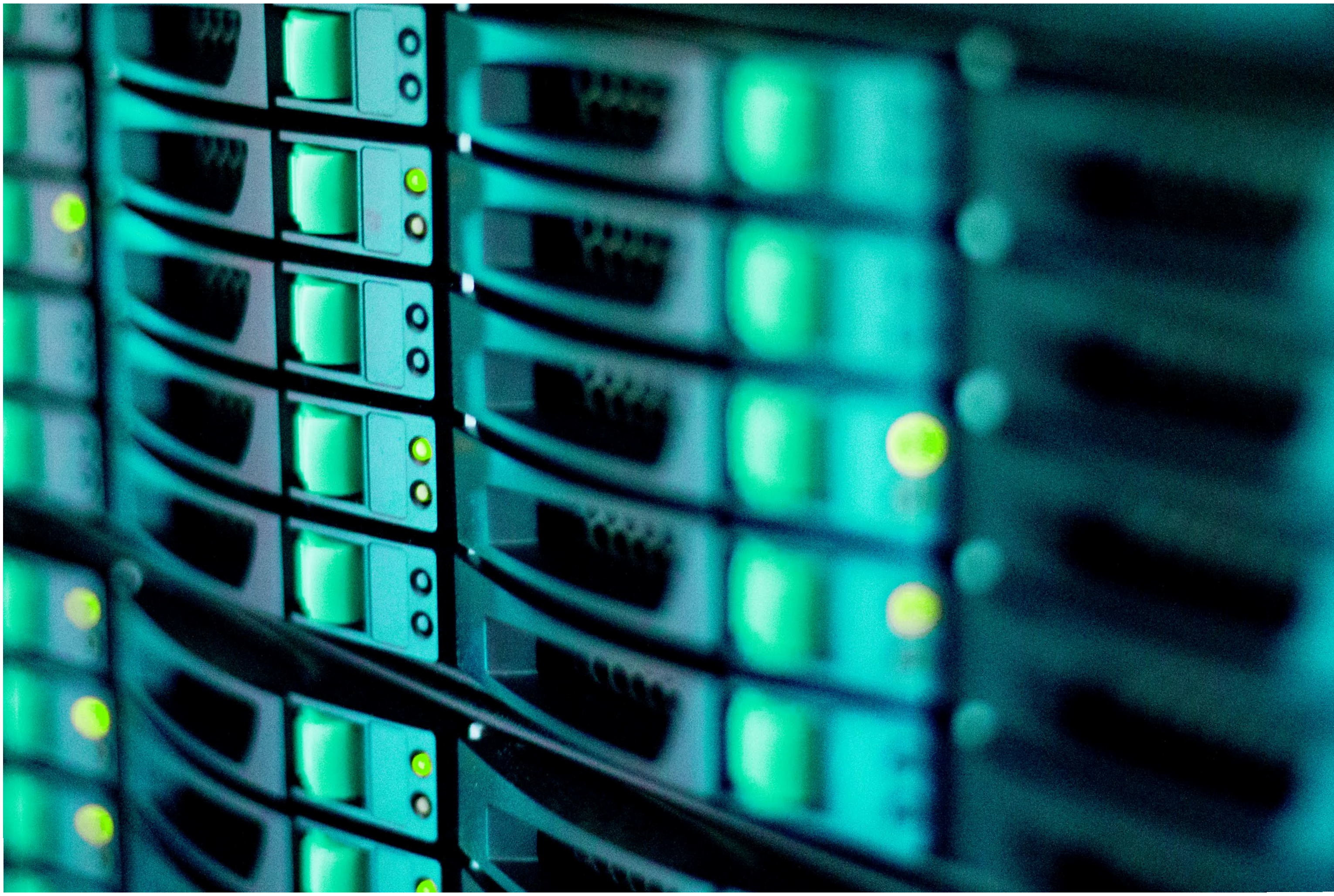
Technical White Paper

Leveraging Bloom Fuel Cells' Native 800 VDC Output for Data Center DC Power



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Introduction

Among the available DC distribution voltages, **800 VDC** has emerged as a compelling balance between electrical efficiency, equipment availability, safety, and system scalability. While no single voltage is optimal for every facility, 800 VDC aligns well with current power-electronics technology and the requirements of next-generation AI data centers.[1]

Traditional alternating current (AC) architectures require multiple stages of voltage conversion, each introducing efficiency losses, additional equipment, maintenance requirements, and capital cost. As rack densities increase, the electrical distribution system becomes a critical design constraint. These challenges have renewed interest in direct current (DC) architectures that minimize unnecessary power conversion.

Fuel cells are particularly well suited to this approach because they generate electricity as direct current. Rather than converting DC to AC and then back to DC before it reaches the computing equipment, a native DC architecture seeks to preserve DC power through as much of the electrical distribution system as practical.

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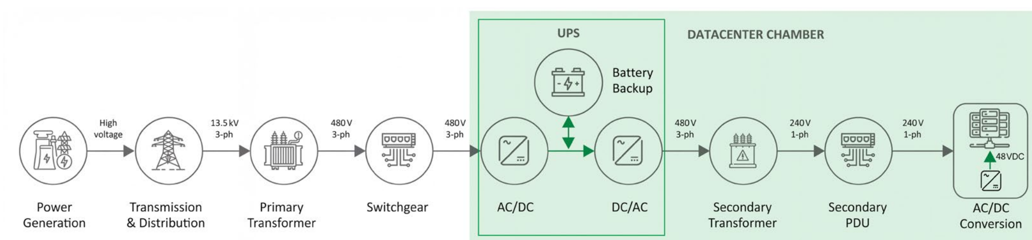
[1] For more information, read Bloom Energy's special report: *The New Rules of AI Power*.

