Load Following Solid Oxide Fuel Cell

February 2024

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Abstract

Today's electricity supply and demand are experiencing significant temporal variations. Weather-dependent renewable sources are causing supply-side fluctuations. Consumer and business applications like electric vehicle (EV) charging and artificial intelligence (AI) have highly variable loads with steep ramp-ups that also challenge the ability to deliver steady and predictable power. As a result, utilities are increasingly finding it hard to match supply and demand dynamically. Businesses rely on Distributed Energy Resources (DER) such as gas turbines, combustion engines, or fuel cells to meet their need for variable and reliable power.

This white paper discusses the latest technological breakthrough in Bloom Energy's solid oxide fuel cell (SOFC) technology to enable load following for both Front-of-the-Meter applications for utilities and Behind-the-Meter applications for various end-use customers such as retail, EV chargers, and AI data centers. We call this solution the **Be** Flexible™ Energy Server.

The Challenge of Today's Power Generation: Balancing Variable Power Generation with Variable Load

Variable Power Generation

Today's energy system is going through unprecedented rapid changes, in the race to decarbonize electricity. On the supply side, due to the increased penetration of renewable energy, the grid is becoming highly intermittent (Figure 1) and unpredictable.

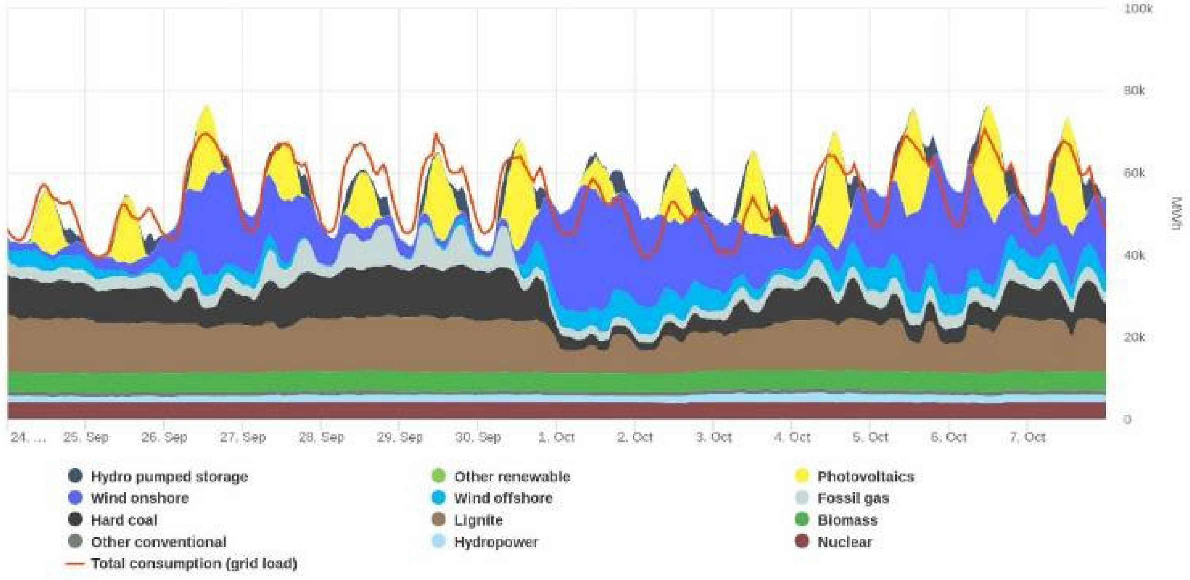


Figure 1: Energy production and demand over two weeks with high renewable penetration[1]

[1] SMARD Generation Market Data - Germany

This has led to some unintended consequences.

Duck Curve: The high penetration of renewables during the past years has led grid operators to rapidly retire dispatchable sources such as natural gas power and nuclear plants, as shown by the increased depth of the well-known duck curve (Figure 2). As soon as the renewable capacity is reduced by clouds or lack of wind, the dispatchable sources must be able to react quickly and immediately come back online. But with traditionally slow ramping times, they may not be able to respond appropriately. This makes the grid highly unstable and threatens grid reliability.

