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# Potential of Data Center Controls in Grid Services

June 2026

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U.S. DEPARTMENT  
of **ENERGY**

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## Abstract

The rapid proliferation of large data centers brings both challenges and opportunities for grid reliability. The data center resources and their potential flexibility have the potential to contribute resources to grid operations. Through capabilities like energy shifting and resource coordination, data centers can help reduce their net demand on the transmission network, as well as provide additional grid services to support reliable operation on the grid. While transient and long-term grid planning and operations are the scenarios that draw most attention, the quasi-steady state timeseries (QSTS) operation of data centers and grid bring interesting scenarios that can help evaluate the data center controls to aid grid services. This work is focused on modeling data centers for QSTS applications – incorporating the AI data center load profiles and building on the PNNL digital twin model for the thermal management loads to enable simulation studies to reveal the impact of data center controls on grid performance. This includes the integration of a QSTS battery and natural gas generator model to incorporate local resource impacts to the system. The simulation study is performed with a modified IEEE 24-Bus transmission system. Scenarios are focused on evaluating the data center load impacts on the transmission system and leveraging both data center and local generation controls to mitigate those impacts and provide additional grid services.

The data center controls revealed the ability to contribute to two main kinds of grid services: preventing congestion on a weak grid by coordinating the data center resources with the collocated BESS and onsite generation; and the ability to help the grid operations during stressed times of operation like during a contingency. Leveraging these and other capabilities has the potential to help data centers become grid responsive assets, aiding in both their integration into the power system and grid reliability.

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## Acronyms and Abbreviations

|      |                                                                                        |
|------|----------------------------------------------------------------------------------------|
| AGC  | Automatic Generation Control                                                           |
| AI   | Artificial Intelligence                                                                |
| BESS | Battery Energy Storage                                                                 |
| CRAC | Compute Room Air Conditioning                                                          |
| CRAH | Compute Room Air Handler                                                               |
| DC   | Data Center                                                                            |
| DOE  | Department of Energy                                                                   |
| EMT  | Electromagnetic Transient                                                              |
| FERC | Federal Energy Regulatory Commission                                                   |
| IT   | Information Technology                                                                 |
| MW   | Megawatt                                                                               |
| NERC | North American Electricity Reliability Corporation                                     |
| NG   | Natural Gas                                                                            |
| PCC  | Point of Common Coupling                                                               |
| PF   | Power Factor                                                                           |
| PUE  | Power Usage Effectiveness                                                              |
| QSTS | Quasi Steady State Time Series                                                         |
| SOC  | State of Charge                                                                        |
| UPS  | Uninterruptable Power Supply                                                           |
| VAR  | Volt-Ampere Reactive (unit for reactive power and used synonymously to reactive power) |

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## 1.0 Introduction

Rapid growth in artificial intelligence (AI) compute is driving a new wave of large, energy-intensive data center development across the United States. Unlike many conventional commercial loads, AI data centers—particularly those supporting large-scale model training and inference—can present high load densities, fast ramping behavior at the facility level, and concentrated interconnection requests in constrained transmission zones. At the same time, these facilities increasingly include on-site energy assets such as battery energy storage systems (BESS), backup generation, sophisticated power electronics (e.g., UPS systems), and advanced energy management systems. These characteristics create both operational concerns and a potential opportunity: AI data centers may become “grid-interactive” resources capable of supporting quasi-steady-state grid operations (seconds-to-minutes balancing, load following, congestion management, and other operating-reserve timeframes) if properly integrated through market rules, interconnection requirements, and operating practices.

U.S. reliability organizations and federal agencies have highlighted the operational and planning implications of rapidly changing system conditions, including large new loads and an evolving resource mix. The North American Electric Reliability Corporation (NERC) emphasizes that accurate demand forecasting, deliverability of reserves, and performance of power-electronic resources are increasingly central to reliable operations [1-3]. In parallel, the Federal Energy Regulatory Commission (FERC) is advancing reforms to generator interconnection and long-term regional transmission planning intended to respond to rapid changes in resource siting and grid needs while maintaining just and reasonable rates and reliable operations [4,5]. The U.S. Department of Energy (DOE) and National Laboratories have documented pathways for more flexible demand, enhanced grid services from end-use assets, and the role of storage and advanced inverter controls in maintaining reliability during the energy transition [6-8]. In this context, AI data centers represent a fast-growing class of “large flexible loads” that could either stress quasi-steady-state operations—or be structured to help stabilize them.

### 1.1.1 Quasi-Steady-State Operations and Why AI Loads Matter

Power system operations broadly break down into two timescales: dynamics behaviors that occur in 1  $\mu$ s to 1 second, and quasi-steady state behaviors that are 1 second to longer time durations (typically up to the hourly or daily level). Quasi-steady-state power system operations refer broadly to the operating regime in which the grid is managed around a continuously changing but near-equilibrium balance of generation and demand. This includes regulation via automatic generation control (AGC), load following, contingency and operating reserves, interchange scheduling, and congestion management under normal conditions and credible contingencies. While transient stability and fast frequency response remain critical, day-to-day reliability is strongly shaped by quasi-steady-state challenges such as forecast error, ramping needs, transmission constraints, and the availability and performance of reserves. AI data centers can affect these operations in several ways.

#### 1.1.1.1 Scale and geographic concentration

Many new AI campuses request hundreds of megawatts to gigawatts of service, sometimes clustered within the same load pocket or constrained corridor. This can change local power flows, import requirements, and planning assumptions. NERC’s long-term reliability assessments underscore that regional adequacy and operating risk can be sensitive to

concentrated changes in load growth and to delays in transmission development relative to changing system needs [1-3].

### 1.1.1.2 Operational variability behind the meter

Although data centers are often described as steady loads, AI training clusters can exhibit sudden changes in energy demand due to job scheduling, redundancy events, cooling dynamics, and power capping schemes. At the bulk system level, these step changes can manifest as increased intra-hour variability, which in turn can increase regulation and load-following requirements. DOE's grid modernization and flexibility work has highlighted that end-use flexibility—enabled by controls, measurement, and communications—can reduce operational stress and support reliability when properly integrated [6-8].

### 1.1.1.3 Power-electronics-rich interfaces and control interactions

AI data centers rely on rectifiers and inverters in their uninterruptible power supply (UPS) and DC power systems, and increasingly on-site BESS interfaced through inverters. These power electronic devices often have controls to quickly respond to changes on the system, like performing voltage control or responding to a disturbance. The fast-acting flexibility of these devices also means they have the ability to provide (or avoid degrading) essential reliability services. NERC reliability guidelines and multiple national laboratory efforts emphasize that performance expectations, models, and validation are necessary to ensure power-electronics-rich assets support—not undermine—bulk power system reliability [3, 9, 10].

These factors imply that integrating AI data centers is no longer only about supplying energy and capacity; it also requires defining a robust operational relationship between data centers and the grid—what the grid requires from these large loads to ensure reliability and what services these facilities could provide in return.

## 1.1.2 AI Data centers as Providers of Grid Services in the Quasi-Steady-State Regime

A central opportunity is to treat AI data centers as controllable, grid-interactive resources capable of providing services traditionally supplied only by generators. DOE and National Laboratories have long identified demand flexibility as a potential contributor to reliability and cost reduction, especially when enabled by advanced controls, telemetry, and verification [6-8]. From [11], the six grid services are briefly defined as follows:

- **Energy Service** – a scheduled production or consumption of energy at an electrical location over a committed period.
- **Reserve Service** – a specified capacity to produce or consume energy at an electrical location when called upon over a committed period.
- **Regulation Service** – continuously provides an increase or decrease in active power from an electrical location over a specified schedule period against a predefined active power basepoint following a service requestor's signal. The signal interval is typically one to several seconds, and the associated performance period is ignorantly shorter in duration than the typical energy service period.
- **Frequency Response Service** – responds to change in system frequency nearly instantaneously by consuming or producing power over a committed period.

- **Voltage Management Service** – provides voltage support (raise or lower) within a specified upper and lower voltage range at an electrical location over a committed period.
- **Blackstart Service** – energize or remain available without grid electrical supply to energize part of the system over a committed period.

Figure 1 shows some example services a data center could provide from the fundamental grid services. The mechanism to provide these will be discussed briefly in the next subsections.

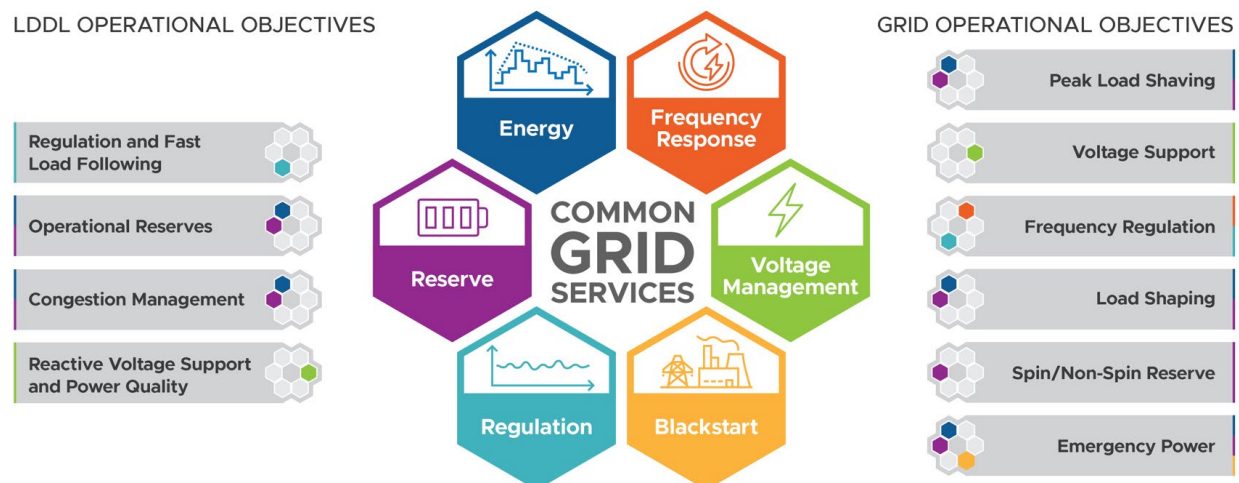


Figure 1. Common grid services and LDDL/data center potential contributions (adapted from [11])

#### 1.1.2.1 Regulation and fast load following (seconds to minutes)

Data centers can modulate non-critical compute, adjust power capacities, or shift workloads among geographically distributed sites. While the energy impact may be modest, the ramping capability can be significant in MW/min terms. Where on-site BESS exists (either as part of a UPS architecture or as dedicated storage), the facility can provide regulation with minimal disruption to compute by buffering power at the point of interconnection. National laboratory work on advanced inverters and grid-forming/grid-supportive control concepts further support the technical feasibility of fast, accurate responses from inverter-interfaced assets when appropriately designed and validated [12].

#### 1.1.2.2 Operating reserves (contingency, supplemental) via load reduction and/or behind-the-meter assets

Depending on market rules and interconnection arrangements, data centers may offer interruptible load, controllable demand, or injections from BESS to support reserves. NERC's reliability framing for resource adequacy and operating risk emphasizes that reserve products must be deliverable, measurable, and dependable under stressed conditions—requirements that imply data center participation must include clear performance standards, telemetry, testing, and verification [1,2].

### 1.1.2.3 Congestion management and local capacity support

In constrained areas, flexible consumption (or injection from BESS) can reduce loading on critical transmission elements during peak periods, forecast errors, or N-1 events, thereby improving operational margin. FERC's transmission planning reforms reflect the growing need for proactive, long-horizon solutions to manage congestion and changing power flow patterns, and they provide a policy backdrop for considering non-traditional solutions—provided they are transparent and do not substitute for needed transmission expansion where it is the least-cost long-term solution [5].

### 1.1.2.4 Voltage support and power quality services

Advanced inverter functions in UPS and BESS systems can provide reactive power and voltage control at the point of interconnection, subject to interconnection requirements and coordination with utility voltage regulation and protection practices. NERC guidance on inverter-based performance, along with national laboratory inverter research, emphasizes that settings, controls, and models must be coordinated and validated to ensure predictable system behavior [3, 12].

Implementing the services discussed in 1.2.2.1 - 1.2.2.4 requires more than technical capability. There must also be:

- (i) Participation pathways (utility programs and/or wholesale market rules)
- (ii) Operational visibility (telemetry, forecasting, and communications)
- (iii) Interconnection agreements that define response time, dispatchability, performance, and cyber/physical security requirements.

DOE grid modernization work highlights that scalable flexibility depends on verification and interoperability; similarly, FERC's interconnection reforms reinforce the importance of clear processes and requirements as new assets connect at scale [4].

## 1.1.3 Role of Onsite Generation and BESS for Reliability and Grid Services

Most large data centers are built around stringent reliability targets, historically achieved through redundant utility service, uninterruptible power supplies, and on-site backup generators (commonly diesel; increasingly natural gas or alternative fuels), with growing adoption of BESS. These assets can be leveraged to manage both facility resilience and grid interaction, but they also introduce operational considerations that must be addressed explicitly.

Onsite generation and BESS can influence quasi-steady-state operations in two ways:

**Potential reliability value:** During system stress events, data centers can reduce net load by transferring to on-site generation, providing rapid load relief. Where permitted and technically configured, certain facilities may be able to export power or operate in coordinated modes that support local reliability (subject to protection, safety, and market participation rules). In quasi-steady-state terms, this can resemble a dispatchable reduction in demand or a localized capacity contribution.

**Operational and coordination challenges:** Backup generators are often designed for emergency use and may have constraints on runtime, emissions permitting, black-start dependence, or fuel supply logistics. From a reliability perspective, NERC’s emphasis on dependable performance under extreme conditions suggests that any reliance on onsite generation for grid services must include clear availability definitions, testing, and realistic assumptions about fuel and environmental constraints [1,2]. Poorly coordinated generator operation can also create local voltage/power quality issues or complicate restoration priorities.

Battery energy storage systems (BESS) are particularly well suited to quasi-steady-state services due to fast response, accuracy, and controllability. However, they may still have constraints similar to standard backup generation from a grid interaction and reliability concern, with local voltage and power quality issues having equal relevance for BESS devices. Furthermore, managing the state of charge of the BESS can look similar to the fuel supply challenges for traditional generation, so proper management is needed to maximize their benefit. These challenges could be addressed with the right mix (energy source) and sizing of onsite generation.

The DOE’s Energy Storage Grand Challenge roadmap identifies storage as a key flexibility resource that can support reliability and resilience across multiple time scales, especially when paired with advanced controls and appropriate operational frameworks [8]. For AI data centers, BESS can:

- Smooth ramps and mitigate step changes in facility demand, reducing regulation burden on the bulk system.
- Provide regulation and reserves without curtailing compute, by buffering power at the grid interface.
- Support voltage/reactive needs through inverter controls (subject to interconnection requirements and coordination).
- Improve ride-through and resilience for short-duration disturbances, potentially reducing the likelihood that a data center disturbance propagates as a noticeable grid event.

National laboratories’ work on grid-forming inverters highlights that inverter-interfaced resources can provide “grid supportive” functions traditionally associated with synchronous machines, but that performance depends on control design, testing, and coordination with system operators [12]. Consequently, a key integration requirement for data center BESS is ensuring that the facility’s inverter controls (UPS and storage) are modeled, validated, and operated in a manner consistent with reliability expectations and local utility practices [1,12].

#### 1.1.4 Motivation and Scope

Given accelerating AI data center deployment, the power sector faces a near-term need to integrate these loads without undermining quasi-steady-state operating reliability, while also exploring whether they can contribute to flexibility and essential reliability services. This work is motivated by the need for a practical framework that:

1. Characterizes AI data center load behavior and controllability relevant to quasi-steady-state operations;

2. Identifies grid services data centers can provide through flexible load, on-site BESS, and coordinated use of onsite generation;
3. Identify potential implementation requirements— performance verification, modeling, and coordination—to enable data centers to function as dependable participants in reliability-critical functions.

The broader objective is to bridge data center power engineering (focused on uptime and power quality inside the fence) with bulk power system operations (focused on balancing, reserves, deliverability, and system security). As DOE, FERC, and NERC publications collectively indicate, the grid is evolving toward a system where flexibility, visibility, and controllability across both supply and demand are increasingly important for maintaining reliability and managing costs [1–12]. AI data centers—given their scale, power-electronics-rich infrastructure, and emerging on-site capabilities—are poised to be a pivotal test case for how large loads can be integrated as active participants in quasi-steady-state grid operations.

## 2.0 QSTS Model of Data centers

Quasi-Static Time Series (QSTS) simulation is widely used in power-system studies to evaluate how voltages, power flows, and equipment loading evolve over time in response to time-varying loads and generation along with energy storage variations [13], [14]. Unlike a single steady-state “snapshot” power flow, QSTS runs many sequential steady-state solutions using time-series inputs (e.g., seconds to minutes to hourly), with control actions updated at each step (e.g., capacitor switching, inverter volt/VAR control, transformer tap changes) [13-15]. This approach is well-suited to data centers because their demand is large and operationally dynamic (IT workload changes, cooling response, UPS behavior, generator testing), and because modern facilities increasingly include onsite resources (UPS batteries and standby generators) that interact with the grid over time [15,16]. QSTS provides a practical middle ground between fast electromagnetic transient (EMT) analysis and system-level planning studies, enabling assessment of feeder voltage excursions, transformer loading, losses, and VAR behavior over realistic operating horizons [13-15].

A QSTS model of a data center typically represents: (i) the grid interconnection and service infrastructure (utility network service transformer, switchgear); (ii) the facility electrical distribution and major conversion stages (MV/LV distribution, UPS, PDUs); (iii) end-use load decomposition (IT load, cooling, auxiliaries); and (iv) onsite sources and controls (generators, UPS battery, and energy management logic) [17]. A key modeling decision is the level of aggregation appropriate for the study objective: distribution-utility QSTS often uses an equivalent “single large load” at the point of common coupling (PCC) with simplified control behavior, while facility-level studies may represent multiple internal buses and redundant paths to capture constraints and failover behavior [17,18].

