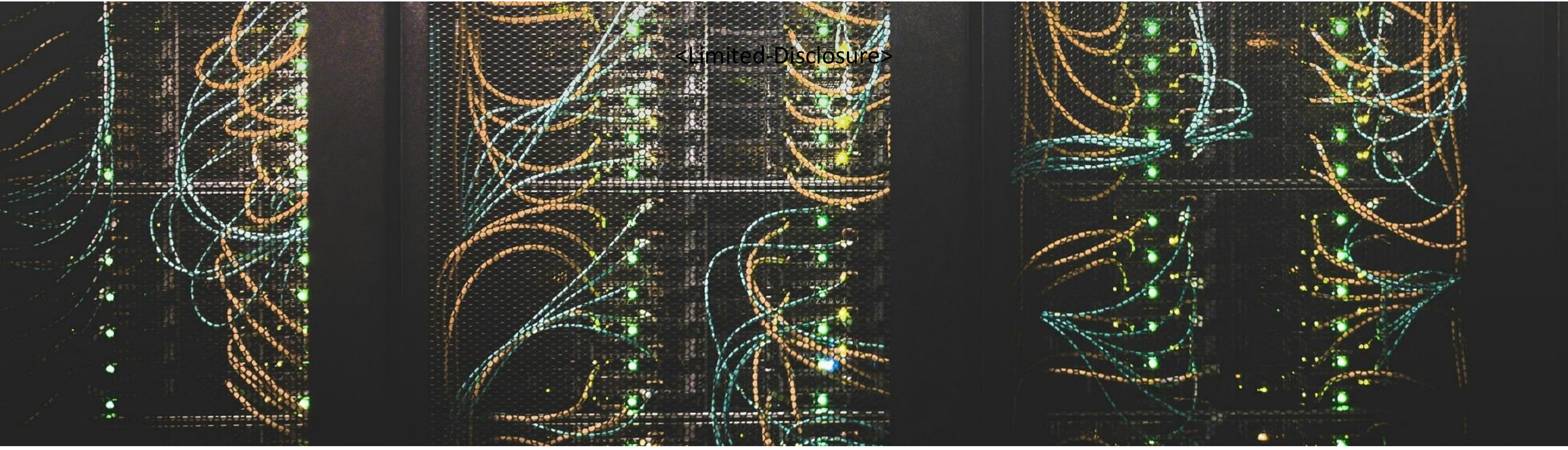

An Assessment of Large Load Interconnection Risks in the Western Interconnection

Technical Report

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Executive Summary

Large load interconnections across the U.S. electric grid, including the Western Interconnection, are growing at an exponential rate. The electricity sector is faced with ensuring the reliable operation of the bulk power system (BPS) by managing and meeting this demand growth, understanding these new facilities, operating the system with new load characteristics and interconnection configurations, and implementing mitigations to address the new reliability challenges and risks that are emerging. These large loads include data centers, cryptocurrency mining operations, large industrial manufacturing facilities, hydrogen electrolyzers, aggregate transportation electrification, aggregate electrified heating and cooling systems, excavation mining, grow houses and electric agricultural loads.

This report intends to educate users, owners, and operators of the electric power system about these new large loads and highlight the challenges and risks to the BPS driven by the interconnection of these new facilities.

While the demand growth forecasts due to these new large loads range significantly (anywhere from 17 GW to 50 GW to 100 GW), the scale of even the low ends of today's forecasts presents exponential growth the electric power system has not seen since the 1950s. Failing to quickly address the unique challenges and risks presented by this exponential growth with adequate risk mitigation strategies may result in unreliable operations of the BPS, an undesired outcome for grid operators and large load operators alike. Many of these large-load facilities provide essential societal services and are a key part of supporting our way of life today. Collaboration, communication, and detailed technical information sharing between all involved parties is critical to solving the interconnection challenges and risks to the BPS, while ensuring reliable and resilient power to the large loads. Regulatory support at the state, regional, and federal level is an additional critical tool that is needed to ensure consistent, fair, and uniform reliability standards and requirements for all load interconnections to the electric grid. Putting reliability and resiliency of the BPS as the focus is the fundamental goal.

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Chapter 1 Introduction

The electricity sector is expected to achieve record power usage and growth in the years to come [1]. Forecasting and understanding changes in electricity demand is a critical part of ensuring reliable operation of the BPS. Demand growth must be met with adequate generation capacity and energy as well as sufficient transmission to maintain reliability during normal and emergency conditions. A 2023 study of nationwide demand trends found that grid planners had nearly doubled their five-year load growth forecasts over the last year, from 2.6% to 4.7% nationally [2]. For example, in the West [3]:

- Puget Sound Energy's 2028 forecast increased nearly 11%, from 4.4 GW to 4.9 GW.
- Arizona Public Service's 2028 forecast increased by almost 11%, from 8.6 GW to 9.5 GW.
- Portland General Electric nearly doubled its five-year summer peak demand growth forecast, from 275 MW to 525 MW.

Historically, load forecasting involved analyzing socioeconomic factors, accounting for weather variability, and major shifts in manufacturing, industrialization, and regional variables. While these factors are still important, the BPS is undergoing a rapid growth of new “large loads” both individually and in aggregate. Data centers are a top priority for the sector but large manufacturing facilities, hydrogen electrolyzers, electric vehicle (EV) charging (i.e., transportation electrification), electrified heating and cooling, and other shifts towards electrifying end-use loads are all contributing to additional pressures on the BPS to provide reliable and resilient electricity.

It is increasingly important to understand the type of large loads being connected to the BPS, their operational characteristics and behavior, and any potential risks or challenges to integrating these new large loads moving forward as they are profoundly different than what has historically been interconnected with the electric grid.

1.1.1 Western Interconnection Load Growth

Electricity demand across the Western Interconnection is projected to increase by an unprecedented 20% over the coming decade [4]. WECC resource adequacy assessments project that peak hour demand for all regions in the Western Interconnection will grow from about 164 GW in 2025 to over 193 GW in 2034, an increase of approximately 17% (see **Figure 1.1**). In terms of energy demand forecasts, resource plans submitted by Balancing Authorities (BA) in 2024 show higher demand increases over the next decade than did plans in 2023. BAs forecast annual demand to increase from 942,000 GWh in 2025 to 1,134,000 GWh in 2034, an over 20% increase.

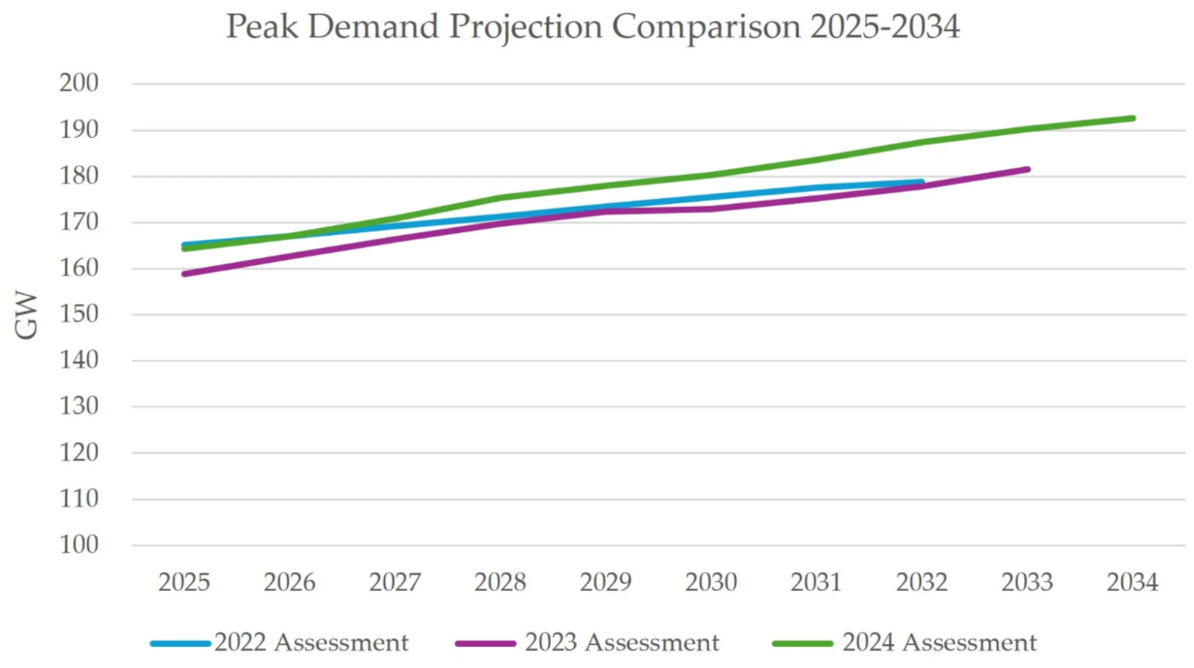

Figure 1.1. Western Interconnection Annual Peak Hour Demand Forecast

1.1.2 Defining Large Loads and a Historical Perspective

This report broadly explores the concept and impacts of large loads on the BPS, and defines two types of large loads:

- **Individual BPS-Connected Large Loads:** These are individual, large end-use load customers connected directly to the BPS (transmission or sub-transmission networks), typically tens to hundreds or even thousands of megawatts.
- Note that these loads may use "distribution-level" connections through large transmission-distribution transformers and many "express" distribution feeders,[1] which make them equivalent to being directly connected to the transmission network. However, there are different ownership models for the distribution-level equipment and feeders. In the case of full utility ownership, these large load customers may submit interconnection requests directly to the distribution utility providers. In the case of the end-use customer owning the distribution equipment (including feeders and step-down transformers), these large load customers would submit interconnection requests directly to the transmission utility providers. The impact of these different interconnection requests and connection-types is discussed further in Chapter 2.
- **Aggregate Large Loads Connected throughout the Distribution System:** These are individual load classes (e.g., EV chargers, heat pumps) connecting throughout the distribution system that, in aggregate, have a notable impact on the BPS. These are individually much smaller loads (tens to thousands of kilowatts), but in aggregate add up.

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[1] Express distribution feeders are distribution feeders going directly from the substation to the end-use customer facility, with no other utility customers connected to that feeder.

Planning, interconnecting, and providing reliable power to large end-use load customers is not a new concept for transmission providers across the Western Interconnection and the U.S. There are a wide range of large loads historically connected to the BPS and still in operation today as illustrated in **Figure 1.2**. These large loads have typically been hundreds of kilowatts (distribution-connected) to hundreds of megawatts (transmission-connected). They have historically had relatively regular and predictable patterns in terms of load profile and load factor (i.e., how often they are run or operated). The electricity sector has had time to understand the unique operating characteristics and behavior of each load, define necessary standards or performance requirements (as needed), and then have sufficient time to plan, design, and construct a BPS that serves their needs.

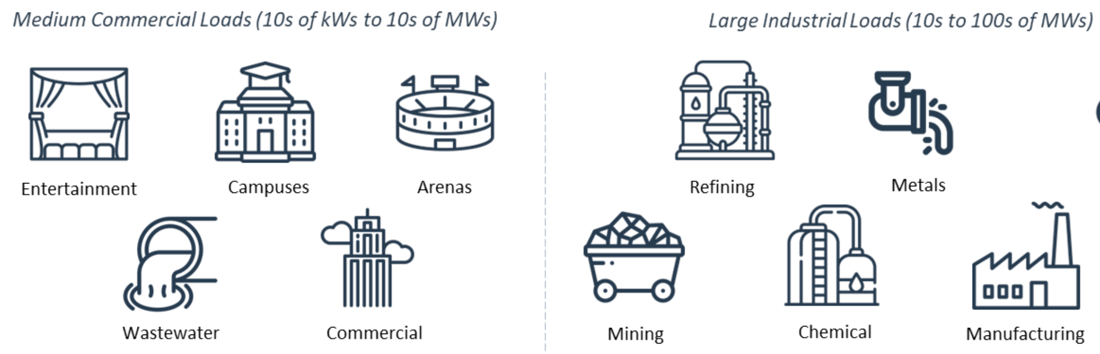

Figure 1.2. Historical Types of Large Loads

1.1.3 Large Loads Considered in this Assessment

The following types of large loads, both individually and in aggregate, are considered in this assessment:

- Data centers, including artificial intelligence (AI) hyperscale data centers[2]
- Cryptocurrency mining operations
- Large industrial manufacturing
- Hydrogen electrolyzers
- (Aggregate) Transportation electrification
- (Aggregate) Electrified heating and cooling
- Excavation mining
- Grow houses/agricultural loads

Refer to **Appendix A** for a brief description of the different types of loads.

