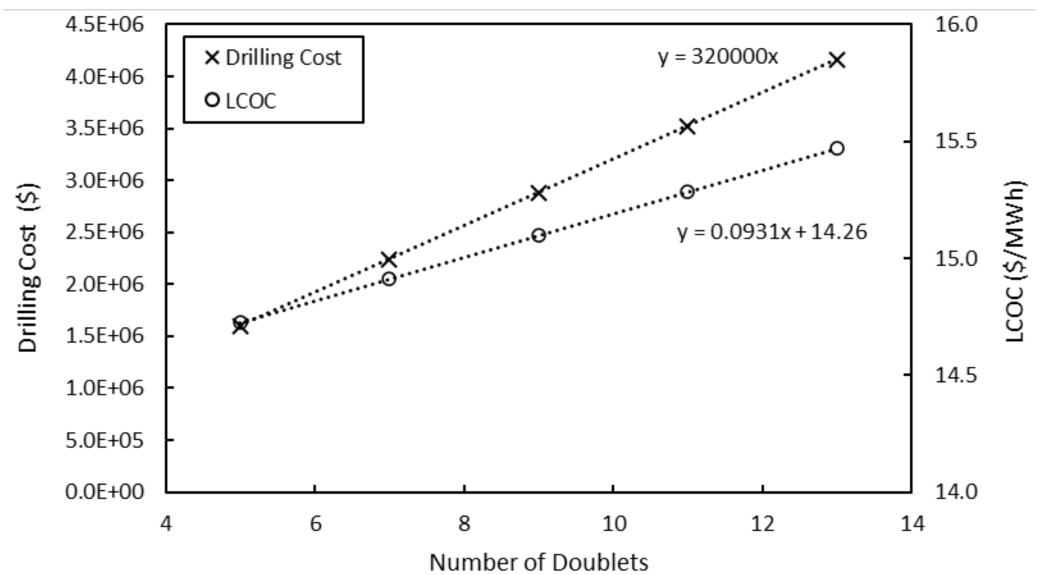
1. LCOC of \$11.9/MWh to \$12.2/MWh with 2 to 10 doublets in the 70 MW data center (Figure 4.5(b));
2. LCOC of \$14.7/MWh to \$15.5/MWh with 5 to 13 doublets in 30 MW data center (Figure 4.5(c));
3. LCOC of \$7.5/MWh to \$7.9/MWh with 1 to 3 doublet systems in 5 MW data center (Figure 4.5(d));
4. LCOC \$7.0/MWh of to \$7.4/MWh with 1 to 3 doublet systems in 5 MW data center heat recovery scenario (Figure 4.5(e)).



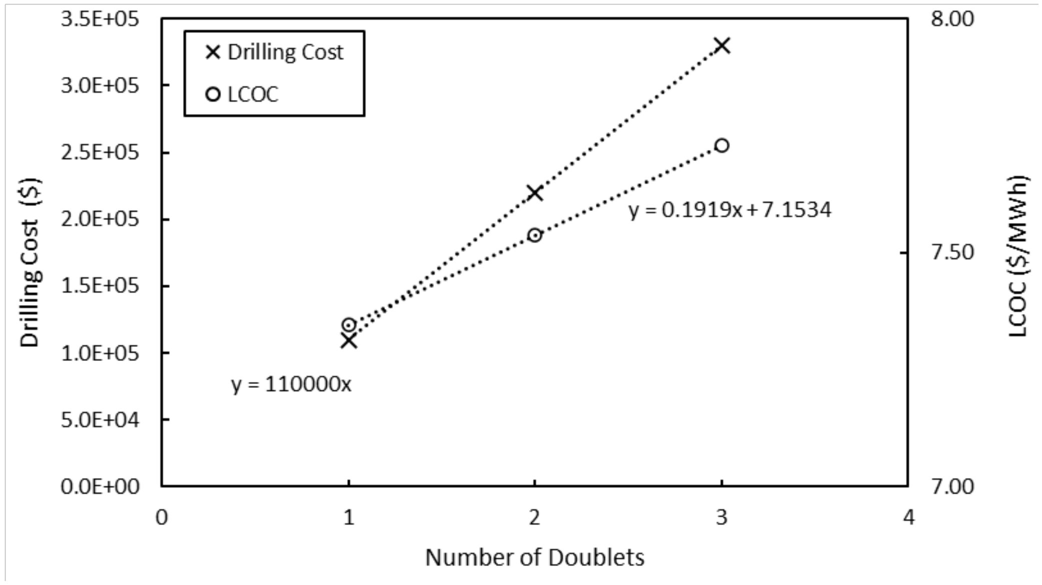
(a)


Drilling Cost
LCOC
y = 0.0318x + 11.83
y = 255000x
Drilling Cost ($)
LCOC ($/MWh)
Number of Doublets
3.0E+06
2.5E+06
2.0E+06
1.5E+06
1.0E+06
5.0E+05
0.0E+00
13.0
12.5
12.0
11.5
11.0
0
2
4
6
8
10
12

