VERTIV

E-book

The data center power train: Managing energy from grid to chip

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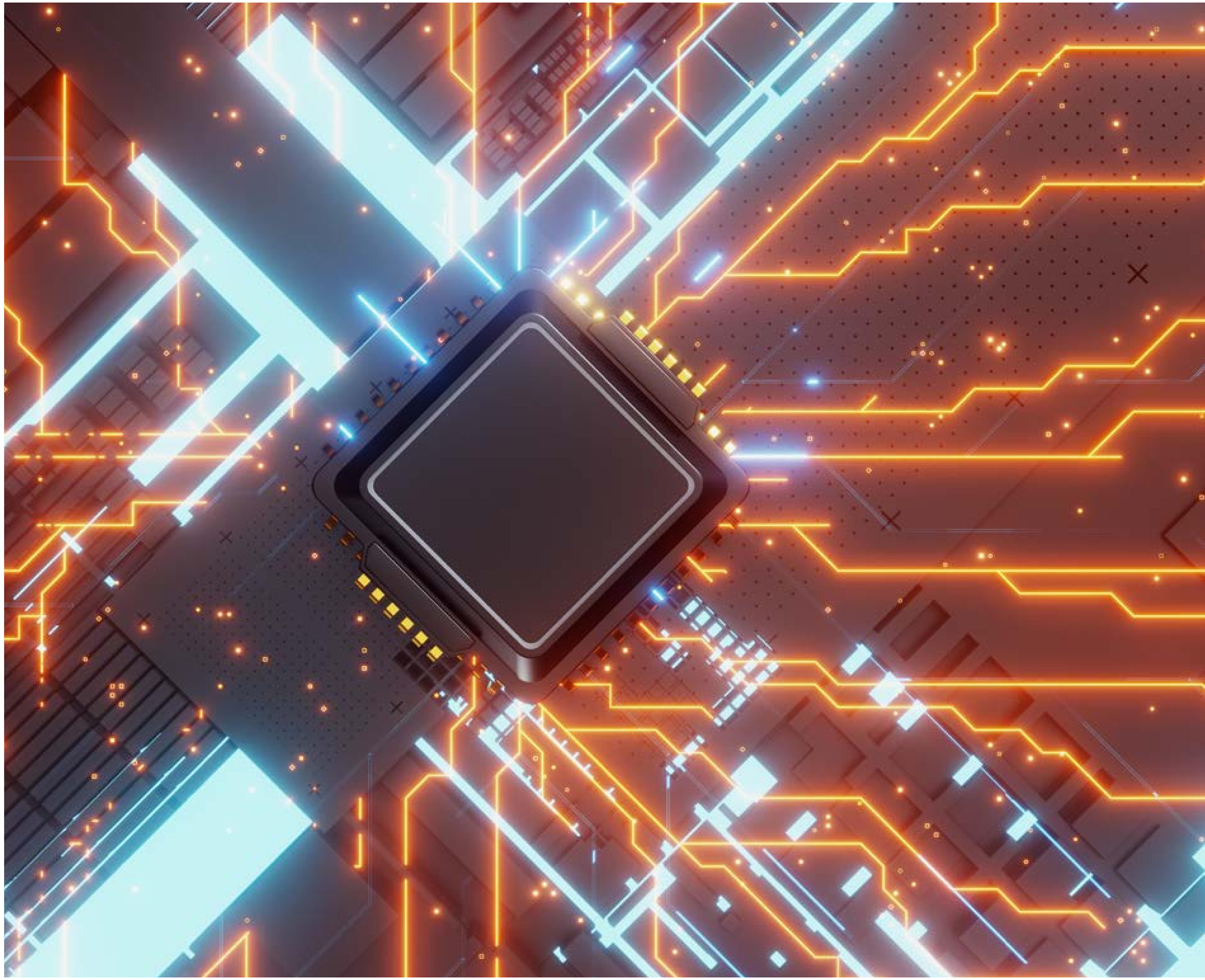

Introduction

The AI era is fueling an extraordinary surge in data demand. Data centers now sit at the heart of this transformation, enabling everything from artificial intelligence to cloud computing and digital services. As these technologies continue to advance, the challenge of delivering reliable, efficient, and scalable power becomes more complex. Power systems must support higher densities, rapid growth, and more dynamic workloads, all while reducing the strain on energy grids and meeting rising expectations for efficiency.

