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EDITORIAL FOCUS



Data Centers

An exclusive collection featuring top-tier articles, visionary experts, and essential industry insights

April 2026 - Edition 1

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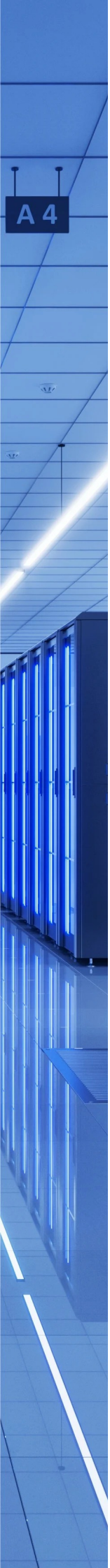
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Foreword

Welcome to the latest edition of our Editorial Focus eBook, where we explore the rapidly evolving world of data centers. As the digital backbone of modern life, data centers support everything from cloud computing and artificial intelligence to global communications and critical business operations. As demand continues to grow, so too does the need for smarter, safer, and more sustainable infrastructure.

This collection highlights the technologies and ideas shaping the future of the sector. In **A2L Leak Detection in Data Center Air Cooling**, we examine the importance of advanced refrigerant monitoring in maintaining safety and efficiency in increasingly sophisticated cooling systems. **Circuit Protection Needs in Server Rack Power Distribution Units** also underscores the vital role of reliability and protection in supporting uninterrupted performance. We are proud to present this eBook in partnership with our sponsor, Sensata.

Sustainability is another major theme running through these pages. **Building Sustainable Data Centers: Innovations in Materials and Energy Use** explores how material science and energy-conscious design are helping facilities reduce their environmental footprint. **What are the Environmental Consequences of Data Centers?** and **Why is Emissions Compliance Critical for Data Centers?** further examine the broader ecological impact of this growing industry and the steps needed to ensure responsible progress.

Innovation is also driving exciting new possibilities. **What to Know About Integrated Photonics in Data Centers** looks at how photonics could transform data transfer and efficiency, while **Grid-Forming Inverters: Shaping the Future of Power Systems** considers the evolving power technologies needed to support resilient operations. In **The Role of Automation in Next-Generation Green Data Centers**, we see how robotics and intelligent systems are helping operators optimize performance in real time.

Finally, **Could we Really Have Data Centers in Space?** offers a fascinating glimpse into a future that once seemed firmly in the realm of science fiction.

As you explore this eBook, I hope you are inspired by the ingenuity, ambition, and interdisciplinary innovation driving the next generation of data centers.

A2L Leak Detection in Data Center Air Cooling

Data centers are essential infrastructure in today's world. They house, process, and analyze immense volumes of data; data centers are key to the digital transformation occurring worldwide.



Image Credit: Chaosamran_Studio/Shutterstock.com

With data use escalating and the drive for efficient energy use and sustainability ever increasing, data center power demand is rising consistently - creating an urgent need for conventional cooling strategies to be reevaluated.

The global drive to lower carbon emissions, along with updated environmental regulations such as the Kigali Amendment, the U.S. AIM Act, and the EU F-Gas Regulation, is compelling the HVAC industry to phase out refrigerants with high global warming potentials (GWPs) and adopt refrigerants with considerably reduced climate impacts.

Distinguished by their low GWP, A2L refrigerants offer a compelling alternative, delivering on performance while supporting sustainability goals. However, they are classified as mildly flammable, requiring additional mitigation measures.

The redevelopment of data center cooling units to support A2L refrigerants requires novel components for detecting leaks of these refrigerant gases and ensuring overall system safety in air cooling systems, which commonly depend on computer room air conditioning (CRAC) or computer room air handling (CRAH) units to circulate cooled air for heat removal from server

racks. Without devices to track refrigerant depletion, these systems face peril.

The Solution

Safety is central to adapting A2L refrigerants to meet environmental and regulatory requirements. A2Ls offer low GWP and effective cooling capabilities, but they are mildly flammable.

Integrating these refrigerants into critical operational environments requires early, accurate leak detection to ensure safety, uptime, and regulatory compliance.

Sensata's Resonix™ MGD leak detection sensor represents an efficient solution, providing swift response and activation times to identify potential complications. Engineered specifically for A2L refrigerants, the sensor enables real-time, continuous monitoring at detection levels well below the Lower Flammability Limit (LFL).

With this early alerting functionality, data center operators can identify and address refrigerant leaks before they pose operational hazards or compromise efficiency. These sensors comply with rigorous international safety standards, confirming their suitability for use in critical data center infrastructure.

Featuring both relay outputs and Modbus interfaces, sensors can be seamlessly integrated into data center platforms for real-time leak detection, alert activation, and automated system shutdowns when required. These sensors are ideally suited for installation in confined spaces used for equipment storage, such as beneath elevated floors or near CRAC units or refrigerant lines.

The incorporation of gas leak detection sensors into A2L air-cooling systems not only helps data centers meet regulatory mandates but also safeguards operational continuity, personnel safety, and prolonged infrastructure reliability. As refrigerants with low GWP become the prevailing industry standard, technologies such as Resonix™ will be instrumental in enabling the next generation of sustainable data center cooling.

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Building Sustainable Data Centers: Innovations in Materials and Energy Use

From rare earth recycling to AI-managed cooling, engineers are racing to make data centers less wasteful and more resilient.



Image Credit: kwarkot/Shutterstock.com

At the end of 2024, data centers accounted for approximately 1-1.2 % of global electricity use and around 0.4 % of greenhouse gas emissions, with figures projected to rise as artificial intelligence (AI), blockchain, and cloud computing scale globally.[1]

The International Energy Agency warns that without major innovation in materials and energy efficiency, this trajectory threatens to undermine net-zero ambitions.[2]

Sustainability in data centers is not simply an engineering challenge but a scientific and ethical imperative.

The Limits of Sustainability in Data Centers

Although digital systems may seem intangible, a world built in the ether, their foundations are firmly tethered to the physical world. Servers, storage units, and network devices depend on metals such as cobalt, lithium, tantalum, and indium, which are all limited in supply, concentrated in specific regions, and often extracted through processes that harm the environment.[2]

The production of each high-density server also generates substantial embodied carbon emissions during manufacturing and transportation. As Meinhold *et al.* (2025) argue, the

depletion of such materials highlights the catch-22 in digital sustainability: technological efficiency gains are often offset by rebound effects in resource consumption.[2]

The physical limits of computation also impose a baseline energy cost. Most of a data center's electricity is consumed not by computation but by the cooling systems that maintain stable operating temperatures.

The Power Usage Effectiveness (PUE) ratio, which compares total facility energy with IT energy, illustrates this inefficiency: the global average remains close to 1.5, meaning that every watt of computational power requires roughly half a watt more for supplementary operations.[2]

To address these constraints, researchers and industry leaders are redesigning materials, rethinking energy flows, and integrating renewable and circular systems.

Advanced Cooling Technologies for Energy-Efficient Data Centers

As the largest non-computational energy burden, cooling equipment accounts for over a third of total electricity consumption in many facilities. The transition from air-based to liquid-based cooling is a significant advancement in making this process more efficient.[3]

According to Chidolue *et al.*, liquid immersion cooling, hot aisle containment, and free-air cooling can dramatically improve efficiency by optimizing heat transfer and reducing dependence on compressors and refrigerants.[3]

Google's Hamina data center in Finland demonstrates this innovation at scale. Using seawater for indirect cooling, it has reduced cooling energy by up to 80 % while eliminating refrigerants entirely.[4]

In a similar move towards sustainability, Microsoft's "Project Natick" tested underwater data centers cooled by ocean currents, achieving up to 40 percent energy savings compared to traditional onshore facilities. These examples show how integrating natural environments into design can redefine thermal management.[5]

An emerging field in developing sustainable data centers is waste heat recovery, where expelled heat is captured and reused for district heating.

For example, Meta's Odense data center in Denmark recycles around 100,000 MWh of heat each year, enough to warm about 11,000 homes.

This closed-loop approach demonstrates how the byproducts of computation can be transformed into valuable community resources.