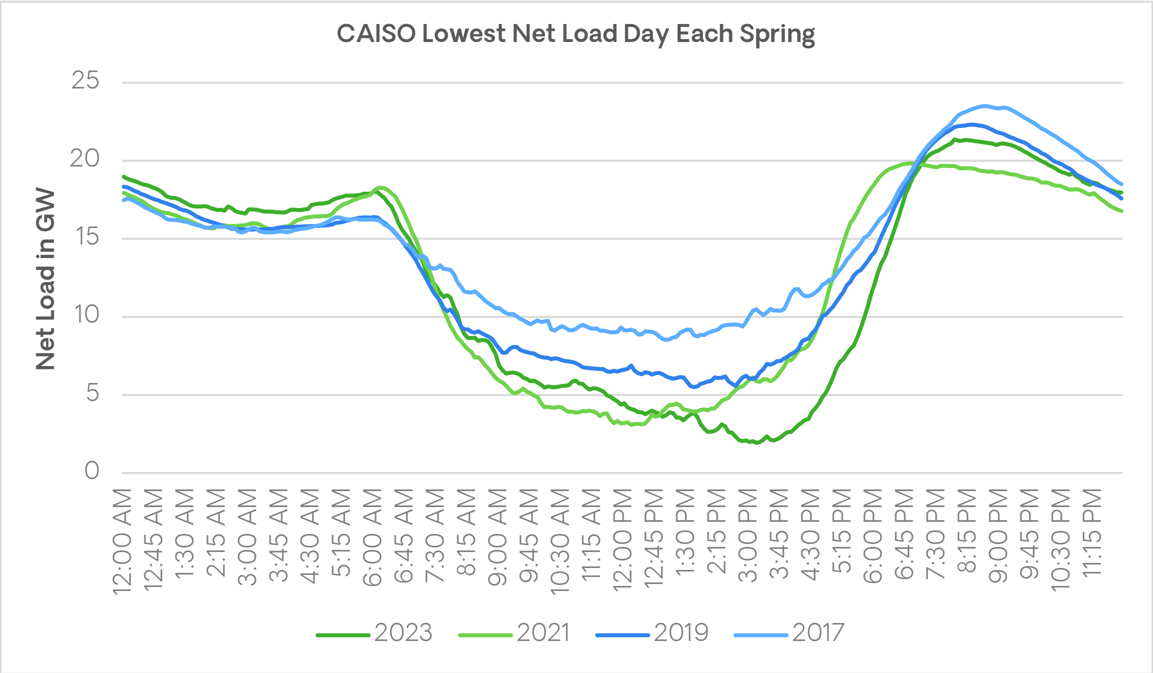


Figure 2: The demand for conventional power generation is decreasing midday when Solar plants produce most electricity, but generators must ramp up rapidly during evening hours[2]

Increased Use of Dirty Backup Generation: During grid emergencies such as heat waves, grid operators must rely on carbon-intense sources such as low-efficiency backup diesel generators. For example, during the September 2022 heat wave in California, electricity demand exceeded 45 GW around 7.00 PM, while solar output had significantly decreased.[3] Diesel generators were deployed to meet this demand.

[2] CAISO Production & Curtailment Data
[3] CAISO - Summer Market Performance Report

Variable demand

Loads have always been variable, and historically grid balancing was possible with minimal risk due to the high availability of dispatchable resources like nuclear and natural gas power plants.

But with increased commercial demand and new applications such as AI data centers and EV charging, the load variation can be significantly higher and very rapid, as seen in Figures 3 and 4.

When the load profiles are extreme, i.e., with deep and frequent load variations, such as AI loads in data centers, the grid is disrupted. This type of grid disruption is caused by the frequency and voltage variations induced into the system and inevitably affects other customers in the area. A better solution would be to have dedicated microgrid controlled power generation onsite to serve such loads.

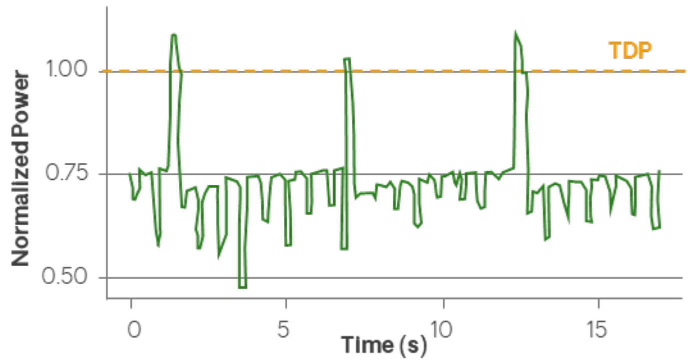


Figure 3. Power usage time series for inference models for a GPT-NeoX GPU server in an AI data center, adapted from Pratyush Patel et. Al.[4]