1.1.4 Background on Large Load Trends and WECC Industry Advisory Group

In early 2024, WECC stood up an informal industry advisory group (IAG) ("Large Load IAG") comprised of transmission providers across the Western Interconnection to foster the sharing of information regarding large load forecasts, interconnection queue practices, and areas of BPS concerns and risks where increased collaboration could be useful moving forward. The Large Load IAG provided estimates of large load interconnection queue size, composition, and additional information so the group could broadly assess

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[2] A hyperscale data center is a large data center that provides rapid scalability to support large-scale computing workloads such as AI computing.

which types of large loads will likely present the biggest impacts and challenges to the BPS moving forward. The Large Load IAG developed a self-administered questionnaire designed to gather information related to two key questions:

1. The estimated large load interconnection queue size and breakdown by large load category.
2. The relative rank priority of each large load category in terms of growth, system impact, and effects on business operations.

Results from the ten respondents of the survey illustrate that data centers are projected to be the largest contributor to demand growth across the West in the next five to ten years and are expected to have the largest impact on BPS reliability. Takeaways include:

- Data center load interconnection requests comprise nearly 80% of the large load interconnection queues, far outweighing the size, breadth, and potential impact of all other large load categories (see **Figure 1.3**).
- The total large load queue size for the ten respondents is 44,650 MW, which is nearly equivalent to the current system peak demand level for those entities (48,425 MW).
- All utilities ranked data center impacts as "high" and each utility described several factors for the ranking such as forecasting, planning, operations, design and engineering, supply chain, transmission service and expansion.
- Following data centers, survey results reflected that utilities are most focused on hydrogen electrolysis, transportation electrification and the growth of electric vehicles (EV), large industrial manufacturing, and heating/cooling electrification, as shown in **Figure 1.4**.

Estimating large load growth is difficult, particularly across entities and given uncertainty and variability in processes and accounting methods. Therefore, these numbers are high-level estimates but send a clear and resounding message regarding the size and magnitude of large load interconnection requests in the Western Interconnection.

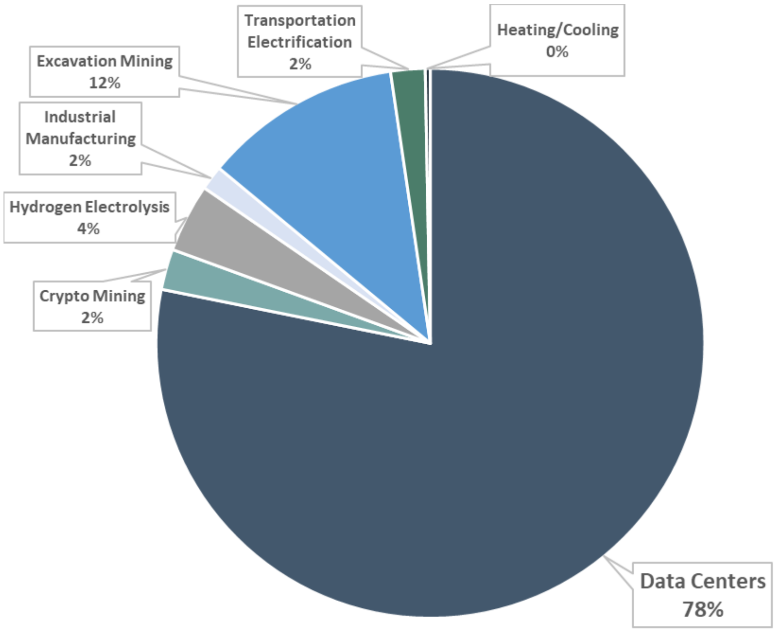


Figure 1.3. Composition of Surveyed Large Load Interconnection Queues

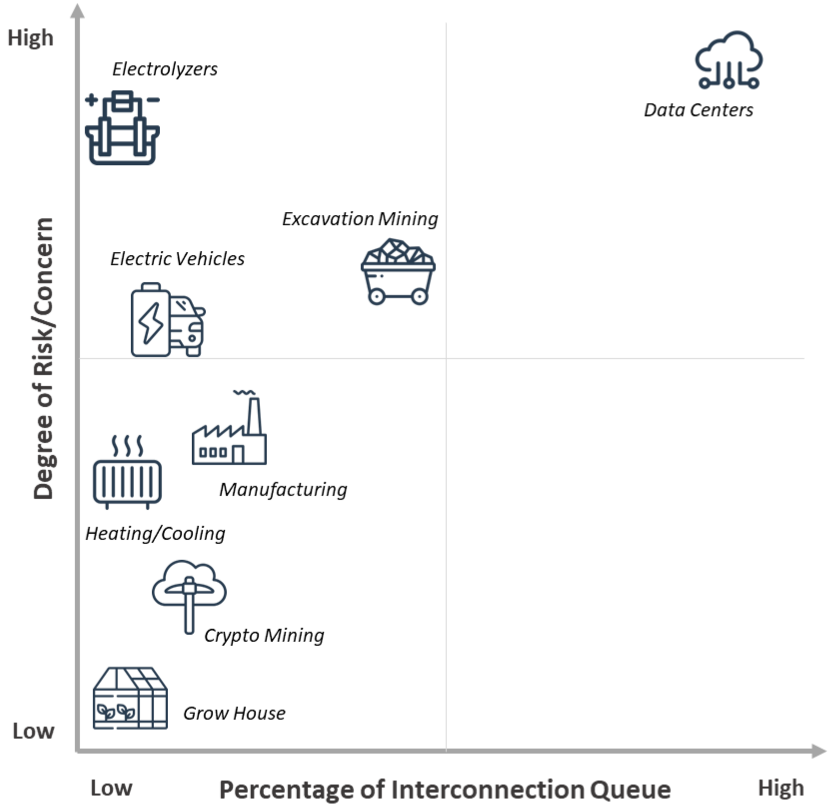


Figure 1.4. Degree of Concern Relative to Queue Size

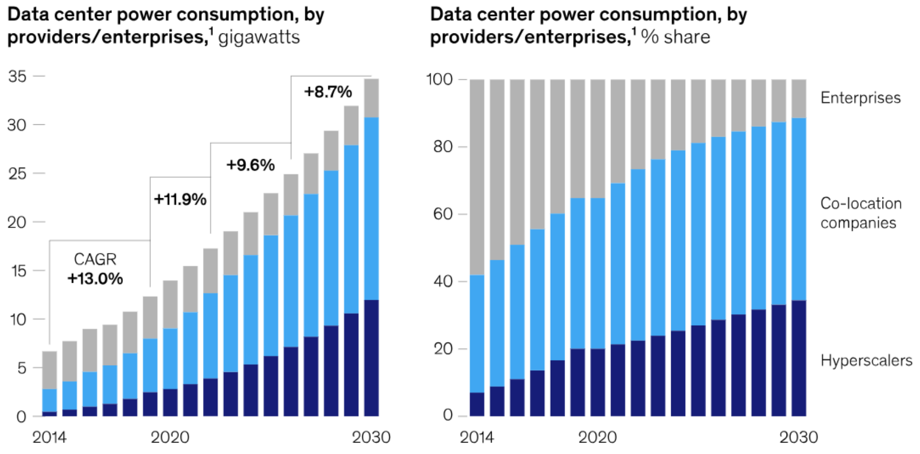
Chapter 2 BPS Reliability Risks Posed by Large Loads

The BPS is designed to provide safe and reliable power to end-use customers. There is a symbiotic relationship between the grid and customers due to the shared mission to provide available electricity to power every facet of modern society. As with generation resources, large loads can have an impact on the reliable operation of the BPS, particularly those connected directly to the BPS or those that in aggregate have a material impact on the BPS. This chapter will describe some of the more critical impacts and risks posed to the BPS by large load interconnections.

2.1.1 Large Load Interconnection Risks and Challenges

The size of large load interconnection queues and individual interconnection requests have increased significantly, exceeding historical norms, which presents new engineering challenges.

Data centers comprise most utility load interconnection queues and will become an increasingly significant portion of utility demand moving forward. Ubiquitous computing and digital technology in modern society combined with advancements in AI and quantum computing are driving significant growth projections for data center demand in the decades ahead. U.S. data center demand is forecast to grow by nearly 10% per year through 2030, reaching 35 gigawatts (GW) by 2030, up from 17 GW in 2022, as shown in **Figure 2.1**. Trends are moving away from enterprise[3] to hyperscale[4] and co-location[5] models, leading to large-scale and centralized data center hubs [5]. This trend is happening internationally as well—Ireland experienced a 400% rise in data center electricity demand between 2015 and 2022, sparking debate about available capacity [6]. In the United Kingdom, National Grid expects data center demand to increase six-fold in the next decade [7].



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

Figure 2.1. U.S. Data Center Demand Forecasts by Type of Data Center (Source: McKinsey & Co.)

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[3] Enterprise data centers are those owned and operated by single companies for exclusive computer and networking use [35].

[4] Hyperscale data centers are capable of quickly scaling up their operations to meet the vast computing needs by the cloud services such as Amazon ASW, Google Cloud, and Microsoft Azure they are hosting [35].

[5] Co-location data centers, also known as multi-tenant data centers, are where many businesses rent space to house their servers and hardware, while sharing the power and cooling infrastructure with all other tenants renting space in the center [35].

The Electric Power Research Institute (EPRI) conducted a survey of utilities across the world and found that almost half of the utilities have data center interconnection requests that exceed 50% of their present system peak demand. Nearly half of the utilities predict that over 10% of their peak demand in five years will come from data centers, and 26% of respondents believe data centers will constitute over 20% of their peak demand in five years [8].

Furthermore, individual load interconnection request sizes have increased in recent years—predominantly driven by data centers and AI. Existing data center demand levels typically range from several up to 400 MW. In the same EPRI survey, 60% of utilities have data center interconnection requests for 500 MW or larger, and 48% have requests that surpass 1,000 MW individually [8]. Hyperscale data center requests continue to emerge. While a large data center may consist of many individual buildings (i.e., a campus), the entire facility comprises a single transmission interconnection request with many transmission-distribution transformers and distribution circuits to supply power to all the buildings to provide adequate transmission service to these customers. This is putting a strain on load interconnection queues that have historically not been a major pain point for utilities.

Large load interconnection processes are evolving and lack consistency and uniformity, leading to speculative interconnection requests and difficulties administering a consistent queue process

While BPS-connected generators undergo a standardized and uniform procedure governed by the U.S. Federal Energy Regulatory Commission (FERC) Generator Interconnection Procedures (GIP) and Agreements (GIA) [9], similar mandated procedures do not exist for large load interconnections in the U.S. Some Transmission Owners (TO) have some degree of established load interconnection procedures and agreements, in accordance with North American Electric Reliability Corporation (NERC) FAC-001 and NERC FAC-002 requirements [10]. However, the procedures and methodologies for investigating the reliability impacts of large loads are often lacking in technical content and transparency. In many cases, a comprehensive list of data sharing requirements, performance requirements, interconnection process timelines, study milestones and fees, cost allocation criteria, and other factors are not documented thoroughly. This may have sufficed when load interconnection requests were orders of magnitude smaller, and the breadth of requests was much lower. Today, an agile and well-documented load interconnection process is critical for ensuring BPS reliability and administering a fair, just, and equitable interconnection process.