Rare Earth Recycling and Circular Design

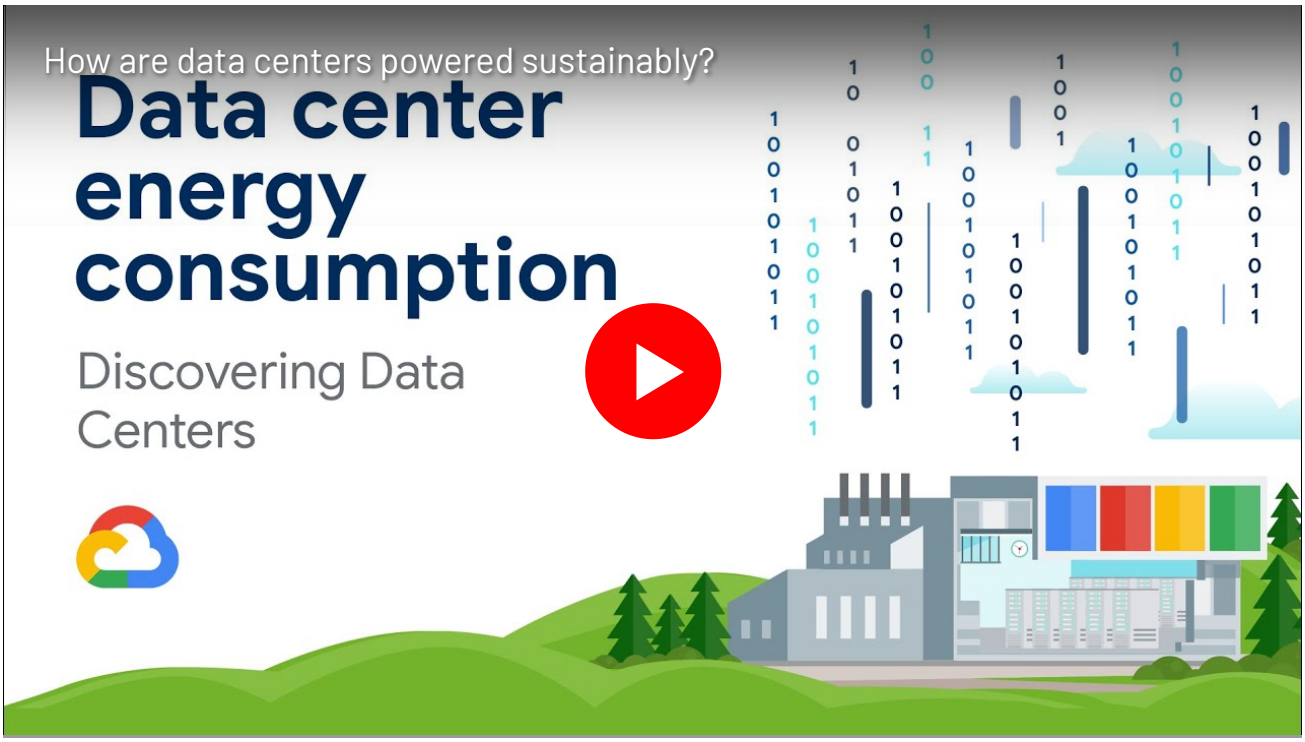
The sustainability of data centers also depends on the materials that compose them. Servers and IT equipment typically have life cycles of only three to five years, leading to large volumes of electronic waste and loss of valuable rare earth materials.[6]

To address this, data center design is increasingly emphasizing modular construction and recyclability. Companies such as Dell and HP now produce servers with standardized, easily disassembled components, simplifying material recovery and reuse.[7]

Efforts to reduce embodied carbon extend to the buildings themselves. Murino *et al.* highlight green building strategies such as low-carbon concrete, cross-laminated timber, and passive ventilation, which significantly reduce lifetime emissions.[6]

Circularity extends beyond materials to energy flows. The integration of renewable energy, storage systems, and intelligent grid balancing forms the basis of sustainable energy management.[8]

On-site solar arrays, wind turbines, and batteries enable facilities to operate independently of fossil fuel grids, while AI-based control systems optimize load distribution and minimize waste in real-time.[7]



Video Credit: Google Cloud Tech/Shutterstock.com

How AI is Optimizing Energy Use in Data Centers

Although artificial intelligence is energy-intensive in itself, it has become a key tool in enhancing sustainability. AI-driven data center infrastructure management systems continuously monitor conditions and adjust cooling loads, server use, and power allocation.[2] Google DeepMind's collaboration with Google Data Center Operations achieved a 40 % reduction in cooling energy use through machine learning optimization.

Similarly, OpenAI uses artificial intelligence–driven resource scheduling to balance computation across GPUs and CPUs, reducing idle energy use.[2] These feedback systems represent digital sustainability in action, applying intelligent control to lessen the environmental impact of digital infrastructure.

Liquid Cooling and Sustainable Water Use

While liquid cooling greatly improves energy performance, it raises new sustainability challenges regarding water use. The U.S. National Renewable Energy Laboratory estimates that data centers consumed over 600 billion liters of water in 2014, primarily for evaporative cooling.

To address this, many facilities have begun a transition to closed-loop cooling systems that rely on non-potable or recycled water.

Microsoft's Arizona data center, for example, operates with zero freshwater consumption, reusing treated wastewater for heat exchange. Meanwhile, Google has committed to being water positive by 2030, returning more water to ecosystems than it withdraws.

These measures highlight the need to strike a balance between energy efficiency and responsible water management, a dual priority for the next generation of data centers.

Sustainable Data Center Construction

Sustainability principles now extend to the architecture and location of data centers. The idea of building with place, which means adapting design to local environmental conditions, has become central to green construction.[3]

Iceland's Verne Global center exemplifies locational efficiency. Powered entirely by geothermal and hydroelectric sources and benefiting from the island's cool climate, it operates without mechanical chillers.



Image Credit: Verne Global

Circular Energy Models and Policy Integration

The broader vision of sustainable data centers aligns with the principles of the circular economy, which emphasize minimizing waste, maximizing reuse, and closing resource loops.

Energy reuse, renewable sourcing, and recyclable materials converge within transparent regulatory frameworks. Metrics such as PUE, Water Usage Effectiveness (WUE), and Carbon Usage Effectiveness (CUE) have become industry standards for measuring environmental performance.[9]

Murino *et al.* emphasize the importance of embedding these metrics into corporate compliance systems to ensure accountability and accelerate progress.

On a policy level, the European Union's "Climate Neutral Data Centre Pact" requires all EU data centers to reach carbon neutrality by 2030, establishing clear targets for renewable integration, heat reuse, and lifecycle transparency. Such frameworks translate voluntary innovation into enforceable standards, driving sector-wide consistency.[6,10]

The Future of Data Center Sustainability

The journey toward sustainable data centers is not a simple tech upgrade, it's a systems-level redesign of how digital infrastructure interacts with the planet. Innovations in materials, cooling systems, renewable integration, and AI-driven management represent vital progress toward reducing environmental impacts.

The data center of the future must embody not only efficiency but also ecological reciprocity, creating facilities that recycle heat, reuse materials, and regenerate water. In this vision, digital progress becomes a process of coexistence rather than consumption, where the growth of computation aligns with the restoration of the planet.

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Could we Really Have Data Centers in Space?

For decades, data centers have operated quietly in secure, often unremarkable buildings, spanning acres of land, demanding massive amounts of energy, and typically consuming millions of liters of water to keep servers cool. But over the past five years, the surge in Artificial Intelligence (AI) and cloud computing has driven rapid global expansion of data center infrastructure. In response to growing concerns over water use and energy efficiency, leading tech companies and researchers are now looking upward, actively exploring the potential of placing data centers in space. The concept of orbital data infrastructure is becoming a serious area of research and development.