This e-book examines the role of the data center power train in addressing these challenges. It highlights the trends shaping power system design and explores the technologies and strategies that are shaping the future of the data center power train.

Trends impacting the data center power train

The data center power train is undergoing significant transformation due to three major trends:

1. **The rise of AI and accelerated compute platforms**
   The rapid adoption of power-hungry AI systems is reshaping energy consumption in data centers. These platforms demand far more energy than traditional workloads and introduce greater variability in power demand. AI workloads are often characterized by short bursts of high demand, causing power systems to operate near the limits of their rated capacity for brief periods. This shift is prompting operators to rethink how energy is distributed and managed within their facilities.

2. **Increasing grid strain from data center energy demand**
   Data centers are placing growing pressure on regional power grids, especially in areas where they are concentrated. In some regions, data centers account for well over 10% of grid load.[1] When grid capacity cannot meet energy demands for expansion or new development, operators face challenges in expanding their capacity and risk delays in connecting new facilities. To help offset grid strain, large operators are increasingly leveraging advanced power train components, like battery energy storage systems (BESS) and grid interactive UPS systems, to optimize grid interaction, provide load flexibility, and support local power generation.

3. **Addressing efficiency and environmental impact**
   With power demand steadily rising, data center operators must reduce losses in the power train and mitigate the environmental impact of increased energy consumption. Proactive measures are essential to increase efficiency and reduce Scope 1 and 2 emissions.

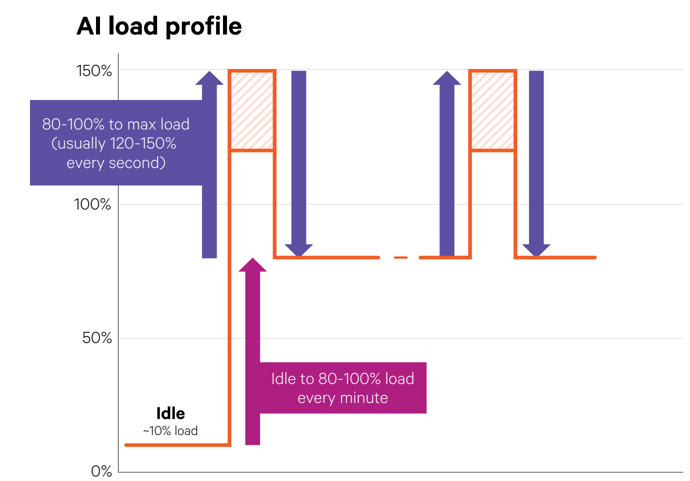

Figure 1: The power requirements of AI loads are characterized by sharp, short-term increases in demand.

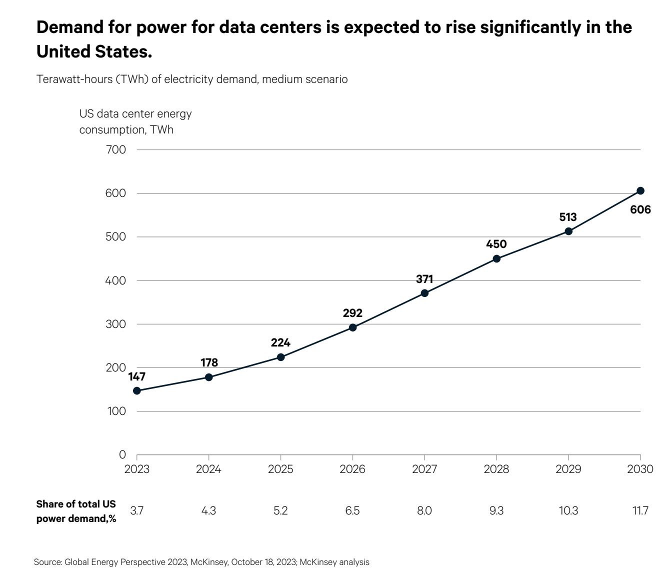

Figure 2: Data center power requirements are projected to increase steadily through the remainder of the decade. Source: McKinsey[2]