### 2.1 Types of Data centers

Data centers can be categorized by ownership/tenancy, size, and availability requirements. Enterprise (on premises) data centers are owned and operated by a single organization, and their electrical and cooling systems are often constrained by existing building infrastructure and upgrade cycles [16,18]. Colocation facilities host multiple tenants; load growth can be stepwise as new halls or customer suites are commissioned, making staged capacity expansion and power allocation key operational concerns [18]. Hyperscale data centers are purpose-built at very large scale and engineered for high efficiency; they increasingly influence grid planning due to their large, relatively steady demand and potential participation in flexibility programs [18, 19]. Edge data centers are smaller sites distributed close to users for low-latency services; while individually modest, their proliferation can create significant aggregate impacts on distribution networks [19,20].

Figure 2 shows the key elements of a typical AI data center interconnected to the transmission grid inspired by the architecture shown in Reference [17]. The illustration shows the different types of loads in a data center, along with the onsite backup generation and battery energy storage system (BESS) that are aimed to be controlled and coordinated to explore the various grid services possible.

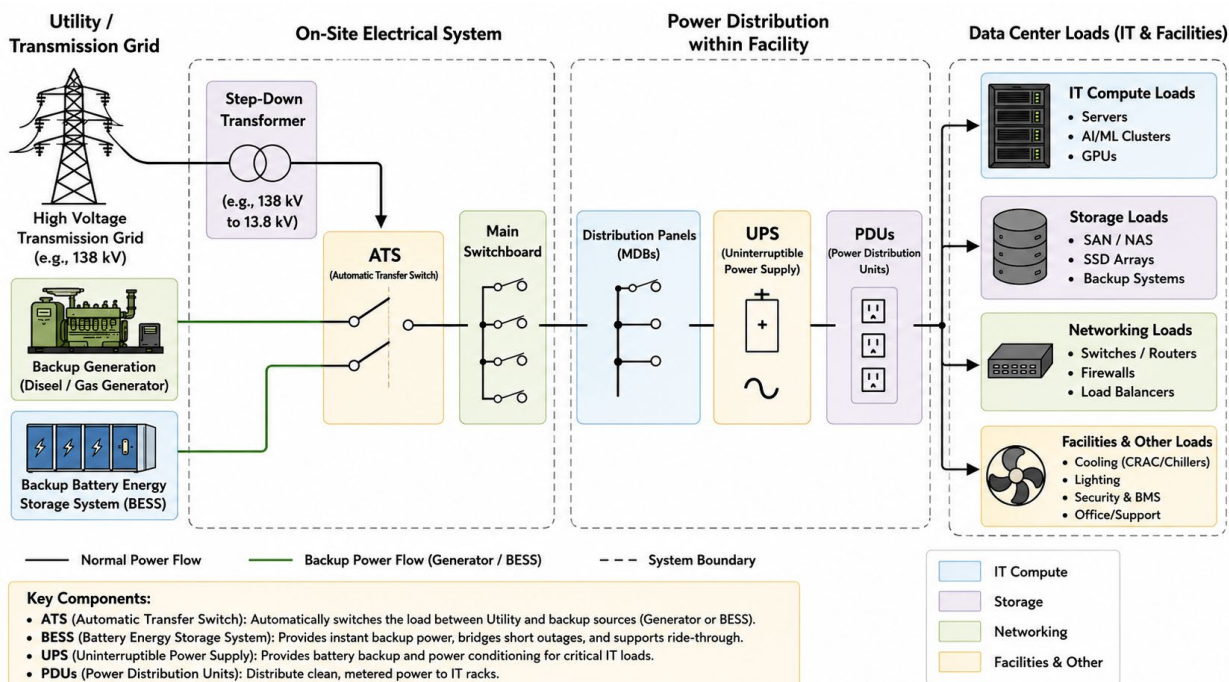


Figure 2. Schematic of a typical AI data center interconnection with the transmission grid

## 2.2 Data center Operating Timescales

Data centers exhibit behavior across multiple timescales, and each scale maps to different modeling approaches and QSTS step-size choices.

**Seconds to minutes (s–min):** Transfer sequences following disturbances—UPS ride-through, generator start, and staged motor restarts—occur on this timescale. These behaviors can be represented in QSTS using 1–10 s resolution when the objective is to capture step changes and control interactions on the distribution feeder or within the facility.

**Minutes to hours (min–h):** IT workload variability, cooling control (e.g., economizer enable/disable), and utility voltage regulation actions often occur over minutes to hours. QSTS with 1–15 min steps are commonly used to evaluate voltage profiles, transformer loading, and VAR flow impacts over representative operational days or events such as demand response.

## 2.3 Architecture and Components of a Typical Data center

A typical data center comprises integrated subsystems: electrical supply and distribution, IT equipment, cooling/thermal management, and supervisory monitoring/control.

**Electrical supply and distribution:** Medium-to-large data centers are commonly served at medium voltage through utility service equipment to facility switchgear and step-down transformers feeding low-voltage distribution. Redundant architectures (A/B feeds) provide alternate power paths to IT loads and reduce the risk of downtime [21-23].

**UPS and short-term power backup:** UPS systems provide ride-through during grid events and condition power to sensitive IT loads. UPS behavior affects facility efficiency, power factor, and the load seen at the PCC. In QSTS, UPS is commonly represented as a controllable power

conversion block with an efficiency curve and battery state-of-charge constraints rather than a switching-level inverter model [21-23].

**Onsite generation and long duration BESS:** Standby generators and BESS support long-duration outages and may be tested periodically. QSTS representations typically include start-up delay, ramp limits, real/reactive power limits, and control mode (fixed PF, voltage control, or VAR support if allowed) [21-23].

**IT load and PUE context:** Facility energy performance is often summarized by Power Usage Effectiveness (PUE), defined as total facility power divided by IT equipment power. While PUE is useful for benchmarking, QSTS studies often benefit from decomposing total demand into IT, cooling, and conversion losses using time-series inputs and simplified performance curves, because cooling and conversion losses vary with ambient conditions and loading [16, 21-23].

**Cooling plant:** Cooling systems include compute room air handler (CRAH) / compute room air conditioning (CRAC) units, chillers (or direct evaporative systems), pumps, towers, and fans. Cooling power is strongly dependent on outdoor conditions and control strategies. QSTS can model cooling demand as an empirical function of IT load and weather or through a simplified physics-based COP approach where appropriate [16].

## 2.4 QSTS Modeling of a Data center

To examine grid impacts of the data center, models of the various components need to be selected. This section will outline the different components of the data center QSTS models, as well as the assumptions built into their operation.

### 2.4.1 Modeling of Electrical Load

The electrical load in a data center primarily consists of the compute load, thermal management load and a small portion of auxiliary loads.

#### 2.4.1.1 Modeling of the Auxiliary Loads

Auxiliary loads are often smaller components of the data center load, representing components such as lighting, security systems, and general facility control and monitoring systems. The auxiliary load is modeled as a part of the static load on the transmission load bus where the data center is integrated. There is no specific model added to model the data center auxiliary load and it is lumped with the compute load for the simulations in this report.

#### 2.4.1.2 Modeling of Thermal Management Load

Modern data centers are mission-critical infrastructures that support cloud services, artificial intelligence, and high-performance computing, and their rapid load growth has intensified the demands placed on power and cooling systems. As IT equipment converts nearly all consumed electrical energy into heat, precise thermal modeling becomes essential for ensuring safe operation, maximizing efficiency, and preventing hotspots that jeopardize reliability. Traditional thermal analysis often relies on computational fluid dynamics (CFD) to resolve airflow patterns and heat transfer within rooms, racks, and cooling subsystems, but these models can be computationally expensive and sensitive to modeling assumptions. As data centers evolve

toward higher rack densities and more dynamic workload patterns, scalable and physically grounded thermal modeling approaches are increasingly important for design, monitoring, and operational decision-making.

The case study considers a chilled-water-cooled AI data center equipped with rear-door heat exchangers (RDHx) (shown in Figure 3). The system is representative of heavily coupled thermal and electrical dynamics: rack heat loads drive rear-door heat exchange, chilled-water return temperature depends on aggregate IT-side heat removal and flow, chiller power depends on both chilled- and condenser-water conditions, and cooling-tower performance depends on ambient wet-bulb temperature. The IT load for each rack is determined by scaling down a typical AI data center (taken from [24]) to emulate IT load at the rack-level. For simplicity, it assumed similar IT-load at the individual rack-level for the data center.

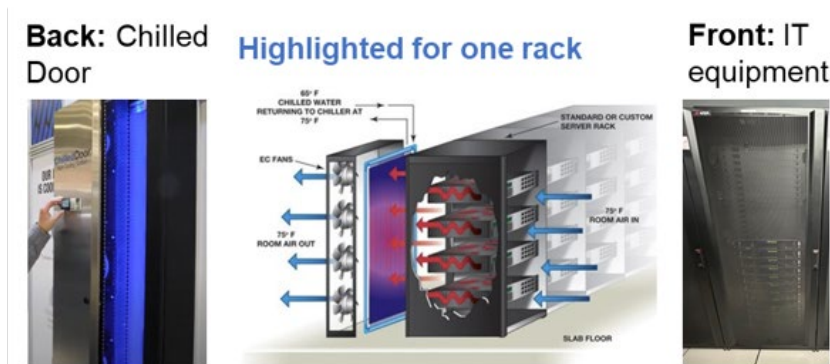


Figure 3. Chilled door cooling configuration

The thermal load of the AI data center is evaluated using a physics-based Modelica model that represents the coupled behavior of chillers, cooling towers, pumps, rear-door heat exchangers (RDHx), rack loads, and room-level thermal dynamics. Figure 4 presents the mapping between subsystem boundaries and the plant and IT variables.

The Modelica framework provides a system-level simulation that enforces energy balances across water-side and air-side loops, incorporates measured rack-level IT power as the heat-generation input, and propagates the

ing thermal loads through plant and room components. The chilled-water pump network corresponds to the primary chilled-water pump block. The cooling-tower network corresponds to the cooling-tower fan and heat rejection block. The chiller network corresponds to the chiller block and includes condenser-water return as an output. The rack networks correspond to rack thermal models that map room inlet conditions and rack loads to rack outlet air temperature. The RDHx networks correspond to the rear-door heat exchanger coil and fan power behavior. The room network corresponds to a reduced-order representation of the data hall volume temperature driven by aggregated rear-door outlet conditions and room setpoint.

This physics-based model captures how changes in IT power, flow rates, setpoints, and ambient conditions influence return-water temperatures, cooling capacity, and room thermal response. Through this structured representation of interconnected subsystems, the Modelica model enables controlled evaluation of counterfactual scenarios and provides a reliable baseline for understanding and predicting the thermal behavior of data centers.

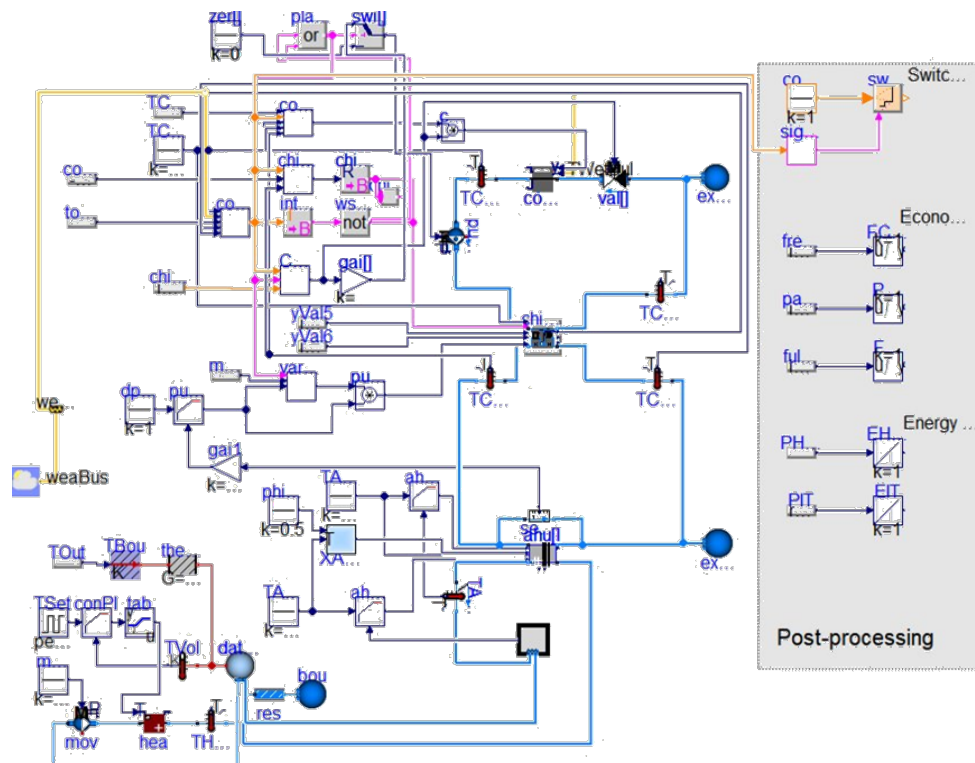


Figure 4 Physics-based data center cooling system Modelica model used to map subsystem interfaces.

The physics-based Modelica model simulates a Data Center room with 20 racks and their associated thermal load from the coupled behavior of rack loads with the chillers, cooling towers, pumps, RDHx), and room-level thermal dynamics. Figure 5 presents rack-level IT load based which is derived by scaling from a typical AI-Data Center load taken from [24].

The rack-level IT load is played in an input to the Modelica model, and the model simulates the thermal dynamics based on the ambient conditions and chilled-water supply temperature setpoint, room temperature setpoint to determine the consumption of the HVAC system. To represent an AI data center, the data center room and the thermal loads are scaled appropriately based on the chosen AI data center load to emulate 95 rooms and 1900 racks. Figure 6 presents the total IT load based on stacked rack-level data scaled to typical data center load (simulated 20 racks scaled to represent 1900 racks). Figure 7 presents the Modelica simulated outputs for average door temperature for individual racks along with the scaled HVAC consumption profile. Results indicate that the Modelica thermal model can maintain a steady door temperature for all the racks for the varying IT load profile and ambient conditions. Figure 8 presents a stacked plot of the scaled IT loads and the HVAC loads.

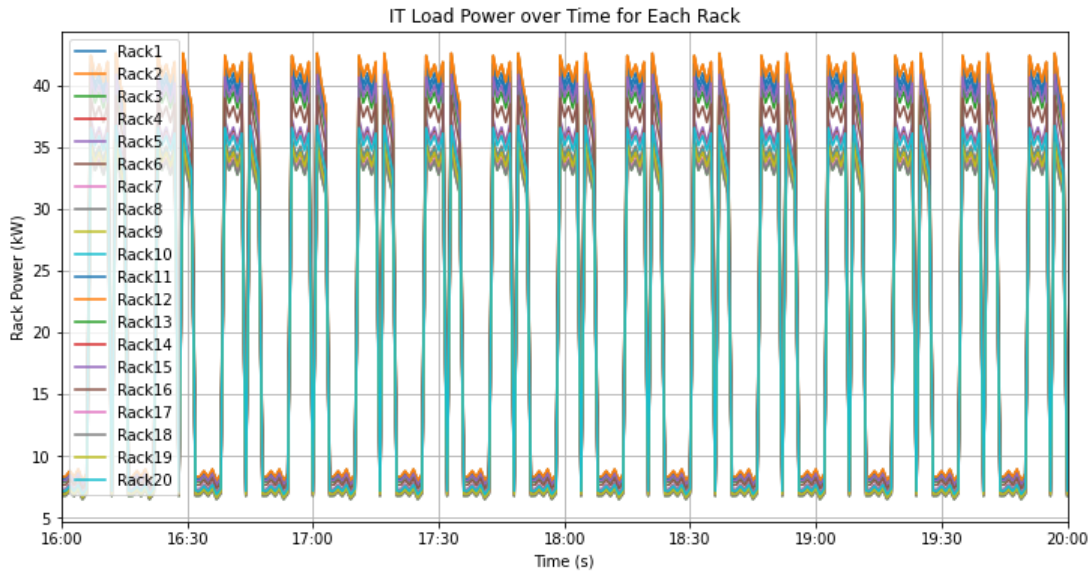


Figure 5. Rack-level IT load based on typical data center load profile

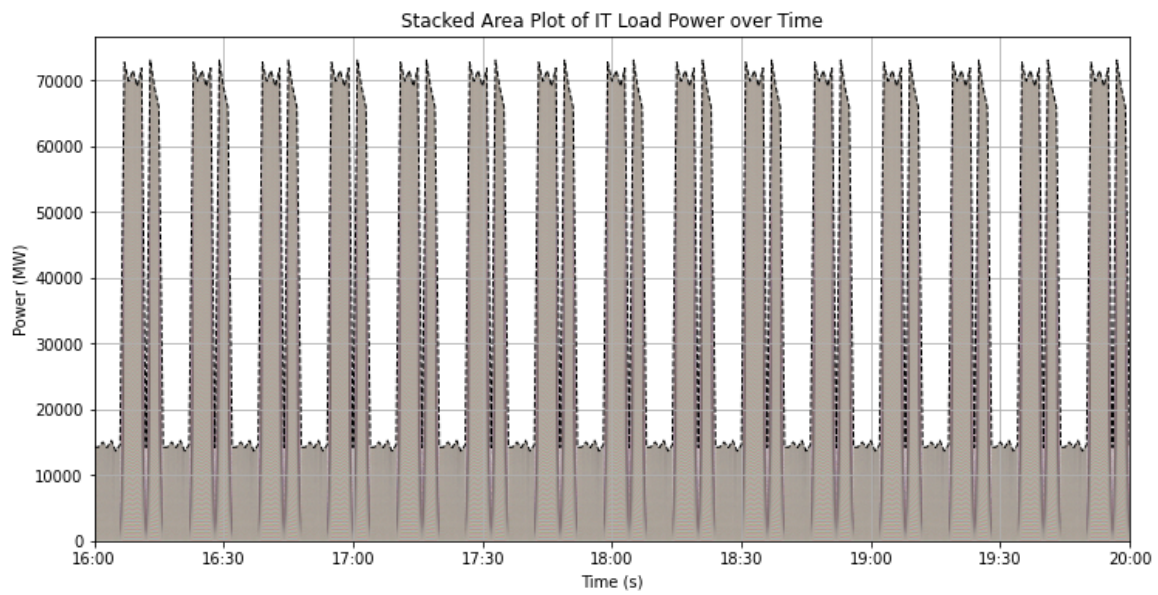


Figure 6. Total IT load based on stacked rack-level data scaled to typical data center load (simulated 20 racks scaled to represent 1900 racks)

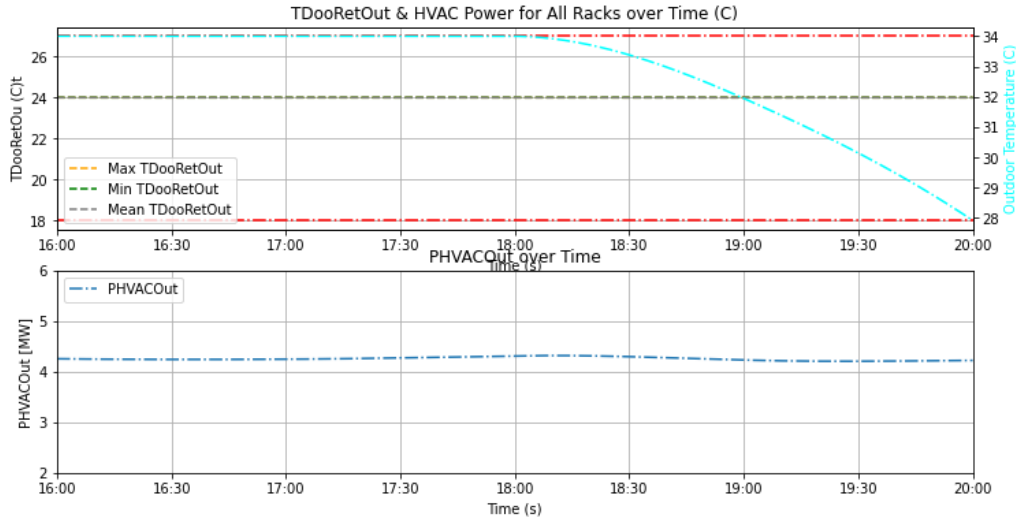


Figure 7. Average door temperature for individual racks along with the scaled (HVAC) consumption profile to represent 1900 racks.

