ESIG
Large Loads
Task Force

Grid Integration of Large Loads

INTRODUCTION TO THE LARGE LOADS TASK FORCE, DATA NEEDS, AND FLEXIBILITY

A Report by the
Energy Systems Integration Group's
Large Loads Task Force
June 2026

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Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility

A Report by the Energy Systems Integration Group's Large Loads Task Force

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Acknowledgment

This work was supported by the U.S. Department of Energy under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Preface to ESIG Large Loads Task Force Reports

This report is one of 11 reports by the ESIG Large Loads Task Force, which was formed to assist the power industry in addressing new challenges introduced by the rapid proliferation of large electronic loads such as data centers, as well as other large loads including manufacturing, electric vehicle fleets, and hydrogen production. The titles of the reports are as follows:

- Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility
- Forecasting for Large Loads: Current Practices and Recommendations
- Interconnection Processes for Large Loads: Current Practices and Recommendations
- Large Load Performance Requirements: Current Practices and Recommendations
- Large Loads: Behaviors, Capabilities, and Limitations
- Reliability Impacts of Large, Power Electronics–Interfaced Loads
- Large Load Disturbance Events
- Large Load Modeling for Dynamic Studies: Current Practices and Recommendations
- Transmission Planning with Large Loads: Current Practices and Recommendations
- Resource Adequacy with Large Loads: Planning for Flexibility to Accelerate Integration
- Wholesale Market Design and Operations for Systems with Large Loads: Current Practices and Recommendations

Suggested Citation

Energy Systems Integration Group. 2026. *Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility.* A report by the Large Loads Task Force. https://www.esig.energy/reports-briefs/large-load-task-force-introduction.

Contents

Abbreviations

AI	Artificial intelligence
ANOPR	Advance Notice of Proposed Rulemaking
BYOC	Bring your own capacity
CHILL	Conditional High Impact Large Load
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
HILLGA	High Impact Large Load Generation Assessment
ISO	Independent system operator
NERC	North American Electric Reliability Corporation
RTO	Regional transmission organization
SCED	Security-constrained economic dispatch
SPP	Southwest Power Pool
U.S. DOE	U.S. Department of Energy
UPS	Uninterruptible power supply

PHOTOS

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Executive Summary

Electric power systems across the country are experiencing a new era of demand growth driven by the rapid emergence of large, complex electricity consumers such as data centers, oil and gas operations, energy-intensive manufacturing, hydrogen electrolysis, and transportation fleets. Unlike traditional loads, new large loads are often far larger, at hundreds of megawatts or more; have short development timelines; are geographically clustered; and interface with the grid through power electronics. These characteristics can create resource adequacy and reliability risks including fault ride-through failures, control interactions and oscillations, and power-quality issues.

Recent utility and regional forecasts project sharply accelerating demand growth through 2030, far exceeding expectations just a few years ago. But there is substantial uncertainty regarding timing, location, and actual load that will materialize. At the same time, the mismatch between short development timelines for large load facilities (often just two to three years) and long lead times for development of generation (often more than three years) and transmission (often more than 10 years) complicates resource and transmission planning, resource adequacy assessments, market design, and infrastructure investment decisions.

The Energy Systems Integration Group (ESIG) convened the Large Loads Task Force to examine each of the areas heavily affected by the increase in large loads on the grid and to provide a neutral, technically focused forum for collaboration among utilities, regional system operators, load developers, technology providers, researchers, and regulators. The task force reports focus on large load forecasting, interconnection processes, performance requirements, modeling, transmission planning, resource adequacy, and market design. In addition, spanning these focus areas are two major cross-cutting topics, expanded on in this introduction report:

- **Insufficient data.** Utilities and regional system operators frequently lack timely, standardized, and sufficiently granular information on large loads' characteristics, ramping behavior, disturbance ride-through capabilities, and flexibility capabilities. Without such data, planning and operational studies rely on assumptions or proxy models that may under-estimate reliability risks or drive overly conservative and costly infrastructure solutions. The industry encountered similar challenges during the early integration of inverter-based generation (wind, solar, and battery storage), requiring coordinated improvements in modeling, high-resolution on-site measurements, and interconnection performance requirements.
- **Potential large load flexibility.** Many of these large load facilities have advanced control systems. Some facilities have associated generation or storage that can enable rapid load modulation, peak shifting, or self-supply during system stress. If large load flexibility is integrated with interconnection, planning, and market frameworks, it could mitigate near-term infrastructure constraints, support resource adequacy, improve operational reliability, and reduce total electricity system costs. However, realizing these benefits requires early consideration of flexibility in facility design, appropriate incentives, regulatory clarity, and sufficient grid operator visibility and confidence in load performance.

This introductory report offers common definitions and an overview of large load growth, system impacts, data needs, and flexibility considerations, and sets the foundation for the series of reports by the ESIG Large Loads Task Force.

A New Era of Electricity Demand Growth

After decades of relatively steady electricity demand growth followed by a prolonged period of low growth in the early 2000s, electricity demand has increased significantly and may continue to increase at a much more rapid rate (Wilson et al., 2025). This resurgence is being driven by a new wave of large and often power electronics–dominated loads, including data centers and artificial intelligence (AI) computing facilities, increased electricity usage in oil and gas mining operations, energy-intensive manufacturing facilities, and charging infrastructure for electric transportation fleets. Unlike traditional load growth, many of these large loads have short development timelines, are geographically concentrated, and exhibit complex dynamic behavior due to their power electronic interface with the grid. Their rapid proliferation is creating both challenges and opportunities across nearly all facets of power system planning and operations, with implications for system reliability, resource adequacy, infrastructure investment, and electricity affordability.

The characteristics of today's large loads create new needs in power system planning and operations, particularly in areas such as data availability and quality, modeling fidelity, interconnection processes, and coordination between load owners, utilities, regional system operators, and regulators. As indicated by the recent North American Electric Reliability Corporation (NERC) Level 2 Alert Aggregated Report, in many regions, system operators and planners lack consistent, timely, and technically sufficient information about large loads' characteristics, operating behavior, and flexibility capabilities, limiting their ability to assess system impacts and design effective mitigation strategies (NERC, 2026a).[1]

In response to these challenges, the Energy Systems Integration Group (ESIG) convened the Large Loads Task Force to provide a collaborative, technically focused forum for addressing large load integration issues. While other major efforts play essential roles in reliability oversight, research, and regulatory action—including efforts led by NERC, EPRI, and the Federal Energy Regulatory Commission (FERC), and regions (Midcontinent Independent System Operator, Electric Reliability Council of Texas (ERCOT), and others)—the ESIG Large Loads Task Force is distinct in its emphasis on cross-stakeholder dialogue, practical engineering perspectives, and consensus-driven best practices. As a neutral, non-regulatory organization, ESIG provides a trusted and open environment for candid technical discussion among utilities, regional system operators, load developers, technology providers, researchers, and regulators.

ESIG's Large Loads Task Force leveraged this collaborative environment to identify key challenges and offer improved practices that support reliable and efficient large load integration. Each project team (Figure 1, p. 2) addressed a key topic in the integration of large loads. Across all project teams, the participants—including utilities, regional transmission organizations (RTOs), independent system operators (ISOs), power system industry consultants and stakeholders, and the data center industry—investigated the system impacts of large loads, possible solutions to reliability challenges, and best practices.

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[1] In response to the NERC Level 2 Alert results, NERC subsequently issued a Level 3 Alert "Essential Action Alert, Computational Load Modeling, Studies, Instrumentation, Commissioning, Operations, Protection, and Control," on May 4, 2026, directing registered entities to strengthen large load interconnection screening, improve data collection and model quality, enhance coordination between utilities and reliability coordinators, and establish operational measures to mitigate reliability risks associated with rapidly growing large loads. See NERC (2026b).

FIGURE 1

ESIG Large Loads Task Force and Project Teams

Large Loads Task Force

ESIG working groups:

- Reliability
- System operations and market design
- System planning

Interconnection Process

- Large load interconnection processes and studies

Interconnection Performance

- Requirements and performance specifications of large loads

Dynamic Modeling Requirements

- Modeling of power systems dynamic assessments for large loads

Load Forecasting

- Policies and practices for forecasting large loads to inform resource and transmission planning

Transmission Planning

- Consideration of large loads in transmission planning processes

Resource Adequacy

- Practices for evaluating large loads, including their flexibility potential, in resource adequacy studies

Markets and Operations

- Market design and operations for large loads and associated resources

Each project team of the ESIG Large Loads Task Force addressed a key topic in the integration of large loads, investigating their system impacts, possible solutions to reliability challenges, and best practices.

Source: Energy Systems Integration Group.

This report serves as an introduction and framing document to the series of reports developed by the Large Loads Task Force. It presents foundational information on large load growth and characteristics used by project teams across the task force; discusses large load flexibility needs and capabilities; and covers cross-cutting focus areas for the task force, including common definitions and terms for large loads, data needs, and data availability for integrating large loads.

Expected Rapid Increase in Electricity Demand

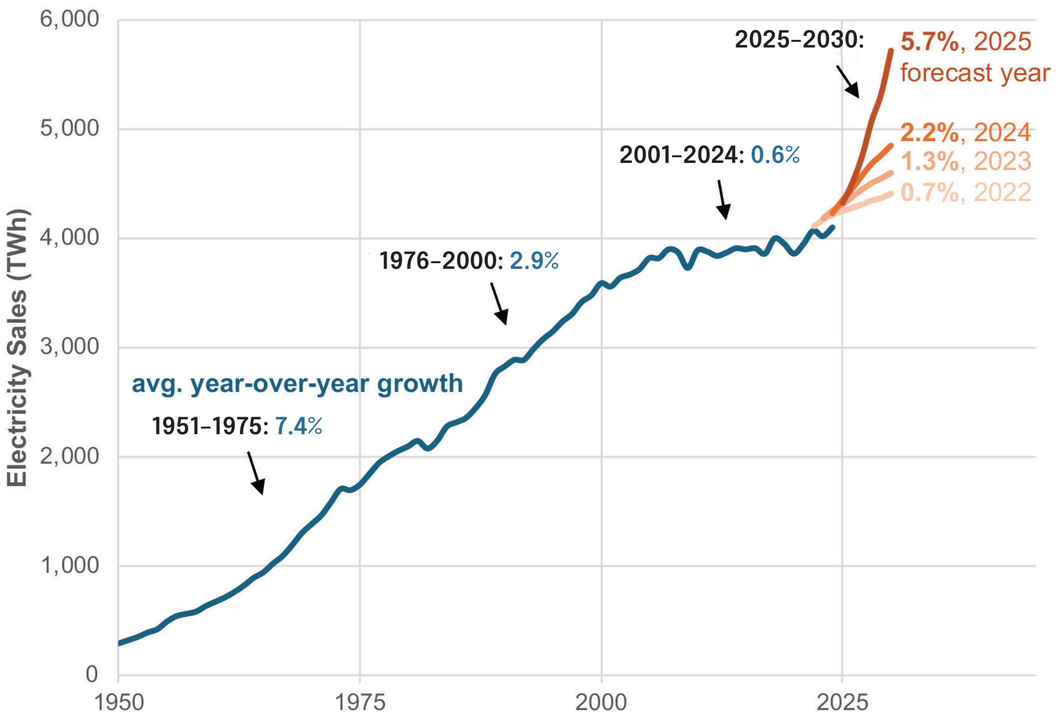
For much of the 20th century, electricity demand in the United States grew steadily, driven primarily by population growth, industrialization, and the proliferation of household appliances. Between the 1950s and 1970s, electricity demand increased on average by about 7% annually, prompting a continuous build-out of generation and transmission (Wilson et al., 2025). Growth slowed in the 1980s and 1990s as energy efficiency, slower economic expansion, and structural shifts in the economy (from heavy industry to services) tempered demand, but growth continued, with annual rates of about 3%. By the 2000s, load growth had fallen to around 1% per year or less in many regions, creating an expectation of flat load trajectories in utility and regional planning (U.S. EIA, 2026).

