The Role of Energy Storage for Data Centers

In today's digital economy, data centers are the backbone of global information flow, cloud computing, AI development, and enterprise operations. Their reliability and efficiency are paramount. However, with rising energy demands and the urgent need for sustainable practices, data center operators are rethinking traditional cooling approaches. One promising solution to gain momentum is thermal energy storage (TES) - a method of capturing energy that offers an innovative path toward cost reduction, efficiency, resilience, and sustainability.

Understanding Thermal Energy Storage in Data Centers

Thermal energy storage systems for cooling remove heat from the storage material, lowering its temperature or changing its phase, during off-peak periods (often when electricity is cheaper or greener) and hold it to assist in cooling during peak demand times. TES can take several forms: chilled water tanks, ice storage systems, phase-change materials (PCMs), and even ground-coupled. Instead of running chillers or compressors at full capacity during hot afternoons — the most expensive and grid-stressed periods — a data center equipped with TES can shift some or all its cooling load to periods of lower demand. This "load shifting" capability helps balance energy supply and demand, reducing operational costs, enhancing grid stability, and potentially decreasing carbon footprint.

Why Thermal Storage Matters for Data Centers

Data centers consume a significant portion of electricity, accounting for approximately 1 to 2 percent of global demand[1] currently. This figure is projected to rise 7 to 12 percent by 2028[2] due to the increasing prevalence of AI, IoT, and streaming applications. Around 20 to 40[3] percent of this energy consumption is dedicated solely to cooling within the data center.

Thermal energy storage for data center owners/operators offers multiple system designs and strategic advantages:

1. **Energy Cost Management:** By producing cooling during off-peak hours when electricity prices are lower and using it during peak pricing periods, operators can optimize overall system efficiency and significantly cut energy expenses. Peak electrical demand reduction will be increasingly important as data center power requirements strain the local grid.

2. **Thermal Ramping Speed:** Data center loads are dynamic, extreme, and change in milliseconds, as compared to cooling plants, which take longer to react. TES is a huge "buffer tank" which can almost instantaneously react to changing loads, thereby giving the chiller plant the time it needs to respond.

3. **Downsizing of the Cooling Plant with no Change in Redundancy:** Adding TES to a system spreads the daily cooling load creation over a 24-hour time frame. In a simplified example, a commercial office has a peak load during the day (3500 kW) and almost zero at night. A 2100 kW chiller plant can create stored cooling at night and leveraging storage with a 2100 kW chiller to meet the 3500 kW load. If the 2100 kW chiller was split into two 1050 kW machines, and N+1 design parameter was specified, that would mean adding a third, 1050 kW machine. For data centers, N+2 or the required redundancy can be met with a combination of storage and a reduction in chiller equipment, reserving CapEx.

4. **Resilience and Redundancy:** TES can serve as a smart thermal backup. Mechanical cooling failures or electrical grid interruptions leading to unplanned downtime are costly in mission critical environments. Stored thermal energy can continue to cool the data center for a critical window, supporting uptime commitments and service-level agreement guarantees.

5. **Grid Stabilization:** As renewable energy sources (like solar and wind) supply more electricity, their intermittency creates challenges for grid operators. TES enables data centers to adjust their loads dynamically, absorbing or shedding demand in response to grid conditions — an increasingly valuable capability in modern energy markets. Additionally, major grid operators have indicated that future supply agreements could contain a mandatory demand reduction clause that cuts all power to the largest users. Should this occur, the value of TES in enabling demand reduction would be significant.

6. **Sustainability Goals:** Shifting cooling to greener, off-peak periods (such as nighttime when wind energy is more prevalent) can reduce the carbon intensity of operations, helping companies meet aggressive sustainability benchmarks like carbon neutrality or net-zero pledges.

Implementation Approaches

There are several practical methods of integrating thermal energy storage into data center infrastructure:

- **Chilled Water Storage:** Large, insulated tanks store chilled water produced during periods of low demand. This chilled water can be used to cool servers directly (liquid-cooled servers) and/or circulated through the facility's air handling systems during high-load periods. Pro: The bigger the system, the lower the cost of storage (economies of scale). Con: The space requirement for the tanks may be a deterrent.

