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Geothermal Exchange Innovations for Data Center Efficiency, Resiliency, Profitability, Sustainability, and Grid-Responsiveness

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ABSTRACT

Geothermal exchange offers golden opportunities for improving the all-important resiliency (uptime) and energy efficiency of data centers (DC), just in time for an artificial intelligence (AI) driven growth surge. Energy performance metrics for DC typically include uptime and power usage effectiveness (PUE). While this is common knowledge in DC vernacular, it is less commonly understood amongst the geothermal community. These performance indicators provide operators with massive profit increase potentials and emissions reduction potentials that drive the geothermal value proposition narrative. Through the marriage of geothermal expertise and data center design, operators can leverage new savings and business verticals by simply capturing waste heat or coolth, whether from power generation coupled with absorption / adsorption chillers, backup electrical generation capacity, or server cooling. These new savings and business verticals introduce new methods of sector coupling for broader regional grids, district heating and cooling, or controlled climate agriculture, among others. New sector coupling geothermal-DC strategies do not always fall within an operational cost model, as is the case with grid services, but their quantification will create more sustainable and financeable DC ventures. The key is thermal energy arbitrage, implemented wherever underground thermal energy storage (UTES) is possible. Similar to aboveground thermal energy storage (TES) tanks, but on a much larger scale, UTES systems open doors for loss of power resiliency, reduced cooling operating costs, electrical demand peak shaving and shifting, utility incentives, demand charge reductions, and favorable time of use rates. One of the most important new approaches to capturing this value stream is through dispatchable load or Virtual Power Plant (VPP) participation. Such amalgamations of geothermal systems, energy market arbitrage, and better DC design open new geographies for near-term DC buildout where utility power infrastructure is otherwise insufficient.

1 INTRODUCTION

The projected expansion of the data center (DC) market, for artificial intelligence (AI) servers, is poised to drive significant growth in electrical demand to power and cool the DCs, in addition to growth in demand for cooling and water. With approximately one third of the more than 8,000 DCs in the world being located in the United States (EIA, 2024), electricity consumption within the U.S. is anticipated to grow from around 200 terawatt-hours (TWh) in 2022 to nearly 260 TWh by 2026, or from 4% to 6% of total electricity demand in the U.S. (Gertler et al., 2025).

Power Usage Effectiveness (PUE), defined in Equation 1, is an indicator of energy efficiency in a DC, being a ratio of the total electricity provided to the DC versus the amount of that electricity utilized to power IT server operations. The remaining electricity demanded is utilized for support facilities, ancillary equipment, and most predominantly cooling equipment to reject heat from the servers. A PUE of 1.0 means all energy powers IT equipment, while higher values indicate more energy is used for non-computing functions like cooling. The average annual PUE of DC surveyed by the Uptime Institute was 2.50 when the program was launched in 2007, and it subsequently dropped to below 1.70 within seven years. The average annual PUE has stabilized at 1.56 as of 2024 (Donnellan et al., 2024), due to efficiency gains being offset by rising data demand, diminishing returns on traditional optimizations, growth in edge and colocation centers, climate constraints, and inconsistent reporting. This plateau highlights the limits of conventional strategies and the need for innovative solutions like geothermal integration to drive further sustainability.

$$\text{PUE} = \text{Total Facility Energy} / \text{IT Equipment Energy} \quad (1)$$

Capturing waste heat and utilizing it to offset heating demands in adjacent communities has already garnered widespread interest and is actively being pursued for full scale designs and implementations (Paulsson et al. 2025). This is particularly true in northern European countries which already have extensive urban-scale district heating systems that require equivalently large-scale heat input, where data center waste heat recovery is replacing fossil fuel heat sources. In part, this is driven by policies and incentives that prioritize waste heat recycling to reduce dependence on foreign sourced combustion fuels.