This paradigm is now changing rapidly (Figure 2, p. 3) (Mai et al., 2026). The drivers behind this new surge in demand are qualitatively different from the household and industrial loads that shaped the 20th century grid. Instead, today's growth is concentrated in new types of large loads, many of which are energy-intensive and technologically distinct from traditional loads. Beginning in 2023, grid planners began to respond to a sharp upward shift in demand projections.

Today's growth is concentrated in new types of large loads, many of which are energy-intensive and technologically distinct from traditional loads.

FIGURE 2

Historical and Forecasted Annual U.S. Electricity Sales

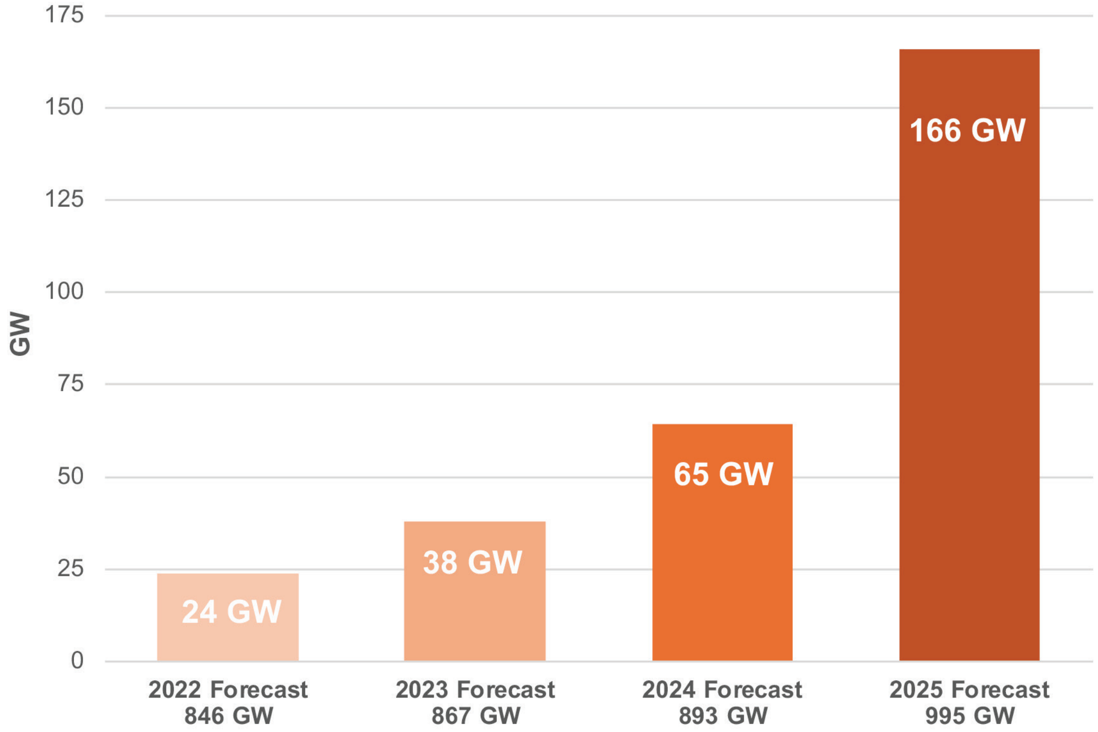


This figure is based on data from Wilson et al. (2025). Historical electricity sales through 2024 (blue line) are based on the U.S. Energy Information Administration's Electric Power Monthly (EIA-861), and forecasts (orange line) show the aggregate of utility and regional forecasts as reported in FERC Form 714. The orange lines show forecasts prepared in 2022 through 2025 for the period 2025–2030 (with 2025 forecast year based on data from 2024). Differences in reporting conventions result in small discrepancies between EIA and FERC data, hence the gap between historical and forecasted data for 2022 to 2024.

Source: Energy Systems Integration Group; historical data from Form EIA-861 (https://www.eia.gov/electricity/data/eia861/), and forecast data from J. D. Wilson, S. Meyer, Z. Zimmerman, and R. Gramlich, *Power Demand Forecasts Revised Up for Third Year Running, Led by Data Centers* (Grid Strategies, 2025), https://gridstrategiesllc.com/wp-content/uploads/Grid-Strategies-National-Load-Growth-Report-2025.pdf.

FIGURE 3

Forecasted Five-Year Growth in Summer Peak Demand, 2025 to 2030



The figure shows the four most recent forecasts for the period 2025–2030, using aggregated utility and regional forecasts as reported in FERC Form 714. More recent forecasts for this period have higher expected five-year growth: the 2025 forecast in summer peak demand growth (166 GW) is more than six times greater than the growth forecasted in the 2022 forecast for the same period (24 GW).

Source: Energy Systems Integration Group; data from J. D. Wilson, S. Meyer, Z. Zimmerman, and R. Gramlich, *Power Demand Forecasts Revised Up for Third Year Running, Led by Data Centers* (Grid Strategies, 2025), https://gridstrategiesllc.com/wp-content/uploads/Grid-Strategies-National-Load-Growth-Report-2025.pdf.

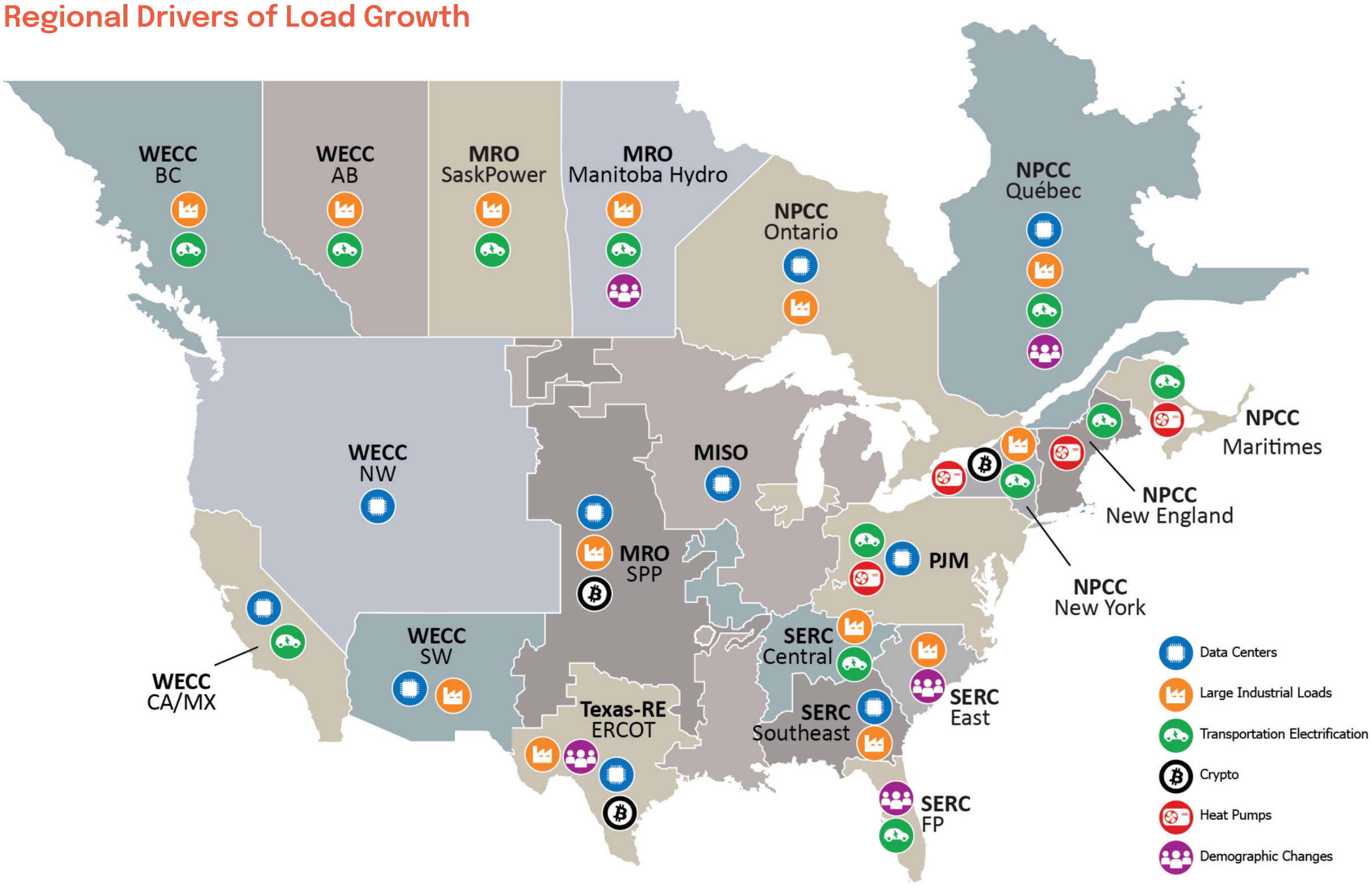
> **The new era of load growth reflects a stark departure from the flat, predictable demand that the current generation of grid planners and operators have been accustomed to in recent decades.**

The latest forecasts (2025) from Grid Strategies' nationwide study, which reports the aggregate utility- and region-reported forecasts, show load growing by an annual average of nearly 6% during the 2025–2030 period. In terms of peak summer demand, five-year (2025–2030) growth forecasts increased by a factor of six in just three years, from 24 GW in the 2022 forecasts to 150 GW in 2025 (Figure 3).

The most prominent type of large loads under development today, data centers and new industrial loads, are affecting utilities and ISOs/RTOs across the country (NERC, 2024) (Figure 4, p. 5). However, the forecasts come with a great degree of uncertainty as acknowledged by many planners. For example, PJM states that "while demand expansion is clearly evident in recent system behavior, there exists a large cone of uncertainty around the trajectory and amplitude of future growth" (Mills, 2025). The new era of load growth reflects a stark departure from the flat, predictable demand that the current generation of grid planners and operators have been accustomed to in recent decades. Meeting such rapid load growth would require an accelerated expansion of generation and transmission resources as well as new practices to integrate new loads.

FIGURE 4

Regional Drivers of Load Growth



Today's load growth is predominantly new types of large loads, many of which are energy-intensive and technologically distinct from traditional loads. The most prominent type of large loads under development today, data centers and new industrial loads, are affecting utilities and regional grid operators across the country.

Source: North American Electric Reliability Corporation, *2024 Long-Term Reliability Assessment*, December, 2024, https://www.nerc.com/globalassets/our-work/assessments/2024-ltra_corrected_july_2025.pdf.

Defining "Large Load"

It is difficult to reach consensus on the definition of a large load, including a specific megawatt threshold, in part because different-sized loads may have different material impacts on the system, depending on the power system's size and characteristics. While there is currently no industry consensus on the definition of a large load, an informal survey in 2024 by NERC's Large Load Task Force suggested a size threshold of over 50 MW, with 75 MW as the most commonly suggested size.[2] In its white paper "Characteristics and Risks of Emerging Large Loads" the NERC Large Load Task Force adopted the following high-level definition:

> Any commercial or industrial individual load facility or aggregation of load facilities at a single site behind one or more point(s) of interconnection that can pose reliability risks to the [bulk power system] due to its demand, operational characteristics, or other factors. Examples include, but are not limited to, data centers, cryptocurrency mining facilities, hydrogen electrolyzers, manufacturing facilities, and arc furnaces (NERC, 2025, p. 1).

