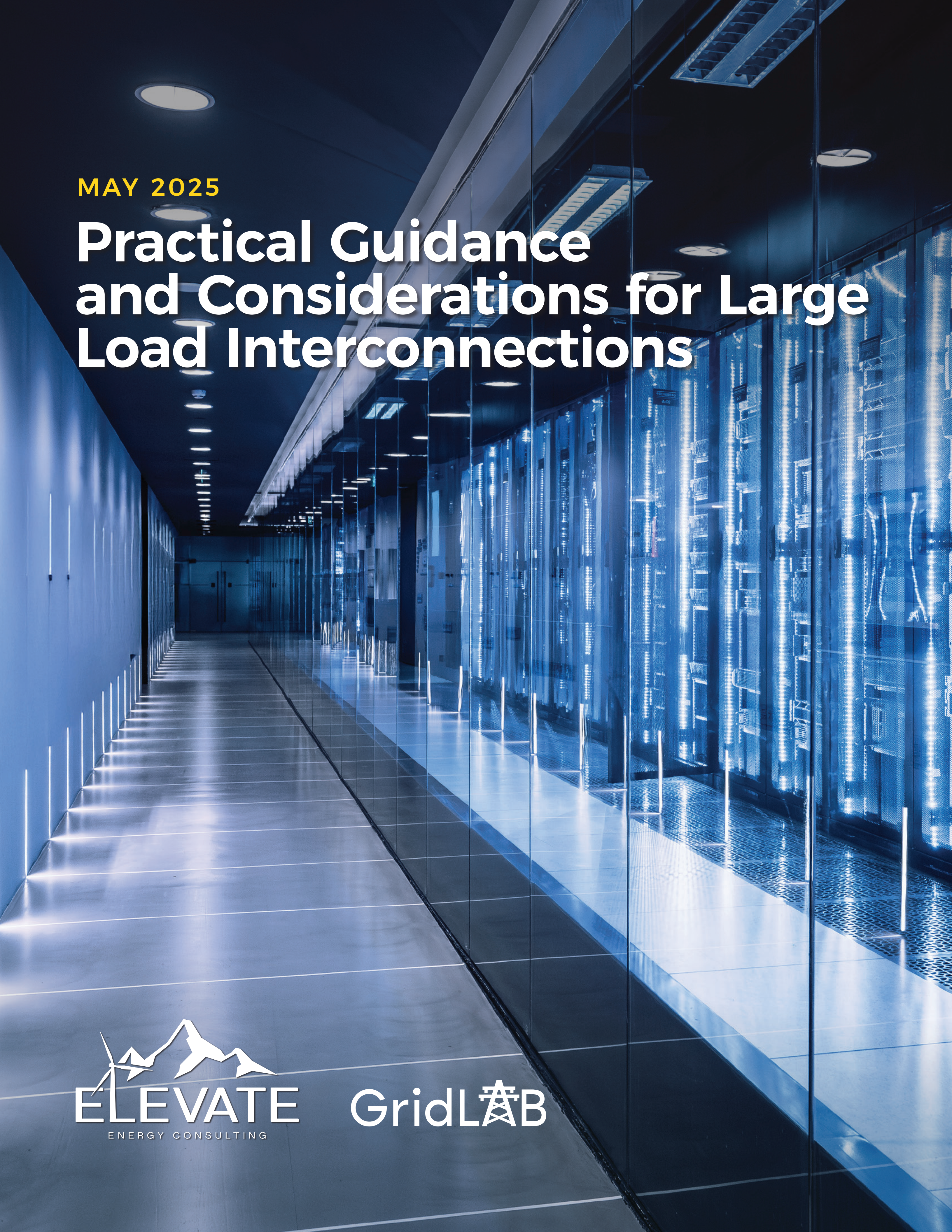
MAY 2025

Practical Guidance and Considerations for Large Load Interconnections



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Elevate Energy Consulting specializes in grid reliability analysis, power system modeling and studies, grid dynamics and controls, transmission planning and operations, inverter-based resource integration, large-load integration, regulatory compliance and policy, technical management consulting, and research and development.

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GridLab delivers expert capacity to solve technical grid challenges and answer reliability questions. Together, the GridLab Team and its network of 75+ power system experts provide technical expertise, resources, and education on the design, operation, and attributes of the grid.

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Executive Summary

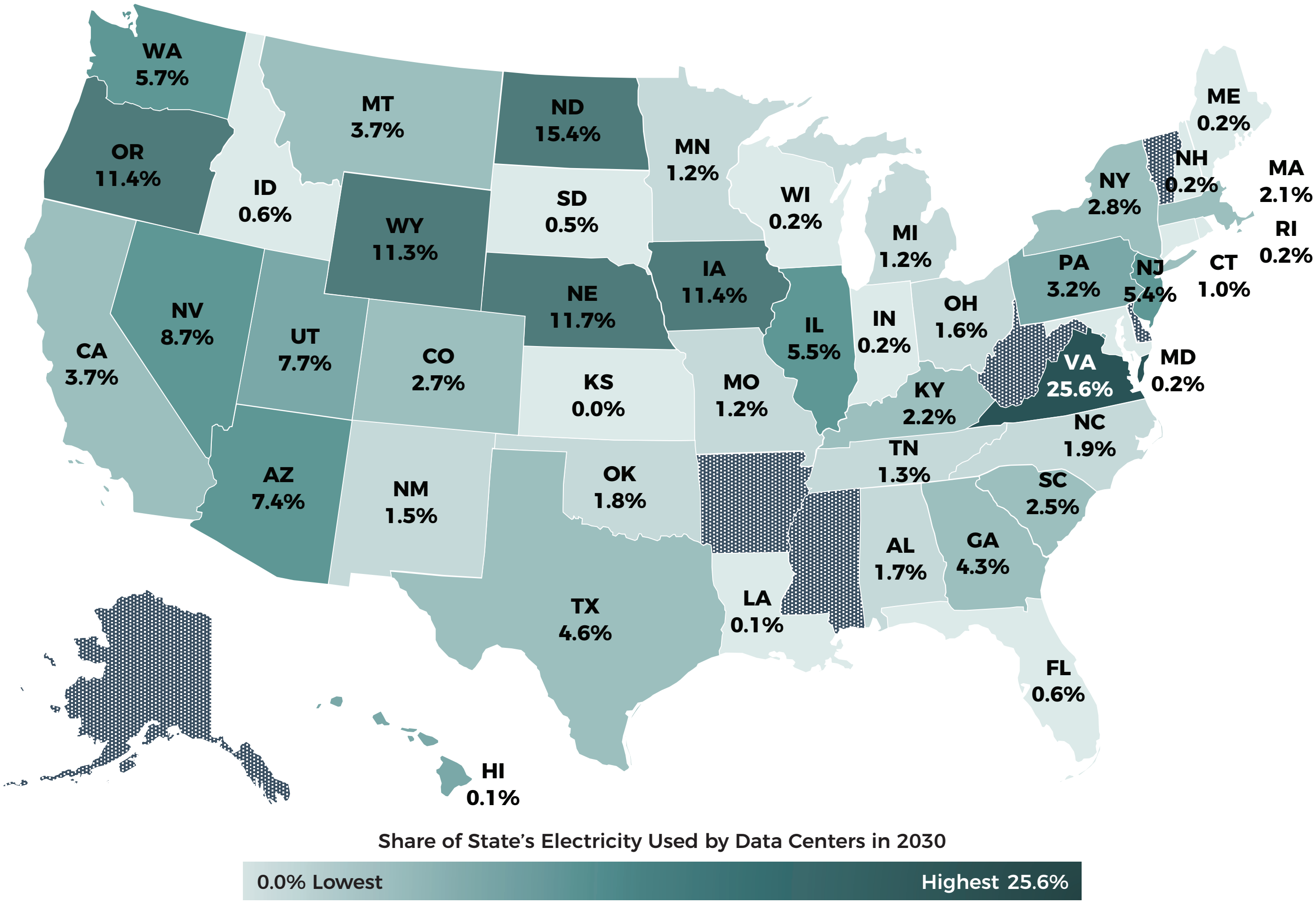
Requests to connect large data center and artificial intelligence (AI) loads are entering transmission planning processes at an unprecedented rate. This surge is driven by a combination of tax incentives, low electricity costs, access to usable land and water, available capital for AI development, and business-friendly regulatory environments. These potential data center customers are relatively price insensitive, prioritizing fast and reliable ***access to electricity as quickly as possible***. However, because transmission system capacity is not broadly transparent or readily available to industry stakeholders, developers submit speculative interconnection requests in an attempt to secure future access.

While the load interconnection queue may be speculative in nature and therefore the actual magnitude and breadth of data center development and AI energy needs is opaque, ***data centers already comprise a significant portion of electricity demand in the US (see Figure ES.1, p. 4) and this trend is expected to accelerate in the years ahead*** [1]. Utilities must evaluate and process these requests fairly and efficiently—studying available transmission capacity and identifying necessary network upgrades—while ensuring continued reliability of the bulk power system (BPS). Given the pace of load growth, the economic benefits of serving these customers, and strong political support for data center development, utilities need streamlined access to resources and recommended practices that can enable this emerging future.

Although the potential benefits to utilities are significant, the technical challenges of integrating large loads cannot be overlooked. Rigorous engineering analysis and due diligence are more critical than ever before to ensure reliable operation of the grid as these substantial loads come online.

This report serves as a practical guide to improving and harmonizing utility practices for processing, studying, and assessing large load interconnection requests. It also serves as a reference for state regulatory bodies in their effort to ensure that utility constituents are fully evaluating the potential impacts that large loads, particularly data centers, can have on grid reliability and existing customers.

FIGURE ES.1: Data Center Electricity Consumption by State



Data centers are a significant consumer of electricity in some states, and these numbers are expected to increase in the years ahead. SOURCE: ADAPTED FROM EPRI.

This guidance is especially useful in regions with limited experience integrating data centers and among utilities with constrained resources or bandwidth to stay current with evolving practices in this area.

Ensuring reliability of the BPS amid the boom in large loads requires:

- Large load customers to provide timeline and accurate data to Transmission Owners (TOs), Transmission Planners (TPs), and Planning Coordinators (PCs) to effectively plan, design, and protect the BPS.
- Large load customers to coordinate and share data with TOs, Transmission Operators (TOPs), Balancing Authorities (BAs), and Reliability Coordinators (RCs) to maintain real-time operational reliability of the BPS.

PHOTO: ISTOCKPHOTO/GERVILLE

- Enhanced communication and coordination across the transmission-distribution interface, ensuring that distribution-connected large loads follow similar requirements and processes as transmission-connected large loads due to their aggregate impact on the BPS.
- Clear and consistent performance expectations and technical requirements for large loads to ensure they contribute to rather than detract from overall BPS reliability and system performance.
- Grid planners to develop accurate models and perform comprehensive studies of BPS performance based on a well-informed understanding of large load behaviors.

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1

Background on Large Load Interconnections

The electricity sector is poised for record demands and sustained growth in the years ahead [1]. A 2023 study of nationwide demand trends found that grid planners had nearly doubled their five-year load growth forecasts from 2.6% to 4.7% in just one year [2]. This surge is fueled by both individual and aggregated end-use loads with high electricity demands. Multi-sector electrification—driven by digitalization, heat pumps, electric vehicle charging, and other factors—continues to push overall electricity demand higher. However, the primary driver of demand growth is the wave of "large load" interconnection requests to the BPS,[1] particularly from data centers [3]. Figure 1.1 (p. 9) illustrates the major categories of large loads connecting to the BPS today and anticipated in the future. This trend is placing unprecedented pressure on the BPS and the broader utility sector, emerging as one of the most significant forces reshaping the electricity industry for decades to come.

BOX 1: SERIOUS RELIABILITY RISKS TO THE GRID

Data center load uncertainty and response to grid events is not theoretical. In July 2024, a normal grid fault in Northern Virginia triggered the sudden disconnection of more than 1,500 MW of data centers across 25–30 substations. About 60 data centers switched to backup power via uninterruptible power supplies (UPS) designed to disconnect from the grid after a preset number of voltage excursions [4]. Figure 1.2 (p. 10) shows the net load reduction during the event and a simplified oneline diagram of the local substations and data center loads affected. In February 2025, an even larger 1,800 MW load loss event occurred for the same reasons. They underscore the lack of insights into data center behavior and the need for greater transparency into their operational performance.

1 The term BPS is used by the Federal Energy Regulatory Commission (FERC) and North American Electric Reliability Corporation (NERC) that broadly defines the interconnected transmission and sub-transmission system, excluding local distribution.

FIGURE 1.1: Drivers of Rapid Load Growth

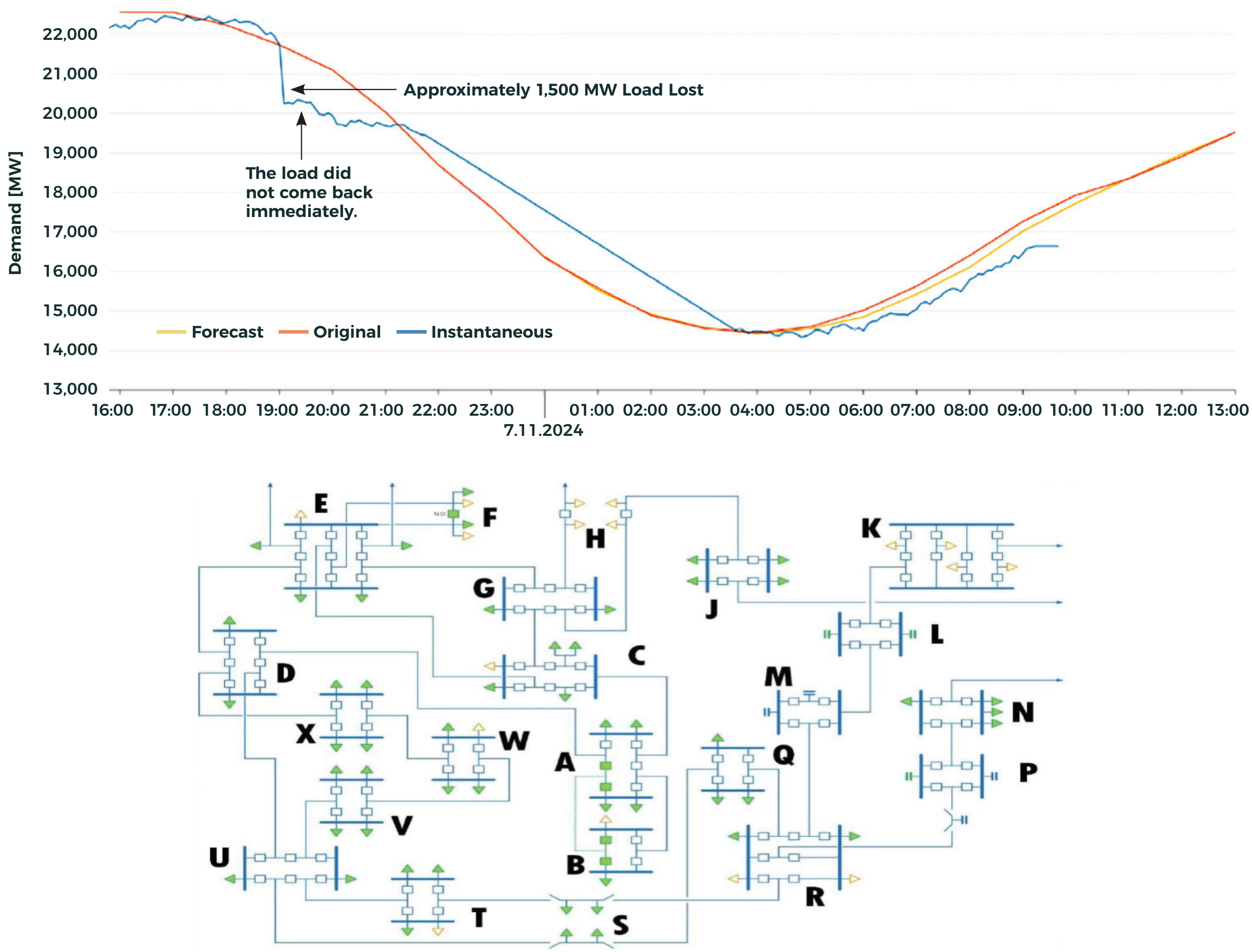
Data centers are by far the primary driver of electricity sector demand forecast growth.

SOURCE: ELEVATE ENERGY CONSULTING.

Data Centers: Large and Unpredictable

Data centers now constitute the vast majority of large load interconnection requests in the U.S. because of their immense power demands and double-digit annual capacity growth, which can present possible grid reliability risks. Unpredictable demand patterns are a primary challenge. Due to intense global competition, data center owners often keep operational and performance details private, limiting visibility into their energy needs, fluctuations, and demand ramps. This prevents utilities and grid operators from properly planning for their impact. A sudden surge or drop in demand from these facilities can pose serious reliability risks to the grid.

FIGURE 1.2: **July 2024 Northern Virginia Data Center Event Visualization**



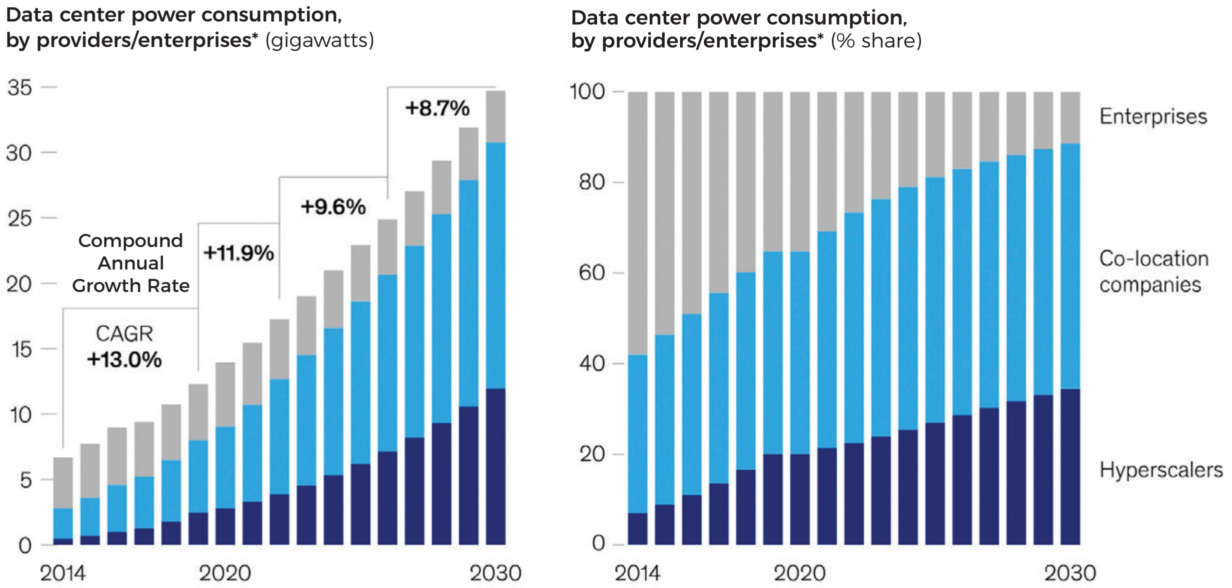
In July 2024, widespread data center disconnection caused by a sequence of grid faults resulted in a significant net load reduction in Northern Virginia. The green in the second image represents load lost during the event.

SOURCE: ADAPTED FROM NERC.

Imbalance Between Supply and Demand

The surge in large load interconnection applications is straining the electricity sector, requiring a rapid expansion of supply to keep pace with soaring demand. Data centers are the primary driver of this demand, accounting for nearly 80% of large load requests submitted to utilities across the Western U.S., Canada, and Mexico in 2024 [3]. Their rapid expansion is expected to place immense pressure on the BPS within a short timeframe. U.S. data center demand is projected to grow by nearly 10% annually, doubling from 17 gigawatts (GW) in 2022 to 35 GW by 2030 [1]. As Figure 1.3 (p. 11) illustrates, this growth is shifting away from individual enterprise facilities toward large-scale data center complexes [2]. These include co-location facilities that lease computing power to multiple businesses and hyperscale data centers dedicated to cloud computing and AI services—critical pillars of the modern economy.

FIGURE 1.3. U.S. Data Center Demand Forecasts by Type of Data Center

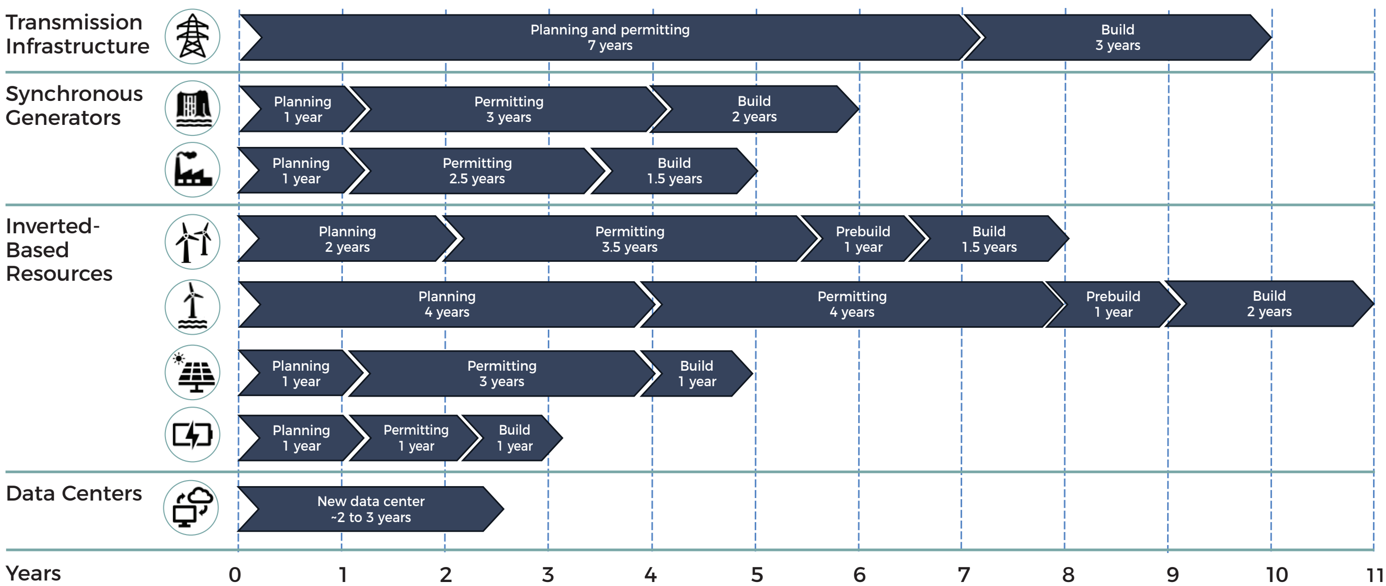


* Demand is measured by power consumption to reflect the number of servers a data center can house. Demand includes megawatts for storage, servers, and networks.

US data center demand is forecast to grow by some 10 percent a year until 2030. SOURCE: McKINSEY & CO.

As demand grows, generation capacity and the infrastructure to transport power must also expand. But upgrading the grid faces major obstacles, especially issues with siting, permitting, and supply chains. While it takes one-and-half to two years to build large load facilities like data centers, new generation plants take three to five years. Electric transmission infrastructure can take up to a decade to plan, permit, and construct. These discrepancies are illustrated in Figure 1.4.

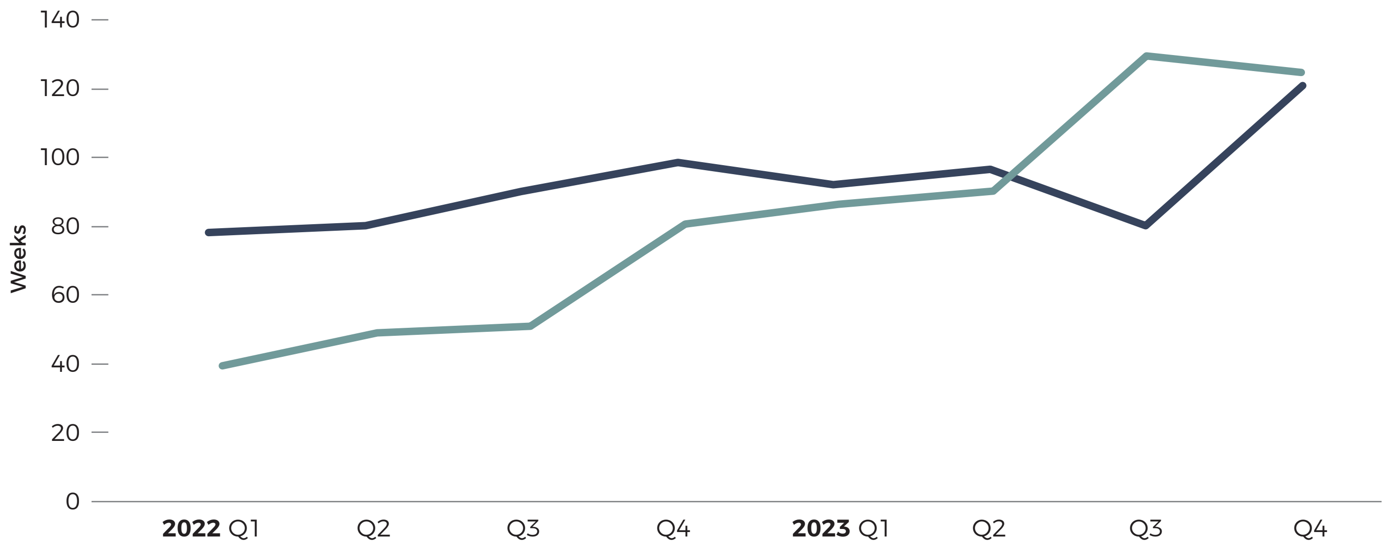
FIGURE 1.4. Illustrative Time to Market for Various Grid Projects



Timelines for grid infrastructure are not aligned with those for large load development, creating bottlenecks for grid supply of electricity. SOURCE: ADAPTED FROM S&P GLOBAL.

Construction timelines are further complicated by the scarcity of core equipment used by entities across the grid, including transmission and large load facilities. For example, nearly 70% of transformers in the U.S. are over 25 years old, and demand is expected to rise significantly by 2030. Prices have already surged by 80%. Lead times for power transformer have increased by 50%, while lead times for generator step up transformers have tripled since 2022 (see Figure 1.5) [6]. Similar supply chain constraints affect other grid equipment such as circuit breakers and switchgear.

FIGURE 1.5. Growth in Large Power Transformer Lead Time



Power transformer lead times have continued to grow, raising growing concerns about a stable and reliable supply chain to enable electricity sector developments. SOURCE: NIAC.