2 PROFIT INCREASE, RESOURCE USE REDUCTION, AND EMISSIONS REDUCTION POTENTIALS

2.1 Power generation coupled with absorption / adsorption chillers

A valuable heat resource at DC is onsite power generation, which often yields significant waste heat. The ongoing rapid growth of DC necessitates a similarly rapid growth in electrical power production, driving many DC developers to consider co-locating power generation facilities at their DC facilities. A practical way to reduce the growth in power demanded by data centers is to improve the efficiency of waste heat recovery for secondary uses, such as cooling and other process loads. Regardless of whether the power generation facilities are interconnected on the grid side or behind-the-meter, waste heat is available for recovery in typical thermal power plants, whether geothermal or combustion based.

For instance, a simple cycle gas combustion turbine may yield as little as 35% of its energy utilized as electrical power output, rejecting the remaining 65% to the atmosphere as hot combustion byproducts. As shown in Figure 1, the exhaust heat contains sufficient thermal energy to drive absorption or adsorption chillers—systems that use heat instead of electricity for cooling—potentially replacing conventional electric chillers and reducing data center electricity demand by 20% or more. For an average US city, the chilling plant operational cost of an absorption chiller could be between 4%-33% lower than that of an electric centrifugal chiller (Dixit, 2019).

The same could be applied to backup generation facilities which are standard in DC design, regardless of co-located base power generation. Although their operation is intermittent and unscheduled, they still offer opportunities for waste heat utilization. Alternatively, geothermal power plants typically operate between 107-182^{0}C (DeLovato et al., 2019) providing low- to medium-grade thermal energy, and can be repurposed to drive absorption chillers or adsorption chillers if this provides a more efficient or necessary use of the geothermal resource. To support decoupling the power production operations from the cooling operations, large Underground Thermal Energy Storage (UTES) systems may be required or may be beneficial – as borehole or reservoir thermal energy storage (BTES or RTES).

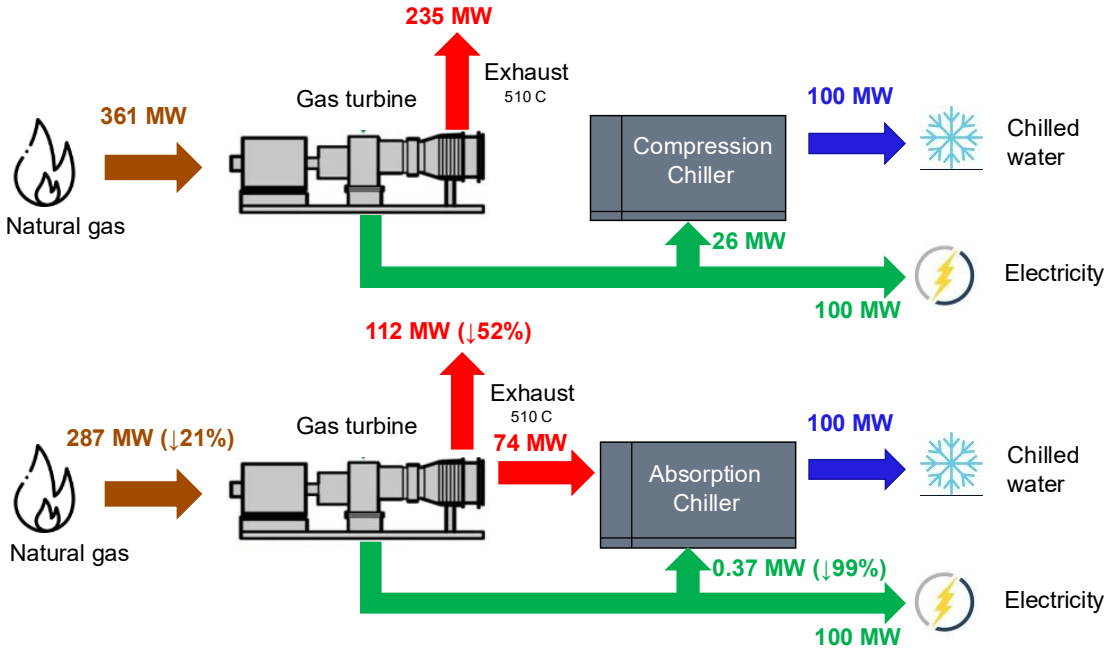


Figure 1: Comparison of natural gas demand for on-site gas turbine power generation at a data center when coupled with compression or absorption chillers for chilled water production. Absorption chillers could lower natural gas demand by 21% from a 99% reduction in chiller electricity demand, while curtailing exhaust waste heat by 52%, offering a more efficient and sustainable solution.