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[2] For more information about the NERC Large Loads Working Group, see https://www.nerc.com/who-we-are/committees/reliability-and-security-technical-committee-rstc/subcommittees-working-groups-and-task-forces/large-loads-working-group-llwg. For context, the 75 MW threshold aligns with inclusion criteria (I2) for generators under the current definition of the bulk power system in the NERC Glossary of Terms.

The ESIG Large Loads Task Force adopted NERC's definition of large load to focus on grid reliability impacts rather than define a specific size.

The U.S. Department of Energy's (DOE's) Advance Notice of Proposed Rulemaking (ANOPR) on Interconnection of Large Loads to the Interstate Transmission System (RM26-4-000) defined large loads as new loads greater than 20 MW,[3] mirroring the large generator interconnection threshold in FERC's pro forma procedures. While public comments on the ANOPR generally agreed that some trigger is needed to identify when new loads warrant enhanced review, there is little consensus on a fixed 20 MW site threshold. Many commenters argued that the 20 MW cut-off is arbitrary and does not definitively distinguish loads that meaningfully affect the transmission system from those that do not. Others supported having a clear threshold for administrative certainty, but stressed the need for clarity on how to measure, aggregate, or stage load size over time. A common theme, similar to the NERC Large Load Task Force's definition, is that MW alone is an imperfect proxy, and that factors such as connection voltage, system strength, regional context, and aggregate impacts on the grid may better indicate when a large load poses reliability or planning concerns.

> **Factors such as connection voltage, system strength, regional context, and aggregate impacts on the grid may better indicate when a large load poses reliability or planning concerns than megawatts alone.**

Broadly taking these definitions into account, the ESIG Large Loads Task Force focused on grid reliability impacts, such as whether large loads can materially affect bulk power system performance, for example, by driving the need for new or accelerated transmission upgrades, altering power flow patterns, or affecting voltage and frequency behavior during normal operations and disturbances. The task force also considered how large loads impact resource adequacy assessments, transmission planning, and market design and operations. The scope of the task force primarily included the bulk power system, though the group acknowledged that some large loads are interconnected at the distribution level, where they can have major impacts as well.[4]

Types of Large Loads

Many types of new large loads today could meet NERC's definition, and the fast-changing nature of some of these loads makes it challenging to develop a classification scheme applicable to all of them. Nonetheless, Figure 5 (p. 7) offers an illustrative example showing four large load categories and several example end uses for each. This classification illustrates the diversity of large loads but is not exhaustive. Currently, the largest impact on the bulk power system is from growth in data center consumption and electricity usage in oil and gas facilities, although other types of large loads may have significant impacts in the future or in specific locations.

Data Centers, Including AI Computing: The Leading Drivers of Load Growth Today

Data centers in particular are currently drawing a great deal of attention, with about 55% of forecasted U.S. peak load growth attributable to this category alone (Wilson et al., 2025). Because of the sizable near-term impact of data centers, the ESIG Large Loads Task Force applied relatively greater emphasis on them, but task force analysis is generally applicable to all large loads in the four categories.

Utility and regional load forecasts are estimated to include about 90 GW of data center demand through 2030, while third-party benchmarks suggest that number may be lower, perhaps 65 GW (Wilson et al., 2025). In any event, at a regional level, electricity systems are seeing sizable increases in the number of interconnection applications from large data centers. Forecasted growth through 2030 in absolute terms is concentrated in ERCOT, PJM, and the Southwest Power Pool (SPP) (Wilson et al., 2025; EPRI, 2024). Growth can also be highly concentrated

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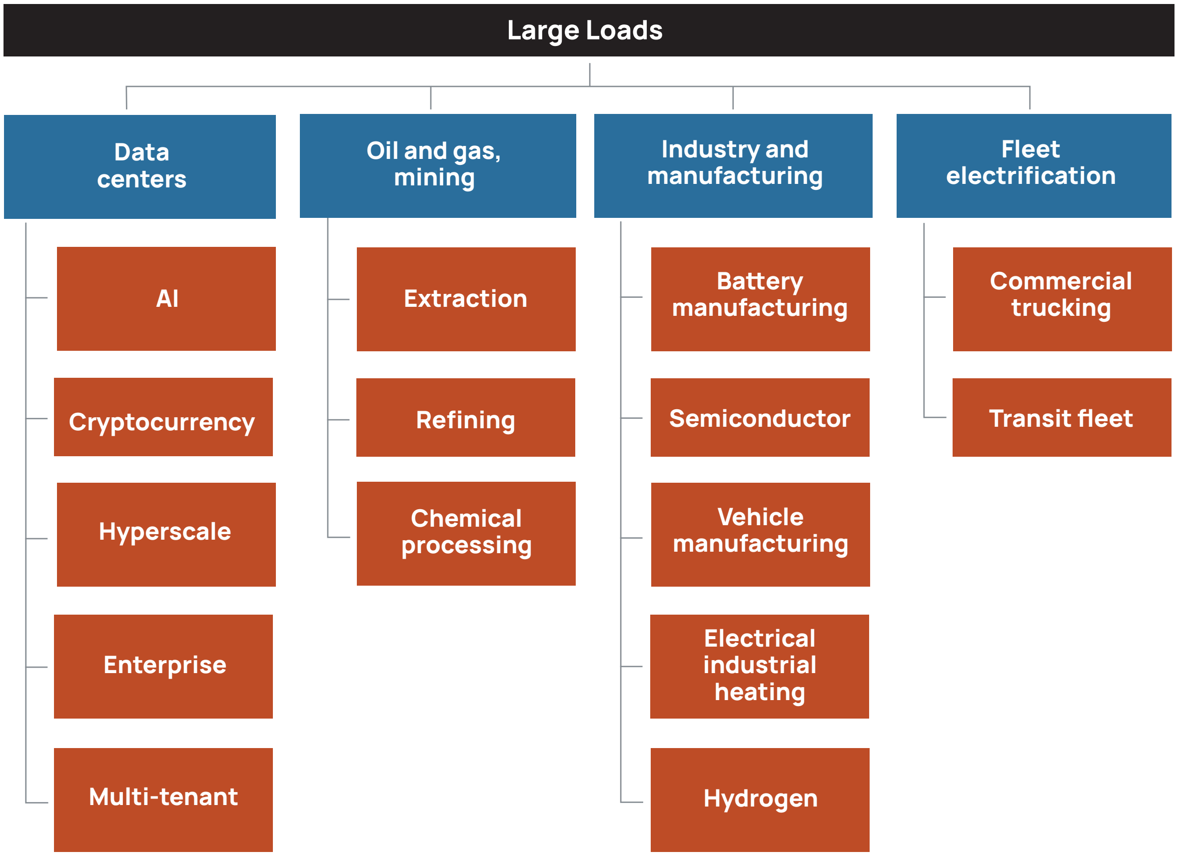
[3] See https://www.energy.gov/sites/default/files/2025-10/403%20Large%20Loads%20Letter.pdf. The 20 MW threshold applies to stand-alone facilities and hybrid facilities, which refer to new load facilities seeking to share a point of interconnection with new or existing generation facilities.

[4] The task force report *Interconnection Processes for Large Loads: Current Practices and Recommendations* includes a section on distribution-connected large loads (https://www.esig.energy/reports-briefs/large-load-interconnection-process).

FIGURE 5

Large Load Segmentation Across Subtypes and End Uses



An illustrative example of four high-level large load categories and several example end uses for each. This classification illustrates the diversity of large loads but is not meant to be exhaustive.

Source: Energy Systems Integration Group.

within a region; for example, PJM has over 15 GW of active interconnection requests that are linked to data center projects in Northern Virginia alone (Skidmore, 2025). According to a suite of recent forecasts, U.S. electricity demand from data centers by 2030 is expected to range from at least 200 TWh to over 600 TWh (Goldsmith and Byrum, 2025).[5]

In today's digital age, data centers are the backbone for much of the world's computational infrastructure. Although data centers have existed for many years, their size, pace of growth, and concentration are rapidly changing. However, these facilities are heterogenous across several dimensions and have different impacts on the bulk power system. Data center facilities provide computing and storage capabilities to diverse end users, which may be the facility owners themselves or other—sometimes multiple—clients leasing the facilities. In addition, part of these multi-purpose data centers may be used for cloud computing, another part for AI training, and another for data storage. These different uses lead to different types of load characteristics such as different uptime requirements (the percentage of time a data center must be available)[6] and latency requirements (the time delay

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[5] In its white paper "Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption," EPRI provided state-by-state data center share of electricity consumption by 2030 (https://www.epri.com/research/products/3002028905).

[6] Availability needs may further shaper large load behavior during grid disturbances as well as configuration and sizing of back-up generation.

between a request being sent to the data center by a user and the user receiving a response), resulting in potentially complex electricity demand profiles within one facility.

Additionally, given facility sizes and uptime requirements, and since owners often desire to expedite the start of commercial operation, many data center and other large load owners or developers are planning to acquire all or part of their own electricity supply, separately from and/or in addition to interconnecting generation with the grid.

Several types of data centers can be large enough to be considered large loads, including the following.[7]

- **Enterprise** data centers serve a single end-use customer, and their compute loads have a single electricity service expectation (e.g., related to availability and latency requirements).
- **Multi-tenant** data centers are facilities where multiple customers lease space and install their own compute equipment or lease equipment already on site. This arrangement may lead to multiple compute load end uses with varying availability and latency requirements within a single large load facility. These facilities serve users beyond the facility's owner: the owner of the facility, while being responsible for grid connection, does not have control over tenants' compute processes and characteristics. Therefore, they typically have high uptime and low latency requirements that may limit flexibility of the large load facility and increase its needs for back-up generation. Another term for multi-tenant data centers is co-located data centers, although the latter term is also used to describe facilities with on-site generation resources.
- **Crypto-mining** data centers are used for the sole or primary purpose of mining cryptocurrencies. Such data centers are highly energy-price sensitive and have flexible consumption patterns.
- **Hyperscale** data centers are much larger than other types of data centers, at several hundred MW or GW-scale. These facilities typically serve a single corporate customer and can be used for a range of applications, such as cloud computing or AI training and inference. Though less numerous than other types of data centers, the hyperscale data centers have outsized impacts on demand growth and grid reliability because of their size.[8]
- **AI** data centers are solely or primarily used for AI training (which occurs offline) and inference-at-deployment (when a trained model is deployed to produce a response online in real time). Specific uses can have implications for a facility's uptime requirements. AI data centers are composed of the same infrastructure as other data centers, but typically a higher share of the overall facilities' electricity consumption is for computations, compared to other data center types.

Broadly speaking, all data centers have the same main subsystems as listed in Table 1 (p. 9), although there can be variations in the design of the facility (how its subsystems are configured, interconnected, and backed up), the facility's load profile, and the energy consumption of each subsystem (IEA, 2025a). For more details about the composition and characteristics of large loads, see the ESIG Large Loads Task Force report *Large Loads: Behaviors, Capabilities, and Limitations* (including Table A-1).[9]

Oil and Gas, Mining: Robust, Geographically Concentrated Growth

Oil and gas production, transport, and processing have always required significant amounts of energy. Recently, electric technologies, such as electric drilling rigs, pumps, and motors, have replaced diesel or other fossil-based technologies in these industries, driving up their electricity consumption. The mining industry is experiencing a similar trend.