Bulk Power System Connection of Large Loads

The size of large loads connecting to the electric grid can often dictate the connection points—whether distribution, sub-transmission, or transmission voltages levels. This may be defined by the local utilities or may be based on cost-effectiveness. Utilities will have different practices and standards in this area [5]. Some illustrative examples could include (see Figure 1.6, p. 13):

Distribution Connected

- Large loads around less than 5 MW may be connected to typical distribution circuits along with other customers. This may require some upgrades to local distribution equipment (e.g., upgrading transformers, increasing circuit capacity, adding voltage devices, etc.).
- Larger loads in the 5–20 MW range may be served with one or multiple distribution circuits (i.e., “express feeders”) extended directly to the site. This may require trenching and conduit to the nearby distribution substation and may also require upgrades to substation equipment such as transformer upgrades and additional circuit bays.

Sub-Transmission Connected

- Larger loads on the order of 20–150 MW may seek connection to the sub-transmission network (e.g., 69 kV), where available, due to the proximity to more urbanized areas fed by these circuits and access to available capacity for larger demand levels. These loads may be served by creating a new substation, transformer, and circuit to the site, as needed.

Transmission Connected

- Large loads on the order of 150+ MW are served by a dedicated substation at higher voltage levels such as 230 kV or 345 kV. So-called "megaloads" of 500 MW and above may require connection to the 500 kV backbone network. Transmission-connected large loads may require dedicated switchyards with utility service brought in to them or other unique configurations/

FIGURE 1.6. **High-Level Illustrative Examples of Grid Connection for Large Loads**

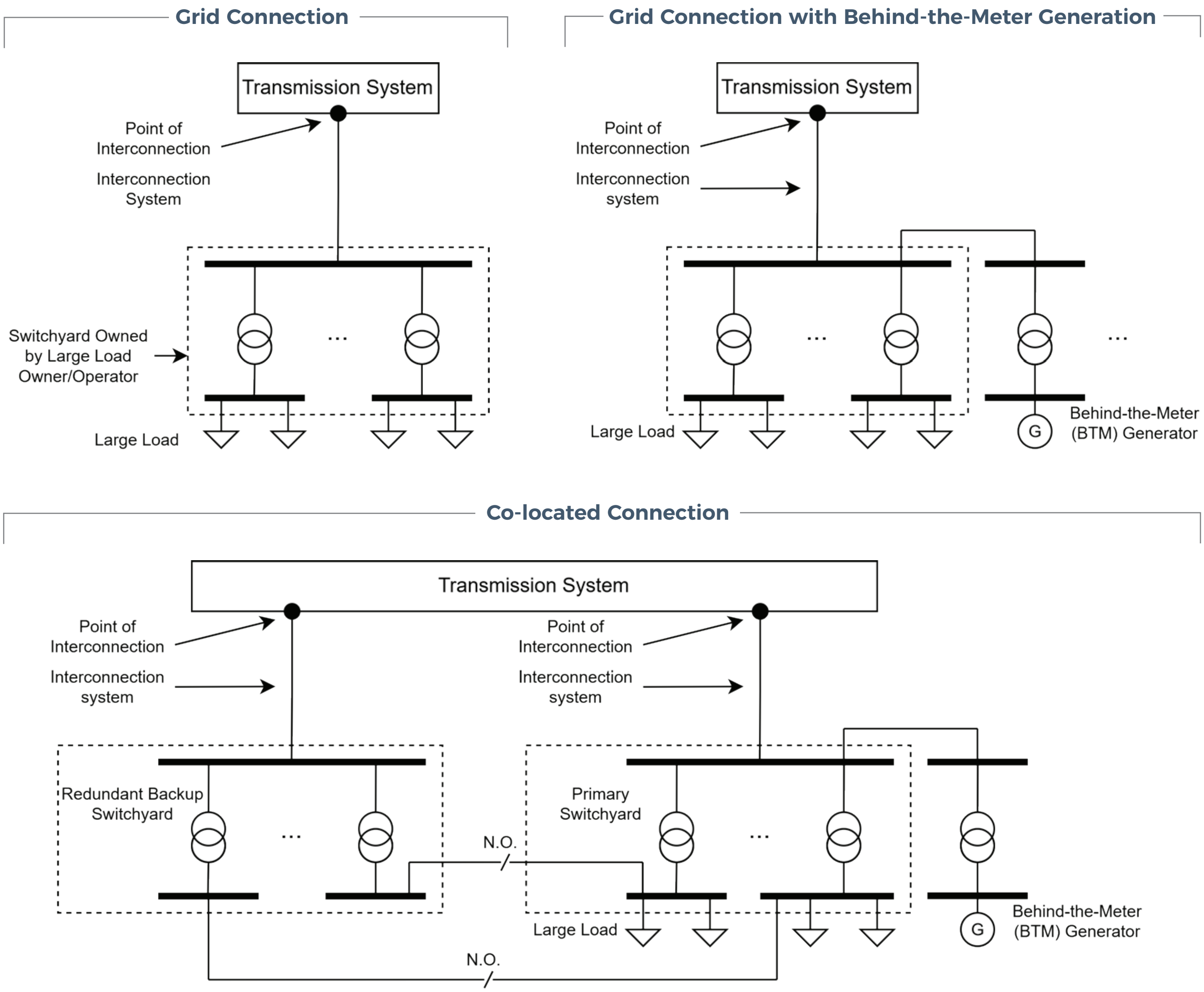


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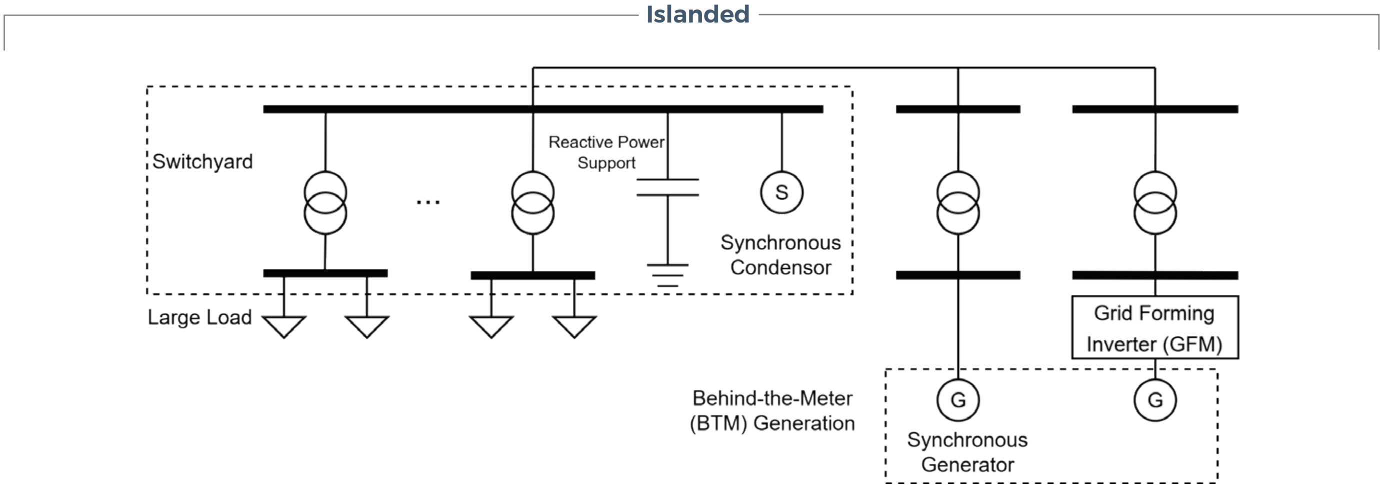
FIGURE 1.6. High-Level Illustrative Examples of Grid Connection for Large Loads (CONTINUED)



Example utility connections for large loads grid connection, grid connection with behind-the-meter (BTM) generation, co-located connection, with BTM generation and redundant backup switchyard, islanded. SOURCE: ELEVATE ENERGY CONSULTING..

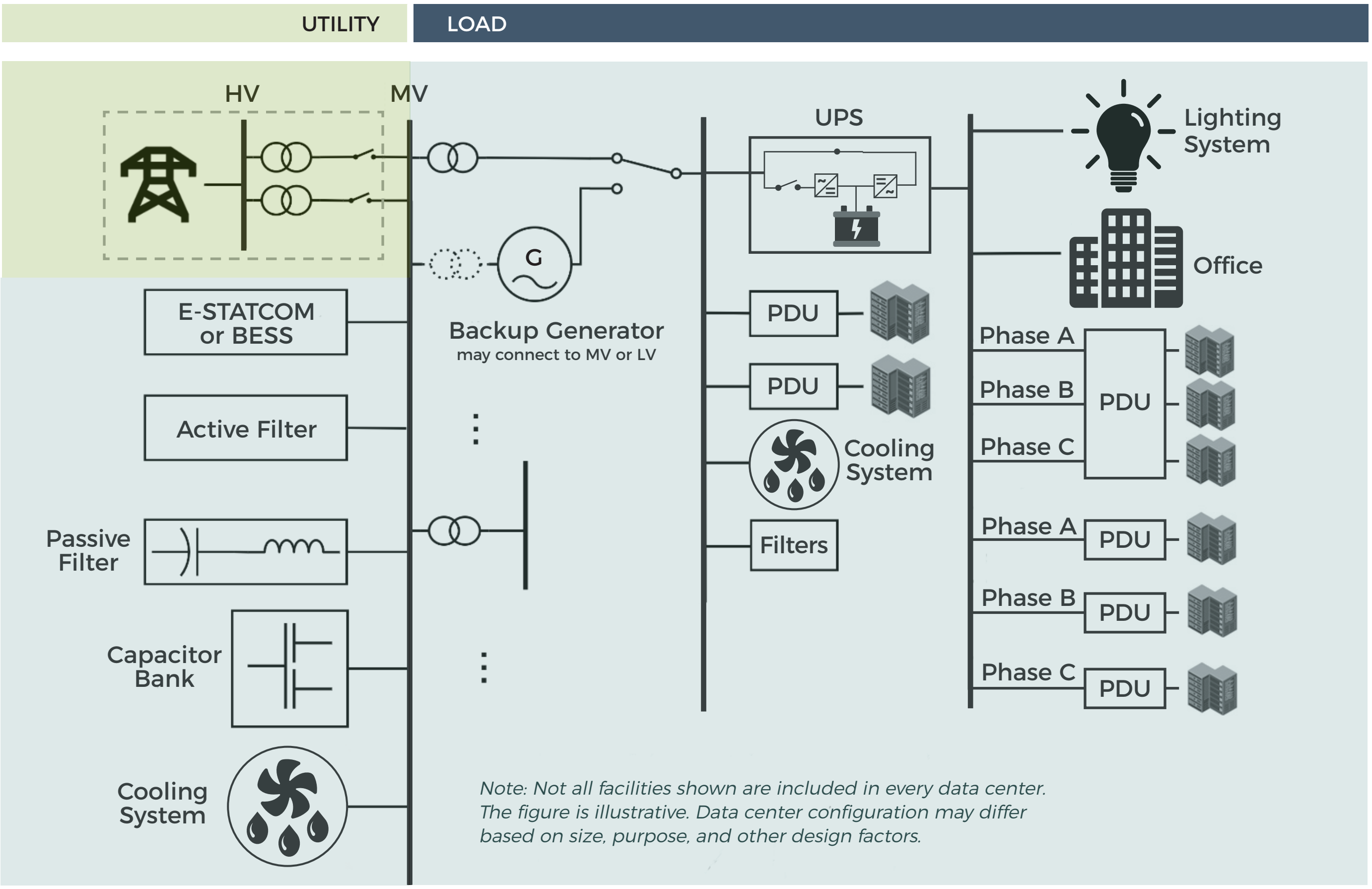
delineations due to their size. Interconnecting systems will typically be redundant or involve a looped network with multiple feeds into a large campus of loads.

As more large loads seek connection at higher voltage levels, it can be assumed that the cost of network upgrades will also increase. This is because the cost of transformers, circuit breakers, switchgears, and other interconnecting network devices increases by voltage class. In addition, larger loads may cause BPS performance violations (thermal overloads, voltage issues, instability conditions, oscillations, or other risks) that must be mitigated to reliably serve these loads.

Example Electrical Layout of a Data Center

While utility service is typically redundant to ensure reliable delivery of power to the customer, electrical infrastructure within the customer fence of a data center is also designed for reliable, continuous power delivery, with built-in redundancy and backup systems to prevent outages. Power typically enters the customer switchyard at high voltage (HV) or medium voltage (MV). The HV/MV bus, switchgear, filters, shunt reactive devices, power factor correction, dynamic reactive power devices, and other auxiliary loads may be tied to this bus. MV to low voltage (LV) transformers step the voltage level down to appropriate levels for distribution within the data center. Large cooling units are typically connected to the LV network to manage IT thermal constraints. The remaining power is distributed through a network of power distribution units (PDUs) or switched-mode power supplies that supply conditioned electricity to individual server racks and IT equipment. This power supply equipment may lie behind uninterruptible power supplies (UPS) that provide temporary backup power in the event of loss of service from the utility and help regulate voltage and frequency stability for the sensitive loads behind them. Figure 1.7 (p. 15) shows an illustrative oneline diagram of the electrical infrastructure of a data center.

FIGURE 1.7. Illustrative One-line Diagram of Data Center Electrical Infrastructure



Example utility connections for large loads grid connection, grid connection with behind-the-meter (BTM) generation, co-located connection, with BTM generation and redundant backup switchyard, islanded. SOURCE: ELEVATE ENERGY CONSULTING.

To further improve uptime and electrical reliability at the facility, data centers may incorporate backup generators, usually powered by diesel, to take over in case of a prolonged grid outage. These generators are automatically engaged through an automatic transfer switch (ATS) when utility power is lost. If present, the UPS devices allow for the servers to maintain power for a short time until the ATS can switch in the backup generation (typically diesel gensets) to continue service. The entire system is monitored and controlled through an energy management system that balances loads, detects faults, and maintains operational efficiency.

Lastly, data centers may also be coupled with co-located generation or battery energy storage systems (BESS), which could be either “behind the meter” or “in front of the meter.” Those resources may participate in wholesale electricity markets or help create a “flexible load” that provides grid services. They may also be used to condition the load in order to shield the external grid from the effects of varying processes (described in the subsequent chapter). This is an evolving aspect of large load interconnections.

2

Grid Reliability Challenges for Data Center Interconnections

While the economic and societal benefits of providing reliable electricity to large load customers are immense, electric utilities are also responsible for ensuring grid reliability at every moment of every day and minimizing risks to serving end-use customers. Establishing a clear baseline understanding of the specific and unique types of grid reliability challenges associated with large loads, particularly data centers, can help industry align with common practices. This chapter aims to educate electricity sector stakeholders about the gravity of the challenges and emphasize the need for swift action.

The Importance of a Reliable Grid

Grid reliability is not just a technical concern—it is the backbone of modern society. A single widespread outage can trigger billions of dollars in economic losses, disrupt critical industries, and erode public trust in utilities and regulators. Hospitals, emergency services, and essential infrastructure rely on uninterrupted power, meaning failures can put lives at risk. In an era of increasing cyber threats and extreme weather, grid instability also poses serious national and local security risks, making communities vulnerable to cascading failures.

Without proactive measures to minimize reliability threats, the consequences could be catastrophic—impacting everything from financial markets to public safety and national defense. Hence, the economic drivers of new large load customers must be delicately balanced with the roles and responsibilities of assuring grid reliability (see Figure 2.1, p. 17).

Challenging Attributes of Data Center Loads

Modern data center loads have unique attributes that can create challenges for conventional grid planning, design, and operations. These challenges include, but are not limited to, the following (see Figure 2.2, p. 18):

- **Size:** Recently proposed data center loads are significantly larger than historical large loads, some by an order of magnitude. And size plays a key role in defining impact to the BPS both individually and in aggregate. As the size of loads increases, technical characteristics which have been in-

FIGURE 2.1. Balancing Act of Economic Drivers of Load Development and Assuring Grid Reliability

ECONOMICS

- Significant long-term, predictable revenue streams for utilities
- Transmission expansion and development
- Enhanced infrastructure utilization
- Potential for demand flexibility
- New service models
- Tax breaks, incentives, and economic development packages
- Local jobs creation

GRID RELIABILITY

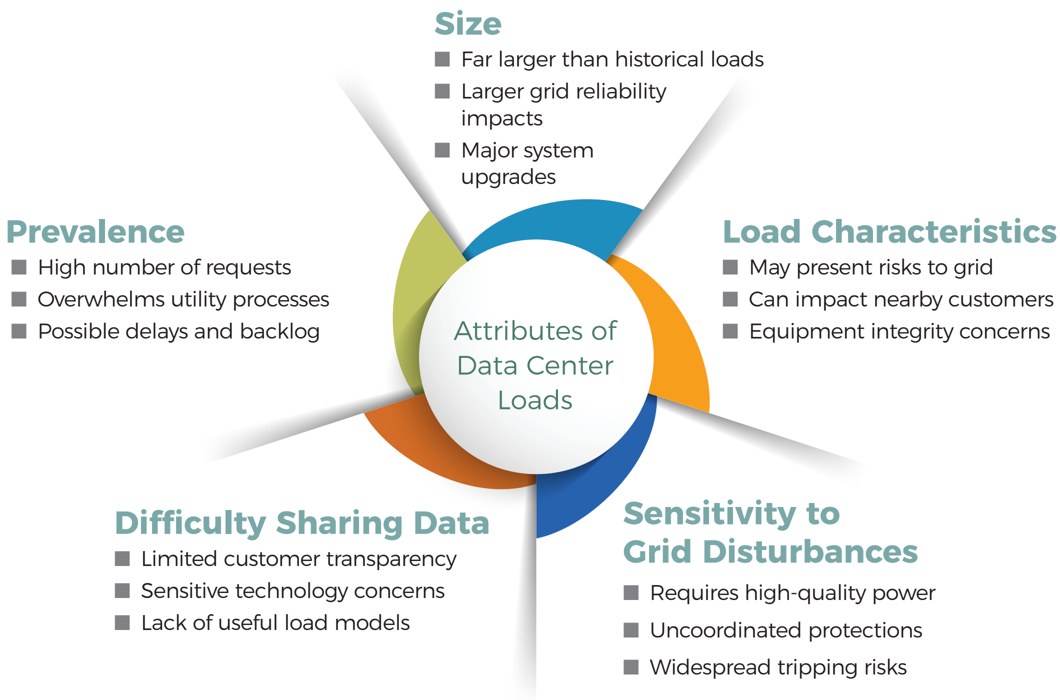
- Overloaded or congested transmission infrastructure
- Voltage and frequency stability issues
- Interconnection backlog inundation
- Regulatory risks and hurdles
- Uncertain operating characteristics
- Reliance on baseload generation to serve loads

Balancing rapid development of large loads such as data centers and grid reliability will be a focal point and notable challenge for the electricity sector in the decades ahead. SOURCE: ELEVATE ENERGY CONSULTING.

significant in the past become very important, and can fundamentally alter the existing ecosystem of generation, transmission, and load. For example, the addition of a very large load in a rural region near existing generation can trigger large high-voltage transmission expansion projects, the need to procure large voltage-supporting devices, and the design of highly complex protection schemes intended to prevent long-term damage to existing generators. Issues like these stem directly from the size of modern large loads and require fundamental reorganization of the existing power system.

- **Prevalence:** Combined with the size of each load and its potential impact on regional grids, the large number of data center requests may easily overwhelm utility interconnection processes and engineering resources. Without (and even with) overhauling existing processes and practices, the aggressive interconnection schedules desired by both customers and utilities are infeasible.
- **Difficulty in Sharing Data:** Data center customers are often unable or unwilling to share the information and data necessary for grid planners and operators to make informed decisions, even with strict confidentiality agreements in place. This is due in part to the sensitive nature of the technology being used, but also to the customer's own data gaps: They may not even know the necessary details about their site's design and performance characteristics.
- **Load Characteristics:** The varying nature of data center loads and of AI data center loads in particular can result in disruption to nearby existing loads, including residential, commercial, and industrial customers. These disruptions can range from mere annoyances (e.g., flickering lights) to severe disturbances that cause the interruption of industrial processes. In the most severe cases, unmitigated variance in output from the loads can cause damage to large substation equipment or permanent damage to BPS generators.
- **Sensitivity to Grid Disturbances:** Data center loads require very high-quality power supply from the grid and are extremely sensitive to variations in this supply. Routine disturbances in the power grid can result in disconnection of the load or take-up of the load by backup systems on site. Sudden

FIGURE 2.2. Attributes of Data Center Loads



Data center loads have unique attributes and operational characteristics that create new challenges for grid planners and operators compared with historical large loads. SOURCE: ELEVATE ENERGY CONSULTING

removal of a large load from the grid puts significant strain on the power system and introduces the risk of instability, requiring operators to maintain additional reserves and potentially dispatch generation resources with special flexible characteristics.

Grid Impact and Risks Caused by Data Center Loads

Given the factors above, operational characteristics of data centers could manifest into grid reliability risks if not properly modeled, studied, and mitigated. To be clear, data centers, like all large loads, are not an inherent risk to grid reliability. But failing to adequately plan for and mitigate the impacts of large data centers dramatically increases the potential for problems. So it is imperative that utilities analyze their operational characteristics and potential impacts to the BPS during the interconnection process.

The following subsections describe in more technical detail the operational characteristics of data centers and the types of impact they can have on the power grid.

Load Ramping, Variability, and Uncertainty

The power electronic nature of data centers allows them to ramp very quickly, which can induce swings in power consumption that affect the balance of generation and load. This can have the following effects:

2 This involves the automatic and autonomous response of generator turbine-governor or active power-frequency controls that change active power output for variations in frequency beyond small deadbands.

- **Frequency Control and Balancing Reserves:** Balancing Authorities (BAs) constantly maintain frequency within acceptable limits using the automatic response of generator primary frequency response[2] and secondary controls like automatic generation control (AGC). These measures are not designed to handle large fluctuations in demand. Rather, they are designed for random variability of smaller loads (e.g., residences, businesses, commercial buildings, and even industrial processes) that average out to "noise" on the system. Variability of large loads on the order of 500 to 1,000+ MW have a notable impact on the ability of BAs to maintain tie line flows and frequency within limits, which requires BAs to carry more balancing reserves.
- **Difficulty in Dynamic Voltage Control:** Large variations in load are accompanied by large changes in power flowing through transmission corridors, which in turn causes fluctuating demand for reactive power used to hold voltages within normal levels throughout the system. Just as the existing system is designed to accommodate small random variations in active power but not large variations, it is also generally not designed to accommodate large random variations in reactive power. Depending on the variation of the load, additional large voltage-controlling devices may be required throughout the transmission system to ensure operators are able to control voltage during real-time operations.
- **Synchronous Generation Strain:** Fast ramping of loads may cause frequency variations beyond generator control deadbands[3] which could strain and adversely affect the lifespan of synchronous generator turbines. Inverter-based resources (IBRs) like wind and solar plants may need to provide more frequency control, which could require procuring more fast-acting reserves. Grid operators may need to increase regulation of reserves to manage these spikes.
- **Restoration:** Utilities must manage large ramps during system restoration following severe outages or emergency conditions. Establishing ramp rate limits on large loads could help smooth system operations.

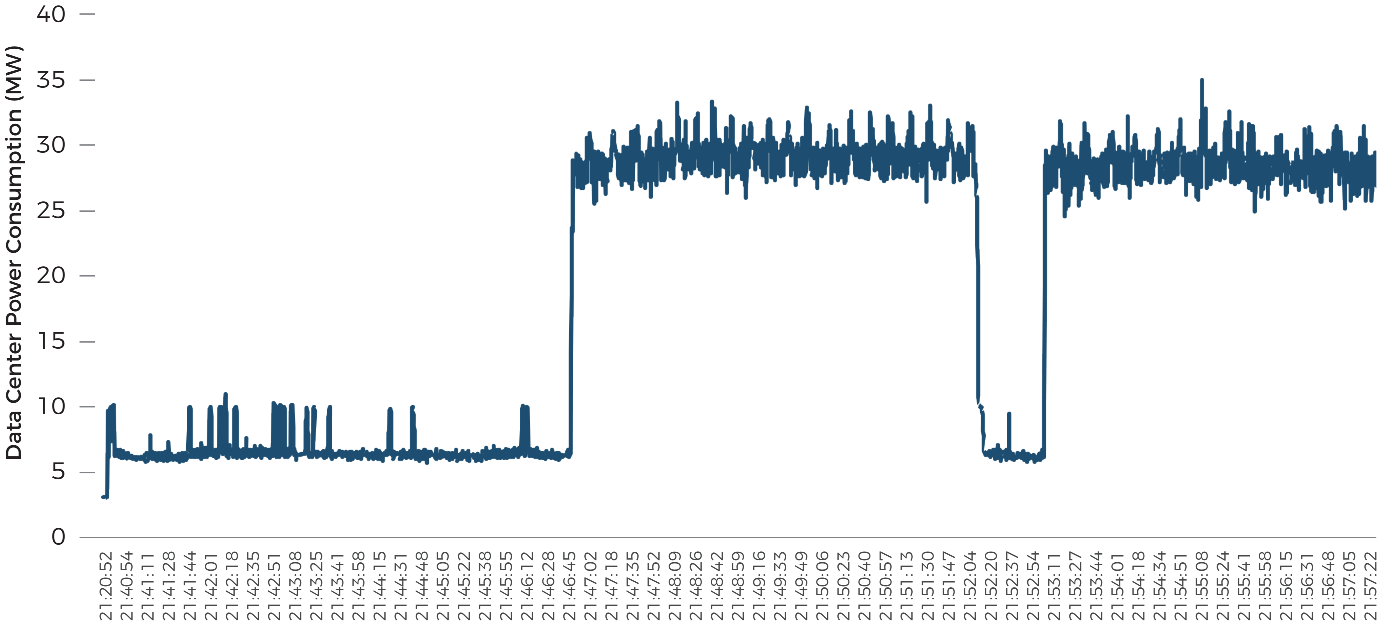
Note that not all data centers exhibit significant ramping, variability, and uncertainty; some may be relatively constant loads with high load factor (i.e., rarely offline). This depends on the digital services provided by the data center and on the design of the facility. However, even in designs with high load factor and low variability, the sheer size of these loads can present problems during more infrequent events such as when the site comes offline or back online, requiring mitigations discussed above.

Load Cycling and Oscillation Risks

Related to their capacity for short-term load ramping, data centers may cycle through multiple periods of higher and lower demand over time. AI workloads such as deep learning training and inference involve significant yet intermittent computational power. Graphics processing units (GPUs) and accelerator-based workloads often process data in batches, causing rapid swings in power consumption as different job phases execute. AI models leverage parallelized computations across

3 Deadbands are small margins around nominal 60 Hz frequency to avoid constant action of controls, which is particularly important for wear and tear on electromechanical systems.