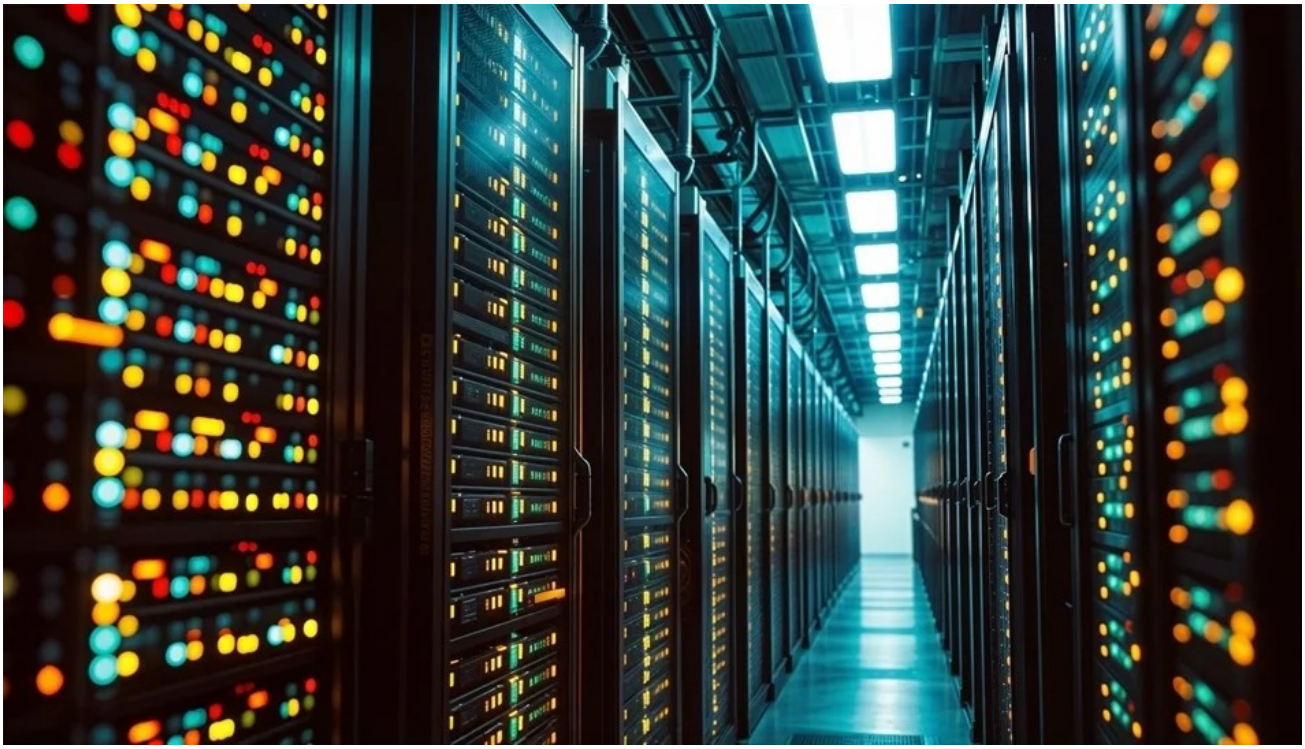


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Major Ecological Challenges for Terrestrial Data Centers

AI, cloud computing, and digital tools hosted in the cloud have become essential for professionals and organizations worldwide. This widespread adoption has dramatically increased the demand for online computational resources. However, traditional terrestrial data centers come with steep operational costs, particularly when it comes to power and cooling. Maintaining optimal temperatures for high-performance servers often requires specialized cooling fluids and significant amounts of water, leading to massive energy bills and ongoing sustainability concerns.

As reliance on AI and IoT-driven cloud tools continues to grow, so too does the power demand of modern data centers, bringing with it a corresponding rise in carbon dioxide emissions. In an effort to curb environmental impact, some operators have turned to "free cooling" methods that use outside air or naturally cool environments to regulate temperature. While this approach offers some benefits, its effectiveness is limited. For most large-scale operations, water and specialized cooling fluids remain essential to maintain the precise thermal conditions needed for optimal performance.[1]

Heavy Investments in Sustainable Cloud Operations

Governments around the world are aligning their policies with the pursuit of Sustainable Development Goals (SDGs), with a strong emphasis on ecological sustainability. The United States government, the European Commission, and countries such as China and Japan have all shown full support for digitalization initiatives led by major tech companies, particularly those that prioritize energy efficiency and environmentally responsible innovation. These efforts reflect a broader commitment to leveraging digital transformation as a pathway to sustainable growth.

Hyperscalers like Amazon Web Services (AWS), Microsoft, and Google are investing in promoting and purchasing clean and green energy, with AWS being committed to utilize renewable energy for all operations in the coming years. Using energy efficient operational frameworks, and machine-learning (ML) based heating and cooling solutions, Google has saved around 20 billion kwh energy by 2023.[2] In 2024, Microsoft has also announced that around 70% of its data centers are utilizing renewable energy for operations, utilizing AI-driven tools for controlling emissions.[3]

These tech giants are also showing growing interest in space-based data centers, viewing them as a promising long-term solution to the environmental issues they pose. Google is investing in and researching a moonshot project, titled “Project Suncatcher,” which will utilize a highly organized framework of solar-powered satellites utilizing Google TPUs for developing an orbital infrastructure for powering and scaling cloud operations.[4] NVIDIA is pioneering “Project Inception,” which involves sending an AI-equipped satellite from Starcloud serving as the initial step to develop state-of-the-art data centers in outer space.[5] These strategic investments signal a clear belief that space-based data centers could play a key role in the future of sustainable, energy-efficient digital infrastructure.

Concept and Feasibility of Space Data Centers

Space-based data centers are expected to play a pivotal role in enabling future technological

advancements. A critical goal researchers are working toward is achieving what's known as "Earth Independence." This concept envisions orbital data centers capable of supporting AI and cloud operations entirely from space, without relying on terrestrial power, water, or cooling resources. If realized, it could dramatically reduce the environmental footprint of digital infrastructure and redefine how global computing systems operate.[6]

Space-based data centers could also support carbon neutrality. By harnessing abundant solar energy through highly efficient solar cells, these centers offer a far more sustainable way to power digital operations. Researchers and private companies are focusing on two primary models: orbital edge data centers and orbital space data centers.

Orbital edge data centers are designed for localized data processing closer to where data is generated, helping reduce latency and bandwidth load. In contrast, orbital space data centers are intended to handle large-scale, complex, and resource-intensive operations that support AI, cloud computing, and global digital services on Earth. Together, these frameworks could form the backbone of a cleaner, more resilient digital infrastructure.

The Orbital Edge Space Data Center Framework

Orbital edge data centers are equipped with advanced data sensors and highly optimized processors, such as AI accelerators tailored for tasks like vision processing. These centers draw power from large solar panels and maintain performance using active radiative cooling systems, designed to manage heat efficiently in the vacuum of space.

Their processing framework significantly enhances the computational capabilities of satellites, enabling powerful edge computing directly in orbit. This setup not only reduces the need for constant data transmission back to Earth but also allows for real-time analysis and decision-making in space. Companies like AMD have contributed to this frontier by developing specialized "radiation-hardened" accelerators and CPUs, built specifically to withstand the harsh conditions of space while delivering high-performance computing.

The Orbital Cloud Space Data Center Framework

Orbital cloud data centers share many similarities with edge data centers but come with a few key functional distinctions. These systems can be thought of as a constellation of specialized computational satellites operating in Low Earth Orbit (LEO), typically a few hundred kilometers above the Earth's surface.

While orbital edge data centers focus on localized, near-instant processing, orbital cloud data centers are designed for broader, large-scale cloud services, acting as an extension of

traditional cloud infrastructure, but from space. This setup enables high-speed, low-latency processing and data delivery across regions, while reducing the reliance on energy-intensive, Earth-based facilities.

Each of these satellites is equipped with broadband connectivity and specialized high-speed servers. Specially fabricated, highly compact components like computational processing chips (CPUs), RAM, ultra-fast storage components like SSDs, GPUs, and an operating system ensure that the servers work in parallel without any obstruction. The power to operate these components is delivered via an array of large solar cells, with each component and the body fabricated with radiation shielding coatings and specialized materials.

While low-power processors and chips in space can often rely on passive cooling, the demands of highly complex orbital data centers require a more advanced solution. These systems are equipped with active radiative cooling mechanisms specifically designed to dissipate large amounts of heat into the cold vacuum of space.

As with other components onboard, the cooling infrastructure is engineered to be both compact and energy-efficient. This ensures not only thermal stability but also supports multi-cloud capabilities while keeping operational costs low, a critical balance for maintaining performance and sustainability in space-based computing environments.[7]

Commercial Advantage

High-intensity solar power is estimated to drastically slash the energy costs for AI model training. Carbon emissions from space-based data centers are estimated to be 10 to 20 times lower than those of traditional terrestrial facilities, even when accounting for the greenhouse gases released during rocket launches.

In addition to lower costs and environmental footprint, the space-based data centers allow low-latency data transmission and internet connectivity to even remote and harsh areas like the polar regions. Space-based data stations offer a vital advantage by providing reliable data access to even the most remote regions on Earth. Their ability to maintain seamless service, especially during natural disasters, makes them a powerful tool for emergency response and continuity.

With significantly lower latency, these systems enable faster, real-time processing, which can dramatically improve response times in crisis scenarios. Beyond disaster relief, this capability also opens new frontiers in national defense and environmental monitoring, offering faster insights, broader coverage, and enhanced situational awareness in critical moments.

The autonomy of space-based systems, operating independently of ground-based resources, paves the way for rapid and flexible scalability. Unlike terrestrial data centers, which are constrained by land availability, zoning regulations, and infrastructure costs, orbital facilities eliminate these limitations entirely.