[1] Singh, 2024. IEA.
[2] Green, A., et. al., 2024. McKinsey & Company.

	Load variability	Power availability	Decarbonization
What's happening	Data centers are rapidly deploying AI platforms, which have more variable power demands than traditional workloads.	Utilities can't keep pace with growing data center power requirements.	Growth in data center power consumption is increasing scrutiny on data center efficiency and emissions.
Why it's happening	AI platforms use GPUs that process thousands of operations simultaneously and consume huge amounts of data in both training and inference. This creates sharp, short increases in demand.	The industry is expanding to support increased digitalization and the evolution of AI. Newer data center systems are more power-intensive than previous generations.	When data center power is generated from fossil fuels, increased energy consumption correlates with an increase in Scope 2 emissions attributed to data centers.
Impact on the power train	Power train systems capable of supporting highly variable AI loads will be essential in enabling businesses to deploy and optimize AI and other accelerated compute platforms.	By supporting grid interactivity and enabling use of local power sources, the power train will play a critical role in enabling industry expansion within current grid limitations.	Newer power train systems and effective designs can reduce data center energy losses and enable use of alternative energy sources.

Table 1. *Major trends shaping the evolution of the data center power train.*

Understanding the data center power train

The power train in a data center can be divided into three main stages. Each stage includes multiple systems that must work together to power critical systems reliably and efficiently:

- **Facility power conversion and distribution:** In this stage, utility power is converted to a lower voltage, distributed to major subsystems, conditioned to meet IT system requirements, and supported by backup systems that maintain continuity during utility outages.
- **Room/row switching and distribution:** This stage manages, monitors, and distributes conditioned power to individual rows and racks within the data center.
- **Rack power distribution:** In this final stage, power is distributed directly to IT devices in the equipment rack.

