Superconductivity used in data centers

B. Marchionini[1], D. Mosteller[1]; L. Serri[2], G. Angeli[2], H. Ohsaki[3] and P. Feldman[4]

1 CLEAResult Energetics LLC, Columbia, MD, United States
2 Ricerca sul Sistema Energetico - RSE S.p.A., Milan, Italy
3 Graduate School of Frontier Sciences, The University of Tokyo, Japan
4 QTD Systems LLC, New York, NY, United States

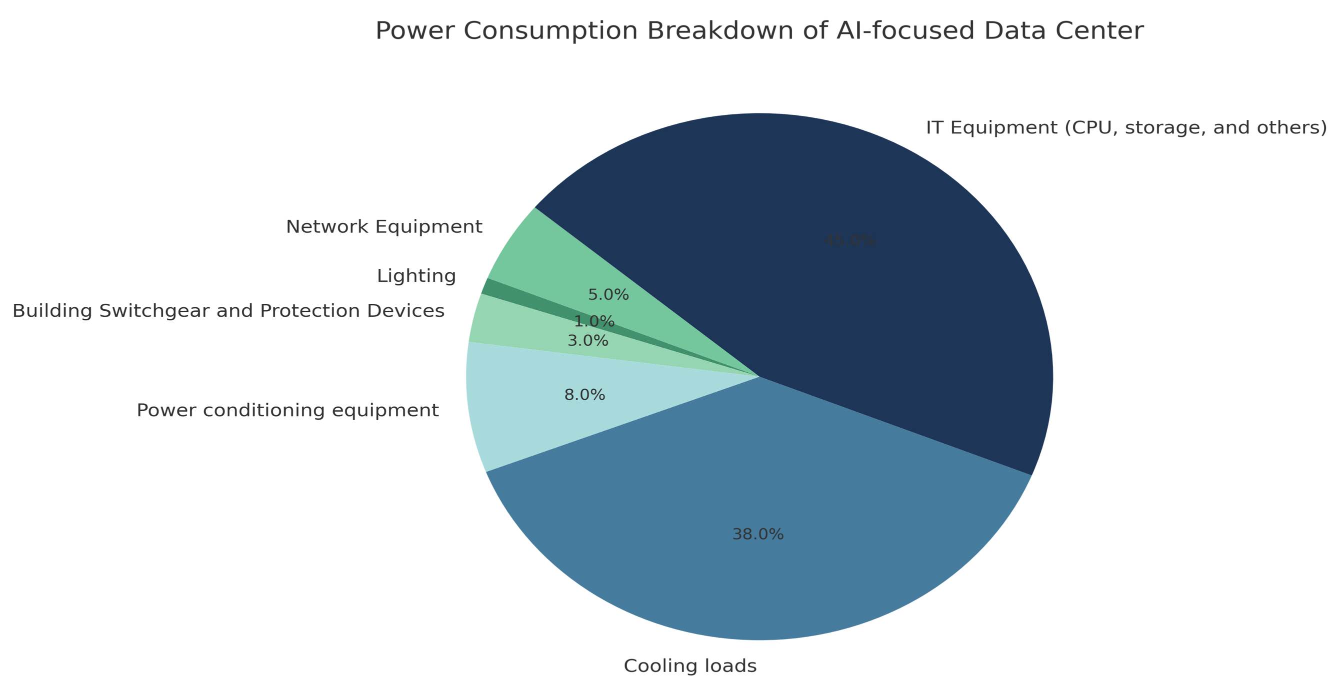
ABSTRACT: The International Energy Agency's Technology Collaborative Programme (IEA TCP) on High Temperature Superconductivity (HTS) is conducting a research project that explores how the use of HTS offers a transformative solution for data centers by reducing energy consumption and enhancing computational efficiency. Traditional data centers face substantial power and cooling demands due to the high energy dissipation of conventional electronic components. HTS materials, which exhibit zero electrical resistance above the boiling point of liquid nitrogen (77 K), enable the development of ultra-efficient power distribution systems, superconducting interconnects, and cryogenic computing technologies. One key application of HTS in data centers is in superconducting power cables, which minimize resistive losses and improve power delivery efficiency. Additionally, HTS-based cryogenic processors can dramatically reduce heat generation while increasing processing speed. By operating at cryogenic temperatures, HTS systems have the potential to enable more effective thermal management, reducing the need for conventional cooling solutions and further cutting energy costs. The integration of HTS technology can lead to data centers with higher performance, lower operational costs, and a smaller environmental footprint. While challenges remain in material scalability, refrigeration infrastructure, and standardization, ongoing advancements in HTS research and manufacturing are making superconducting data centers increasingly viable. As demand for high-performance computing and artificial intelligence-driven workloads continues to grow, HTS presents a promising path toward more sustainable and efficient data center architectures.