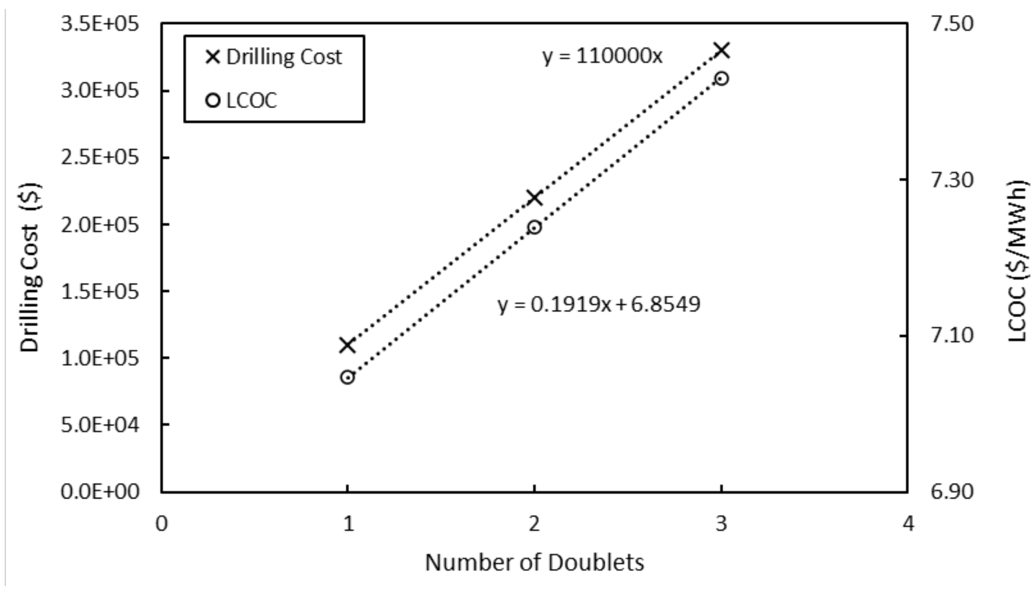
(b)


Drilling Cost
LCOC
y = 320000x
y = 0.0931x + 14.26
Drilling Cost ($)
LCOC ($/MWh)
Number of Doublets
4.5E+06
4.0E+06
3.5E+06
3.0E+06
2.5E+06
2.0E+06
1.5E+06
1.0E+06
5.0E+05
0.0E+00
16.0
15.5
15.0
14.5
14.0
4
6
8
10
12
14

(c)



(d)



(e)

Figure 4-3. Sensitivity analysis: (a) different chiller costs and LCOC of non-RTES scenario in 70 MW data center, (b) different numbers of doublets and LCOC of RTES scenario in 70 MW data center, (c) different numbers of doublets and LCOC of RTES scenario in 30 MW data center, (d) different numbers of doublets and LCOC of RTES scenario in 5 MW data center, and (e) different numbers of doublets and LCOC of RTES + heat recovery scenario in 5 MW data center.

4.7 Annual Electricity Consumption and CO_2 Emissions

In this section, CO_2 emissions in each scenario were calculated with a conversion factor and compared. It is important to note that the CO_2 emissions estimations do not constitute a life cycle assessment. The annual electricity consumption total was calculated for each scenario (e.g., electricity consumed for circulating pump and cooling tower in 70 MW cooling tower scenario) (Table 4-10). Then, the electricity consumption total was incorporated with conversion factors obtained from State Electricity Profiles in the U.S. Energy Information Administration for Virginia (70 MW), Texas (30 MW), and Colorado (5 MW) to come up with estimates of corresponding CO_2 emissions. As expected, the chiller and dry cooler scenario in 70 MW consumed a significant amount of electricity with chillers and the corresponding CO_2 emissions were highest.

Table 4-10 Summary of annual electricity consumption total and CO_2 emissions.

	70 MW Hyperscale			30 MW Crypto		5 MW Institutional		
	Cooling Tower	Chiller & Dry Cooler	RTES	Non-RTES	RTES	Cooling Tower	RTES	RTES & [1]Heat Recovery
Annual Electricity Consumption Total (GWh/yr)	5.07	213.5	55.8	4.2	27.6	0.4	1.7	1.5
Peak Electricity Consumption (MW)	2.15	29.17	7.78	0.71	146.05	0.15	0.32	0.32
[2]Conversion Factor (kgCO₂/MWh)	291.2	291.2	291.2	405.5	405.5	511.2	511.2	511.2
CO_2 Emissions (tCO_2/yr)	1,477	62,182	16,243	1,480	11,204	211	861	784

[1]Note: CO2 emissions avoided with heat recovery (by replacing existing natural gas-fired or electrical heating equipment) were not included.

[2]Note: Conversion factors changes as the technologies develop and electrical grid in the U.S. becomes decarbonized over time.

In addition to the annual electricity consumption total for CO_2 emissions estimations, peak electricity consumptions in each scenario were calculated. The electricity consumed for circulating pump, dry cooler used for partial (Mode 2) or full (Mode 3) data center cooling, and dry cooler used to recharge the RTES (Mode 3) was combined for the same timestep. Then, the peak was obtained. In general, the peak electricity consumption in RTES scenarios was higher than non-compressor-based cooling scenario due to the additional operations of dry coolers for the RTES recharging (Mode 3) that was not included in the dry cooler-based cooling scenarios. In particular, the peak electricity consumption of dry cooler used to recharge the RTES in 30 MW data center was tremendously higher than any other peak load. This is because delta temperature between the cold-water injection temperature and ambient temperature at the same timestep was extremely small. For example, at the timestep of 7,877 hours in 30 MW RTES result, 41.2 MW cooling was injected into the cold well at 20.07 °C temperature with 39.83 kg/s for the RTES recharging, while the ambient temperature was 20 °C. To prepare the cold water at 20.07 °C for the 41.2 MW cooling recharge, when the ambient temperature is 20 °C, the air flow rate should be 581,209.92 kg/s theoretically, due to the small delta temperature of 0.07 °C, which may not be possible in rear world. Thus, the peak electricity consumption of the 30 MW RTES scenario should be carefully reviewed.