By removing the burden of territorial land use, space-based data centers offer virtually unlimited physical room for expansion. This not only supports future growth in AI and cloud computing demand but also allows for strategic deployment tailored to global coverage and efficiency.[8]

Technical Challenges

Despite the benefits associated with space-based data centers, there are certain critical technical and business challenges associated with them. First of all, launching a satellite into orbit for the transport of crucial components is highly expensive, with estimates ranging from 8.2 million USD for a single launch. In addition, the harsh conditions of space, such as cosmic radiation and space debris, can lead to more frequent failures and data corruption, resulting in increased maintenance needs.[9]

Moreover, extensive research is needed to develop a framework that can overcome atmospheric interference and maintain low latency. One of the key challenges lies in enabling reliable inter-satellite communication while ensuring adherence to precise orbital formation control.[10]

Radiation damage and orbital debris risk are a major threat limiting the life-cycle of space-based data centers. Even the specially designed, highly complex state-of-the-art International Space Station (ISS) has a limited lifespan and is expected to be decommissioned around 2035 due to the vacuum, radiation, and temperature-based abnormalities. What's more, in case of any mishaps or hardware damage, specialized teams and missions would be required in space, making the repairs highly complex and quite expensive.[11]

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Grid Forming Inverters: Shaping the Grid for the Future

The increasing penetration of Inverter-Based Resources (IBRs), along with the rapid growth in electricity demand driven by artificial intelligence (AI) and data centers, poses unprecedented challenges to the modern power grid. Traditional synchronous generation is retiring faster than firm capacity is being added, which compromises system stability and increases the risk of large-scale power outages. To address this, grid-forming (GFM) inverter technology is emerging as a key solution to enhance system resiliency, provide virtual inertia, and support weak grid conditions.

What is Grid Forming Technology?

The concept of grid-forming control was originally introduced for microgrids and islanded systems, but has now become essential in large, interconnected networks with a high share of power electronics-based generation. The grid forming inverter behaves like a voltage source and creates the AC voltage reference (frequency & amplitude) rather than only following the grid as has been the case with traditional solar and storage inverters for the past several decades. Grid forming inverters can provide virtual inertia, primary frequency response, voltage regulation, and ridethrough.

Download the Whitepaper here

Circuit Protection Needs in Server Rack Power Distribution Units

The global rise in computing power has driven steady growth in telecommunications and server infrastructure. As data center technologies continue to advance rapidly, their power systems have evolved alongside them.



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Data center architecture has shifted from 120 VAC and 208/120 VAC to 208 VAC Delta, 230 VAC, and 240 VAC voltage levels. Server racks can now accommodate increasing volumes of data in progressively smaller spaces.

Managing power delivery to these units relies on rack power distribution units (PDUs), typically positioned vertically inside the IT rack enclosure. A thin power strip package is also beneficial for enhancing equipment airflow cooling and simplifying cable organization – placing greater importance on the dimensions of the circuit breakers housed within.

Regarding performance, the interrupting capacity of these breakers continues to increase. This is partly driven by insurers that assess the risks associated with both technology and

server expenditures, as well as the potential liability for data stored.

The Approach

Collectively, these developments have generated substantial demand for UL-listed circuit breakers rated at 240 VAC.

Sensata | Airpax LEJ and LUX series are well-suited for these applications. Being UL489 listed, their compact form factor contributes to achieving the slender profile sought after in this type of equipment.

The LEJ series has been enhanced to accommodate current ratings up to 30A. Its 10 kA interrupting capacity delivers the performance required to handle the demands of these high-value facilities. Additional attributes of the LEJ series are engineered for optimal fit in datacom applications, including rear-access terminal screws that facilitate straightforward assembly and wire routing within confined enclosures.

The LEX series is also an excellent choice for datacom applications. Its even more compact design (39.6 mm depth compared to 52.6 mm standard LEJ depth) offers an even tighter footprint.

Like all Sensata | Airpax hydraulic magnetic circuit breakers, these units are resilient to variations in ambient temperature. They can also be customized with specific trip values to effectively manage the inrush currents inherent in the equipment they serve.



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What to Know About Integrated Photonics in Data Centers

Data centers play an important role in storing, processing, and managing vast amounts of data. Integrated photonics uses light to transmit data, offering high bandwidths and improved energy efficiency compared to traditional electronic elements. This article discusses integrated photonic elements, their background, use in data centers, and recent relevant studies.



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What are Integrated Photonics?

Integrated photonics involves fabricating and integrating various photonic elements, like interferometers, polarisers, couplers, gratings, beam splitters, etc, onto a shared planar substrate. These components serve as foundational elements for constructing more intricate planar devices, enabling a diverse range of functionalities applicable to optical communication systems, instrumentation, and sensor technologies.

Integrated photonics combines optics and electronics to create compact and integrated optical circuits that rely on photon manipulation to transmit and process information. For instance, in data centers, where rapid data transfer is critical, integrated photonics presents a compelling alternative to traditional copper-based interconnects.

Brief Background of Integrated Photonics

The evolution of integrated photonics spans over three decades, shifting from early bidimensional optical waveguides to tridimensional structures by the mid-1970s. Pioneering developments in lithium niobate ($LiNbO_3$) at AT&T Bell Labs during the mid-1980s led to integrated intensity modulators and photonic chips with up to 50 switches. The demand surged in the 1980s, aligning with the growth of monomode optical fiber systems. Over the following decades, diverse materials like polymers, glasses, and semiconductors expanded the market for advanced integrated photonic devices, meeting the escalating data transfer needs of the 21st century.

Applications of Integrated Photonics in Data Centers

Optical interconnects are replacing traditional copper-based cables since they facilitate the rapid exchange of data between servers, storage devices, and networking equipment, offering higher data rates, increased reliability, and enhanced overall performance of the data center.

Similarly, optical switches in data centers leveraging integrated photonics are also replacing traditional electronic switches since optical switches enable the rapid routing of data without the bottlenecks associated with electronic switches, resulting in improved network scalability and reduced contention for resources within the data center.

Integrated photonics are also used in photonic processors that offer the potential for significantly higher processing speeds and lower power consumption compared to their electronic counterparts.

Recent Studies

Advancing Data Center Photonics with MEMS Technology

In a 2023 study, researchers introduced a silicon photonic microelectromechanical systems (MEMS) platform that integrates high-performance nano-opto-electromechanical devices with standard silicon photonics foundry components. The technology showcases wafer-level sealing for long-term reliability, flip-chip bonding to redistribution interposers, and fiber-array attachment for high port count optical and electrical interfacing. Overcoming limitations of traditional silicon photonics, the MEMS technology enables compact, low-loss, broadband, and low-power components.

The study demonstrates fundamental silicon photonic MEMS circuit elements like power couplers, phase shifters, and wavelength-division multiplexing devices, paving the way for very large-scale photonic integrated circuits. The applications of silicon photonic MEMS encompass quantum computing, programmable photonics, sensing, neuromorphic computing, and telecommunications, addressing the increasing demand for high-speed transceivers in data centers.

2.5D Integrated Photonics for Data Centers

In another study on integrated photonics in data centers, researchers developed a 2.5D integrated multi-chip module (MCM) for a 4-channel wavelength division multiplexed (WDM) microdisk modulation targeting 10 Gbps per channel. The silicon photonic transceiver design utilized a silicon interposer to establish connectivity between the photonic integrated circuit (PIC) and commercial transimpedance amplifiers (TIAs).

The study demonstrated error-free modulation at 10 Gbps with –16 dBm received power for the photonic bare die and at 6 Gbps with –15 dBm received power for the MCM transceiver. The researchers discussed various integration approaches, including monolithic, 2D, 3D, and 2.5D, highlighting notable demonstrations. Future prototypes involve custom electronic integrated circuits (EICs) for enhanced functionality and scalability in high-performance data centers. The study emphasizes the importance of co-integrating silicon photonics with driving electronics for optimal data center performance.

Advantages and Challenges of Integrated Photonics in Data Centers

There are many advantages of integrated photonics in data centers, including high bandwidth, low latency, energy efficiency, compact design, and improved signal integrity. For instance, optical signals, being immune to electromagnetic interference, can transmit data at speeds higher than electrical signals, allowing for seamless handling of the massive amounts of data generated and processed in data centers. Integrated photonics also allows miniaturization by creating compact and densely packed optical components on a single chip, which saves physical space within data centers and enhances the scalability of the infrastructure.