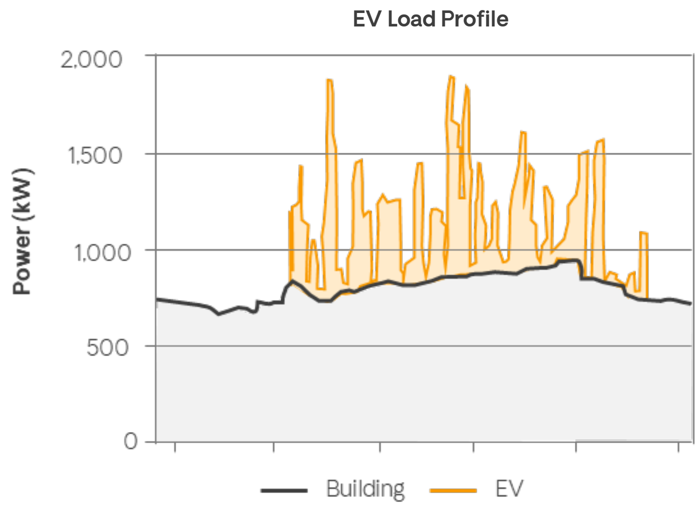


Figure 4. Monthly average and instant peak power demand breakdown for a 2-port, high utilization 350 kW EV charging at a big store in Phoenix, chart adapted from M. Gilleran et. Al.[5]

[4] Pratyush Patel, et. al. (2023). POLCA: Power Oversubscription in LLM Cloud Providers. arXiv>cs>arXiv:2308.12908

[5] M. Gilleran et. al. (2021). Impact of electric vehicle charging on the power demand of retail buildings. Advances in Applied Energy vol 4.

Temporal Balancing of Supply and Demand

Maintaining a stable grid is like riding a unicycle—one must constantly adjust one's position to stay balanced. It was easier to maintain this balance in the past due to the availability of dispatchable resources such as fossil fuel and nuclear power plants. As discussed above, balancing supply and demand has become challenging due to the rapid retirement of these resources combined with increased penetration of renewable and highly variable loads.

Bloom's technological breakthrough is improving fuel cell ramp up and ramp down capability. Bloom Energy's SOFC platform is now uniquely suitable to provide dispatchability, along with a cleaner and highly efficient power solution to the temporal balancing of supply and demand in today's highly dynamic applications. The remainder of this white paper will discuss the technical performance of Bloom's newest solution, allowing Bloom's Energy Server to perform load following with high accuracy and superior efficiency, making it significantly more appealing to a broader customer base, such as utilities, data centers, EV charging stations, and other commercial customers. Since this new offering can be deployed in Front-Of-The-Meter for utilities to solve the duck curve problem or Behind-The-Meter to help commercial customers manage their peak loads, Bloom's Energy Server has become even more valuable to the worlds energy transition and is available today, at utility scale.

Ramping

For several reasons, fuel cells outperform their rotating machine counterparts regarding response time when ramping from part load to full load. Fuel cells also simplify the energy conversion process. Unlike traditional power generation methods that use rotating machinery, such as gas turbines, which require a multi-step conversion from chemical to electrical energy, fuel cells accomplish this transformation directly in a single step, as shown in Figure 5. Fuel cells, being solid-state devices, do not possess any large inertia like rotating machines, and unlike turbines, there is no efficiency drop from full load to part load.

Figure 5. Energy conversion process from Fuel to Electricity for a) conventional gas turbines; b) solid oxide fuel cells

Bloom's Energy Server Breakthrough

As mentioned above, fuel cells are inherently better for ramping than their combustion counterparts. Historically, the Bloom Energy Server® was utilized chiefly as a baseload electricity generator. Through rigorous R&D in the last five years, two significant developments have enabled the technological breakthrough in enabling our fuel cells to ramp up and ramp down.

1. Bloom significantly increased the life and reliability of our fuel cell stacks through continuous improvements in design, materials, and manufacturing.
2. Bloom made significant improvements at the system level through innovations in the balance of plant infrastructure. These optimizations were enabled by creating a digital twin of our fuel cell and leveraging the extensive data Bloom obtained from our field operations.