4.8 Conclusion and Discussion

In this chapter, the LCOCs with RTES-based and non-RTES-based cooling systems were analyzed for 70 MW, 30 MW, and 5 MW data centers. The comparison of the LCOC served as the basis of the technical and economic evaluation of the RTES-based data center cooling systems. As a first step, useful cooling delivered to the data center from heat rejection alternatives including dry coolers, evaporative cooling towers, air-cooled chiller, tower-cooled chillers, and/or RTES, was estimated using the ambient temperature and the hourly RTES modeling results developed in Section 3. Then, CAPEX and OPEX were calculated for key components including drilling, heat exchangers, pumping, dry coolers, and distribution piping for the RTES scenarios and evaporative cooling towers, dry coolers, chillers, heat exchangers, pumping, and piping in the non-RTES scenarios.

The chiller-based scenario for the 70 MW data center had a higher LCOC than the RTES scenario due to high CAPEX and OPEX of the chiller. The LCOC of RTES scenarios for the 30 MW and 5 MW data centers was higher than those of the non-RTES scenarios. This was particularly the case in the 30 MW crypto mining data center where the base case uses no compressor-based cooling, so there is no cooling energy to save. This situation is also found in many hyperscale data centers as well NREL (5 MW scenario 1). These data centers solely using "free" cooling (no compressor-based cooling) can suffer from higher IT equipment operating temperatures especially in the summer. The warmer operation temperatures can result in lower IT equipment performance and lower life expectancies.

RTES systems have a lower CAPEX and OPEX than chiller-based cooling systems and provide the same benefit of lower and consistent operating temperatures. When compared to compressor-less cooling systems (outside air or tower cooled) RTES will have a higher first cost but will provide lower and consistent operating temperatures. This can yield higher computational productivity and longer IT equipment lives especially when going to liquid cooling as the crypto industry has discovered. With higher productivity, the number of crypto miners (servers) can be reduced yielding lower overall costs. In addition, the benefit of water saving by using RTES instead of cooling towers (which in general has less LCOC) is not quantified. As shown in Figure 2-13, the potential saving is significant, which could have huge implications in regions where water is scarce.

With the different number of RTES wells and the range of potential costs for the chiller CAPEX, the LCOC can change considerably, emphasizing the importance of accurate investigations on the regional subsurface geological conditions and more robust cost estimating. A more thorough investigation of the productivity and life expectancy benefits of operating naturally cooled data centers at cooler temperatures without chillers needs to be further investigated. In addition to the techno-economic feasibility, additional analysis is recommended to evaluate the full benefits of RTES including 1) life cycle assessment, 2) analysis on resilience of data center cooling systems improved with the RTES allowing the operations during extreme heat events, 3) a comprehensive analysis on water savings, which may be a critical factor in areas where water availability is an issue, and 4) analysis on improved compute performance of the IT equipment in data centers due to providing for cooler operating conditions.

5. Conclusions

This project addresses the significant energy and water consumption and cost to cool information technology (IT) equipment in data centers and potential improvements by utilizing subsurface thermal energy storage systems, more specifically, reservoir thermal energy storage (RTES). A scenario-based method was applied to perform techno-economic feasibility analysis based on three types of data centers covering a range of sizes and in three geographical locations. The summary and conclusions of the analysis include:

1. An industrial advisory group (IAG) which included both data center and subsurface thermal energy storage experts, was formed to provide input and feedback to the project. Feedback from the IAG showed interest toward RTES technology in general, but concern regarding its economic performance related to deeper aquifers.
2. The three representative data centers included: Colorado (NREL) for institutional (5 MW), Texas for crypto mining (30 MW), and northern Virginia/DC for hyperscale (70MW). Key assumptions (i.e., water temperature differences, approach temperatures) in the cooling scenarios were determined based on literature review and input from the IAG. A number of cooling scenarios were defined, and later down-selected to compare RTES-based scenarios and commonly used non-RTES scenarios for techno-economic analysis.
3. Three reservoir models were used to investigate the potential performance of the RTES systems, and to provide inputs to the TEA analysis. 2D and 3D model results were compared, and it was demonstrated that a 2D reservoir model is capable of predicting pore pressure and fluid temperatures for the well doublets for the RTES system at NREL. Although such a comparison was not made at the other two sites, the 2D models are considered sufficient due to the systems mainly being driven by horizontal flow between the doublets.
4. Significant cooling can be provided by RTES. The average cooling provided by RTES in the RTES scenarios was 34% to 40% for the 5 MW and 30 MW data centers. For the 70 MW hyperscale data center, 60% of the cooling is from RTES (mostly in the summer) and 40% directly from the dry coolers.
5. With seasonal cooling in the winter for use in the summer, RTES allows data centers to be operated at lower temperatures than state-of-the-art compressor-less data center cooling. This provides two advantages: first, the servers can be overclocked, increasing their productivity and computational efficiency; second, it will avoid the inevitable high operating temperatures encountered during increasing summer “heat storms”. Such extreme operating temperatures reduce computing efficiency and can reduce equipment life and reliability. At very hot temperatures, servers self-protect, first slowing down their clock speed and ultimately turning off, potentially causing major disruptions in service.
6. Although the total cooling needed does not change, taking advantage of the dry cooler’s partial cooling capacity can reduce the amount of cooling that would be provided by RTES, and consequently, reduce the total flow needed to and from the RTES system, and the overall system cost.