1. The evolution of data center power architecture

Historically, large data centers have depended on the electric utility grid as their primary power source. Electricity is delivered as medium-voltage alternating current (MVAC), transformed to lower voltages, conditioned by Uninterruptible Power Supply (UPS) systems, distributed throughout the facility, and ultimately converted back to DC within every server.

Figure 1: The conventional AC-centered power chain

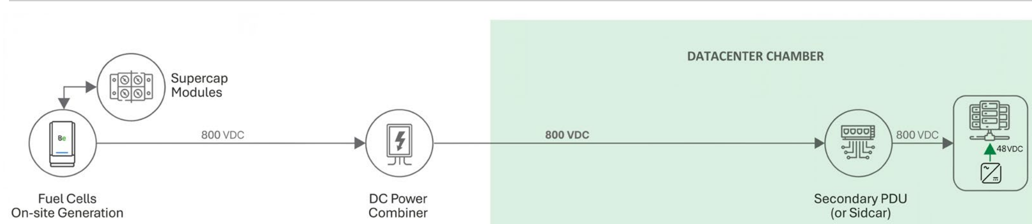


Each conversion stage introduces losses, additional equipment, maintenance requirements, and potential failure points. As AI facilities approach hundreds of megawatts in capacity, even small efficiency improvements translate into millions of dollars in annual operating savings. This has accelerated interest in **on-site power generation**, particularly technologies capable of delivering highly reliable power with minimal environmental impact.

Additionally, inside the data center the transition to an **800 VDC voltage distribution** has been driven by a common objective: delivering more power while reducing current. Since conductor size, heat generation, and resistive losses scale with current, increasing distribution voltage allows significantly more efficient power transfer without increasing conductor cross-sectional area.

Bloom Energy fuel cells is the only technology that meets both expectations: they are an **on-site power generation system that delivers a native 800 VDC architecture** allowing direct DC distribution from fuel cells to rack.

Figure 2: Generic 800 VDC system architecture for data centers using fuel cells



2. Bloom Fuel Cells as Native DC Power Sources

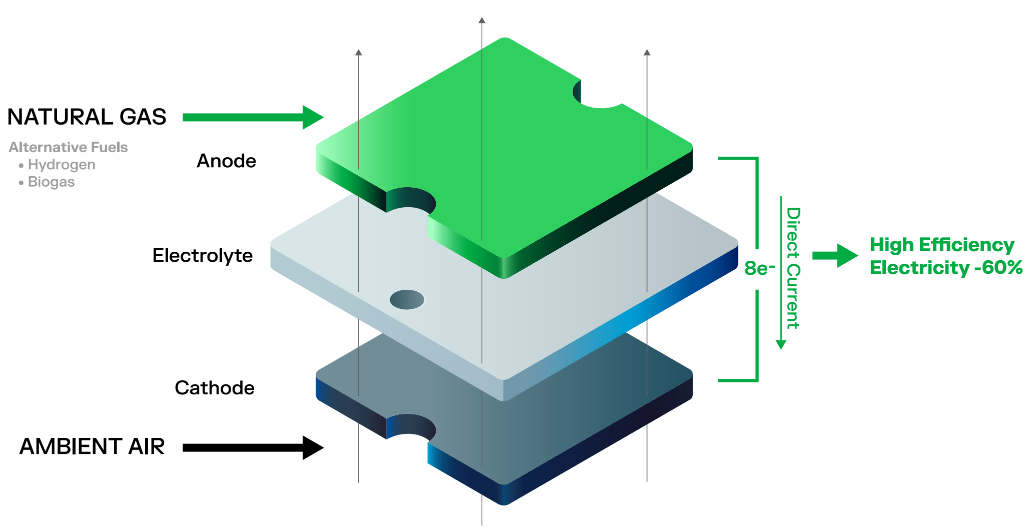
Fuel cells represent a fundamentally different approach to electricity generation than conventional rotating generators. Rather than converting mechanical energy into electrical energy through electromagnetic induction, fuel cells generate electricity directly from an electrochemical reaction. The resulting output is **direct current (DC)**, making fuel cells a natural complement to modern semiconductor-based computing systems, which also operate internally on DC power.

This characteristic provides an opportunity to simplify the electrical architecture of AI data centers by reducing unnecessary power conversion stages, improving overall efficiency, and enabling new approaches to distributed power generation.

Every fuel cell contains three primary components: an anode, an electrolyte and a cathode.

The fuel — typically hydrogen or hydrogen extracted from natural gas through an internal reforming process — is introduced at the anode. Oxygen from ambient air enters the cathode. The electrolyte permits only oxygen ions to pass. Neither nitrogen nor free electrons can cross the electrolyte. Instead, electrons released from oxygen ions on the anode side travel through an external electrical circuit where they perform useful work before returning to the cathode, while the nitrogen is returned to the ambient atmosphere.