2.2 Server cooling

The electrical power input to the data center, including IT servers and ancillary equipment, is largely converted into heat which must then be removed on a continuous basis to prevent overheating and ensure reliable operation. Traditionally, reducing the required chiller lift and increasing the opportunities for "free" cooling without compressor-driven chillers has long been the driver for energy efficiency in data center cooling. However, a shift toward harnessing this waste heat for offsite applications, such as low-grade industrial processes or building heating, presents a new opportunity. By monetizing this thermal product, data centers can help displace fossil fuel based heating systems which are often required by those offsite customers (e.g., gas furnaces and gas boilers for building heating).

Multiple opportunities for various geothermal exchange systems (e.g., borehole, thermal battery, reservoir) offer viable solutions for capturing and storing waste heat from data centers. These systems enable decoupling of the data center's continuous, high-output thermal generation, driven by computing loads, from the variable and often seasonal heat demands of offsite users, such as batch industrial processes or district heating networks.

Geothermal exchange system designs can be optimized around cooling, heating, or near-ambient temperatures, depending on site specific requirements. For example, geothermal systems could be designed to improve data center energy efficiency by integrating with a district heating network. A near ambient temperature loop can reduce chiller or heat pump lift at the data center, while distributed heat pumps in the district heating system extract usable heat downstream (Oh et al., 2024).

Further, a geothermal exchange system might be designed to optimize cooling operations by storing the cooling energy, pre-charging the geothermal exchange system temperatures to the DC cooling supply setpoint, such that data center cooling can periodically take advantage of "free" cooling from the geothermal exchange system. A pre-charged geothermal exchange system could also act as a thermal energy storage (TES) system during emergencies such as a power outage, to help maintain the chilled water temperature to uninterrupted power supply (UPS)-backed servers at the preferred setpoint. Utilizing geothermal exchange as part of an emergency response can reduce capital costs associated with otherwise necessary backup equipment, enhancing the DCs overall resiliency, uptime, and customer base.

2.2.1 Water use reduction

Existing DCs typically reject heat to the atmosphere using evaporative cooling towers, which require a continuous supply of makeup water to compensate for evaporative and drift losses. Converting to heat pumps or heat exchangers which reject heat to a geothermal exchange system eliminates the need for evaporative cooling, significantly reducing water consumption. This recovered heat, potentially upgraded through heat pumps, can be repurposed to replace steam-based heating systems used in buildings, indoor agriculture, and low grade heat industrial processes. These systems also consume water, particularly for boiler blowdown, making geothermal integration a dual opportunity for water conservation.

Water use reduction carries increasingly high importance in almost every locale for a potentially large water consumer such as a DC, but is particularly important in arid locations that support large data center hubs such as the western states of Nevada, Utah, Colorado, Arizona, New Mexico, and Texas (ASHRAE climate zone 2B, 3B and 5B). The environmental costs of evaporative systems may outweigh their energy efficiency benefits in such climates, and traditional strategies for water usage reduction, such as air side economizers, are limited in their seasonal availability (Karimi et al., 2025).

In arid regions of the U.S. West, medium sized data centers can withdraw up to 110 million gallons of water annually, equivalent to the usage of roughly 1,000 households, and some facilities in The Dalles, Oregon have drawn over 355 million gallons in a single year (Rogoway, 2022; Yañez-Barnuevo, 2025). In regions with limited water supply, where withdrawal permits are stringent and delivered-water costs are high, such volumes amplify regulatory and financial risks. By integrating geothermal exchange with closed loop cooling, operators can eliminate evaporative losses and reduce water consumption by more than 90 percent. This strategy lowers operating expenses, enhances uptime resilience during droughts, reduces reliance on volatile water markets, and stabilizes both capital and operational budgets.