Bloom has performed rigorous testing of our load following fuel cell products for a typical AI data center load profile using an AI load simulator (see Figure 6)

Figure 6. Bloom Testing System dedicated to simulating and supporting dynamic loads (see configuration in Figure 7)

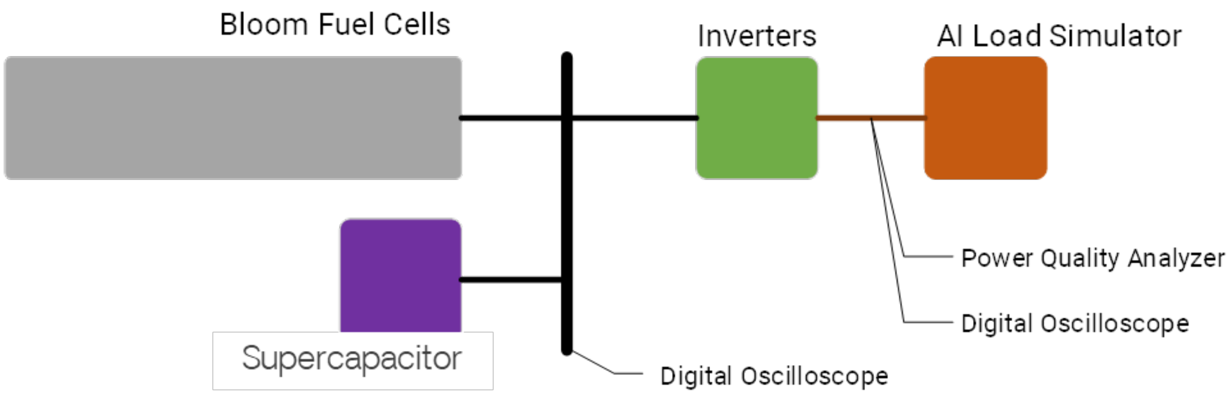


Figure 7. Single Bloom Energy Server architecture for testing dynamic loads.

The AI load is simulated using a controllable resistor load. The resistor load is chosen to replicate AI servers' near instantaneous step load. The load profiles are managed through computer-generated signals with adjustable amplitude, frequency, and duty cycles. This closely mirrors the power consumption observed during AI training in data center racks. Bloom Energy's fuel cells are paired with an inverter and supercapacitors for these tests. Figure 8 shows the typical load profile using the AI load simulator and the dynamic response of the fuel cell.

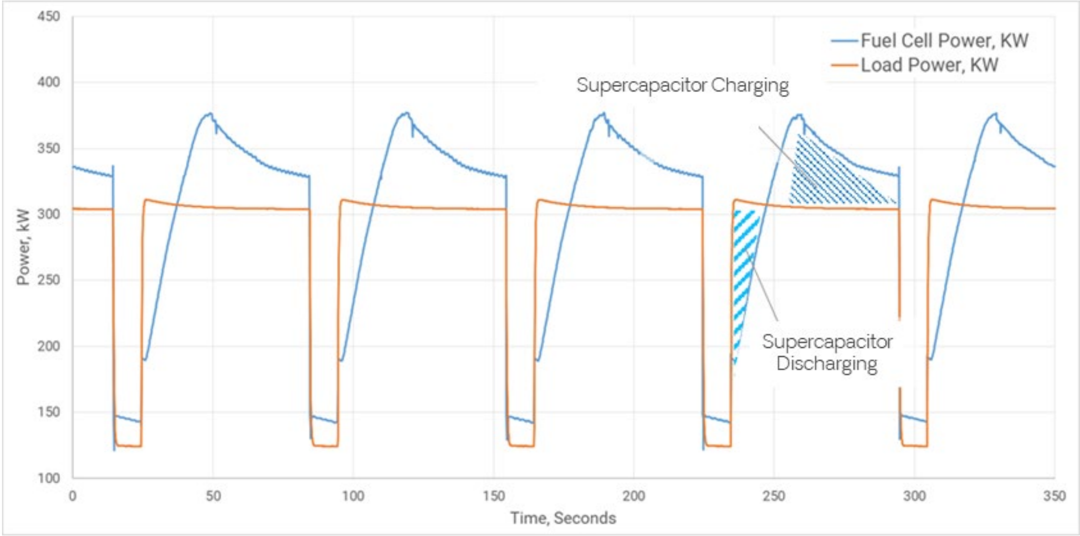


Figure 8. Fuel cell response to a step-load varying from 40% to 100% when using Supercapacitors for ramping support

Figure 9 demonstrates the inverter AC output voltage response to an instantaneous step increase load with an extreme-case slope of 2000%/min. To meet that instant demand, the fuel cell system uses Bloom's supercapacitor banks that discharge the power instantly. Once the target power is reached, the fuel cell supports the load and recharges the capacitors to prepare them for the next step. When the load drops, the fuel cell ramps down, instantaneously reaching 40% of capacity.