Figure 3: Simplified fuel cell operating principle



Consequently, current always flows in one direction (direct current), output polarity remains constant, frequency synchronization is unnecessary and harmonic distortion is negligible at the source.

The output voltage depends on 1) Number of cells connected in series; 2) Fuel utilization; 3) Operating temperature; 4) Current demand and 5) Stack health. Because electrons always flow in one direction, the electrical output behaves as a controllable DC voltage source rather than as an AC generator.

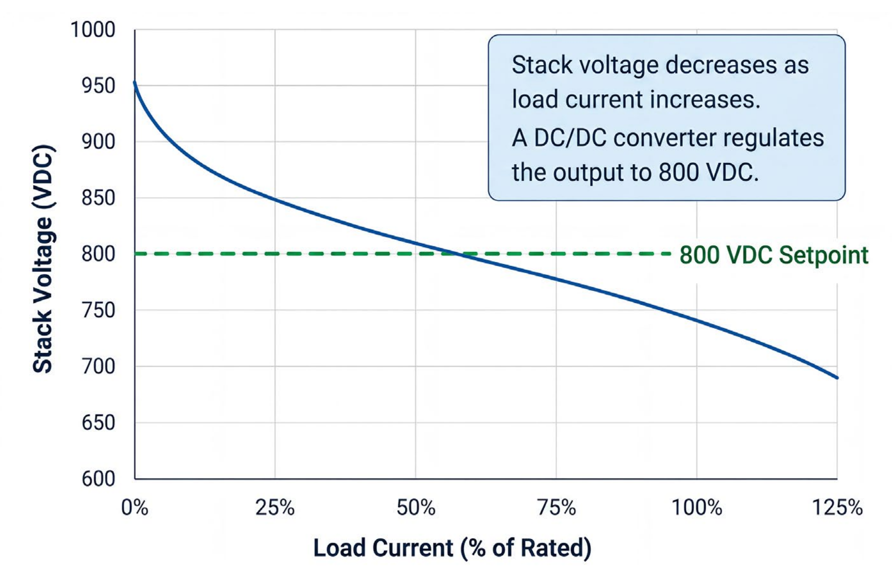
Voltage Characteristics and Control

Fuel cells are not constant-voltage devices. Their output varies with electrical load. At light load voltage is highest. As current increases, voltage gradually decreases due to:

- Electrochemical activation losses
- Internal resistance (ohmic losses)
- Concentration losses caused by reactant transport limitations

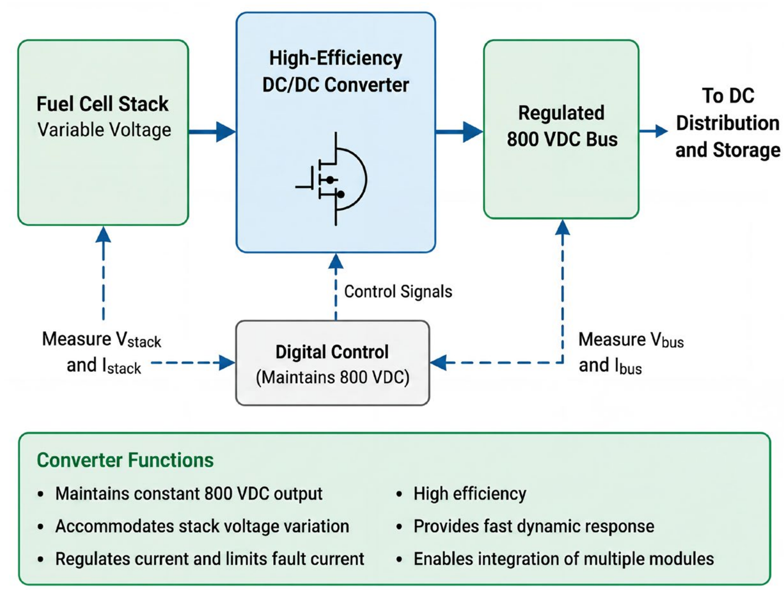
This voltage-current relationship is well understood and predictable. Modern digital control systems continuously regulate power output while maintaining operation within the optimal efficiency region.

Figure 4: Typical Fuel Cell Polarization Curve



The graph in Figure 4 illustrates the stack voltage decreasing as output current increases, highlighting the operating region typically used for maximum efficiency.

Figure 5: Regulating the power output and maintaining a steady 800 VDC Bus with a DC/DC converter



To support direct 800 VDC output to the load, Bloom fuel cells use high-efficiency DC/DC converters that regulate on the input stage the current/fuel ratio such that the fuel cell operates as a current source. On the output stage, the converter regulates the voltage and maintains a constant DC Bus. The result is a regulated ±400 VDC or 800 VDC (when measured rail-to-rail) output under any power setpoint conditions. Additionally to accommodating the stack voltage variations, the converter limits the fault current and supports dynamic load changes in coordination with multiple fuel cell modules.

With extremely high efficiencies of 98-99%, Bloom's DC/DC converter performs simultaneously a number of primary functions which include maintaining a constant 800 VDC output, accommodating stack voltage variations, limiting fault current, supporting dynamic load changes and coordinating operation of multiple fuel cell modules.