Although integrated photonics is playing its part in revolutionizing data centers, challenges like integration with existing electronic infrastructure pose technical and compatibility issues. Moreover, the manufacturing cost of integrated photonic components is another concern, although advancements in manufacturing processes are gradually addressing this issue.

Conclusion

In conclusion, integrated photonics presents a transformative solution for data centers, offering high bandwidth, energy efficiency, and compact design. Despite their advantages, challenges such as integration with existing electronic infrastructure and manufacturing costs still need to be addressed. However, as data centers strive to keep pace with the escalating demands of a data-driven world, integrated photonics are gradually becoming a necessity.

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What are the Environmental Consequences of Data Centers?

Environmental concerns related to data centers have been around for years and are only getting bigger. In addition to growing demand for more processing power, driven by the rise of artificial intelligence, massive tech companies have started building hyperscale data centers.



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These new data centers are even more ravenous when it comes to energy, water, and land demands. For example, the previous generation of data centers can demand as much as 10 megawatt hours per month, while hyperscale data centers typically use 100 or more megawatt hours per month.[1]

This article will highlight the environmental consequences of data centers, responses to these consequences, and emerging clean technology solutions.

How Much Energy Do Data Centers Use?

The amount of energy used by data centers is constantly growing. In 2023, data centers in the US used nearly 180 terawatt hours of electricity, representing 4 % of total US electricity demand.[2] By 2028, usage is expected to increase by 6 to 12 %, demonstrating a significant share of the total demand projection of 15 to 20 % through the end of the decade.[3]

Key Environmental Impacts

The environmental consequences of data centers include carbon emissions, high water usage, electronic waste, and land use.

a. Carbon emissions

According to the International Energy Agency (IEA), data centers are responsible for between 1 and 1.5 % of global carbon emissions.[4] However, data centers could be emitting more carbon than has been officially reported.

An independent analysis by The Guardian indicated that real emissions from data centers owned by Apple, Google, Meta, and Microsoft are likely more than 7.6 times their reported emissions.[5]

In addition to carbon emissions, many data centers release large amounts of nitrogen oxides and other pollutants from their backup generators, which are used during high-demand periods.[6] These air pollutants pose risks to human health and the environment.

b. Water use

Data centers use water to cool their servers in two different ways. Evaporative cooling methods release water vapor into the environment, while non-evaporative cooling methods recover water for reuse or discharge it into the environment.

While tech companies are relatively transparent when it comes to releasing data on energy use and emissions, they are less transparent when it comes to reporting water consumption. In a recent report from Google, the company acknowledged that one of its data centers used more than 20 billion liters of water per year, which was used for both cooling and generating electricity.[7]

To make matters worse, many data centers are located in arid regions, especially in the US. Approximately two-thirds of data centers built in the US since 2022 are located in water-stressed regions.[8]

c. Electronic waste and land use

Data centers also generate significant electronic waste and require large tracts of land. Electronic waste typically contains hazardous materials such as lead and mercury. The typical

computer requires more than 800 kilograms of raw materials, which includes rare earth elements that are often mined in non-sustainable ways.[9]

Another key impact of data centers is the significant amount of land they require, which could be left as green space or used more sustainably. For example, Meta is planning a data center in Louisiana to occupy 2,225 acres of former farmland, taking a large swath of arable land off the map. The data center will require significant infrastructure upgrades to support it, but it will only produce several hundred new jobs, which is not a significant increase in tax revenue.



Video Credit: Associated Press/YouTube.com

Industry Responses: Greener Infrastructure

The environmental consequences of data centers are so acute that the tech industry has taken action to address them. Meta has pledged to match its electricity use with clean and renewable energy production for the data center it is planning for Louisiana. The company has also pledged to restore more water than the facility uses.

Other large tech companies have made similar gestures related to their overall operations. Google has pledged to achieve net-zero carbon emissions by 2030, while Amazon has set the same goal for 2040. Notably, smaller tech companies lack the capital to make similar pledges for their data centers.[10]

Clean Technologies Driving Sustainable Data Centers

As technology companies work to make their data centers more sustainable, several key clean technologies are emerging as viable solutions.

a. Liquid immersion cooling and advanced HVAC

Liquid immersion cooling is an emerging approach that involves fully submerging servers in a thermally conductive and electrically nonconductive liquid. The circulating liquid removes heat more efficiently than traditional fans and ventilation.

The latest technologies, such as heat exchangers and high-efficiency filters, make HVAC systems more sustainable by lowering power demands.

b. AI for energy optimization

Companies are increasingly using AI to design, maintain, and optimize the energy efficiency of their data centers. AI can be used for everything from server physical configuration to airflow management and predictive maintenance.

c. Modular data centers

Comprised of prefabricated mobile units with configured equipment, modular data centers allow for more flexibility with respect to location, timing, scaling, and maintenance. Their mobility allows them to be placed closer to renewable energy sources or natural cooling sources, reducing environmental impacts. These data centers also support right-sizing processing power to better fit demand, reducing waste.

d. Battery storage and microgrids

Battery storage and microgrids increase the power resilience of their data centers and improve sustainability when combined with renewable energy sources. Microsoft recently announced it would partner with a microgrid provider and energy project developer to protect a new data center in San Jose from grid outages.[11]

In addition to protecting against outages and supporting renewable energy, microgrids allow operators to route power dynamically based on need. This approach is much more sustainable than building grid infrastructure based on projected maximum demand.

Policy and Standards Supporting Sustainability

Most policies and standards supporting data center sustainability are focused on transparency and providing incentives. In the European Union, the Energy Efficiency Directive compels data center operators to report on their operations' energy performance. The European Commission is responsible for collecting and publishing this data to highlight any data centers "with significant energy consumption."

Some European nations have gone a step further by imposing standards for data center efficiency. In Germany, the Energy Efficiency Act set standards for data center cooling systems and mandates the reuse of energy, such as waste heat.

In the US, the most significant policies are at the state level. Rather than offering unconditional incentives to lure data centers, states are increasingly attaching requirements to incentive packages, often requiring third-party certifications such as LEED. For example, Michigan recently enacted an incentive package that required companies to show their data center uses clean energy, meets specific energy efficiency targets, and is connected to the municipal water system.[12]

Future Outlook: Building the Sustainable Cloud

Advances in clean energy technology will undoubtedly lead to more sustainable data centers, but there are industry-specific developments that have significant potential for a more sustainable cloud.

Direct-to-Chip (DTC) and immersion cooling are being touted as more efficient methods than conventional HVAC cooling. Data center operators are also developing ways to repurpose waste heat. For example, a city district in Dublin is looking to send waste heat from a data center to provide hot water and heating to public housing.[13]

Backed by industry initiatives and public policy, the push toward more sustainable data centers will increase, but so too will the industry's environmental footprint.

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Grid-Forming Inverters: Shaping the Future of Power Systems

The growing use of inverter-based resources (IBRs), combined with rising electricity demand from artificial intelligence and data centers, is creating new and significant challenges for the modern power grid.

The phase-out of traditional synchronous generation is outpacing the addition of reliable capacity, jeopardizing system stability and elevating the likelihood of large-scale power disruptions. To counter this, grid-forming (GFM) inverter technology could be a vital solution for bolstering system resilience, supplying virtual inertia, and supporting weak grid conditions.

Understanding Grid Forming Technology

As a concept, grid-forming control was introduced for microgrids and islanded systems. However, it has now become indispensable in large, interconnected networks that incorporate significant power-electronics-based generation.

A grid-forming inverter functions as a voltage source and generates the AC voltage reference (frequency & amplitude) rather than simply following the grid, as has been the case with traditional solar and storage inverters for decades. Grid-forming inverters can provide virtual inertia, primary frequency response, voltage regulation, and ride-through capabilities.

As renewable energy's share of grid assets rises, GFM technology is expected to play a significant role in supporting grid reliability and facilitating a stable energy transition. Unlike conventional grid-following (GFL) units, GFM inverters can independently support voltage and frequency and contribute to grid stability amid disturbances or in areas with low short-circuit ratio (SCR).

In essence, grid-forming technologies are fundamental to shaping the future grid. With increasing electrification, the proliferation of decentralized energy resources, and the advancement of digital technologies, the power system is undergoing extensive transformation. GFM inverters will serve as the cornerstone of this evolution, facilitating flexible, decentralized, and resilient control of energy flow.

Grid inertia refers to the energy stored in the rotating components of conventional power plants, which acts as a buffer against fluctuations in grid frequency.