For example, over the past five years, ERCOT has seen rapid growth in oil- and gas-related electric loads, driven largely by rapid increases in electricity use for extraction operations in northwestern Texas and southeastern

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[7] These large load types listed are not mutually exclusive. For example, a data center can be an enterprise hyperscale data center used for AI applications. EPRI classifies data centers by size, workload type, ownership model, and reliability tiers (https://www.epri.com/research/products/3002031504).

[8] Grid Strategies reports that 16 GW-scale projects with an aggregate demand of nearly 30 GW are scheduled to come online by 2027 (Wilson et al., 2025).

[9] See https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements.

TABLE 1

Power Consumption of the Main Subsystems in Data Centers

Data Center Subsystem	Percentage of Power Consumption	Examples of Equipment and Functions
Servers and computation equipment	~45-75%	Devices like central processing units (CPUs), graphics processing units (GPUs), and tensor processing units (TPUs)
Data storage	~5%	Devices that store information
Networking	~5%	Equipment that connects servers within the data center
Cooling and environmental controls	~5% to 30%	Equipment that manages temperature and humidity
Other infrastructure	~5-15%	Lighting, office equipment, and other

Note: The percentages of power consumption do not add up to 100% due to variations in percentages for different data centers.

Source: Energy Systems Integration Group; data from International Energy Agency, *Energy and AI* (2025), https://www.iea.org/reports/energy-and-ai/energy-demand-from-ai.

New Mexico. Producers are increasingly shifting drilling rigs, water handling, gas compression, and processing equipment from diesel or other on-site generation to grid-supplied electricity to reduce fuel logistics, cost, and emissions. As of 2022, electric oil and gas loads in ERCOT were already on the order of around 4.2 GW, with forecasts showing continued growth through the 2030s (S&P Global Commodity Insights, 2023). The individual facility size is also growing. While electric drilling rigs have typically been in the 1 to 2 MW range, newer facilities can require tens of megawatts per site, meaning individual projects increasingly resemble large industrial loads. This increasing electricity demand has implications for energy markets, transmission build-out, local reliability, and operational flexibility.

PJM is also experiencing increasing electricity use for oil- and gas-sector infrastructure, particularly natural gas transmission compression in the Appalachian region. Unlike ERCOT's upstream oil and gas mining uses, PJM's load growth appears as discrete, large industrial interconnections tied to natural gas compressor stations, driven by fuel economics (i.e., PJM sources and transport lower-cost natural gas from other regions). Electric compressor stations range from less than 1 MW to nearly 100 MW, with average sizes around 10 to 15 MW. As a result, oil and gas electricity use in PJM is emerging primarily as a large load siting and interconnection challenge, with localized transmission and reliability implications, rather than system-wide capacity impacts.

Energy-Intensive Manufacturing

The industrial sector is also undergoing a structural shift. Electricity use in semiconductor and battery manufacturing has been rapidly increasing since 2020 (IEA, 2025b), with a large facility often requiring 50 to 200 MW of continuous power (Tran, 2026). Large energy-intensive manufacturing projects are disproportionately located in Texas, Arizona, and New York. Within those states, projects are often clustered into relatively small geographical areas, which intensifies local grid impacts. Other new industrial loads, such as vehicle manufacturing and emerging agricultural industries such as vertical farming and controlled-environment cultivation, are not only starting to significantly add to aggregate demand in some regions, but also introducing new temporal and locational load characteristics that diverge from historical industrial patterns.

Hydrogen production via electrolysis is another potentially significant industrial electricity consumer. U.S. DOE's "Hydrogen Shot" scenarios envision electrolysis capacity reaching 20 to 40 GW in 10 years or more, which would translate to annual consumption of 100 to 200 TWh depending on electrolyzer utilization rates (U.S. DOE,

2024) and would be comparable to current data center energy consumption. However, while there have been many announced hydrogen production facilities, the elimination of federal subsidies has put these projects at risk, and hydrogen demand is currently only considered in a few planning regions.

Transportation Fleets

While data centers and oil and gas tend to be driving near-term large load growth, transportation is a potential major driver in the longer term. Although light-duty electric vehicles (EVs) have the potential to be transformative and have their own unique characteristics (e.g., managed charging opportunities, winter peaking challenges), these new loads have many similarities with traditional commercial and residential loads and thus were not the focus of the Large Loads Task Force. Neither were public chargers for EVs, which often have high electricity demand, because many would be located within distribution systems. On the other hand, heavy-duty electric trucks and EV fleets are likely to constitute large loads in the long term, as their charging depots require MW-scale infrastructure. These new loads are only beginning to emerge in California and a few other U.S. markets, while the uptake in some other countries is much higher.

The Difference Between New Large Loads and Traditional Load Growth

New large loads fundamentally differ from large industrial loads of previous decades. Historically, major loads like aluminum smelters or chemical manufacturing plants were limited in number, large but relatively predictable, with steady demand profiles and clear regional siting around generation resource hubs. In contrast, today's new large loads are characterized by their size and geographical concentration, rapid and uncertain growth, difficult-to-predict electricity demand profiles, power electronics–based grid interface, and potential periodic changes of load characteristics over the lifetime of the site.[10]

Size and Concentration

While historically the largest industrial loads rarely exceeded a few hundred megawatts,[11] individual facilities for new large loads are now routinely at that scale, with some reaching gigawatt scale. About half of planned data center capacity through 2030 is from hyperscale data centers over 1 GW (Wilson et al., 2025). The size of these individual facilities can be on par with or exceed the largest individual generator unit or transmission line capacity ratings in many regions. This introduces a gamut of new reliability challenges for power system planning and operations.

An additional consequence of the large size of new large loads is that they often connect directly to the high-voltage transmission system, when, historically, much of the power system's load has connected to the (lower-voltage) distribution system. This calls for changes in interconnection processes (or the introduction of a new interconnection process for large loads on the transmission side) and grid planning in general. The Large Loads Task Force report *Interconnection Processes for Large Loads: Current Practices and Recommendations* discusses this in greater detail.[12]

The impacts on system operation and planning are exacerbated by the geographically concentrated development of multiple large facilities, especially in grid-constrained areas. Data centers cluster in regions like northern Virginia and Dallas–Fort Worth in Texas, and semiconductor and battery manufacturing plants are often similarly clustered. This creates localized step increases in demand, either from one or a few hyperscale data centers or from the concentrated development of multiple smaller, but still sizable, large load facilities.

Rapid and Uncertain Growth

The rapid rate of load growth seen in recent forecasts would result in load outpacing generation interconnection and upgrades in grid infrastructure, especially as generator interconnections have slowed (LBNL, 2026).[13] Many

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[10] For further discussion of these differences, see the ESIG white paper "Historical and Modern Large Loads: Characteristics, Context, and Industry Actions to Meet Grid and Customer Needs," https://www.esig.energy/reports-briefs/historical-and-modern-large-loads.

[11] The Paducah Gaseous Diffusion Plant is an example of an exception, with demand exceeding 3,000 MW until it shut down in 2013.

[12] See https://www.esig.energy/reports-briefs/large-load-interconnection-process.

[13] See the Large Loads Task Force report *Resource Adequacy with Large Loads: Planning for Flexibility to Accelerate Integration*, Figure 1, https://www.esig.energy/reports-briefs/large-loads-resource-adequacy.

large loads can come online within two to three years, while new generation can take three years or more and new transmission more than 10 years, creating timing mismatches that cause backlogs in the interconnection of large loads, resource adequacy concerns (sufficiency of generation resources to support newly connected loads), and transmission bottlenecks.

While many forecasts show rapid and accelerating growth in large loads, they also acknowledge a great deal of uncertainty (ESIG, 2025). For example, S&P's high and low demand growth scenarios differ by more than 200 TWh in 2030, with the difference growing to over 600 TWh by 2040 (S&P Global Commodity Insights, 2025). Near-term (approximately 5-year) forecasts of annual electricity use by data centers alone differ by hundreds of terawatt-hours (EPRI, 2026b; Shehabi et al., 2024). Forecasts between different organizations—including between the data center industry and the electricity industry—can also differ greatly (ESIG, 2025). The significant uncertainty in the future growth of large loads is driven by large numbers of exploratory interconnection requests,[14] evolving business models (from "real estate" developers that are looking to acquire a site that is suitable for certain MW load connection to hyperscalers), complex supply chains for large load industries, and changing AI and computing processor technologies.

Electricity Consumption Patterns

Highly Dynamic Load Profiles

Uncertainties extend not only to the peak power demand and annual electricity consumption of large loads but also to the hourly and sub-hourly patterns of individual facilities. While many forecasters and planners expect data centers and other new large loads to have high utilization and reliability demands, leading to expectations for flat 24/7 electricity consumption patterns, in reality, large load demand can change rapidly. Demand profiles have broad impacts on grid economics and reliability as they influence the amount and type of resources that are best suited to serve demand (ESIG, 2026g). As the share of large load grows, their highly dynamic load profiles can have an outsized impact on grid planning and operations.

Introduction of Oscillatory Behavior

In addition to these dynamic load profiles having impact on type of supply resources needed to serve large loads, they can also create reliability issues. Rapid, highly variable cyclical power consumption patterns during AI training cycles can introduce oscillatory behavior into the grid swinging tens of megawatts, particularly at sub-second to several-second time scales. When aggregated across large AI campuses, such cyclic

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[14] Exploratory interconnection requests refer to a large load developer submitting multiple interconnection applications for a single potential large load facility project due to lack of information about which of the interconnection points is the most viable in terms of speed to connection and connection costs.

demand patterns can resonate with grid or inverter controls, leading to voltage and frequency oscillations, reduced damping, and even inadvertent activation of protection systems. Recent analyses suggest that without coordinated control and filtering mechanisms, clustered AI training facilities could amplify local or system-wide oscillatory modes, underscoring the need for refined load-modeling practices, measurement-based stability screening, and interconnection requirements similar to those applied to large inverter-based generation.[15]

Potential to Participate in Demand Response and Other Load Flexibility Mechanisms

New large loads may have the flexibility to be able to participate in demand response or other flexibility mechanisms. How large loads will provide flexibility is subject to multiple uncertain factors. On the one hand, reliability requirements and high opportunity costs of load curtailment of data centers and other large loads create obstacles to participation in load flexibility programs, while on the other hand, these loads often have the sophistication, technical capability, and infrastructure to fundamentally advance demand-side flexibility beyond the limited role it has played historically. Cryptocurrency mining provides a demonstrated example of highly flexible demand (U.S. EIA, 2024), and many utilities, states, regions, and large load industries are actively exploring innovative load flexibility mechanisms (EPRI, 2026a).

Associated Generation and Battery Storage

New large loads—especially the hyperscale facilities—commonly have associated generation or storage resources. Different load and resource configurations can affect electricity demand profiles and flexibility, configurations such as the amount and type of on-site generation, whether the load and resource use the same or separate meter(s), system operator visibility and controllability, and disconnectability. In addition, in these load/resource configurations a generation resource could be as large as the largest generator units controlled by a system operator. It could thus have a major influence on grid reliability and transmission and resource planning.

More extensive discussion of flexibility from large loads, including those with diverse load and resource configurations, is included in the section "Potential for Large Load Flexibility."