Output Flexibility

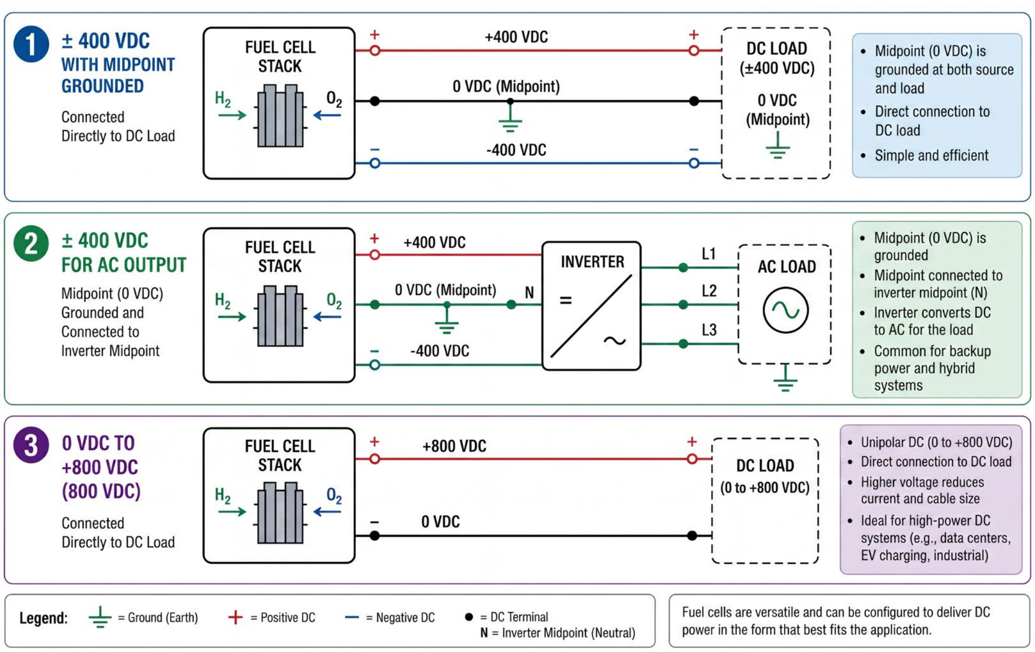
Fuel cells provide exceptional flexibility in supporting both AC and DC power architectures with all types of voltages endorsed by various Hyperscalers: 800 VDC ungrounded, ±400 VDC grounded or ungrounded, or they can provide AC voltage output via an inverter to be used for AC distribution to a load or a data center campus. Figure 6 summarizes all the possible ways the fuel cells output can be converted to support DC or AC loads.

In the ±400 VDC midpoint-grounded configuration, the fuel cell delivers a balanced bipolar DC output with the 0 V midpoint connected to ground. This architecture provides a clear voltage reference, simplifies fault detection, and reduces the voltage stress on conductors and equipment relative to ground. Because both the source and load share the same grounded midpoint, power can be delivered directly to DC loads with minimal conversion equipment, resulting in higher overall efficiency and improved reliability. This approach is particularly attractive for critical infrastructure where safety, protection coordination, and straightforward operation are important design considerations.

For ±400 VDC feeding an inverter for AC output, the fuel cell's bipolar DC output aligns naturally with modern power electronic converters. The grounded midpoint serves as a stable neutral reference for the inverter, allowing efficient synthesis of three-phase AC power while maintaining balanced operation of the DC bus. This configuration reduces the size and complexity of the inverter power stage compared to lower-voltage DC architectures and enables seamless support for conventional AC loads. It is especially useful for facilities that must support existing AC equipment while benefiting from the high efficiency and resilience of fuel cell generation.

In the 0 to +800 VDC configuration, the fuel cell supplies a high-voltage DC bus directly to DC loads without an intermediate inverter. This architecture is well suited for emerging high-power applications such as AI data centers, EV charging infrastructure, battery energy storage systems, and industrial DC microgrids.

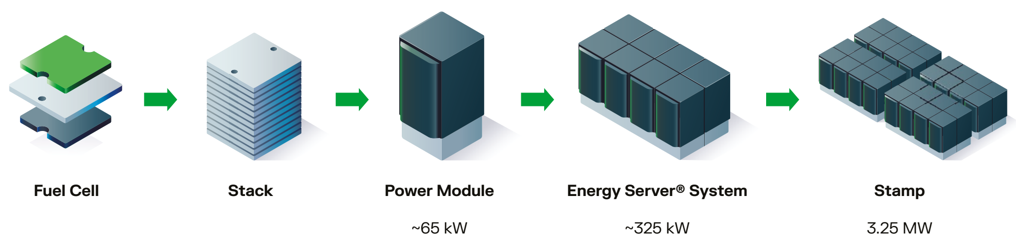
Figure 6: Fuel cells can produce multiple DC Output configurations