FIGURE 2.3. AI Training Power Consumption Example



New and challenging load consumption patterns have been observed particularly for AI data centers, which can pose potential grid stability and reliability risks and thus must be effectively modeled, studied, and mitigated.. SOURCE: EDGETUNEPOWER, INC.

thousands of GPUs, tensor processing units (TPU), and central processing units (CPU).[4] These units often synchronize at certain steps, leading to periodic spikes and dips in power demand. Large-scale AI training involves massive and possibly cyclical or quasi-periodic surges in computational power demands. These effects may multiply if they are synchronized across data center locations.

Observations of power consumption of data center load have shown how unconventional they are compared with historical end-use loads, with activity like AI training runs leading to extremely intermittent power consumption. Figure 2.3 shows an example of a 50 MW data center block (the entire facility has four points of connection totaling 200 MW). Active power consumption captured with a microprocessor-based relay high speed data recorder shows power consumption jump from 6 MW to 30 MW in a matter of 290 ms (about one-quarter of a second). Power consumption is then highly variable for about 5 mins, with numerous 5+ MW spikes. Then it drops briefly to low power consumption levels before returning to high power consumption. Note that this facility is not interfaced with the grid though a UPS, so the power consumption is observed directly on the grid side of the customer interface.

These fluctuations could present risks to the interconnected BPS and its natural modes of oscillation (with frequency and oscillatory characteristics that affect the entire system).[5] If demand from data centers (particularly AI data centers) exhibit oscillatory behavior at frequencies in the range of natural power system modes (typically 0.1–0.4 Hz or so), the system could experience poorly damped oscillations on a wide scale that could lead to system instability. For example, an event

4 Data centers may use a combination of these types of processing units to optimize performance and efficiency.

5 Similar in nature to the infamous Tacoma Narrows Bridge collapse in 1940 where wind-induced oscillations at or near the resonant frequency of the bridge cause amplifying movements until it eventually catastrophically collapsed.

in 2019 involving a malfunction at a synchronous generator site in Florida caused amplified power oscillations across the entire Eastern Interconnection up to Minnesota and into New England [6].

Load Ride-Through Performance

Inadvertent disconnection of large end-use loads, particularly when aggregated across multiple locations, can pose a serious threat to grid reliability. Data centers may be prone to disconnection during grid events if not coordinated with utility protection system designs (e.g., fault duration, number of reclosing attempts). This is due to the sensitivity of power electronic server loads, strict requirements of digital uptime, and the availability of on-site backup generation. Yet faults and other grid events are inevitable, and they occur daily due to a variety of natural and manmade causes. As mentioned earlier, a large data center disconnection event in Northern Virginia in 2024 raised serious concerns among utilities and regulators. These types of behaviors are not adequately modeled today or included in grid reliability studies, given current industry practices, which could create blind spots for grid operators that could exacerbate emergency operating conditions during grid events.

Data Center Load Dynamic Performance

The dynamic performance of end-use loads depends on the composition and control systems of the facility and can significantly influence local and regional grid stability, particularly for large-scale installations. Data center loads typically consist of power electronic equipment, cooling systems, and supporting power infrastructure. The power electronics include servers, storage systems, and networking equipment that handle digital data processing. Cooling systems manage the substantial heat produced by this equipment and may include computer room air conditioners and handlers, liquid cooling systems for high-density AI workloads, and water-based pumps and fans. The power infrastructure includes UPS systems, power distribution units (PDUs),[6] power converters, backup systems, BESS, generators, and other electrical equipment. Most of the end-use loads are interfaced with the grid through UPS systems, which significantly influence the facility's electrical behavior. Collectively, these components determine the facility's dynamic response and can impact grid stability depending on the facility's size and integration characteristics.

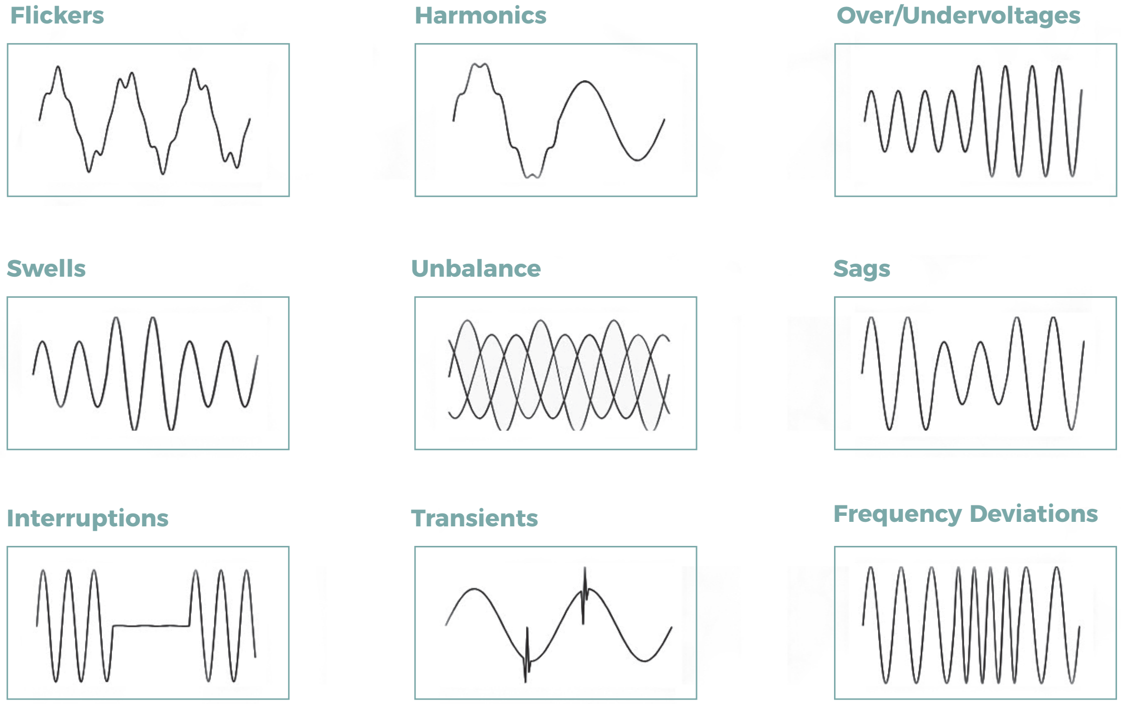
Power Quality and Harmonic Emissions Concerns

All power system components may introduce potential power quality issues that must be studied, monitored, and addressed. These issues can range from voltage sags and swells to harmonics, frequency variations, flicker, transient surges, power factor correction, electromagnetic compatibility, and more. Utilities normally evaluate and mitigate these concerns using a suite of measurement devices and specialized studies. Some of these studies require significant amounts of carefully specified data to correctly analyze and mitigate concerns.

Harmonic emissions from data centers stem primarily from the nonlinear nature of components at the site. UPS systems, switched mode power supplies, and variable frequency drive (VFD)-driven cooling loads are often the main culprits, because of the rectifiers they use for power conversion.

6 PDUs convert higher voltage power to voltages suitable for power electronic IT equipment (e.g., 480V or 208V).

FIGURE 2.4. Types of Power Quality Issues



SOURCE: ELEVATE ENERGY CONSULTING. ADAPTED FROM FS, INC. (WWW.FS.COM).

Utilities have applied stringent power quality requirements (e.g., IEEE 519) to large loads for many years [7]. Customers may need to install harmonic filters, higher performance equipment with lower harmonic distortion, and power factor corrections to meet these requirements and mitigate problems.

Subsynchronous Oscillation Risks

Subsynchronous oscillations (SSO) are a family of oscillation phenomena that have been studied for many decades. These oscillations have multiple contributing factors including series resonances in the external grid, resonant mechanical modes in synchronous generator shaft systems, and damping characteristics of power electronic converters. There are several types of SSO that are of concern with data center loads, including:

- The load cycling and oscillatory behavior driven by digital processing described previously. If the fluctuations are large enough and their frequency overlaps with critical generator shaft mode frequencies for nearby generators, the generators can be permanently damaged.
- Subsynchronous torsional interaction (SSTI) where load rectifier controls are negatively damped at frequencies overlapping with generator torsional frequencies.
- Subsynchronous control interactions (SSCI), which are similar to SSTI except that the instability results from overall negative system damping overlapping resonance points in the network due to series compensated transmission lines. This is of large concern for IBR generation systems, but the extent of the risk for data center controls will depend on the specific nature of the load.

All forms of SSO require highly detailed data and sophisticated modeling to analyze and mitigate. Components of load which interface with the system via power electronics are of particular interest, but the relevant details of these elements are not easily available to date. In regions where synchronous machines are present, a significant amount of detailed design data is required from the machine manufacturers, and this data is often difficult to obtain.

As data center interconnections grow in both size and number, the need for conducting these studies—particularly in areas with synchronous generators and series-compensated lines—may grow as well. Utilities and customers can resolve issues with SSO with careful tuning, damping devices, filters, special protection schemes, energy storage, and other mechanisms.

Protection System Impacts

Data centers are unlikely to contribute significant amounts of fault current to the system, primarily because most of the facility load is electronic. The IT equipment is almost entirely power electronic, and the cooling loads are driven by VFDs that decouple the motor from the grid, have current-limiting features, and/or reduce output during faults.

Nonetheless, rapid load variability, harmonics, and grid-paralleled on-site generation could cause issues with utility protection systems. So utilities must study how connecting a new large load would affect these protection systems, especially with any grid-paralleled onsite generation and any fault current that could be contributed by the large load facility. Protection studies will show whether utilities can properly detect and clear faults within their standards, as well as whether they need to modify an existing protection system to align with features of the large load facility. The impact and cost of these modifications may vary depending on the type of protection system (distance relaying, current differential, communication-assisted schemes, etc.).

3

Challenges With the Large Load Interconnection Process

Utilities may find themselves torn between the economic opportunity of quickly connecting large loads and the obligation to thoroughly assess the impact those loads will have on the reliability and cost of electricity across the grid. As the size and breadth of large load interconnections grows, and the economic pressure of quickly connecting these loads to the system rises, it becomes critically important for customers and utilities to conduct the engineering studies, assessments, and analyses necessary to maintain reliable operation of the grid.

Currently, a lack of standardized interconnection processes for large loads may be weakening the ability of the utility to effectively meet those obligations. This chapter summarizes some of the limitations of historical large load interconnection processes, possible areas of opportunity and improvement, and how utilities can improve interconnection processes to better assess potential grid reliability risks.

Issues with Rate Design and Customer Equity

Regulated electric utilities are responsible for delivering reliable, secure, and safe electricity to customers in a just and affordable manner. State utility regulatory agencies approve retail electricity rates and tariffs to ensure utilities can meet electricity demand, maintain affordability, support economic development by attracting new loads, and align with state energy policies. In the context of large load interconnections, several areas of rate design warrant particular attention [8]:

- **Cost allocation** for network upgrades associated with large load interconnections, and the possibility of shifting costs onto existing ratepayers.
- **Minimizing stranded asset risk** from underutilized transmission or generation infrastructure if forecasted demand levels fail to materialize.
- **Resource adequacy and energy assurance** challenges stemming from challenges building new generation and transmission fast enough to meet these demands.
- **Grid reliability risks** associated with the volatile and uncertain characteristics of newer large loads such as rapid voltage and frequency fluctuations or impacts on power quality.

- **Deployment of emerging technologies** including grid enhancing technologies (GETs), small modular reactors, and long-duration energy storage, while managing financial and societal risks.
- **Balancing state policy objectives** such as decarbonization and economic development with grid reliability limitations amid rapid changes in generation mix and consumption behaviors.

Tariff designs must clearly define eligibility based on customer demand characteristics, establish contract terms that provide sufficient certainty for utility infrastructure investments, and implement rate structures that reflect the true cost of service while incentivizing reliable and beneficial consumption behaviors.

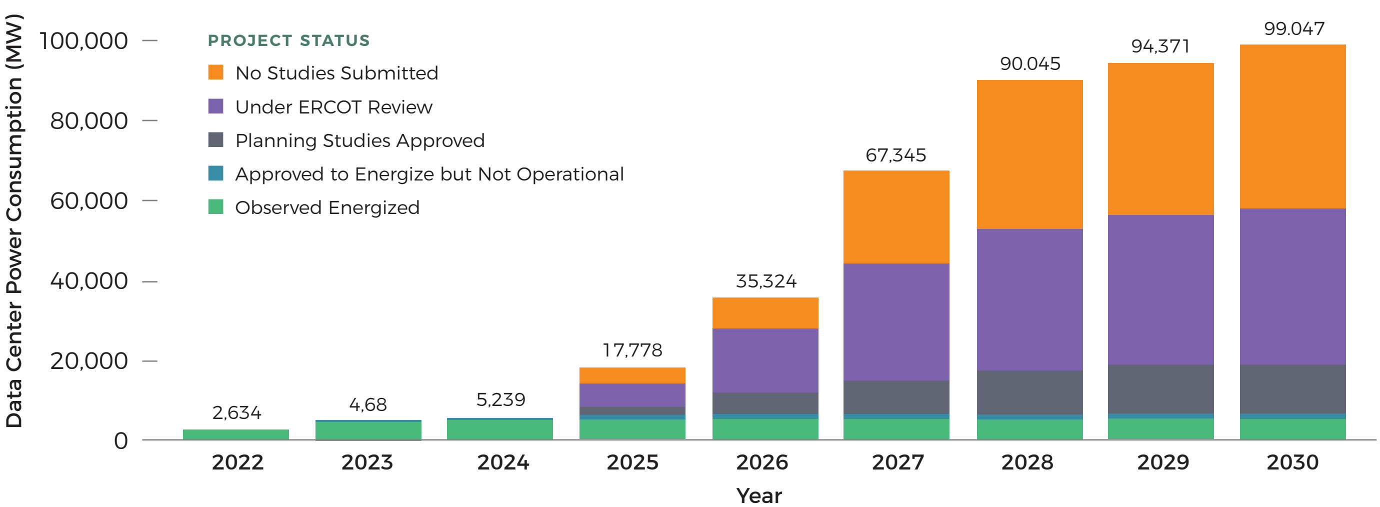
> **In this environment, utilities and system operators have to wonder: "Which large load applications are real?" Introducing a standardized and transparent load-side interconnection process can help minimize speculative load application behavior and provide clarity for both utilities and developers**

Problems with Speculative Interconnection Requests

The electricity sector is experiencing a surge in speculative interconnection requests for data centers, stemming from a fragmented and opaque load interconnection process. Currently, there is often no formal or transparent load interconnection queue, and the barriers to entry in terms of time, technicality, and financial commitment are quite low. This environment encourages developers to submit multiple requests for potential projects, seeking out least-cost connection locations and leading to inflated demand projections and inefficiencies.

For example, Figure 3.1 shows how the ERCOT large load interconnection queue balloons from 2025 to 2030. Most projects in this queue have no studies submitted to ERCOT or currently under review, and only a small fraction have completed studies approved or approval to energize.

FIGURE 3.1. ERCOT Large Load Interconnection Queue



The large load interconnection queue has ballooned in ERCOT and is expected to continue; however, many of the proposed interconnection applications have not had reliability studies submitted or those studies are under ERCOT review. SOURCE: ERCOT.

In this environment, utilities and system operators have to wonder: "Which large load applications are real?" Introducing a standardized and transparent load-side interconnection process can help minimize speculative load application behavior and provide clarity for both utilities and developers [9], [10].

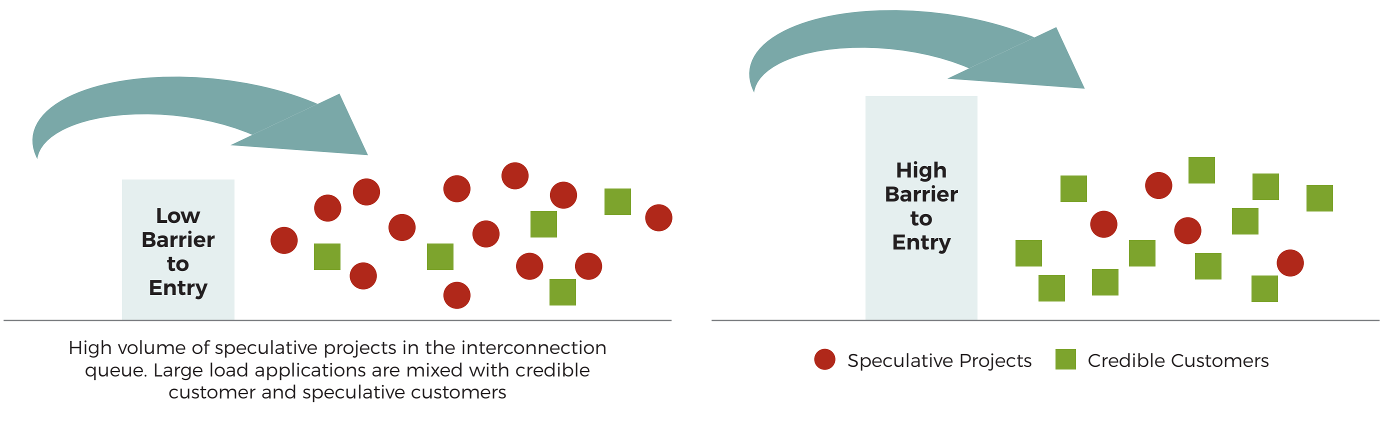
Little to No Barrier to Entry

The prevalence of speculative load interconnection applications makes it increasingly difficult to distinguish credible customers from those submitting speculative requests. This issue arises due to a combination of factors that reduce the barriers to entry for prospective applicants, effectively allowing them to engage with the utility without significant consequences. In many cases, large load interconnection applicants face minimal or no financial commitments, lack site control, have limited financial credibility, submit redundant or duplicative applications, or are technologically unprepared. Some regions even allow applicants to enter the queue with little to no "readiness" indicators—a simple phone call or email may be enough to initiate the utility's analysis. Refundable application fees, low or no study costs, and the absence of strict site control requirements further lower the threshold for participation.

While such ease of access may have worked when most applicants were established commercial and industrial customers, today's landscape is different. Growing demand from multiple industries has led to a surge in speculative applications, with many entities seeking to secure a queue position "just in case." Without stronger readiness requirements, these speculative projects can overwhelm the interconnection process, delaying legitimate projects and creating inefficiencies across the system. Figure 3.2 illustrates how a low barrier to entry results in a high volume of applications dominated by speculative projects, leading to significant downstream consequences.

FIGURE 3.2. Illustration of Speculative Interconnection Projects with a Low Barrier to Entry

THE BARRIERS: Financial Commitments; Site Control; Financial Credibility; Unique Applications; Technical Requirements Met



Raising the barrier to entry for new large load interconnection requests can help weed out more of the speculative requests, leaving more certainty and likelihood of interconnection success. SOURCE: ELEVATE ENERGY CONSULTING.

An Opaque Large Load Interconnection Process

In most cases, the large load interconnection process is bespoke and varies across utilities and jurisdictions. Large load policies and procedures are subject to a broad and changing set of stakeholders, which prevents standardized application requirements, study assumptions, and cost allocation.

This opaque load interconnection process creates significant challenges for both utilities and large load customers. Applicants struggle to understand interconnection timelines, costs, and technical requirements—another reason many applications may be speculative in nature. Utilities must process redundant or unviable requests, diverting resources from legitimate projects and slowing down the queue. Additionally, uncertainty around available capacity and project feasibility can lead to misinformed investment decisions, increasing financial risk for developers and utilities alike.

Without a clear and structured interconnection framework, utilities risk bottlenecking grid expansion efforts, delaying critical infrastructure, and ultimately hindering economic growth

The absence of a formal, transparent queue exacerbates these issues, as moving up or down the list of loads being studied can seem arbitrary or be influenced by factors like a project's economic development priority for the utility or state. This unpredictability discourages collaboration, erodes stakeholder trust, and may lead to disputes or regulatory intervention. Furthermore, a non-transparent process makes it difficult for policymakers and regulators to assess system constraints and plan for future infrastructure needs. Without a clear and structured interconnection framework, utilities risk bottlenecking grid expansion efforts, delaying critical infrastructure, and ultimately hindering economic growth [10].

PHOTO: ISTOCKPHOTO/GERVILLE

Minimal or Nonexistent Technical Requirements for Large Loads

Traditional load interconnection processes have been built around a "load-serving" philosophy, where utilities are expected to meet customer demand without imposing stringent technical requirements. As a result, large load customers are rarely required to provide detailed performance specifications before interconnection.

To properly assess and mitigate potential reliability risks, utilities need critical data, including ride-through capabilities, power quality characteristics, load composition, time-varying behavior, and comprehensive system models. Without this information, utilities face major blind spots in planning and reliability assessments.

The absence of standardized technical requirements has far-reaching consequences. Utilities must dedicate significant time and resources to identifying and obtaining missing data from applicants. Without clear performance standards, latent reliability risks can arise, potentially requiring costly network upgrades that may be passed on to existing ratepayers. At worst, inadequate interconnection practices could result in voltage instability, equipment damage, or even safety hazards for utility personnel and the public. Establishing structured technical requirements is essential to ensuring grid reliability and mitigating these risks.

Inadequate Large Load Interconnection Studies

The NERC FAC-002-4 Reliability Standard establishes requirements for each Transmission Planner and each Planning Coordinator to study the reliability impacts of interconnecting new electricity end-user facilities. These studies assess the reliability impact of the new interconnection on affected systems; assure the end user's adherence to the NERC Reliability Standards, TO planning criteria, and facility interconnection requirements; and must include steady-state, short-circuit, and dynamics studies, as necessary.

Although the NERC standard requires studies, there are no established standard industry practices in this area, leaving utilities to set them on a case-by-case basis. While some utility judgment is typically acceptable, too much leeway can lead to biases and disparities between specific projects or customers, and unclear and potentially unjust interconnection processes for customers. Case-by-case judgment is also prone to error, because individual engineers are tasked with filtering industry data and creating their own practices rather than relying on a consensus of informed industry experts. Further, lack of standardized studies can also lead to missed reliability risks before interconnection and potential grid instability, damage to electrical equipment, and public safety risks down the line. These systemic risks and the need for standards to address them are precisely why the energy sector has reliability organizations like NERC.

Lastly, because of the low barrier to entry and high volume of speculative interconnection requests, utilities may be too overwhelmed to conduct detailed studies for all applications. Moving toward a cluster study-based approach, similar to the generator interconnection queue reforms, could alleviate the serial challenges in the interconnection queue [11].

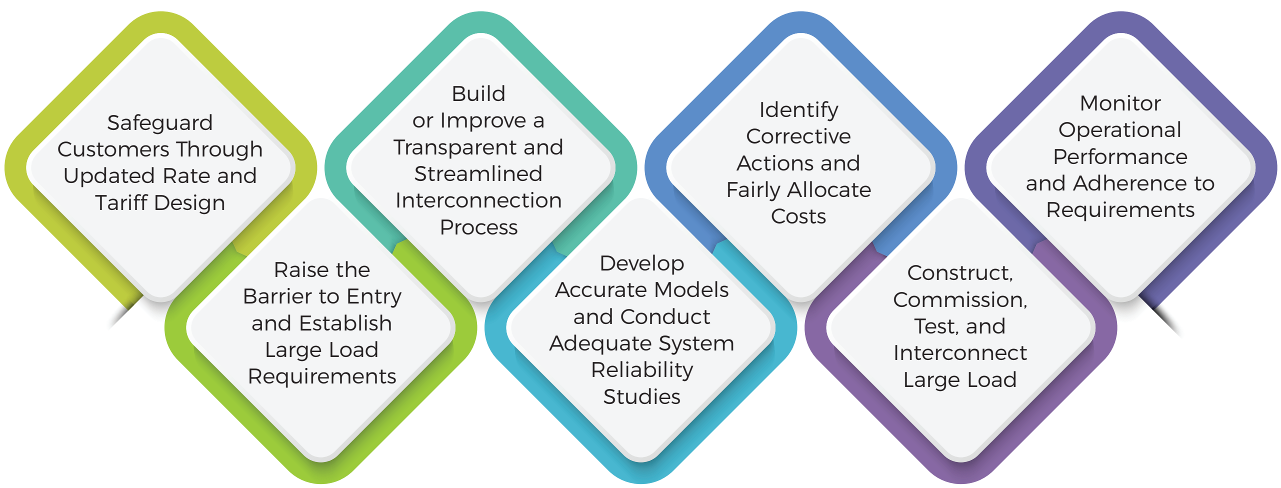
4

Process Improvements for Large Load Interconnections

The rapid growth of large loads seeking connection to the BPS—mostly driven by data centers and AI loads—is reshaping utility interconnection processes. While large load customers bring economic opportunity, they also introduce significant planning, operational, and financial challenges that utilities must navigate. If not carefully managed, large loads can strain grid reliability, create cost shifts that unfairly burden existing ratepayers, and disrupt long-term system planning.

To balance these risks with the potential benefits, utilities must modernize their approach to large load integration—ensuring fair cost allocation, clear interconnection requirements, and robust reliability protections. By proactively addressing these challenges, utilities can safeguard system stability, create a more predictable and efficient interconnection process, and foster a regulatory environment that supports both customer growth and grid resilience. This chapter covers some of the areas for large load interconnection improvement, as illustrated in Figure 4.1.

FIGURE 4.1. Key Components to Large Load Interconnection Process Improvements



While different transmission providers may have varying large load interconnection processes, there are some rather consistent key components of an effective process described in this report. SOURCE: ELEVATE ENERGY CONSULTING.

BOX 2

Safeguard Existing Customers during Large Load Growth

To protect existing ratepayers during such volatile conditions, utilities and regulators can consider implementing safeguards when designing tariffs for large load customers. These may include [12], [8]:

FINANCIAL SAFEGUARDS

Customer-Paid Interconnection and Grid Upgrade Costs: Large load customers should pay the full cost of transmission and distribution system upgrades associated with the direct connection of the load to the utility system.

Fair Allocation of Network Upgrade Costs: Large load customers should pay an equitable portion of any broader system network upgrades needed to reliably connect the large load (e.g., new transmission infrastructure to address overloads). The cost allocation methodology should be carefully reviewed to protect existing ratepayers from subsidizing infrastructure upgrades that benefit a subset of customers.

Financial Guarantees and Collateral Requirements: Utilities can require high security deposits or collateral to prevent applicants from defaulting and protect ratepayers from stranded costs.

Contractual Commitments and Exit Penalties: Utilities can require long-term contracts (e.g., 15-20 years) for large load customers with notable and enforceable exit penalties to help ensure utilities can recover infrastructure investment costs and avoid stranded assets.

DEMAND CHARGE SAFEGUARDS

Minimum Demand Charges: Utilities can require large load customers to contribute to fixed costs (i.e., fixed level of demand), even during periods of usage below this level.

Demand Ratchets: Utilities can bill demand on a percentage of the highest recorded demand over a specified period, ensuring stable cost recovery (e.g., 50-80% demand ratchet based on the highest demand in the past 3 to 6 months).

Minimum Load Factor Requirements: Large load customers must maintain a baseline level of demand or load factor to help avoid network underutilization and associated costs.