A Power Electronics–Based Grid Interface

New large loads such as data centers, crypto-mining, EV fleet charging stations, hydrogen electrolyzers, and other facilities use power electronic converters in their interface with the grid. This differs from most historical industrial loads and brings new technical challenges—such as a lack of high- and low-voltage ride-through capability, potential control interactions, and power quality issues—at the facility-grid interface.[16]

Potential to Exacerbate Routine Grid Disturbances

Power systems are designed to withstand routine disturbances, such as normally cleared faults, without major consequences or cascading disconnection of generation or load. During these disturbances it is preferred that all grid devices remain connected to the grid and not rapidly reduce their active power output (for generators) or their consumption (for loads), as any further changes to the system state can exacerbate the impacts of the initial disturbance. However, AI data centers and crypto-mining sites tend to switch over to their back-up supply during normally cleared grid faults, even with relatively shallow voltage depressions. From the grid's perspective, this looks like the large load has tripped offline. Tripping of large load facilities, and especially the simultaneous tripping of multiple facilities if they are geographically concentrated, can cause over-voltage or over-frequency conditions, grid instability, cascading loss of generation, involuntary load shed, and even potentially a blackout.

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[15] See https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements, https://www.esig.energy/reports-briefs/large-loads-reliability-impacts, and https://www.esig.energy/reports-briefs/large-load-disturbance-events.

[16] NERC has produced numerous major event reports that show some of the reliability risks associated with power electronics–connected generating resources: https://www.nerc.com/our-work/reports/event-analysis-reports. While large loads are not generating resources, their power electronics interface causes them to be susceptible to many of the performance deficiencies present in power electronics–connected generating resources. This is becoming evident in recent NERC Load Reduction Incident Reports: https://www.nerc.com/programs/event-analysis.

These ride-through issues are occurring because power electronics in large load facilities are highly sensitive to voltage dips. This sensitivity is governed by proprietary protection logic, uninterruptible power supply (UPS) transfer schemes, or internal voltage-dip counting algorithms. Unlike traditional industrial loads, the response of power electronics–interfaced loads is fast, discontinuous, and not always coordinated with transmission protection assumptions. While the phenomenon is most pronounced for electronic loads such as data centers and crypto-mining, it is not limited to a single large load category. Oil and gas facilities in ERCOT have also exhibited partial ride-through failures and sustained MW reductions following shallow voltage sags.[17]

Potential to Cause Electrical Oscillations That Grow

In addition to oscillation events related to AI training cycles, covered in the previous subsection, oscillatory behaviors can also result from large loads' increasingly complex control systems that can introduce negative damping or unintentional feedback interactions with the grid. This behavior is akin to control interactions observed in inverter-based resources, especially in weak grid areas, where a small change in current injection or withdrawal can result in large changes in voltage.[18]

Crucially, existing load models often fail to represent these dynamics, leaving system operators blind until oscillations manifest in real-time operation; see the ESIG Large Loads Task Force report *Large Load Modeling for Dynamic Studies: Current Practices and Recommendations*.[19] Even when oscillations occur in real-time operation, these events are difficult to diagnose without close coordination and high-resolution monitoring. While these oscillatory behaviors are currently observed for data center loads, the phenomenon is applicable to all power electronics–dominated loads and is not inherently tied to a specific large load category. New standards, requirements, and models are needed to manage the different fault-ride-through and oscillatory behaviors of new large loads. See the ESIG Large Loads Task Force report *Large Load Performance Requirements: Current Practices and Recommendations*.[20]

Impacts from Large Loads on Operation and Planning Processes

Rapid and uncertain load growth, along with the unique characteristics of new large loads, are impacting several areas of grid planning and operations. These impacts can be disruptive and require new processes, models, and rules to ensure reliability and affordability. At the same time, these new loads may spur improvements in overall system planning and operation.

Planning Impacts and Mismatches in Timing

Traditional planning processes were not designed to manage the speed and scale of new load developments. There is a tremendous mismatch in the timing of large load development versus the build-out of transmission and generation resources. The uncertainty in load growth forecasts, combined with uncertainty in load profiles and load flexibility, inhibits effective, proactive, and multi-value transmission planning and introduces resource adequacy concerns. The locations of new large loads can also be misaligned with available generation and transmission capacity.

Reliability Impacts

Figure 6 (p. 14) illustrates the reliability impact of large loads, on scales of seconds, hours, and days or years.

- In operations, short-term load forecasting uncertainty (day-ahead and intraday) and volatile consumption patterns can lead to inefficient scheduling, transmission congestion, balancing, and frequency control challenges.[21]

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[17] See https://www.esig.energy/reports-briefs/large-load-disturbance-events and https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements.

[18] Among the grid impacts of these oscillations are potential excitation of normally damped system modes, including subsynchronous torsional modes (between approximately 5 and 50 Hz) in synchronous generators or inter-area electromechanical modes (below 5 Hz), depending on the frequency and location of the load.

[19] See https://www.esig.energy/reports-briefs/large-load-modeling.

[20] See https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements.

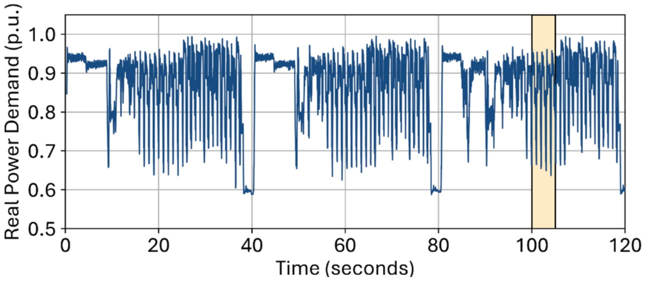
[21] See the ESIG Large Loads Task Force report *Wholesale Market Design and Operations for Systems with Large Loads: Current Practices and Recommendations*, https://www.esig.energy/reports-briefs/large-loads-markets-operations.

FIGURE 6

Reliability Impacts of Large Loads

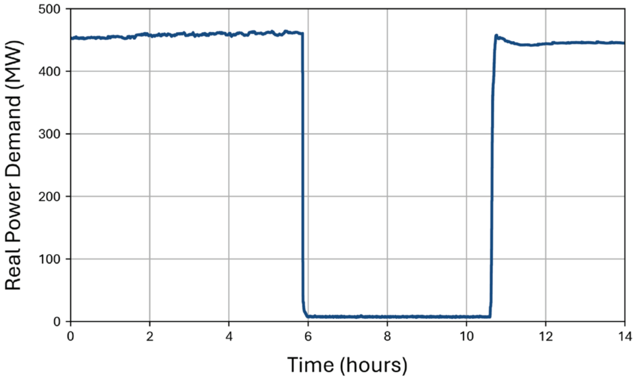
System Stability (Seconds)

- Fast dynamic variability/oscillations
- Lack of ride-through capability
- Power quality issues



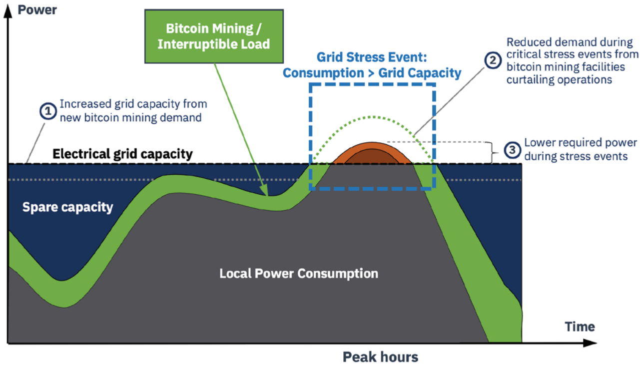
Balancing (Hours)

- Load profile uncertainty and variability
- Large ramps
- Rapid and large load steps



Resource Adequacy (Days/Years)

- Capacity shortfalls
- Planning uncertainty
- Infrastructure uncertainty



Sources: Top and middle: North American Electric Reliability Corporation, “Characteristics and Risks of Emerging Large Loads: Large Loads Task Force White Paper,” July 2025, https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/whitepaper-characteristics-and-risks-of-emerging-large-loads.pdf. Bottom: J. Peltan, LFLTF Collaboration Deck, Presentation to ERCOT Large Flexible Load Task Force Meeting, April 22, 2022, https://www.ercot.com/calendar/04262022-Large-Flexible-Load-Task.

Operational reliability and stability concerns lead to the risk of local or system-widestress. Additionally, large loads may complicate load-shedding and restoration schemes due to size and location.

- Inefficient management of large loads within the wholesale electricity markets can lead to higher costs, higher market prices, and the possibility of inequities. Market designs may need to be adjusted to accommodate flexible loads and energy parks.
- Operational reliability and stability concerns (ride-through issues, voltage/frequency stability, and oscillatory behavior) lead to the risk of local or system-wide stress. Additionally, large loads may complicate load shedding and restoration schemes due to size and location.
- Power electronics–interfaced large loads introduce power quality concerns including harmonic distortion, voltage flicker from rapid load variations, and dynamic reactive power behavior driven primarily by converter controls, with additional variability arising from motor-driven auxiliary systems such as cooling equipment.
- The impacts of large loads can be even further reaching. For example, competition for generation resources for large loads (to serve as back-up supply) could impact utility procurement for those same resources and overall resource adequacy in a given region.

Other large load impacts include supply chain constraints for transmission infrastructure (e.g., transformers), which could impact the grid’s ability to serve other loads, such as residential or smaller commercial customers. The growth in large loads also raises important questions about cost allocation for ISOs/RTOs, utilities, and customers, which are embedded in many of the grid planning and operations components in Figure 6. These issues, along with broader impacts such as economic development and workforce, highlight the importance of more efficient integration of large loads.

Data Needs and Availability

This section outlines the data needed from large load facilities to support load forecasting, interconnection studies and requirements, large load modeling, market participation frameworks, resource adequacy assessments, and transmission planning. It also examines the level of data granularity required for these applications, highlights the risks associated with insufficient or incomplete data, and evaluates the current availability of such information.

Data Needs

For all types of new large loads, robust data inputs and models are essential across all of the domains for which the ESIG Large Loads Task Force has formed a project team:

- For **load forecasting**, utilities and planners need granular information on load types, expected peak load and load profiles, energization schedules, geographical siting, load ramp schedules and rates (how demand will grow over time), and drivers of adoption (e.g., corporate commitments, industrial clustering).[22]
- For **interconnection processes and studies**, key data needs include siting (i.e., point of interconnection and voltage level), electrical characteristics of the load (including, for example, maximum and minimum demand and load profiles) and load composition (power electronic loads, motor loads, UPS systems), coincidence factors,[23] expected monthly or annual load ramp schedules, power factor, connection topology (e.g., direct, via UPS, via on-site transformer), short-circuit current contribution, ride-through behavior for disturbances (voltage and frequency), harmonic and flicker emissions, redundancy or back-up design (including any on-site generation), and models capable of capturing important grid impacts, for example, interaction with grid protection and control systems of other grid devices.[24]
- For **interconnection requirements** and performance specifications, operators require clarity on large loads' ride-through capabilities (voltage and frequency), controllability options, flexibility to reduce or modulate load, and compliance with voltage/frequency support obligations.[25]
- Detailed dynamic and steady-state **models** of large loads are needed to integrate into planning and operational simulations, with models including data on power electronic versus non-power electronic components, UPS, connection topology (direct, via UPS, via on-site transformer), internal protections that impact grid performance, and controls and settings.[26]
- For **market operations**, data on flexibility options (interruptibility, storage coupling, co-located generation, and demand bidding strategies) are required to assess a potential participation of large loads in energy and ancillary service markets and impacts to balancing operation.[27]

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[22] See https://www.esig.energy/reports-briefs/forecasting-for-large-loads.