Modularity & Scalability for AI Data Center Architectures

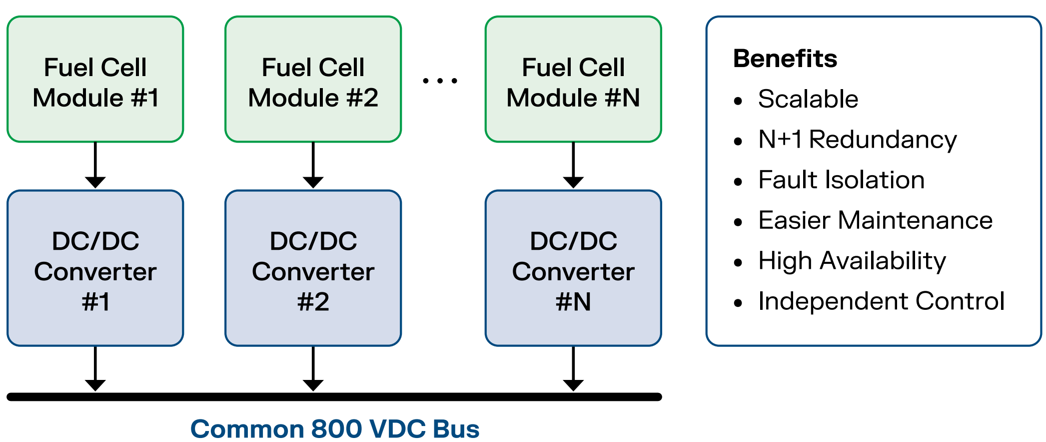
Depending on the design, a large power system requires connecting several cells in stacks to reach required operating voltages. Multiple stacks can be connected into modular power units which are rated at 65 kW. The power modules can then be arranged into stamps of 3.25 MW. Bloom Fuel Cell installations may combine dozens or hundreds of stamps to create power blocks with which data center campuses exceeding 1 GW are being built.

Figure 7: Bloom fuel cells modularity and scalability for DC power output



Up to the 3.25 MW stamp level with their inherent modularity Bloom fuel cells are scaled up in DC by simply adding additional power modules and Energy Server® systems. DC sources don't need to synchronize in frequency and phase like their AC counterparts. In this way fuel cell modules, other sources and loads can be connected to an expanding DC bus as computing demand grows.

Figure 8: Modular architecture for large power systems



This modular approach can support phased capacity additions, incremental capital investment and simplified maintenance, while reducing dependence on oversized initial infrastructure.

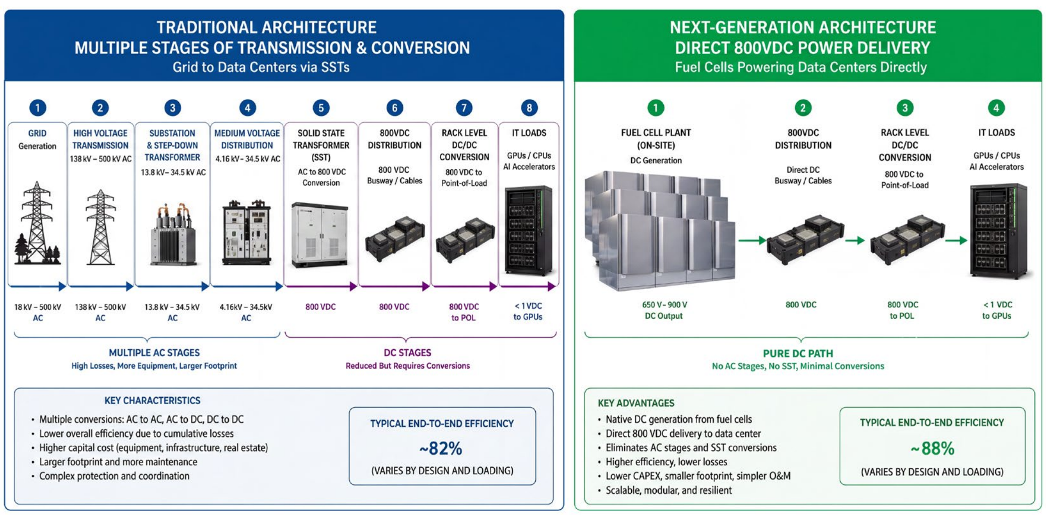
From an availability perspective, the modular approach allows achieving 99.99% - 99.999% with low overbuilt N+1 redundancy, and easy elimination of single points of failure.

Efficiency through fewer conversion stages

When a facility is designed around a DC distribution architecture, using Bloom fuel cells makes it possible to preserve DC power from generation through distribution until the final voltage conversion at the rack or server level. This approach can reduce conversion equipment and associated losses, though the exact architecture must satisfy applicable electrical codes, protection requirements, and operational objectives.

In AC distribution schemes each conversion stage introduces incremental losses. While individual devices may achieve efficiencies exceeding 95–99%, cumulative losses increase as additional stages are added.

Figure 9: The direct 800 VDC architecture with fuel cells eliminates unnecessary conversions



3. Role of ultracapacitors in fuel cell systems

Positioned on the DC bus supplying the IT load (see Figure 10a), ultracapacitors act as a high-power energy buffer, instantly supplying or absorbing current during rapid load changes. Their extremely low equivalent series resistance (ESR), high power density, and sub-millisecond response enable them to maintain a stable DC bus voltage while the fuel cell adjusts its output to the new steady-state operating point. This decoupling of fast electrical transients from the slower electrochemical dynamics of the fuel cell improves overall system stability and allows the fuel cell to operate closer to its optimal efficiency point.