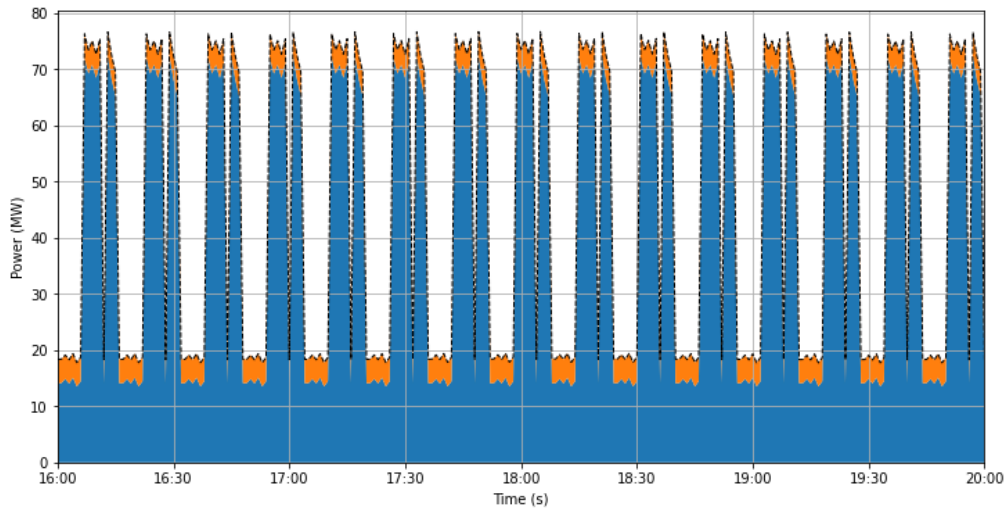


Figure 8. Total data center load including IT and HVAC load.

To evaluate the flexibility potential of data-center thermal loads, a series of scenarios were simulated in which the chiller cold-water supply setpoint varied from 18 °C to 28 °C, 35 °C, and 50 °C as shown in Table 1. The setpoints 18 °C to 28 °C represents the lower and upper limit of the recommended rack temperatures, and 35 °C, and 50 °C presents a set of allowable rack temperatures where the rack can handle temporarily. These setpoint adjustments were done for a 2-hour duration during grid evening peak (17:00-19:00) to directly influence chiller power consumption because higher chilled-water temperatures improve chiller efficiency and reduce compressor workload, thereby lowering HVAC electrical demand during peak periods.

Table 1. Peak demand and daily energy consumption of the simulated AI data center for different demand response scenarios.

| Demand Response Scenarios                       | Chiller Setpoint      | Peak AI-DC Load (17:00-19:00) | Peak AI-DC Load (19:00-20:00) | Daily Energy Consumption |
|-------------------------------------------------|-----------------------|-------------------------------|-------------------------------|--------------------------|
| Base Case                                       | 18°C                  | 76.7 MW                       | 76.5 MW                       | 66.7 GWH                 |
| Demand Response (within recommended rack temp.) | 28°C                  | 76.5 MW                       | 77.4 MW                       | 66.7 GWH                 |
| Demand Response (within allowable rack temp.)   | 35°C                  | 75.2 MW                       | 80.6 MW                       | 65.4 GWH                 |
| Demand Response (within allowable rack temp.)   | 50°C                  | 74.5 MW                       | 80.8 MW                       | 65.3 GWH                 |
| Demand Response with rebound load management    | 50°C (28°C - rebound) | 74.5 MW                       | 78.1 MW                       | 65.1 GWH                 |

Simulation results indicate that as the chiller setpoint are increased during the peak hours (17:00-19:00), the rack temperature also increases (see Figure 9) and at the end of the demand response (DR) period, the chiller setpoints return to the original level (18°C), the rack setpoint falls back to the recommend level based on associate thermal dynamics. Figure 10 presents the corresponding HVAC loads (scaled at the AI-Data Center level) and demonstrates that increasing the chiller setpoint progressively reduced total facility thermal load while maintaining rack temperatures within allowable ranges—modulating the chilled-water temperature provides an effective, fast-acting demand-response lever. Figure 11 presents the data center load for the simulated scenarios which shows that increasing the chiller cold-water setpoint provides measurable demand-response benefits: peak load during 17:00–19:00 drops from 76.7 MW in the base case to 76.5 MW at 28°C, 75.2 MW at 35°C, and 74.5 MW at 50°C.

Figure 10 also shows that at the end of the demand response period (19:00) when the chiller-setpoints are returned to the original values, there is a sudden increase in HVAC load as the chillers are running in a higher capacity to get the rack temperatures at the desired level. This effect is commonly known as the rebound effect, often present in HVAC systems when a demand call is released and the systems need to recover their temperature. To control the rebound during post-DR period, a stepped control strategy where the chiller setpoints were returned to original in two steps. Figure 10 also shows the effectiveness of the cold-load management strategy in reducing the post DR demand peak.

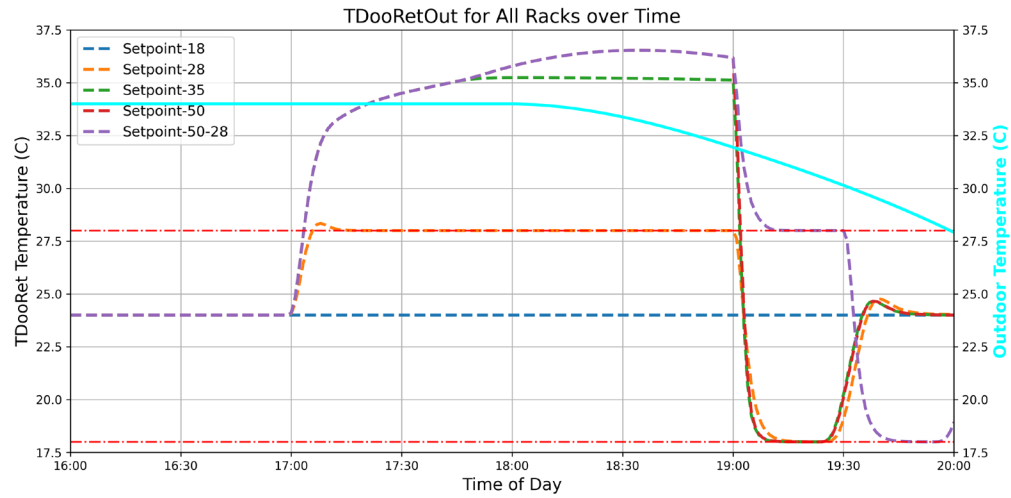


Figure 9. Average door temperature for individual racks for different chiller setpoints between 17:00 and 19:00

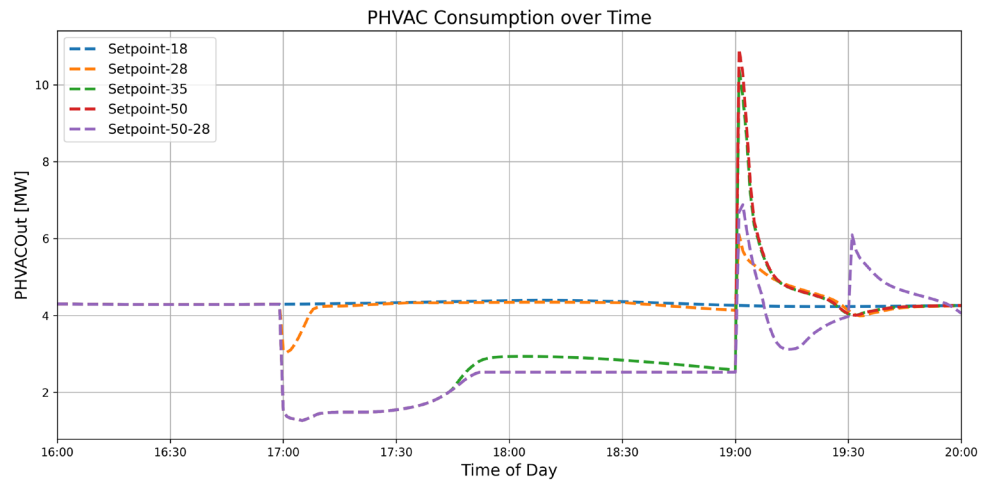


Figure 10. HVAC consumption profile (scaled) for different chiller setpoints between 17:00 and 19:00

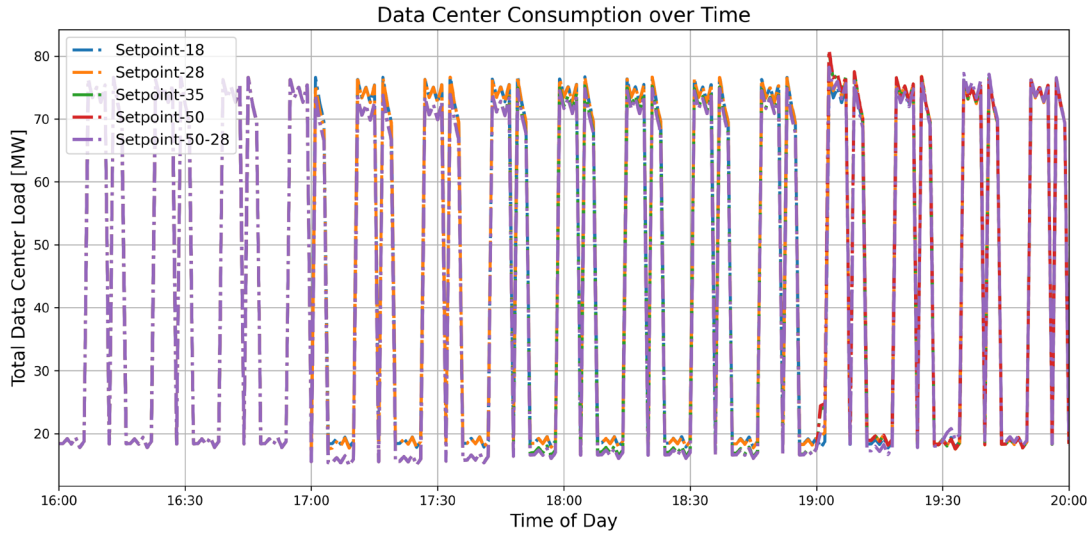


Figure 11. Total data center load for different chiller setpoints between 17:00 and 19:00

### 2.4.1.3 Modeling of Data center Load

An AI data center is considered for this work, and the load profile as shown in Figure 12 is taken from [24], representing the AI data center demand during the training of AI models. This data center load profile is used as a reference to derive the data center load profile for the use case studies undertaken to evaluate the flexibility available with the data centers to provide grid services.

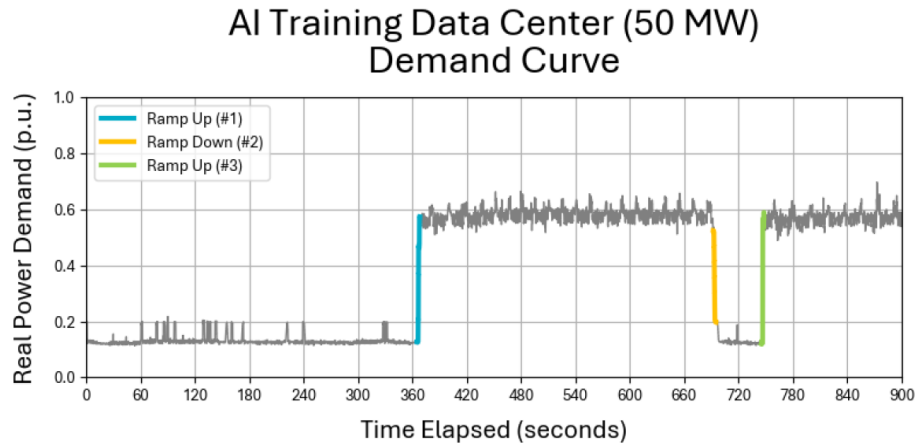


Figure 12. Data center load profile from whitepaper published by NERC [24]

The aggregated data center load is shown in Figure 13. Figure 12 provides the basis for the new load profile. The connection of the data center load to the grid is illustrated in Section 3.

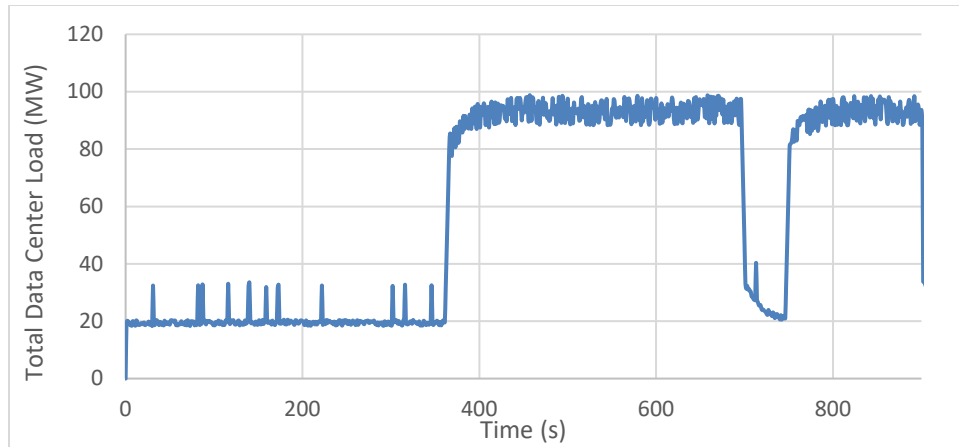


Figure 13. Aggregated data center load profile used for the simulation studies

For the initial studies, the load profile in Figure 13 is used. However, for some of the datacenter load control and the final simulation study, the thermal management load profile derived in Section 2.4.1.2 is utilized and is integrated into the PSS-E data center load model.

To split the data center load profiles into IT load and cooling load, the Modelica model mentioned in Section 2.4.1.2 used Figure 12 as an input compute load to generate the total data center load (IT load and cooling load). The Modelica model is run for a four-hour time window representing the evening time, which usually is the time duration of peak demand in the system. The resultant load profile is a 4-hour load profile with 1 minute resolution. A snapshot of the load profile of the data center load is shown in Figure 14. The load profile of Figure 14 will then be used as a time-varying load component in PSS-E; Modelica and PSS-E are loosely coupled through a flat file exchange, rather than a direct cosimulation or API approach. Figure 14 shows one hour of the load profile that is extended for the duration of the simulation. The expected reduction in the thermal management load (cooling load) used in the simulations is based on the findings from Section 2.4.1.2.

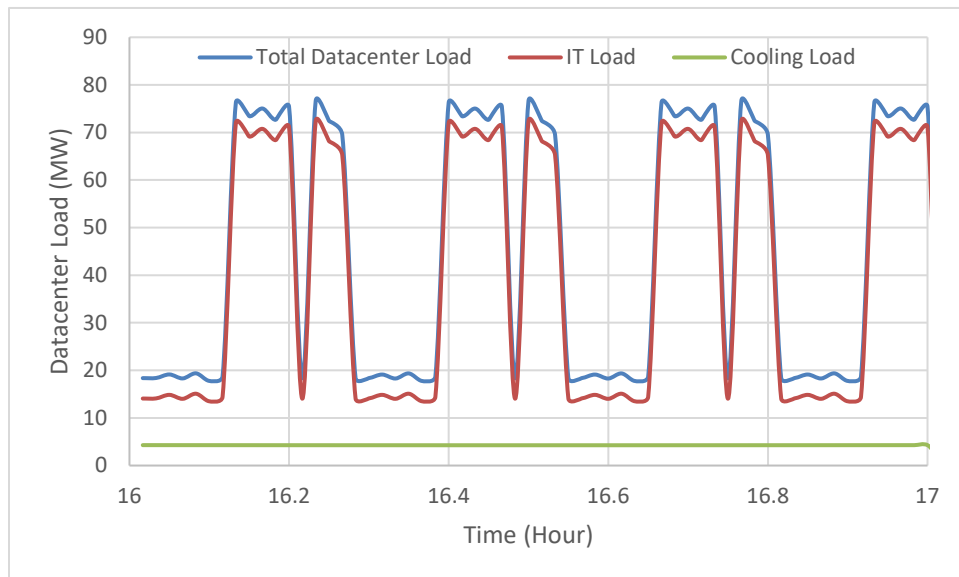


Figure 14. Data center load profile for the Modelica and PSS-E simulations with the IT load, thermal management load (cooling load) and total data center load

## 2.4.2 Modeling of Onsite Generation and BESS

The collocated onsite generation consists of a natural gas (NG) generator and a battery energy storage system (BESS). Simulation case studies are carried out with near 60% and 100% onsite generations. For 60% scenario, NG and BESS are rated 20 MW and 40 MW, while these values are 40 MW and 60 MW for 100% scenario. The power dispatch of BESS is limited to the apparent power magnitude being less than the inverter rating. On the contrary, NG can have maximum dispatch of 95% of the rated value, accommodate for generator efficiencies [25]. Section 3 shows the connection of onsite generators to the grid.