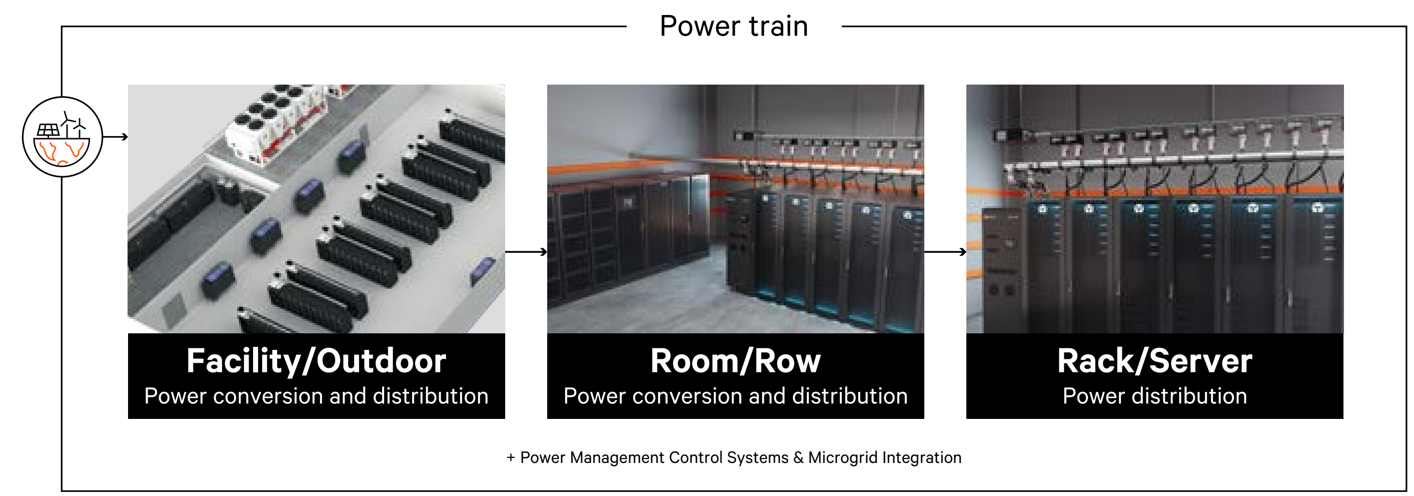

Figure 3. *Working together, the three stages of the data center power train support efficient delivery of clean, continuous power to critical systems from grid to chip.*

Design considerations

No two data centers are exactly alike, so the data center power train must be designed to meet application and business requirements. Designing power train solutions is a collaborative process between in-house electrical engineers, the engineer of record, and power train vendors. Here are just some of the variables that must be considered in the design process.

- **Power density:** The amount of power needed per rack or per square foot to support current and future IT loads.
- **Backup time:** The duration of time the system needs to remain operating after a major grid outage.
- **Power capacity:** The maximum power the facility must supply to all equipment, including IT, cooling, and supporting infrastructure.
- **Safety:** Mitigating electrical hazards and arc flash risks, supporting safe maintenance access, and complying with relevant electrical safety standards to protect personnel and equipment.
- **Redundancy and reliability:** The level of redundancy needed to maintain uptime during component failures or maintenance, balanced against the added cost of redundant systems.
- **Voltage levels:** The voltage levels for efficient power delivery and minimal losses. As power density increases, higher voltage power distribution is called for.
- **Load balancing:** Providing even distribution of power across circuits and phases to prevent stranded power and maximize efficiency.
- **Power monitoring and management:** Use of an energy power management system (EPMS) to provide real-time visibility into energy usage, power quality, and equipment performance.
- **Physical space and cabling:** The layout and routing of power cables, switchgear, and distribution units to minimize heat buildup and footprint and support efficient power delivery. Cable and piping weight should also be factored into the design.
- **Loss reduction:** The use of energy-efficient practices and even alternative energy sources to reduce operational costs and environmental impact.

For large hyperscale data centers, customized power train components and solutions are typically needed to support their unique IT architectures and custom-built systems. Colocation providers and enterprise data centers typically use commercially available systems that are then configured to their requirements through the design process.

	Customized solutions	Configured solutions
Why it is needed	Hyperscale operators typically use custom-built IT systems to achieve greater scalability, efficiency, and flexibility. These systems need unique power train components and designs.	Enterprises and colocation providers typically use standardized IT systems and architectures so standardized power systems can meet most requirements. By using standardized equipment diverse loads, applications, and customers can easily be supported.
Benefits	IT and infrastructure configurations can be aligned to maximize efficiency and support reliability and flexibility goals. Customized designs then serve as the standard for future data centers.	Commercialized systems can be quickly configured to application requirements, enabling rapid expansion or new development.
Vendor requirements	• Deep understanding of customer requirements. • Power solutions capable of handling AI workloads. • Global engineering and service expertise. • Vendor-agnostic approach to component selection.	• Broad portfolio of AI-ready power solutions. • Global engineering and service expertise. • Experience with a range of customer application requirements.