The power quality of the inverter output meets various standards available in the market, including ITIC, IEC 62040, and SEMI. As these are inverter-based resources, the frequency doesn't change with load beyond the narrow droop setting equipped for load sharing.

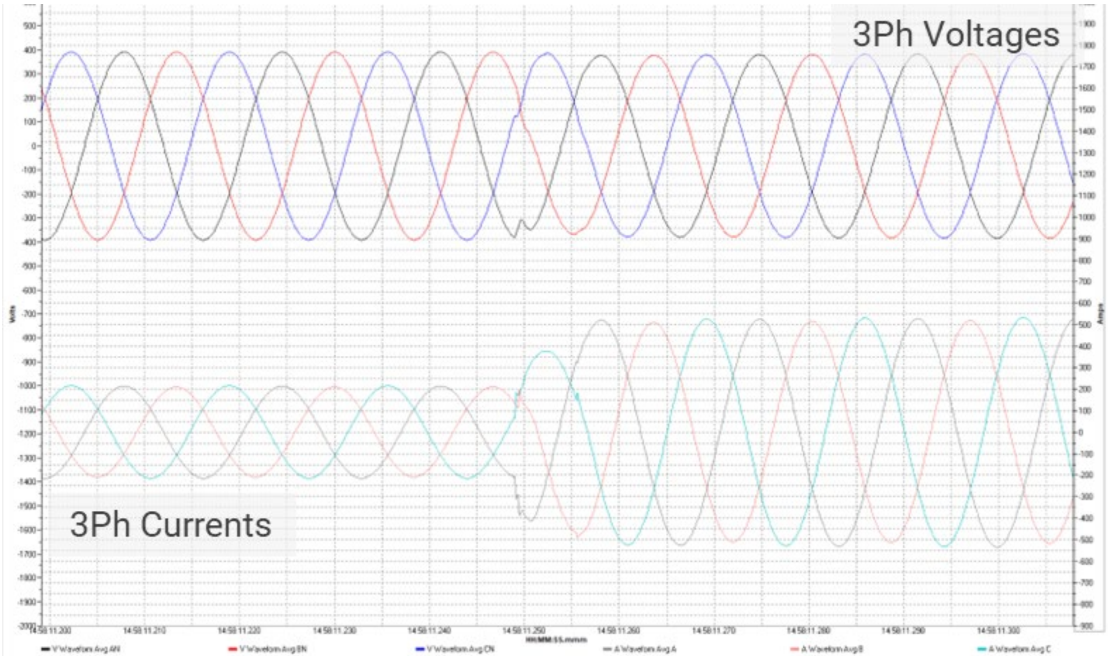


Figure 9. Voltage and Current waveforms during a load transient of 40% to 100% capacity.

Part Load Efficiency and Emissions

Due to the multiple steps involved in converting the chemical energy of the fuel to electrical energy (See Figure 5), the efficiency of turbines is inherently lower than that of the fuel cells. Since turbines are rotating machines, the part load efficiency is much lower than full load efficiency.

Given the solid-state nature of Bloom Energy fuel cells, the efficiency does not drop from full load to part load. Since carbon emission is inversely proportional to the efficiency, emissions of turbines increase significantly at part load. Table 1 compares the performance of Bloom's fuel cells and gas turbines. We also note that Bloom Energy fuel cells are hydrogen-ready and can run on 100% hydrogen or a blend of hydrogen and natural gas.

	On-Site Micro Turbine (e.g., Aeroderivative)	Bloom Fuel Cell
Efficiency @ Full Load	0.371[6]	0.54
Efficiency @ 30% Load	0.257[7]	0.53
CO_2 footprint @ full load (lbs/MWh)	1095	800
CO_2 footprint @ 30% load (lbs/MWh)	1620	815
Environmental pollutants (lbs/MWh)	NOx ~ 0.858, CO ~ 0.52, VOC~ 0.175	NOx ~ 0.0017, CO ~ 0.012, VOC~ 0.01

Table 1: Technology comparison between On-Site Micro Turbines and Bloom fuel cells

6 EIA - Cost and Performance Characterestics of New Generating Technologies, Annual Energy Outlook 2023
7 Suarez et al., Energy Procedia, 157, 719, 2019

Techno-Economic Analysis

In this section, we discuss two use cases that illustrate the significant economic advantage of our load-following fuel cell.