Many utilities note that the barrier to entry for the load interconnection queue is very low or nonexistent. One IAG member highlighted that even a speculative phone call regarding load interconnection is subsequently treated as a formal request and the utility will conduct cursory studies to explore the potential interconnection. While utilities seek to make the interconnection of large customers as efficient as possible, speculative requests should be avoided and disincentivized. Establishing criteria for entering the large load interconnection queue would be an important step in administering an effective process where ideally large load requests that are ready for interconnection will be studied in detail.

Many entities also use a serial load interconnection process where each request is treated in queue order (i.e., network upgrades are assessed and assigned serially per interconnection request, which can create backlog and difficulties when the queue consists of speculative projects). The electric industry's recent experience with the overhaul of the generator interconnection process driven by the exponential growth of inverter-based resources (IBR), particularly moving to a cluster system impact assessment process per FERC Order No. 2023, may prove to be a preferred approach for load interconnection processes and queues in our current environment [11]. As large load interconnection requests increase rapidly, legacy load interconnection queues may become increasingly backlogged and require alternative approaches that use the "first-ready" principles. This requires close coordination between the transmission service providers, distribution service providers, and the Independent System Operator (ISO)/Regional Transmission Operator (RTO), where applicable, to ensure network upgrades are adequately assessed. Historically distribution and transmission requests and queues were managed through separate processes and queues. Going forward it would be valuable for these separate processes and queues to be closely coordinated and similarly structured to ensure efficient, fair, and technically thorough interconnection processes are performed and communicated between all electric grid providers and the end use customers.

Large load interconnection requirements are relatively non-existent and lack standardizations and harmonization at a regional or national level

Regardless of large load queue processes, it is imperative that large loads have clear, consistent, and appropriate interconnection requirements to facilitate effective and reliable interconnection. Generally, industry is lacking well-defined interconnection requirements for large loads that comprehensively address the potential BPS reliability and performance risks posed by these loads. Lack of requirements appears to result in a lack of information and data regarding the interconnecting facility, leading to gaps in modeling and concerns with the accuracy of interconnection studies conducted. Multiple TOs have highlighted that there are significant challenges getting useful information voluntarily from large load customers, particularly data center customers.

These same interconnection requirements should also be considered at the distribution level for distribution providers that are receiving these large load interconnection requests as well. Coordination of these requirements between transmission and distribution providers is essential for BPS reliability.

Lack of structured load interconnection procedures and requirements leads to speculative requests and subsequent difficulties in forecasting large load demands

Large load interconnection requests are an input into demand forecasts that are used across planning and operations. Demand forecasts are included in Integrated Resource Plans (IRP), resource adequacy and energy assessments, transmission planning, and operational studies. Currently, there are no consistent practices regarding when a Distribution Provider (DP), Resource Planner (RP), or TP includes large load interconnection requests into IRPs or other studies to make large grid investment decisions. As large load interconnection queues increase exponentially, this issue becomes amplified. Therefore, it is an important area to seek standardization and consistency in terms of interconnection project milestones wherein large load interconnection requests should be included in planning decisions.

Figure 2.2 from the Electric Reliability Council of Texas (ERCOT) region shows an example of large loads approved to energize versus the actual operational demand [12]. The figure shows only some percentage of the requested transmission service is used on peak load conditions (between 58–78% within a year). This highlights that even when service is granted, ramp up time may be extended as, for example, the data center brings on additional tenants or builds out its full server capacity over time. Long-term forecasting challenges involve tracking and adjusting forecasts based on macro-level trends and technological breakthroughs (e.g., generative AI). Data center siting requirements have evolved from access to internet connectivity and lowest latency (i.e., fiber optic lines), to nodal prices, and now towards transmission hosting capacity (i.e., transmission access) and time to build or upgrade the transmission and distribution system for interconnection.

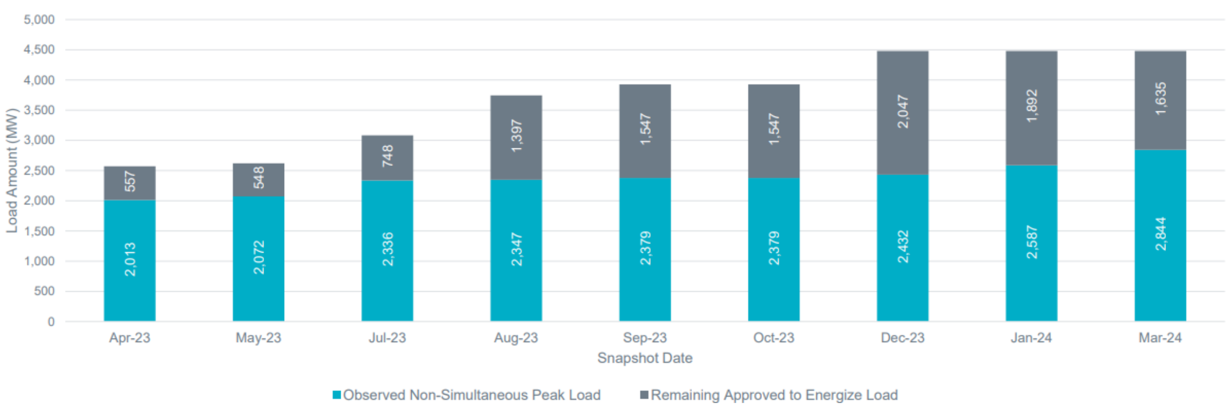


Figure 2.2. Operational Large Load vs. Approved Large Load in ERCOT (Source: ERCOT)

Load forecasting requires information from each BPS-connected large load customer regarding the size, location, voltage level, time to build facility to full capacity, and operational attributes of the load behavior. BPS-connected large loads may also need to include information regarding price sensitivity, load factors (i.e., uptime), and any other metrics used for modeling and study purposes. This information is often used in downstream modeling and studies such as production cost modeling and power flow studies.

Aggregate large loads are more likely to be captured in load forecasting efforts; however, careful consideration for electrification of heat pumps, EVs, and other aggregate loads should be given so as not to underestimate the potential trends occurring. Some aggregate load growth may shift peak demand conditions such as heat pumps increasing winter peak load levels and shifting demands into morning hours in commercial applications. For example, a study estimated that an Ithaca, NY, proposal to retrofit and electrify 1,600 residential and commercial buildings in four years would triple winter electric loads even with a 30% efficiency improvement [13].

In some utilities, the load forecast, generation interconnection, distribution load interconnection, distributed energy resource (DER) interconnection processes, and transmission interconnection processes are managed by different departments with only loose coordination. Data owned by one department may not be clearly visible to other departments. Holistic planning approaches are needed to optimize solutions, minimize costs, and reduce repetitive work in this space.

Lack of requirements has led to a severe lack of data sharing and understanding about the operational characteristics of large loads, primarily data centers

Data sharing is a backbone for successful large load interconnection and BPS planning and operations. Lack of data sharing and transparency of large loads presents a major roadblock regarding the ability to understand the operational characteristics of the load, being able to model the load, and accurately study the reliability impacts of the load.

Data regarding aggregate large loads such as EVs and heat pumps can be estimated since modeling the individual characteristics and impacts is untenable and not necessary. Industry standards, for example Underwriters Laboratories (UL) certification [14] and Society of Automative Engineers standards like SAE J2894 [15], govern the performance of this equipment. Engineering societies, research institutes, and laboratories help understand the performance of end-use devices which can be converted into aggregate models using engineering judgment [16].

Data sharing from large load interconnection customers connecting directly to the BPS needs to be dramatically improved. These interconnections must be adequately studied including steady-state and dynamic performance effects. Data sharing requirements would facilitate getting more accurate information about the interconnection request, as described above. Understanding the operational performance of large loads—ramping, price sensitivity, variability, uptime, frequency and voltage protection settings, facility and Uninterruptable Power Supply (UPS) configuration, dynamic controls, harmonics, etc.—all play a key role in accurate modeling and studies. Not receiving this data from the large load customers can present serious reliability risks to the BPS.

2.1.2 Large Load Modeling and Study Risks and Challenges

Limited understanding of large loads precludes the creation of models, which prevents accurate studies to justify the need for additional mitigating measures (i.e., a chicken and egg situation)

Modeling large loads is a highly complex topic. However, at a high level, the lack of understanding of large load behavior, composition, and performance creates a barrier to create load models used in various reliability studies (ranging from capacity expansion and production cost to steady-state power flow and into phasor domain transient (PDT), short-circuit, and electromagnetic transient (EMT) modeling and studies). Some simulation domains and platforms require modeling the load using standardized models, but without sufficient information to create or populate these models, TPs and PCs are challenged in conducting accurate assessments of system performance.

As behind-the-meter (BTM) and co-located configurations with generation resources evolve, data centers may play a more active role in electricity markets and have an increasingly impactful role on BPS reliability. Hence, similar capability and performance expectations (including provision of accurate and validated models) should be applied to these entities. Furthermore, modeling load flexibility will play a key role in assessing not only the risks but also the operational benefits of demand response loads moving forward.

Basic modeling approaches used today may not capture large load behaviors and may present serious reliability risks

Currently, modeling practices are in the early stages and significantly more work is needed to standardize the models and practices for large loads, particularly in the PDT and EMT domains. Very large BPS-connected loads should be undergoing detailed reliability studies including both PDT and EMT due to the BPS reliability risks that could be posed by any abnormal performance of these large loads. Industry efforts are seeking to move the needle in this area but are faced with difficulties that may need to be elevated to cross-sector collaboration venues.

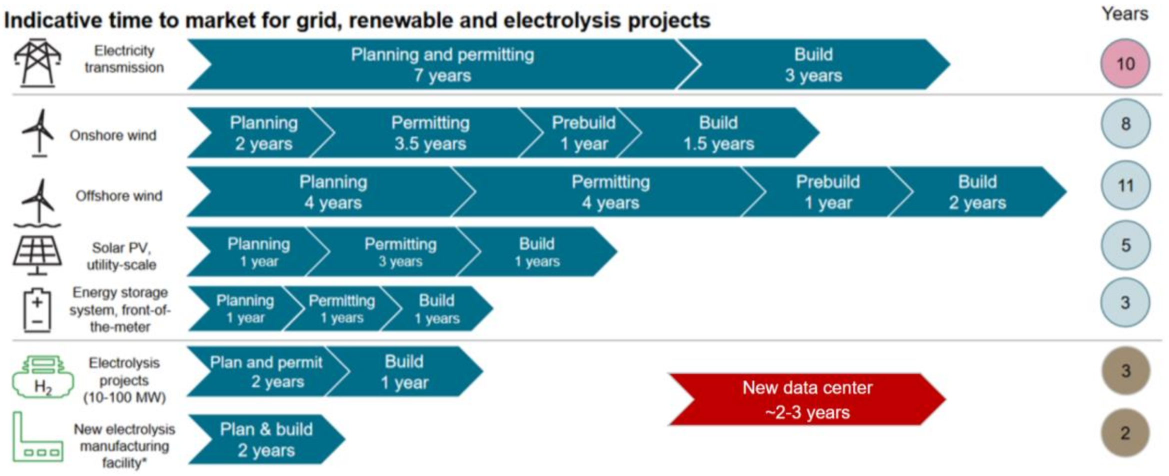
Use of simplified static load models fails to recognize the dynamic nature of these loads, and omitting voltage and frequency trip settings could underestimate the potential adverse impacts these loads could have during ride-through events. These types of system impacts are discussed in more detail below. However, accurate modeling is of paramount importance such that TOs, TPs, and PCs, can make informed and appropriate engineering decisions moving forward. Overcoming data availability and model limitations needs to be a high priority.