Table 2. *Power train designs can use customized systems to meet unique requirements or be configured to the application using standardized systems.*

Stage 1: Facility power conversion and distribution

The first stage of the data center power train is the most complex. It converts incoming electricity to a lower voltage and divides it across major systems. This stage also includes systems that provide backup power in the event of a utility outage. The main systems used in this phase are switchgear or switchboards, a UPS system with battery storage, and a backup power source. In general, here's how it works:

- The main data center switchboard/switchgear receives power from the building switchgear or directly from the utility and divides it into smaller, more manageable circuits that feed the UPS and mechanical systems. It also provides fault protection for each circuit to protect downstream equipment and isolate the impact of electrical faults.
- The UPS system uses energy stored in batteries to power the data center through short interruptions in utility power and conditions utility power to remove spikes, sags, and other variations in power quality that can damage or disrupt microelectronics.
- The automatic transfer switch (ATS) sits between the UPS and backup power source and detects when utility power fails or becomes unstable and switches the electrical load to the backup power source.
- The backup power source powers the data center through utility outages that exceed UPS battery capacity. Generators are used for backup power in many data centers today. The emergence of battery energy storage systems creates an opportunity for operators to reduce their dependence on generators.

***Figure 4.** The Vertiv™ Trinergy™ UPS features three-dimensional scalability to enable rapid and flexible response to growing power demand from IT systems.center.*

The heart of the data center power system

The data center UPS system has historically played a central role in enabling data centers to achieve high levels of availability and is today evolving to support changing requirements.

For example, innovative approaches to UPS scalability, such as modular designs and parallel system configurations, are enabling data centers to flexibly adapt to growing power demands. These solutions allow operators to incrementally add capacity or redundancy without disrupting operations, providing efficient support for increased energy consumption.

Another subtle but powerful change is the move toward smaller-footprint UPS modules that is being achieved without sacrificing reliability or functionality. This is necessary to offset the growing power density of IT equipment racks. By saving space within the power system, compact UPS designs enable operators to deploy more IT systems in their data centers, increasing their return on investment. Forward-thinking power vendors are also integrating switchgear and UPS systems into a single block to enable further space savings while accelerating deployment speeds.

Finally, and perhaps most significantly, UPS controls are advancing to allow the UPS to play an active role in managing demand from the grid. With more sophisticated controls, the UPS system can dynamically balance energy supply and demand by interacting with the grid. This innovation helps operators support capacity-constrained utilities by using stored energy to reduce grid loads during peak demand or inject power back into the grid, improving stability and enabling growth within current grid limitations.

UPS controls are advancing to allow the UPS to play an active role in managing demand from the grid.

***Figure 5.** Dynamic grid support promises to fundamentally change the relationship between the grid and the data center.*

Stage 2: Room and row power distribution

As energy is moved from stage one to stage two and three of the power train, it must be carefully managed to maintain consistent voltage, minimize losses, and provide support for high-density computing loads. Effective design of the distribution system safeguards critical IT equipment from power disturbances and overloads and enables operational flexibility and energy optimization.

> Power train designers today must plan to support distribution of higher voltage electricity as required by high-density AI racks.

Room PDUs are a proven and cost-efficient method for power distribution in raised floor environments. They can provide high power capacity from a single unit, enable branch circuit monitoring, and be equipped with power conditioning. However, they take up valuable white space in the data center and, as more data centers have been developed without a raised floor, busway systems have grown in popularity.

In a busway system, the busway is connected to an upstream low-voltage electrical switchboard. Because the busway is installed overhead, it improves space efficiency.

Open busway designs are preferred over closed designs because they provide continuous access along the length of the busway. This allows plug-in units to be located anywhere along the busway for quick installation and easy relocation of IT equipment racks. Open busways are also easy to scale and maintain and can be configured with built-in power monitoring.

Figure 6. *An example of an open busbar design, which provides a flexible, efficient and scalable solution for power distribution to the rack.*

Stage 3: Rack power distribution

Power train designers today must plan to support distribution of higher voltage electricity as required by high-density AI racks. Data centers are increasingly being designed or retrofitted to support three-phase power distribution at 240V, 415V, or 480V rather than the traditional 208V. Distributing at higher voltages not only increases the power that can be delivered to racks but also improves load balancing and reduces wiring losses.

Once an IT equipment rack is connected to the distribution system, power must be distributed to the various devices within the rack. With rack power requirements on the rise, the role of the rack PDU (rPDU) becomes even more important.