### 2.4.2.1 BESS Dispatch and Control

Figure 15 shows a simulation sequence to evaluate the response of the developed BESS model to varying collocated data center load and varying grid capacity limits. Table 2 explains the sequence of events in Figure 15 that result in the various BESS responses.

Table 2. BESS behavior under changing grid capacity limit and load as shown in Figure 15.

| Time (s)              | BESS Behavior                                                                                                                                                                                                                                              |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $0 \leq t \leq t_1$   | The minimum load is 6 MW, the grid capacity limit is 5 MW and the BESS supplies the balance load. The BESS SOC starts reducing.                                                                                                                            |
| $t_1 < t \leq t_2$    | The grid capacity limit is increased to 20 MW and remains as such until $t = t_5$ . The load is unchanged. The available grid power is used to supply the load. The BESS switches to charging mode and charges while supplying the occasional load spikes. |
| $t_2 < t \leq t_3$    | The BESS SOC has reached its maximum value and stops charging. The available grid capacity is sufficient to supply the load.                                                                                                                               |
| $t_3 < t < t_4$       | The grid capacity remains at 20MW. However, the load is increased to about 30 MW. This triggers the BESS to supply the load demand that exceeds grid capacity. The BESS SOC continues to drop as the BESS supplies the load.                               |
| $t_4 \leq t \leq t_5$ | At $t_4$ the grid capacity is increased to 40MW. The BESS starts charging such that the load and the BESS charging consume the grid capacity limit of 40 MW. At $t_5$ the load suddenly drops.                                                             |
| $t_5 < t < t_6$       | The BESS now charges at a faster rate as significant grid power is available for BESS consumption due to the drop in the load. The rate at which the SOC increases is greater than the previous time interval as the charging power is higher.             |
| $t_6 \leq t \leq 900$ | At $t_6$ the BESS SOC reaches its maximum permissible value and the BESS charging stops. After this the available grid capacity is larger than the load and the power supplied by the grid is equal to the load demand.                                    |

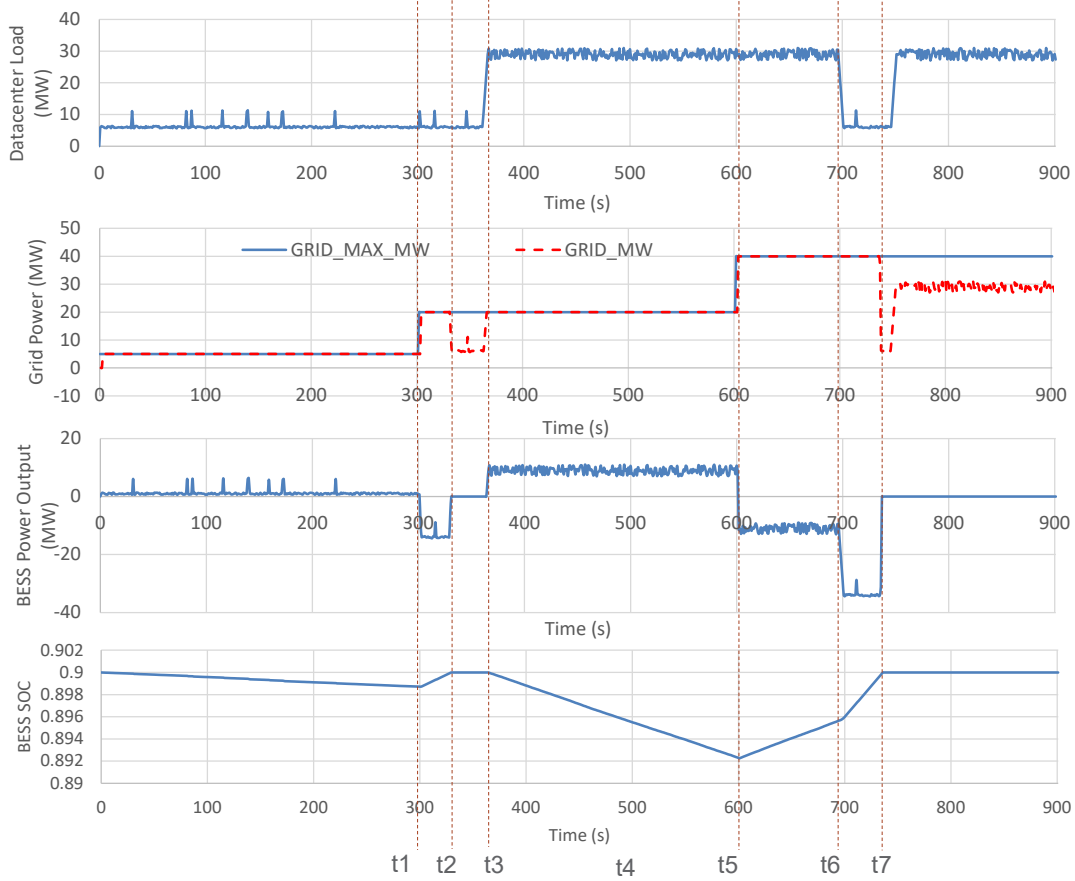


Figure 15. Control of BESS to limit the minor oscillations on the power grid.

### 2.4.3 BESS Model to integrate VAR support Capability

In addition to the BESS coordination and control with local generation, the BESS model also integrates VAR support to be provided as a grid service. To add the VAR support capability, the BESS model considers the inverter rating constraint of  $S_{Batt} = \sqrt{P_{Batt}^2 + Q_{Batt}^2}$  where  $S_{Batt}$  is the MVA rating of the battery inverter,  $P_{Batt}$  is the battery inverter active power, and  $Q_{Batt}$  is the reactive power of the battery inverter. This ensures the magnitude of the inverter output (both active and reactive power) does not exceed its rating. The VAR support feature in the BESS is modeled such that it does not directly impact the SOC. In reactive-only situations, the BESS would require a miniscule amount of active power from the grid to perform the reactive power injection. Most reactive power dispatches will be when active power is flowing in or out of the battery, so this negligible value is ignored in the simulations. The SOC is only impacted by the active power modulation of the BESS. Figure 16 shows the BESS performance with and without VAR injection. The voltage is recorded at the bus where the data center connects to the grid.

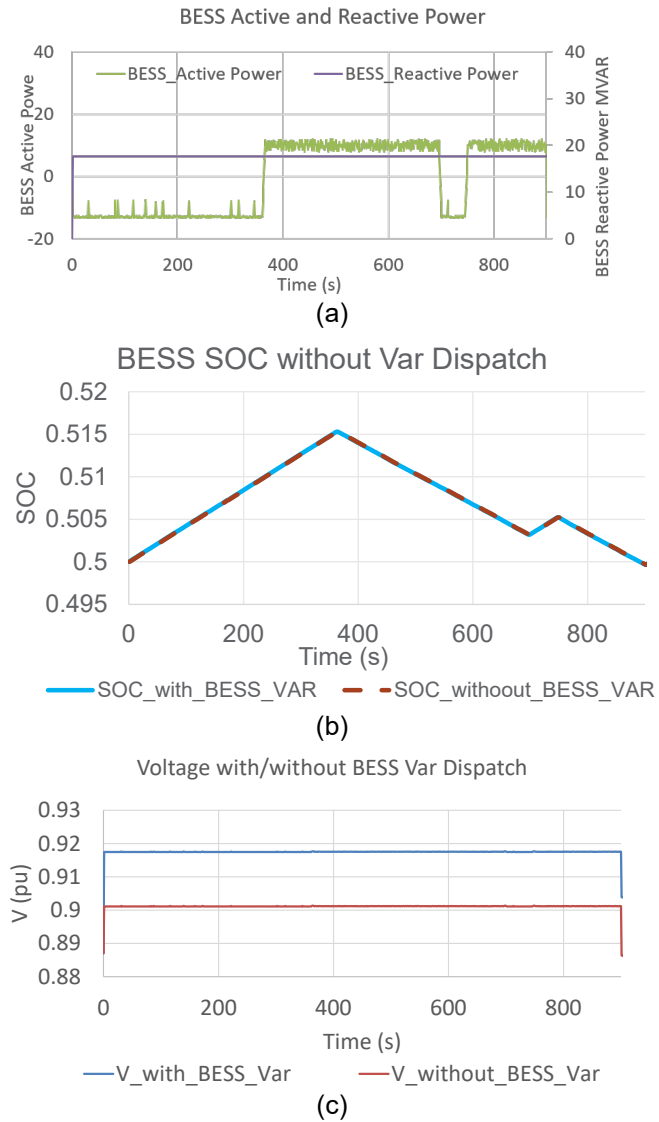


Figure 16. BESS performance with and without VAR generation: (a) BESS active and reactive power output, (b) the Battery SOC with and without VAR Dispatch, (c) data center connected transmission bus voltage

### 3.0 Test System and Scenario Definitions

The test system used for the case studies is the modified IEEE 24-Bus transmission system model. This model has 10 generation buses and 17 load buses with two major voltages: 230 kV (transmission system) and 138 kV (sub transmission system). Figure 17 shows the one-line diagram of the IEEE 24-Bus test system with the data center integrated.

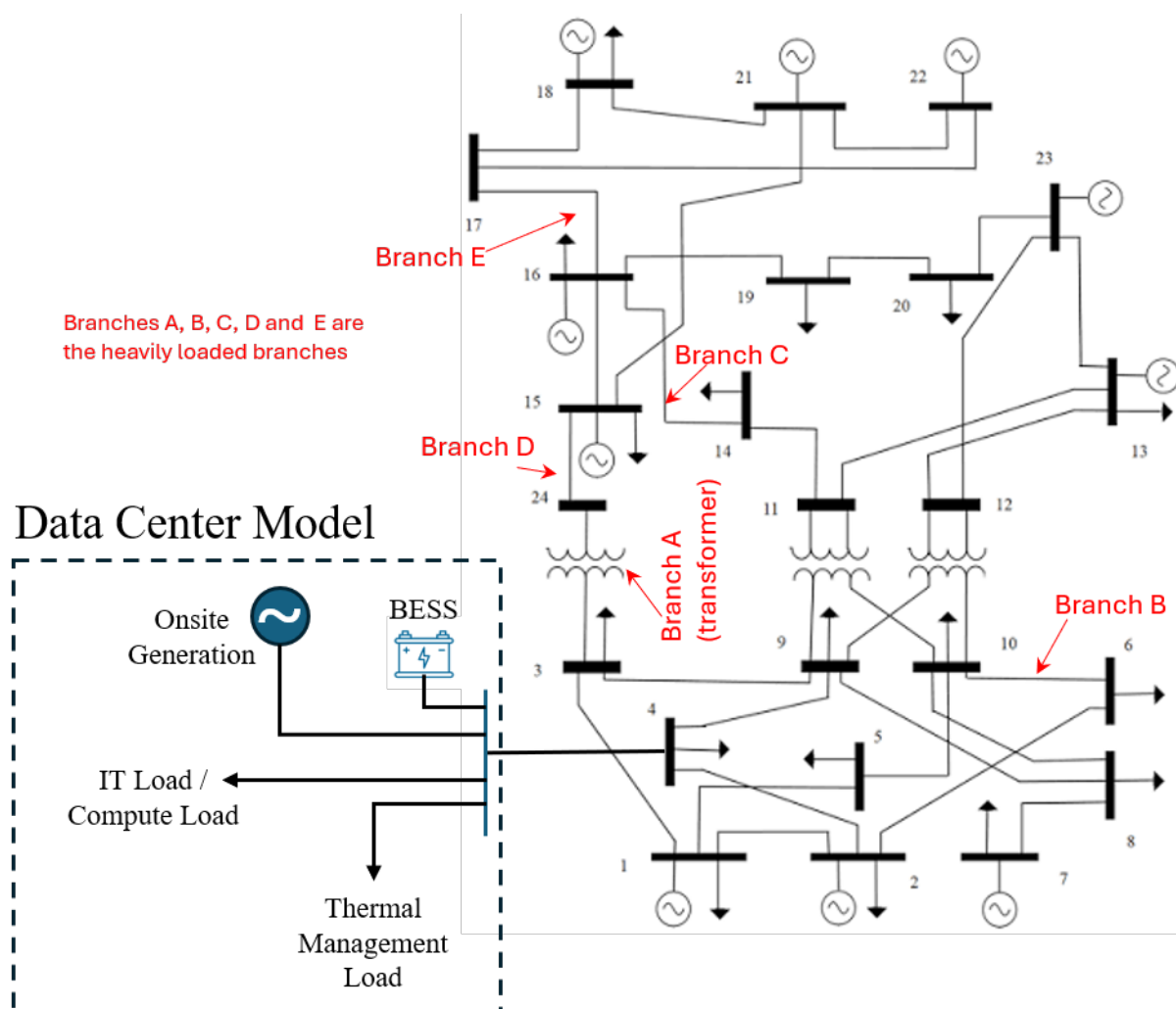


Figure 17. One line diagram of the modified IEEE 24-bus test system with the data center

The test system is modified to increase the base case load to reflect a system with limited capacity to integrate additional load where a few transmission lines are overloaded to ~135% of its rated capacity. The system is in a heavily-stressed condition, where significant changes in the load could cause further outages or violate stability operating criteria (e.g., N-1 security constraints). The focus of using this model will be on the data center impacts in this heavily loaded case – an actual system would include other controls such as additional imports from neighboring territories, generator redispatch or load shed/demand response programs.

On the modified test system, a data center load is added at Bus 4 along with some collocated generation and battery energy storage system (BESS). The size of the BESS and generation are varied in the case studies to understand the impact of their capacity on the data center controls and the impact on the grid performance. Also note the BESS is continually providing local voltage support (Volt/VAR mode) at the data center bus, helping maintain operational voltages within constraints.

The data center load is modeled according to the developed QSTS model of the data center and its load profile. Most of the simulations are run for one-hour long snapshots. The data center load is modeled with two components: the compute load with auxiliary load combined, and the thermal management load.

### 3.1 Scenario Definitions

The scenarios for evaluating the potential of controlling data center resources under different operating conditions of the grid. The various scenarios that are being evaluated are:

1. Base Case System Performance: This scenario reflects on the grid performance when the data center load is integrated.
2. Grid Constrained Operation: This scenario is aimed to illustrate the utility of the on-site generation and BESS at the data center in cases of limited grid capacity to support the data center loads. This scenario is closely tied to the “bring your own capacity” approach that is being evaluated by the industry and the utilities.
3. Controlling Onsite Resources: These scenarios illustrate how the grid-constrained operation can be supported by specific control of the local resources like the collocated BESS. These controls are evaluated with limited grid capacity and unlimited grid capacities.
4. Controlling the Data Center Load: These scenarios illustrate the effects of controlling the data center load on grid performance. These scenarios inform the potential of data center load control aimed to support constrained grid operations.

## 4.0 Simulation Studies

The simulation studies aim to understand scale of the challenge of data center load integration on a transmission system and the ability of the data center resources (loads and onsite generation with collocated BESS) to help address some of the challenges faced by the grid operators. The test system is modified to be overloaded to test and evaluate how the data center controls can help to improve the grid operating conditions. Demonstrating grid flexibility during normal operating conditions is helpful to overall grid stability, but demonstrating data center contributions on the overloaded system helps quantify a data center role in providing critical grid services to aid in stabilizing the stressed power system. All plots and analysis will focus on active power and congestion on the system. Reactive power capabilities were utilized for local voltage regulation and power factor correction, but the VAR injections had minimal impact on the overloaded system; plots of this behavior are omitted for space. Furthermore, all simulations and scenarios in this section demonstrate the impact and flexibility of data center load and local resources on the grid. The data center resources are expected to be a part of the overall grid services that include demand response, generation redispatch and capacity reserves. The focus of these simulations is to explore the flexibility of data center controls.

### 4.1 Data center Load and Grid Performance

The base case represents the power grid with data center load, without any collocated onsite generation. The data center load is demonstrated in Figure 18. The data center load consists of the compute load or the IT load and the thermal management load. The data center load profile is derived from a recently published AI data center load profile by NERC [24]. In this base case, the grid supplies all the required power to meet the data center load, with no onsite resources leveraged to provide additional capabilities.

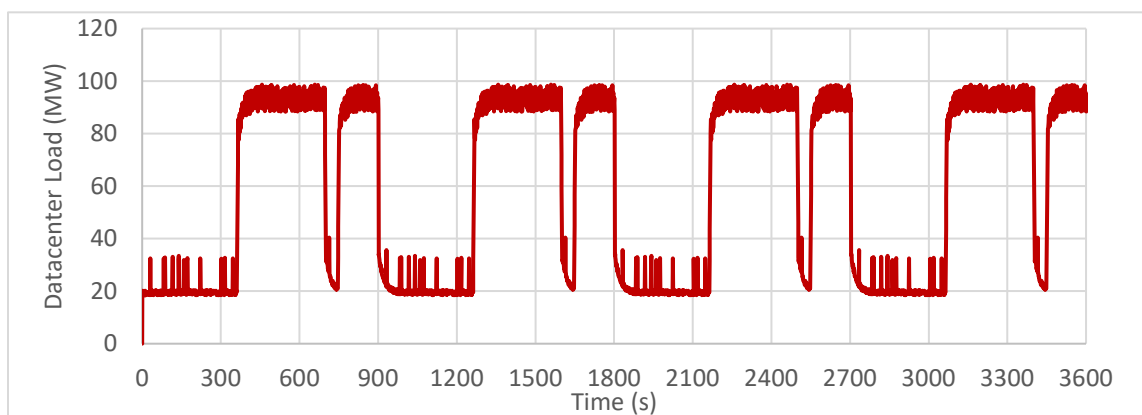


Figure 18. Demand of the data center load integrated in the IEEE 24- Bus test system

Using the IEEE 24-node system described in Section 3.0 and with the data center load profile shown in Figure 18, the base case produces a system with five branches that are carrying apparent power greater than 90% of their nominal rating. These branches are named Branch A through Branch E as shown in Table 3, and as annotated in Figure 17 above.