7. Pre-cooling of the storage reservoirs is needed if the initial reservoir temperature is warmer than the required temperature to cool the data centers. Deeper reservoirs with higher initial temperatures require more cold water injection to start.
8. The designs for the three reservoirs (with assumed properties and yearly ambient temperatures) are sustainable for at least 20 years. The results can be used as a basis for other scoping studies. For sites with similar depth, but with different transmissivity, the pressure change can be scaled when the same layouts are used. Therefore, a quick calculation of the number of doublets needed can be obtained.
9. For the three scenarios for the 70 MW hyperscale data center in DC/Northern Virginia:
    a. The cooling tower scenario has the lowest LCOC ($2.2/MWh) due to its high efficiency.
    b. LCOC for the RTES scenario ($11.9/MWh) is higher (than the cooling tower scenario) due to high capital cost including piping, and annual pumping cost.
    c. LCOC for a combined dry cooler and chiller scenario ($15.5/MWh) is the highest due to the high capital and operation cost of the air-cooled chillers. Note many hyperscale data centers do not use compressor-based cooling (e.g., chillers), or if they do, it is for backing up compressor-less cooling (e.g., air or tower side economizers) on extremely hot days.
    d. Closer spacing of wells and other system optimization could potentially make RTES more attractive.
10. The LCOC for the RTES scenario is higher compared to a non-RTES scenario for the 30 MW crypto-mining data center in Texas:
    a. because of the high drilling and pumping cost due to a deeper storage reservoir, as well as the heat exchanger cost that was not included in the non-RTES scenario.
    b. Furthermore, the base case (non-RTES) uses very low cost (to build and operate) outside air (only) cooling.
    c. The efficiency loss due to the higher operational temperature in both RTES and non-RTES scenarios was not quantified in the cost analysis. In addition, the efficiency loss due to the 13°C difference between the RTES and non-RTES is not quantified due to lack of detailed information.
11. LCOC for the two RTES scenarios is higher than the cooling tower scenario for the 5 MW institutional data center at NREL because:
    a. The cooling tower solely supplies the cooling load without any supplementary cooling systems (LCOC: $3.1/MWh).
    b. There is a slightly higher CAPEX due to the cost of the RTES components involved and higher operational cost.
    c. The benefit of using the stored heat is not fully evaluated, except it resulted in a lower OPEX of pumping and dry cooler compared to the RTES scenario without heat recovery.

12. In general, scenarios using free cooling (cooling towers or outside air) operating at higher temperature had lower LCOC. A high-level characterization of water use was provided for these scenarios. Water saving (even the outside air-cooled systems use evaporation in the supply air stream) by using RTES for cooling and the benefits of lower operating temperatures described above were not included in LCOC. Further, resilience is improved with no water used (hence no dependence on a secure water supply) and no increasing threat of operating (or failing to operate) at excessive temperatures due to climate change.
13. Geographic location is a key factor in determining the techno-economic feasibility of using RTES for cooling, both from a climate standpoint and the available geological formation and hydrogeological properties (as well as the degree of subsurface characterization).
14. The current study is built on generic information at the three locations (with more site specificity at NREL) without detailed geological characterization data. While they provide generally realistic results, the actual feasibility of an RTES cooling system for a data center needs to be based on site-specific geological information as well as the data center's design. For deployment at a specific site, the design of the RTES system must be based on physical properties (such as permeability, reservoir thickness and depth) of the actual storage formation, and other site-specific information. For example, there might be constraints for well locations, which will affect piping length and cost. Well locations and distances should be investigated along with other factors for optimization. System design and optimization should be performed to maximize the potential benefits of RTES, which can accrue to both users and grid operators. Even at a specific site there will be uncertainty that needs to be considered; for example, future ambient temperature and reservoir geological properties may be uncertain. In addition, other uses of the subsurface that might conflict with RTES (potable water aquifers, oil and gas reservoirs, natural gas storage reservoirs, water disposal wells, etc.) also need to be considered.
15. In addition, the trade-off between the drilling cost, circulation pump cost, piping cost and pumping cost illustrates the importance of system optimization in achieving best economic performance.
16. RTES has a role in decarbonization. First, any energy efficiency gains will contribute to decarbonization as long as carbon fuels are being used in the electricity supply mix. With all energy use sectors decarbonizing and electrifying, electrical generation must grow rapidly, and it is likely that carbon-based sources will remain in the mix for some time. Further, RTES offers the ability to time the electrical energy use to correspond to carbon free generation (and avoid times requiring fossil fuel generation). Lastly, with the potential for heat recovery, heat from data centers can displace fossil fuels that are typically used for low-temperature heating.
17. Finally, to look for subsurface reservoirs for data center cooling, low water quality, brackish water aquifers are considered to prevent potential groundwater temperature changes. In general, Regions with low geothermal heat flow are preferred to minimize heat loss. Large transmissivity will allow higher flow rate, therefore, less wells to be drilled. Shallower depth can also result in lower drilling cost and (typically) initial reservoir temperature. The national-scale RTES pre-assessment study conducted by Pepin et al. (2021) indicates substantial RTES potential throughout the US, therefore, there is potential for them to be used for data center cooling.