[23] The coincidence factor is the ratio of the maximum coincident (simultaneous) demand of a group of large loads to the sum of their individual non-coincident peak demand.

[24] See https://www.esig.energy/reports-briefs/large-load-interconnection-process.

[25] See https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements.

[26] See https://www.esig.energy/reports-briefs/large-load-modeling.

[27] See https://www.esig.energy/reports-briefs/large-loads-markets-operations.

- For **transmission planning**, it is crucial to have information on siting and geographical concentration, expected peak and minimum load and load profiles, temporal coincidence of demand growth, forecast uncertainty, flexibility options including on-site generation, and likely expansion scenarios to evaluate grid reinforcement, congestion, and long-lead infrastructure investments. Together, these datasets form the foundation for ensuring reliable integration of large loads at scale.[28]
- For **resource adequacy**, planners need detailed data on load profiles, load forecast uncertainty, coincidence with system load peaks, elasticity during scarcity events, and availability of flexibility resources to ensure that applicable reliability criteria can be maintained.[29]

Data Granularity

Data granularity is critical for effectively addressing the challenges of large loads, because aggregated or annual averages often obscure the operational realities that drive system impacts.

- For **forecasting**, sub-hourly and seasonal granularity of load profiles is essential to capture daily ramping, coincidence with generation patterns, and winter/summer peak risks.
- In the **interconnection process**, information on millisecond-to-minute load variability is necessary for accurate system impact studies.
- **Interconnection requirements** call for detailed understanding of large load behavior through the analysis of disturbance-response measurements (e.g., voltage/frequency ride-through) as well as rapid high-amplitude swings during continuous operation rather than static load ratings.
- Since both time and space can influence stability and reliability outcomes, **modeling** requires granularity at multiple time scales (sub-second dynamic response and hourly/seasonal load variation) and multiple spatial scales (individual plant versus aggregated cluster). Here, too, disturbance-response measurements with high resolution are necessary for large load model validation based on actual grid events.
- For **market aspects**, granularity is needed on the operational flexibility of loads, such as the minimum modulation block, response times, or availability windows, to enable accurate participation in energy and ancillary service markets.
- In **transmission planning** it is far more important to have locational granularity (specific substation or node siting) and coincident hourly/seasonal demand patterns than aggregate annual growth figures, since transmission constraints and reinforcement needs are driven by when and where loads materialize.
- For **resource adequacy** analyses, load granularity is particularly critical: system operators must know not just annual peaks, but the hourly and seasonal coincidence of large loads with resource availability and scarcity, as well as the extent to which loads can be reduced during tight capacity conditions. Without such granularity, planners risk mis-estimating resource adequacy margins and capacity needs.

Data Availability

While the data needs across forecasting, interconnection, modeling, market integration, and transmission planning are clear, in practice the availability of high-quality, consistent datasets for new large loads is limited:

- Load developers and industrial customers often treat demand profiles, ramping behavior, and flexibility characteristics as proprietary, which restricts transparency and hinders accurate **forecasting**.
- In the **interconnection process**, utilities frequently receive incomplete or late-stage information, leading to system studies based on assumptions rather than verified design data.
- Standardized **models** of large loads for power system studies are not available, forcing planners to adapt or approximate with inadequate proxies that may not capture power electronic behavior or controllability.

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[28] See https://www.esig.energy/reports-briefs/transmission-planning-large-loads.

[29] See https://www.esig.energy/reports-briefs/large-loads-markets-operations.

- **Market**-relevant data on loads' price sensitivity, operational flexibility, or willingness to curtail are generally anecdotal or pilot-based rather than systematically collected.
- For **transmission planning**, siting information and long-term expansion trajectories are uncertain, often tied to confidential corporate strategies or explorative development pipelines.
- For **resource adequacy**, perhaps the most acute gap is the absence of representative, hourly 8,760 demand profiles and the ability to quantify the elasticity of large loads during system stress conditions, data that are essential for probabilistic resource adequacy studies yet rarely shared or systematically collected (ESIG, 2026h).

The result is a patchwork of partial data that does not align with the rigor required for reliable system operation and planning. Addressing these gaps requires more specific data-sharing frameworks, standardization of load modeling, and regulatory or market mechanisms that incentivize transparency while balancing commercial sensitivities. A similar evolution occurred in the past two decades with data collection from inverter-based resources, such as wind, solar, and battery storage, where the industry evolved from having very little information about these resources to having relatively standardized frameworks for data collection and modeling today.

Risks of Insufficient Data

The absence of data, or data at the necessary granularity, introduces significant risks across all dimensions of large load impact assessment.

- In **forecasting**, insufficiently detailed data can lead to underestimating large loads' contributions to system peaks or misjudging the pace of demand growth, resulting in capacity shortfalls or stranded investments.
- In the **interconnection process**, lack of information about precise load characteristics (ramp rates, fault behavior, back-up supply configurations) forces a reliance on generic assumptions. This may mask hidden reliability risks and lead to delays and high costs or compromised system reliability.
- For **interconnection requirements**, missing granular disturbance-response data creates blind spots in assessing whether loads can withstand voltage and frequency excursions, potentially leading to widespread tripping during disturbances and cascading reliability events.
- In **modeling**, the use of coarse or proxy representations undermines dynamic and stability studies, making it impossible to capture real-world behaviors such as fast ramping, oscillatory behaviors, control interactions, or harmonic emissions.
- For **market aspects**, limited visibility into flexibility potential or response characteristics could distort price formation, hinder integration of demand flexibility resources, and erode system operator confidence in relying on these large loads for ancillary services.
- In **transmission planning**, the absence of locational and temporal detail risks misallocation of infrastructure investments, either over-building in areas where large loads do not materialize or under-preparing in hotspots with rapid clustering of new large loads.
- For **resource adequacy**, missing or overly coarse load data undermine probabilistic resource adequacy assessments, either overstating total capacity needs by assuming flat, static data center demand or masking the risk that large loads could drive peaks during hours without sufficient generation to serve them or could fail to curtail during scarcity events. This increases the likelihood of resource shortages, reliability events, and costly emergency procurement, underscoring the importance of standardized, granular datasets for system adequacy as well as operational reliability. Conversely, under-estimating load flexibility capability or over-estimating load forecasts risks overbuilding and higher electricity costs.

Collectively, these risks elevate the chance of reliability events, inefficient capital deployment, and lost economic opportunities, underscoring the central importance of robust, granular, and standardized data frameworks for managing large load integration.

Potential for Large Load Flexibility

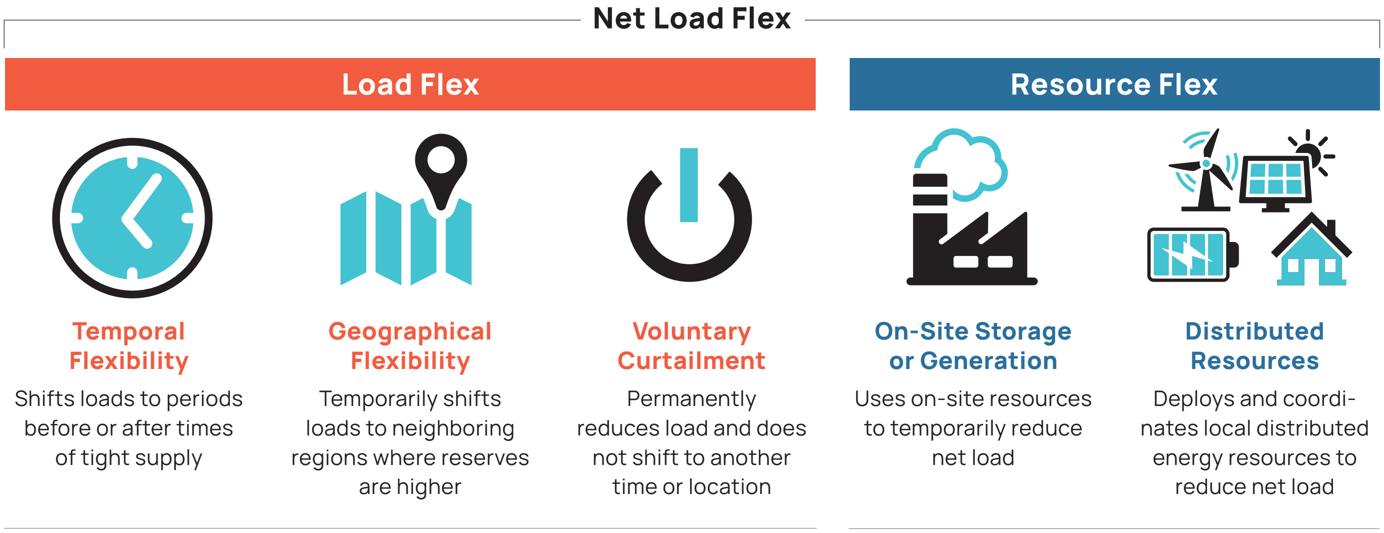
Demand-side flexibility is defined as the customer's capability and commitment to temporarily change its net consumption of electricity to better align with the needs of the power grid or to provide grid services. Flexibility can be achieved by curtailing electricity use, temporally shifting demand across time periods, geographically shifting demand between co-owned facilities across regions, and operating generation or storage associated with the load (Figure 7).

Flexibility from Different Types of Large Loads

The potential for demand flexibility varies with different facility-specific technical constraints, incentives, and business models. For example, multi-tenant data centers are likely to have varying flexibility, depending on the business model of each tenant within the facility. These attributes affect the nature of the flexibility the load can offer, which can be characterized by four factors: how early, for how long, how much, and how often (Figure 8, p. 19). *How early* corresponds to how much lead time (minutes, hours, days, months) is needed for the customer to respond to the grid operator's calls to reduce load or to price signals and how quickly the full response is required. *How long* refers to the duration of the response (minutes or hours). *How much* can be measured as a percentage of the facility's peak demand or in power capacity units, and can also have a directional aspect: whether load is

FIGURE 7

Large Load Flexibility Options



Five options for large load flexibility include temporal flexibility, geographical flexibility, voluntary curtailment, use of on-site storage or generation, and use of new, nearby available distributed energy resources or local capacity resources.

Source: Energy Systems Integration Group.

FIGURE 8

Four Dimensions of Large Load Flexibility

How EARLY
- Lead time to respond
- Speed of response

How LONG
- Duration of response

How MUCH
- Magnitude of response
- Direction of response

How OFTEN
- Frequency of responses
- Event vs. non-event

How early **corresponds to how much lead time (minutes, hours, days, months) is needed for the customer to respond to the grid operator's calls to reduce load or to price signals and how quickly the full response is required.** ***How long*** **refers to the duration of the response (minutes or hours).** ***How much*** **can be measured as a percentage of the facility's peak demand or in power capacity units, and can also have a directional aspect: whether load is decreasing or increasing.** ***How often*** **is the frequency that the response will be requested or required—the number of times or hours or the amount of energy per year—with the choice of metric depending on whether the response is event-based (emergency conditions) or continuous (an operating reserve provision).**

Source: Energy Systems Integration Group.

decreasing or increasing. *How often* is the frequency that the response will be requested or required—the number of times or hours or the amount of energy per year—with the choice of metric depending on whether the response is event-based (emergency conditions) or continuous (an operating reserve provision).