- **Ice Storage:** Some facilities use ice-based systems, where chillers freeze water overnight and the melting ice provides cooling during the day. Pro: Ice storage is compact, storing 5 to 8 times the amount of heat compared to chilled water storage. Con: Stores cooling at a lower temperature than required by most data centers currently.

- **Phase Change Materials (PCMs):** PCMs (other than water/ice, which is a PCM) can store and release energy at a selectable phase change temperature. Pro: PCMs bring the temperature closer to the required load temperature. Con: Their storage capacity is about 50% larger than water/ice (double the amount of storage tanks), and the material cost is approximately $2.50 per lb, compared to water, which is free at the site.

- **Thermal Ground Storage (TGS):** In some designs, natural geological formations or engineered underground systems can store or reject heat, depending on the season. Pro: Used strategically, TGS can positively impact energy and cost savings and can help improve grid resilience during extreme weather. Con: The capital costs can be high, and the environmental impact of ground warming is a factor.

Selecting the optimal thermal energy storage solution depends on various factors, including local climate, electricity prices, regulations, building design, and operational requirements. However, for data centers with substantial energy demands, chilled water storage is often the preferred option, assuming there is sufficient space available for the storage tanks.

Challenges, Limitations and Synergies

Applying thermal energy storage in data centers is not without challenges.

- **Capital Costs:** TES systems may require substantial upfront investment. Storage tanks, specialized chillers, control systems, and additional piping can be significant expenditures. Operational savings often justify the investment over time. The payback period can vary greatly, especially in regions with flat electricity pricing, but this is rare. Space Requirements: In high-density, urban environments where many hyperscale data centers are located, dedicating valuable real estate to thermal storage tanks can be a constraint.
- **Energy Cost Reduction and Backup Emergency Cooling:** For decades, TES (mainly water storage) has been used in data centers to instantly supply cooling for short periods (15 to 30 minutes) following a power outage. These systems were necessary and added cost. However, this emergency backup requirement is easily met if the data center is designed with a storage system that reduces peak demand for four or more hours. The systems not only pay for themselves in reduced energy costs but can also provide 15-minute emergency cooling with no change in design, thereby reducing payback periods even further.

Case Study Proof of Concept

Forward-thinking data center operators are already demonstrating the benefits of TES.

For example, in California, a large university's data center utilizes a campus-wide chilled water thermal energy storage system that significantly reduces peak energy demand.

In commercial settings, Trane® has over 4000 installations of TES meeting cooling loads. Data centers have large loads that fluctuate, and TES is designed to serve large loads regardless of the application. The advantage is that the cooling is pre-stored, and peak time resources aren't needed to serve on-demand needs.

The Future: Integrated Thermal Management

Looking ahead, the most promising TES applications will likely be in combination with other advanced energy strategies:

- **AI-Driven Energy Management:** Intelligent software can optimize when and how TES is charged and discharged based on real-time energy prices, grid conditions, and workload forecasts.
- **Liquid Cooling Synergies:** As data centers transition to high-density racks with direct-to-chip liquid cooling, integrating TES systems with liquid loops will open new opportunities for efficiency and resiliency.
- **Renewable Energy Integration:** Pairing TES with on-site solar or wind generation can dramatically increase the self-consumption of renewables.
- **Demand Response and Carbon Credits:** TES can support participation in grid demand response programs or carbon credit markets, creating new revenue streams for data center operators, while giving them negotiating power on mandatory demand reduction rules.

Conclusion

Thermal energy storage represents a highly strategic innovation for data center operators facing a future of escalating costs from increasing energy demands, tighter regulatory pressure, and public scrutiny and accountability for sustainability efforts. Although it requires a holistic view, thoughtful system design, and investment, the ability to decouple cooling loads from real-time energy use gives data centers powerful flexibility and resilience.

In the next decade, as grid dynamics become more volatile and energy costs continue to rise, facilities that integrate TES will have a significant competitive advantage, not just in cost savings, but in operational reliability and corporate responsibility. Forward-thinking operators should not ask if they can afford to implement thermal energy storage, but rather whether they can afford not to.

About the Author

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