Retail Use Case

For the retail industry, utility costs continue to rise globally at an accelerated pace, with increasing emphasis on demand charges to account for more variability in supply and demand. Many retail stores and distribution centers are adopting Bloom Energy Servers today to provide significant savings vs. baseload power from the grid.

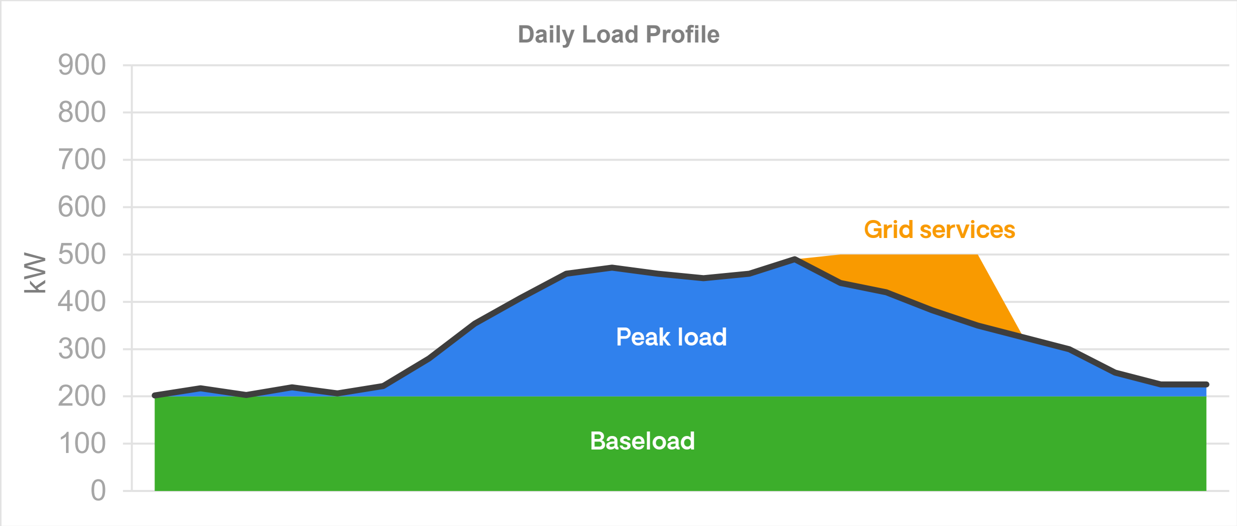


Figure 10. Illustrative load profile for a retail store

Assuming a **Be** Flexible Energy Server is installed at a retail store in California. It can offset the grid entirely and avoid the expensive energy and demand charges at up to 50% savings versus the grid. Bloom helps reduce the utility bill completely by covering the store's baseload and the mid-day ramping, including peak load, thereby reducing demand charges. Bloom can participate in grid services markets where applicable to provide additional value. This particular use case indicates that the load following **Be** Flexible Energy Server can potentially reduce the electricity cost by more than 50% for the customers.