Although demand flexibility has a long history in the U.S. (FERC, 2024) that can inform the treatment of flexibility for new large loads, there are also unique considerations due to the size of individual facilities, geographical concentration, and the common presence of associated generation or storage. Additionally, the technical capabilities, and willingness, of large loads to provide flexibility can vary significantly between load types: for example, the flexibility available at AI training data centers differs from that at cryptocurrency mining facilities. Historically, demand flexibility was primarily dispersed and available at the distribution voltage level, often requiring an aggregator to provide a predictable and controllable response that system operators could rely on during real-time operations. New large loads primarily connect at the transmission level, and a single site can provide sizable flexibility (in terms of MW per unit time), eliminating the need for aggregation of smaller loads. Transmission-level large load connections also often have specific telemetry requirements, which offer more visibility and, potentially, controllability to a system operator.

Data Centers and AI Computing

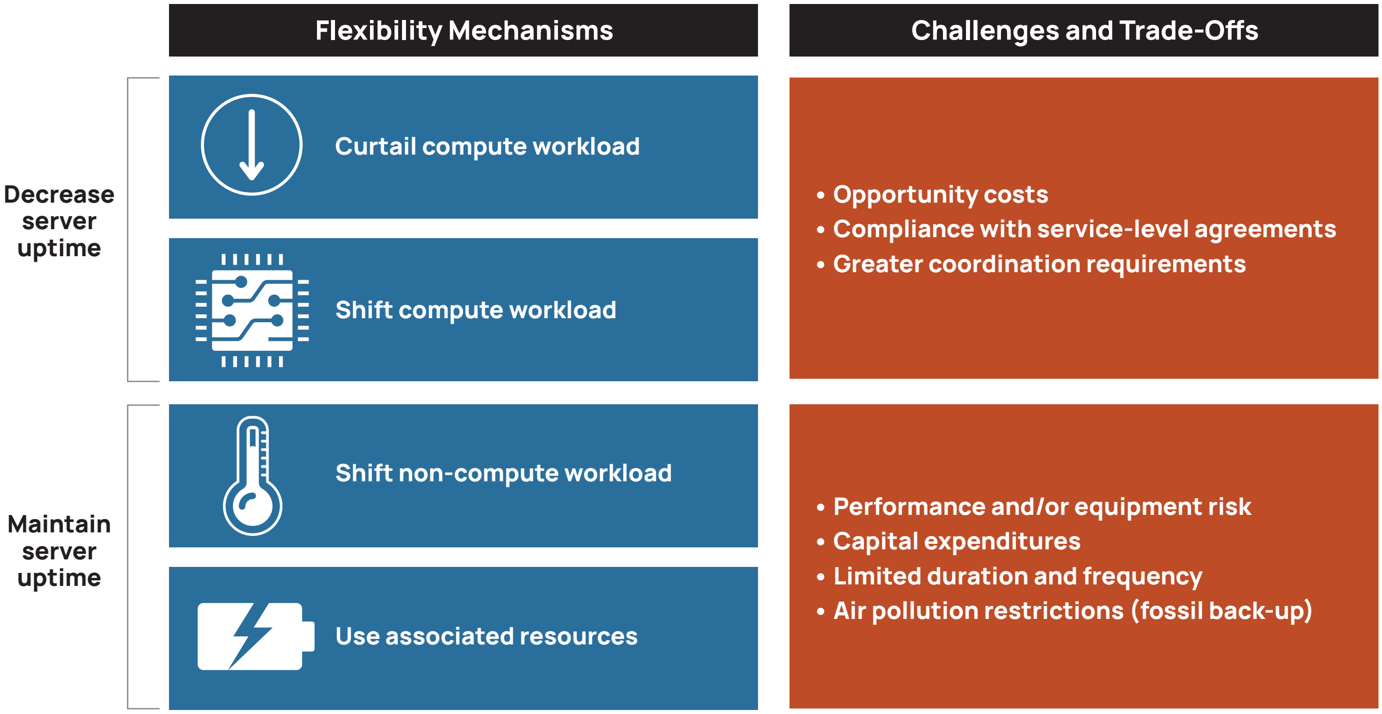
Data center flexibility can be enabled through server load management to curtail computing or shift computing. Or, it can be enabled through flexible operations of non-server electricity uses or shifting loads to other time periods (e.g., pre-cooling or other heating and cooling management strategies). Although many data centers have high server-availability requirements (e.g., 99.999% or "five-nines" uptime), electricity demand can still be lowered, as non-critical server demands can be reduced or temporally shifted without major degradation of service.

> **Data center flexibility can be enabled through server load management to curtail or shift computing, or can be enabled through flexible operations of nonserver electricity uses or shifting loads to other time periods.**

Data centers for cryptocurrency mining tend to have significant flexibility in pausing activity when necessary (due to high energy prices or grid needs) without much detriment to the process. Geographical shifting also is a possibility for data centers as computing needs can be transferred to other (co-owned) facilities. And data center facilities often have associated generation or storage that can control the amount of grid power consumption or power injection to the grid while maintaining server reliability. Figure 9 (p. 20) shows mechanisms, challenges, and trade-offs for different types of data center flexibility.

FIGURE 9

Mechanisms and Considerations for Data Center Flexibility



Source: Energy Systems Integration Group.

EV Fleet Charging

EV fleet charging offers a source of flexibility over a long period (e.g., weekly), as most daily driving uses do not require vehicle batteries to be fully charged each day. EV charging can be shifted to off-peak periods, avoiding conditions when the grid is most stressed. Managed charging for medium- or heavy-duty trucks and buses can help scale the flexibility potential for EV charging. However, the extent to which EV fleet charging can offer flexibility valued by the grid remains uncertain given the nascent stage of such facilities. Vehicle-to-grid is an emerging possibility for even greater flexibility by enabling bidirectional flows of energy and ancillary services from EVs.

Hydrogen Production

Electrolytic hydrogen production can offer flexibility over very long time scales, as the timing of hydrogen production is largely decoupled from its consumption. Decoupling allows electricity consumption in electrolysis facilities to be optimized for electricity costs or other grid considerations. For example, hydrogen production can be timed for mutually beneficial use of excess generation. Hydrogen can also be a source of electricity generation through fuel cells or combustion turbines, providing long-duration or seasonal storage although with very low round-trip efficiency.[30]

Flexibility from Different Load and Resource Configurations

The flexibility capabilities of a large load facility can depend in part on whether there are generation or battery storage resources associated with the load, as well as the characteristics of those resources, including the following. See the box (p. 21) for definitions of different load and resource configurations.

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[30] For more information, see the ESIG report *Assessing the Flexibility of Green Hydrogen in Power System Models*, https://www.esig.energy/green-hydrogen-in-power-system-models.

- **Resource types and size:** What are the characteristics associated with the resource(s)—e.g., capacity, ramping capability, profiles for variable generation resources, fuel availability and air permits for fossil resources, and duration for storage?
- **Electrical and geographical location:** Does each component of the configuration inject and withdraw energy at the same point of interconnection or at separate points?
- **Metering configuration:** Are the combined facilities behind the same meter (behind-the-meter, hybrid), or does each facility have separate metering and operation (front of the meter, co-located)?
- **Synchronicity with the grid:** Is the resource fully synchronized (in terms of frequency and phase) with the grid and/or operating continuously, or is the resource only used as a back-up for the large load facility in case of emergency?
- **Ability to disconnect:** In the event of a forced (unplanned) resource outage, does the load facility automatically disconnect through protection settings to ensure no usage of the grid? How quickly does that protection setting apply?
- **Operator visibility and controllability:** What information is passed, through telemetry or other means, from individual facilities to the system operator (or market operator), and how much control might the operator have over the resource?

As new large load industries scale, in some cases rapidly, demand flexibility could similarly scale. Such scale-up would require intentional facility designs for flexibility as well as regulatory, financial, and business conditions conducive to flexibility. Fundamentally, the flexibility capability of the loads would need to be aligned with the power grid's need for flexibility. EPRI (2025) presents a flexibility framework for data centers and their alignment with grid flexibility needs.

Benefits of Load Flexibility

The benefits to the power system of load flexibility include improved power system reliability and lower costs for the electricity system and therefore for utility customers. These benefits are achieved through reducing or deferring transmission system upgrades, lowering the need for new generation resources, and operating power systems more efficiently. Offering flexibility can also benefit large loads by facilitating faster interconnections, leading to lower electricity costs, or providing financial compensation (e.g., for large loads providing ancillary services).

Types of Load and Resource Configurations

There is as-yet no consensus on terms to describe load and resource configurations, and we use this phrase to encompass a wide range of characteristics. "Back up" generation is often used, but this generally applies to diesel back-up generators that have long been used in industry and critical facilities (such as hospitals) and offer only limited flexibility to the grid since they are not synchronized with the grid all the time, have air pollution permitting and fuel storage constraints, and are relied upon only under emergency conditions. "Co-location" and "on site" are other commonly used terms, but they exclude resources that do not share the same point of interconnection but that nonetheless may operate in tight coordination with the load. (The term "co-location" is also used with multi-tenant data centers that are co-located in the same facility and has no relationship to generation or resources associated with the facility.) Other commonly used terms in the industry are hybrids, energy parks, private use networks, and bring your own capacity (BYOC).

Expedited Interconnection Pathways for Large Loads

Large load flexibility is most prominently materializing in load interconnection processes, where in some cases, large loads that offer flexibility (e.g., willingness to reduce consumption) can benefit from expedited interconnection pathways. Flexible consumption helps to avoid local transmission upgrades that would otherwise be triggered by the interconnecting load as well as avoid generation capacity additions that otherwise would be needed for resource adequacy.

For example, Texas State Bill 6 (SB 6) outlines an expedited interconnection pathway for large loads that commit to being flexible or that bring behind-the-meter generation (Texas Legislature, 2025). SPP is proposing (1) a Conditional

High-Impact Large Load (CHILL) service that provides a faster interconnection path for large loads that agree to the potential for temporary pre-emergency curtailments, and (2) a High-Impact Large Load Generation Assessment (HILLGA) for a fast-track study path for large loads paired with generation (SPP, 2026). Additional examples include agreements for demand response from Google's machine learning training facilities with host utilities, in exchange for accelerated interconnections (Terrell, 2025).

The U.S. DOE's Speed to Power Initiative and its "403 Large Loads Letter" to FERC are efforts to facilitate faster interconnections for large loads more broadly (U.S. DOE, 2026; FERC, 2025). Many of the 14 principles in the DOE letter relate to flexibility, and the seventh states: "the interconnection study of large loads that agree to be curtailable and hybrid facilities that agree to be curtailable and dispatchable should be expedited" (p. 12). Recent white papers from the Nicholas Institute discuss how the U.S. DOE's proposed interconnection process could unlock flexibility (Farmer et al., 2025) and how large load flexibility can be implemented while protecting customer rates (Walsh et al., 2026).