Figure 10a: Representation of a fuel cell block supplying up to 3.25 MW to an 800 VDC data center distribution bus

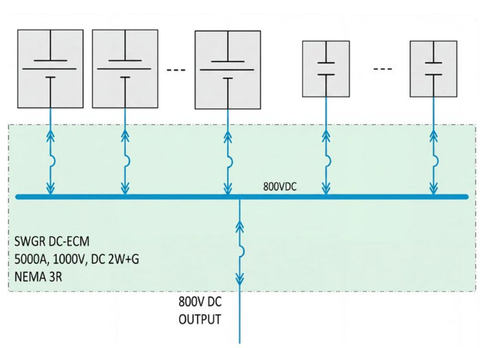


Figure 10b: Fuel cells and Ultracaps operation during AI type loads @ ~50% duty cycle

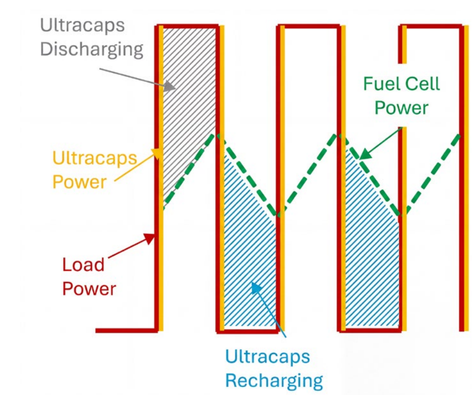


Figure 10c: Fuel cells and Ultracaps operation during AI type loads @ ~50% duty cycle

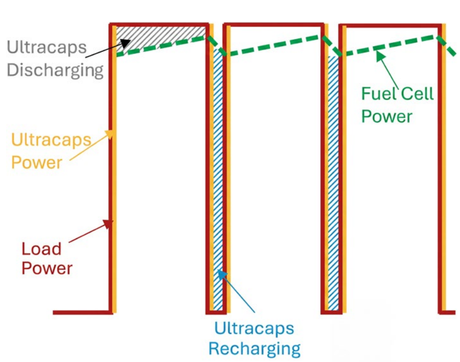
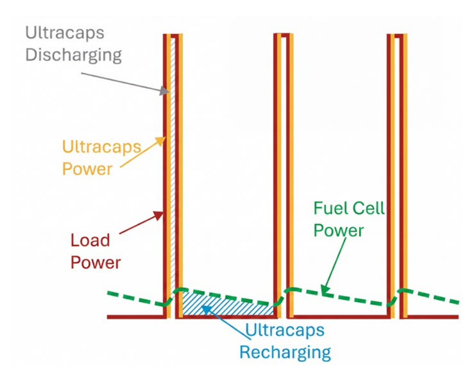


Figure 10d: Fuel cells and Ultracaps operation during AI type loads @ ~50% duty cycle



By handling these frequent load excursions, ultracapacitors reduce dynamic stress on both the fuel cell stack and the associated power electronics, potentially extending equipment life and improving long-term reliability.

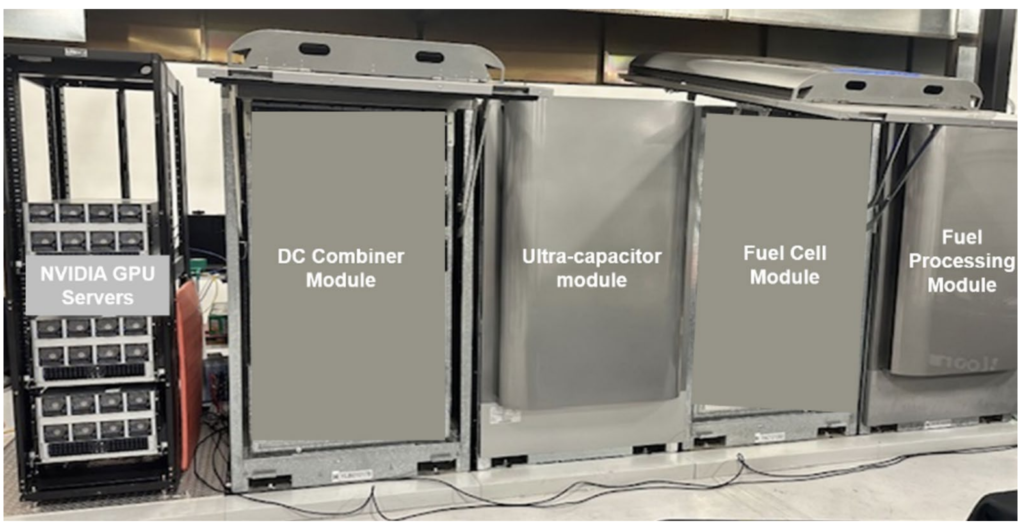
Under normal operation, the converter maintains the ultracapacitor bank at its optimal state of charge. During a sudden increase in GPU demand, the ultracapacitors immediately inject power into the DC bus, limiting voltage sag until the fuel cell output ramps to the new operating level. Conversely, during a rapid decrease in load, excess energy can be temporarily absorbed by the ultracapacitors, preventing voltage overshoot while the fuel cell reduces its output. This bidirectional energy exchange enables seamless power balancing without interrupting the computing workload.

The integration of ultracapacitors also creates opportunities to simplify the overall electrical architecture. In conventional AC-powered data centers, large UPS battery systems are required to maintain power quality and provide short-duration ride-through during disturbances. In a fuel-cell-powered 800 VDC system, many of these fast-response functions can instead be performed by ultracapacitors, while the fuel cells provide the continuous energy source.