2.1.3 Large Load Planning Risks and Challenges

Serious discrepancies exist between large load interconnection request timelines and the ability to build BPS infrastructure

Many large loads including data centers, crypto mining facilities, and industrial manufacturing facilities are able to design, site, permit, and construct on time scales that are dramatically faster than building BPS network infrastructure such as transmission equipment. Time to market is a very high priority for large load customers such as data centers, particularly AI data centers. Speed of construction and connection challenges interconnection planning, construction, and forecasting. The forecasted pace of load growth could far exceed the pace of large transmission expansion projects. The escalated demand driven by new large loads and the geographically disbursed nature of renewable generation requires significant transmission capacity expansion, including upgrading existing facilities and building new infrastructure. This is particularly an issue in less populated regions with more abundant land and lower rates for electricity (advantageous to large load customers) that do not have sufficiently robust transmission infrastructure.

Large loads are often able to plan, permit, and build within one or two years (or quicker) whereas utility-scale generation can take three to ten years. Small transmission upgrades typically take two to three years from planning to energization whereas large transmission infrastructure projects often require more than ten years due to long stakeholder engagement, permitting, and building timelines. **Figure 2.3** shows an illustration of the time to market for different technologies, showing the dilemma and misalignment between data center needs and the realities of building new infrastructure [17].



PV = photovoltaics.
*Once heads of terms /purchase contracts are in place, based on indicative Europe timelines.
Source: S&P Global Commodity Insights.

Figure 2.3. Indicative Time to Market Comparison
(Source: S&P Global Commodity Insights)

While some data center owners are willing to accept lower service levels rather than wait years for network upgrades to connect, many utilities do not have experience dealing with such situations.

Supply chain challenges may lead to interconnection delays, creating a bottleneck and leading data center developers to explore alternative solutions

Regardless of large-scale transmission infrastructure build-out, large load customers seeking connection and transmission service will require network upgrades to directly connect their equipment to the grid. This includes upgrades to transmission circuits, breakers, switchyards, substations, new transmission-distribution transformers, and protection and control elements. Transformers are long lead-time equipment that can take multiple years to procure. Similar issues may arise for extra high voltage (EHV) breakers and other switchgear. These supply chain issues may be exacerbated given the massive influx of requests for connection from many customers.

Grid interconnection challenges are incentivizing data center developers and owners to seek alternative solutions including co-location with generation assets

The challenges associated with finding adequate transmission capacity and the long lead times associated with transmission network infrastructure buildout are leading large load developers to seek creative alternative solutions to interconnection. FERC recently held a Commissioner-led Technical Conference regarding large loads co-located at generating facilities, where discussions centered around the market and reliability impacts associated with the co-location of large loads with existing or future generating resources (see **Figure 2.4**) [18]. Subsequently, FERC rejected an amended interconnection service agreement (ISA) that would facilitate expanded power sales between Talen Energy's Susquehanna nuclear power plant and a co-located data center [19]. Regardless, investor interest in this configuration remains high because of the unique opportunities presented; however, market redesign, cost, and other legal considerations need to be addressed. Nuclear energy remains a prime candidate for this configuration as it seeks to provide constant clean energy for extended periods of time, aligning with large load customer needs.

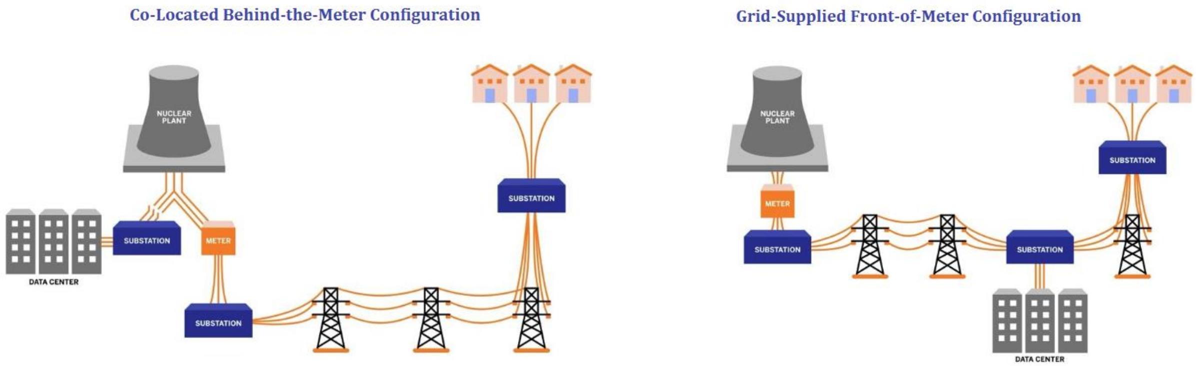


Figure 2.4. Behind-the-Meter (Left) and Front-of-Meter (Right) Configurations (Source: M. Kormos)

Similarly, zero carbon emissions requirements may also lead large load customers to new design practices. BESSs may replace conventional diesel generators as short-term backup power and the concept of microgrids is another practice that could be employed to supplement data center power needs. These flexible generating resources may serve as multi-purpose resources that can provide energy to the grid when needed and/or provide power quality corrections or other reliability issue mitigations.

Some electrolyzer sites are also exploring repower projects at existing coal and gas facilities to use existing infrastructure and transmission capacity, and to expedite the approval and construction process. One example: at the time of writing this report the coal-fired Intermountain Power Project (IPP) located in Delta, UT is planned to be transformed into a hydrogen electrolysis plant by Los Angeles Department of Water and Power (LADWP) through multiple phases (see Figure 2.5) [20]. Due to the change of fuel type and technology, repowering will need to abide by applicable interconnection procedures.

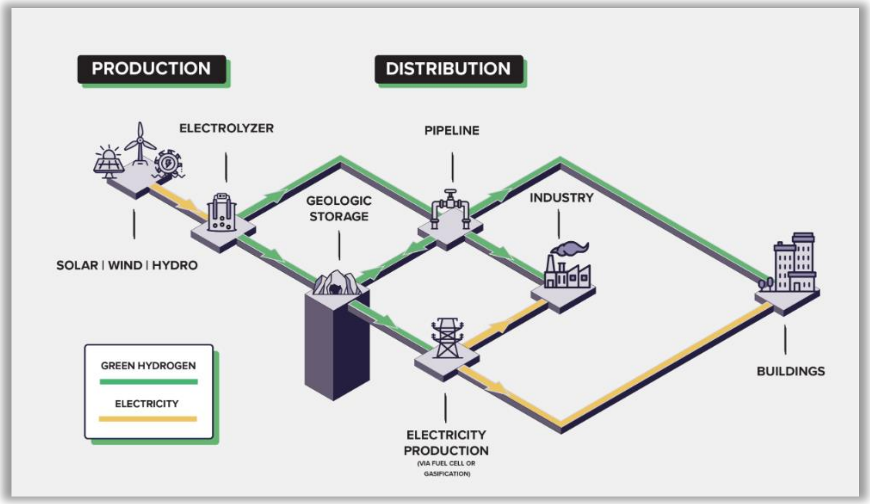


Figure 2.5. Conceptual Flow of Energy for IPP (Source: Green Hydrogen Coalition)

Generation capacity and energy adequacy will be a major challenge with uncertainties regarding individual and aggregate large load behaviors and patterns

The strong correlation between large load interconnections and the continued boom of renewable energy resources will continue to challenge grid planners and operators to ensure sufficient generation capacity and energy is available under all operating conditions. The NERC Reliability Assessments continue to highlight capacity shortfalls under certain operating conditions, driven by resource type, extreme weather, fuel risks, and reliance on imports. These issues are of moderate risk in the WECC region, with certain regions experiencing elevated risk scenarios [21]. Large load interconnections and the reliance on variable energy resources present challenges under extreme weather conditions, periods of prolonged high energy demands, or unexpected transmission outage conditions.

The boom of large load interconnections and clean energy resources will require redesigning everything from interconnection reforms to BPS stability assessments

Large load customers such as hyperscaler organizations (e.g., Google, Amazon, Meta) acknowledge the significant energy demands required by new technologies and many are committed to net-zero carbon emission targets. The data center industry has increased demand for renewable energy and is a significant purchaser of clean energy resources to meet sustainability goals [22]. In 2021, Amazon and Microsoft were two of the largest corporate buyers of renewable energy through Power Purchase Agreements (PPA) [23]. Further, green hydrogen creation is energy intensive which is likely to further spur demand in renewables.

As mentioned, large load interconnection times are far shorter than conventional generation development due to backlogs in the generation interconnection process. FERC introduced Order No. 2023 to expedite the processing and analysis of the generator interconnection queue [11]; however, this will still require significant time to design, plan, procure, construct, commission, and subsequently operate these plants. Timelines are not entirely aligned, which could lead to renewable energy shortages to meet large load customer needs.

The ERCOT “connect and manage” process has been lauded by many as a more streamlined interconnection process for generators and, in many ways, puts risks on the development community yet enables a much faster time to market. In essence, the process allows generators to connect to the grid if they pass a set of reliability tests throughout the interconnection process. Deliverability is not guaranteed, and any congestion is managed in real-time operations. Studies are conducted to ensure reliability but not to build transmission. Transmission planning processes separately build a backbone network to support interconnection. The ERCOT process is 18 to 30 months for large generators (≥ 10 MW) [24].

Large loads will have impacts on transmission planning (and operational planning) studies and must be modeled and accounted for properly

As mentioned, large load forecasts will be crucial for developing realistic and meaningful future planning cases and scenarios to study. As always, accurate forecasts will be a critical aspect of proper base case development. Planning assessments will also need to consider the unique operational characteristics of large loads, including protection settings and control philosophies. Large load patterns will affect base case steady-state dispatch assumptions, and these large loads will have significant impacts on power flow patterns, network upgrades, stability margins, voltage control, oscillations, and other factors. Long-term planning studies may increasingly need to conduct EMT studies as part of the annual planning process, particularly when large load facilities are near pockets of IBRs where possible weak grid conditions may arise. Contingency selection, scenario planning, and sensitivity analyses will all need to account for large load assumptions. Loss of large loads, particularly where uncertainties in operational characteristics exist, may also need to be studied in closer detail.

Multi-sector electrification and aggregate load growth will create challenges and require upgrades to distribution system infrastructure

Heat pumps, EV charging, and other multi-sector electrification across residential and commercial industries are expected to challenge the capacity of the distribution system. Growing adoption of EVs and deployment of EV charging infrastructure will continue to require distribution circuit upgrades and replacements. One major challenge is transmission-distribution transformers, which are in high demand and have long lead times to procure. When the demand levels rise too quickly, this may put serious strains on deploying network upgrades quickly enough given such an unprecedented pace of change. Large fleet charging depots are also becoming more prevalent for electric buses, last-mile delivery services, and future urban transport. The aggregate demands from all electrified sectors will also have impacts on the transmission system and require careful consideration of transmission-distribution congestion management, modeling, and studies. A highly electrified distribution system also unlocks opportunities for virtual power plants and more active end-use load participation in wholesale electricity markets per FERC Order No. 2222 [25]. These shifts in electrified loads and more active participation of grid-edge technologies will shift load profiles and affect BPS planning and operations decisions.

2.1.4 Large Load Operational Risk and Challenges

Large load demand variability, fluctuations, and ramping can present grid steady-state and dynamic performance issues

Large load variability and fluctuations, particularly from data centers, crypto mining facilities, and electrolyzers, can have large impacts on BPS reliability. Large flexible loads may be price sensitive or respond to other signals. When understood, modeled, studied, and/or controlled, this is a service and asset to the grid. Yet when these fluctuations cause increased variability and uncertainty for real-time operations, they are a detriment. To handle increased variability and uncertainty, grid operators would need to carry additional regulation reserves. These reserves are set aside for that service, reducing the pool of dispatchable generation and raising costs for ratepayers.