Table 3. Transmission lines and transformer of interest along with the details of location in the test system

| Branch/ Transmission Path Name | Terminal 1 (Bus #) | Terminal 2 (Bus #) |
|--------------------------------|--------------------|--------------------|
| Branch A                       | 3                  | 24                 |
| Branch B                       | 6                  | 10                 |
| Branch C                       | 14                 | 16                 |
| Branch D                       | 15                 | 24                 |
| Branch E                       | 16                 | 17                 |

Branch A is a transformer and Branches B, C, D and E are transmission lines. Both transformers and transmission lines are sensitive to overloading and congestion and so are being grouped for the overloading impacts.

The impact of the data center load on the grid side, in terms of line congestion, is presented in Figure 19. Branch C and Branch E are overloaded to greater than 115% due to the overall stressed operating condition. This base case scenario represents a peak loading condition of the grid that could be vulnerable during a contingency. Branches A, B and D are also expected to have higher branch flows if there is a system contingency. Branch E is a critical path in the system that is transferring most of the power from the largest generator in the system.

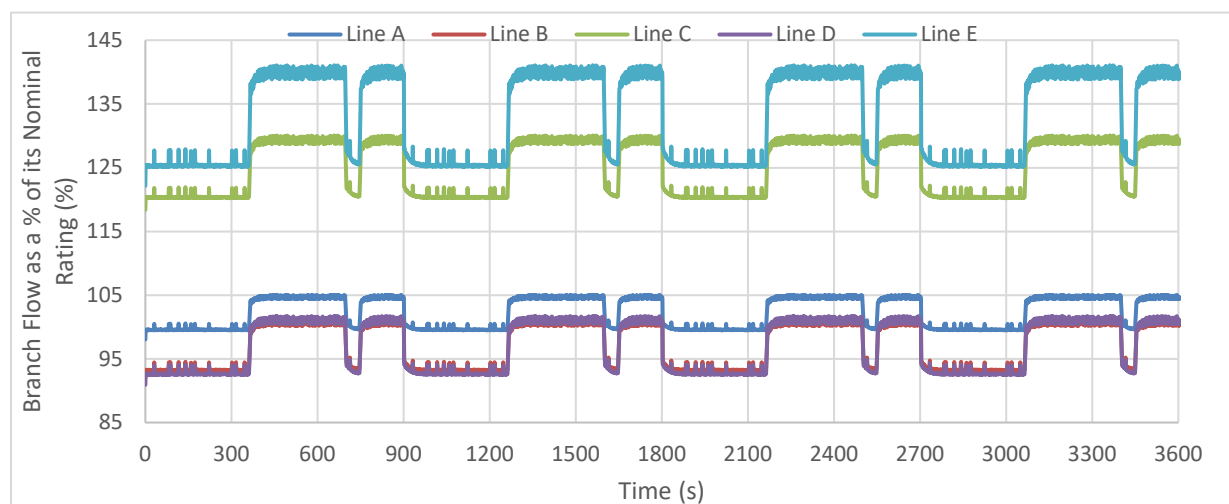


Figure 19. Branch MVA flows in terms of percentage of corresponding RATE-1 in the Base Case

The powerflow in these branches and grid energy supply are the two main metrics that will be used to show the impact of the data center controls on the grid performance and evaluate the ability to provide grid services to mitigate the overall impact.

## 4.2 Grid Constrained Operating Scenarios (Stressed Condition)

The impact of data center load on the grid after an N-1 contingency and how the onsite data center generation with collocated BESS can coordinate to provide grid service are illustrated in this section. The underlying system is already modified to reflect the peak operating scenario with the identified branches operating close to overload and some being overloaded. This

scenario's simulation reflects the benefit of having the data center resources like the onsite generation with BESS as these can help alleviate the overloads on the identified branches, while ensuring reliable supply to the data center load is available. For this scenario, consider two cases:

- 1) No onsite generation is available to power the data center to reduce the impact of the contingency on the grid.
- 2) There is onsite generation and collocated BESS (it is assumed for this case that the combined capacity of 100% of the data center load) that can help minimize the net data center load on the grid.

#### 4.2.1 Data Center with No Onsite Generation and BESS

For this scenario, no onsite generation is available to help meet part of the data center demand to establish the impact of the contingency. The load profile is similar to the case in Section 4.1; however, at  $t = 900s$ , a transformer outage occurs. The system is N-1 secure and this outage does not disrupt the supply to any loads or the data center. However, the transmission branch loading increases leading to further congestion in the system. The entire data center demand is still supplied by the grid as shown in Figure 20. However, the transmission branch loading on the branches of interest (Branches A, B, C, D and E) has increased to the levels shown in Figure 21, showing a 15% increase in overloading of some of the branches. This scenario further limits the time the grid can operate in this condition. The overloaded branches may be tripped offline by thermal protection schemes, especially if the weather conditions are unfavorable (e.g.; hot summer day). This could lead to cascading outages and a blackout.

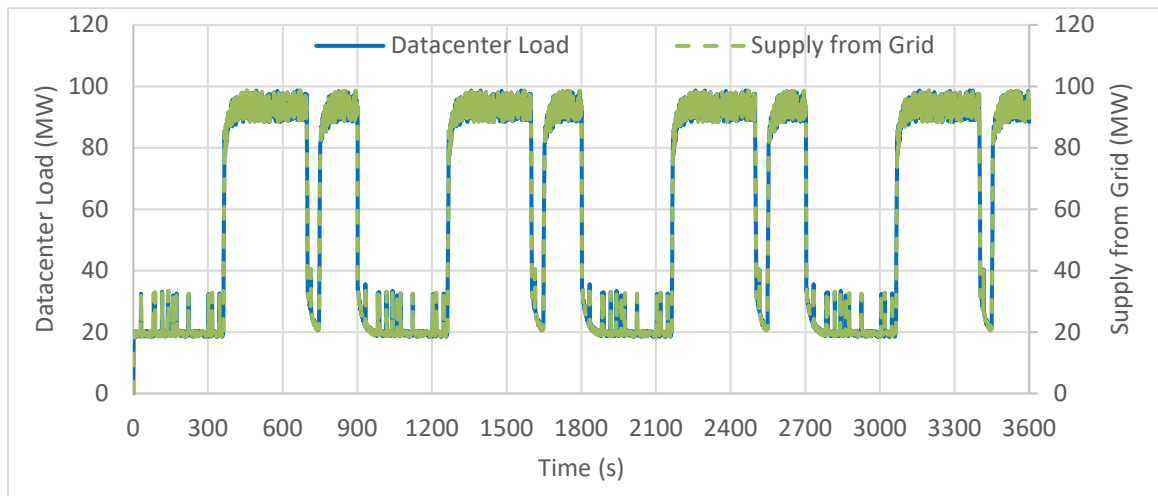


Figure 20. Data center load and supplied power from grid under N-1 contingency without any onsite generation

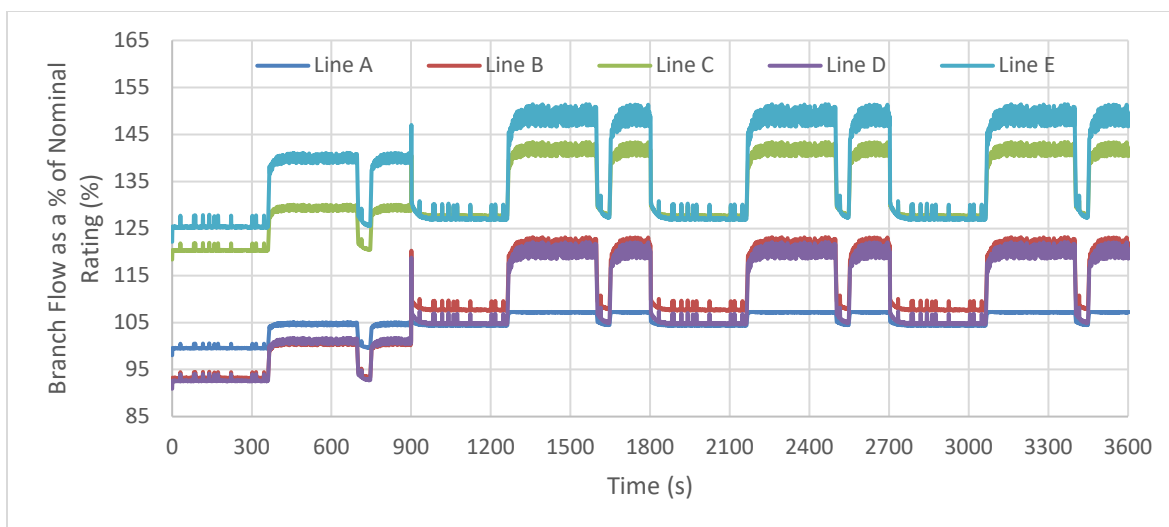


Figure 21. Branch MVA flows with N-1 contingency and no onsite generation

#### 4.2.2 Data center with onsite generation and collocated BESS

This scenario has a data center modeled with onsite generation in the form of natural gas (NG) generation and BESS. While there is no grid capacity limit imposed by the transmission grid, the data center will still leverage the onsite generation resources to mitigate its impact to the grid. Due to the lack of a grid constraint, this scenario explores two different control paradigms: one where the battery only performs regulation services/ramping mitigate while discharging, and one scenario where both charging and discharging can provide that service.

##### 4.2.2.1 Collocated BESS – Regulation Services on Discharge Only, SOC-prioritized Recovery

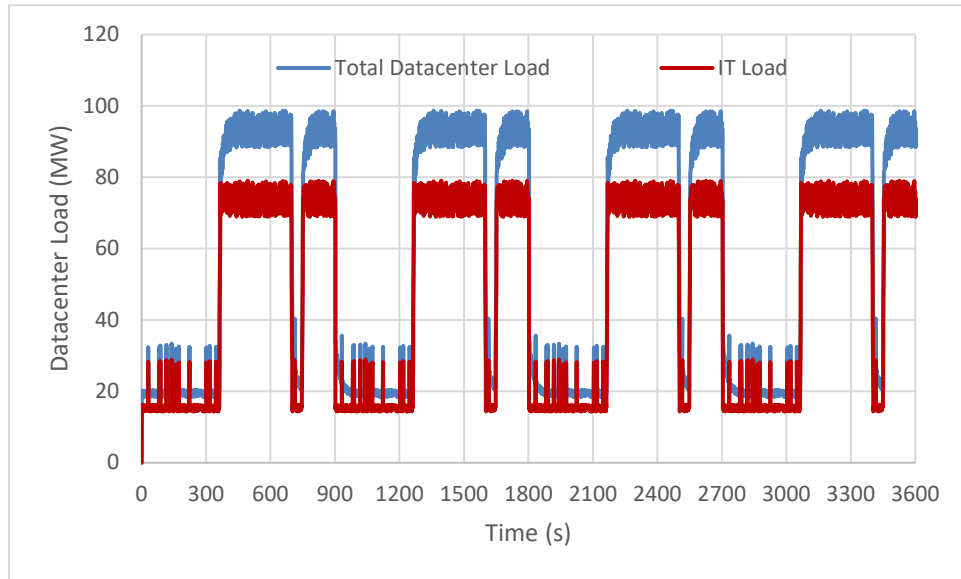
The data center load, generation and BESS dispatches are shown in Figure 22 (a) and Figure 22 (b), demonstrating overall energy or reserve service to the transmission grid, and some regulation services when the battery is discharging. This reduces the demand on the grid by the data center.

Given the overloaded grid condition described in the base case, the data center is already utilizing the onsite NG generation to offset its demand. Between 0-366 s, the data center demand is lower than the capacity of the NG generation. The data center load is entirely supplied by the NG generator and additional energy services could potentially be provided to the grid using the available generation capacity. However, this reserve is maintained by the data center owner/operator in preparation for a data center compute load which will ramp up again soon. During this time, BESS does not charge because its SOC is at maximum value of 0.9 pu (for an emergency charge capacity), which is shown in Figure 23.

During 366 to 698 s, data center load oscillates with a large magnitude owing to its typical load profile. The onsite generation and BESS are utilized (BESS discharges) to provide more energy and reserve service, and the small amount of balance demand is supplied by the grid. However, the charge control for the BESS prioritizes SOC recovery, quickly ramping grid demand back up when the IT load pauses for a few seconds (700 s to 740 s). When the compute load returns, the NG and BESS once again offset the demand, resulting in a very small amount pulled from the grid.

At  $t = 900$  s, the N-1 transformer outage contingency occurs that causes an increase in the MVA flow in transmission branches (shown in Figure 24). Due to the services provided by the onsite generation and BESS, the data center impact to the grid is minimized and the branch loading is managed to stay closer to the base case scenario. While the branches are still overloaded, they are not nearly as high as the scenario in Section 4.2.2. enabling more time for the operators to adjust the power system back to better operating conditions.

Post contingency, during 901 to 1266 s, the data center load fluctuates with smaller amplitudes. However, the same BESS SOC-prioritized recovery control is still active. Any decrease in compute load that goes below the NG dispatch results in the BESS adding load to recover its charge (negative power in Figure 22(b)). In the grid stress condition with the heavily loaded lines in Figure 24, this causes an increase in overall line loading, which may lead to additional contingencies on the grid and a destabilized system.



(a)

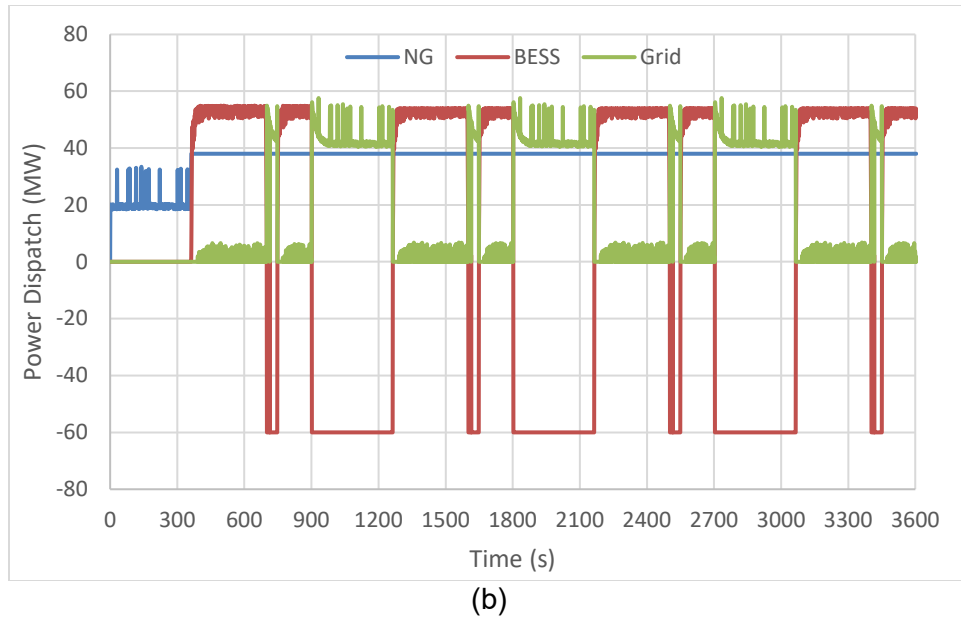


Figure 22. Grid under N-1 contingency and Data center with 100% onsite generation: (a) data center load demand, and (b) power dispatch from NG, BESS and grid.

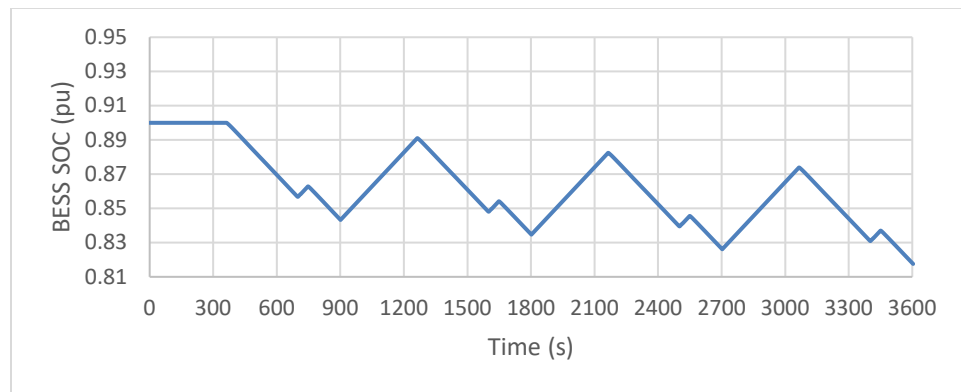


Figure 23. BESS SOC with the N-1 contingency and 100% onsite generation scenario.

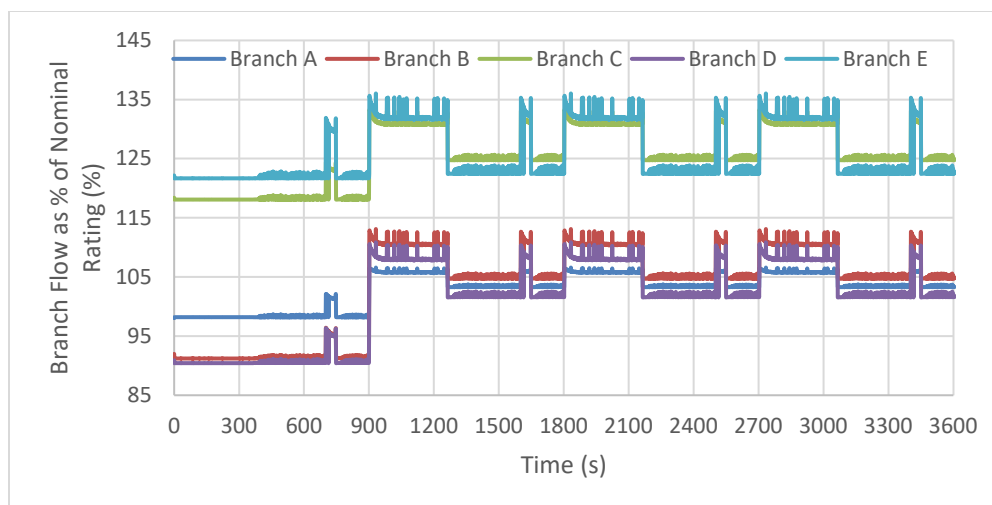


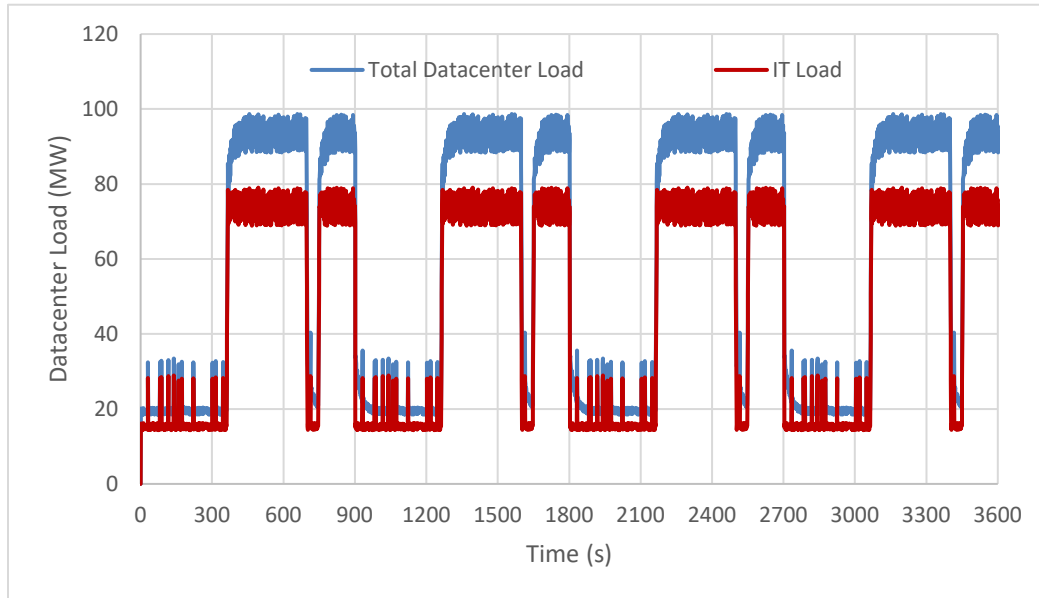
Figure 24. MVA flows in heavily-loaded branches with N-1 contingency and 100% onsite generation.