The rPDU is more than just a power strip for IT devices. Several features available in rPDUs can streamline installation, protect against accidental disconnects, and improve cable management. For example, color-coded, alternating-phase receptacles simplify load balancing. Combination outlets that allow every receptacle to connect to equipment with C13 or C19 plugs increase versatility and simplify equipment changes.

As rack density increases, so too must rPDU capacity and functionality. The new generation of rPDUs can support power densities above 100 kW per rack with modular, hot-swappable components, and support for both AC and high-voltage DC input. These advanced rPDUs enable seamless expansion as power needs grow, while their compact design helps maximize usable rack space and minimize complexity.

> As rack density increases, so too must rPDU capacity and functionality.

Intelligent monitoring and management capabilities included with some rPDUs allow operators to track energy usage, optimize load balancing, and proactively address potential issues.

Integration, service, and energy management

While this e-book has presented the challenges and opportunities associated with each stage of the power train separately, a holistic approach to power train design and management is essential to enable the reliable, efficient, and scalable delivery of power for HPC and AI workloads. As part of that approach, operators should evaluate the value of integrated solutions, energy power management systems (EPMS), and lifecycle services.

Integrated solutions

The prefabrication and integration of power train systems, or the entire data center, can reduce the time to deploy new capacity by up to 50% while providing high efficiency, interoperability and scalability.

A fully integrated skid-mounted power system enables deployment of isolated, power-dense, critical infrastructure capacity in modules. Modules can be configured for redundancy, are hot scalable, and offer multiple switchboard configurations to meet distribution requirements.

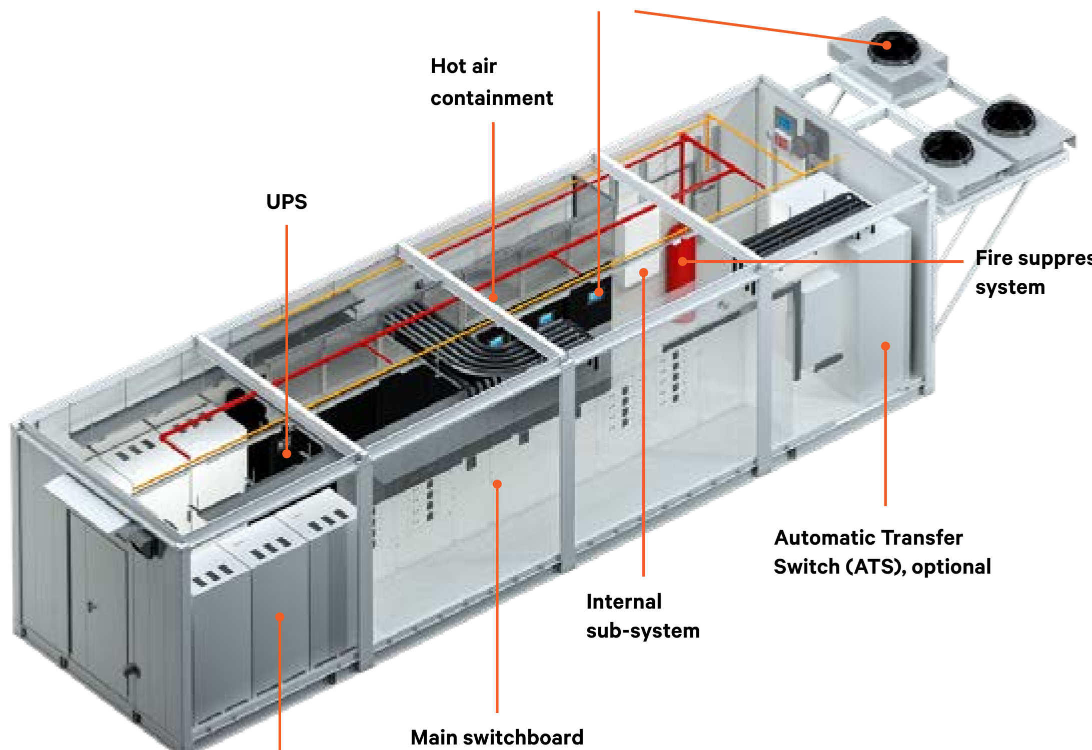

Figure 8. *Fully integrated power modules enable operators to add capacity quickly and efficiently.*