Illustrative Savings vs. the Grid

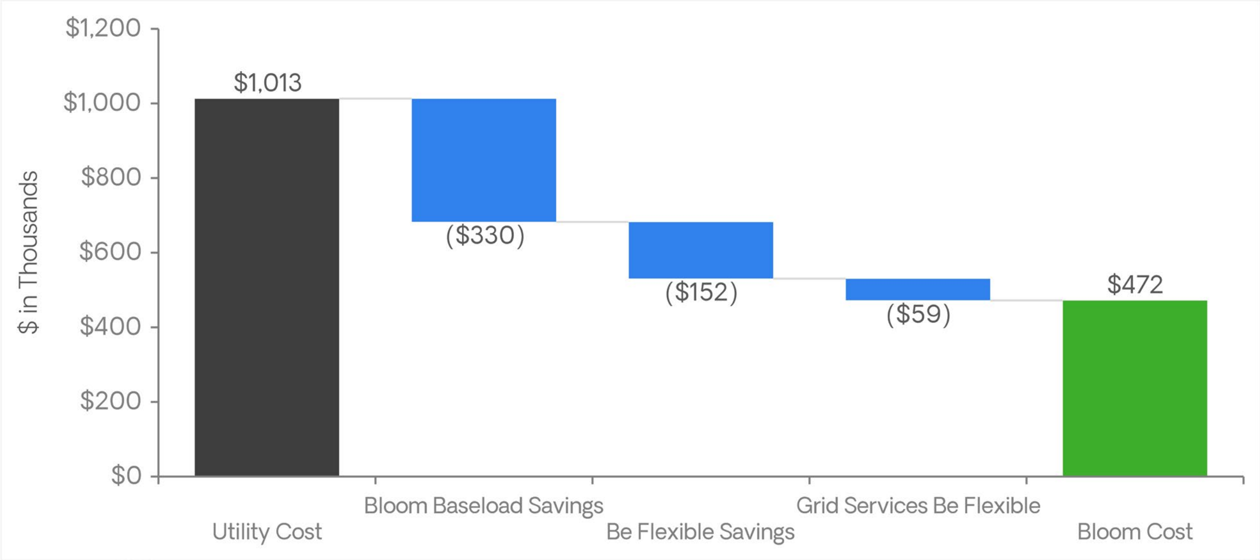


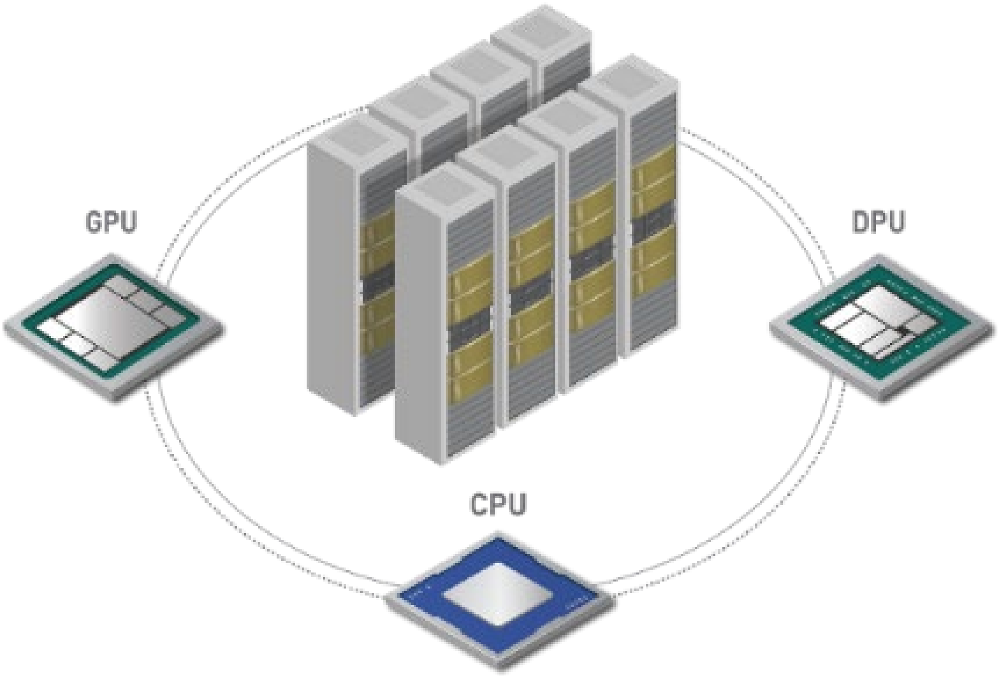
Figure 11. Illustrative annual savings of Bloom's microgrid solution vs. the grid for a retail store[8]

AI Data Center Use Case

The emergence of AI has only added to today's burgeoning data center needs, which the current grid cannot address. Many data center providers are seeing multi-year wait times to receive grid interconnections, leading to significant opportunity costs for data centers and their tenants. For example, Ireland imposed a de facto moratorium on data center developments in the greater Dublin area[9]. In addition, these large and highly variable loads are difficult for the grid to address even when the power is available. The issue is that the substations delivering power to existing facilities need to prepare to handle high variability. Large swings in power create fluctuations in frequency that would disturb all the adjacent consumers and lead to possible shutdowns due to under-frequency or under-voltage events. **Be** Flexible Energy Server solution can be online within months and address the dynamic load profiles as a standalone microgrid at an energy price competitive with the grid charges today.