Results from this study are published in Oh et al. (2025) and Zhang et al., (2025).

6. Future Work

The following topics are recommended for future work, and are listed in order of general priority:

1. **Characterize additional scenarios for large (e.g., 70 MW) data center scenarios, perform subsurface simulations and techno-economic analysis (TEA) based on a more accurate grid profile.** The goal is to shift power consumption from peak hours to off-peak hours, instead of minimizing total power consumption. The underlying hypothesis are:
    - Energy prices are very low when there is excess renewable power or at other times when power demand is low. It is possible to use dry coolers and electric chillers to charge the RTES during those hours. Chillers could lower temperatures and Increase hours for charging RTES leading to fewer wells and perhaps lower costs.
    - Similarly, the carbon profile varies as supply options come on line and off. The difference in the carbon profile between peak and off-peak hours may continue to grow. Using electrically driven chillers during off peak or high production hours to charge the RTES may result in lower carbon emissions.
    - A specific scenario to be analyzed involves electrical chillers for charging RTES to potentially decrease the number of wells that are needed, and/or to charge RTES at a lower temperature. The key is to identify the hours with low and high power cost to ensure that the increased energy consumption and capital cost of the chillers is cost-effective. The analysis will need detailed knowledge of electricity price structure, which will vary depending on location and could vary over time; a utility that has excess capacity now (or unmanageable peaks), may not in the future. In addition, the economic feasibility of using chillers also depends on their capital cost.

    Thermal energy storage can shift load from grid-straining peaks to off-peak (e.g., surplus) periods. RTES and short-term above-ground TES using chillers for charging will be characterized, and compared to state-of-the-art compressor-less options (with and without storage). TEA will be based on a detailed electricity rate structure for the region (e.g., https://openei.org/wiki/Utility_Rate_Database). The benefit to the grid will be quantified at a high-level.

2. **Evaluate different RTES design parameters (varying the number of wells, well layout and well spacing) and related TEA for a large data center, understand how cost may vary and demonstrate how system design can maximize the potential benefit of RTES cooling**:

    The cost components and their proportions in the total cost demonstrated how system configuration could affect both capital and O&M cost. Specifically, this includes:
    - Examining alternative well layouts (for example, a 5-spot pattern), different well spacing, and therefore, the total number of wells.
    - Examining alternative well geometries such as horizontal wells.
    - Exploring different scenarios to understand an optimal RTES charging scheme, which is a function of ambient temperature, the temperature of the chilled water, and the

hourly cost of electricity (currently the RTES is charged whenever the ambient temperature allows, which could result in higher peak electricity consumption). Again, the goal is to minimize overall cost taking into account the peak and off peak power consumption.

- Studying system designs and seeking professional cost estimates for TEA analysis.

3. **Quantify the benefits of enhanced computational performance at lower temperature**:
    - The opportunity to increase computational performance by operating computers at lower temperatures is likely the biggest economic benefit of long term (seasonal) TES. Current data center cooling best practices rely on ambient weather conditions for compressor-less cooling. As peak temperatures and compute density increase "free" (compressor-less) cooling becomes more difficult. Significant effort is going into raising the cooling temperature to accommodate these changes, but this can come at the expense of computational performance. As computers warm, clock speeds reduce. On the other hand, computers running at cooler temperatures can enhance their performance (e.g. increased clock speed, efficiency). We have some insights on this benefit for crypto mining where industry leaders are moving from outside air cooling to immersion cooling, but it needs to be developed for other computer applications (and for multiple temperature options). One obvious high growth and energy dense application to evaluate would be AI. This could be a standalone project, but would be a potential major driver for RTES.
    - Based on industry interviews and literature review, benefits will be incorporated into the TEA.

4. **Evaluate greenhouse gas emission of the RTES system:**

    Even though we estimated total CO_2 emissions at a high level using annual electricity consumption in each scenario, a more detailed life cycle assessment is needed to fully understand the impact of RTES-based cooling systems. Formulation of a life cycle inventory and impact assessment will be executed for RTES and non-RTES systems. The environmental impact of manufacturing and operating the data center cooling systems will be evaluated and compared to a non-RTES basecase. the CO_2 emissions vary by the power source and during peak periods dirtier plants are often brought on line. As mentioned previously (item 1), carbon profile varies as supply options come on line and off, and the difference between peak and off-peak hours may continue to grow. Grid modeling results will serve as inputs to calculate CO_2 emissions and capture the hourly-level grid supply on emissions. The cost of electricity as well as the CO_2 emissions associated with the power mix will be modeled dynamically.

5. **Summarize lessons learned, case study, and scoping of demonstration project(s):**
    - Based on the current study and real-world application by industry partners (e.g., Digital Realty, and Equinix) develop a lessons-learned document, and if appropriate a case study. Provide guidelines and resources (for example, what factors should be considered, and where needed information might be found). A set of screening tools

can be developed to help identify more favorable conditions (i.e., climate, suitable subsurface reservoir conditions at moderate depths (<1 km), etc.) for use of RTES for data center cooling.
- Identify one or more sites for potential demonstrations working with our industrial partners. Develop an initial feasibility study for each site including identifying potential project partners. Ideally the site-specific feasibility analysis would be sufficient for the partner(s) to decide if they want to go further (e.g., commit to cost sharing).