2.2.2 Energy use and cost reduction

A DC can effectively control the temperature of its heat sink by rejecting heat to a geothermal exchange system and leveraging its TES capacity. This allows the DC cooling plant's coefficient of performance (COP) to be decoupled from external air conditions (temperature and humidity) and its cooling plant's electrical costs to be decoupled from real-time electrical prices. Because outside air conditions and electrical prices are often

correlated, and both influence cooling demand, peak cooling loads typically occur during periods of high ambient temperatures and elevated electricity prices.

Decoupling cooling system performance from varying ambient air conditions, as is the case with ground-source heat pumps compared to conventional air or cooling-tower-cooled chillers, enables stable and efficient cooling operation that leads to higher COP, lower energy use and cost. Integrating a geothermal exchange system with heat off-takers that can productively use the recovered heat significantly increases the system's overall efficiency. In this configuration, the COP reflects the combined benefits of both cooling and heating, rather than just cooling alone.

2.2.3 Carbon emissions reduction and grid responsiveness

Beyond reducing water consumption and electrical consumption, as well as their associated operating costs, DCs carry significant responsibility for minimizing carbon emissions linked to their energy use. A renewable power plant co-located on site can directly offset carbon emissions from power generation to meet the DC's electrical demands, and if opting for an intermittent source such as solar or wind instead of a baseload source such as geothermal power, associated battery or thermal storage would enhance the opportunity to make full use of the renewable energy without recourse to other fuel sources.

A geothermal exchange system with sufficient TES capacity enables a DC to shift the timing of their cooling operations. This flexibility allows DC operators to align their electricity consumption with periods of low or zero carbon power generation, either from co-located renewable power generation facility and/or the broader electrical grid, particularly during times when renewable energy sources are peaking.

At these periods, renewables often drive very low or even negative prices or may otherwise be curtailed due to oversupply. DCs with geothermal exchange systems can provide a variable demand that takes advantage of excess clean energy production when available and similarly reduces demand on the grid when clean energy is unavailable. This grid interaction and responsiveness provides massive benefits to DC operators as well as grid operators and power producers. These demand-response capabilities open doors for DCs to participate in Virtual Power Plant (VPP) programs.

On top of reducing DC operating costs by enabling electrical demand peak shaving and shifting, the DC-scale TES capability carried by a geothermal exchange system could be utilized to reduce the overall peak demand of a DC to increase the feasibility of siting the DC at a location that otherwise does not have sufficient electrical capacity to fully power the DC, specifically at peak grid demand periods.

3 GEOTHERMAL ENERGY NETWORK COUPLING

Deploying geothermal exchange systems at a DC would establish resources which can be utilized to enhance data center operations – particularly by reducing the substantial operating costs that might quickly surpass the initial capital investments. Additionally, these systems can generate monetizable energy streams by supplying raw or upgraded waste heat to external off-takers, creating new revenue opportunities.

Strategically co-locating a DC near geothermal resources and potential heat off-takers can unlock valuable revenue streams. As such, siting considerations should be prioritized early in the development process to fully capitalize on these opportunities. A district heating system can be built entirely around the waste heat from a DC, using it as an "anchor" or baseload heat source. Alternatively, the DC can serve as one of several contributors within a broader geothermal energy network (GEN) that integrates multiple heat sources and sinks (Figure 2).

Partnership agreements for dedicated heat needs such as for controlled climate agriculture to be co-located with DCs can also make beneficial use of otherwise waste heat, rather than the need for a broader thermal energy network. Quantifying and pursuing such arrangements would enable improved financial bottom lines and reductions in energy use, water use, and carbon emissions for DCs and their heat off-taker customers.