A weak grid is defined as one with high source impedance, low short-circuit ratio (SCR), and is therefore prone to voltage swings and stability issues. Generally, a 'weak grid' is characterized as an SCR ≤ 3, a moderately weak one would have an SCR of 3 – 10, and Strong grids have an SCR of ≥ 10. The SCR refers to the ratio of the short circuit capacity of the grid at the Point of Interconnection (POI) to the rated apparent power of the connected inverter-based resource (IBR) or plant.

The Significance of Grid Forming Today

Driven by massive increases in electricity demand from AI and manufacturing, with projections indicating over 800 hours of annual outages by 2030 if capacity is not replaced, the demand for advanced, robust energy solutions is more critical than ever. Given the lower cost of installation and operation of solar and battery energy storage systems ("PVS") compared to new natural gas plants, and their ability to be deployed much faster, projections from NREL suggest a sharp increase in power supply from IBRs. This underscores the necessity of addressing grid inertia in this rapidly evolving energy-landscape.

To accommodate this growth in load while transitioning to cleaner energy sources, the grid needs flexible, resilient solutions. Grid-forming inverters are a technical enhancement essential for future-proofing the grid. Their ability to stabilize voltage and frequency, even when the system is weak or disturbed, makes them a critical tool for achieving reliable, clean power systems.

Dynapower's Grid Forming Control Approach

Dynapower's grid-forming technology is engineered to deliver stability and resilience in challenging or weak grid conditions. It not only introduces virtual inertia to the grid but also provides exceptional active and reactive power dynamics. As a result, these capacities make it ideal for supplying fast-changing loads, such as AI data centers, using renewable energy resources.

Unlike droop control or virtual oscillator methods, Dynapower's grid-forming control employs a model-based, decoupled power-control system operating in the rotating reference frame. The technology eliminates the need for impedance measurement or estimation and enables fast, accurate power tracking without a phase-locked loop (PLL).

It is recognized that grid-following inverters depend on synchronizing with the grid voltage and frequency via a PLL. While this approach works effectively in strong grid conditions, it can pose difficulties for GFL inverters in weak grids, where the grid is more sensitive to changes

and may struggle to maintain synchronization. As a result, the conditions may lead to instability or disconnection (see Figure 1).

Contrastingly, a GFM inverter can establish and maintain voltage and frequency references, even in a weak grid (see Figure 2). This characteristic renders them particularly valuable in areas with low short circuit ratios (SCRs). Operation under weak grid conditions is a primary challenge for modern energy systems, and Dynapower's grid-forming technology addresses this challenge through a robust, self-sustaining control architecture.

Droop control is a method of grid-forming control in which the inverter frequency and voltage are adjusted proportionally to the active and reactive power outputs.

A virtual oscillator is defined as a grid-forming control strategy that causes the inverter to emulate a nonlinear oscillator, naturally synchronizing with the grid and other inverters.

Virtual inertia is a control technique mimicking the inertial response of synchronous machines by temporarily injecting or absorbing power to resist rapid frequency changes.

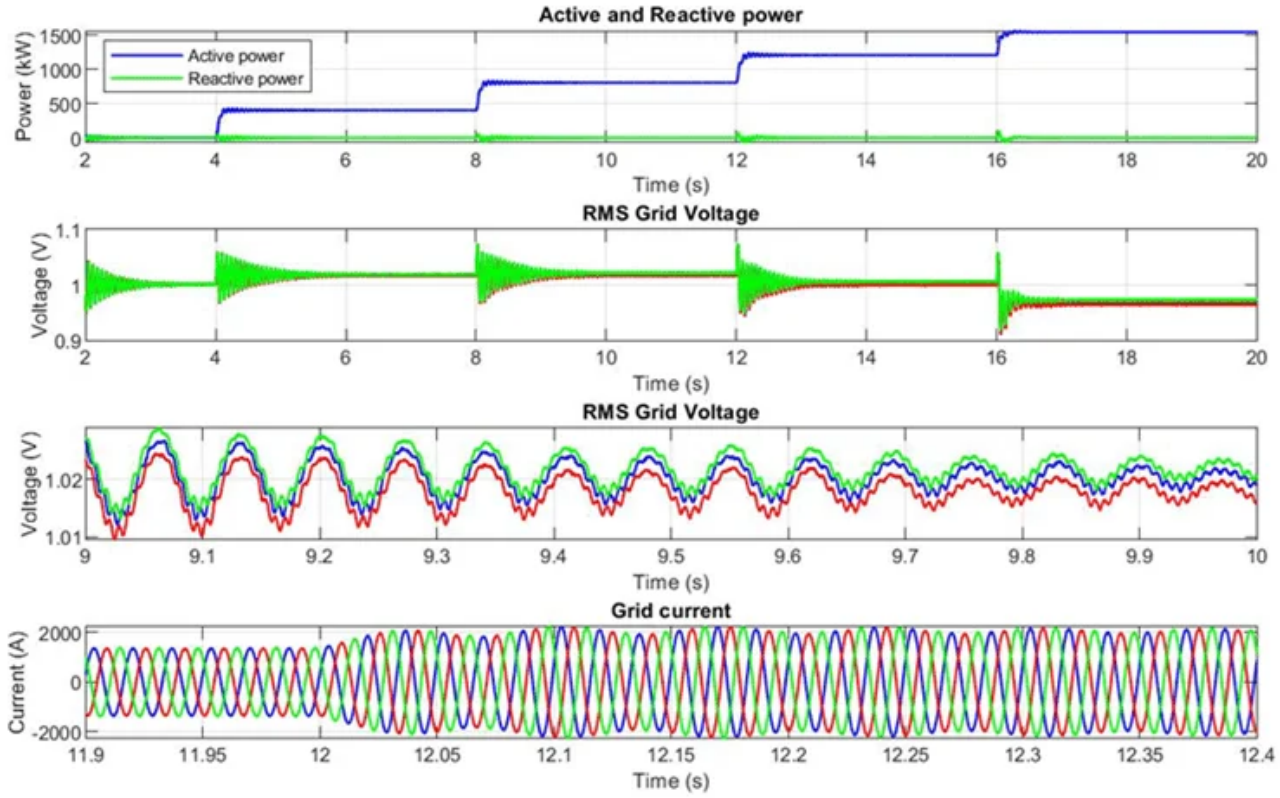


Figure 1. *Grid-following inverter under weak-grid conditions. Image Credit: Sensata Technologies, Inc.*

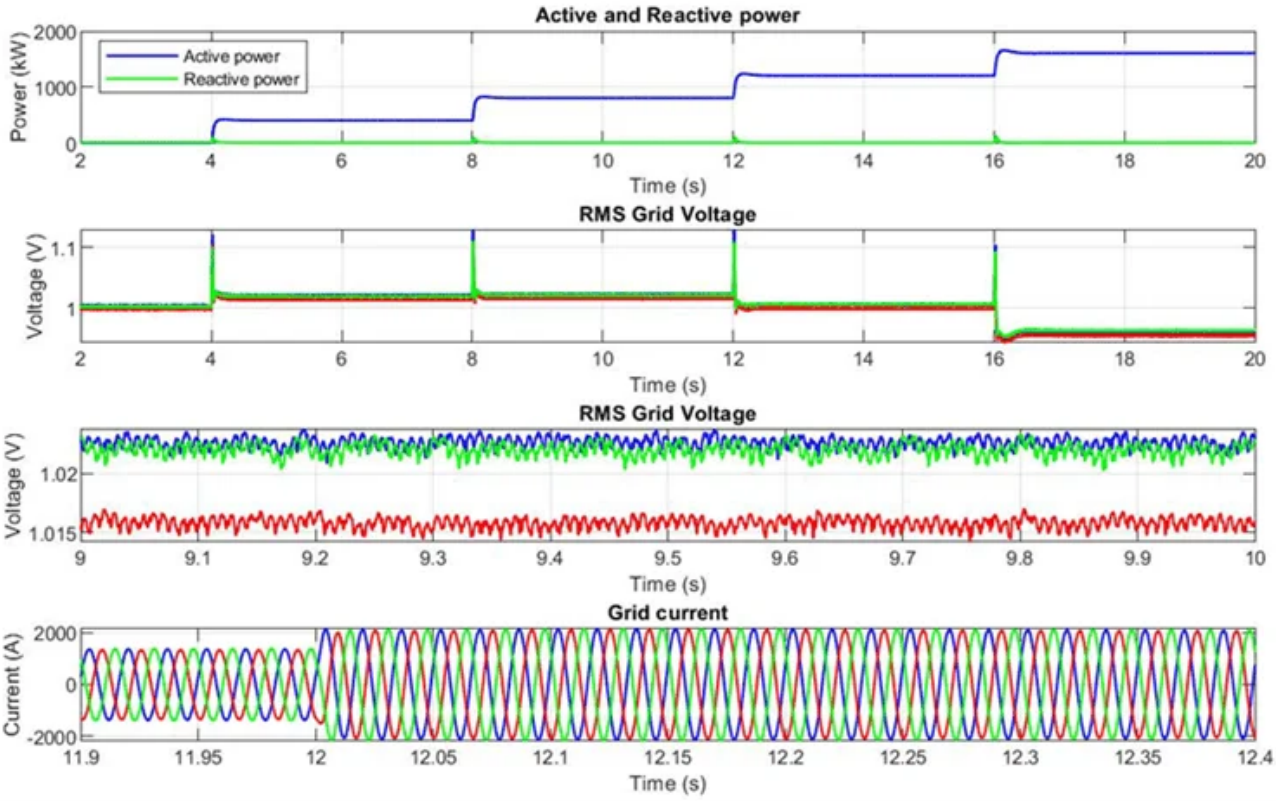


Figure 2. *Grid-forming inverter under weak-grid conditions. Image Credit: Sensata Technologies, Inc.*

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The Role of Automation in Next-Generation Green Data Centers

Data centers power everything from social media to cloud gaming, but behind the scenes, they consume massive amounts of energy and water. As digital demand grows, so does the environmental impact.