GRID RELIABILITY AND OPERATIONAL SAFEGUARDS

Resource Adequacy Contributions: Large load customers may be required to provide some degree of resource adequacy contributions or be subject to higher demand charges or capacity fees. Some customers may be able to lower rates or receive credits, such as those who participate in demand response, have self-generation or storage capabilities, or can reduce demand during peak operating conditions.

Demand Response and Curtailment Options: Utilities can require large load customers to reduce net consumption during peak periods or grid emergencies (e.g., through curtailing demand or on-site generation).

ENVIRONMENTAL AND SUSTAINABILITY REQUIREMENTS

Renewable Energy Procurement: Large load customers may be required by state policies to purchase new electricity from clean energy resources rather than contractually consume energy from existing zero-carbon resources intended for existing customers.

The safeguards described in Box 2 (p. 30) are intended to balance the economic benefits of large load customers with the need to protect existing ratepayers from financial risks and to support the utility in terms of operational reliability obligations. Regulators and utilities must carefully structure tariffs to ensure large customers contribute fairly to system costs while maintaining grid reliability and affordability.

ADDITIONAL CONSIDERATIONS AND SAFEGUARDS

Table 4.1 outlines some additional non-market considerations and safeguards that utilities could consider to ensure fairness, prevent cost shifting to existing ratepayers, and maintain grid reliability when large load customers make financial arrangements outside traditional utility tariffs.

TABLE 4.1. Additional Considerations and Safeguards for Large Loads

Topic	Consideration	Safeguard
Power Purchase Agreements (PPAs)	Some large-load customers enter PPAs that allow them to procure power directly from generators at wholesale prices while still relying on the grid for backup power or peak needs.	Regulators should ensure that customers with PPAs contribute appropriately to transmission and reliability costs if they intermittently use power outside their established PPA. Ensure standby service rates and grid access fees reflect the true cost of reliability support for large loads that rely on the transmission system.
Market Participation Risks	If large loads have access to behind-the-meter generation, they may manipulate market pricing to their advantage.	Regulators should monitor market manipulation (e.g., demand reduction in exchange for market payments) and ensure compliance with grid reliability obligations.
Economic Development Riders (EDRs)	Large loads consume vast amounts of energy, increasing utility and local tax revenues yet provide mixed levels of employment opportunities or other benefits and may foreclose the possibility of service other loads.	Tie rider benefits to clear and measurable contributions beyond energy consumption and revenues such as investments back into the community, local hiring, or grid support services.
Contract Transparency and Regulatory Oversight	Private PPAs, bilateral contracts, and EDRs often occur outside traditional utility ratemaking processes, limiting transparency.	Regulators should require disclosure and approval of key contract terms and revisions thereof.

SOURCE: ELEVATE ENERGY CONSULTING.

EMERGING CONSIDERATIONS FOR RATEPAYER SAFEGUARDS

Load-serving entities, regulatory commissions, grid operators, and other stakeholders must consider how adding new large loads can affect rates and service for other ratepayers. For example:

- Can existing resources be used to reliably serve these loads?
  - If existing resources (e.g., merchant generators or renewable projects under virtual PPAs)[7] are brought under a load serving entity's control for the purpose of serving large loads, what are the resource adequacy impacts of doing so?

7 A virtual PPA (VPPA) contract is typically between a new renewable generator and a new large load. The new large load does not own and is not responsible for the physical electrons generated by the generator. Instead, the VPPA allows the new large load to acquire RECs while continuing to consume energy from its utility [39].

- What impacts will large loads have on fuel, congestion, and ancillary services costs?
  - Oftentimes these charges are passed through in rates via fuel adjustment clauses that are allocated to all retail customers. Should that allocation change with large loads?
  - How should those costs be assigned if they are not explicitly priced (e.g., as in an organized energy market)?

Raise the Barrier to Entry and Establish Interconnection Requirements

Utilities can limit the interconnection queue to creditable customers with viable projects by bolstering application requirements with measures such as:

- **Higher Financial Commitments:**
  - Significantly higher non-refundable application fees and deposits, sometimes based on $/MW demand capacity.
  - Higher study fees to allow utilities to hire adequate staff to perform increasingly complex studies.
  - Milestone-based payment schedules.
  - Pre-payment for network upgrades.
  - Long-term electric service contracts.
  - Higher minimum demand charges of their contract capacity.
  - Withdrawal penalties.
- **Site Control:**
  - Signed purchase agreement, long-term lease, or option contract (with substantial commitment) with property owner(s).
  - Proof of zoning compatibility.
  - Conditional use permits, in some cases.
  - Local governmental approval or conditional approval.
  - Air quality, water use, stormwater, and wetland permits.
- **Financial Credibility:**
  - Demonstration of customer financial strength, such as credit rating.
  - Audited financial statements.
- **Avoiding Duplicative Requests:**
  - Agreements between third-party developers and end-use customers.
  - Contract, letter of intent, or binding agreement between developers and end-use customers.
  - Disallowing multiple interconnection requests from a single entity (or parent entity) for the same site or project, unless there is a technically justified need.
  - Restrictions on queue position transfer.

Technical Requirements (see Chapter 5 for more details)

- Site plans and electric designs such as oneline diagrams, transformer and substation specifications, and protection and control designs.
- Settings and equipment capabilities for UPS, on-site generation, and other devices.
- Detailed expectations for system performance and power system-facing behavior and dynamic characteristics, which may include modeling in some cases.
- Equipment procurement timelines or proof of orders.
- Signed agreements with engineering, procurement, and construction contractors.

Measures like these can help utilities reduce backlogs in the queue and avoid wasting resources on nonviable applications. For further help, Appendix A of this report provides a list of questions that utilities can ask during the interconnection process and information they should expect large load applicants to provide.

To be effective, these measures need to be enforced. For example, applicants who fail to meet the technical requirements, site control, payment schedules, or other milestones should risk losing their queue position or being removed from the queue entirely. This can help shift utility resources and attention to more serious, committed customers.

Build or Improve a Transparent and Streamlined Load Interconnection Process

A well-defined and transparent interconnection process is essential to ensuring that all large load customers are treated fairly while maintaining grid reliability and efficiency. Establishing clear procedures not only improves consistency for how requests are handled but also expedites processing, reducing uncertainty for both utilities and customers.

A well-defined and transparent interconnection process is essential to ensuring that all large load customers are treated fairly while maintaining grid reliability and efficiency. Establishing clear procedures not only improves consistency for how requests are handled but also expedites processing, reducing uncertainty for both utilities and customers.

Currently, utility approaches to large load interconnection vary widely. Some utilities lack a formal process altogether, addressing large load requests on an ad hoc basis, which can lead to inconsistent decision-making and delays [13]. Others have queue-based processes, but a lack of transparency leaves customers uncertain about their position in the queue or expected timelines. Implementing established milestones and clear timelines—covering application processing, system impact studies, upgrade determinations, and interconnection agreements—creates predictability for all stakeholders and fosters a more effective planning environment.

As mentioned above, one key improvement is the adoption of a cluster study approach, similar to the generator interconnection process reforms seen in Federal Energy Regulatory Commission

FIGURE 4.2. Milestones of a Large Load Interconnection Process

MILESTONE 1
Pre-Application Phase
Large load customers engage with utilities early in the process to discuss their tentative plans for load interconnection, including project details, siting, and other plans. Utilities can share their expectations for interconnection timelines, requirements, processes, and more. This allows both parties to gain a mutual understanding and align on expectations between the utility/independent system operator (ISO) and the customer.

MILESTONE 2
Interconnection Application
The large load customer submits a formal interconnection application with details about demand size, location, technical aspects (design, diagrams, models, etc.), and load ramp-up, accompanied by financial deposits.

MILESTONE 3
Initial Screening and Feasibility Study
The utility may conduct high-level viability assessments for the proposed large load interconnection, focused on items such as the voltage level required for interconnection, access to nearby transmission infrastructure, potential direct-connect network impacts, the need for broader network upgrades, and known obstacles or issues.

MILESTONE 4
Large Load System Impact Study
The utility will perform detailed reliability studies (see Section 7) to quantify the effects the large load has on the transmission and distribution system (if applicable). The studies will analyze the impacts on thermal overloading, system voltages, stability, and other reliability factors. They will also determine the necessary system upgrades needed to alleviate any system performance issues identified.

MILESTONE 5
Large Load Facilities Study
The utility performs a study focused on the detailed engineering designs, substation configuration, protection system upgrades, and other cost estimates required for direct-connect infrastructure modifications. This information is an input into the construction phase of the project.

MILESTONE 6
Signed Interconnection Agreement
The utility/ISO and customer should sign an agreement to formalize the terms and conditions for interconnection. Both parties will draft and negotiate the terms, outlining roles and responsibilities, cost responsibility, schedule, and operational performance expectations, as well as ensuring compliance with regulatory requirements and other industry standards.

MILESTONE 7
Construction and Commissioning
The large load customer constructs the facility itself. Depending on their agreement, the utility and/or customer may construct the electrical facilities required to connect the load. The utility also constructs any broader network upgrades required to connect the facility reliably. The load customer conducts testing and commissioning procedures to verify system readiness. The utility may require documentation and verification that the facility is operating reliably and compliant with applicable requirements.

MILESTONE 8
Post-Interconnection Monitoring and Compliance
The utility and large load customer each monitor reliability of the facility and adherence to requirements and procedures, as applicable. Post-commissioning monitoring equipment (power quality, disturbance reporting, harmonics meters, etc.) may be analyzed to monitor performance. Periodic reviews may be done by the utility or customer to verify compliance with requirements.

Large load interconnection processes vary by transmission provider; however, there are common milestones for a large load interconnection process. SOURCE: ELEVATE ENERGY CONSULTING.

(FERC) Order No. 2023. By evaluating multiple large load requests together, utilities can assess system impacts more holistically, streamline study efforts, and fairly allocate necessary network upgrades. This approach enhances efficiency while ensuring that new loads do not impose undue costs or reliability risks on existing customers.

Developing or improving a structured large load interconnection process requires careful consideration of fairness, efficiency, and long-term grid stability. By adopting best practices from generator interconnection reforms, utilities can modernize their approach, providing a framework that supports growing load demand while maintaining reliability and equitable cost allocation. Figure 4.2 (p. 34) illustrates high-level milestones in the large load interconnection process that utilities could consider.

Each step in the process will have additional details regarding expectations, requirements, deadlines, data sharing, etc. However, having a structured approach such as the one listed above will help emphasize early engagement between the utility and customer, a thorough analysis by the utility, clear expectations and agreements, and continuous oversight throughout the process.

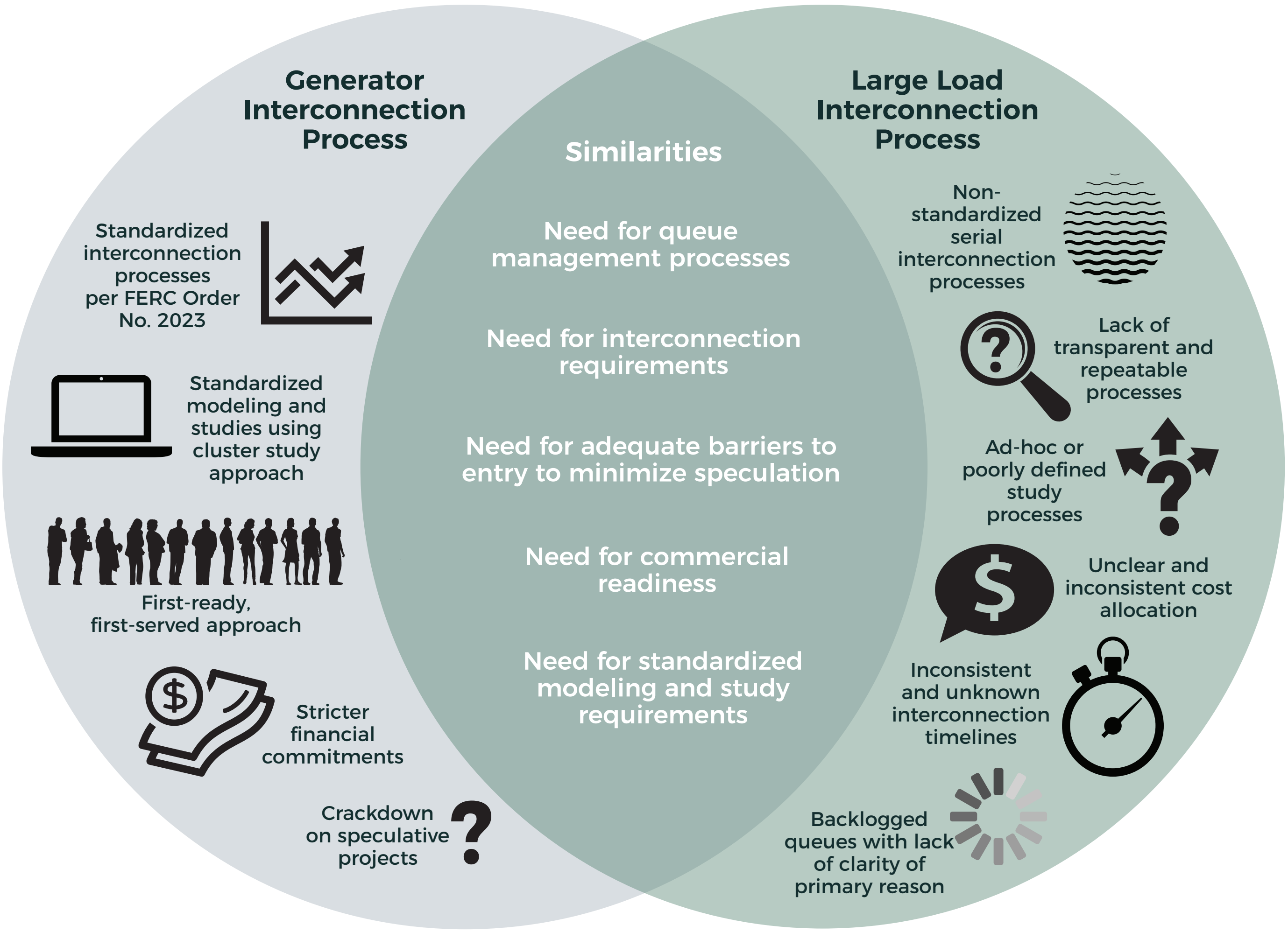
Similarities with Generator Interconnection Reforms and Standards Improvements

Over the past decade, generator interconnection reform has been a focal point for FERC, culminating in Order No. 2023 [14]. This rule sought to address mounting interconnection backlogs, improve study accuracy, and ensure fair cost allocation in response to an influx of renewable generation projects. Prior to these reforms, interconnection queues in regional transmission organizations (RTOs) and ISOs had ballooned, with projects facing delays of three to five years or longer due to inefficient serial study processes and uncertain network upgrade costs as projects dropped out of the queue. FERC Order No. 2023 introduced several measures, including a "first-ready, first-served" cluster study approach, stricter financial commitments from developers, and standardized modeling requirements. These measures aimed to reduce speculative projects clogging the queue and ensure that only viable projects progressed, ultimately benefiting both new generation developers and the reliability of the broader grid [11].

Utilities now face a strikingly similar challenge with large load interconnection. Just as uncoordinated generator interconnection processes led to overwhelmed queues and uncertain system impacts, the rapid influx of high-demand customers such as hyperscale data centers, cryptocurrency mining operations, and industrial electrification projects threaten existing planning frameworks. Many utilities still rely on relatively ad-hoc processes to evaluate large load interconnection requests, leading to inconsistent study timelines, possible gaps in load analysis and grid preparation, uncertainty in

Many utilities may still rely on ad-hoc processes to evaluate large load interconnections which could lead to inconsistent study timelines, possible reliability risks that remain unearthed, uncertainty in upgrade costs and cost allocation, and potential risks to grid reliability.

FIGURE 4.3. Similarities and Differences between the Generator and Large Load Interconnection Processes



The generator interconnection queue and the large load interconnection process have key differences yet also have a number of similarities that industry could learn from as large load interconnection processes mature. SOURCE: ELEVATE ENERGY CONSULTING

upgrade cost allocation, and risks to local grid reliability. Without clearer interconnection requirements, well-defined study methodologies, and structured queue management reforms, utilities risk exacerbating delays, misallocating costs, and overlooking potential system reliability concerns. Applying lessons from FERC's generator interconnection reforms—implementing transparent queue management rules, requiring financial readiness milestones, standardizing studies, etc.—may help utilities create a more efficient, fair, and proactive approach to integrating large loads while maintaining grid stability. Figure 4.3 shows similarities and difference between these processes.

Develop Accurate Large Load Models and Perform Interconnection Studies

The entire large load interconnection study process relies on the customer providing accurate, site-specific, and detailed information regarding the electrical details of the facility across different simulation domains. These studies are critically necessary for ensuring grid reliability, particularly

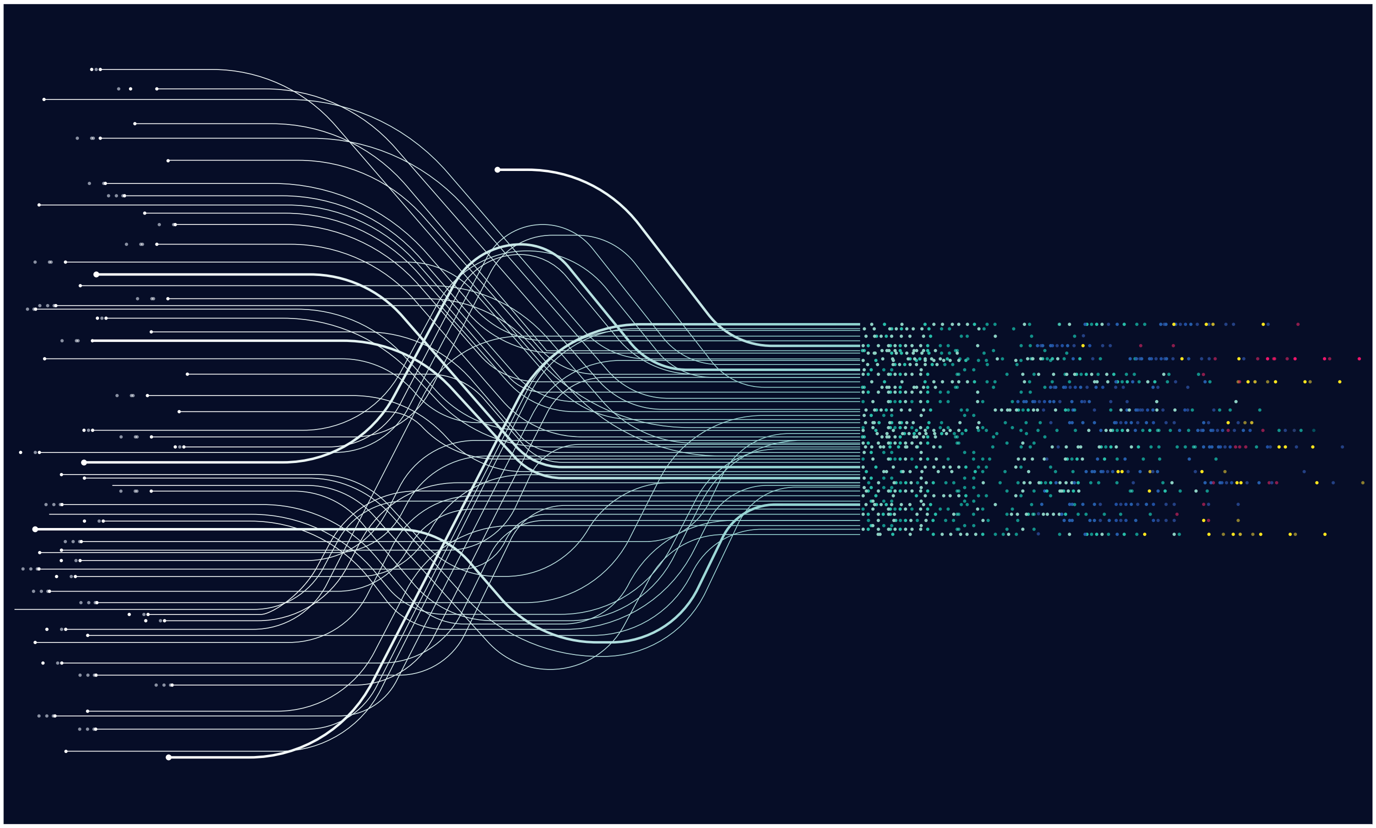


IMAGE: ISTOCKPHOTO/KROT STUDIO

given the size and operational nature of the large loads being connected. Thus, in most cases, basic powerflow studies are insufficient to adequately assess the reliability impacts of large loads on the distribution and transmission system. Different types of models are required based on the studies needed, and determination of the types of studies needed depend on many factors including location, size, technology, etc. Models may include phasor domain transient (PDT) dynamic models (standard library or user-defined), electromagnetic transient (EMT) models (non-manufacturer-specific or manufacturer-specific), a harmonics model, and possibly a short-circuit model if grid-paralleled on-site generation is present. Chapter 6 describes these models in detail. Chapter 7 describes the types of reliability studies performed during the System Impact Study and the Facility Study phases.

Identify Corrective Actions

The results of the interconnection studies will identify if any corrective actions are needed to address potential reliability risks presented by the addition of large loads. These corrective actions may involve a lower demand level that avoids the reliability issues, building new transmission infrastructure or upgrading existing infrastructure (e.g., reconductoring), and other solutions.

It is important to recognize that the solutions should be tailored to the specific reliability issues, and multi-value solutions may play a key role in alleviating multiple reliability risks. For example, if the addition of the load causes grid voltage control or voltage stability issues, these types of challenges can be solved by an array of voltage solutions such as shunt capacitors, static synchronous compensators (STATCOMs), and static var compensators (SVCs). However, if grid strength or fault current levels are also a concern, then synchronous condensers may be a better solution. Lastly, if generation assets are being connected in the area, requiring dynamic reactive capability or grid forming (GFM) batteries could be ideal. Thus, there are many solutions to solve new load issues that can be deployed to solve specific grid reliability risks [15].

Equitably Allocate Costs

The cost allocation of network upgrades should be carefully reviewed to ensure that undue costs are not placed on existing customers. To that end, utilities and state regulators can consider the following steps:

- Use a cost causation principle that ensures that customers triggering the necessity of network upgrades bear an appropriate share of the costs. Direct connection facilities should be paid entirely by the large load customer. Careful attention to cost causation for the broader network upgrades helps avoid shifting undue cost to other ratepayers.
- Identify and differentiate shared and direct assignment costs. Costs can be allocated based on whether they benefit a single customer (direct assignment) or allocated across multiple customers (shared). This could apply to multiple interconnection requests simultaneously or could assign a portion of costs to existing customers.
- Establish cost sharing mechanisms for high-growth areas where network upgrade costs can be equitably distributed among multiple interconnecting customers.
- Use transparent and predictable cost allocation formulas that ensure a clear methodology and a fair and equitable approach. These formulas should be approved by the appropriate regulatory bodies.
- Consider refund and/or credit mechanisms that fairly reimburse early customers who fund system improvements that benefit future customers.
- Again, reduce speculative projects by raising the barrier to entry such that only credible requests are considered and costs are more reasonably assigned.

Construct, Commission, Test, and Interconnect Large Loads

Both the utility and the large load customer will enter a period of engineering, procurement, and construction of their respective facilities to connect the load to the grid. Once those facilities are constructed, adequate commissioning tests are needed to ensure both the load and the grid facilities operate as designed and are tested to ensure personnel and public safety as well as reliable service. Given how fast large loads are growing, utilities are strongly encouraged to play an active role in the large load commissioning process to ensure that they acquire final electrical drawings and documentation, as-left settings, protection and controls, and other data. The final as-left settings of the site should match those used during the interconnection study process, and any discrepancies should be reviewed by the utility. For example, if the as-left protection and control settings are configured in a way that does not align with the utility protection system reclosing schemes, this could lead to systemic risks of data centers tripping offline during normal grid faults. This was a root cause of the large data center event that occurred in Northern Virginia [4].

Lack of coordination and communication between the utility and the large load customer could result in hidden failure modes that could result in catastrophic grid risks. Furthermore, these types of issues result in modeling and study efforts that fail to match reality, further exacerbating the risk of grid reliability issues.

Monitor Operational Performance and Adherence to Requirements

Utilities should require large load customers have adequate disturbance monitoring and operational real-time telemetry so that the utility can adequately assess the operational performance of the site and conduct forensic event analysis when needed. This will include requirements for the large load customer to participate in forensic event analysis efforts conducted by the utility in the event of any abnormal performance detected. These efforts not only help the utility ensure reliable operation of the grid but also can help the customer mitigate any issues that could result in its unexpected tripping or disconnection from the grid, improving operational uptime.

BOX 3: NEED FOR MORE RESOURCES AND STAFF

The industry has broadly struggled, and in some ways failed, to address these types of issues during the construction and commissioning of new generation over the past decade [16]. While work continues to get new generators caught up, the industry cannot afford to make a similar mistake with the forthcoming wave of large loads. Utility leadership, large load developers, and regulatory staff must devote more resources and staff to properly model, commission, and document the capabilities, performance, and as-left settings at these installations. Failure to complete these critical steps can and will introduce catastrophic risks to BPS reliability.

PHOTO: ISTOCKPHOTO/GERVILLE

5

Technical Interconnection Requirements for Large Loads

The large load interconnection process assesses BPS reliability impacts of new large loads and identifies corrective actions necessary to mitigate any reliability risks posed by the new connection. These assessments rely on performance criteria which the newly connecting resource must adhere to. All transmission providers, transmission planners, and planning coordinators have system performance requirements for the transmission system per applicable NERC Reliability Standards [17]. However, they may lack in terms of technical detail for large load interconnections. If large loads can connect without satisfying specific reliability needs, the transmission system could experience a notable degradation of performance and risk. The risk grows when new technologies are introduced on the grid before system planners have gained an adequate understanding of the technology to establish appropriate requirements.

A new level of diligence is required given the degree of highly speculative requests for interconnection driven by speed and minimizing economic impacts.

Historically, industry has not defined comprehensive technical requirements for large load customers because such customers were less common and could be handled on a case-by-case basis. Utilities have also preferred a customer-serving approach that minimizes adverse impacts on end-use customers. This approach worked in the past but is no longer sufficient. A new level of diligence is required given the degree of highly speculative requests for interconnection driven by speed and minimizing economic impacts.

Therefore, to help ensure reliable operation of the BPS, it may be time for transmission providers to define clear, effective, and appropriate requirements for large load customers. Such requirements place demands on prospective customers but—as the utility industry has observed with IBRs—present them with a more transparent and equitable process. All large load customers are held to the same expectations and can proactively prepare and design facilities to meet these expectations along the way.

Learnings from Europe and the UK

The European Network of Transmission System Operators for Electricity (ENTSO-E),[8] established the *Demand Connection Code (DCC),* which was approved by the European Commission in 2016 [18]. The DCC established standardized grid code requirements for different types of demand connections to the transmission system. The regulation applies to new and significantly modified transmission-connected demand facilities, distribution networks connecting to the transmission system, and end-use demand units providing demand response. Of relevance to this paper is the former category: transmission-connected demand facilities (see Table 5.1, p. 42).