The evolution of energy storage

Data center UPS systems have historically relied on valve-regulated lead-acid (VRLA) batteries to provide short-term backup power during power interruptions. However, in recent years, lithium-ion batteries (LIBs) have emerged as a compelling alternative to VRLA technology.

The lithium-ion advantage

Vertiv estimates that lithium-ion batteries can last up to four times longer than VRLA batteries, with many installations reaching eight to 10 years[3] or more. This extended lifespan reduces the frequency of battery replacements, minimizes operational disruptions, and lowers total cost of ownership (TCO). Lithium-ion batteries are also lighter and more compact, freeing up valuable floor space and improving installation flexibility.

Beyond longevity, lithium-ion batteries offer faster recharge times and greater cycle durability. They can reach up to 90% charge in under two hours for rack-based systems, compared to more than four hours for VRLA batteries.[4]

> Lithium-ion batteries can reach 90% charge in under two hours for rack-based systems, compared to more than four hours for VRLA batteries.

Lithium-ion batteries also tolerate more charge and discharge cycles with less degradation, making them ideal for environments with frequent power cycling or advanced energy management strategies. These attributes are especially valuable as data centers begin to integrate alternative energy sources.

Expanding the role of battery energy storage

The characteristics of lithium-ion batteries make them suitable for use in battery energy storage systems (BESS), which can power data center systems for longer durations than the UPS battery system. Integrating BESS modules into the data center is opening up new opportunities to enhance and expand data center power train performance and functionality.

A BESS can essentially create a bridge between the utility grid and the data center's internal power train that enhances reliability, efficiency, and stability. A BESS can store energy from the grid during off-peak periods, release stored energy during peak demand, provide backup power during outages, and even return power to the grid when needed. Working alongside the data center UPS system, a BESS delivers extended backup capacity and supports a multi-layered power protection strategy that covers different timeframes and scenarios.

[3] Chattopadhyay, 2021. Vertiv.
[4] Chattopadhyay, 2021. Vertiv

What a BESS Can Do

- Store energy from the grid during off-peak periods
- Release stored energy during peaks to reduce demand on grid
- Provide backup power during outages to reduce generator starts
- Return power to the grid when needed.