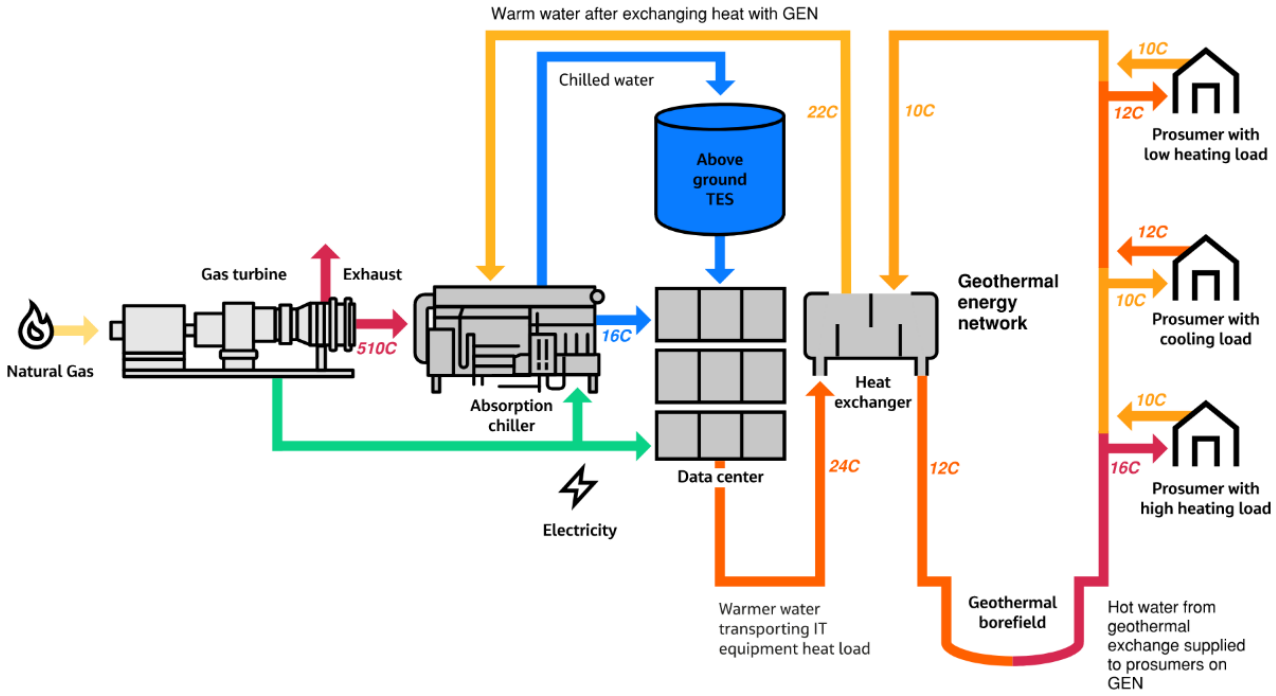


Figure 2: Utilizing data center waste heat as an input to a GEN. The temperature ranges are estimates based on authors' experience with each depicted component but do not represent temperature in any real-world GEN.

4 THERMAL ENERGY ARBITRAGE

Thermal arbitrage refers to the strategic shifting of thermal energy generation or use – typically for cooling – across time to optimize both economic performance and operational efficiency. In DCs, where cooling represents a dominant energy demand and uptime is mission-critical, this approach can yield substantial cost savings and resilience benefits. The energy flexibility concept of thermal load shifting – storing cooling when energy is cheap and clean (e.g., nighttime or off-peak hours) or demand is low, and discharging it during peak periods – reduces the operating costs of mechanical chillers. This not only improves energy efficiency but also enhances thermal system reliability and grid responsiveness. Taking advantage of favorable time of use electrical rates enables DC operators to manage their operating costs that are largely based on consumption of electricity. Additional electrical cost savings can be pursued on a case-by-case basis to take advantage of electric utility incentives and/or reductions in demand or capacity charges.

One of the most promising enablers of thermal arbitrage is Underground Thermal Energy Storage (UTES) (Zhang et al., 2023). Technologies such as Borehole TES (BTES), Aquifer TES (ATES), and Reservoir TES (RTES) allow excess thermal energy – either heating or cooling – to be stored in the ground and retrieved later. UTES systems typically reject heat from data center equipment via ground heat exchangers, which are connected to hydronic loops or direct-exchange systems. This decouples thermal generation from real-time demand, enabling more flexible and efficient system operation. In geothermal-based cooling systems, UTES leverages the earth's stable subsurface temperatures to support both: (a) seasonal storage (e.g., storing summer heat for winter use or winter cold for summer cooling), and (b) short-term cycling (e.g., daily or weekly load shifting). This is particularly valuable in DCs, where cooling loads are continuous but vary with time of day and season.