As the electric reliability organization in North America, NERC is well suited to take on the role of coordinating these harmonized standards, particularly for transmission-connected large loads.

The United States lacks a similar framework for large load interconnection requirements, leaving a patchwork of regional standards and in many regions no standards at all. This presents an opportunity to establish nationwide harmonized standards and requirements that ensure grid reliability and resilience amid a boom of large load demand in the decades ahead. As the electric reliability organization in North America, NERC is well suited to take on the role of coordinating these harmonized standards, particularly for transmission-connected large loads. The EU's structured approach could inform similar regulatory frameworks in the U.S. for integrating large industrial and data center loads into the transmission system.

PHOTO: ISTOCKPHOTO/SEFA OZEL

8 ENTSO-E is the association for cooperation of the European transmission system operators (TSOs) with 40 member TSOs representing 36 countries, and is responsible for the reliable and coordinated operation of Europe's electricity system.

TABLE 5.1. High-Level Overview of EU Demand Connection Code Requirements

Requirement	Details
Frequency Stability	
Disconnection and Reconnection	Facilities must disconnect if system frequency exceeds defined thresholds (e.g., above 51.5 Hz or below 47.5 Hz). Reconnection must be staggered to avoid sudden load surges that could destabilize the grid.
Limited Frequency Sensitivity Mode (LFSM)	Industrial loads must automatically reduce consumption when frequency is too high (LFSM-O) and may increase consumption when frequency is too low (LFSM-U) to help stabilize the grid.
Rate of Change of Frequency (RoCoF) Immunity	Facilities must remain connected during fast frequency changes (e.g., up to 2 Hz/s), preventing unnecessary tripping that could worsen instability.
Voltage Stability	
Voltage Ride-Through (VRT)	Industrial loads must remain connected during voltage dips (e.g., down to 0.15 p.u. for 150 ms) and surges, following defined recovery curves to prevent cascading disconnections.
Reactive Power Capability	Facilities must provide reactive power support within a specified range (e.g., 0.95 lagging to 0.95 leading power factor) to help regulate voltage.
Voltage Setpoint Adjustments	Facilities must allow transmission operators to adjust voltage setpoints dynamically to maintain grid stability.
System Restoration	
Blackstart Contribution	Certain industrial loads must coordinate with transmission operators to adjust demand during blackstart restoration processes, ensuring a stable power-up sequence.
Islanded Operation	Some facilities must be able to operate in islanded mode, supporting grid sections that have been temporarily disconnected from the main system.
Demand Response	
Frequency Control Demand Response	Large loads must be able to adjust power consumption dynamically in response to frequency deviations, with response times as low as 2 seconds.
Voltage Control Demand Response	Facilities must support voltage regulation by adjusting reactive power consumption or generation when requested by the transmission operator.
System Balancing Demand Response	Large industrial consumers participating in balancing markets must meet performance standards for load modulation, including response speed and duration.
Compliance, Monitoring, and Testing	
Pre-Connection Compliance Studies	Facilities must perform system impact studies, including dynamic stability analyses, before receiving approval to connect.
Real-Time Monitoring	Loads above a certain capacity must provide real-time telemetry (e.g., MW, MVAr, voltage) to transmission system operators (TSOs) for continuous monitoring.
Periodic Testing and Reporting	Transmission operators may require periodic testing and compliance reporting to verify that facilities continue to meet grid code requirements.

The EU Demand Code Requirements lay a solid foundation for establishing capability and performance expectations for large loads that the US and other areas can likely learn from. SOURCE: ELEVATE ENERGY CONSULTING

Categories of Large Load Technical Interconnection Requirements

A comprehensive set of technical interconnection requirements for large loads is essential to support a reliable BPS. While a full evaluation is beyond the scope of this paper, transmission providers and ISO/RTOs should consider the following high-priority categories:

- **Load Interconnection Size Limits:** Historically, the loss of a single large end-use load has not posed significant reliability risks, as many customers sought multiple service connections for redundancy. However, as load interconnection request sizes grow, single points of connection may introduce new reliability challenges. Advances in digital service transfer between data centers reduce the need for multiple service points, making it critical for transmission providers to assess the risks associated with losing single or aggregated large loads. To mitigate these risks, transmission providers may impose interconnection size limits such as capping the amount of load at a single point of connection or limiting the number of direct-connect tapped loads [5]. It may also be possible to ramp up the requirements and gating as the interconnection size becomes larger.
- **Model Sharing:** Transmission planners should define modeling requirements for large loads across power flow, transient stability, electromagnetic transient (EMT), and short-circuit studies. Required models should include equipment characteristics, control narratives, and verification details. Grid planners must specify whether standard library models suffice or if user-defined models are necessary, ensuring accurate models for use in grid planning and operational studies.
- **Data Recording and Monitoring Requirements:** Large load customers should have recording and monitoring data to support real-time monitoring, event analysis, and model validation. Required data sources may include SCADA telemetry (e.g., breaker status, voltage, current, power), sequence of events recording (SER), digital fault recording (DFR), dynamic disturbance recording (DDR), and power quality monitoring. Not all data may need to be transmitted in real-time; in some cases, data can be stored locally for quick retrieval upon request. This large load monitoring data should be shared with transmission providers to support event analysis activities, confirm operational characteristics and performance, and validate technical performance requirements of the large load facilities.
- **Voltage and Frequency Ride-Through Requirements:** Electric reliability organizations and/or ISO/RTOs should establish large load ride-through requirements, defining the voltage and frequency ranges for which large loads must remain connected. Without these capabilities, large loads may trip unexpectedly during disturbances, exacerbating grid instability. Ride-through standards should align with industry guidelines such as NERC PRC-024, NERC PRC-029, and IEEE 2800-2022.
- **Power Factor and Reactive Power Requirements:** Large load facilities must operate within a defined power factor limit, typically ±0.95, to manage reactive power impacts on system stability. For large loads, tighter limits may be necessary to prevent excessive reactive power consumption. Customers unable to meet these standards may need to install power factor correction (e.g., shunt capacitors, reactors) or dynamic compensation devices such as STATCOMs to support voltage stability, and may require more detailed power quality and dynamic reactive power resource studies.

PHOTO: ISTOCKPHOTO/GERVILLE

- **Power Quality Requirements:** Transmission providers should enforce power quality standards to protect grid stability and customer infrastructure. Key criteria include voltage range compliance (ANSI C84.1), harmonic distortion limits (IEEE 519), flicker mitigation (IEEE 1453), phase imbalance control (IEC 61000-3-13), and transient surge protection. Compliance testing and periodic reporting should be required, with corrective actions enforced for non-compliance. Specialized studies and monitoring equipment may be required to adequately protect existing customers.
- **Oscillation Requirements:** Large load facilities must not introduce or amplify oscillations that could destabilize the grid. Loads with power electronics, motor drives, or cyclical operation must be assessed for forced oscillation risks. Facilities near series-compensated lines, synchronous generation, or large inverters should undergo EMT studies to evaluate SSO risks. Pre-operational assessments, real-time monitoring and protection, and forensic event analysis should be implemented to detect and mitigate oscillatory disturbances. It is important to be clear and specific when defining requirements for oscillations. For example, quantification of the maximum level of oscillation at each voltage level, as well as the allowed frequency content of the oscillations, will determine the cost of mitigation on the part of the load customer.
- **Short-Circuit Requirements:** Transmission providers should define minimum and maximum short-circuit current levels at the customer interface to ensure the customer rates equipment appropriately. If a facility configuration contributes to excessive fault currents, customers may be responsible for mitigation measures identified in the interconnection study process.
- **Protection Requirements:** Protection coordination studies should extend beyond circuit-level protection to include facility-level schemes. Coordination should cover UPS/rack-level protection for data centers, ensuring integration with utility systems. Utility protection departments are

already resource constrained, so standardized approaches and industry guidelines in this area would be valuable moving forward. Utilities should have visibility into critical facility protection and control systems to coordinate responses to faults, reclosing events, and UPS load pick-up and/or trip conditions. If backup generation operates in parallel with the grid, studies must evaluate fault contributions, breaker duty impacts, and coordination with utility system protection schemes.

- **Data Sharing Requirements:** In addition to providing models, large load customers must provide operational and planning data to support system modeling, reliability assessments, and real-time operations. Required data may include load forecasts, equipment specifications, real-time telemetry, outage and maintenance notifications, and event logs. Submission must adhere to utility-defined formats and update frequencies.
- **Operations and Control Requirements:** Large loads must operate in compliance with utility-defined operational reliability criteria. This may include ramp rate limits, real-time dispatchability, voltage/reactive power support, and ride-through capabilities. Automated and manual controls should be in place to respond to utility directives during normal operations and emergency conditions.
- **Communication with Utility Requirements:** Secure, reliable communication channels must be established between large load customers and utilities to enable real-time monitoring, coordination, and emergency response. Communication protocols should align with industry standards (e.g., IEEE, IEC 61850, NERC CIP) and support SCADA integration, event reporting, and 24/7 availability of key personnel.
- **Emergency Response and Coordination:** Large load customers must maintain an emergency response plan outlining contingency actions, communication protocols, and coordination with the utility during blackouts, frequency/voltage excursions, cyber incidents, or natural disasters. Designated personnel must be available for emergency coordination and drills as required. Facilities with backup generation or islanding capabilities must follow approved procedures for safe transitions.
- **Operations and Maintenance Requirements:** Large load customers must maintain electrical infrastructure, protection systems, and control equipment per utility and industry standards. Scheduled maintenance that could impact grid reliability must be coordinated in advance, and emergency maintenance must be reported immediately. Compliance with utility inspection, testing, and reporting requirements is mandatory. Maintenance requirements for the utility's interconnecting equipment must also be clearly defined and allow so the utility can provide periodic maintenance and testing of its electrical equipment.
- **Backup Generation Requirements:** Facilities with onsite backup generation must disclose details on capacity, operational modes, protection schemes, and interconnection status. Backup generators operating in parallel with the grid require fault contribution analysis and coordination with protection schemes. Utility approval may be needed for parallel operation, blackstart capabilities, and transfer switching arrangements.

- **Demand Response Requirements:** Large load customers participating in demand response programs must comply with dispatch signals, response times, and performance verification criteria. Load curtailment or shifting should be coordinated to minimize adverse grid impacts while aligning with market and reliability requirements. Customers must provide performance data to the system operator to verify compliance.
- **Cybersecurity Measures:** Large load facilities must implement cybersecurity protections to safeguard grid operations from cyber threats. Requirements may include secure authentication, encrypted communications, firewall protections, and compliance with applicable standards such as NERC CIP, ISO/IEC 27001, or NIST frameworks. Utilities may conduct audits, request compliance evidence, and require corrective actions. In severe cyber incidents, emergency disconnection may be necessary.
- **Utility Right to Monitor and Enforce Compliance:** Transmission providers must have the authority to monitor, verify, and enforce compliance with interconnection requirements to ensure system safety and reliability. This includes real-time operational data access, site inspections, and compliance testing. If a facility is found non-compliant, utilities must have the authority to mandate corrective actions at the customer's expense. If non-compliance poses reliability or safety risks, utility operators must be empowered to exercise disconnection rights as outlined in interconnection agreements.

All requirements should be grounded in the need for ensuring an adequate level of BPS reliability, and costs for large load customers should be considered in defining reasonable yet necessary requirements that support the BPS while minimizing excessive costs to all customers. The size and nature of the new class of loads being connected to the system today necessitates the introduction of increased standards for interconnection. Failure to implement new, robust standards is placing unprecedented risk on the bulk electric system.

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Appendix B provides more details on each of the topics listed above.

6

Large Load Modeling Considerations

Accurate models are necessary for transmission planners to study the reliability impacts of large loads connecting to the BPS. Customers must address any issues identified by planners before connecting to ensure reliable operation for all customers and to avoid system instability, uncontrolled separation, or cascading outages. Some utilities may require the large load customer to prepare and submit the models and supplemental documentation for review. Other utilities may prepare models themselves based on documentation provided by the customer.

In any case, the following models are generally required by the utility:[9]

- **Positive Sequence Powerflow Model:** Represents the steady-state operating conditions of the facility, including real and reactive power consumption, voltage levels, and network topology. This model is essential for assessing thermal loading, voltage stability, and contingency analysis.
- **Phasor Domain Transient (PDT) Dynamic Model (standard library model):** Uses standard model components in commercial software platforms (e.g., PSLF, PSS®E, PowerWorld) to represent the dynamic response of the facility to system disturbances. Suitable when load behavior can be captured using predefined library models.
- **PDT Dynamic Model (user-defined model):** Required when standard library models are insufficient to represent the facility's dynamic behavior such as unique power consumption characteristics, variable or oscillatory behavior, special control schemes, or power electronic interfaces. This model may be provided as a compiled DLL or equivalent for compatibility with utility simulation tools.
- **Electromagnetic Transient (EMT) Model (not manufacturer-specific):** Captures high-frequency and fast-response behavior of power electronics and control systems, as well as unbalanced conditions. This model is useful for evaluating voltage flicker, studying sub-synchronous impacts on generators due to variation in load output, and other impacts. Typically developed in EMT software such as PSCAD, EMTP-RV, or ATP.

9 The section does not discuss production cost modeling or capacity expansion modeling.

- **EMT Model (manufacturer-specific):** Captures highly detailed responses from the load, often representing power electronic interfaces specific to the equipment suppliers used in the plant. These models may be necessary for assessing interactions with nearby IBRs, assessing SSTI and SSCI, creating harmonics models (described below), or in some cases evaluating ride-through capability.
- **Short-Circuit Model:** Represents the fault current contribution of the facility, including contributions from rotating machinery, transformers, and power electronic interfaces including batteries and UPSs. This model is used for the coordination of protection schemes between the utility and large load facility and for system protection impact assessments. These models are typically provided in formats compatible with short-circuit analysis tools like ASPEN OneLiner, CYME, or CAPE.
- **Harmonics Model:** Details the harmonic emissions of the facility, including expected current and voltage harmonic distortion levels under normal and contingency conditions at varying load levels. This model must accommodate the harmonic impact from all the major components of the load plant. Essential for evaluating compliance with IEEE 519 limits and assessing potential resonance issues with system impedance characteristics. Typically developed using tools such as ETAP, PSCAD, CYME, or Harmonic Analyzer in DIgSILENT PowerFactory.
- **Documentation:** All models should be accompanied by sufficient documentation that includes equipment characteristics, control narratives, verification details, and how to use the models (where applicable). This ensures that utility planners can correctly interpret and apply the models in their studies.

The following sections provide a cursory overview of the different types of models that may be used in reliability studies today, with a specific focus on data center modeling.

Data Center Load Composition

Each data center load model should be developed and verified based on a detailed review of the site design and its specific operational characteristics. Percentages of load composition vary depending on the size of the facility, cooling method, density of power electronic equipment, type of servers and workloads, external temperature, load cycling, types of power conditioning equipment, etc. However, a high-level estimate of data center load composition can help improve overall awareness, data quality, and reasonability checks in the absence of actual data.

Data centers are typically comprised of the following end-use load components (see Table 6.1, p. 49) [19], [20]:

Percentages of load composition vary depending on the size of the facility, cooling method, density of power electronic equipment, type of servers and workloads, external temperature, load cycling, types of power conditioning equipment, etc. However, a high-level estimate of data center load composition can help improve overall awareness, data quality, and reasonability checks in the absence of actual data.

- **Power Electronics:** Highly nonlinear power draw, primarily from servers based on digital workloads and type of infrastructure. Power consumption from networking equipment and storage is minor by comparison.
- **Cooling Systems:** Continuous yet variable demands dependent on external weather conditions (e.g., ambient temperature). Consists of large 3-phase motor loads and some smaller 1-phase auxiliary loads. Variable frequency drives (VFDs) used extensively for fans and pumps to improve energy efficiency; redundant systems often available to avoid data center downtime due to cooling issues.
- **Power Infrastructure:** May introduce harmonics emissions from rectifiers and inverters. Could cause switching transients, interactions with other power electronic devices such as IBRs, voltage and frequency ride-through effects, etc.

The information in Table 6.1 pertains to the consumption of electricity, and this allocation of end-use load is less relevant to modeling these loads in grid reliability studies. For example, the power electronics interface with the AC grid through a UPS or a PDU and thus need to be modeled accordingly. Details regarding how data center load composition is considered in load modeling is described in subsequent sections.

TABLE 6.1.

Estimated Data Center Load Composition

Category	Load %	Description
Power Electronics	40–60%	**Servers (30–40%)** Rack-mounted and blade servers for compute workloads driven by CPUs, GPUs, and TPUs for AI, machine learning, and cloud **Storage Systems (5–10%)** Hard disk drive (HDD) and solid-state drive (SSD)/flash memory **Networking Equipment (5-10%)** Switches, routers, firewalls, and other communication equipment
Cooling Systems[a]	20–40%	**Computer Room A/C or Handlers (CRAC/CRAH Units) (10–20%)** Traditional air-cooled chillers, condensers, and compressors to maintain server room temperatures **Immersion and Direct-to-Chip Cooling (5–10%)** Emerging for high-density AI workloads, which reduces air cooling demand **Cooling Tower Pumps & Fans (5–10%)** Includes water-cooled systems and evaporative cooling units
Power Infrastructure[b]	10–15%	**Uninterruptible Power Supplies (UPS) (5–10%)** UPS systems convert AC electricity to DC and then to AC, providing fast transition to backup energy **Power Distribution Units (PDU) (2–3%)** PDUs convert high-voltage power to IT-friendly levels

a Many of the cooling system components are industrial 3-phase motors. The fans and pumps in particular use VFDs for energy efficiency purposes and are thus electronically connected to the AC grid.

b The power infrastructure equipment are electronically connected to the AC grid.

SOURCE: ELEVATE ENERGY CONSULTING.

Note that the list above excludes substation equipment such as power conditioning equipment (e.g., STATCOMs), power factor correction such as shunt capacitors or reactors, or on-site backup generation (diesel gensets or BESS).

Powerflow Modeling

Steady-state power flow model representation includes a bus number, bus name, load ID, and snapshot representation of the active and reactive power consumption of the load for the given system conditions. Some simulation platforms have fields for scalability and any interruptible nature of the load. The load is assigned an area, zone, and owner ID code and may have specific parameters for representing behind-the-meter generation (although this may be explicitly modeled if sufficiently large). Figure 6.1 (p. 50) provides an example of a load record in the power flow case.

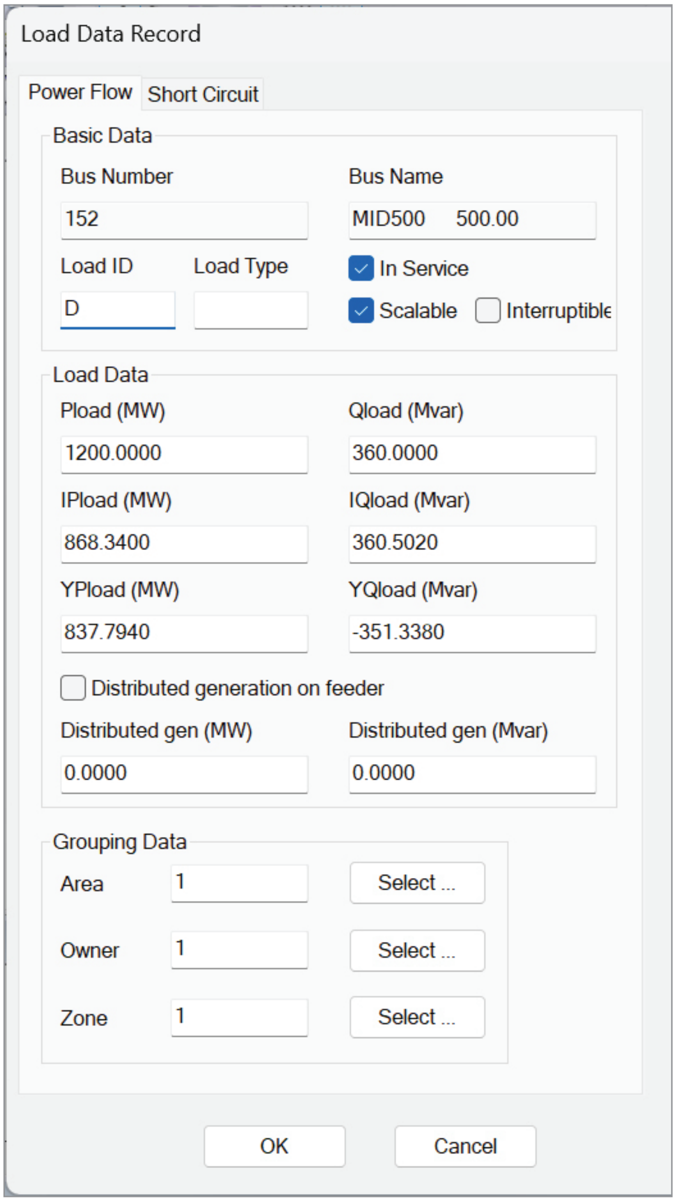
The utility may provide guidance as to how the active and reactive power demand should be modeled, and these values may be adjusted by the transmission planner during studies based on information supplied to them during the application process. For example, seasonal variations in cooling demand at the large load facility due to ambient temperate differences between winter and summer will need to be reflected in the model based on information supplied by the load customer.

Positive Sequence Dynamic Load Modeling

There are various standard library dynamic load models used in stability studies; each has its benefits and drawbacks. One of the more common dynamic load models is the composite load model [21]. The composite load model includes the following elements:

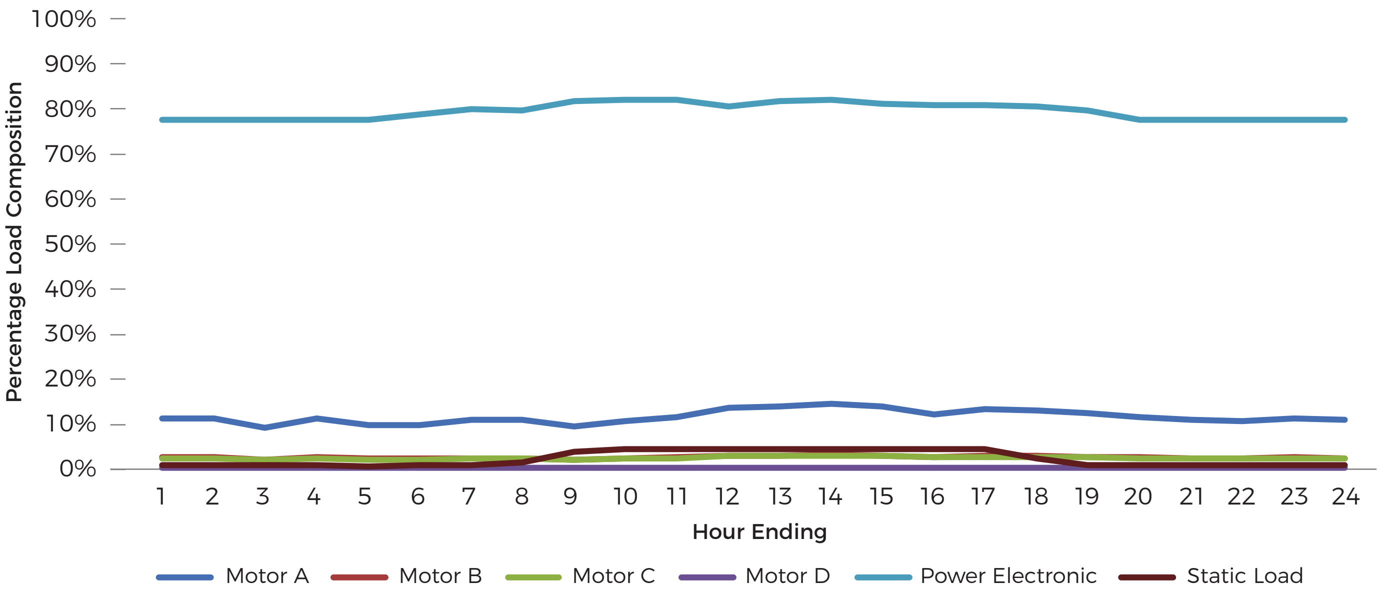
- **Collector System Equivalent:** Equivalent collector system impedances (resistance, reactance, susceptance).
- **Motor Loads:** Four types of motor loads including:
  - **Motor A:** 3-phase, constant-torque compressors used in air conditioning and refrigeration.
  - **Motor B:** 3-phase, higher-inertia fans whose torque is proportional to speed.
  - **Motor C:** 3-phase, lower-inertia pumps whose torque is proportional to speed squared.
  - **Motor D:** Single-phase air-conditioning compressors.
- **Power Electronic Loads:** Basic constant power load that ramps down based on voltage.
- **Static Load:** Conventional static load representation.
- **Distributed Generation:** Aggregate distributed energy resource (DER) representation.

FIGURE 6.1.
Powerflow Load Model Representation



SOURCE: SIEMENS PTI.

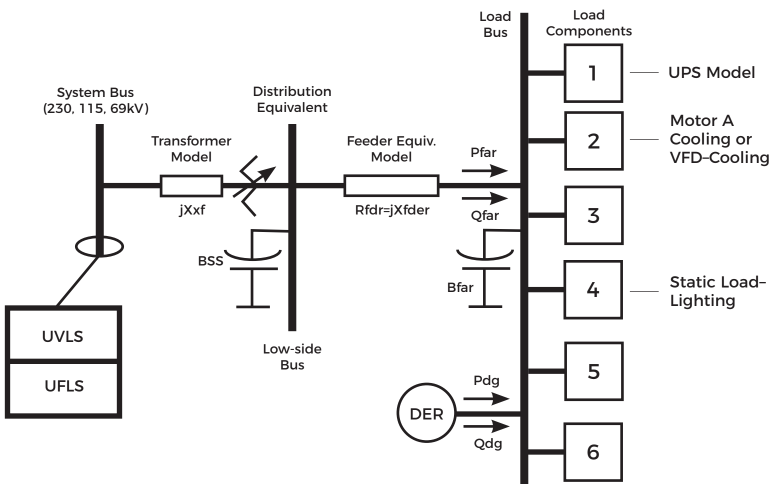
FIGURE 6.2. Percentage Load Composition for Composite Load Model Components



The majority of end-use loads at large data centers is power electronic. SOURCE: ELEVATE ENERGY CONSULTING.

The fractional percentage of the load composition must be assigned to the different load components. For example, in the WECC region, a default "data center" load model has been developed and is used for interconnection-wide base case creation and standard data center load modeling [22]. Figure 6.2 shows the load composition assumption for data center load over the course of a typical day. As the graph shows, almost 80% of the load is defined as power electronic, about 10% is Motor A, and the remaining 10% is Motor B, Motor C, and static load. Thus, the power electronic representation dominates the dynamic response of the load.