1. What is the IEA HTS TCP?

The IEA HS TCP [1] is a co-operative program with the aim of assessing the impacts of high-temperature superconductivity on the electric power sector. Its member countries span three continents (America, Asia and Europe) and constitute an un-biased, privileged observatory to follow the developments of HTS applications, to share information about projects and demonstrations, to be in contact with the main industrial players, and to investigate potential emerging sectors, such as the application of high-temperature superconductivity in data centers.

2. The benefits and challenges of using High-Temperature Superconductivity in data centers

Evocative image of a data center interior with superconductive technology (AI generated)



Data centers are relatively new actors in the energy system at the global level, but their share of electricity demand has exploded in just a few years as artificial intelligence (AI) has become widespread. According to IEA [2] today's AI-focused data centers consume as much electricity as 100,000 households, but the largest ones under construction will consume 20 times as much. IEA estimates that global data center electricity consumption will double in just five years, reaching 945 TWh by 2030, which will represent just under 3% of total global electricity consumption, or approximately what Japan consumes today.

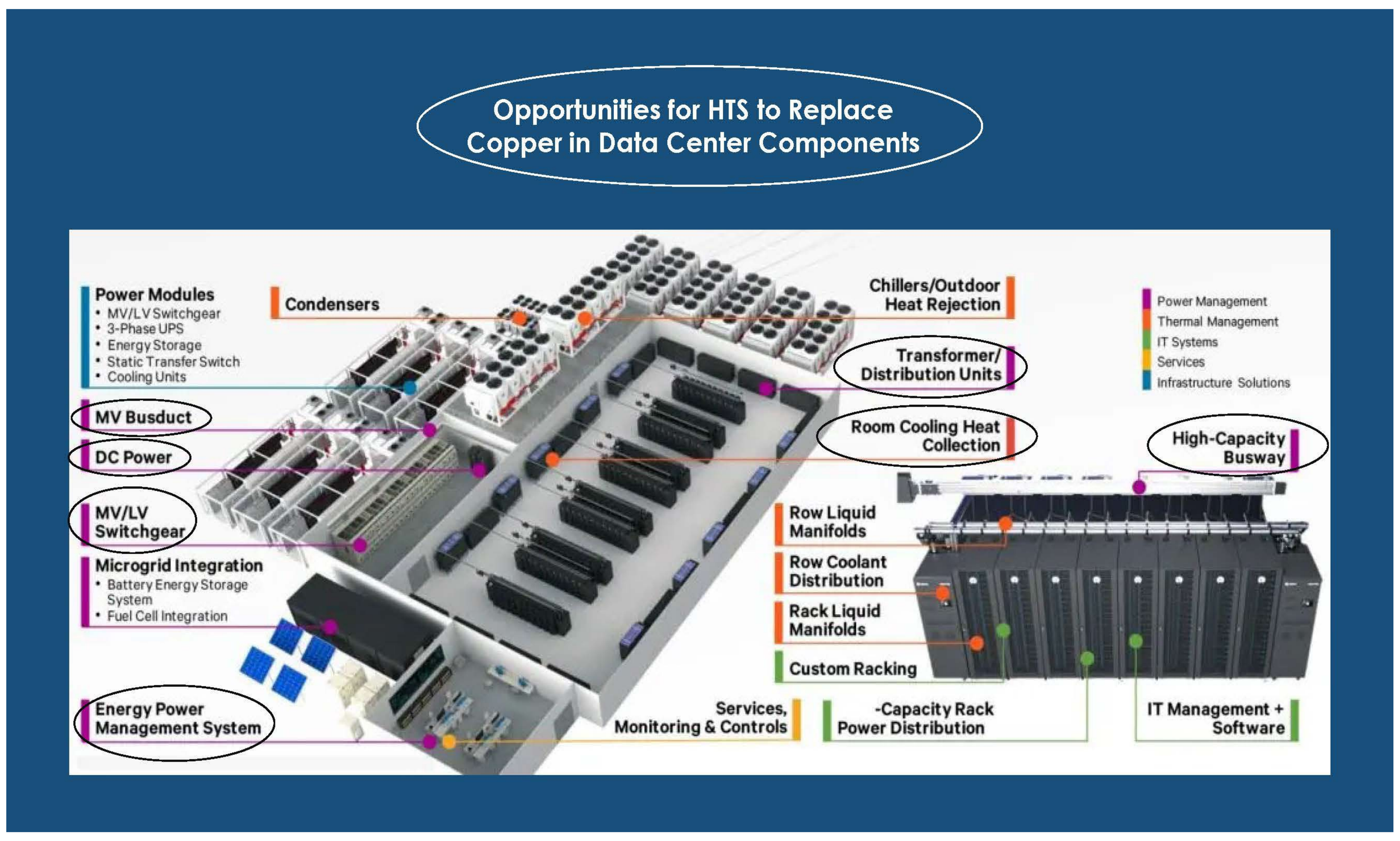
Energy savings and efficiency are, therefore, critical goals of data center development, especially for future hyperscale types projected to consume hundreds of megawatts of electricity. Many authors have highlighted the benefits of using high-temperature superconductivity technologies in data centers to achieve these goals. On the **computing-side,** some benefits can arise from low temperature applications, such as in the Imec's superconducting processors [3]. On the power distribution side, traditional AC-based systems suffer from multiple conversion stages and resistive losses, which account for up to 15–30% of total energy waste. By contrast, **superconducting busbars and cables offer zero-resistance transmission, drastically reducing losses and heat dissipation**. A recent IEEE study [4] demonstrated that replacing copper with HTS cables in low-voltage DC (LVDC) distribution can achieve >98% efficiency beyond 25 m, while **integrating superconducting magnetic energy storage (SMES)** [5] improves power quality and resilience. Building on this, Chen et al. [6] proposed and evaluated a **10 MW-class data center architecture using superconducting DC busbar networks**. Their design achieves ultra-dense energy distribution with minimal conversion stages, reducing electrical losses by up to 90% compared to conventional AC systems. The economic analysis shows that, despite higher initial capital costs, the total cost of ownership becomes favorable within 3–5 years due to significant energy savings and reduced cooling requirements. The use of HTS DC cables also enable the **delivery of renewable energy to large-scale (100 MW) data centers** [7] increasing with an expected cost reduction; HTS systems reduce operating costs by 10–50× compared to AC/DC systems) and CO_2 emissions reduction (lower energy losses and integration with renewable sources).