UTES can also enable free cooling, using naturally cold ground temperatures to offset cooling demand without consuming additional electricity. Critically, the UTES add redundancy and resiliency, acting as a thermal buffer in case of chiller failures or power disruptions. Moreover, UTES in DCs supports carbon reduction by reducing the need for refrigerants and mechanical cooling systems. When combined with predictive controls and dynamic thermal management systems, geothermal UTES can optimize charge and discharge cycles based on weather forecasts, IT load profiles, and electricity prices – maximizing economic and environmental benefits.

Furthermore, UTES enables DC to generate revenue by participating in demand response programs (i.e., shifting demand based on time-of-use (TOU), critical-peak-pricing (CPP), or real-time pricing) and providing ancillary grid services in emerging markets. In volatile markets like CAISO and Guangdong, arbitrage strategies integrating TES can deliver up to 2.39x return on investment (ROI)—nearly double that of battery storage (1.29x)—due to lower capital costs, longer lifespan, and efficient load shifting without conversion losses (Zhang et al., 2025).

In recognition of the potential energy and water-use efficiency benefits of UTES, the US Department of Energy's Geothermal Technologies Office is actively supporting research and development in areas of system sizing and configuration with respect to data center installation scale, performance, cost, grid impact and policy-making (Winick et al., 2025).

5 VIRTUAL POWER PLANT PARTICIPATION

As utilities push for decarbonized and distributed grid infrastructure, geothermal-integrated DCs positioned within VPPs can play a critical role in enabling smarter, cleaner, and more adaptive energy systems. A VPP aggregates and coordinates distributed energy resources – such as geothermal-based heating and cooling systems, battery storage, and flexible loads – into a unified, dispatchable asset for grid operators. DCs, with their high and controllable energy demand, can participate in VPPs by modulating cooling loads or shifting energy use through (U)TES.

For instance, during grid stress or high electricity prices, a VPP-enabled data center can send real-time commands to flexible assets to discharge pre-cooled, stored thermal energy to reduce electrical load without compromising IT uptime. In return, it may earn incentives for providing demand-side flexibility, frequency regulation, or capacity support. API-based integration and AI-driven platforms enable predictive coordination and aligning operations with grid needs. These mechanisms support renewable energy goals, especially when paired with Virtual Power Purchase Agreements (VPPAs), and enhance resilience by enabling islanded operation or grid-responsive dispatch during emergencies.

6 TRANSIENT ANALYSES

Unlocking the synergies between DCs and geothermal exchange systems requires analysis of time-dependent and dynamic thermal system-of-systems. Dynamic models that capture the transient nature of these thermal systems are necessary to adequately size and recommend design solutions. Modern DCs are shifting from redundancy-focused design to resiliency-driven strategies. To fully leverage thermal resiliency, designers must move beyond traditional steady-state models and adopt dynamic, real-time approaches.

Traditional approaches have relied on steady-state models and spreadsheet calculators to size cooling systems, assuming constant loads, fixed boundary conditions (e.g., weather and subsurface properties), and static operational schedules. These models operate under the premise that the system has reached equilibrium and remains static. However, real-world DC thermal network operation that is subject to instantaneous utilization load spikes, electric grid instability, weather and climate fluctuations call for more adaptive and responsive design techniques to overcome these shortcomings and improve outcomes. While the steady state models can size components under typical or peak demand conditions, they fail to capture the real-world operations – resulting in over- and under-design, inefficiencies, and missed opportunities for optimization.

A dynamic modeling approach captures the full mass and energy evolution of thermal systems over high-resolution time intervals in response to changing boundary conditions and control actions. This approach also lays the foundation for intelligent, digital-twin-based systems designed not only for the current operations, but also future-proofed for fault detection and diagnostics, predictive maintenance, and real-time system tuning/optimization. Transient analyses of data center thermal networks could link the precision of simulation with the intelligence of real-time data, delivering design and operations that are adaptive, efficient and reliable.