The loads themselves may be variable in nature. For example, a data center may be owned by one entity but leased to many tenants using the servers for various purposes. Therefore, predicting the behavior and operational characteristics of the load can be challenging. Tenants, in many cases, are not required to share information with the data center owner, further complicating the issue. This causes further uncertainty during real-time operations.

Without requirements on ramping (e.g., ramp rate limits), the BPS may be challenged to manage operating conditions within acceptable limits, particularly for very large load customers. A multi-hundred-megawatt data center, or even one of over 1,000 megawatts, causing large fluctuations on the BPS would have a significant impact and require corrective actions to address this performance. The magnitude and speed of ramping would dictate the types of solutions that can be deployed.

Lastly, AI processes may be leading to large load operational characteristics the BPS has never experienced before. A Central Processing Unit (CPU) processes work tasks sequentially whereas a Graphics Processing Unit (GPU) processes multiple tasks in parallel and the parallel processing results are merged while the GPU waits for the next task. Therefore, AI load profiles may ramp up and down frequently and significantly. Figure 2.6 shows an illustrative example. When a GPU is idle, it consumes ~10% of its nominal power. During working time, it quickly ramps to its maximum load (120~150% of its nominal power), and the power consumption between each maximum load is ~80-100% of its nominal power when it processes the parallel computation results. When GPUs at a data center operate in coordination at the scale of these data centers, corresponding massive load swings can be observed at the minute, second, and even sub-second level. The leadership of multiple technology companies pioneering AI efforts have recognized that power fluctuations may range from tens to hundreds of megawatts today, and these swings are expected to reach into the thousands in the future.

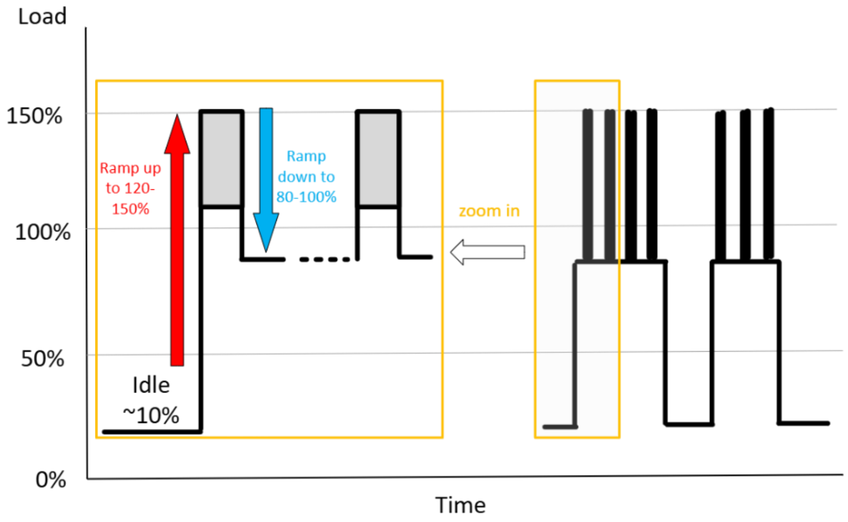


Figure 2.6. Conceptual Representation of Variability and Ramping of AI Demand Profile

Fast ramps or spikes in demand from AI data centers, if not addressed locally, have the potential to cause adverse impacts on the BPS including triggering inter-area oscillations, inducing power quality issues such as flicker, causing large deviations in frequency and intertie flows, causing large swings in voltage, affecting the lifespan of BPS equipment such as transformers. The IAG stated that they have observed these types of behavior in relatively small levels already, and that mitigating measures are needed before these impacts become much larger.

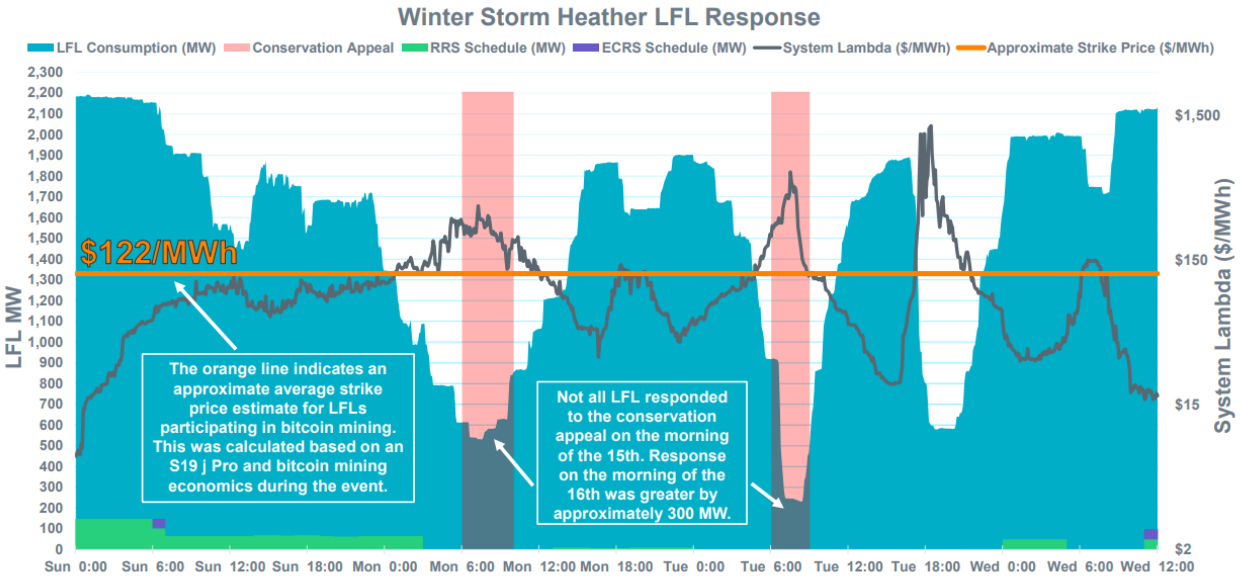
Due to the lack of requirements established, information provided during interconnection, and transparency from large load customers, these types of issues may go undetected until after commercial operation, putting the onus and burden on the utility to address these risks themselves—and in real time. This may inadvertently push costs and obligations onto entities and ratepayers that are not directly causing the issues.

Large load cybersecurity risks to the BPS

These large load facilities, especially data centers, could potentially be managed remotely from personnel and organizations located geographically far away from the physical data centers, including outside of the U.S. The potential cybersecurity risks this creates requires further research to understand the potential for remote access and control of these facilities which could force sudden load trips, swings, and reclosing of the facilities unexpectedly.

Price sensitive large loads can have a significant impact on grid operations and markets

Large loads such as crypto mining facilities are extremely sensitive to wholesale electricity prices and can ramp up and down very quickly in response to changing market signals. When the strike price is higher than the agreed power purchase settlement price, the cryptocurrency mining facility may curtail to avoid paying extra money for the electricity. For example, ERCOT conducted an analysis of curtailment behavior of large loads during the 2024 Winter Storm Heather when price fluctuated quickly. ERCOT observed that large load consumption ramps quickly up and down when the price curve surpasses the estimated average strike price, as shown in **Figure 2.7** [26]. The system operator must manage these fluctuations in forecasting, planning, and real-time operations.



The orange line indicates an approximate average strike price estimate for LFLs participating in bitcoin mining. This was calculated based on an S19 j Pro and bitcoin mining economics during the event.

Not all LFL responded to the conservation appeal on the morning of the 15th. Response on the morning of the 16th was greater by approximately 300 MW.

Figure 2.7. Winter Storm Heather Large Load Response (Source: ERCOT)

Hydrogen electrolyzers may also be price-sensitive, as electricity is a majority of operational cost. Similar to a Battery Energy Storage System (BESS), a hydrogen production facility may start or stop electrolysis in response to electricity prices. This may bring challenges to grid balancing but is also an opportunity to provide valuable grid services for balancing, reserves, frequency control, and other ancillary services.

The size of individual or aggregate data center loads is necessitating ride-through performance to support BPS stability

Industrial loads and data centers have high power quality and reliability requirements due to the sensitivity of equipment and process controls. For example, loss of data center liquid cooling for a short duration (i.e., seconds) will result in server shutdown and significant economic loss. Therefore, large loads are often equipped with backup power supplies to handle these discontinuities in service. However, grid events such as faults and generator trips occur regularly, and the BPS is designed to withstand these events. Ideally, large loads should be designed and operated in alignment with the performance obligations of the BPS. Furthermore, given the size of large load interconnection requests and the effects they can have on the BPS individually and in aggregate, it is important for large loads to meet BPS performance requirements including disturbance ride-through. Significant loss of load can cause instability, uncontrolled separation, and cascading.

Large load equipment is designed to be notoriously prone to disconnection or tripping for grid events such as faults in order to protect the equipment. Supplemental equipment at the load facility can help support ride-through performance of end-use load components such as servers and industrial processes. Yet the end-use device design curves fall within normal ride-through curves such as NERC PRC-024 and NERC PRC-029 [27]. Two examples are:

- SEMI F47-0706 is the specification for voltage sag immunity for semiconductor processing equipment, originally published in 2000 and updated in 2006 [28] (see **Figure 2.8**). This curve is prone to tripping for nearby bolted faults.

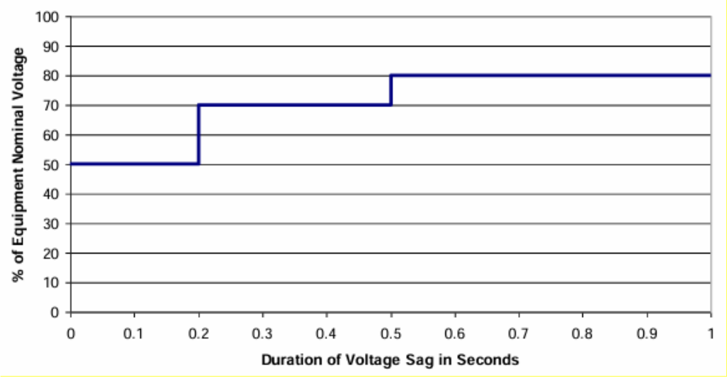


Figure 2.8. Voltage Sag Immunity Required by SEMI F47-0706

- The Information Technology Industry Council (ITIC) curve shown in **Figure 2.9** [29], is used in designing IT equipment such as computers and servers. Transient AC overvoltage and undervoltage conditions on the BPS can fall well outside these limits.

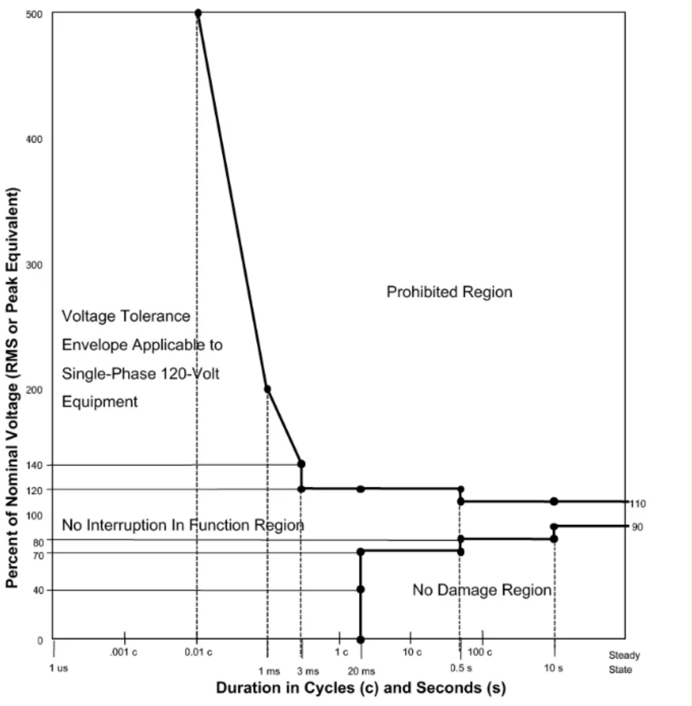


Figure 2.9. ITIC (formerly CBEMA) Curve (Revised 2000)

These types of design and performance considerations are critically important for BPS reliability. Examples of notable large load events across different areas of the North American BPS include:

- **Large Load Loss Events in Northern Virginia:** In July 2024, Northern Virginia experienced a normally cleared fault that unexpectedly resulted in 1,500 MW of data center load switching to backup power. Nearly 60 data centers spread across 25 to 30 substations disconnected from the BPS (see Figure 2.10). Voltages throughout the area rose significantly and local capacitor banks were removed by operators to bring voltage back within limits. This type of response is not part of normal modeling and planning studies and could have caused severe BPS reliability issues.