Industry-driven designs, such as the superconductive Data Center EOS specification, align with these findings by proposing a 380 V DC backbone with superconducting busbars cooled by liquid nitrogen, eliminating UPS systems and power shelves, and enabling 30% higher rack density [8]. Modular Data Centers (MDCs) optimized for AI workloads with superconductive busbars, bi-directional microgrids, and direct-to-chip liquid cooling are also analyzed in [9]. These MDCs support rack densities exceeding 100 kW and simplify electrical infrastructure by avoiding medium-voltage distribution inside the white space. Superconductors not only eliminate voltage drops but also enhance stability and safety, thanks to their zero fire load and integrated nitrogen-based cooling.
However, at present, HTS technologies still face some **challenges**, among which the high initial capital cost, the cryogenic cooling requirements, the complexity of integration, the proof of reliability and maintenance, and the standards and certification gaps. Some emerging applications, such as HTS magnets for fusion, could accelerate cost reduction, massive manufacturer and wide commercialization of these components [10].

3. The stakeholder's point of view: QTD Systems

QTD Systems owns and operates a 20,000-square-foot data center in downtown New York, New York that serves as a real-world living laboratory for integrating, testing, and demonstrating next-generation data center components like HTS technologies. QTD Systems is exploring the development of a superconducting data center, seeing potential in replacing copper with high-temperature superconducting (HTS) cables for most system components, including the Energy Power Management System, MV/LV Switchgear, DC power systems, condensers, room cooling, heat collection, transformers/distribution units, and high-capacity busways. QTD has assessed several benefits of deploying superconducting cables in data centers, which can lead to reductions in various costs, including capital expenditures(CAPEX), operational expenditures (OPEX), cable costs, maintenance expenses, and the need for electrical transformers, ranging from 10% to 50%.Additionally, incorporating superconducting technologies in data centers will support the introduction and integration of quantum computing.

However, QTD has identified significant challenges to adopting HTS cables and superconducting devices in data centers, including concerns about the risk of cable failures compared to copper, a shortage of trained engineers and technicians, the need for mechanical system contractors for widespread cryogenic installations and service, and a necessity to scale-up operations to effectively reduce costs. Currently, only cryogenics systems for medical devices and research, for instance, are available as commercial products, which are too small for data centers of any scale. These challenges must be addressed to fully realize the advantages of superconducting technology in data centers.



4. Conclusion

Based on literature, members' information, and stakeholder contributions, the IEA HTS TCP identified the main benefits and challenges of applying superconductivity in data centers, an emerging and promising sector. With respect to other sectors involving HTS applications, i.e. the power grid, innovation is necessary for data center developers to control costs and resource requirements like land, water, and energy. The availability and readiness of the stakeholders could play a fundamental role in accelerating the development and application of proper and effective HTS solutions. The huge expected market of data center and superconducting data center can also act as leverage for the success of other HTS grid applications.

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