Compared to the case in Section 4.2.1 (without onsite generation and BESS), the simulations give a mixed result. When data center load is high, the BESS and NG successfully compensate for the data center demand, dropping its apparent grid demand to nearly zero. However, the charging control for the BESS prioritizes SOC recovery and is not coordinating with the NG, resulting in additional demand on the system that would not ordinarily be present if the BESS controls were tuned for a different objective in an optimal case. The result is branches that are more overloaded than an optimal case, but the overloading is less than the base, no-local-resource scenario. To properly mitigate the demand and provide benefit to the grid, the BESS charging control would need to be adjusted to avoid charging during the high grid stress periods.

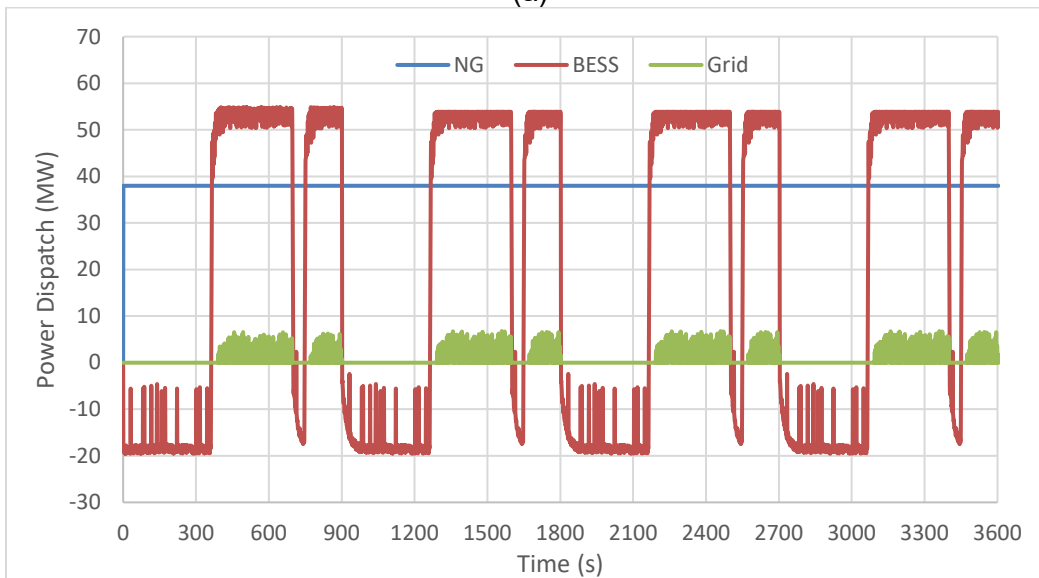
#### 4.2.2.2 Collocated BESS – Regulation Services on Charge and Discharge

The prior control scenario demonstrated the onsite NG and BESS can provide beneficial services to the grid, but the prioritized SOC recovery for the BESS still resulted in large system demand requests and fast ramping adjustments being absorbed by the larger electric grid. Such a scenario may be deployed if the BESS is primarily serving as a backup power supply, and grid services are a marginal element of the dispatch. In this control variant, the BESS is not primarily a backup power source, so charging is not prioritized and the target BESS SOC is reduced to provide both charging and discharging headroom (SOC starts at 60%).

Figure 25(a) shows the data center load, which is identical to the profile shown in Figure 22(a). However, Figure 25(b) shows the approach to meeting the demand has changed, with the BESS leveraging its charging to regulate toward a zero-grid power condition. When data center load drops below the set output of the NG, the BESS switches to charging mode and absorbs the excess power, but does not draw additional power from the grid. In this control regime, the BESS is providing both energy reserve and regulation service capabilities. The low demand time regulation ( $t = 900$  to  $1250$  s) is more effective due to the BESS not reaching the power limit (BESS has charging and discharging headroom), whereas the high load scenarios ( $t = 360$  to  $900$  s), some portion of the regulation needs to come from the grid. However, in both cases, the large 100 MW swings in data center load are absorbed by the BESS and mitigate their impact on potential grid stability during the stressed condition.



(a)



(b)

Figure 25. Grid under N-1 contingency and Data center with fixed NG and initial BESS SOC of 0.6 pu: (a) data center load demand, and (b) power dispatch from NG, BESS and grid.

Figure 26 shows the SOC for the BESS in this control regime, with the initial 0.60 pu SOC reflecting this energy storage is not purely for backup power. The BESS is biased toward discharging under these conditions, so additional demand mitigation or generation will be needed in approximately an hour, when the BESS would be nearing the 0.20 pu operational SOC limit.

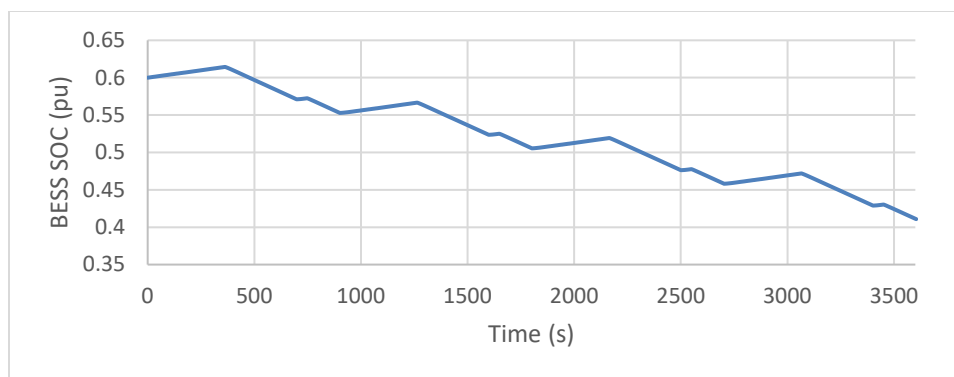


Figure 26. BESS SOC with the N-1 contingency and fixed NG and initial BESS SOC of 0.6 pu.

With the regulation-services-prioritized BESS charging control, Figure 27 shows the overloads on the branches of interest are reduced compared to the SOC-prioritized BESS charging control (Figure 24). The rapid fluctuations in branch loading are also reduced or eliminated with the change in BESS controls, which should help maintain the overall stability of the grid. The branches are still overloaded and additional mitigations are needed, but per the earlier sections, the primary focus was to examine the data center direct impacts to the system condition.

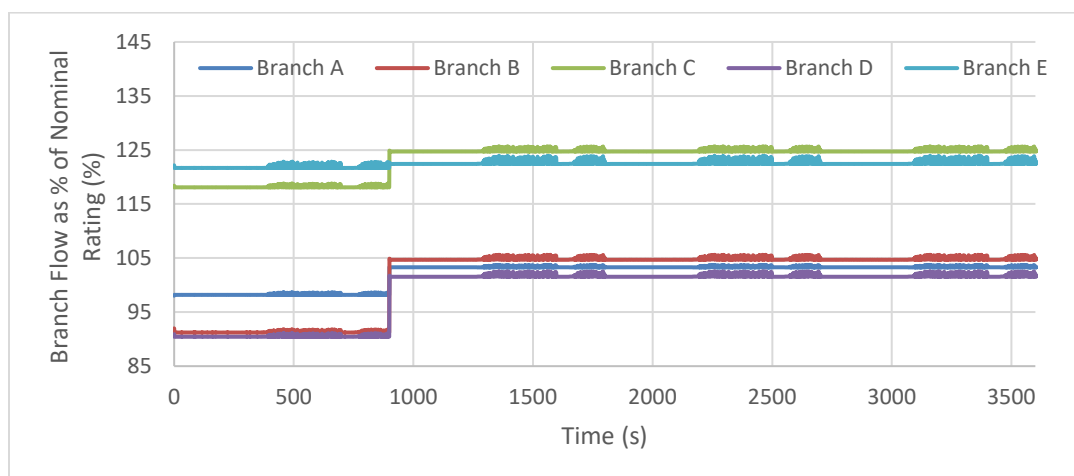


Figure 27. MVA flows in heavily-loaded branches with N-1 contingency and fixed NG and initial BESS SOC of 0.6 pu.

#### 4.2.2.3 Collocated BESS – Control Scenario Impacts

Utilizing the onsite generation and BESS helped reduce the data center load during the initial grid stress period and helped maintain the branch loading closer to pre-contingency levels. However, the SOC-prioritized BESS charging in Section 4.2.2.1 quickly offset this benefit and caused an increase in the overload on the lines. The regulation-services-prioritized charging approach in Section 4.2.2.2 minimized this detriment, but the SOC drops faster and the BESS would no longer be deployed purely for backup power purposes. In both control scenarios,  $t = 0$  s to 700 s demonstrates the NG and BESS may help reduce demand and provide the transmission operator additional time to dispatch additional generation or instigate demand reduction calls. With closer coordination of the assets during this time, including leveraging flexible loads in the data centers, grid performance can be further enhanced, and the data

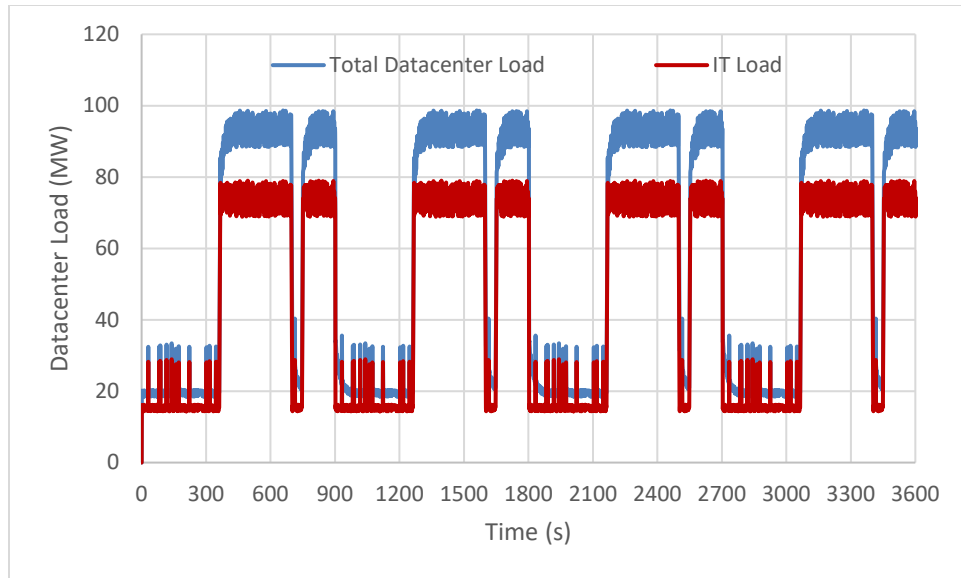
center can potentially aid in grid services aimed at normal operations and stressed operations. However, the branch overloads caused by the SOC-prioritized recovery in the BESS demonstrate how an uncoordinated control mechanism can change a beneficial device into a liability to both the data center and the grid.

### 4.3 Onsite Generation and Collocated BESS Size and Control Impact

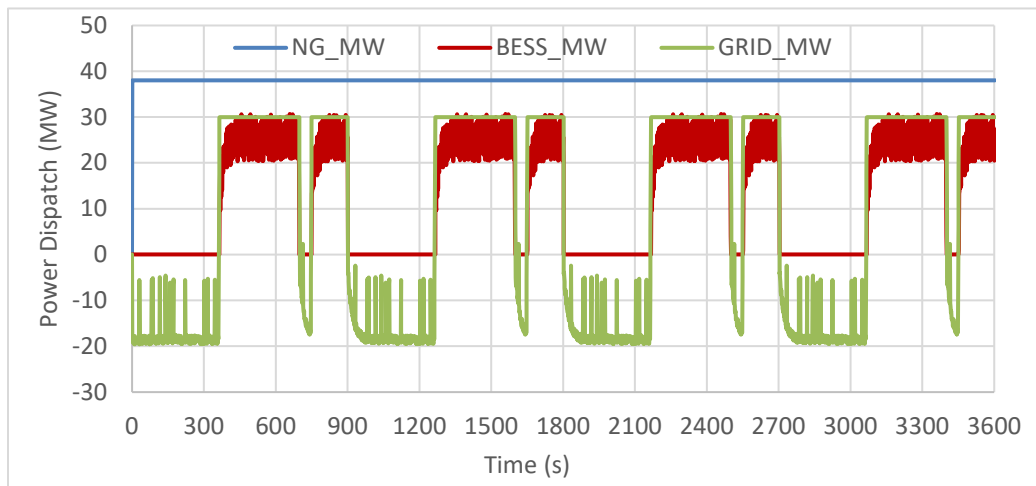
In the previous section, the results revealed the benefits of the onsite generation and BESS along with potential reserves and ability to provide grid services. This section of the report discusses the impact of sizing of the onsite generation and BESS when a demand constraint is present. For both scenarios, the grid connection is limited to 30 MW of demand. Any load beyond 30 MW, the data center must either curtail its load (compute/IT and thermal) or utilize the local resources to meet the excess demand. The generation is assumed to be dispatchable and available; if its primary purpose is for an emergency backup, those devices may have further constraints. If used as emergency backup generation only, the BESS may have SOC limits to ensure critical loads can run for a specific duration, and the NG or other fuel-based generation may have runtime limitations from local or federal regulations.

#### 4.3.1 Limited Grid Capacity with 100% onsite generation

The first scenario considers local generation resources and the BESS to be capable of providing 100% of the data center peak power; the generation and BESS were sized to provide full backup power capabilities to the data center. In this case, the NG can produce 38 MW of active power and the BESS can provide up to 60 MW of active power. The BESS is sized to provide 2 hours of rated power, or 120 MWh. The data center load and generation dispatches are shown in Figure 28. The NG generator is dispatched to a constant power first, with the BESS providing additional generation capabilities as needed. The 30 MW demand limit is maximized, with the BESS providing regulation of the fluctuations of the IT load and keeping the grid demand fixed at the limit. The generator and BESS capabilities are sufficient to maintain the grid limit for the data center load, but Figure 29 does demonstrate the BESS loses about 10% SOC over the hour. If the constraint is sustained for longer than 8 hours (to maintain a 10% minimum SOC) or the NG generation changes, the data center may have to start curtailing compute load to maintain the grid constraint.



(a)



(b)

Figure 28. Limited grid with 100% onsite generation: (a) data center load, and (b) power dispatch from NG, BESS and grid.

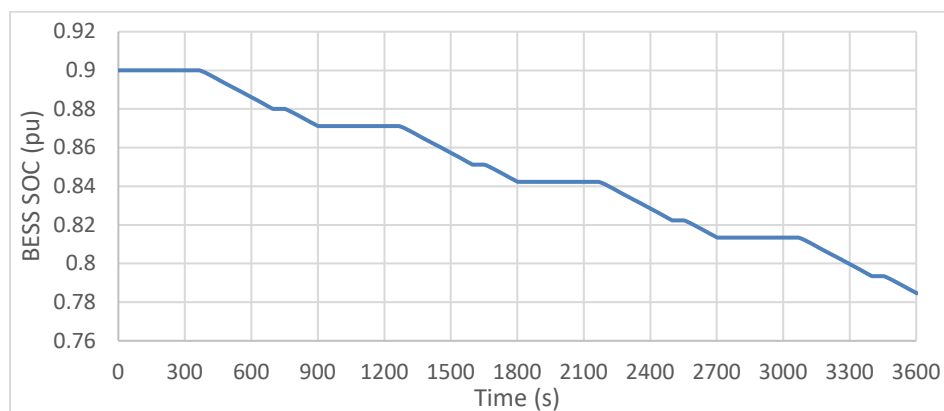


Figure 29. BESS SOC with limited grid capacity and 100% onsite generation.

The branch loading shown in Figure 30 reinforces the reduced impacts the grid, compared to the base scenario. Branch A and C are still overloaded, but the data center load fluctuations are limited due to the onsite generation and BESS limiting grid impact to 30 MW. Per earlier discussions, these results reflect only the data center impacts on the system. In such an overloaded condition, other resources and control mechanisms would also be engaged to help reduce the overload on the branches.