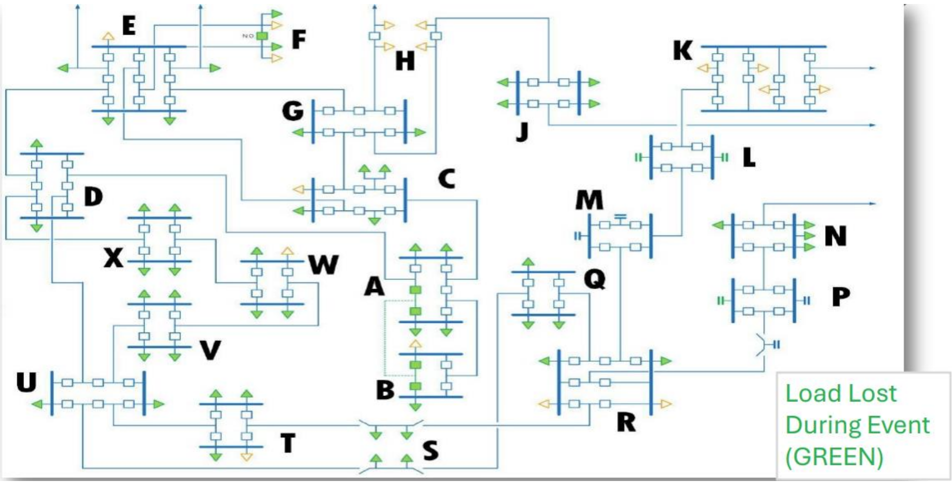


Figure 2.10. Illustration of Data Center Load Loss for Grid Event (Source: NERC)

- **Large Load Loss Events in Texas:** ERCOT has observed multiple load loss events in Texas (see Figure 2.11) with one event involving the unexpected reduction and loss of nearly 1,600 MW of load including data centers, oil/gas loads, and other industrial loads. This event occurred when multiple faults were experienced on 138 kV lines near Odessa, Texas in December 2022. System frequency rose to abnormal levels in response to the event and recovered to nominal in over 12 minutes [30].

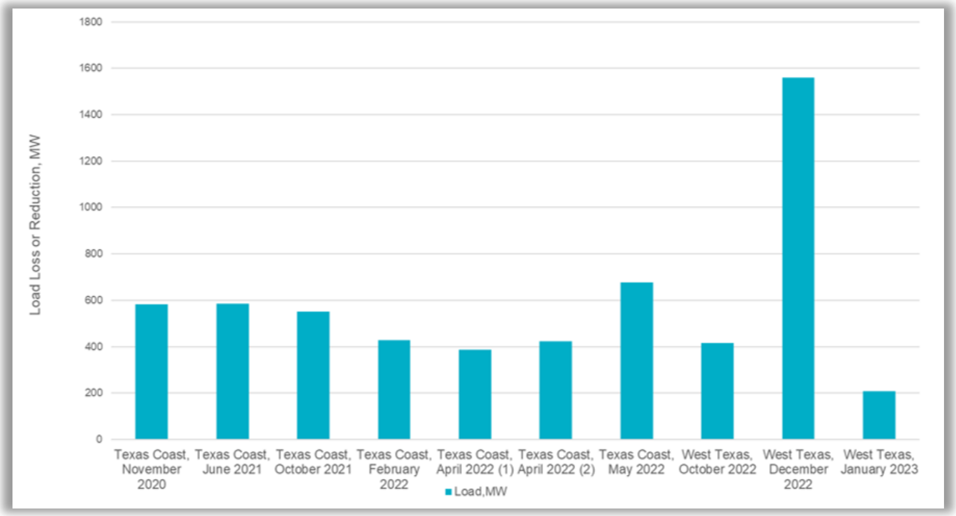


Figure 2.11. Recent ERCOT VRT and Load Loss Events (Source: ERCOT)

These performance issues are typically not modeled in sufficient resolution due to the data availability issues described above. Thus, it is important to ensure large loads have some degree of ride-through performance capability and expectations. Switching to backup power is a necessity for large load customers in some cases but they should be designed in coordination with BPS reliability needs such that this behavior can be modeled, studied, and planned for at specific voltage and frequency levels.

Large loads may introduce power quality or BPS performance issues, particularly with lack of requirements

Industrial loads such as electric arc furnaces are known to cause power quality issues such as voltage flickers and harmonics, and mitigating measures (e.g., Static Synchronous Compensators (STATCOM)) are used to ensure that electrical performance issues are addressed locally so they do not affect nearby customers or grid reliability. The same issues exist with newer large load customers, and careful attention must be given to the power quality impacts that large loads may have on neighboring customers and the BPS. EMT studies may be required to study the power electronic interactions, harmonic distortion, flicker, and voltage sag/swell impacts that large loads such as electrolyzers and data centers can have on the BPS. This is particularly relevant when large power electronic loads are located near other IBRs. An assortment of studies and techniques can be used to assess power quality impacts and should be commonplace for large load interconnections.

High uptime loads could put significant strain on transmission system maintenance and outage coordination unless additional capacity is added

Historically, load levels have been diurnal and seasonal in nature, allowing TOs and TOPs to schedule outages to conduct necessary maintenance on transmission elements. Some large loads, particularly data center loads, operate with a high uptime and many at or near peak demand (i.e., high load factor). Newer AI loads may not fully use peak demand, yet the spikes in use introduce their own unique challenges. This may present challenges for TOPs and RCs to schedule maintenance outages since overall use of the transmission system may increase over time. Without variations in demand levels, new maintenance practices will need to be developed as well as additional capacity on the transmission network to enable outage scheduling.

2.1.5 Large Load Regulatory Risks and Challenges

Delayed regulatory action at the federal level could put overreliance on utilities and lead to BPS reliability risks

Large loads are not presently NERC-registered entities and hence are not subject to NERC Reliability Standards. Therefore, mandatory and enforceable performance-based standards are not applied to these entities or assets directly. Rather, obligations and requirements are placed on Distribution Providers (DP), TOs, etc. to address these challenges.

As described above, transmission providers typically do not have adequate interconnection requirements in place for large loads and may be challenged to enforce requirements on interconnection customers. As has been observed with IBR risks, ensuring that clear, consistent, and applicable interconnection requirements are in place to ensure that adequate data sharing, modeling, studies, and operational performance are achieved is a critical aspect for BPS reliability [31].

Any regulations put in place for large loads will need to be flexible, agile, and updated frequently to adapt to the changing technology landscape and complex needs of large load interconnections. Key questions that have arisen include handling any future BTM large load connections, data sharing and notifications, operational performance, modeling, and studies. Furthermore, some entities have raised questions regarding retroactive applicability of requirements to existing large load customers.

Chapter 3 Concluding Remarks

Over the last decade, the electric power system experienced exponential growth of IBR interconnection on every level of the system. During that time frame, the industry experienced many significant grid disturbances and reliability issues involving IBRs that led to a deep technical dive into IBR technology and its integration into the grid, technical guidelines and recommendations, and now regulatory mandates for new reliability standards of IBRs and their performance on the grid (see Figure 3.1).

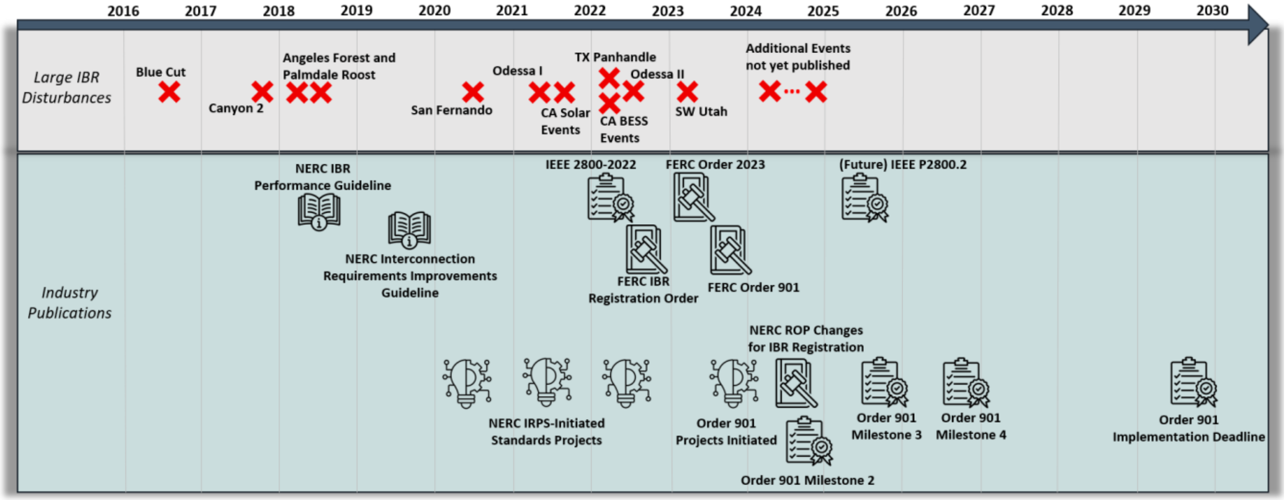


Figure 3.1. Timeline of Industry Activities with the Integration of IBRs onto the U.S. Grid

The industry is now facing its next exponential growth challenge of new technology getting interconnected onto the grid: large loads, driven by data centers. This growth of large loads is already starting to show signs of the same timeline and path that the industry saw with IBRs (see Figure 3.2). The first major disturbances on the grid that involved data centers occurred in 2024. It is clear that the path ahead for the industry with these large load interconnections may follow a very similar trajectory as the interconnection of IBRs onto the grid. The experience integrating IBRs can be used as a playbook for mitigating the reliability risks from large loads. The industry must learn from its past with IBRs and act rapidly to address the BPS reliability risks before larger and larger grid disturbances occur and impact the BPS.

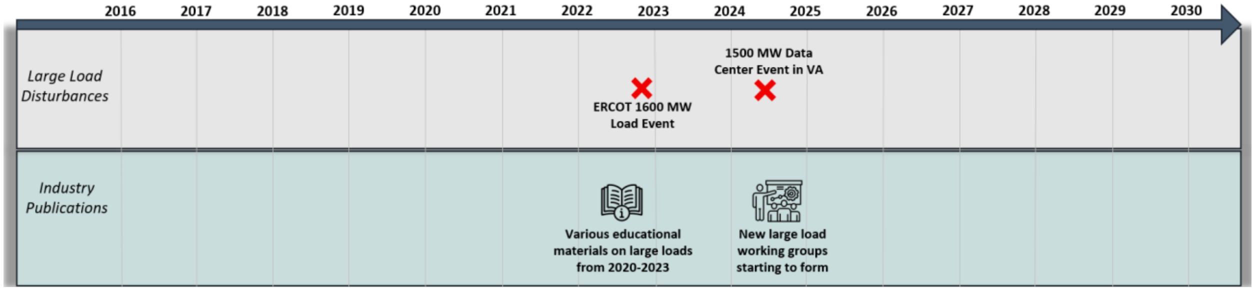


Figure 3.2. Timeline of Industry Activities with the Integration of Large Loads onto the U.S. Grid

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Appendix A Large Loads Considered in this Assessment

This section briefly describes the types of large loads considered in this assessment and provides a short explanation of the unique characteristics and observed trends associated with each load type.