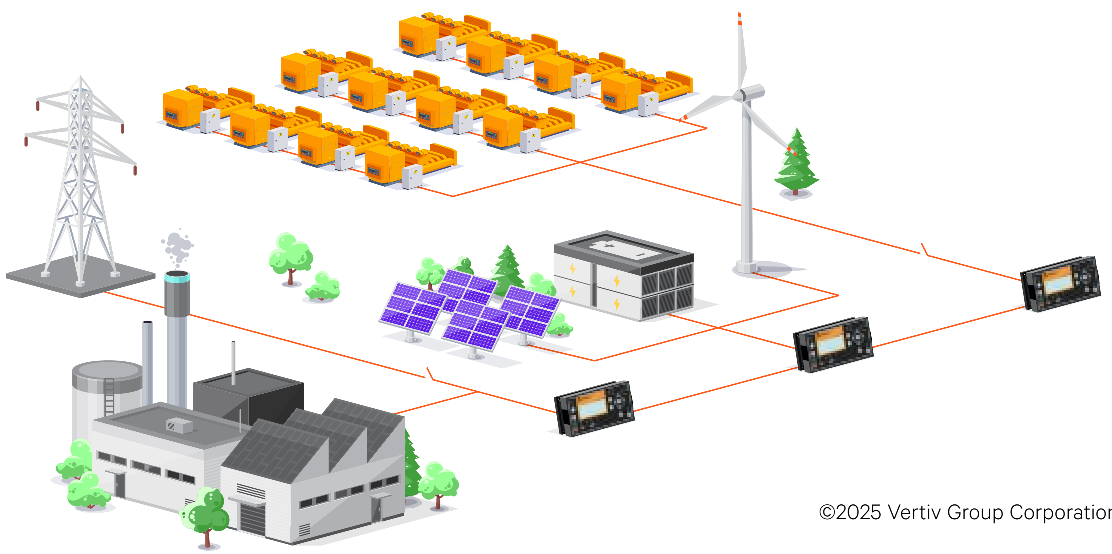

Figure 6. *Battery energy storage systems (BESS) enable multi-layered backup power strategies and support grid interactivity.*

The BESS can also store energy generated by solar and other alternative sources, transforming intermittent power sources into continuous data center power. BESS modules are located outside the data center to conserve space within the facility.

Debottlenecking the grid

An emerging issue for operators selecting sites for new data centers is securing enough power. In many regions of the country grid infrastructure is at capacity, but often for only 30-60 hours each year.[5] A BESS can be effective at curtailing data center loads during these periods and debottlenecking massive amounts of grid capacity.

[5] NESCOE, 2024.

Power controls and service

Resilient power management solutions have become essential to effective data center management. An EPMS provides real-time monitoring capabilities, offering increased visibility into power consumption for electrical and facilities teams.

EPMS includes software, hardware, and digital services for comprehensive power management, are customized to specific equipment, and can be configured to deliver comprehensive power management.

In addition to visibility, these systems offer automated fault response and power rerouting to maintain operational continuity and prevent revenue losses due to outages. A robust EPMS should be accessible from mobile devices to enhance troubleshooting and team collaboration.

Organizations will also need to develop a service strategy when deploying or upgrading power train components. Providers with deep multi-technology expertise, a resilient global service operation, customizable service solutions, and remote diagnostics and management capabilities make the best partners.

Key takeaways

1. **Trends impacting the data center power train**
   Power train vendors and their customers must be willing to innovate to adapt to evolving energy demands. In many cases, legacy systems will prove unable to provide the capacity, scalability, and efficiency needed.

2. **Understanding the data center power train**
   There is no one-size-fits-all solution for data center power. The power train must be designed to support current and future power requirements. A high level of domain expertise combined with a broad portfolio of power solutions is needed to provide effective power train design.

3. **Facility power conversion and distribution**
   As data centers account for an increasing share of grid load in some regions, advances in UPS technology—such as grid interactivity, modular scalability, and enhanced energy management—will help operators adapt to rising power demands and evolving grid conditions.

4. **Room, row, and rack power switching and distribution**
   As data centers grow in size and power density, operators need to move to higher capacity and more flexible power distribution systems as represented by open busway solutions and newer rPDUs to provide reliable power delivery, minimize losses, and enable scalability.

5. **Integration, service, and energy management**
   To maximize efficiency, capacity, and flexibility, the power train should be designed as one system whenever possible. Organizations capable of providing complete solutions that include integration, controls and services are best positioned to help operators adapt to changing energy requirements.

6. **The evolution of energy storage**
   The transition from VRLA to lithium-ion batteries and the application of battery energy storage systems have the potential to transform data center power infrastructure. These advances deliver longer life, greater efficiency, and new capabilities that, working with grid-interactive UPS systems, enable data centers to meet rising power demands, support grid stability, and achieve greater operational flexibility.

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About Vertiv

Vertiv (NYSE: VRT) brings together hardware, software, analytics and ongoing services to enable its customers' vital applications to run continuously, perform optimally and grow with their business needs. Vertiv solves the most important challenges facing today's data centers, communication networks and commercial and industrial facilities with a portfolio of power, cooling and IT infrastructure solutions and services that extends from the cloud to the edge of the network. Headquartered in Westerville, Ohio, USA, Vertiv does business in more than 130 countries.

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