In response, governments are introducing stricter sustainability rules, and operators are under pressure to cut emissions, reduce waste, and prove they're running more efficiently.

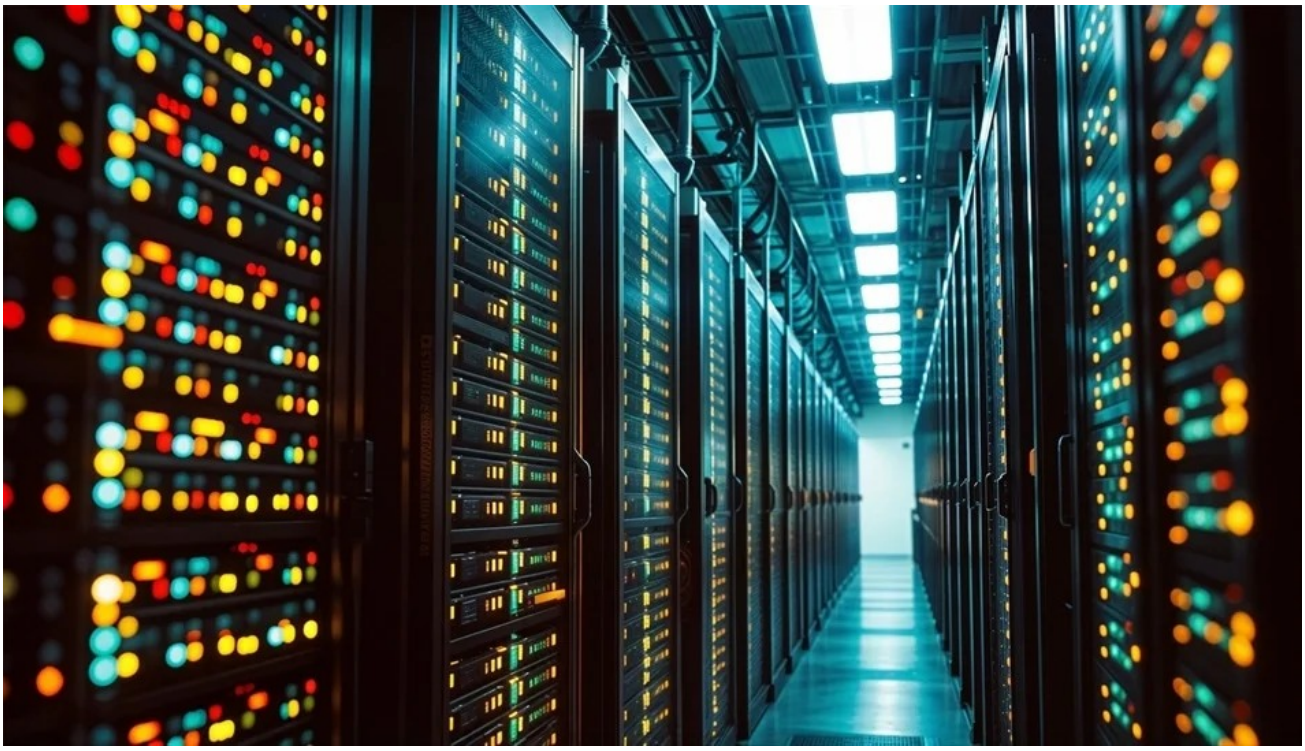


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This is where automation comes in.

From real-time energy tracking to AI-driven cooling systems, automated technologies are helping data centers meet rising environmental standards while improving operational performance. This article explores how automation is reshaping the way data centers manage energy, cooling, emissions, and compliance in a more climate-conscious world.

Environmental Regulations and Data Center Automation

As the environmental impact of data centers becomes harder to ignore, regulation has

become one of the strongest forces shaping how these facilities operate. Governments are no longer just encouraging efficiency; they are requiring it.

Nowhere is this more visible than in the European Union, where policies such as the Energy Efficiency Directive (EED) mandate detailed reporting on energy use, water consumption, and emissions.

Under these rules, data center operators must regularly submit standardized metrics like Power Usage Effectiveness (PUE), renewable energy share, and cooling efficiency to centralized reporting platforms. Meeting these requirements consistently is difficult to manage manually, especially at scale. As a result, automation has shifted from being an operational advantage to a practical necessity.[1]

A 2024 report from the Lawrence Berkeley National Laboratory (LBNL) and the US Department of Energy (DOE) underscores this shift. The study shows that operators increasingly rely on automated metering, real-time telemetry, and AI-driven workload management to monitor and optimize energy use. These systems generate accurate, audit-ready data on power and carbon intensity (two core requirements of modern sustainability regulations).[2]

Beyond reporting, automation also gives operators more control over how and when energy is consumed. During periods of peak demand, automated systems can dynamically adjust power usage, helping data centers stay within efficiency limits while reducing strain on the electrical grid. In this way, automation supports both regulatory compliance and broader energy system stability.[2]

Automation Technologies for Intelligent Energy and Emission Control

Tracking energy use is one thing; managing it in real-time is another. That's where automation makes a real difference. Modern data centers are equipped with networks of sensors, AI systems, and machine learning tools that not only monitor conditions but also respond automatically to keep things efficient.

Cooling is one of the biggest energy drains in any data center. To cut that down, automated systems constantly adjust cooling settings, optimize airflow, and balance how power is distributed. Two strategies that are widely used today are model-based HVAC control and machine learning–driven cooling optimization.

These approaches rely on predictive algorithms that simulate heat patterns and airflow

throughout the space. Instead of reacting after temperatures rise, the system stays ahead, tweaking fan speeds, chiller output, or airflow direction before conditions become inefficient. Google saw this in action with DeepMind's reinforcement learning platform, which reduced its cooling energy use by 40 % and total energy use by 15 %, just by optimizing system behavior minute-by-minute.

A lot of this tech is now built into Data Center Infrastructure Management (DCIM) platforms, which create automated feedback loops that constantly fine-tune operations. They're designed to maintain performance, improve efficiency, and generate the kind of real-time reporting needed for compliance with standards like ISO 50001 and the EU's Energy Efficiency Directive. It also means smarter, leaner data centers that are easier to manage and are more environmentally friendly.[3]

AI-Driven Optimization Tools

Beyond cooling and energy monitoring, AI is also helping data centers decide *when* and *how* to run workloads more efficiently. Instead of running tasks whenever there's capacity, smart scheduling systems now take into account things like carbon intensity on the grid, real-time electricity prices, and current cooling load.

Dynamic workload scheduling and optimization enable data centers to align computing demand with available low-carbon or energy-efficient resources. These systems use AI and ML to continuously monitor grid carbon intensity, real-time energy prices, and cooling capacity, then schedule non-critical workloads such as analytics or batch processing during periods of higher renewable energy availability or lower facility load.

A 2024 study published in *Applied Energy* demonstrated that reinforcement learning-based workload scheduling reduced total energy consumption by about 12 % while maintaining service-level agreements. Integrating these automated orchestration strategies and opitimization tools helps operators lower operational costs, reduce indirect emissions, and support compliance with carbon-reporting requirements without compromising system reliability. [4]

Automated Prediction Models

Automation needs to look ahead into the future to help predict and even prevent issues from cropping up. That's where predictive models come in. Powered by AI and real-time data, these systems help data centers forecast future resource needs and avoid waste before it happens.