A.1 Data Centers

While data center loads are also described as an existing large load on the BPS today, their prevalence, size, and growth projections are creating an entirely new category of hyperscale data center loads that present new challenges (see **Figure 3.3**) [32], [33], [17]. Cloud computing has expanded by over 2,600% although associated energy usage increase has only grown by 10% due to significant power usage effectiveness (PUE) innovations from the large hyperscale data center owners and users (e.g., Google, Meta, Amazon) [34]. Regardless of these efficiencies, data center demand in the US market is expected to reach 35 GW by 2030, up from 17 GW in 2022—nearly doubling in eight years, and that trend is expected to continue upwards [5], [35] (see the Jevons paradox[6]). The hyperscale data center owners, being large multi-national corporations, are environmentally conscious due to their size and their core missions [36], [37]. Acknowledging that data centers demand continuous, high-quality, and clean power, this has led to a boom of power purchase agreements between data centers and renewable energy resources as well as focused attention on new clean energy electricity tariff designs [38].

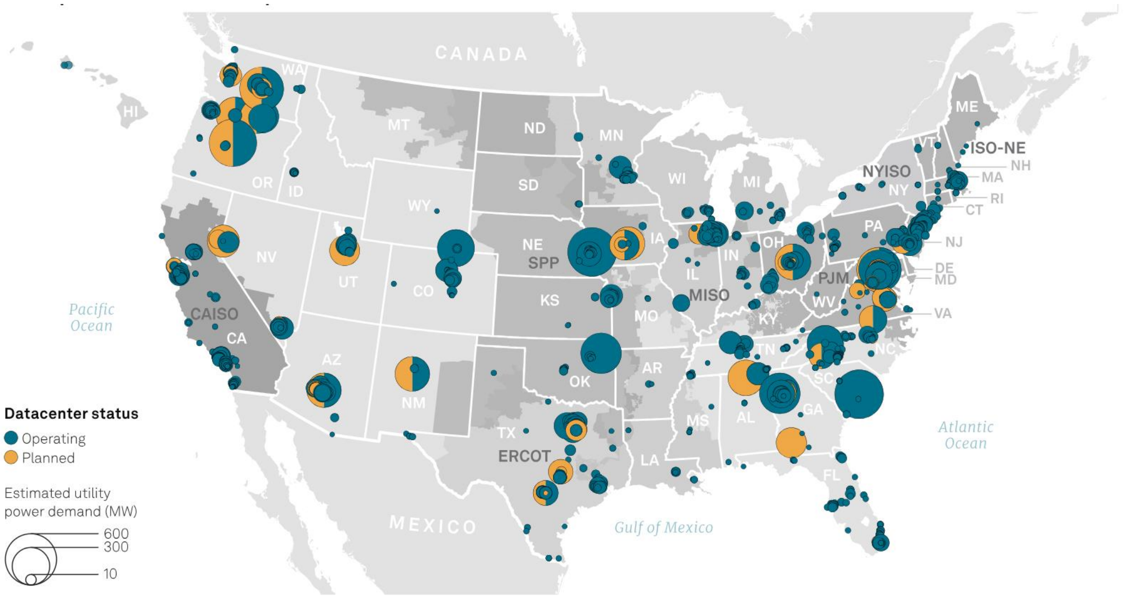

Figure 3.3. U.S. Data Center Trends (Source: S&P Global Market Intelligence)

A.2 Artificial Intelligence Data Centers

Emerging AI technologies such as large language models (LLM) are contributing to the rapid growth of data centers. Compared to conventional data centers, AI data centers mainly consist of GPUs instead of CPU servers. GPU servers typically require on the order 4 times more power consumption than typical CPU servers. For example, a single NVIDIA rack may consist of 11 GPUs requiring nearly 14 kW of power [39].

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[6] "The Jevons paradox occurs when technological progress increases the efficiency with which a resource is used (reducing the amount necessary for any one use), but the falling cost of use induces increases in demand enough that resource use is increased, rather than reduced." https://en.wikipedia.org/wiki/Jevons_paradox#:~:text=At%20that%20time%2C%20many%20in,increase%20the%20use%20of%20coal

The racks of servers require significant cooling to handle the power density levels. For example, traditional data centers require around 12 kW of cooling per rack while AI data centers require a dramatically higher cooling demand with ultra high-density racks consuming 85 kW per cabinet [40]. The result is that AI data center demand levels are typically much higher than conventional data centers and contribute to the influx of massive load interconnection requests.

AI is also a relatively energy-intensive technology, requiring very high energy consumption levels. Training new AI models, for example, requires significantly more power compared to running developed AI models (call AI inference). This makes AI data centers unique in terms of their operational characteristics, ramping, and variability under the different phases of an AI model lifecycle. As the AI models expand and their use increases, especially with increased training of new AI models, energy consumption is expected to grow dramatically [41].

A.3 Cryptocurrency Mining Facilities

Cryptocurrency ("crypto") is a type of digital or virtual currency that uses cryptography[7] and cryptocurrency transactions—the transfer of digital assets—are recorded on a decentralized blockchain[8] ledger. Cryptocurrency networks consist of nodes, which are computers and servers, which communicate with each other to maintain the blockchain and validate transactions. Cryptocurrency mining is the process of validating the transactions and adding them to a blockchain ledger, and miners complete complex mathematical algorithms to add these new blocks to the blockchain. The algorithms are run on advanced high-performance computing hardware that require a significant amount of computational power and energy. Cryptocurrency mining uses similar structures of a typical data center but operates differently. The core objective is to maximize profit, and therefore these loads are price-sensitive to electricity market prices and cryptocurrency market prices to minimize power usage costs while maximizing its buying and selling of cryptocurrency.

The amount of electricity used by cryptocurrency mining is dependent on a number of factors. Most notably, different currencies use different algorithms that demand vastly different levels of electricity. For example, Bitcoin uses a "proof of work" concept that relies on high-powered computers to solve trial and error puzzles. This leads to a significant amount of energy consumption. On the other hand, Ethereum switched to a "proof of stake" concept that requires miners to put up a stake with their own coins and to share their history of validating transactions. This reportedly reduces energy consumption by over 99.9% [42]. One could assume that energy-intensive currencies would become less favorable; however, the Bitcoin hashrate—an estimate of how many hashes are being generated by Bitcoin miners trying to solve the blockchain algorithms—has skyrocketed over the past few years alone (see **Figure 3.4**) [43]. Bitcoin alone is estimated to consume well over 125+ TWh per year, which is more than many small to mid-size countries [44]. According to the US EIA, cryptocurrency mining was estimated to be 0.6% to 2.3% of U.S. electricity consumption in 2023 [45].

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[7] Mathematical algorithms and techniques that secure the transactions, control the creations of new currency units, and verify the transfer of digital assets on a decentralized network.

[8] A decentralized, distributed ledger system that securely records and verifies transactions across a vast network of computers with the goal of ensuring transparency and immutability, leading to increased trust, in the digital asset transfer process.

Figure 3.4. Bitcoin Hashrate Chart (Source: CoinWarz)

Note the downward trend in mid-2021 in **Figure 3.4** when Bitcoin price had a steep decline, attributed to China cracking down on cryptocurrency mining operations. The Chinese government deemed these activities as wasteful and harmful to the environment due to their energy usage levels, causing many mining operations to abruptly relocate to more favorable locations such as the United States.

U.S. cryptocurrency mining operations have continued to rise over the last few years. Cryptocurrency continues to gain popularity and acceptance, and rising values of cryptocurrency incentivize mining activities to acquire digital assets and participate in the market. High-performance computing technology also continues to advance rapidly, leading to both an increase in energy efficiency and the mining power and capabilities. Some areas of the U.S. have favorable cryptocurrency mining conditions that attract crypto mining operations, including low electricity costs, supportive policies, minimal regulations, and tax incentives. **Figure 3.5** shows the locations of known cryptocurrency mining operations as of January 2024, as reported by the U.S. Energy Information Administration (EIA) [45]. Many facilities require up to 50 MW of power while some sites require upwards of 100+ MW (one site requires more than 500 MW). Many of these reported cryptocurrency mining sites are not located in the Western Interconnection.

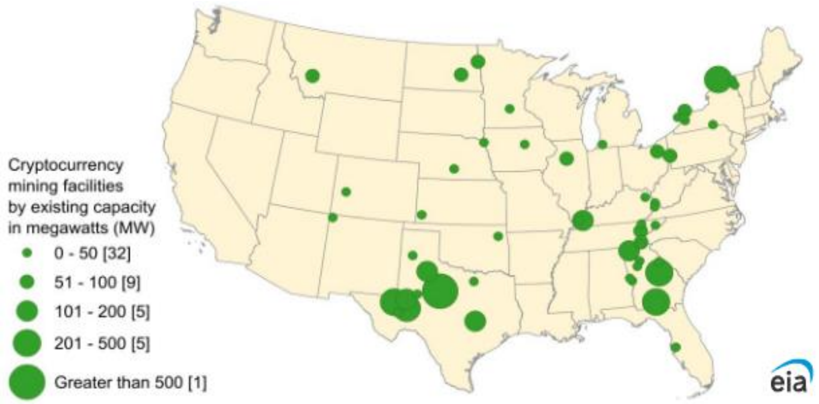

Figure 3.5. Location of Cryptocurrency Mining Operations (Jan 2024) (Source: EIA)

Cryptocurrency mining loads continue to grow in the U.S. and all indicators point towards increasing demand given the growing prevalence of cryptocurrency and its favorable market conditions.

Cryptocurrency mining can take place in an array of locations ranging from inside a residential home (less than 1 MW) to mobile containerized "rigs" that can be transported between sites (a few MWMW). For example, the Merkle Standard Ponderay location is a 100 MW site located at a repurposed paper mill compound (note that this is not on the graphic above) [46].

A.4 Hydrogen Electrolysis Facilities

Hydrogen can be produced through various methods. The most common method, "gray hydrogen," involves a reaction of natural gas with steam[9] to produce hydrogen and carbon dioxide (CO_2), which is released into the atmosphere and contributes to greenhouse gas emissions. Another method similar to gray hydrogen, referred to as "blue hydrogen," involves a similar process except that CO_2 emissions are captured and stored through carbon capture and storage (CCS) or captured and used through carbon capture and utilization (CCU) technologies. Lastly, and most relevant for this assessment, is "green hydrogen" produced through electrolysis where water is split into hydrogen and oxygen using electricity. If the electricity used in this process comes from renewable sources, the resulting hydrogen is considered green because it does not produce greenhouse gas emissions during production.

The use of hydrogen may be a key factor in achieving long-term decarbonization policies and goals, particularly for specific industries, and electrifying hydrogen fuel creation has gained notable attention due to its potential to decarbonize multiple sectors [47]. Today, hydrogen is mainly used in petroleum refining and chemical production; however, the *U.S. National Clean Hydrogen Strategy and Roadmap* [48] lays out research pathways [49] for hydrogen to be used in other industries such as transportation, broad chemical and metal production, heat and distributed power applications, and even power generation (see Figure 3.6) [50].[10] Deep decarbonization is expected to require green hydrogen use across multiple sectors.