6. **Quantify benefits of improved resiliency with RTES**:
   - **Resilience to extreme heat:** Climate change and increased density are increasing peak cooling loads in data centers. This increases the risk of potential interruptions, especially for data centers that rely on compressor-less cooling. Storing chilled water in the subsurface to accommodate growing summer peaks can decrease expensive downtime or eliminate the very high capital cost of redundant/backup systems (or increasing the capacity of existing systems).
   - **Water resiliency:** While water savings is a potential operating cost savings, the area needing more research is the opportunity and monetary value of increasing resiliency by completely eliminating the need for water consumption in cooling. The resiliency benefits are likely higher than the cost savings of the water consumption. Alternatively, data centers must install redundant water supply systems and/or large on-site storage.
   - The cost of data center downtime will be evaluated based on literature reviews and interviews. The cost of mitigation - increasing redundancy or adding backup cooling and adding multiple water supply systems and/or water storage, will be evaluated and assessed for their impact on LCOC. Both capital and operating costs will be considered in the LCOC calculations (assuming mitigation measures are deployed).

7. Improve the model for the 5MW heat recovery scenarios:

The heat recovery scenario is currently simplified assuming direct-use applications with a constant recovery rate. This recovery rate should also be dependent on the ambient temperature for applications such as heating buildings, which occurs primarily during the wintertime. Techno-economic analysis of heat recovery systems will be conducted with different case scenarios using heat pump and direct-use applications, including space heating to evaluate the full benefit of the RTES systems combined with heat recovery.

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Appendix A. Data Center Cooling Components/Nomenclature

The following table defines common data center cooling components as listed in the Chapter 2 scenario tables for the three data center types.

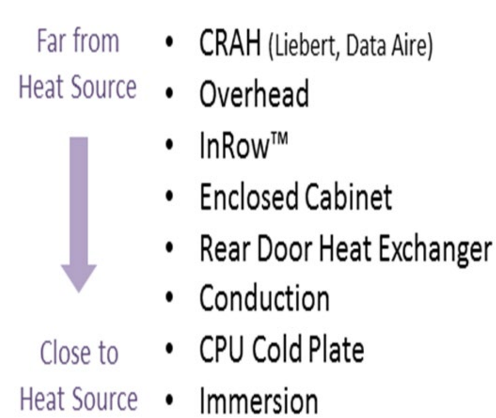
Heat Rejection Alternatives	
Dry cooler An exterior fan and coil unit that removes heat from water or a water and glycol fluid using sensible heat rejection (no evaporation, hence “dry”).	Examples can be found at: https://www.evapco.com/dry-cooling-101
Evaporative cooling tower Cooling towers reject heat from water cooling systems to the atmosphere using evaporation. Hot water from the system enters the cooling tower and is distributed over the fill (heat transfer surface). Air is induced or forced through the fill, causing a portion of the water to evaporate. This evaporation removes heat from the remaining water, which is collected in the cold-water basin and returned to the system to absorb more heat. By using evaporation, the water can efficiently be cooled below the ambient air temperature. A reliable source of water is required, as is water treatment (maintenance).	Examples can be found at: https://baltimoreaircoil.com/what-is-a-cooling-tower
Hybrid cooler A hybrid cooler combines dry and evaporative cooling (allowing evaporative assist when the ambient air is hot).	Examples (both dry mode and evaporative mode) can be found at: https://www.evapco.com/products/closed-circuit-coolers-evaporative/eco-atwb-h-hybrid
Air cooled chiller Chillers make cold water or a water/glycol mixture to cool processes. An air-cooled chiller rejects the heat absorbed from the process directly to the outdoor air using refrigerant to air coils. Fans blow outdoor air directly over the coils and the refrigerant cycle uses a compressor and expansion valve to cool. See below for a tower or water-cooled chiller that uses a tower to reject the heat.	A photo of an air cooled chiller is shown at: https://www.trane.com/commercial/north-america/us/en/products-systems/chillers/air-cooled-chillers/sintesis.html

Subsurface reservoir w ht exch (reservoir thermal energy storage - RTES): Subsurface reservoirs can be used to store thermal energy, referred to as reservoir thermal energy storage (RTES). Energy is stored when the work fluid is injected at a different temperature (than reservoir temperature), and recovered when the work fluid is withdrawn later. RTES distinguishes itself from aquifer thermal energy storage (ATES) in that the reservoir in RTES contains saline or brackish water that cannot be used as a drinking water source. In an RTES The working fluid from the reservoir cannot be used directly in the circulation pipes for heating or cooling purposes due to its low-quality and potential geochemical effects, therefore heat exchangers are used to separate the fluids.	An illustration figure can be found from**:** Pepin, J. D., Burns, E.R., Dickenson, J.E., Duncan, L.L., Kuniansky, E.L., and Reeves, H.W. 2021. National-scale reservoir thermal energy storage pre-assessment for the United States. Proceedings, 46th Workshop on Geothermal Reservoir Engineering, Stanford University.
Heat recovery (e.g., district heating) In some cases, there is a local need for a low-grade heat (for example a district heating system) which can be used to reject data center heat. In these cases, heat recovered from the data center can be used productively to heat the return water from a hydronic heating system. Other applications for data center heat recovery can include heating commercial greenhouses and warm water aquaculture. In some cases, the low grade recovered heat is elevated to a higher temperature with a heat pump (see Plant Alternatives below).	An illustration is shown at (Figure 2) https://www.upsite.com/blog/data-center-heat-energy-re-use-part-2-tap-the-chilled-water-loop/ A thermal network illustration can be found at: https://www.engie.com/en/businesses/district-heating-cooling-systems