7 CONSIDERATIONS AND CHALLENGES

7.1 Scalability

The suitability of these geothermal exchange opportunities may depend on the data center scale that drives electrical and thermal loads, and siting constraints that may drive energy transportation costs. Data centers with high energy demand can take advantage of on-site generation with exhaust heat recovery in absorption chiller cooling, while freeing up existing grid infrastructure for data centers with lower demand. Likewise, the economies of scale for UTES investment may be more favorable to larger data centers with high cooling loads compared to edge or co-location datacenters with smaller initial investment prior to UTES add-on.

To take full advantage of the energy arbitrage model provided by UTES, the electricity pricing scheme at a given location will need to be variable enough to provide opportunities for load shifting that are economically favorable. While targeted UTES charging at times of cooler temperature may indeed reduce energy costs, a flat rate pricing scheme will provide less economic benefit compared to a TOU or dynamic pricing rate. However, in flat-rate jurisdictions there are opportunities that offer financial incentives or bill credits for participating in grid-

balancing efforts, such as capacity-based programs (e.g., PJM's Emergency Load Response Program) and ancillary services. The applicability of GEN coupling will be driven by proximity to potential off takers.

Remotely located larger data centers may be constrained by energy transmission costs to participate in a GEN model unless such costs are taken on by a different entity, e.g., a utility company. Yet, these larger scale data centers, expel more waste heat from cooling that if repurposed, could reduce the ROI of a GEN. Additionally, the type of data center and nature of load profile will determine the feasibility of participation in VPP programs. AI data centers with instantaneous load spikes during model training will be less suitable in providing the grid with quick demand response compared to cloud data centers that have predictable loads.

7.2 Implementation

Implementation challenges that may need to be addressed will border on technical, economic, cultural, and policy related issues. Geothermal integration in existing data centers compared to green land projects could see higher implementation costs from retrofit to the facility cooling loop including heat exchanger and underground pipe installation, rerouting of existing pipes and new controls to support VPP participation. Existing underground utilities and favorable soil properties that drive system size and cost are other techno-economic implementation challenges to consider. The installation of geothermal technologies will also require buy-in from local communities and stakeholders where educational material on the benefits of geothermal exchange will attract approval. Also, drilling workforce availability may pose a challenge when considering data center siting in one location or another. Tax incentives could reduce the financial burden of retrofits while favorable utility bill incentives can cover any capital costs incurred in VPP participation.

Government-funded pilot projects will help reduce the risk of exploring these data center – geothermal technologies resulting in valuable data collection and technical learnings that will be beneficial at a scale. The oil and gas industry already possesses the skilled expertise and technology needed for geothermal drilling and in the face of an energy transition towards low to no carbon alternatives, repurposing these existing skills will both provide the geothermal industry with much-needed workforce and provide this skilled workforce with job security.

8 CONCLUSION

While a departure from legacy DC design approaches, geothermal exchange systems offer a scalable and site-adaptable solution for enhancing the sustainability and resiliency of modern data centers. Geothermal exchange opportunities have tremendous potential to reduce carbon emissions, lower operating costs, and improve thermal efficiency when integrated with advanced control strategies and energy market participation. Additionally, any new geothermal exchange installations will primarily be installed in the subsurface, shielded from weather conditions that otherwise would degrade their performance and quality. Such integration of geothermal systems and better DC design open up numerous mutually beneficial opportunities for developers, designers, owners, and operators of data centers, geothermal exchange systems, power generation facilities, thermal energy networks, and district energy systems for heating and cooling. As demand for low-carbon, high-performance data centers grows, geothermal exchange will play a key role in shaping future deployments.

Continued research, pilot demonstrations, supportive policy frameworks, and new key performance indicators that quantify the benefits as well as trade-offs of synergizing data center design with geothermal exchange will be essential to accelerate adoption and unlock the full value of these integrated systems. Future work will present case studies on simulated or real-world data center and geothermal exchange systems integration that touches on one or more synergies discussed in this work. Transient modeling approaches will be critical towards establishing design practices that guarantee optimal performance at scale.

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