4. Testing AI load following with fuel cells direct DC power

To characterize power quality, transient response, and energy efficiency, Bloom has put together a demonstration facility where a fuel cell system was connected to and supplied an 800 VDC rack equipped with NVIDIA H100 GPU servers. On this test bench standardized AI workload profiles were performed to emulate realistic operating conditions. Two representative benchmarks — Llama 2 inference/training and Stable Diffusion image generation — were used to capture a broad range of AI behaviors, while fuel cells were supplying DC power directly to the Rack powershelf. The results from these tests are presented in the following figures.

Figure 11: Test Bench for Direct DC power to IT racks



TEST SUITE #1 – Llama 2: Large Language Model Workloads

Llama 2 workloads are representative of generative AI inference and training in modern hyperscale data centers. During inference, GPUs experience bursts of computation corresponding to token generation, resulting in repetitive fluctuations in power demand. Training (tested below) produces longer periods of sustained high utilization interspersed with synchronization events across GPUs.

Figure 12: Llama 2 70B-LoRA AI Load Profile

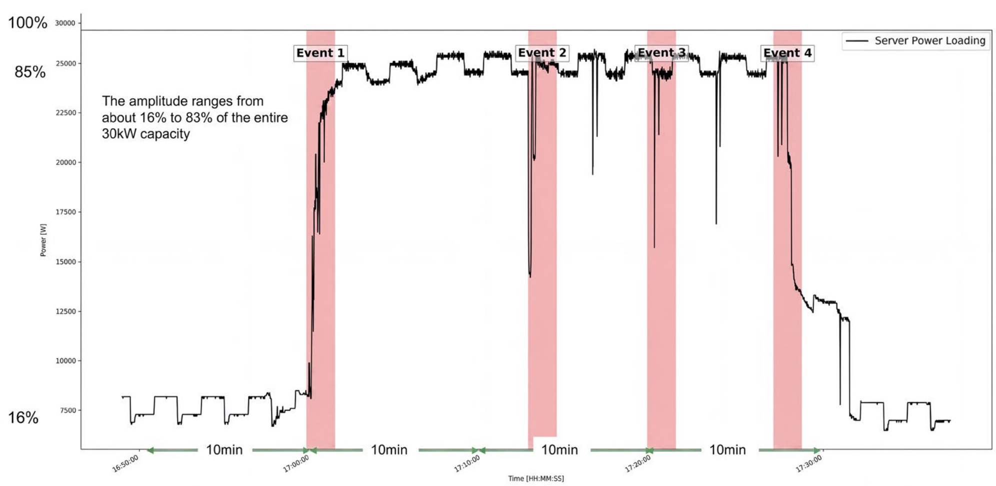
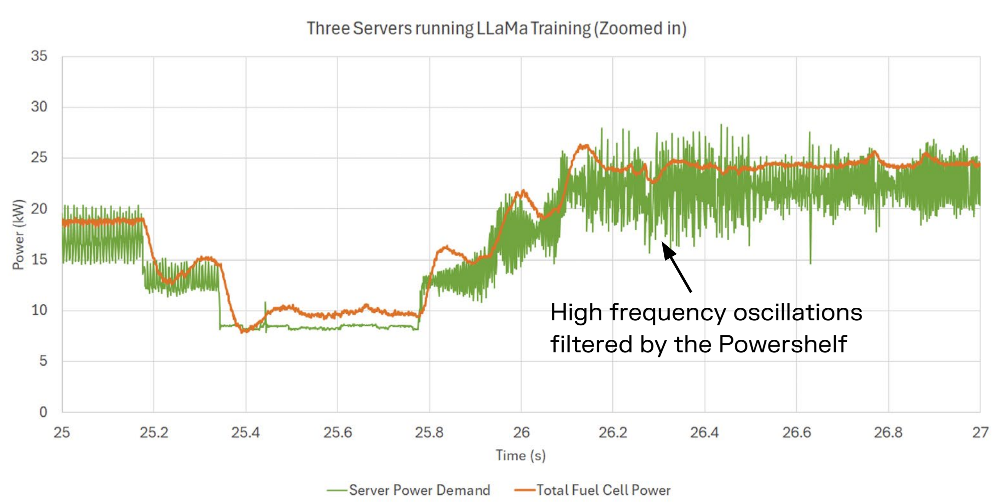


Figure 13: Real-time responses to Llama 2 profile loads: a) green — output of the AI Servers; b) orange — output of the fuel cell after the ultracapacitor



H100 GPUs are extremely noisy, injecting 200 Hz harmonics into the 48 VDC line. The Powershelf converter smooths out these spikes using its input/output capacitors. The orange waveform shows the combined ultracapacitor and fuel cells output displaying no problem following the steps of 50-100 ms duration and 25-50 ms slopes both in downward and upward direction.

TEST SUITE #2 – Stable Diffusion: Bursty AI Inference

Stable Diffusion represents a different class of AI workload corresponding to image generation which alternates between intense matrix computation and comparatively lighter processing stages. Because image generation jobs often execute in parallel across many GPUs, these transient events can aggregate into substantial fluctuations at the rack level.