Plant Alternatives	
Air side economizer An air side economizer uses outside air to cool a data center when the outside air is cooler than the warm return air. In hot climates, the air side economizer is often combined with direct evaporative cooling (see below) to provide "free" compressorless cooling. In more extreme climates a cooling coil (in conjunction with a chiller) may supply additional cooling. When the outside air is warmer than the return air, a damper shuts to stop the flow of outside air into the system.	An example is shown in Figure 1 at: https://www.energystar.gov/products/data_center_equipment/16-more-ways-cut-energy-waste-data-center/use-air-side-economizer
Evaporative mist or pad Direct evaporative cooling of outside air can be applied to an air side economizer (with or without a cooling coil – often without) and is an energy efficient way to cool data centers. After being cooled evaporatively, the air is used to cool the data center. These coolers have a wet pad or utilize misting nozzles in the supply air. The only power that evaporative cooling needs is for the fans and the water pumps. Many data centers don't have compressor based cooling and the inside air temperature can get warm. (see ASHRAE allowable temperatures below) especially on hot and humid days.	An example image of Evaporative pad can be found at: https://www.munters.com/en-us/solutions/data-center-cooling/direct-evaporative-cooling/ Examples of evaporative mist in supply air can be found at: https://evapopedia.com/facebook-data-center-evaporative-cooling/
Indirect evaporative cooler Data center air (outside air or return air) can be cooled indirectly with evaporation. This typically involves an air-to-air heat exchanger where evaporatively cooled outside air is used to cool the data center air. This reduces the chance for contamination from the outside, and does not increase the humidity in the data center. These systems are less commonly used, and we did not assume its use in any of the scenarios.	An illustrative image (outside air) can be found at: https://www.heatex.com/applications/data-center-cooling/ Another illustrative image (indoor air) can be found at: https://www.linkedin.com/pulse/al-emran-hossain-y1mlc/

Tower cooled chiller Chillers can be air or water cooled. Air cooled chillers were described above. Towers cool water with evaporation to temperatures approaching the wet bulb temperature (below the ambient air temperature). Chillers can produce even colder water to cool processes and can operate on very hot days. They typically use compressors and a refrigeration cycle. Together cooling towers and water cooled chillers are generally more efficient than air cooled chillers, however they require a reliable source of water.	An example is the Figure 1 at: https://www.energy.gov/femp/cooling-water-efficiency-opportunities-federal-data-centers Other examples can be found at: https://www.alfalaval.us/industries/hvac/data-center-cooling/cooling-tower-interchanger/
Water side economizer A water side economizer is a variation of a tower cooled chiller offering even greater energy efficiency. In many locations most if not all hours are cool and dry enough that the data center can be cooled solely with the tower. The chiller, if installed, is only used under extreme conditions. However, if the data center is critical, as many are, such robustness is an expensive requirement.	See an example at: https://www.alfalaval.us/industries/hvac/data-center-cooling/cooling-tower-interchanger/
Air cooled chiller See Heat Rejection Alternatives	
Refrigerant economizer Refrigerant economizers utilize pumps to move refrigerant from the condenser to the evaporator, bypassing the compressor (on cool days). This provides an economizer option for air cooled chillers while getting double duty on the condenser and evaporator heat exchangers. These systems are less commonly used, and we did not assume its use in any of the scenarios.	An image of *data center refrigerant economizer* can be found at: https://mepacademy.com/data-center-refrigerant-economizer/ Another illustrative figure can be found at: Armstrong, Peter & Jiang, Wei & Winiarski, David & Katipamula, Srinivas & Norford, Leslie & Willingham, Ryan. (2009). Efficient Low-Lift Cooling with Radiant Distribution, Thermal Storage and Variable-Speed Chiller Controls Part I: Component and Subsystem Models. © 2009, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (www.ashrae.org). Published in HVAC&R Research, Vol. 15, No. 2, March 2009.

Water to water heat pump Even with liquid cooled data centers, the temperature of the cooling water is a low-grade heat (e.g., up to 45 °C) and may be insufficient for practical recovery and use such as for a district heating system. Heat pumps draw heat from one side and elevate the temperature on the other using a refrigeration process. For example, a refrigerator is an air-to-air heat pump removing heat from inside the refrigerator and dissipating to the outside. A water-to-water heat pump can remove heat from one water stream and elevate it in another (takes heat from one, and puts it in the other). They can be used to transfer heat from the data center's cooling system (or a water reservoir) to a process load (e.g., district heating system) that requires a higher temperature. The heat pump cools the data center while providing useful heat for another purpose. While the heat pump does use electricity to drive a compressor, the warm water from the data center makes the process very efficient (as compared to taking the heat from the ambient air or large body of water). The closer the temperature between the cooling side and the heating side, the lower the "lift" and the more efficient the heat pump can be.	An illustrative image of heat pumps in district heating system can be found at: https://www.iea.org/articles/heat-pumps-in-district-heating-and-cooling-systems A photo of twin water *source heat pump can be found at*: https://www.star-ref.co.uk/smart-thinking/river-source-heat-pumps-for-district-heating/
Fan Coil Alternatives As the name implies a Fan Coil is a combination of a fan and a water to air heat exchanger (coil). In a data center, cold water runs through the coil for cooling. If the cooling (chilled) water is below the dew point moisture will condense on the coil and collects in a drip pan.	See an illustrative image of Fan coil unit at: https://constructandcommission.com/what-is-a-fan-coil-unit/