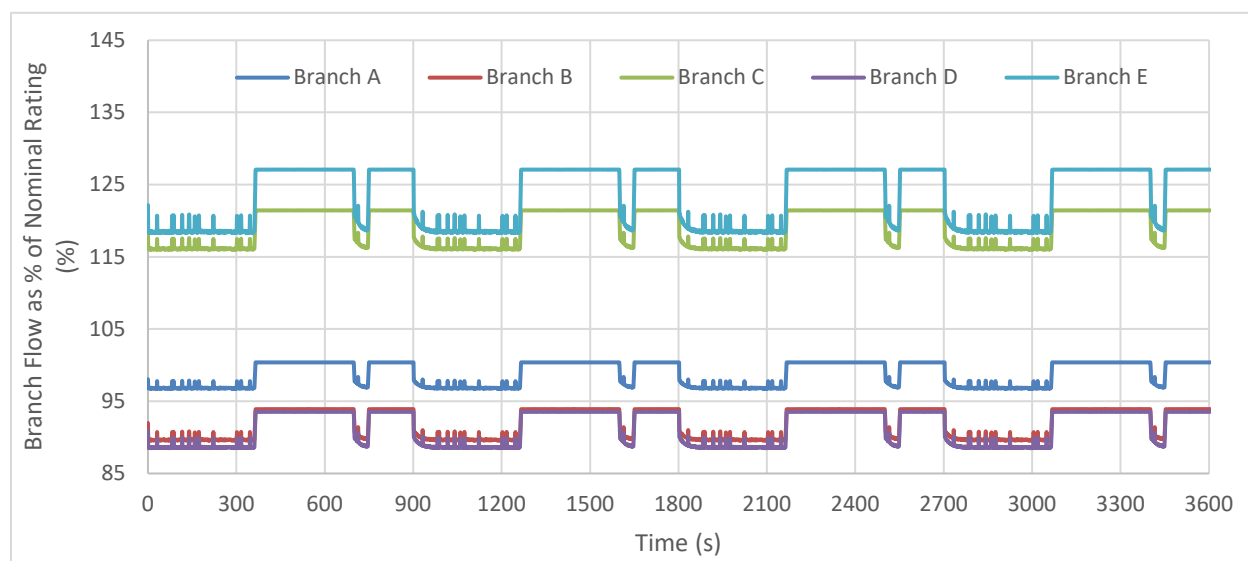


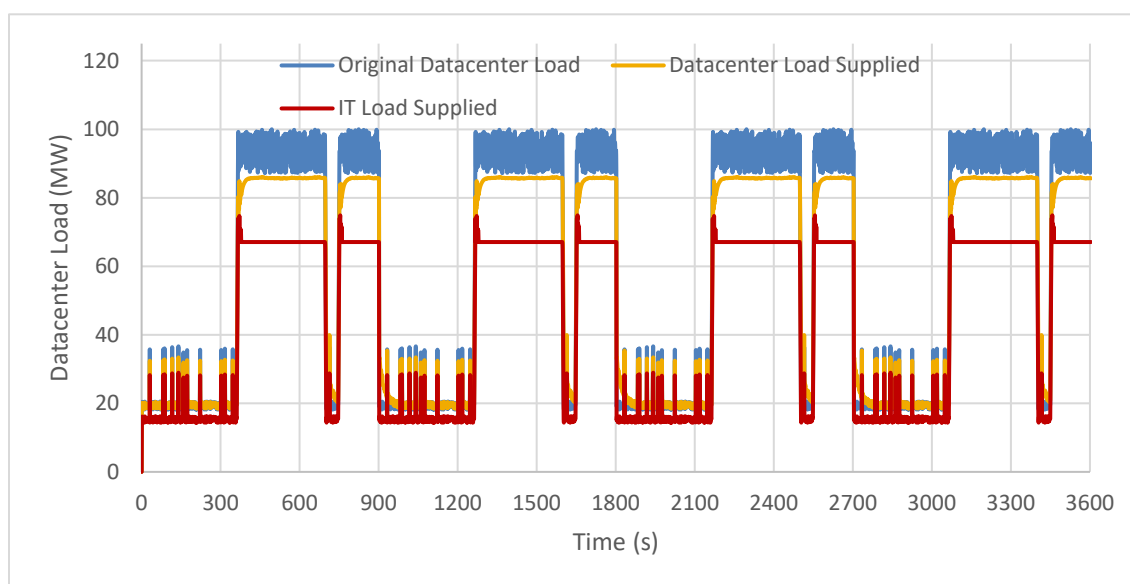
Figure 30. Branch flows with limited grid capacity and 100% onsite generation.

This simulation study showed that sufficient onsite generation can enable data centers to operate uninterrupted though an interconnection constraint. This may be a temporary demand limitation due to grid conditions, or a longer-duration restriction while infrastructure is built out. The onsite NG generator and BESS provide sufficient energy, reserve, and regulatory services to serve the data center. As more capacity opens up on the transmission grid, or if additional agreements are put in place, the extra capacity on the NG generator and BESS could also be leveraged to provide extra services back to the electric grid, or moved to another data center location needing additional power capacity or capabilities.

### 4.3.2 Limited Grid Capacity with 60% onsite generation

Sizing onsite generation and resources to meet 100% of the data center load may not always be feasible. If sufficient power is not available, additional methods to limit demand will need to be deployed. In this instance, the local generation is sized to only be 60% of the rated data center peak load; the NG generator provides 20 MW of active power and the BESS can provide up to 40 MW. The battery is sized to provide 2 hours of rated production, or 80 MWh.

In this scenario, the 30 MW demand limit from the transmission grid remains. However, the onsite generation and BESS can only provide up to 60 MW total power. When the data center demand goes above 90 MW (60 MW local resources + 30 MW grid limitation), the load cannot be met. Figure 31 shows the demand and generation for the data center, with Figure 31(a) showing the “original” and “supplied” load – as expected, about 10 MW of data center load cannot be met. This represents a scenario where the data center operator needs to shut down a portion of the site (IT/compute load) to meet the demand limit. Section 4.4.2 provides an example of limiting the compute load and the impacts to the system.



(a)

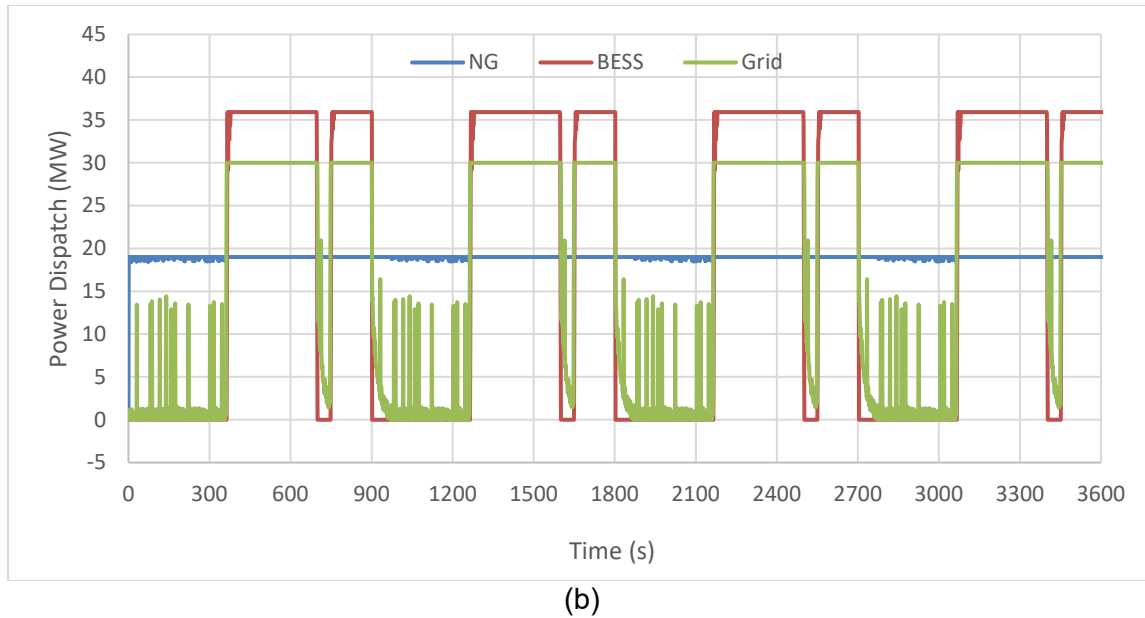


Figure 31. Limited grid with 60% onsite generation: (a) data center load, and (b) power dispatch from NG, BESS and grid.

While the demand, particularly the IT load, is artificially limited to the grid constraint, the implications to the overall resource sizing are still apparent. With a smaller NG generator and BESS, each resource is operating at maximum capacity sooner and longer. Figure 32 shows the SOC for the BESS, demonstrating the smaller energy capacity and greater demands leading to a larger SOC difference than the 100% scenario in Section 4.3.1. Even with proper curtailment, the BESS will reach the 10% minimum SOC in a little less than 4 hours of operation. If the grid constraint is still in place, further curtailments will be necessary at that point.

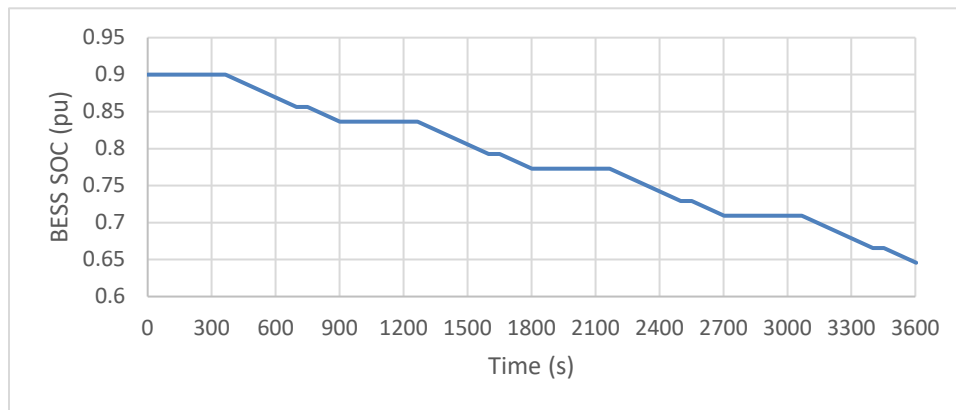


Figure 32. BESS SOC with limited grid capacity and 60% onsite generation.

## 4.4 Controlling Data center Load

The flexible load components of the data center are mainly the thermal management load and the computational load (referenced as IT load). Both the IT and thermal load are based on the model explained in Section 2.4. Changes to either property are reflected in detailed data center model, which captures the interaction between IT/compute load and the thermal load of the

system to properly update the total data center load presented to the transmission system model.

The simulation duration for these scenarios is modified to four hours from 16:00 hours to 20:00 hours to consider a peak demand duration on the grid (17:00 to 20:00). Greater simulation fidelity is used when examining data center load, which helps capture thermal management load and the IT load interactions. For example, sudden IT load changes do not instantaneously impact the cooling load; the chilled air and chilled water systems both have thermal mass that slowly changes in temperature. The cooling system responds to this mass temperature, so thermal control actions and dynamics will often occur a short time period after any IT load change and will be more gradual as that thermal mass is heated or chilled.

#### 4.4.1 Controlling Thermal Management Load

Cooling loads are adjusted by changing the chiller water target temperature, as was described in Section 2.4. Per the overview, a peak demand condition occurs on the grid between 17 h and 20 h, so demand limitations are imposed during that time period. To get maximum short-term demand, the chiller water is set from 18°C to 50°C for 17 h to 17.5 h. However, this high temperature setpoint can only be accommodated for a short interval, so temperatures are adjusted down back to 38°C for the 17.5 h to 19 h. Another short-term operating limit is reached, so at 19 h the temperature has to be adjusted back to 28°C to maintain the hardware temperature. Here it would remain until the demand limitation expires, which is beyond the time shown in the simulation.

The demand impact of these changes is shown in Figure 33. Note that the cooling load demand does not change instantaneously with the different temperature set point changes above. As the set point adjusts, the pumps, air conditioning system, and even the working fluid (air and water) have dynamics associated with the system adjusting to meet the new requirement. While the response is within two minutes, it limits the cooling load adjustments to only be useful for slower grid service applications like reserve or energy services.

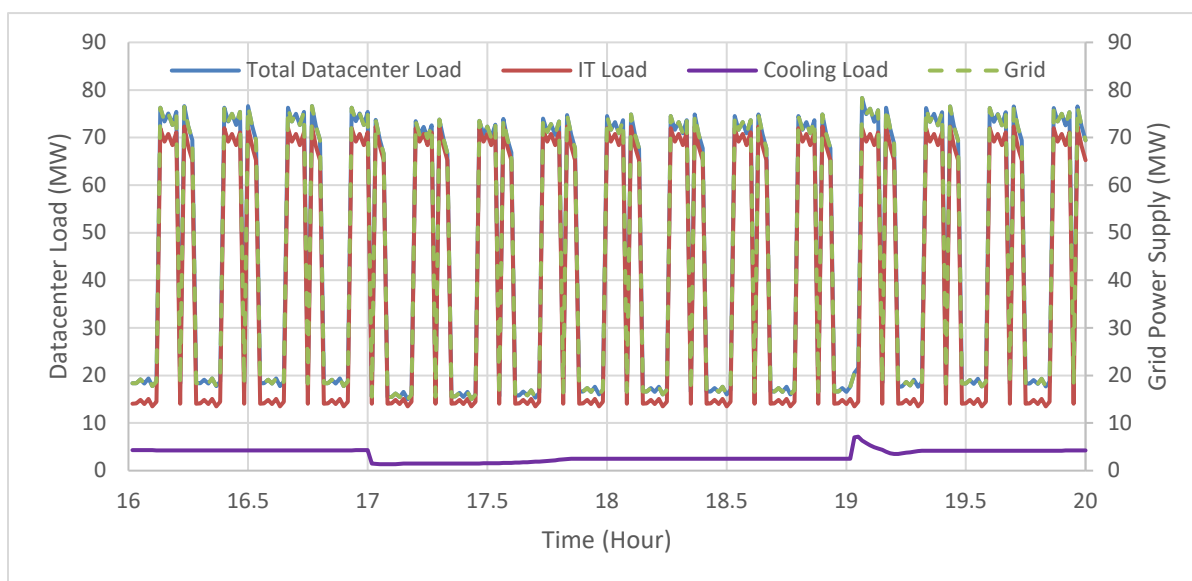


Figure 33. Data center demand and grid power supply in cooling control without onsite generation scenario.

The initial adjustment in chiller temperature changes data center demand by about 2.7 MW (for 50°C operations). When it is adjusted to 35°C at 17:30, the demand reduction is now only 1.7 MW over the baseline. From 19:00 onward, the 28°C chilling only reduces overall demand by about 0.2 MW over the base case. This causes the branch flows to decline, though only slightly, as illustrated in Figure 34.

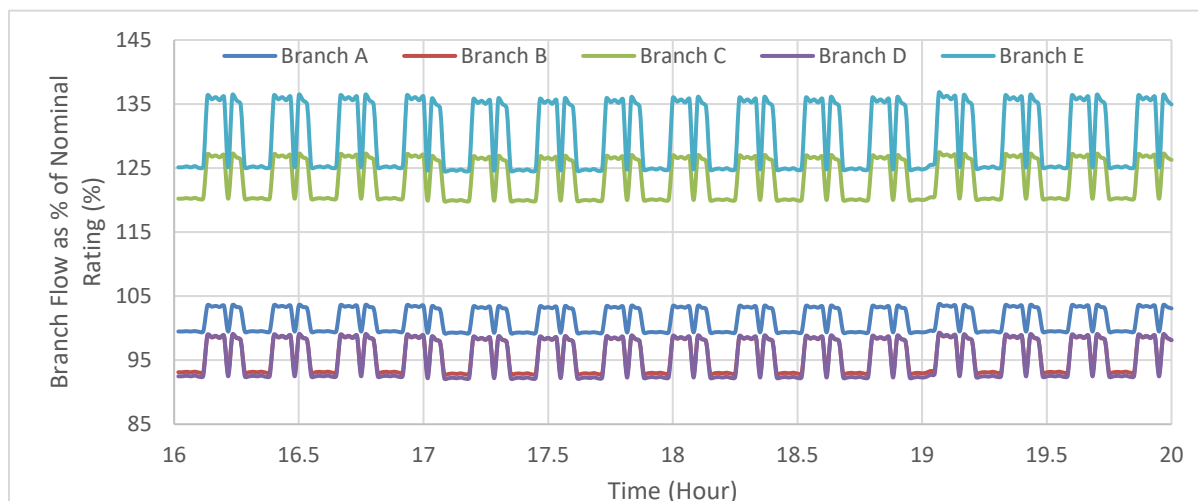


Figure 34. MVA flows heavily loaded branches in cooling control without onsite generation scenario.

For the data center examined, the cooling load does not make up a significant portion of the demand and has a response time that takes minutes. Even with a large temperature setpoint change, only 2.7 MW of demand reduction occurred, which could only be maintained for about 30 minutes. Operational restrictions required easing that as the demand restriction continued. The step change at 19:00 is also noteworthy in that it did not align with an IT load minimum, so power demand spiked slightly while the chiller loop worked to reach the new setpoint of 28°C. For heavy compute load scenarios, manipulating thermal set points can get some temporary demand reductions, but much smaller scale compared to other elements in the data center.

#### 4.4.2 Controlling IT Load

The compute/IT load of a data center is far a more significant component of the energy consumption and peak power demand than cooling load. This scenario uses the same data center load from the digital twin model as in Section 4.4.1; however, the IT load is controlled to see its impact on grid side. The same demand restriction from 17:00 to 20:00 exists. To help reduce demand on the system, the compute load is curtailed (or re-dispatched to a data center connected to another transmission region) by 30%. Large data center owners have facilities spread across the country and connected to different regions of the power system, allowing them to utilize the time difference and geographic dispersion to avoid coincident peak demands. The demand impact is demonstrated in Figure 35, with overall data center demand dropping around 24 MW. The 24 MW is a combination of approximately 23 MW of reduced power consumption in the IT loads, but also a 1 MW cooling load reduction due to less heat being rejected by the system.