Cost Savings for Large Loads

Flexibility could provide cost savings to large loads through network upgrade deferrals and associated lower interconnection costs. For example, ERCOT proposed to allow loads that chose to register as controllable load resources to connect in an expedited fashion ahead of transmission upgrades if any N-1 violations can be managed through redispatch of the controllable load resource in the security-constrained economic dispatch (SCED) (Sharma Frank, 2025). The ESIG Large Loads Task Force report *Large Load Performance Requirements: Current Practices and Recommendations* further discusses the interplay between flexibility and speed to connection, as well as interconnection costs.[31]

Grid Benefits

Load Forecasting

Load flexibility can impact load forecasting, which feeds into utility and regional transmission and resource planning. However, very few load forecasts consider large load flexibility today. Instead, forecasts often start with the full interconnection capacity of large loads followed by adjustments for expected load factors—without load flexibility explicitly considered. The ESIG Large Loads Task Force report *Forecasting for Large Loads: Current Practices and Recommendations* describes the need for flexibility to be coordinated across load forecasting, resource planning, and transmission planning.[32]

Transmission Planning

Flexibility from large loads (often with associated new generation) can reduce or defer the need for new high-voltage transmission lines but is not commonly factored in current transmission planning processes. Flexibility could also increase utilization rates for transmission, enhancing the economic viability of transmission projects. The ESIG Large Loads Task Force report *Transmission Planning with Large Loads: Current Practices and Recommendations* discusses load flexibility in transmission planning.[33]

Resource Adequacy

Load flexibility can provide substantial resource adequacy benefits. By reducing electricity consumption during the most critical hours, flexible large loads (or the dispatch of associated generation to reduce net load) would lower firm capacity resource adequacy requirements. In addition, flexible large loads and associated resources can supply capacity to the market or local utility, reducing supply-side resources needed to meet resource adequacy requirements. Given the long lead times for new generation resources, large loads may be willing to offer flexibility in exchange for speed-to-power (i.e., expedited interconnection). Using flexible large loads to support resource adequacy may only require infrequent curtailment or occasional shifting by large loads. One study

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[31] See https://www.esig.energy/reports-briefs/large-load-interconnection-performance-requirements.

[32] See https://www.esig.energy/reports-briefs/forecasting-for-large-loads.

[33] See https://www.esig.energy/reports-briefs/transmission-planning-large-loads.

found that the existing U.S. system has headroom for nearly 100 GW of new load with an average annual load curtailment rate of 0.5% and an average duration of 2.1 hours per curtailment event (Norris et al., 2025). The ESIG Large Loads Task Force report *Resource Adequacy with Large Loads: Planning for Flexibility to Accelerate Integration* discusses the potential role of load flexibility in supporting resource adequacy.[34]

Markets and Operations

Large load flexibility can play an important role in power system operations and wholesale markets. In principle, flexible large loads could be dispatched to provide energy and ancillary services according to bids representing their willingness to consume based on price. Flexible loads could also participate in markets as traditional wholesale demand response. Emerging concepts envision treating large load demand resources equivalent to supply resources in wholesale markets, but that would require fundamental changes to market participation models (O'Neill, Lew, and Ela, 2023). Load flexibility can also be leveraged during operational emergencies in a manner that is similar to, but separate from, how planning processes consider load flexibility for resource adequacy.

Overall, using flexible loads in power systems operations could result in lower operating costs through more efficient use of generation (e.g., less need for headroom capacity in generators, efficiency gains from operating generators closer to full load) and greater reliability during critical or emergency conditions. The ESIG Large Loads Task Force report *Wholesale Market Design and Operations for Systems with Large Loads: Current Practices and Recommendations* discusses load flexibility in systems and market operations.[35]

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Barriers to Enabling Large Load Flexibility

Effective mechanisms to enable load flexibility would help align grid operational and planning needs with the technical capabilities and business interests of new large loads. These mechanisms could include mandates to require flexibility or incentives to motivative voluntary large load participation in flexibility programs. Incentives could include speed-to-market, as exemplified by Texas SB 6 and SPP's CHILL initiative (Texas Legislature, 2025; SPP, 2026), or direct financial compensation for providing grid services. A challenge with financial incentives is the high opportunity cost for certain large loads compared to the potentially relatively modest compensation for some grid flexibility services. Tariff designs and utility contracts can also influence the flexibility of new large loads.

Other possible challenges include additional costs and regulatory or market uncertainties, insufficient financial incentives, and the need for coordination between loads and grid operators.

Costs and the Changing Nature of Large Load Tariffs, Regulations, and Markets

While a large load would incur capital costs to enable flexibility (e.g., associated generation, facility controls), these costs are modest compared to other capital expenditures (e.g., computer chips). Enabling large load flexibility requires flexibility to be considered in the design phase of the facility, since adapting large loads to be flexible after the fact may be costly due to spatial, technological, or contractual constraints. The changing nature of large load tariffs, regulations, market rules, and other flexibility mechanisms can make it challenging for loads to consider flexibility-related investments and design decisions upfront.

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[34] See https://www.esig.energy/reports-briefs/large-loads-resource-adequacy.

[35] See https://www.esig.energy/reports-briefs/large-loads-markets-operations.

Flexibility as Secondary to Business Focus

Energy and grid services are secondary to the business focus of modern large loads. The additional overhead of participating in complex energy markets or utility flexibility programs could deter participation by large loads. Third-party providers are a potential solution to ease this challenge. Examples include developers of ready-to-build sites that take care of the grid interface, including flexibility offerings, which enables data center operators to avoid this overhead. Other business model challenges include real or perceived risks to the competitiveness of a data center by reductions in compute availability because of curtailment, commitments to tenants for firm service made by data center owners in multi-tenant data center arrangements, and other complex business arrangements could pose barriers to load flexibility.

Grid Operators' Need for Visibility

Grid operators must have confidence that flexible loads will behave as instructed or expected in order for the flexible loads to be accounted for in planning processes (e.g., for resource adequacy or transmission planning) or to be relied on during stressful conditions or grid emergencies. In many cases, flexibility without coordination is less desirable than no flexibility. Considering flexibility only in planning and not in operations, or vice versa, may result in the expected benefits of flexibility not being realized. When generation or storage resources are associated with a large load, this could further expose these challenges as the grid operator may not have visibility into or control of behind-the-meter assets. Grid operator control or financial penalties for lack of flexible performance in operations may be needed to overcome this barrier.

Overcoming the Barriers to Flexibility for Potentially Large System Benefits

Despite these challenges, the significant benefits of large load flexibility are motivating innovative new approaches for integrating demand flexibility considerations tailored to large loads in electricity system planning and operations. That could yield economic savings and reliability improvements system-wide as well as to individual participants.

Recent studies show that the benefits of large load flexibility can be substantial. The Nicholas Institute found that about 76 GW to 126 GW of new large flexible loads could be added onto the U.S. grid with only modest curtailment (0.25% to 1.0%) (Norris et al., 2025). An updated economic analysis estimates $40 billion to $150 billion in savings over the next decade through the ability to shift data center workloads (Ross and Ewing, 2026).

Detailed regional studies also indicate that large load flexibility can offer substantial economic benefits. A joint study from Camus, encoord, and Princeton examined six data center sites and found that flexible grid connections combined with BYOC can yield three to five years faster interconnection for the data centers (Brancucci, Cutler, and Jenkins, 2025). Flexibility through 20% conditional firm agreement avoids the need for new capacity and reduces incremental costs by $78 million per GW, and BYOC would avoid additional costs to other customers. A case study of the NV Energy system, conducted by GridLab and Telos Energy, similarly showed how 1 to 2 GW of flexible data center load could yield $300 to $400 million in savings (Cox, Schwartz, and Stenclik, 2025). A study by the Massachusetts Institute of Technology of three U.S. regions (Mid-Atlantic, Texas, and the Western Electricity Coordinating Council) estimated system cost savings of 2% to 5% from reducing net-demand peaks, reducing transmission congestion, and improving utilization of existing infrastructure through geographically and

Conclusions

The electric power system is entering a fundamentally new phase of demand growth, driven not just by incremental expansion of traditional loads but by the rapid emergence of large, technologically complex, primarily power electronics–interfaced large load facilities. These loads, including data centers such as AI computing facilities, electric oil and gas operations, and energy-intensive manufacturing, differ from historical demand growth in their size, speed of development, geographical concentration, and dynamic behavior. These characteristics challenge long-standing assumptions embedded in load forecasting, interconnection processes, transmission and resource planning, resource adequacy assessments, and wholesale market design. Several cross-cutting themes emerged throughout this report that highlight both the challenges and opportunities associated with the rapid growth of large loads, particularly related to uncertainty in future load development, limitations in available data and modeling inputs, and the evolving role that large load flexibility could play in supporting reliable and efficient grid planning and operations.

Uncertainty Around When, Where, and How Large Loads Will Materialize and Operate

Existing grid planning and operational frameworks are being strained not only by the magnitude of projected load growth but also by limited visibility into when, where, and how large loads will materialize and operate. Unlike

generation resources, large loads typically do not progress through transparent, standardized interconnection queues, and their development timelines, ramp rates, and final operating characteristics are often uncertain until late in the process (and may continue changing over the lifetime of the facility). This uncertainty complicates forecasting and planning, increases the possibility of timing mismatches between load energization and infrastructure availability, and heightens planning and operational challenges for both system operators and regulators.

Insufficient Data for Accurate Planning Studies

The industry lacks high-quality, consistent datasets for new large load facilities, particularly at the temporal and spatial granularity required for modern power system studies. Gaps in information on load composition, operational ramping behavior, disturbance response, and flexibility capabilities mean that planners and operators must rely on assumptions or proxy models that may not adequately capture real-world behavior. These limitations can lead to outcomes that either increase costs and delay economic development or are insufficiently protective of system reliability. As large loads increasingly connect at the transmission level and reach sizes comparable to major generation units or mid-sized cities, the consequences of these blind spots become more significant.

Potential for Load Flexibility

New large loads also present a meaningful opportunity to enhance grid flexibility, efficiency, and resilience. Many new large load facilities possess the technical capabilities to be flexible grid assets through advanced controls enabling fast response, associated generation or storage, and operational sophistication. If appropriately designed, incentivized, and integrated, large load flexibility could help mitigate near-term infrastructure constraints, support resource adequacy, improve operational reliability, and reduce total system costs. Realizing these benefits requires intentional alignment between grid needs, facility design decisions, regulatory frameworks, market mechanisms, and other incentives.

Even if incentives are put in place, demand flexibility will require the ability and willingness of large loads to provide grid services, which depends on business models, uptime requirements, contractual obligations, and regulatory certainty. Flexibility will need to be considered early during site selection, facility design, and interconnection negotiations, as retrofitting large load facilities to be flexible after the fact may not be possible without significant capital investments. Further, system operators will need to have sufficient visibility, confidence, and operational authority to rely on flexible load behavior during both planning studies and real-time operations.

Against this backdrop of rapidly changing electricity demand, ESIG's Large Loads Task Force provided a neutral, technically grounded forum for advancing shared understanding and practical recommendations related to large load forecasting, the interconnection process, interconnection performance specifications, transmission planning and resource adequacy assessments, and market design.

Even if near-term demand forecasts change, the structural shift toward large, power electronics–based electricity consumption is likely to persist. Addressing these challenges in a timely and coordinated manner is essential, not only to maintain bulk power system reliability and electricity affordability but also to enable economic growth and technological innovation. Through continued collaboration, improved data transparency, refined technical requirements, and thoughtful integration of flexibility, the electric power industry can adapt its planning and operational paradigms to meet the demands of this new era of electricity consumption.

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Grid Integration of Large Loads: Introduction to the Large Loads Task Force, Data Needs, and Flexibility

A Report by the Energy Systems Integration Group's Large Loads Task Force

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This report is available at https://www.esig.energy/resources/reports-and-briefs/.

To learn more about the ESIG Large Loads Task Force and the recommendations in this report, please visit https://www.esig.energy/working-groups/large-loads/ or send an email to info@esig.energy.

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. More information is available at https://www.esig.energy.

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