CRAH (underfloor air dist.) Computer Room Air Handlers (CRAH) are very common modular fan coil units that sit on a data center's floor. Warm air from the servers typically enters the top of the CRAH and flows downward through the heat exchanger(s). The cool air is discharged under the raised floor where it circulates to perforated floor tiles on the cold side of the server racks. The illustration shows an enclosed hot aisle in the data center that improves air management and performance.	See an image at: https://www.vertiv.com/en-us/products-catalog/thermal-management/room-cooling/liebert-chilled-water-air-handler/ Another illustrative image can be found at: https://blog.climatesystemsinc.com/?m=201507
Central AH A central air handler (AH) is a large fan coil unit serving a large area via ducts, raised floors or dropped ceilings, or by flooding the room from the parameter.	A Cutaway Drawing of Air Handling Unit can be found at: https://www.daikin.com/products/ac/lineup/ahu_fcu Another illustrative image of air handling unit can be found at: https://www.stulz.com/en-de/products/detail/indoor-ahu/
Fan Wall Fan walls are gaining popularity in data centers where they are used to flood the room with cool air above the floor (no underfloor air distribution). Fan walls are often placed on exterior walls to facilitate an air side economizer. Contained hot aisles (see illustration above under CRAH) isolate the hot exhaust air to minimize mixing with the cool air.	Examples can be found at: https://www.nortekair.com/brand/fanwall-technology/ and: https://www.nortekair.com/product/fan-systems/
Liquid Cooling Alternatives Liquid cooling is also gaining in popularity in data centers especially as power density is increasing. Generally, the closer the liquid is to the heat source (e.g., CPU and GPUs) the more efficient they are which allows the use of warmer liquid temperatures and greater opportunity for heat recovery and "free" economizer cooling with cooling towers and/or dry coolers.	

In row fan coil In row fan coils fit between server racks. They are typically installed with hot aisle enclosures (see above). They draw hot air from the hot aisle, cool it, and discharge to the data center on the "cold" (inlet) side of the servers.	An example image can be found at: https://www.se.com/ww/en/work/solutions/for-business/data-centers-and-networks/row/ Examples of "In row cooler with hot aisle enclosed" can be found from Page 6 of: www.stulz-usa.com/fileadmin/user_upload/products/Brochures_Manuals/STULZ_USA/STULZ_CyberRow_CW_Engineering_Manual_QEWR001D.pdf
Rear door heat exchanger Rear door heat exchangers cover the entire back of the server rack with a coil. They can be "passive" using the internal server fans to blow hot air through the coil, or they can be active fan powered rear doors. The Lenovo illustration shows the door open (it is normally shut).	See an example from Lawrence Berkeley National Laboratory from Figure 1 at: https://datacenters.lbl.gov/sites/default/files/rdhx-doe-femp.pdf
On board (cold plate) Cold plate or on-board cooling mounts heat exchangers directly on the hot components. Typically, not all the heat is removed, so additional cooling is provided for heat that gets transferred to the air. For example, rear door heat exchangers can be used in conjunction with cold plates for a room neutral solution.	Photos of cold plate for liquid cooling systems can be found at: https://www.boydcorp.com/thermal/liquid-cooling-systems.html Another example can be found from Figure 2 at: https://community.hpe.com/t5/servers-systems-the-right/keep-cool-lower-power-usage-effectiveness-with-direct-liquid/ba-p/7093514
Immersion With immersion cooling the IT components are submerged in a non-conductive fluid. The fluid can be single or two phase (boils at the heat source). Immersion can be in tanks with dozens of server blades as shown, or individual servers can be immersed in "clam shells."	Illustrations can be found at the ebook "The definitive guide to immersion cooling" from: https://www.grcooling.com/ i.e., https://www.grcooling.com/wp-content/uploads/2021/06/grc_ebook_%E2%80%94_the_definitive_guide_to_single-phase_immersion_cooling.pdf

Cooling air supply temp (Class) The American Society of Heating Refrigeration and Air- Conditioning Engineers (ASHRAE) 2021 Equipment Thermal Guidelines for Data Processing Environments established four classes of data center equipment based on temperature and humidity. The recommended or target temperature is 18–27°C is the same for all four classes, but the allowable temperature varies. IT equipment designed for higher operating temperatures will be better suited for “free” or compressorless cooling. The classification does not account for potential reduction of computer performance (clock speed) at higher temperatures. ASHRAE defines the four primary classes as:. • A1: 15–32°C (59–89.6°F) at 20–80% relative humidity • A2: 10–35°C (50–95°F) at 20–80% relative humidity • A3: 5–40°C (41–104°F) at 8–85% relative humidity • A4: 5–45°C (41–113°F) at 8–90% relative humidity	ASHRAE A (Air) Classes are shown in Figure 3-1 and 3-2 of Best Practices Guide for Energy-Efficient Data Center Design (FEMP) at: https://www.nrel.gov/docs/fy24osti/89843.pdf Data Source: Thermal Guidelines for Data Processing Environments, ASHRAE
Facility Water Supply Temp (Class) Similar to the air supply temperature classes above, the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) established liquid cooling classes. A summary of the classes and typical infrastructure design is shown.	See Table 3.1 from American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE - www.ashrae.org), Thermal Guidelines for Data Processing Environments, fifth edition. https://store.accuristech.com/ashrae/standards/thermal-guidelines-for-data-processing-environments-fifth-edition-revised-and-expanded?product_id=2582186