FIGURE 6.3. Evolving Composite Load Model Capabilities



Changes to the composite load model may enable a more accurate representation of data center loads in the future.

SOURCE: ELEVATE ENERGY CONSULTING. ADAPTED FROM EPRI..

The model was originally developed to represent aggregate loads connected throughout a distribution system, not individual large loads.[10] Researchers are investigating improvements to these models currently (see Figure 6.3) [23]. However, due to the lack of standard library dynamic load models available in the commercial software platforms, industry has used this model to fit other load types.

10 The model also includes a DER_A dynamic model component intended to represent aggregate amounts of distributed energy resources such as rooftop solar systems. Thus, it may be inadequate to represent co-located generation at large load facilities.

Technological advancements are far outpacing industry modeling improvements efforts to develop standard library models, which could lead to inaccurate modeling and potential reliability risks as data center load integration continues. Given these limitations, it may not be sufficient to continue modeling large loads such as data centers with simplified models such as the composite load model; industry may need to turn to more customized models to reduce risk.

User-Defined Dynamic Models

Existing standard library dynamic load models in commercial software programs lack sufficient control and protection components to properly model large loads such as data centers. Recent events in Northern Virginia and ERCOT have indicated that some large loads are highly voltage sensitive. For example, grid disturbances that are not very severe (e.g., shallow voltage dips with voltage that only reaches 85% of nominal) can lead to significant reduction of large loads. Furthermore, consecutive voltage dips that may occur typically during auto-reclosing attempts could lead to partial or full tripping of large loads. Neither of these phenomena can be currently captured using standard library load models. Furthermore, peculiar behavior of these loads even during normal grid conditions such as large and rapid fluctuations in power consumptions, as illustrated earlier in this report, may necessitate more sophisticated dynamic models. Therefore, a user-defined model may be necessary to capture such characteristics. In-depth and thorough understanding of the large load's behavior under normal and abnormal grid conditions is crucial for developing accurate and reliable user-defined dynamic models.

Electromagnetic Transient Modeling

EMT models are the highest-fidelity models used by power systems engineers for reliability analysis. These models represent the load and the grid in sufficient detail to accurately represent system

IMAGE: ISTOCKPHOTO/NICO EL NINO

behavior during very fast events. The models typically are created with specific studies in mind and can vary in complexity and construction depending on what is being analyzed. For example, the following types of studies will require different elements to be represented accurately within the EMT model:

- **Detailed Ride-Through Evaluation:** Protection systems within the controls and plant relaying should be included in the model in sufficient detail to accurately disconnect the plant during grid faults of various severities and types, as well as frequency excursions and voltage transients. This includes the various protective systems in PDUs, VFD-based cooling systems, UPS load take-up logic, and others.
- **SSO Impacts:** If synchronous generators are nearby, the EMT model must have the capability to flexibly represent the possible range of oscillations or continuous variations in power consumption. Studies that evaluate the impact on generator shaft systems must also include a higher layer of detail in the synchronous generators. For studies evaluating SSTI and SSCI, correct representation of damping within the load is also required. This typically requires the EMT model for key components such as PDUs and UPS units to be specific to the individual equipment suppliers.
- **High-Frequency Impacts:** For special evaluation of higher frequency effects like harmonics or transients, the EMT model of the load and nearby system should consider impact of frequency on electrical characteristics of each component. For evaluating harmonic impact or creating harmonic models, the load model should also include the correct representation of switching and control circuits within each element, which may require manufacturer specific information.
- **Interactions with IBRs:** To correctly represent the impact of the load on nearby IBR control or protection circuits, the EMT model of the load should include correct dynamic representation at the frequencies of concern to the IBR. For example, if a STATCOM is installed nearby to mitigate voltage fluctuations caused by the load, the STATCOM could incorrectly interpret these fluctuations as system instability and act to protect itself. The EMT model should therefore include an accurate representation of the range of possible fluctuations, as well as the STATCOM controls.

In general, EMT models must be carefully specified and requested by the utility with a firm understanding of their end use in mind. Given that specification, they must be carefully constructed using detailed information about the ultimate load plant design.

In general, EMT models must be carefully specified and requested by the utility with a firm understanding of their end use in mind. Given that specification, they must be carefully constructed using detailed information about the ultimate load plant design.

Short-Circuit Modeling

Short-circuit models and studies are performed in order to adequately set the protection and control systems of a facility under various worst-case fault conditions. These studies aim to ensure that protection systems are both dependable and secure, ensuring that any faulted equipment is reliably tripped offline as quickly as possible under all scenarios, while also ensuring that any non-faulted equipment remains electrically connected and is not unintentionally tripped offline. Protection and

PHOTO: ISTOCKPHOTO/STREKOZA2

control systems between the utility and large load facilities must be closely coordinated to ensure reliable and secure performance of these systems, and likely may include some form of communications-assisted schemes between both sides of the interconnection. Critical components of the large load facility must be appropriately modeled in these short-circuit models, including maximum ramp rates of the load, grid-connected backup generation of the facility, any power quality impacts from the operational characteristics of the facility, and transfer switch functionality and settings.

Harmonics Modeling

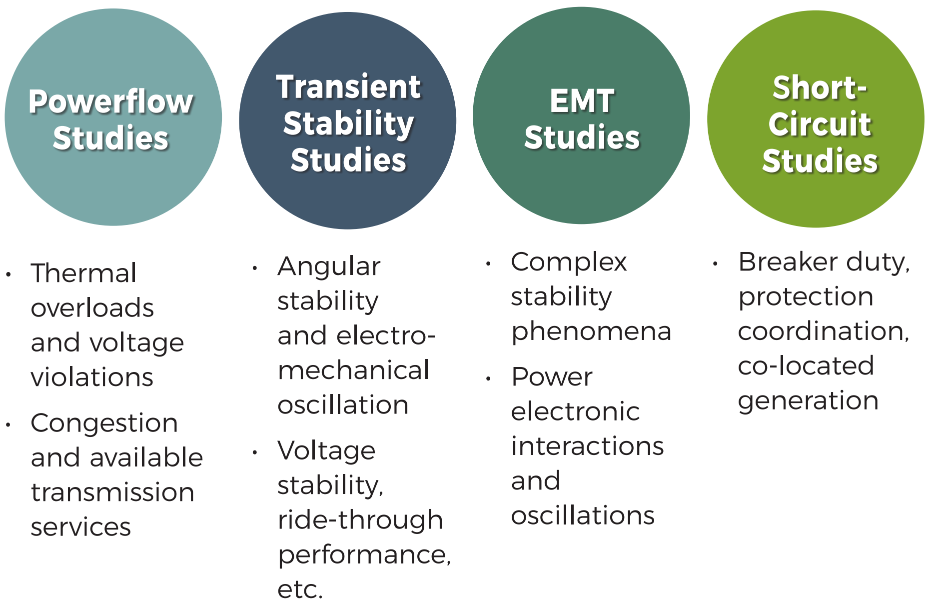
Harmonics studies are typically performed in conjunction with measurement-based evaluations to understand the potential for equipment damage. Since the studies can be very complex and ultimately drive the design of expensive mitigation such as large filters, the models used in the studies must be as accurate as possible and minimize the use of “worst-case” assumptions. Creation of these models often utilizes either available measurement data (in cases where similar equipment already exists in operation), or detailed EMT models that correctly represent component harmonic injections. In both cases, the final harmonic model is typically either a voltage source or current source with an associated impedance. This representation varies with harmonic frequency and often varies with the operating point of the load.

7

Large Load Interconnection Studies

Utilities must conduct reliability studies when a new large load seeks interconnection to the grid. These studies quantitatively identify whether the large load can be reliably integrated to the BPS or whether network upgrades are needed to ensure reliable operation within acceptable performance limits. Transmission providers may have a defined study process that outlines how these studies are conducted, and this process may or may not be publicly available for prospective customers. Regardless, the process generally includes the studies shown in Figure 7.1. Each of these studies are described briefly in this chapter.

FIGURE 7.1. **Types of Reliability Studies for Large Load Interconnection Studies**



Some of the more common reliability studies used for studying large load interconnections. SOURCE: ELEVATE ENERGY CONSULTING.

Regulatory Guidance

The NERC FAC-002 Facility Interconnection Studies standard requires each Transmission Planner and each Planning Coordinator to study the reliability impact of “interconnecting new generation, transmission, or electricity end-user Facilities,” as well as existing facilities “seeking to make a qualified change.” The standard specifies the following studies [24]:

- The reliability impact of the new interconnecting facility.
- Adherence to applicable NERC Reliability Standards, regional and Transmission Owner planning criteria, and facility interconnection requirements.
- Steady-state, short-circuit, and dynamics studies, as necessary, to evaluate system performance under both normal and contingency conditions.
- Study assumptions, system performance, alternatives considered, and coordinated recommendations.

Further guidance is available in the NERC TPL-001 *Transmission System Planning Performance Requirements* standard, which defines performance criteria for the BPS and serves as a starting point for contingency definitions. Utilities can have more stringent requirements, but the NERC standard establishes a ***minimum*** bar.

In particular, the NERC TPL-001 standard Table 1 includes the steady-state and dynamic stability performance planning events, defined as P0–P7 (see Table 7.1) [25]. Each category of transmission planning event includes whether non-consequential load loss and interruption of firm transmission service are allowed.

TABLE 7.1. NERC TPL-001-5.1 Table 1

Category	Initial Condition	Event[1]	Fault Type[2]	BES Level[3]	Interruption of Firm Transmission Service Allowed[4]	Non-Consequential Load Loss Allowed
P0 **No Contingency**	Normal System	None	N/A	EHV, HV	No	No
P1 **Single Contingency**	Normal System	Loss of one of the following: 1. Generator 2. Transmission Circuit 3. Transformer[5] 4. Shunt Device[6]	3Ø	EHV, HV	No[9]	No[12]
		5. Single Pole of a DC line	SLG			
P2 **Single Contingency**	Normal System	1. Opening of a line section w/o a fault[7]	N/A	EHV, HV	No[9]	No[12]
		2. Bus Section Fault	SLG	EHV	No[9]	No
				HV	Yes	Yes
		3. Internal Breaker Fault8 (non-Bus-tie Breaker)	SLG	EHV	No[9]	No
				HV	Yes	Yes
		4. Internal Breaker Fault (Bus-tie Breaker)[8]	SLG	EHV, HV	Yes	Yes

CONTINUED ON PAGE 57

TABLE 7.1. NERC TPL-001-5.1 Table 1 (CONTINUED)

Category	Initial Condition	Event[1]	Fault Type[2]	BES Level[3]	Interruption of Firm Transmission Service Allowed[4]	Non-Consequential Load Loss Allowed
P3 **Multiple Contingency**	Loss of generator unit followed by System adjustments[9]	Loss of one of the following: 1. Generator 2. Transmission Circuit 3. Transformer[5] 4. Shunt Device[6]	3Ø	EHV, HV	No[9]	No[12]
		5. Single pole of a DC line	SLG			
P4 **Multiple Contingency (Fault plus stuck breaker[10])**	Normal System	Loss of multiple elements caused by a stuck breaker[10] (non-Bus-tie Breaker) attempting to clear a Fault on one of the following: 1. Generator 2. Transmission Circuit 3. Transformer[5] 4. Shunt Device[6] 5. Bus Section	SLG	EHV, HV	No[9]	No
				HV	Yes	Yes
		6. Loss of multiple elements caused by a stuck breaker[10] (Bus-tie Breaker) attempting to clear a Fault on the associated bus	SLG	EHV, HV	Yes	Yes
P5 **Multiple Contingency (Fault plus non-redundant component of a Protection System failure to operate)**	Normal System	Delayed Fault Clearing due to the failure of a non-redundant component of a Protection System[13] protecting the Faulted element to operate as designed, for one of the following: 1. Generator 2. Transmission Circuit 3. Transformer[5] 4. Shunt Device[6] 5. Bus Section	SLG	EHV	No[9]	No
				HV	Yes	Yes
P6 **Multiple Contingency (Two overlap-ping singles)**	Loss of one of the following followed by System adjustments.[9] 1. Transmission Circuit 2. Transformer[5] 3. Shunt Device[6] 4. Single pole of a DC line	Loss of one of the following: 1. Transmission Circuit 2. Transformer[5] 3. Shunt Device[6]	3Ø	EHV, HV	Yes	Yes
		5. Single pole of a DC line	SLG	EHV, HV	Yes	Yes
P7 **Multiple Contingency (Common Structure)**	Normal System	The loss of: 1. Any two adjacent (vertically or horizontally) circuits on common structure [11] 2. Loss of a bipolar DC line	SLG	EHV, HV	Yes	Yes

Note: The footnotes above are identified in the NERC standard and should be referenced directly from the standard, if needed.

SOURCE: RECREATED FROM NERC.

Powerflow Studies

Powerflow and contingency studies are the foundational tools for power systems analysis, and are used to identify any thermal overloads and voltage violations under normal and contingency operating conditions. These studies also consider the effect of regional shifts in power transfers and outline any network upgrades required to mitigate the performance violations they identify. In some cases, powerflow tools are also used to assist in power quality analysis and flicker evaluation.

Considerations for these studies include:

- **Study Case Selection:** The most stressed study cases spanning a range of operating conditions (e.g., peak summer, peak winter, spring) to ensure reliability in all cases.
- **Load Level Assumptions:** Load at the full power consumption proposed in the customer contract, including worse-case power factor (i.e., reactive power demand) operating conditions.
- **Load Service:** A means of defining load study assumptions. Types may include:
  - **Firm Loads:** Requires network upgrades for power consumption beyond the level at which the thermal overloads or voltage violations occur.
  - **Controllable/Flexible Loads:** May be able to connect at higher demand levels, with agreement that the utility may curtail the load or dispatch it to a lower level to address specific network performance issues. This approach will likely differ between utilities and regions based on their system operating limit procedures.
- System Performance Deficiencies and Solutions: Potential system performance deficiencies that can affect reliability, along with solutions to overcome them. Solutions should consider a range of options, including transmission infrastructure investment and more advanced technologies. Types of solutions depend on the specific performance issue.

Transmission system upgrades are expensive, and a detailed discussion of how to allocate these costs lies beyond the scope of this paper. In general, larger transmission system upgrades can provide additional value to customers, unlock generator interconnections to meet regional or state policies, and support utility long-term planning. These impacts should be considered, and costs can be allocated fairly and equitably for the large load customer and existing ratepayers. However, multi-value alternative solution options should also be considered alongside expensive network upgrades to create a diverse and flexible system.

Transient Stability Studies

Transient stability studies explore and identify any stability-related issues that may arise with the connection of a new large load. They typically study a smaller subset of contingencies where potential instability risks are greatest. The transmission planner should have a process for identifying these contingencies and specifying the cases being studied.

Specific areas of focus for these types of studies include:

- **Angular Stability and Impact on Nearby Generation:** Ensuring that nearby generating units remain stable for new or modified contingencies and that large, fast changes in the load do not strain the mechanical systems of the generators unduly.
- **Impacts to Stability-Limited Transfer Paths:** Ensuring larger system-level stability metrics are met, particularly for intra-area or inter-area path flows across the system.
- **Transient Voltage Recovery:** Ensuring that the load does not adversely affect the ability of the system to recover voltages after a fault or other event.
- **Voltage Stability:** Ensuring that there is sufficient dynamic reactive support in the area to maintain reliability during and immediately following large events.
- **Large Load Ride-Through and Dynamic Performance Assessment:** Ensuring that the load can suitably ride through grid disturbances and that the dynamic response of the load does not have any adverse impacts on the system. This may require additional load protection system modeling beyond the standard library models and may require even more detailed analysis, as described below. In addition, the impact of possible ride-through failure on the system must be assessed.
- **Impacts on Local and Inter-Area Electromechanical Oscillations:** Ensuring there are no adverse impacts on local or inter-area oscillatory modes. This generally will require custom dynamic load modeling beyond standard library models, particularly when studying the effect of forced oscillations driven by cyclic load behavior from facilities like AI data centers.

EMT Studies

Electromagnetic transient (EMT) simulations are increasingly necessary due to the electronic nature of large loads such as data centers and the potential interactions these loads can have on other grid-connected components. EMT studies represent the data center and the surrounding grid in much more detail than conventional positive sequence stability studies and can study and identify more complex reliability risks. Examples of phenomena studied using EMT simulations include, but are not limited to:

- Impact on synchronous generator shaft systems.
- Sub-synchronous oscillations and torsional interactions.
- Harmonics and power quality.
- Capacitor switching transients and other types of transients.
- Inverter-based technology controller interactions.
- Ride-through evaluation and load take-off.
- Other complex stability phenomena.

Short-Circuit Studies

Short-circuit studies assess fault current levels, ensure equipment remains within acceptable fault duty ratings, and establish and verify protection settings for both the customer and the utility. These studies ultimately protect both the electrical infrastructure and the personnel working at these facilities.

While data centers are not a significant contributor of fault current, their electrical impedance characteristics will influence fault current levels and protective relay settings, particularly around the interconnection location. Thus, any new facilities study will ensure protection system coordination, identify upgrades required for direct interconnecting facilities, and screen for unacceptable impacts on the BPS. Utilities also conduct arc flash studies to ensure safe working distances and personal protective equipment requirements.

Co-Located Projects

With the transmission system increasingly congested, co-location of generation and load facilities has become increasingly attractive [26]. Many data centers are paired with or seek location alongside existing generating facilities. Many others pursue a "bring your own generation (BYOG)" approach, where the data center and generating facilities are developed together. These approaches may enable energy suppliers and large load developers to ramp up operations more quickly and leverage the grid for additional expansion if and when possible. It may also enable utilities to reduce burdens while seeking to ensure the same levels of reliability and cost for existing ratepayers.

New development models and partnerships are introducing large campuses of data centers driven by hyperscalers and combined with generation resources. These partnerships assure a power offtaker for the generation developer and spur development of the data center. The large parks may also be able to provide grid services and participate in wholesale electricity markets. However, this is an evolving landscape with regulatory obstacles, uncertainty regarding tariffs, and other factors. A lack of standardized frameworks for handling large loads, particularly large load co-location with generation, may be slowing development.

As a result, it is difficult to characterize how to study the addition of these resources and in which utility interconnection process they belong. Considerations include which study assumptions to use based on the generation and load agreements in place, the type of load service, and whether the resource (load and generation) is providing grid services.

8

Solutions for Bulk Power System Risk Mitigations for Large Loads

Rapid growth of large load consumers, particularly data centers, presents significant challenges for grid reliability, infrastructure planning, and real-time operations. Data center interconnection requests exacerbate challenges across the board: demand forecasting, minimizing stranded assets, supply chain issues, managing transmission system congestion, handling grid voltages and system stability margins, resource adequacy concerns, and policy implications. Utilities have many ways to mitigate these challenges. This section outlines some of the technical solutions being considered by industry today; however, this is not intended to be a comprehensive list.

Baseline Operational Performance Requirements Solutions

TECHNICAL INTERCONNECTION REQUIREMENTS

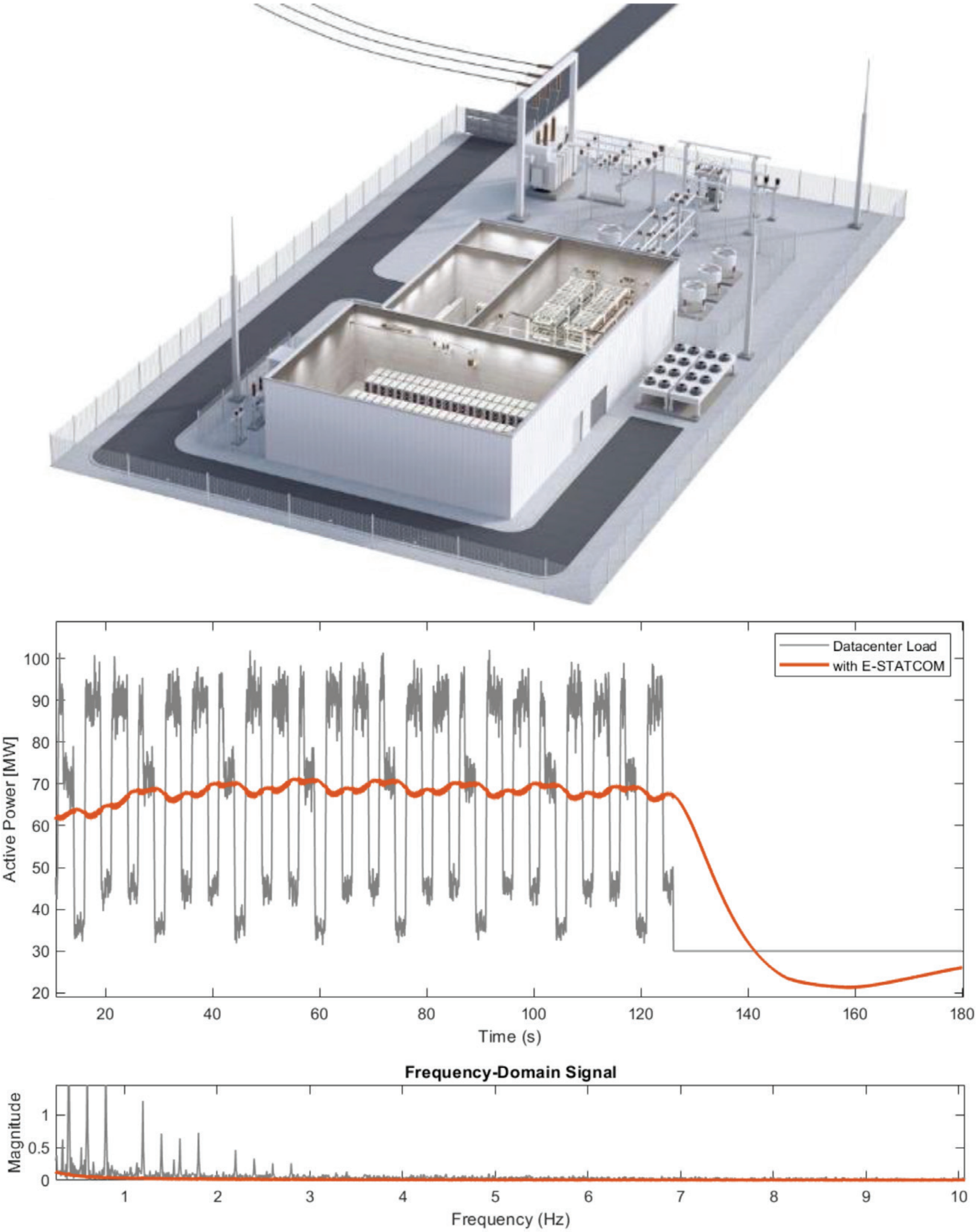
As discussed in Chapter 5, one of the most fundamental solutions to mitigate data center integration challenges is the development of clear, technically grounded interconnection requirements. These requirements help ensure that large load customers understand the performance expectations associated with connecting to the grid. By establishing obligations related to performance of the large load—power quality, voltage control, ramp rates, and disturbance ride-through, etc.—utilities can set a consistent baseline for system compatibility. Additionally, as detailed in Chapter 6, utilities should establish clear, consistent modeling requirements for large load interconnection studies. When these requirements are clearly communicated early in the planning process, data center developers can design their facilities to comply from the outset. This proactive alignment reduces the risk of costly redesign, delays, and operational issues during interconnection. Refer to Chapters 5 and 6 and Appendix B for more details.

Grid Stability and Load Power Quality Solutions

FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) DEVICES AND OTHER GRID SUPPORT DEVICES

Numerous FACTS devices and other grid support devices can support grid reliability and stability. These include static synchronous compensators (STATCOMs), static var compensators (SVCs), synchronous condensers, medium voltage or high voltage direct current (MVDC/HVDC), and others.

FIGURE 8.1. **E-STATCOM Solution – SVC PLUS FS**



The E-STATCOM is placed between the grid and the variable load and helps smooth out active power demands from fluctuating loads.

SOURCE: SIEMENS ENERGY.

Enhanced static synchronous compensators (E-STATCOMs) are an emerging solution to help stabilize power demands for highly variable loads like data centers. E-STATCOMs are placed between the grid (or generator) and the variable load and include an energy buffer with tuned controls that inject and consume energy for short periods of time. The E-STATCOM provides dynamic voltage control, and an additional active power energy buffer smooths the demands from the variable loads. Reactive power compensation and voltage control combined with active power smoothing helps minimize system oscillations, improve power quality, and support system stability. Figure 8.1 (p. 62) shows an example +/- 75 MW, +/- 75 MVAR E-STATCOM and an illustration of how the energy buffer smooths active power consumption at the load point of connection.

BATTERY ENERGY STORAGE SYSTEMS

BESS can also provide grid reliability and stability benefits, helping smooth variable demands from AI, provide on-site backup power solutions, and deliver other grid services benefits. BESS may be coupled with other on-site generation to provide off-grid solutions for large data center campuses, and the BESS may participate in electricity markets and provide grid services if regulatory and market rules allow for such participation. The BESS may enable valuable load flexibility and support broader grid stability. Examples may include [27]:

- Peak shaving by discharging the BESS during high-demand periods to reduce net system load. This lowers electricity costs during times of scarcity and lessens resource adequacy concerns.
- Fast-responding controls that smooth power demand variability, particularly for AI data centers.
- Voltage ride-through support for nearby grid faults or other severe disturbances.

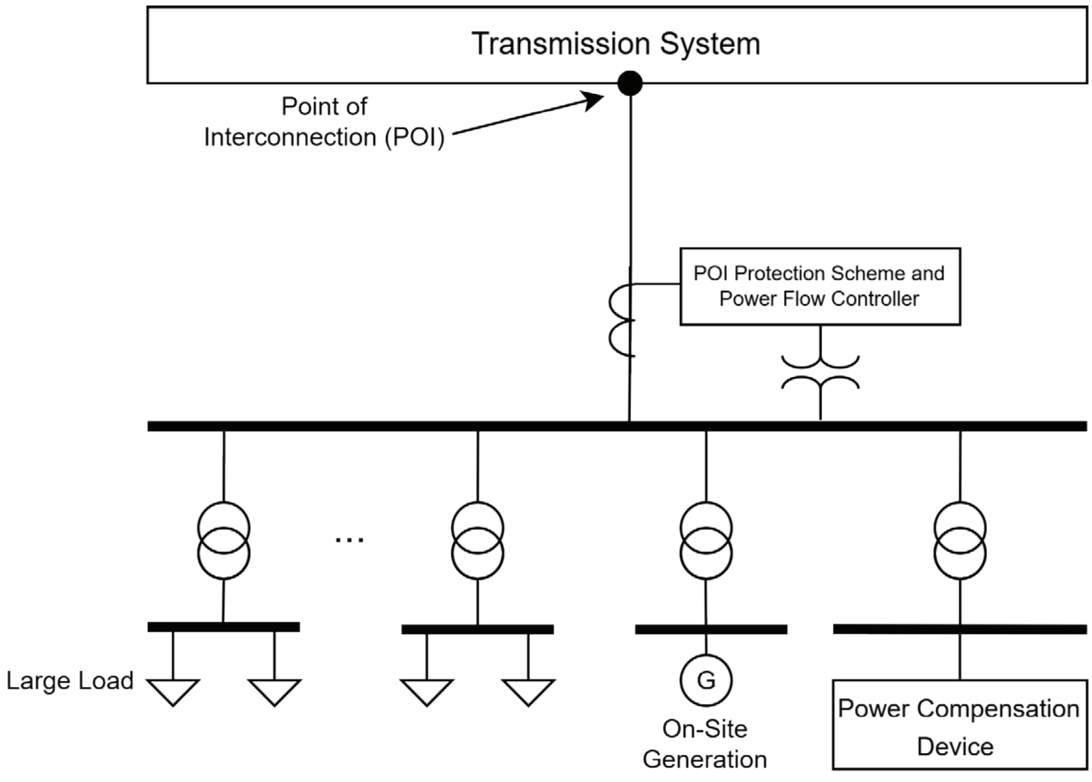
PHOTO: SMA.