8 Utility tariff assumed: PG&E B-19S tariff. Bloom costs amortized over a 15-year term and a $9/MMBTU total delivered gas price. Grid services assume an additional ~150kW of power exported to the grid 5 hours a day, five months a year at $50/MWh value.

9 RTE - No new data centers for the capital for the foreseeable future, greater Dublin area "constrained"



Illustrative Total Cost for 10MW AI Data Center

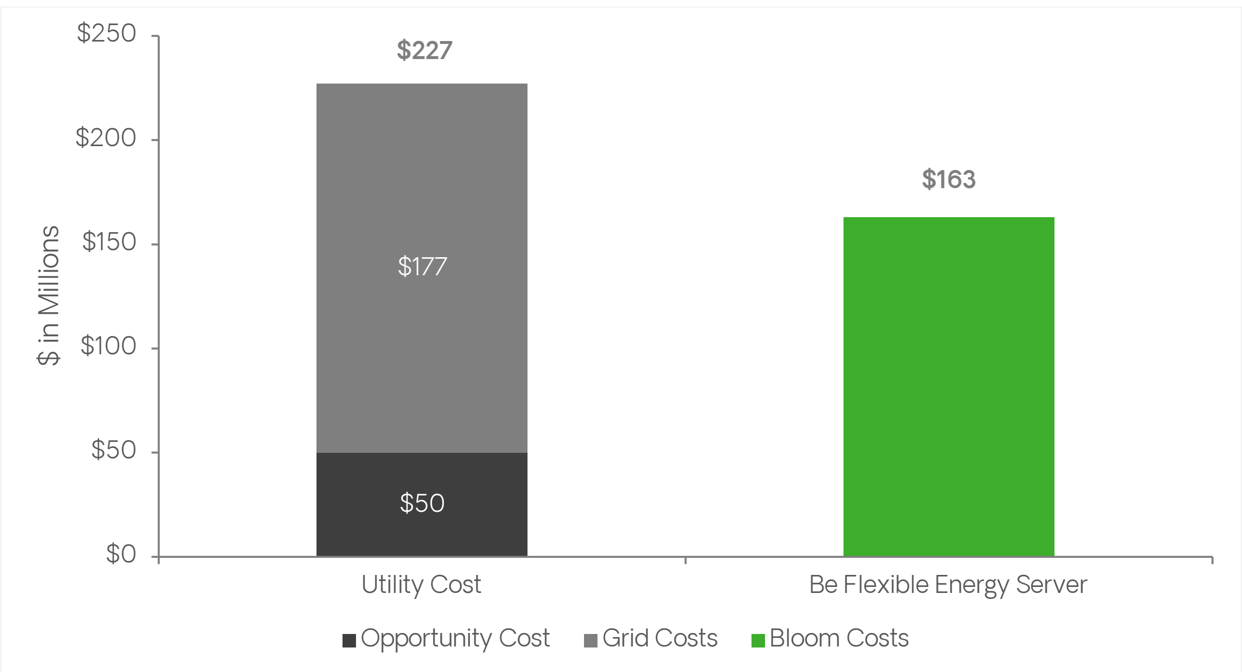


Figure 11. Illustrative total delivered cost of power for a 10MW data center over 15 years

Time to power value assumes three years of grid unavailability, data center rental rates of $200/kW-month[10], and 30% operating costs. Grid costs based on a 15-year term with a starting COE of 12.5 cents escalated at 3.5% annually. Bloom cost is based on the **Be** Flexible Energy

[10] CBRE estimates for data center lease rates in Silicon Valley

Server solution with capital and service costs over a 15-year term, and a $9.50/MMBTU average delivered gas price. Figure 11 shows that a data center can save up to 28% compared to the grid cost. As mentioned, even when grid power is available, it's highly unlikely that the grid can tolerate such a high level of variability, as discussed. Therefore, a grid-connected power will require additional technologies.

Conclusion

Load following **Be** Flexible Energy Server offers a significant advantage as compared to other competing technologies for providing temporal balancing of supply and demand. The results reported in this white paper show the ability of **Be** Flexible Energy Server to ramp at a very high rate, and the output matches various standards available in the market. **Be** Flexible Energy Server can be applied for various Front-of-the-Meter and Behind-the-Meter applications.