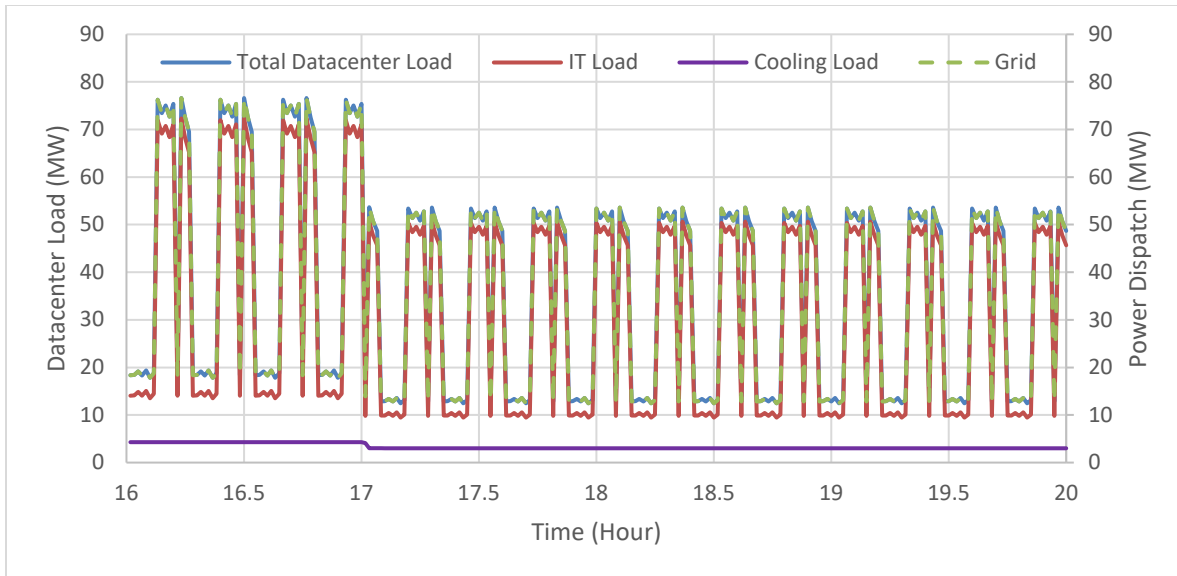


Figure 35. Data center demand and grid power supply in the scenario of IT load control without onsite generation

The impact of IT load control on branch flows is reflected in Figure 36. It is observed that the branch flows through the branches of interest have significantly dropped once the IT load control is activated. The demand reduction and congestion reduction can clearly provide a benefit to grid stability, but this is heavily contingent on the ability to curtail the compute load. The ability to redispatch IT load to a data center in another region is more likely for a data center serving a themselves or if a specific provision has been built into the hosting contract. To move the IT load to another facility, insight into the compute job queue helps prevent data loss and manage service disruptions, which are more likely if in a self-owned data center or if the client is contractually obligated to provide that insight. Onsite generation and BESS could be used to offset this or serve critical compute jobs during the curtailment period, which would require an additional level of complexity in the control.

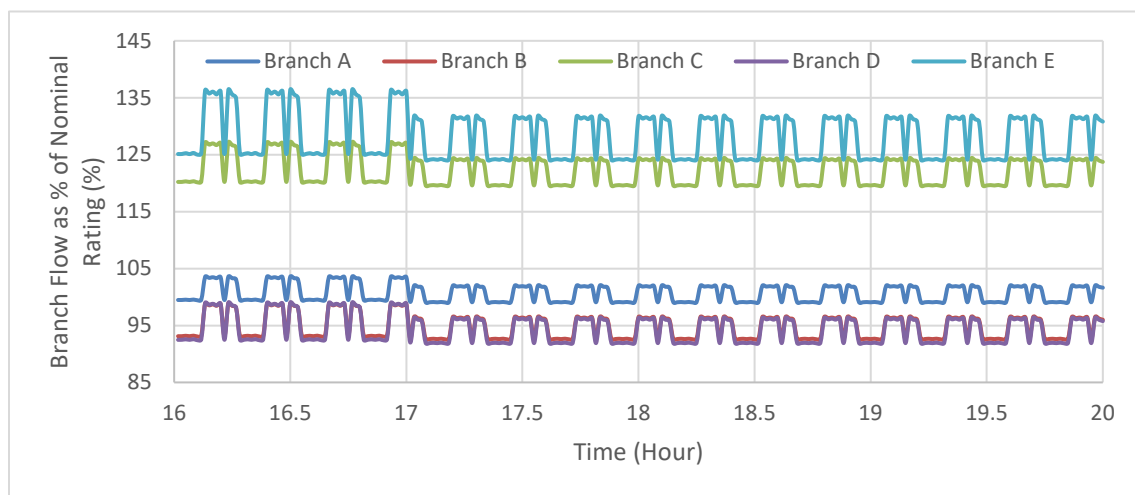


Figure 36. Branch flows in the scenario of IT load control without onsite generation

## 5.0 LDDL Control and Grid Services

The data center control for grid support and grid services have potential to impact the overall grid performance. The exact impact will depend on the size of the available resources at the data center (generation resources, IT load, and cooling load). Larger data centers have greater resources and more flexibility to provide larger grid services, but are also a larger load and impact on the grid. A large power and large energy-capacity BESS provides the greatest flexibility and ability to provide grid services, but at a large capital expense. The simulation studies discussed in the previous section demonstrated that with sufficient observability and controllability, the data center resources can provide varying levels of capability back to the electric grid. However, there are several considerations that need to be taken into account when planning for grid services from data center resources.

### 5.1 Data center Generation and BESS related Controls and Grid Services

1. BESS can prove to be a very useful resource as it has the potential to inject or absorb power, but the state-of-charge (SOC) of the BESS needs to be maintained at certain levels to derive this flexibility. The BESS may also have underlying SOC limits if it is in place to provide backup power, so that limit will need to be respected as well. The BESS control will need to be a function of the SOC.
2. BESS can provide reactive power to help regulate local voltage. While the reactive power flexibility does not significantly impact SOC significantly, the overall rating of the inverter needs to consider expected active and reactive power (MW and MVAR) to ensure proper sizing – active power capabilities are expected to be the primary capability of interest from the BESS.
3. Onsite generation, especially leveraging the BESS, can be crucial in helping with peak shifting and peak shaving applications (energy and reserve grid services). This is true both in normal operations and during contingencies to help minimize the data center impact on the grid.

### 5.2 Data center Load Control and Grid Services

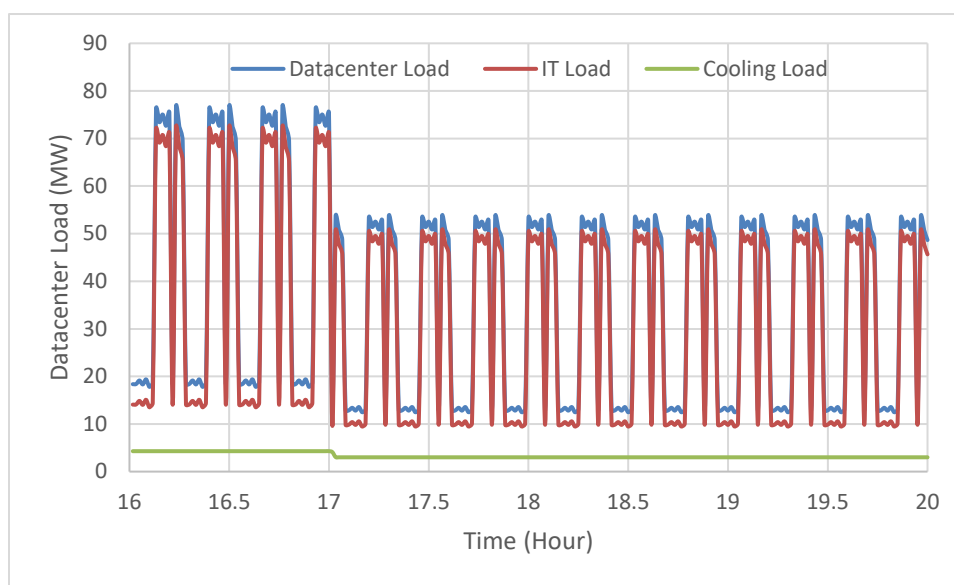
1. Data center compute/IT load control will be heavily dependent on the types of applications the data center hosts. Results were shown for LLM training loads, which tend to be the “worst case” in terms of magnitude and fluctuations. Data centers that are not based on client web services (e.g., social media organizations, crypto currency mining) will have different load profiles, and potentially greater compute load flexibility. Crypto mining applications have especially shown great value in providing energy and reserve services [19].
2. Data center thermal management load control also provides some capability for grid services. Detailed knowledge of the cooling system (e.g., direct HVAC, chilled water systems, and rack vs. facility-level controls) is needed to define the capabilities of the system to provide grid services. During stressed grid operating conditions, the load control of data centers can be important as it provides short-term demand relief.

### 5.3 Simulation Results with Sequential Control Actions for Grid Services

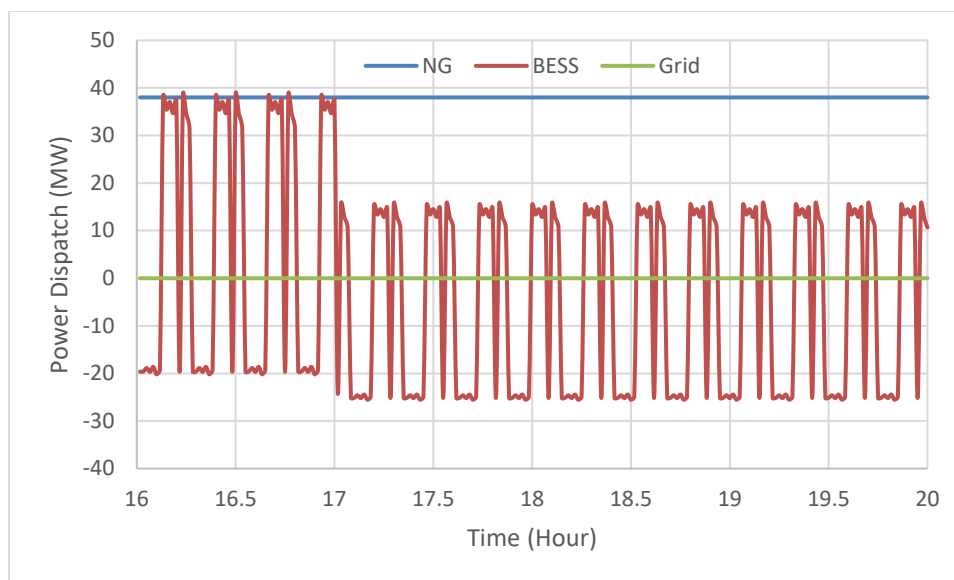
The various controls evaluated in Section 4 examined individual controls and capabilities. The full value of these controls requires that they be combined and coordinated. This scenario combines the different controls from Section 4 to demonstrate a benefit to the grid.

For this simulation, grid capacity is limited due to daily congestion. Onsite generation and BESS power capabilities are sized to provide 100% backup of the peak data center demand, but the BESS control is selected to also prioritize regulation of the load fluctuations. In this use case, the simulation occurs during a peak demand time 16 h to 20 h. The grid is operating in a stressed condition (see the Section 4.1 base case scenario), and a grid contingency occurs at 16.75 h. This contingency causes an increase in the overload of the branches of interest and additional congestion on the grid.

At 17 h, a known, congestion-based demand limit is enacted, and data center load needs to reduce its consumption. The data center manages its internal IT and cooling load, while also coordinating with the local generation resources and BESS to maintain an energy service to the grid, reducing overall demand. Figure 37(a) and Figure 37(b) show the data center demand and the NG Generation, BESS, and grid import respectively. Figure 38 depicts the SOC of the battery during this scenario, highlighting the BESS was sized to sustain operations like these for much longer time periods.



(a)



(b)

Figure 37. Sequential control actions for grid services: (a) data center load demand, and (b) power dispatch from NG, BESS and grid

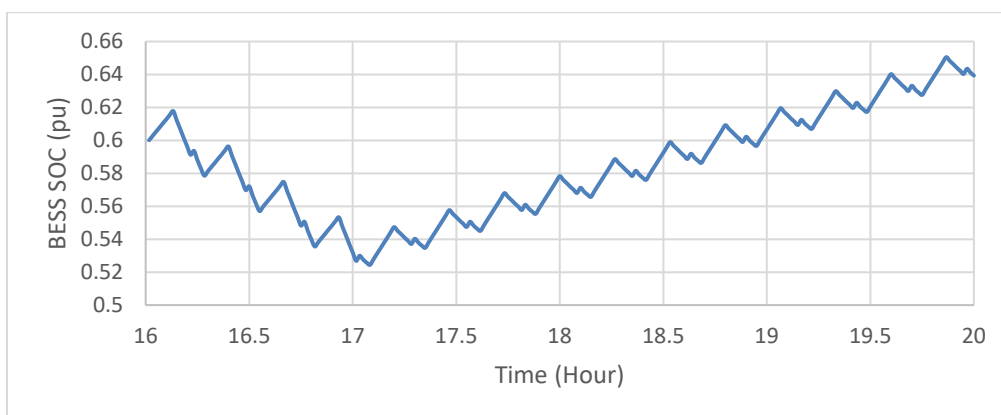


Figure 38. BESS SOC with sequential control actions for grid services

For this scenario, the onsite resources (NG and BESS) are also providing regulation services against large load fluctuations of the data center load, but their primary function is to limit the demand. When demand drops below the NG value, the battery absorbs the excess power/energy via charging. This also allows the battery to regulate the large load fluctuations, preventing those large power swings from imposing on the already congested grid.

For this scenario, the coordination between the NG and BESS could be improved. There may be benefit in adjusting the BESS control to maintain the ability to regulate the large fluctuations, but still allow more of the excess generation to pass to the grid as an energy or reserve grid service. The transmission system would still benefit from the excess generation, but without the rapid ramping that comes with the NG output exceeding the data center load.

With the controls activated, the grid import is reduced, helping aid congestion management on the larger system. From Figure 39, Branch E (the most overloaded branch) does not see a significant change in its loading level, despite the contingency at 16:45 local time. Due to the

contingency, Branch C becomes the most overloaded, but at a lower percentage than it would if the full data center load were present. The BESS is successfully mitigating all of the large load fluctuations from the data center, helping manage a potential destabilizing behavior on the grid. As with prior scenarios, the mitigations only represent the impacts the data center-controlled actions have on the system. The system is obviously still overloaded and additional load actions or controlled devices would need to be used to mitigate the branch overload condition.

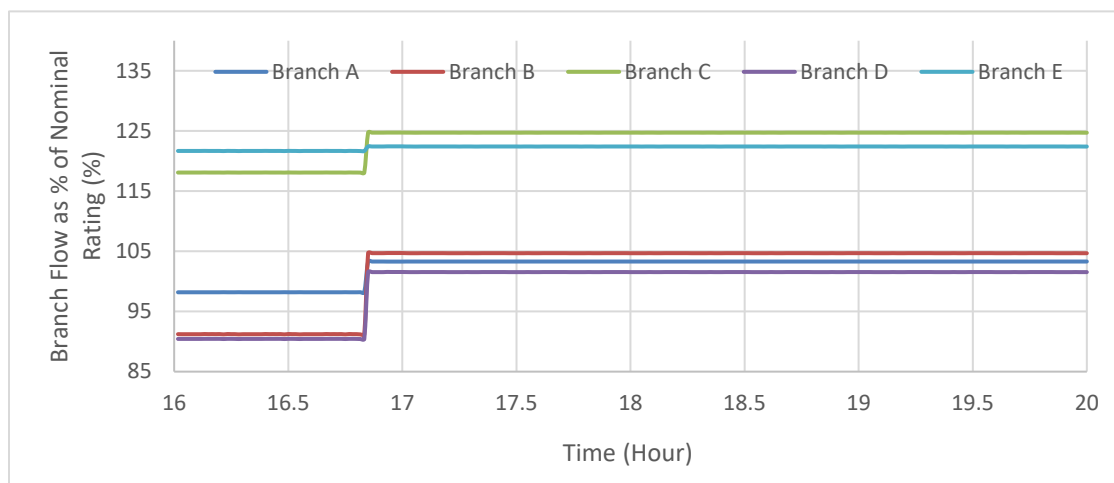


Figure 39. MVA flows on heavily loaded branches with sequential control actions for grid services

With the SOC available (Figure 38) and the current generation dispatch (Figure 37(b)), the data center may have additional grid services it could lend to the grid to help alleviate congestion further. Since the local generation and BESS resources are sized to provide backup power, they have additional capacity that could be used to send power back into the electric grid. The scenario does have an IT load reduction in place at the data center, so incentives to provide that power to the grid instead of resuming normal data center operations would need to be evaluated. In addition to the appropriate coordination and risk evaluation of the data center operations and BESS SOC, it may also require new agreements and coordination with the utility to manage the reverse power condition on the system (from the NG and BESS over-production into the system).

## 6.0 Conclusions

Data center controls, including controlling the data center onsite generation, collocated BESS and the constituent data center IT and thermal load, has potential to contribute to enhance grid performance. This report has discussed data center modeling for QSTS timescales and integration of the models with transmission models with commercial solver, PSS-E.

The data center QSTS model includes model development based on the available AI data center load profiles from the NERC data center whitepaper. The modeling also included models coupling data center compute/IT load and thermal loading to help evaluate potential capabilities there, leveraging prior PNNL modeling efforts. Onsite generation and local resource contributions were considered through inclusion of a natural gas turbine and BESS. Impacts on an overloaded IEEE 24-bus transmission model helped evaluate the impact of different control actions, especially on grid congestion/line load in the region.

With the scenarios examined, the key findings from this analysis are broadly threefold:

1. The data center onsite resources are capable of directly and indirectly contributing to grid operations through grid services like:
  - a. Reactive power control to improve the local grid voltage regulation.
  - b. Providing energy and/or reserve services by supplying the data center load in durations of limited grid capacity.
  - c. Regulation services can be provided through fast acting controls of BESS to help absorb some of the data center load fluctuations to produce a relatively smooth demand on the grid.
2. The data center load control can potentially help with demand management on the grid during normal and stressed operating scenarios:
  - a. The thermal load management and adjustment of internal cooling temperatures can provide some demand relief. However, thermal load and savings are much smaller compared to the larger compute/IT load, so grid service potential is oriented more toward smaller requirements or marginal gains during times of extreme grid stress or contingencies. Thermal load management coupled with local thermal energy storage solutions may provide greater value, but that scenario was not explored in this study.
  - b. The IT load control (e.g., data storage management scheduling) can also be useful in stressed operating conditions with limited grid capacity. Coordination with the compute application requirements is necessary to determine the level of reduction feasible. Geographic redispatch of the compute/IT load to other data centers needs to ensure the grid impact is not simply moved to an equally-stressed region.
3. Use of the local resources (onsite generation and BESS) and manipulation of the data center load can provide grid services and overall positive grid impacts. However, compute application sensitivities and “roles” of the local resources must be considered in their potential to provide grid services. If local generation and the BESS are sized primarily for backup capabilities, grid services must be balanced against the increased risk to data center operations.

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