Take water use, for example. Over the past two decades, Microsoft has dramatically cut down on how much water its data centers consume per kilowatt-hour of computing. Between its early 2000s facilities and those built in 2023, the company reduced water consumption by over 80 % through a mix of design changes and smarter operations.[5]

A big part of that progress comes from using prediction models. These systems analyze weather data, historical usage patterns, and live operational inputs to forecast water demand. If the system sees a spike coming, it can adjust cooling strategies in advance. In one case, an audit in 2022 helped eliminate about 90 % of excess water use, thanks to insights from these models.[5]

Microsoft is also moving toward zero-water evaporation cooling systems in all new facilities. These closed-loop systems don't rely on fresh water at all, and are expected to save over 125 million liters per data center per year. That's a huge shift and one that wouldn't be possible without automation helping operators make smarter long-term decisions.[5]

Emerging Trends that are Guiding Data Centers' Future

As automation continues to evolve, data centers are heading toward something even more advanced: autonomous or self-regulating data centers. These next-gen facilities are being designed to operate with minimal human input, using tools like digital twins, robotic maintenance, and fully automated control loops that span everything from infrastructure to IT workloads.

A digital twin is basically a virtual model of a data center. It mirrors the physical environment in detail, tracking power flow, cooling performance, workload distribution, and even external conditions such as climate. Operators can use it to run simulations before making changes in the real world. Want to know what happens if you double the rack density or shift to a new cooling strategy? The digital twin can test that scenario safely and instantly.

This kind of modeling makes automation smarter. Instead of just reacting to what's happening, the system can predict outcomes, weigh trade-offs, and make adjustments on its own. Combined with AI and real-time data, it moves data centers closer to being truly self-regulating, able to adapt, optimize, and maintain sustainability targets without constant human oversight.

We're not all the way there yet, but the tools are already in place. What's emerging is a more intelligent, responsive data center that can manage complexity at a scale humans can't handle

alone, and do it while hitting stricter environmental standards.

Want to explore more on tech and sustainability? Check out these topics:

- **Building Sustainable Data Centers: Innovations in Materials and Energy Use**
- **Why is Emissions Compliance Critical for Data Centers?**
- **Sustainable AI: Balancing Tech and Ethics**
- **Is AI the Key to a Sustainable Future? Researchers Explore the Evidence**

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Why is Emissions Compliance Critical for Data Centers?

Data centers have become increasingly essential, driven by the growing demand for artificial intelligence (AI), cloud computing, and digital services. As economies shift toward greater digital engagement, data centers have emerged as some of the largest electricity consumers. Recent research indicates that data centers account for approximately 1 % of global energy consumption, comparable to the energy used by medium-sized countries. As online activities continue to rise, the energy demand from data centers is expected to grow significantly, raising concerns about their environmental impact.[1]



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Emissions compliance is crucial for these facilities as it involves following regulations to reduce greenhouse gas emissions and other pollutants, such as nitrogen oxides and refrigerants. As consumers, investors, and regulators increasingly expect more environmental responsibility from businesses, data centers face challenges and opportunities. By adopting sustainable practices, they can play a key role in reducing emissions and contributing to a

cleaner future.[1]

What is Emissions Compliance?

Emissions compliance for data centers refers to the systems, policies, and standards implemented to measure, control, and mitigate emissions generated during normal operations. Major sources of these emissions are diesel generators used for backup power, electricity from the grid that is often produced using fossil fuels, and refrigerants in cooling systems that can leak potent greenhouse gases into the environment. These emissions are categorized into three scopes as defined by the Greenhouse Gas Protocol.[1,2]

- **Scope 1**: Direct emissions from owned or controlled sources, such as on-site diesel generators
- **Scope 2**: Indirect emissions from the generation of purchased electricity used by the data center
- **Scope 3**: All other indirect emissions in the value chain, including emissions from the manufacturing of equipment, supply chain logistics, and emissions associated with cloud computing services

Regulatory bodies such as the United States Environmental Protection Agency (EPA), European Union (EU) regulators, and the California Air Resources Board (CARB) establish frameworks and regulations aimed at controlling emissions from various sources. For example, the EPA regulates generator emissions under the Clean Air Act, while the EU enforces emissions trading systems that include large data centers.?[3]

Why Does it Matter Now?

Emissions compliance has gained urgency due to sweeping government net-zero targets and climate policy mandates. Many countries now require data center operators to track and lower their emissions, with some enforcing penalties for non-compliance or inaccurate reporting.

Pressure from investors has intensified through the prioritization of Environmental, Social, and Governance (ESG) criteria. Customers also expect service providers to be transparent and to take clear, measurable actions toward sustainability.[1,4]

Several industry studies highlight that carbon footprint, water usage, and energy sourcing have become core considerations for data center procurement decisions.

A recent analysis in *Frontiers in Sustainability* warns that expanding data centers in the US

could increase CO_2 emissions by 0.4–1.9 % by 2030, an increase equivalent to up to 14 % of the power sector's emissions during the same period.

Major companies like Google, Microsoft, and Amazon have experienced a 30–100 % rise in operational emissions over the past three years, leading them to set strong reduction targets.[1,4]

Key Challenges

Achieving emissions compliance in data centers presents several complex challenges.[1,2,5]

- **Regulatory Patchwork**: Data centers often operate across multiple regions subject to diverse and sometimes conflicting regulatory requirements. Navigating these differing rules is complex.
- **Backup Generator Emissions**: Diesel generators release harmful emissions such as nitrogen oxides, particulate matter, and carbon dioxide. Even though they are rarely used, strict regulations are in place to limit their environmental impact.
- **Grid Reliance and Energy Mix**: Most data centers draw electricity from the grid, where reliance on fossil fuels varies regionally. This impacts indirect Scope 2 emissions, which are difficult to control directly.
- **Refrigerant Leaks**: Cooling systems use refrigerants, such as hydrofluorocarbons (HFCs), which harm the environment. It is important to manage these leaks and switch to safer alternatives with low global warming potential (GWP), although this can be technically challenging.
- **Tracking Scope 3 Emissions**: These indirect emissions from suppliers and cloud service ecosystems are difficult to measure and regulate, but represent a large fraction of total impact.

Industry Solutions

Data centers are responding with various tactical and strategic solutions that support emissions compliance and accelerate efforts to reduce emissions.

Renewable energy procurement is a central approach, often realized through power purchase agreements (PPAs) and on-site solar or wind installations. Some hyperscale providers match annual consumption with renewable generation, dramatically lowering Scope 2 emissions. Battery storage is also starting to replace diesel generators, offering a cleaner backup option with fewer pollutants. Better cooling systems, such as liquid or immersion, save energy and reduce the risk of refrigerant leaks.[1,6]

Data centers use Data Center Infrastructure Management (DCIM) software and emissions tracking tools to enhance their energy management. These technologies can monitor and optimize energy and environmental performance in real-time. Leading companies such as Google, Microsoft, and Equinix are at the forefront, utilizing AI to predict emissions and actively engaging in industry standards to improve sustainability. These efforts show a strong commitment to reducing their carbon footprints and supporting regulatory compliance.[1,6,7]

What's Next?

The landscape for emissions compliance is defined by tightening global standards and growing attention to embodied carbon. The Climate Neutral Data Centre Pact is a key initiative that engages operators to meet the EU's net-zero goals with clear timelines. Moreover, new regulations in Europe, the US, and East Asia require detailed reporting and verification of emissions from data centers. Some regions are also focusing on the environmental effects of construction and supply chains related to new data center projects.[4,8]

Research initiatives focus on further decarbonizing the energy mix, integrating hydrogen fuel cells, and using AI-based modeling for predictive efficiency and better resource planning. Data center operators anticipate that compliance will extend beyond emissions to include water use, recycling, and transparency for customers and regulators.

Innovation in technical and management strategies will support deeper reductions across all scopes, positioning emissions compliance as a fundamental dimension of building and operating competitive, sustainable data centers.?[4,8]

Final Takeaway

Emissions compliance is now central to modern data center management and carries significant legal, reputational, and operational weight. It is no longer just about avoiding regulatory penalties - data centers are expected to demonstrate genuine environmental responsibility to investors, customers, and the broader public.

This shift presents a clear opportunity: with the right technologies in place - particularly advanced sensing and monitoring solutions - data centers can actively reduce emissions, improve efficiency, and demonstrate credible progress toward sustainability goals.

As regulations tighten and digital emissions tracking becomes more transparent, staying compliant is emerging as a catalyst for innovation and long-term business resilience across

the industry.

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