- Grid forming (GFM) BESS that stabilize network stability, improve grid strength, and provide grid services that enable more widespread adoption of other IBRs across the system [28]. This can be advantageous in areas of the grid with limited or no synchronous generation nearby.
- Participation in ancillary service markets such as primary frequency response or fast frequency response and improved power quality.

PROTECTION SYSTEM COORDINATION AND ISOLATION SCHEMES

Large generation or load losses can affect adjacent turbine-generators or inverter-based resources, as well as causing large swings on the grid. Co-located load and generation facilities can design protection schemes to avoid large imbalances in generation and load at the point of connection to the grid and also protect their own infrastructure. These schemes may include rapid disconnection or power reduction of the behind-the-meter resources and loads at the facility. This can help avoid thermal network overloads, and stabilize grid stability under (if communication-assisted protections are put in place). Protection schemes enable large loads to connect without introducing stability implications, further enabling a more rapid large load buildout [29].

FIGURE 8.2. **Illustration of POI Protection Scheme to Manage and Maintain Power Flow**



SOURCE: ELEVATE ENERGY CONSULTING.

Transmission Infrastructure Buildout Solutions

TRANSMISSION INFRASTRUCTURE SOLUTIONS

Building out the transmission system is a long-term strategy and national goal in addition to answering the short-term need to serve the large loads of today. Investments in new transmission lines, substations, and reinforcement projects ensure that capacity keeps pace with increasing demand. Long-term planning efforts should prioritize transmission corridors that serve high-growth areas with significant data center activity. Identifying effective strategies to develop large-scale transmission projects—while maintaining affordability and meeting permitting requirements—is a critical priority for the industry.

To help accelerate large load connection, industry can look at innovative ideas beyond conventional transmission infrastructure construction. Some examples include:

- **Hot Line Reconductoring:** Upgrading some transmission and distribution circuits can be completed without de-energizing them, which minimizes service disruptions while increasing capacity. This method is particularly beneficial in areas with high load growth where outages for traditional reconductoring would be rather impractical.
- **Advanced Conductor Technologies:** Reconductoring existing transmission lines with advanced conductors can be a fast, cost-effective way to expand grid capacity using existing rights-of-way. Often this solution has faster permitting and regulatory approvals and shorter construction times compared with conventional new line construction [30].
- **Tower Raising:** For thermally limited issues caused by ground clearance on sagging transmission lines, tower raising can be a viable solution to increase line capacity beyond existing facility ratings. This may be paired with advanced conductor technologies to further maximize existing right-of-way utilization [31].

GRID-ENHANCING TECHNOLOGIES AND OTHER ADVANCED TECHNOLOGIES

Numerous grid-enhancing technologies (GETs) and other advanced technologies can help alleviate grid impacts for new large loads. Some examples include:

- **Dynamic Line Rating:** Dynamic line rating allow utilities to adjust transmission capacity based on real-time conditions such as ambient temperature, wind speed, etc., which may unlock additional real-time transmission capacity.
- **Power Flow Controls:** Power flow controls may help optimize grid utilization, alleviating network constraints such as thermal overloads or voltage violations.
- **Transmission Optimization:** Transmission operators can leverage real-time data to maximize grid capacity by optimizing the transmission system network topology.

Deploying these advanced technologies can improve system utilization and flexibility, reduce network constraints and congestion in real-time, minimize the need for curtailment, and enable faster interconnection of large loads. A combination of these solutions can improve hosting capacity for large loads without requiring extensive new infrastructure.

Load Flexibility and Utility Service Solutions

LARGE LOAD CUSTOMER FLEXIBILITY OPTIONS

Data centers have the technical potential to act as flexible loads, offering value to the grid. In certain cases, this load flexibility could help mitigate peak demands and support grid stability. While several pilot projects and research efforts show promise, widespread deployment remains limited due to technical, economic, and regulatory barriers. Load flexibility can be achieved various ways, including:

- Load reduction such as workload shifting/rescheduling and cooling system control.
- Onsite generation or energy storage dispatch to offset net demand.
- Participation in demand response or controllable load programs.

Flexible load strategies are well-suited for non-critical IT workloads that can be deferred and rescheduled without impacting business operations. When deployed at scale, flexible data centers could support local grid congestion issues as well as regional resource adequacy needs, serving as controllable and dispatchable demand.

UTILITY FLEXIBILITY OPTIONS AND SERVICE OFFERINGS

Utilities are considering developing customized interconnection offerings to enable more rapid integration of large-scale loads such as data centers. Some examples include:

- **Firm vs. Interruptible Service:** Allows for defined curtailment rights in exchange for lower cost of service and possible far less network upgrade costs.
- **Peak Load Curtailment Agreements:** Incentivizes demand reduction during grid stress events through financial or reliability-based incentives.
- **Flexible Interconnection Frameworks:** May include phased load deployments as generation or transmission expansion occurs, mobile generation or other interim solutions, expedited permitting, etc.

These types of utility services seek to provide scalable and grid-friendly integration opportunities that balance speed of deployment with critical grid reliability needs. Embedding load flexibility into utility planning practices can help accommodate a more aggressive data center expansion plan while preserving reliability.

9

Key Considerations for State Regulatory Proceedings

The pressure that large loads place on the transmission system, grid reliability, and cost allocation frameworks are already an issue in many state Integrated Resource Planning (IRP) processes, which include assessments of loads, resources, and reserve margins. However, planning frameworks may not be keeping pace with the unique challenges presented by large load interconnections, presenting an opportunity for reform. Regulators should require utilities to study and report on the impacts of large load interconnection requests as part of their existing resource planning obligations. In particular, utilities should be responsible for assessing how these loads affect system performance, reliability, and fairness to existing customers—and for proposing any needed investments, upgrades, or programmatic responses to manage those impacts.

This chapter is intended to support state regulators, utilities, and intervenors engaged in resource planning proceedings, with relevant considerations that may extend to rate and depreciation proceedings. The guiding questions in Box 4 and Appendix C may help these parties identify the types of information and analyses the utility should incorporate into resource planning processes to ensure that reliability and reasonable rates are maintained across all customer classes. Appendix C provides a more extensive list of questions for state regulators and other stakeholders to use when overseeing IRPs.

The high technical and economic stakes at the heart of interconnection make these questions complex, and they are not intended for regulators to answer directly. Rather, regulators can use these questions as a rule framework to help utilities systematically assess and transparently report the impact of large load interconnections on transmission system reliability and costs. Utilities should have the analytical responsibility of providing this information and are best positioned to carry out the studies and report results as part of their IRPs or filings.

Regulatory Rule Framework Considerations

At a high level, regulatory rules should address the following concepts (example draft language included in italics for reference):

PHOTO: ISTOCKPHOTO/BRIAN BROWN

- **Purpose:** This rule ensures that electric utilities systematically assess and transparently report the impacts of large load interconnections on transmission system reliability, network upgrade needs, and cost allocation.
- **Data Disclosure and Characterization of Large Load Requests:** Ensuring utilities collect and disclose[11] information about large load interconnections to support meaningful planning analysis.

  Utilities shall identify and characterize anticipated or pending large load interconnection requests above [X MW] as part of their Integrated Resource Plan (IRP). For each request, utilities shall:

  - *Provide expected peak demand and load shape (hourly or sub-hourly where available).*
  - *Indicate the interconnection point (transmission or distribution).*
  - *Describe the customer class and load use case (e.g., data center, industrial, crypto).*
  - *Identify known or proposed timing for energization and ramp-up.*
  - *Report whether and how these loads are included in the base load forecast.*

11 Utilities may anonymize data but should preserve sufficient detail to support planning analyses.

- **Transmission and Reliability Impact Assessments:** Ensuring that utilities study the impacts of large loads on system performance, capacity, and reliability using appropriate modeling methods.

  Utilities shall conduct transmission system impact assessments for each large load interconnection request, including:

  - *Power flow, stability, and contingency analysis under peak and shoulder conditions.*
  - *Impacts on local and system-wide planning reserve margins.*
  - *Implications for transmission congestion and curtailment risk.*
  - *Evaluation of any required network upgrades to maintain NERC-compliant reliability.*

  The utility shall summarize these results in the IRP and discuss mitigation measures or proposed investments.

- **Economic impact and cost allocation analyses:** Ensuring the cost impacts of large load interconnections are not unfairly shifted to existing customers.

  Utilities shall analyze and disclose the cost impacts of large load interconnections, including:

  - *Identification of direct and indirect costs (e.g., network upgrades, capacity procurement).*
  - *Proposed mechanisms for allocating those costs (e.g., direct assignment vs. socialization).*
  - *Analysis of rate impacts for existing customers under different cost recovery scenarios.*

  The utility shall propose just and reasonable cost allocation methodologies consistent with state and federal ratemaking principles.

- **Planning Integration and Investment Response:** Ensuring utilities incorporate study results into their actionable plans, budgets, and investment priorities.

  Based on reliability and economic analyses above, utilities shall propose any necessary:

  - *Transmission or distribution investments.*
  - *Demand response or non-wires alternatives.*
  - *Resource adequacy additions.*
  - *Revisions to interconnection study processes or thresholds.*

  These proposals shall be clearly linked to the identified large load interconnection impacts and included in the utility's IRP action plan or preferred portfolio.

- **Reporting, accountability, and continuous improvement:** Institutionalizing regular updates and adaptive improvement of planning rules.

  Each utility shall file an annual or biennial update on large load interconnections, including:

  - *New or withdrawn interconnection requests.*
  - *Updated load characterizations and timing.*
  - *Adjustments to system impact or cost allocation analysis.*
  - *Progress on any infrastructure investments proposed in previous IRPs.*

  Additionally, every [X] years, each utility shall propose improvements to this rule framework based on lessons learned and evolving system needs.

BOX 4

Questions for Regulators to Consier When Assessing Whether Utility Proposals to Serve Large Loads are Just and Reasonable

Grid Reliability and System Planning

- How does the proposed large load impact local and regional reliability, including contingency planning and system stress scenarios?
- Are existing transmission and distribution infrastructure upgrades needed, and who bears the cost?
- What are the risks of large load concentrations creating localized voltage stability or congestion issues?
- How will the seasonal and daily load shape of the large load impact resource adequacy, peak demand, and capacity planning for the larger network?
- Does the utility have sufficient generation capacity to meet the demand without triggering excessive reliance on emergency generation or imports?

Cost Allocation and Consumer Protection

- Who is paying for the interconnection and transmission upgrades, and how are costs allocated between the requesting customer, existing ratepayers, and utility shareholders?
- Are interconnection applicants being asked to make appropriate financial commitments, such as deposits or guarantees, to prevent speculative projects? [32], [33]
- Does the interconnection process prioritize the public interest, ensuring that large commercial loads do not unfairly shift costs onto existing residential and small business customers?
- Are cost-recovery mechanisms transparent, and do they align with regulatory principles of fairness?
- What happens if the large load (e.g., a data center) ceases operations prematurely? Will existing customers be left with the cost of underutilized infrastructure?

Prioritization

- What controls or processes do you have in place to ensure that all customers are treated fairly with respect to study and construction timelines?
- How does the utility or grid operator ensure transparency in interconnection studies and approvals for large loads?
- Are interconnection requests first-come, first-served, or are they prioritized based on economic benefits, reliability needs, or emissions reduction goals?

Stakeholder Engagement

- Is there a neutral third-party evaluation of the interconnection's impacts to ensure objectivity and protect public interest?

Demand Flexibility

- Can the large load be curtailed or shifted during peak demand periods to avoid unnecessary capacity expansions?
- Has the utility considered whether it is in the public interest to require contractual provisions that allow for interruptible service, pricing incentives, or time-of-use (TOU) rates to shape demand?

10

Potential Federal Actions to Address Large Load Risks

The Federal Power Act (FPA) established the legal framework for regulation of electricity in the United States. The Energy Policy Act of 2005 added Section 215 to the FPA, calling for the creation and certification of an Electric Reliability Organization (ERO) as directed by FERC [34]. Since 2006, NERC has fulfilled the role of the ERO, and NERC and its six Regional Entities comprise the ERO Enterprise.

NERC establishes and enforces Reliability Standards for the bulk power system, subject to FERC's review and approval [17]. The ERO Enterprise assesses, investigates, and audits Registered Entities to measure compliance with the Reliability Standards, and can also impose penalties for violations of the Reliability Standards through its compliance and enforcement division [35]. Section 215 applies specifically to the bulk power system and excludes local distribution facilities. The activities of NERC (and NERC members) are governed by the NERC Rules of Procedure [36].

The Rules of Procedure state that "each bulk power system owner, operator, and user shall comply with all Rules of Procedure of NERC that are made applicable to such entities by approval pursuant to applicable legislation or regulation" [36]. Hence, NERC has an Organization Registration program that identifies and registers bulk power system users, owners, and operators "who are responsible for performing specified reliability functions to which requirements of mandatory NERC Reliability Standards are applicable" [37]. The standards also use defined terms and acronyms defined in the NERC Glossary of Terms Used in NERC Reliability Standards [38].

The NERC Compliance Registry includes fourteen (14) entity types that are subject to applicable NERC Reliability Standards:

- Balancing Authority
- Distribution Provider
- Generator Owner
- Generator Operator
- Planning Coordinator
- Reliability Coordinator
- Resource Planner
- Reserve Sharing Group
- Frequency Response Sharing Group
- Regulation Reserve Sharing Group
- Transmission Owner
- Transmission Operator
- Transmission Planner
- Transmission Service Provider

There presently is no defined NERC registration classification for large load customers. Large loads connected directly to the bulk power system or connected indirectly through distribution circuits (even if dedicated connections) are not subject to any applicable NERC Reliability Standards. Thus, there are no federal reliability-based regulations imposed on large loads to support bulk power system reliability, resilience, and security.

Historically, this may have sufficed as individual large loads were unique in nature and typically not a significant size. However, with the changing nature of large loads, it may be suitable for federal regulators to set clear, effective, just, and nondiscriminatory requirements on large load customers through applicability of the NERC Reliability Standards.

Table 10.1 (p. 73) summarizes the NERC Reliability Standards that could apply to NERC-registered large load entities connecting to the BPS [17].

TABLE 10.1. Review of NERC Reliability Standards and Potential Applicability to Large Loads

Standard	Standard Title
CIP-002-7	Cyber Security — BES Cyber System Categorization
CIP-003-10	Cyber Security — Security Management Controls
CIP-004-8	Cyber Security — Personnel & Training
CIP-005-8	Cyber Security — Electronic Security Perimeter(s)
CIP-006-7	Cyber Security — Physical Security of BES Cyber Systems
CIP-007-7	Cyber Security — System Security Management
CIP-008-7	Cyber Security — Incident Reporting and Response Planning
CIP-009-7	Cyber Security — Recovery Plans for BES Cyber Systems
CIP-010-5	Cyber Security — Configuration Change Management and Vulnerability Assessments
CIP-011-4	Cyber Security — Information Protection
CIP-012-2	Cyber Security – Communications between Control Centers
CIP-013-3	Cyber Security – Supply Chain Risk Management
CIP-015-1	Cyber Security – Internal Network Security Monitoring
COM-001-3	Communications
COM-002-4	Operating Personnel Communications Protocols
EOP-012-2	Extreme Cold Weather Preparedness and Operations
FAC-001-4	Facility Interconnection Requirements
FAC-002-4	Facility Interconnection Studies
FAC-008-5	Facility Ratings
IRO-001-4	Reliability Coordination - Responsibilities
IRO-010-5	Reliability Coordinator Data and information Specification and Collection
MOD-032-1	Data for Power System Modeling and Analysis
PER-006-1	Specific Training for Personnel
PRC-004-6	Protection System Misoperation Identification and Correction
PRC-005-6	Protection System, Automatic Reclosing, and Sudden Pressure Relaying Maintenance
PRC-012-2	Remedial Action Schemes
PRC-017-1	Remedial Action Scheme Maintenance and Testing
PRC-019-2	Coordination of Generating Unit or Plant Capabilities, Voltage Regulating Controls, and Protection
PRC-027-1	Coordination of Protection Systems for Performance During Faults
PRC-028-1	Disturbance Monitoring and Reporting Requirements for Inverter-Based Resources (*only IBRs)
PRC-029-1	Frequency and Voltage Ride-through Requirements for Inverter-based Resources (*only IBRs)
PRC-030-1	Unexpected Inverter-Based Resource Event Mitigation (*only IBRs)
TOP-001-6	Transmission Operations
TOP-003-7	Transmission Operator and Balancing Authority Data and Information Specification and Collection
VAR-002-4.1	Generator Operation for Maintaining Network Voltage Schedules

SOURCE: ELEVATE ENERGY CONSULTING.

APPENDIX A
Large Load Data Submittals

It is important to gather sufficient information from large load customers, particularly data center customers, that provides the utility with sufficient information to conduct reliability studies and assessments of grid impacts.

This appendix outlines fundamental information utilities should request from data center developers for new delivery points. The same types of information can be adapted for modification of existing delivery points. The information is based on various utility large load interconnection forms, applications, and requirements [39], [40], [5], [41].

Customer Information

Company name	
Current customer?	
Company address	
Company point of contact (POC) name	
Company POC phone number	
Company POC email	
Company POC fax number	

Readiness Information

Site control obtained?	
If no, what are the plans to obtain site control?	
If yes, what is the name, address, and contact information for property owner of record?	
Financial institution name, address, and contact information	
Property owner signature	
Financial institutions signature	

Load Interconnection Request Information

New load interconnection request or modification to existing request?	
Load address or GPS coordinates	
Load delivery point to transmission/distribution system	
Description of load connection to electric grid	
Prefer overhead or underground service?	
Delivery point nominal voltage level	
Seasonal Peak MVA Transmission Service Request	
Description of inter-hourly, hourly, daily, seasonal, and annual load characteristics including peak MVA demand, load profile, etc.	
Expected load capacity factor (annual % of peak demand) and calculation of capacity factor	
Expected demand ramp-up (phase-in) including month and year, and peak demand requested	
Description of power requirements at startup (i.e., commissioning, testing, etc.)	
Description of reliability or redundancy requirement (i.e., dual feeds, redundant systems, coordination with UPS, etc.)	

Interconnection Request Timeline

Requested load energization date	
Expected date for load customer construction to start	
Expected date for load customer construction to be complete	
Requested date for utility construction to commence	
Requested data for utility construction to be completed	
Other related engineering, procurement, or construction milestones	

Load Substation Transformer Information

Transformer primary voltage	
Transformer secondary voltage	
Transformer nameplate capacity (MVA)	
Transformer impedance (R/X/B) and base values	
Transformer tap ranges	
Transformer tap position	
Fixed or under-load tap changing	
Transformer connection (e.g., wye-wye, delta-wye, etc.)	
Transformer make and model	

Load Composition Information

Load Type	Spring Day (50–70 ˚F)	Summer Peak (100–115 ˚F)	Winter Peak (0–30 ˚F)
Motor A: % of total load consisting of 3-phase induction motors used in industrial air conditioning compressors or refrigeration systems (e.g., large building central air cooling)[a]			
Power Electronic Motor A: % of Motor A load comprised of electronically-interfaced motor loads such as variable frequency drives (VFDs)[b]			
Motor B: % of total load consisting of 3-phase induction motors used in commercial ventilation fans and air handler systems[a]			
Power Electronic Motor B: % of Motor B load comprised of electronically-interfaced motor loads such as VFDs[b]			
Motor C: % of total load consisting of 3-phase induction motors used in water circulation pumps in cooling systems.[a]			
Power Electronic Motor C: % of Motor C load comprised of electronically-interfaced motor loads such as VFDs[b]			
Motor D: % of total load consisting of single-phase air conditioning loads (most commonly found in residential A/C units, not commercial)[a]			
Power Electronic Load: % of total load consisting of power electronic devices/converters such as servers, high-efficiency appliances, consumer electronics, computers, etc.[a]			
Static/Other: % of total load remaining consisting of other loads such as lighting, cooking, small water heaters, etc.[a]			
Equivalent impedance (R and X) between customer delivery point and end-use loads (i.e., tie lines, transformers, substation delivery equipment, etc.) with description impedance base values and how this impedance was derived.			

a Total % of load should sum to 100%; otherwise, an explanation shall be provided.

b These %'s should be a percentage of the reported value preceding this cell. For example, if Motor A load is 10% of the load yet if it is all connected via VFD, then the subsequent cell should state 100% (not 10%).

Load Reconnection Information

Manual or automatic reconnection to grid? (Explain characteristics)	
Immediate reconnection or delayed reconnection? (Explain process)	
Time to reconnect, if automatic (seconds)	
Reconnection frequency and voltage settings (thresholds, deadband, duration), hysteresis curve, etc.	
Reconnection ramp rate and ramp rate limit (% of total load/min)	
Description of reconnection process and time (stages, specific loads, etc.)	

Load Backup Power and UPS Information

Total backup (emergency) generation capacity (MVA)	
Backup generation fuel type	
Backup generation duration (based on typical access to fuel/energy)	
Total discharge capacity of backup battery energy storage systems (BESS) (MVA)	
% of digital load processes shifted to redundant locations off-site	
Time duration for load transfers to occur	
UPS voltage sag threshold and duration curve for disconnection (list of trip values and durations)	
UPS voltage swell threshold and duration curve for disconnection (list of trip values and durations)	
Description of measurement quantities used for voltage sag and swell measurements (location(s) at site, per-phase or 3-phase, RMS filtered quantity or instantaneous point of wave measurement, etc.)	
UPS high and low frequency threshold and duration curve for disconnection (list of trip values and durations)	

Load Operational Performance Information

Load power factor range (lead/lag)	
Description of load cycling performance (random, price-sensitive, hourly, daily, seasonal, etc.)	
Maximum ramp limits (% of total load/min)[a]	
Narrative describing the frequency or variability of expected load ramping	
Power quality issues or concerns that affect system performance (e.g., large motor loads starting, power factor, total harmonic distortion, chopped waveform loads, planned capacitors and filters, etc.)	

a If the load is expected to ramp or cycle within a minute (i.e., seconds or less), this information should be provided separately with a description of the load ramping, oscillation, and/or cycling characteristics—magnitude, duration, frequency, etc.

Grid-Connected Generation

Total capacity of customer generation that connects and interacts with the grid (MVA) (additional generation information will be required)	
Operational characteristics of generation behavior when connected to the grid such as participation in wholesale electricity market, ancillary services, charging/discharging patterns, demand-side management, etc.	

Interconnection Request Documentation

Site Plan, Layout, and Electrical Design	
Site plan including layout, substation configuration, access roads, and equipment	
Electrical single line diagram including layout and configuration of customer electrical equipment	
Site Electrical Protection Design	
Electrical protection and control design functional diagrams including protection system equipment (make and model), protective functions enabled, and protection settings for each protection	
Transformer nameplate ratings, test reports, specification sheets, and saturation curves	
Site Electrical Controls	
Electrical operating procedures and operational characteristics description	
Control narrative explaining any applicable load control set points, operating characteristics, etc.	
Ride-Through Performance	
All UPS protection and control settings, including voltage and frequency disconnect and reconnect measurements and settings	
Load site voltage and frequency ride-through capability curve and a description of how the curve was derived	
Number of successive faults and the duration of faults the load can successfully ride-through including a description of how this information was derived	
Modeling Information	
Positive sequence dynamic model using the composite load model (or other utility-accepted dynamic model(s))	
Positive sequence user-defined dynamic model, when requested by utility	
Electromagnetic transient (EMT) model	
Short-circuit model	
Harmonics model or information, if required	
Control block diagrams, control narratives, model documentation, and technical justification narrative of model development	

APPENDIX B

Technical Requirements for Large Loads

This appendix provides additional details and insights regarding some of the technical requirements outlined in Chapter 5.

Load Interconnection Size Limits

Loss of a single end-use load has not historically had a significant reliability risk to the BPS, and large load customers often have sought multiple service connection points to improve reliability of service. However, with ever-increasing load interconnection request sizes, single load connection points may pose reliability risks to the local or interconnected grid. The ability to transfer digital services across loads (e.g., cloud data center resilience) may reduce the need for customers to seek additional service points.

Thus, transmission providers should consider the loss of single large load customers, loss of credible multiple load connection points, and the aggregate loss of large load customers due to common grid events in reliability studies. In some cases, it may be prudent to establish load interconnection limits at a single point of interconnection to minimize risk. Large load customers can connect larger loads to the system; however, they would require multiple service points. Above a certain size threshold, service points may need to be from different transmission substations to avoid risks of loss of a substation.[12]

ERCOT has proposed such limits due to concerns with grid frequency and voltage control for inadvertent tripping of large loads. Dominion Energy also limits the number of direct-connect loads (tapped facilities) on transmission lines to four and relies on engineering judgment in applying this criterion. Dominion also limits the amount of direct-connect load at any substation to 300 MW for reliability reasons [5].

12 This is a credible contingency studied as part of NERC CIP-014 risk assessments: https://www.nerc.com/pa/Stand/Reliability%20Standards/CIP-014-3.pdf

Model Sharing

Each transmission provider should specify modeling requirements for large load customers that span the different types of simulation domains used to conduct reliability studies. Types of models may include:

- Powerflow model and/or information.
- Phasor domain transient (PDT)[13] dynamic model.
- Electromagnetic transient (EMT) model.
- Short-circuit model.

Each transmission provider should specify the format and level of detail for each model type and specify the corresponding documentation (model structure and block diagrams, controls narrative, load composition breakdown, etc.) that must accompany the model submission. Given the depth and complexity of some of these studies, these types of requirements must be rather detailed. The transmission planner and large load customer can work collaboratively through the study, and the requirements should be defined clearly to help facilitate effective collaboration.

The transmission provider should determine if standard library models are sufficient or if detailed user-defined models are needed, where applicable. The dynamic models should also be accompanied by a controls narrative, and electrical protection systems should be represented in each model, where applicable.