Figure 14: Stable Diffusion Load Profile

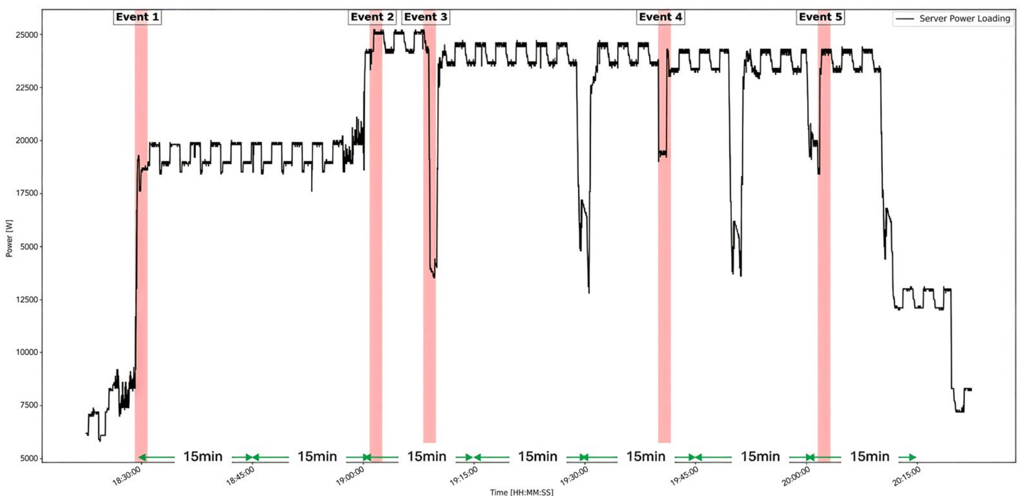
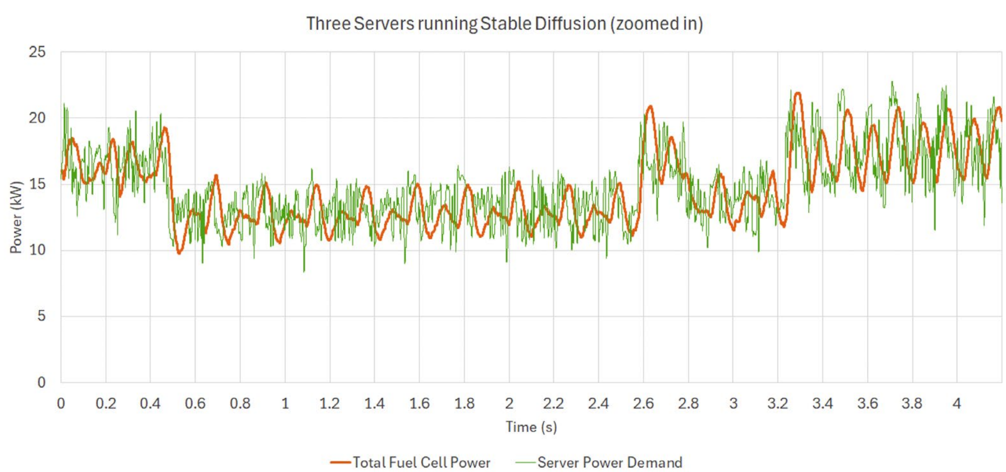


Figure 15: Real-time responses to Stable Diffusion profile loads: a) green – output of the AI Servers; b) orange – output of the fuel cell after the ultracapacitor



While the noise observed on the 48 VDC bus supplying the GPU still remains, the Stable Diffusion profile has a significantly different signature than the Llama 2. Not only are there still step loads and checkpoints in its execution, but it looks like the loads are constantly oscillating with a relatively low frequency of about 8 Hz. These oscillations require constant following, and the fuel cells are doing a great job tracking these variations. For a rotating generator tracking these 8 Hz oscillations would require constant accelerations and decelerations creating oscillating torques that in time may weaken the generator shaft leading to potential material damages. Fuel cells are well suited for supplying the variable low frequency energy requirements of these workloads as they absorb rapid load changes due to their solid-state like behavior.

Summary

Fuel cells represent a significant departure from conventional power generation technologies. By producing electricity as direct current through electrochemical reactions, they eliminate the mechanical generation stage inherent to rotating machines and provide an electrical output that is fundamentally compatible with modern electronic loads.

For the future 800 VDC AI data centers fuel cells possess several characteristics that naturally align with direct-current power systems:

- They generate DC power directly.
- They eliminate the need for a mechanical alternator.
- Their output can be efficiently regulated by power electronics.
- They integrate readily with battery energy storage and other DC resources.
- They support modular expansion and distributed generation.

As AI data centers continue to demand higher power densities, greater efficiency, and improved resilience, fuel cells offer a scalable and modular platform capable of supporting both conventional AC and emerging 800 VDC distribution architectures. Their native DC output, combined with advances in power electronics, creates new opportunities to simplify electrical systems, reduce conversion losses, and support the evolution of highly efficient AI infrastructure.

About Bloom Energy

Bloom Energy empowers enterprises to meet soaring energy demands and responsibly take charge of their power needs. The company's fuel cell systems provide ultra-resilient, clean and highly scalable onsite electricity for Fortune 500 customers around the world, including data centers, semiconductor manufacturing, large utilities, and other commercial and industrial sectors, as well as mission-critical organizations in local communities such as hospitals, college campuses and retailers. Headquartered in Silicon Valley, Bloom Energy employs more than 2,000 people worldwide and manufactures its systems in the United States. For more information, visit **bloomenergy.com/industries/data-center-power**

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