Data Recording and Monitoring Requirements

Each transmission provider should specify data recording requirements for large load customers. This data is used for monitoring the performance of large loads during grid events, conducting model validation, and forensic event analysis. Examples of measurements include:

- **SCADA Telemetry:** Data within the customer substation—whether utility- or customer-owned—capturing the status of all breakers, switches, and electrical devices, as well as voltage, current, and power quantities throughout the station.
- **Sequence of Events Recording (SER):** Recording enabled in all protective relays and other similar devices capturing the status and cause of change for any devices within the facility—breakers, reactive devices, switches, transformers, auxiliary loads, etc.
- **Digital Fault Recording (DFR):** Data about the main connections between the load customer and the utility including triggered, high-speed, point-on-wave measurements voltage, current, frequency, and active and reactive power.

13 i.e., fundamental frequency positive sequence dynamic simulation models such as PSLF, PSS®E, etc.

- **Dynamic Disturbance Recording (DDR):** A continuous recording device (e.g., a phasor measurement unit) capturing positive sequence voltage and current phasors, frequency, active power, and reactive power at the connections between the load customer and the utility. This functionality can be integrated into most modern microprocessor-based relays.
- **Power Quality Monitoring:** Power quality indicators to ensure compliance with the utility's power quality standards and to support forensic event analysis.

Voltage Ride-Through Requirements

Each transmission provider should establish voltage ride-through requirements that define the range of voltages for which the large load must remain connected to the BPS. Without some degree of ride-through capability, large loads could unexpectedly or abnormally trip or disconnect from the system for normal grid faults. As illustrated in Chapter 2, unexpected disconnection from the grid due to normal grid faults can cause severe performance issues to the grid that can result in instability, uncontrolled separation, or cascading outages.

Voltage ride-through requirements should strike a balance that considers the following:

- Normal clearing time of transmission and/or sub-transmission system protective relaying.
- Large load facility design (end-use component capabilities, PDU and UPS ride-through settings and capabilities, etc.).
- Generator ride-through capability curves.
- Latest versions of NERC PRC-024 and NERC PRC-029 [17] and international requirements [18].
- IEEE 2800-2022 Clause 7 ride-through requirements [42].

While there may be some additional costs to ensuring ride-through performance, these pale in comparison to the costs associated with system-wide network upgrades to minimize voltage drop during and immediately following grid fault events (e.g., STATCOMs, synchronous condensers, and transmission infrastructure). This is an inevitable situation due to the physics of the electric power system. Grid planners and operators cannot expect to lose unknown and potentially significant amounts of power every time a fault occurs.

Large load customers can design their equipment, protection systems, and controls to reasonably accommodate the need for some degree of ride-through performance. However, excessively wide ride-through performance curves should not be unnecessarily introduced to avoid costly solution options.

Frequency Ride-Through Requirements

Each transmission provider should also establish frequency ride-through requirements that define the range of frequencies for which the large load must remain connected to the BPS. Again, abnormal or unexpected disconnection of large loads during abnormal frequency events could further exacerbate grid reliability risks. This is particularly a concern during overfrequency conditions where excess generation versus load is driving frequency high. Additional load tripping would further drive frequency upward and could disconnect additional loads, resulting in cascading outages and widespread system instability.

While frequency disconnection is less of a concern and risk for large loads, particularly in large, interconnected bulk power systems, it is still important to establish a performance basis to be able to effectively plan and operate the system. These requirements will often get programmed into protective relaying at the site and are used as a basis for designing other protection systems within the facility.

Utilities establishing frequency ride-through requirements for large loads should consider requirements for generation assets such as NERC PRC-024, NERC PRC-029, and IEEE 2800-2022, along with reasonable equipment capabilities for large load facilities.

Power Factor / Reactive Power Requirements

Each transmission provider should establish power factor requirements that ensure large load facilities are designed and operated to maintain steady-state reactive power limits within a defined range of consumption (or production). For example, large loads may be required to remain within ± 0.95 power factor within the normal operating range around nominal voltage schedule. For a 1,000 MW data center, this would equate to consuming upwards of 330 MVAR reactive power from the system. Thus, for very large loads, tighter power factor limits may be required.

Large load customers unable to meet these requirements may be required to install supplemental reactive power devices to keep reactive power within defined limits. Depending on the reactive power profile of the load, this may require shunt capacitors/reactors for slowly varying changes or dynamic reactive devices such as STATCOMs for variable or sporadic changes in reactive power.

Power Quality Requirements

Each transmission provider should establish power quality requirements to prevent equipment damage for both the utility and customer infrastructure, ensure high quality of service, and avoid instability and harmonics issues. Power quality requirements may include the following:

- **Acceptable Voltage Range:** The large load facility shall not cause voltages to exceed acceptable ranges, in accordance with utility practices and/or applicable standards (e.g., ANSI C84.1 [43]).
- **Harmonics:** The large load facility shall not contribute total harmonic distortion (THD) at its point of interconnection (POI) beyond the limits specified in IEEE Standard 519 or its successor [44]. Individual harmonic components may be specified and shall be operated within.
- **Flicker:** The large load facility shall not cause voltage flicker to exceed defined permissible levels and must align with IEEE Standard 1453 [45]. Flicker events shall not cause undue interference to other customers or compromise utility operations.

14 Note that forced oscillations can occur at the generation, transmission, or distribution level and interact with the larger grid.

- **Imbalance:** The large load facility shall maintain balanced load across all electrical phases to limit voltage unbalance at the POI to less than defined limits and/or applicable standards (e.g., IEC 61000-3-13 [46]).
- **Transients and Surges:** Equipment installed at the large load facility shall not introduce transients or surges that negatively impact the utility infrastructure or operations; protection and mitigation measures such as filters or surge suppressors may be required.

Large load customers are required to perform compliance testing for power quality and submit periodic reports to verify ongoing compliance. Acceptable testing methods are outlined in IEEE, IEC, or other relevant standards. Failure to comply with power quality requirements may result in disconnecting the facility from the utility system until it complies.

Oscillation Damping Requirements

Each transmission provider should establish oscillation damping requirements to ensure that large loads are contributing positive damping to the bulk power system and are not inadvertently causing forced oscillations, particularly those that can interact with local or system modes. Equipment and processes within the large load facility (e.g., motors, drive, power electronics, digital processes) may seek to operate on a cyclic or repetitive oscillatory basis, and these types of behaviors can have adverse impacts on the local and large interconnected grid. The large load facility shall not introduce or amplify oscillations at synchronous, subsynchronous, or supersynchronous frequencies.

Oscillatory behavior of the large load facility (i.e., ramps up and down on a cyclical basis) can interact with the natural system modes (i.e., inter-area modes) which can amplify the forced oscillation across the entire interconnected system. These types of forced oscillations should be carefully studied and avoided. An example of this occurred at a generation[14] facility in Florida in 2019, where a measurement error resulted in cyclical oscillations in the plant at about a 4-second periodicity (i.e., 0.25 Hz frequency). This coincides with one of the natural system modes and resulted in the entire Eastern Interconnection experiencing multi-hundred MW swings for 18 minutes, until the plant was disconnected. Upon further investigation, the facility experienced damage that required significant repairs and maintenance before bringing the unit back online [6].

Additionally, if the large load facility is being connected near other large power electronic devices or transmission network series compensation, this could introduce SSO risks. These conditions require EMT simulations to ensure that subsynchronous interactions (SSI) will not occur. This requires accurate and careful modeling of the large load facility, the surrounding transmission network, and any nearby generation and loads.

These types of oscillations, depending on the nature and cause of the oscillation, can occur very quickly and unexpectedly. Therefore, it is important to study them ahead of real-time operation and to have adequate monitoring equipment to detect and mitigate them, if possible. This may require immediate operational actions to address the oscillation as well as forensic event analysis and information sharing between parties to make any design, protection and control, or operational adjustments.

Short-Circuit and Protection Requirements

Each transmission provider should establish minimum and maximum short-circuit current levels at the customer interface to ensure customer equipment is rated appropriately. This is particularly relevant in situations where the large load facility may have grid-paralleled generation that can notably affect short-circuit levels. The load customer (or co-located generator customer) may be responsible for mitigation measures regarding excess fault current levels.

Load customer protection schemes will also need to be coordinated with the utility protection system philosophy. These utility protection philosophies can vary widely, and the industry would benefit from aligning on common or best practices. Regardless, the following are a few areas where careful coordination is necessary:

- Using utility-defined protection schemes, equipment, and/or settings for the direct connection facilities in which the load customer is connecting to the larger grid.
- Ensuring that facility-level protections and settings are provided to the utility to ensure that grid faults do not cause any misoperation or adverse impacts system-wide. Coordination should cover UPS/rack-level protection for data centers, ensuring alignment with utility systems.
    - In the Northern Virginia event described in Chapter 1, data center protection settings were not properly coordinated with utility reclosing schemes; thus, widespread data center tripping occurred for what the utility considered "normal operation."
- If backup generation operates in parallel with the grid, studies must evaluate fault contributions, breaker duty impacts, and coordination with system protection schemes.

Data Sharing

Each transmission provider should establish data sharing requirements that ensure large load customers provide the transmission providers with all relevant operational and planning data for each large load facility to support system modeling, reliability assessments, engineering evaluation, protection coordination, and real-time operations. Examples of such data include:

- Load forecasts, including both short-term (days and weeks ahead) and long-term (load growth over months and years).
- Equipment specifications, ratings, and nameplate diagrams.
- Protection and control schematics and settings relevant to utilities interconnection requirements.
- Real-time telemetry (SCADA) for operational data exchange.
- Event monitoring data and logs following grid disturbances, trips, and other major types of facility operations.
- Backup generation information, including details on capacity, operational modes, protection schemes, interconnection status, and designs that adhere to utility back-up generation requirements.
- Demand response capabilities and real-time status.

- Outage and maintenance activities (both planned and unplanned) and corresponding impacts to facility load forecasts.

All data submissions by large load customers must adhere to utility-defined formats and update frequencies.

Given the sensitive and competitive nature of large load facility information, utilities may also want to establish non-disclosure agreements (NDAs) or similar contracts to ensure both the utility data and large load customer data are fully protected. One enhancement to these contracts could include specific language that prohibits either party from selling, sharing, or disclosing any shared/submitted information.

Operational Control and Communications Requirements

Each transmission provider should establish requirements for real-time operation and communication for large load customers. Large load facilities must operate in compliance with utility-defined operational reliability criteria. This may include ramp rate limits, real-time dispatchability, voltage/reactive power support, and ride-through capabilities. Automated and manual controls should be in place to respond to utility directives during normal operations and emergency conditions.

Transmission providers must set requirements for secure, reliable communication channels between large load customers and utilities to enable real-time monitoring, coordination, and emergency response. Communication protocols should align with industry standards (e.g., IEEE, IEC 61850, NERC CIP) and support SCADA integration, event reporting, and 24/7 availability of key personnel.

In addition, specific types of operational notifications by the large load to the utility should be put into the transmission providers requirements. These may include:

- Energization notifications and communications.
- Interim operations notification when the large load is only operating for a defined period of time (e.g., not continuous operations).
- Emergency operational conditions at the large load facility.
- SCADA and other real-time control status, including failures and communications outages.
- Limited operations notification when outages, maintenance, equipment failure, or other incidents at the large load facility occur that impact the load level of the facility or the grid interconnection.

Emergency Response and Coordination

Each transmission provider should establish requirements for large loads to develop, maintain, and share an emergency response plan that outlines contingency actions, communication protocols, and coordination with the utility during equipment failures, blackouts, frequency/voltage excursions, cyber incidents, natural disasters, or other major types of incidents. The emergency response plan should also include designated personnel that must be available for emergency coordination and drills with the utility, as required. Emergency response plans must also include backup generation details and conditions when they would be in operation, all of which must adhere to the transmission provider's backup and parallel generation requirements. Facilities with backup generation or islanding capabilities must follow approved procedures for safe transitions, as defined by the transmission provider and relevant industry standards.

Emergency response plans must be shared with the transmission provider upon any updates to the plan. Key information to be shared with the utility includes:

- Key personal contact information for the utility, including 24/7 Emergency Hotline, local facility operation center, local onsite staff, dedicated account representative, dedicated grid/electrical engineer for the facility, on-site technicians, on-site security, and facility manager.
- Initial notification procedures.
- On-going update procedures as emergencies progress in time.
- Post-emergency review process between large load and transmission provider.

Operations and Maintenance Requirements

Each transmission provider should establish requirements for large load customers to maintain their facility's electrical infrastructure, protection systems, and control equipment per utility and industry standards. These requirements should include communication and coordination of scheduled maintenance; large load customers should be required to immediately report emergency maintenance or operational outages to their transmission provider. Compliance with utility inspection, testing, and reporting requirements should be mandatory and defined in the requirements.

Transmission providers should clearly define ownership and maintenance responsibilities for all grid-connected equipment. Maintenance schedules should be set in accordance with equipment manufacturer recommendations and coordinate these schedules far in advance so that planned outages and other maintenance events do not affect grid reliability. Requirements can also set the expectation for quick communication and coordination between the two parties regarding any urgent or unplanned maintenance that may be required over the life of the facility.

Demand Response Requirements

Each transmission provider should require any large load facility that is participating in demand response programs to share all relevant demand response details and to comply with demand response dispatch signals, response times, and performance verification criteria. Important requirements include:

- Coordination of load curtailment or shifting to minimize adverse grid impacts while aligning with market and reliability requirements.
- Utility audits of load demand response capabilities and performance over time.

- Definitions for all monitoring data and other information necessary to evaluate the demand response of the facility over time.

Utility Right to Monitor and Enforce Requirements

Each transmission provider should have the right to monitor and enforce compliance with the requirements outlined for large load customers to maintain the safety, reliability, and quality of service across the electric system. Specific rights include:

- **Monitoring and Data Access:** The transmission provider has the right to monitor the performance and operational characteristics of the large load facility at the point of interconnection. The large load customer shall provide the utility with access to relevant operational data, including but not limited to real-time measurements, event logs, protection and control settings, electrical equipment configuration and design, and any applicable compliance reports, upon request.
- **Site Inspections:** The transmission provider may conduct electrical site inspections of the large load facility to verify compliance with interconnection and operational requirements. The large load customer shall provide reasonable access to authorized utility personnel.
- **Compliance Verification:** The transmission provider should reserve the right to require the large load customer to perform tests and verification procedures to demonstrate compliance with other specified requirements. Such procedures may include, but are not limited to, desktop engineering analysis, harmonic measurement and analysis, load flow and dynamic studies, protection coordination assessments, and power quality assessments.
- **Corrective Actions:** If the large load facility is non-compliant with any of the requirements, the transmission provider may issue a notice requiring corrective actions within a specified timeframe. The customer is responsible for implementing corrective measures at their own expense to restore compliance.
- **Disconnection Authority:** The utility reserves the right to temporarily or permanently disconnect the large load facility from the electric system if non-compliance with requirements poses a risk to system reliability, safety, or other customers; if the customer fails to implement corrective measures within the specified timeframe; or if emergency conditions arise that necessitate disconnection to protect the grid. Disconnection should be performed in accordance with the defined requirements and within applicable regulatory and contractual provisions.
- **Notification:** The utility should provide reasonable notice of any required monitoring, inspections, or enforcement actions, except in cases where immediate action is necessary to protect system reliability or public safety.

These types of provisions should be included in the contractual requirements between the transmission provider and the large load customer as a condition of interconnection and continued service, but may also be documented in the facility interconnection requirements.

APPENDIX C

Detailed List of Questions for State Regulators

As large loads become more common and impactful, utilities need clear, proactive plans to manage them. This chapter provides state regulators, utilities, and intervenors involved in planning, rate, or depreciation proceedings with questions to support rigor and accountability throughout the interconnection process. These questions help ensure that large load interconnections are reviewed fairly, that reliability risks are identified, that consumers are protected, and that costs and responsibilities are shared appropriately.

Protecting Existing Customers

- What measures are being taken to ensure that costs and risks associated with the interconnecting large load are not being passed onto existing customers?
- What financial safeguards are in place to ensure that debts or financial obligations do not adversely impact ratepayers?
- Will existing customers be subsidizing infrastructure investments or operational costs in any way? Why or why not? How is this guaranteed?
- What is the plan for dealing with stranded assets if large load customers do not materialize, suspend development, or operate for a shorter duration than the generator assets?
- What contingency plans are in place to ensure that unrealized demand (e.g., from abandoned projects or loads that demand less energy than projected) does not adversely affect existing customers?
- How is the utility assuring that large load customers will remain in the region long term?
- Are existing customers adequately represented and educated on the benefits and risks presented by large load customers? Is the commission ensuring that ratepayers and stakeholders have opportunities for informed input into current and future decisions?
- How are existing customers and ratepayers being protected from higher energy costs and prices given the large increase and demand and incremental generation costs?

- What are the projected economic benefits (e.g., construction job creation, permanent job creation, tax revenue) of this project?

Jurisdictional and/or Legal Issues

- Do the proposals or plans for large load interconnection seek or require changes to the existing regulatory process? What are the primary drivers or reasons for such changes?
- What specific regulatory requirements are being avoided with such changes, and what measures are in place for oversite, where applicable?
- Does the proposed approach align with other utilities and states? If not, would the petition or proposal establish new precedents for avoiding any specific jurisdictional obligations?
- What impacts would this have on existing ratepayers?
- Does the petition or request align with broader state-level resource goals and goals of the broader electricity market?

Large Load Application Process

- What information is required for the initial large load interconnection request? Is the information adequate to assess the credibility, certainty, and readiness of the interconnection customer to seek transmission service?
- How does the transmission provider assess the adequacy and completeness of the information provided at the time of interconnection request to ensure that all models are provided and all technical requirements are met by the proposed facility?
- What financial commitments (i.e., deposits) are required for large load interconnection requests? Do those financial commitments escalate throughout the interconnection process?
- What site control requirements exist for large load interconnection requests, and are these considered as part of a "readiness" assessment?
- What technical and financial capabilities are required for an interconnection customer to be deemed a credible applicant? Is that criteria made public?
- How does the transmission provider ensure that this project is not being added to other interconnection queues in other regions around the region or country?

Large Load Interconnection Requirements

- Are the large loads connecting to the distribution system or transmission system? Who is the interconnecting entity?
- How are the distribution and transmission providers coordinating interconnection requirements to ensure alignment of transmission and distribution system reliability needs?
- Have the distribution and/or transmission provider established clear, effective, consistent interconnection requirements for large loads that include the key topics described in this paper?

- Do those requirements include data sharing, modeling, operational performance limitations (e.g., ramp rate limits), oscillations, ride-through performance, monitoring data, event analysis support, and the various other topics covered in this report?

Large Load Queue Management

- Does the utility have a dedicated queue process for large load interconnection requests?
- Is this queue process administered by the transmission or distribution organization (or department) or economic development department, and how are these organizations and departments collaborating with each other through the process?
- What type of queue process is used—serial, cluster, other? What is the reasoning for the type of queue process used?
- If using a serial queue process, what checks and balances are in place to ensure that load interconnection requests are processed in a timely manner and that speculative interconnection requests are removed from the queue without causing unnecessary backlogs or delays for other legitimate requests?
- Are there defined timelines for how long a large load interconnection request can remain in the queue before being removed?
- Are clear, explicit queue milestones, costs, and timelines established that hold the large load customer accountable to move the queue process along? Are the costs for queue application and milestone development high enough to discourage speculative projects?

Large Load Operational and Performance Considerations

- Does the transmission provider require the large load customer to provide some form of narrative or other data that explains how the large load facility will operate when connected to the bulk power system?
- Is the large load customer required to provide the following information to the transmission provider/transmission planner?
    - Facility electrical topology and single line diagram.
    - Protection and control systems throughout the facility and their associated settings.
    - Load voltage and frequency ride-through curves (threshold and duration).
    - Load variation narrative and explanation (frequency and magnitude of variations).
    - Expected ramp rates.
    - Restoration settings.
    - UPS protection and control settings.
    - Load composition information.
    - Auxiliary equipment capabilities, ratings, and protection settings.

- Explanation and technical details related to fast ramping and oscillatory behavior.
- Power quality impacts.
- Short-circuit levels.
- Backup generation and grid-paralleled generation information.
- Transformer and other equipment ratings, documentation, etc.

Load Forecasting

- Is there a defined or formalized methodology for determining when large load interconnection requests enter system demand forecasts and are subsequently included in integrated resource planning and other long-term transmission or resource procurement activities?
- What specific interconnection milestones (site control, financial, technical, etc.) must be met for considering large loads in models and studies?
- How are large loads differentiated from other demand growth projections?

Large Load Modeling

- Have large load modeling requirements been established by the transmission provider or transmission planner? Do they include production cost, steady-state powerflow, dynamic stability, EMT, and short-circuit models?
- Are these models required as part of the large load interconnection application? Or are they required at later stages throughout the interconnection study process? Are these milestones established and enforced?
- How are these models verified to be accurate representations of the equipment proposed?

Large Load Interconnection Studies

- What is the process and what are the milestones for initiating large load interconnection studies?
- Are any types of cursory or high-level analyses done prior to conducting a more comprehensive interconnection study? Why or why not?
- What type of large load studies are conducted for each interconnection request? Do they satisfy the study-specific questions detailed below?
- What criteria determine whether a type of study is required (e.g., interconnection request size)? Are these criteria codified, shared with applicants, and available publicly?
- What are the average costs of conducting large load interconnection studies?
- What mechanisms exist for recovering transmission system costs from large load interconnection customer requests? Are large load customers paying for studies performed by the transmission provider, whether qualitative or quantitative? If not, how are these costs covered by the utility?

- **Production Cost Analysis Studies:**
  - Are 8,760-hour studies being conducted to ensure that large loads can be met at all hours of the day given the projected resource mix proposed by the utility?
  - Are large load demand profiles (daily, seasonal, price-sensitive, and other variabilities) documented, well-understood by the utility, and modeled appropriately?
- **Powerflow and Contingency Analysis Studies:**
  - Which powerflow base cases are used to conduct steady-state thermal and voltage violation analysis?
  - How many contingencies are included in these studies?
  - Are the NERC TPL-001 planning standard contingencies included in the analysis, or at least a more stringent list of contingencies?
  - Are N-1-1 operating conditions considered?
- **Dynamic Stability Studies:**
  - What method is used to reduce the list of contingencies to study in dynamic simulations? How many contingencies are studied for each load interconnection in this domain?
  - Are electromechanical oscillations considered in dynamic studies?
  - Are the resonant effects of data center AI load ramping/variability considered in these studies (i.e., a form of forced oscillation)?
  - How are the stability impacts on nearby generators considered in these studies?
  - Are motor restart studies conducted?
- **Short-Circuit Studies:**
  - Are breaker duty studies conducted?
  - Are short-circuit studies (ASPEN, CAPE, etc.) conducted for large load interconnections, or are these studies only conducted in positive sequence simulation platforms?
  - How are impacts to protection systems analyzed for large load interconnections?
  - What protection system modifications must be made for these large loads?
  - What long-term effects are large loads having on short-circuit levels across the system? Are these effects positive or negative?
- **EMT Studies:**
  - Are EMT studies being conducted for large load interconnections? If not, why not?
  - Are fast-ramping and oscillatory behaviors of data centers, particularly AI data centers, studied by the utility in the EMT domain? How is the utility studying potential electromagnetic transients (e.g., capacitor switching)?

- How are subsynchronous oscillations, subsynchronous control interactions, and/or sub-synchronous torsional interactions being studied to ensure large loads do not cause serious adverse impacts or damage with existing power electronic controllers or synchronous generators?

Transmission Network Upgrades

- How is the utility coordinating with stakeholders to address transmission network performance deficiencies and assess potential network upgrades required for large load interconnections?
- What alternative solutions are considered as part of network upgrades beyond transmission infrastructure investments?
- What advanced technologies are included in these sensitivity assessments? Examples include GFMinverter technology, FACTS devices, high voltage DC (HVDC) technologies, controls tuning, BESS, etc.

Cost Allocation for Network Upgrades

- Are the large load customer direct connection facilities allocated the full costs of network upgrades?
- Is this consistent across transmission and distribution connections? Are existing load service requirements for typical residential, commercial, and smaller industrial facilities used for large load interconnections? Do practices need to adapt for large load customers, even if dispersed across multiple distribution load points?
- Is the large load customer entitled to any refund or discount of contributions made to direct connection costs?
- How are broader network upgrade costs allocated to large load customers?
- For any costs not fully accounted for by the large load customer, what cost allocation methodology is used for allocating the broader upgrades to large load customers versus being considered “network benefits”?
- How does the cost allocation methodology compare with utilities in different states or regions, and why?
- How are the full suite of network impacts considered in the cost allocation considerations? Examples include increased congestion levels, voltage issues, degradations in stability, reduced operational maintenance windows, etc.

Financial and Other Terms of Service

- Does the utility use tariffs or special contracts to hold large load customers to minimum load factors or a specified power factor range? How are customers penalized if they fail to meet these targets?
- Does the utility levy monthly demand charges? How are charges calculated—by contract capacity, peak demand from previous months, or a combination of both (i.e., demand ratcheting)?
- Do utility tariffs or contracts reserve the utility's right to reduce supply to large load customers when necessary to maintain grid reliability (e.g., during extreme weather events)?
- What language do utilities use to specify customers that are subject to large load tariffs? Do they identify industries by name, which may be discriminatory? Or do they identify the characteristics (volatility, non-permanence, etc.) that distinguish a load as extraordinary and qualify it for the tariff?
- Do utilities require collateral or minimum credit ratings from customers to protect against delinquent bill payment?
- Do utility tariffs specify an exit fee for large load customers that exit the tariff or terminate service before the end of the term?
- What are the terms of power purchase agreements offered by power plant operators and electricity markets? Do they enable customers to "game the system" (e.g., buying low-cost energy behind the meter and selling it back to the market for profit in times of high demand)?
- Who bestows economic development benefits and how do they determine eligibility? Must the customer meet a threshold for full-time equivalent jobs? Is the threshold too low or too high?

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Practical Guidance and Considerations for Large Load Interconnections

The electricity sector is poised for record demands and sustained growth in the years ahead. A 2023 study of nationwide demand trends found that grid planners had nearly doubled their five-year load growth forecasts from 2.6% to 4.7% in just one year. This surge is fueled by both individual and aggregated end-use loads with high electricity demands. Multi-sector electrification—driven by digitalization, heat pumps, electric vehicle charging, and other factors—continues to push overall electricity demand higher. However, the primary driver of demand growth is the wave of “large load” interconnection requests to the BPS· particularly form data centers.

This report serves as a practical guide to improving and harmonizing utility practices for processing, studying, and assessing large load interconnection requests. It also serves as a reference for state regulatory bodies in their effort to ensure that utility constituents are fully evaluating the potential impacts that large loads, particularly data centers, can have on grid reliability and existing customers. This guidance is especially useful in regions with limited experience integrating data centers and among utilities with constrained resources or bandwidth to stay current with evolving practices in this area.

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