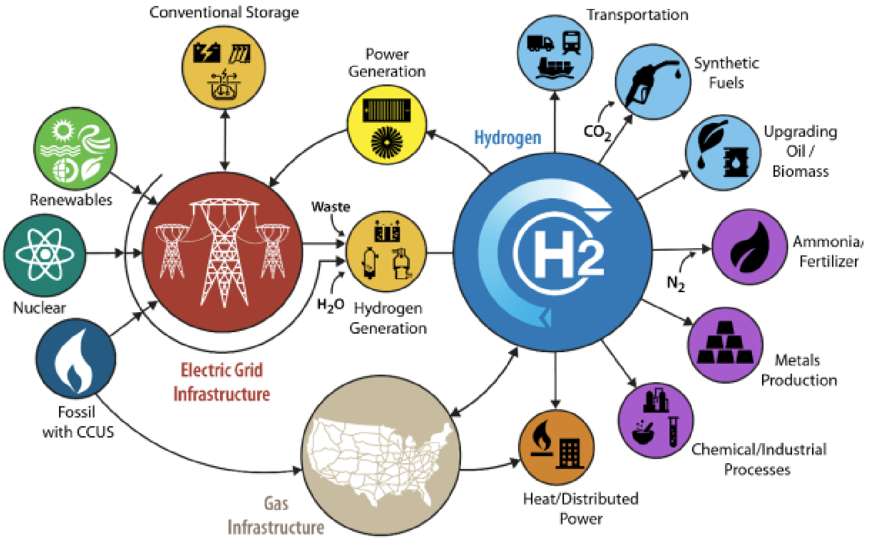

Figure 3.6. Production and Uses of Hydrogen (Source: U.S. DOE)

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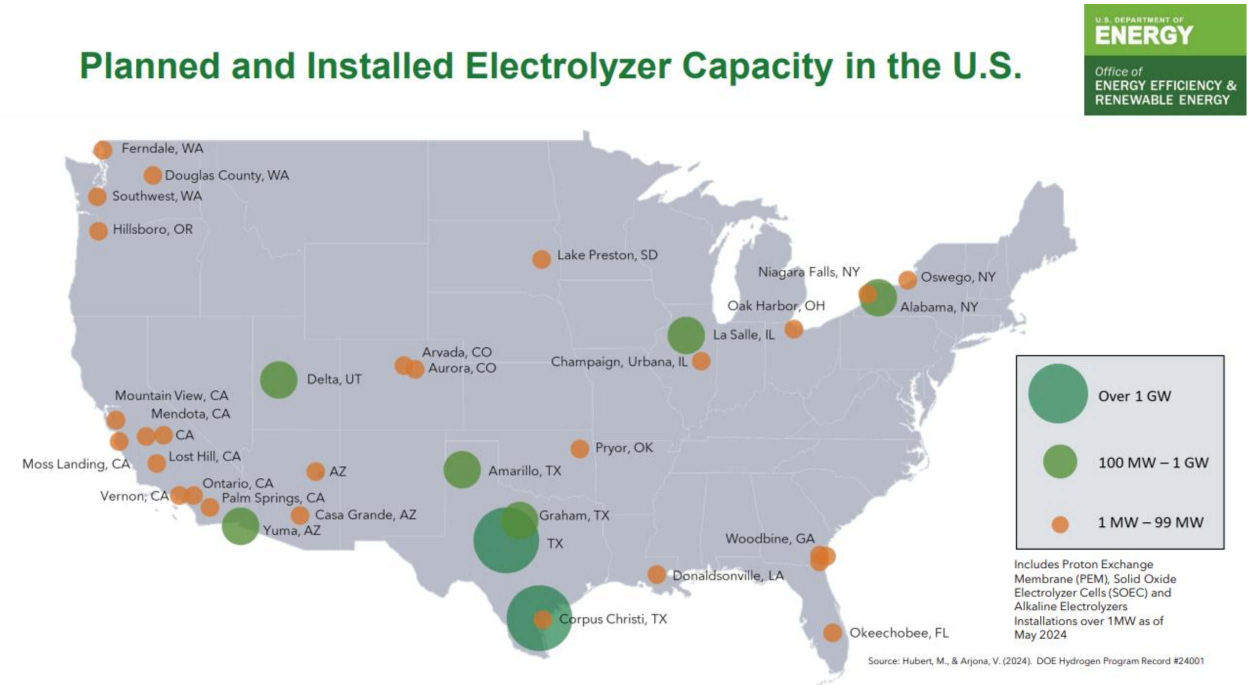
[9] Typically produced through steam methane reforming (SMR) or autothermal reforming (ATR).

[10] As curtailment of renewable generation increases, electrifying hydrogen using this low (negative) cost energy becomes economically more feasible. Furthermore, the hydrogen can then be stored and used to generate electricity when demand is high.

Hydrogen electrolysis involves splitting water molecules (H_2O) into hydrogen gas (H_2) and oxygen gas (O_2) using electricity. When an electric current is passed through an electrolyte solution, water molecules near the cathode are reduced (gain electrons) to form H_2 while water molecules near the anode are oxidized (lose electrons) to form O_2. The hydrogen is then purified and stored, and the oxygen can be used for industrial applications or released into the atmosphere. These facilities involve motor loads such as pumps and fans to move gases, water flows, etc.; however, most of the electric load is the electrolyzer itself, which requires DC current and, therefore, is predominantly a large power electronic load (AC/DC converter).

The U.S. DOE has reported planned and installed hydrogen electrolyzers over 1 MW in the U.S. as of May 2024 (see Figure 3.7) [51]. There are already electrolyzers installed and operational in the West, in the 100 MW–1 GW range. However, there are many more electrolyzers planned across the West in the years ahead.



Source: Hubert, M., & Arjona, V. (2024). DOE Hydrogen Program Record #24001

Figure 3.7. Planned and Installed Hydrogen Electrolyzer Capacity (Source: U.S. DOE)

The Low-Carbon Resources Initiative, Electric Power Research Institute (EPRI), and GTI Energy recently completed a scenario modeling exercise to evaluate alternative strategies for achieving net-zero targets in the U.S. by 2050 [52]. Results showed that hydrogen electrolysis is relatively unused in the 2050 reference case (no CO_2 target) as well as the "all options" scenario where a full portfolio of energy technologies are available. In the "higher fuel cost" scenario where all technologies are available but with higher fuel costs for gas, oil, bioenergy, and CO_2 transport and storage, hydrogen electrolysis demand grows to a level comparable to light-duty electric vehicles. In the "limited options" scenario where geologic storage of CO_2 is not available and bioenergy supply is limited, hydrogen electrolysis becomes a significant demand component surpassing all other sectors (see Figure 3.8) [53]. Even in this case, hydrogen fuel production demand does not start accelerating until the late 2030s and early 2040s. Therefore, the most optimistic hydrogen growth assumptions still project this demand category to be at least 10-15 years out. Therefore, hydrogen electrolysis is more relevant for long-term scenario-based planning.

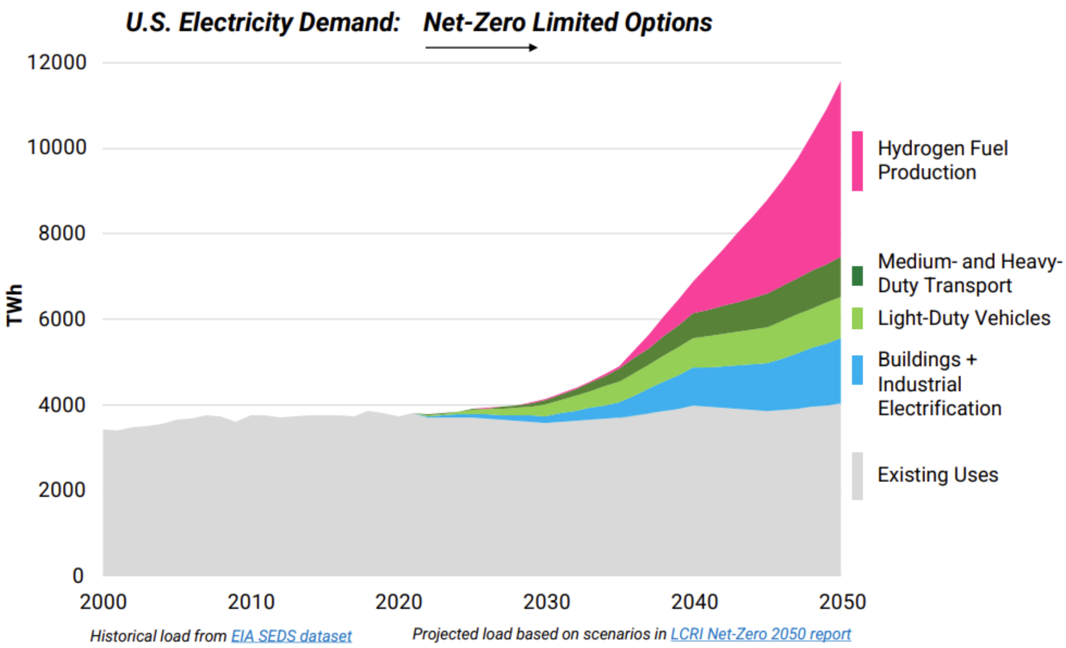


Figure 3.8. Electricity Supply and Demand Across Scenarios (Source: EPRI)

Similarly, the International Energy Agency (IEA) also highlighted that announced low-emissions hydrogen production projects represent 55% of the needed levels for the net-zero scenarios for 2030 and stressed that bold policy action would be needed to create demand and stimulate investment in hydrogen production facilities [54]. IEA highlighted that realization of all projects in the pipeline could lead to global installed electrolyzer capacity of 170-365 GW by 2030 [55].

A.5 Large Industrial Manufacturing

Industrial manufacturing continues to grow across the United States and the Western Interconnection, contributing to overall multi-sector “recarbonization” [56]. Driven by market need and government policies, industrial manufacturing is a major component to large load growth. The resurgence of manufacturing in recent years, nearly tripling since 2020, is in part due to the CHIPS Act, Bipartisan Infrastructure Law, the IRA, and other federal and state programs [57], [58]. Examples of large industrial manufacturing include, but are not limited to, the following:

- **Advanced manufacturing** related to automation, robotics, additive manufacturing (3D printing), AI, lithium-ion battery factories, etc.
- **Clean energy technologies** driven by the boom of renewable energy generation such as solar panels, inverters, wind turbines, BESS, and EV components [57].
- **Biotechnology and pharmaceuticals** expansion driven by advances in healthcare, personalized medicine, gene therapies, vaccines, and biopharmaceutical research.
- **Advanced materials** such as carbon fiber, nanomaterial, advanced ceramics, and composites are leading to manufacturing opportunities in aerospace, automotive, and electronics industries.
- **Information technology and electronics** driven by the constant demand for electronic components and emerging technologies like 5G, Internet of Things (IoT), and edge computing.

- **Defense and aerospace** industry related to military equipment, aircraft, satellites, space exploration, etc., particularly driven by geopolitical tensions and commercial space activity.
- **Food and beverage processing** industries shifting toward electrification to meet regulations, customer preference, and improve efficiencies [59]. One major area of electrification is replacing combustion boilers with electric boilers [60].
- **E-commerce and logistics** driven by online retail including packaging, warehouse automation, and last-mile delivery solutions.

A.6 Aggregate Transportation Electrification

Electrification of the transportation sector ("e-mobility") continues to grow at an exponential pace (see Figure 3.9) due to technological advancements in battery technology, increased market penetration of EVs, deployment of charging infrastructure, and other factors [61]. Light-duty and medium-/heavy-duty EVs are expected to increase by tens of millions in the next five years. For example, light-duty EVs are expected to number 30 to 42 million by 2030. Relatively conservative scenarios anticipate that by 2030, EV charging will consume ~300 TWh globally (about 7.5% of current electricity production) [62], [63].

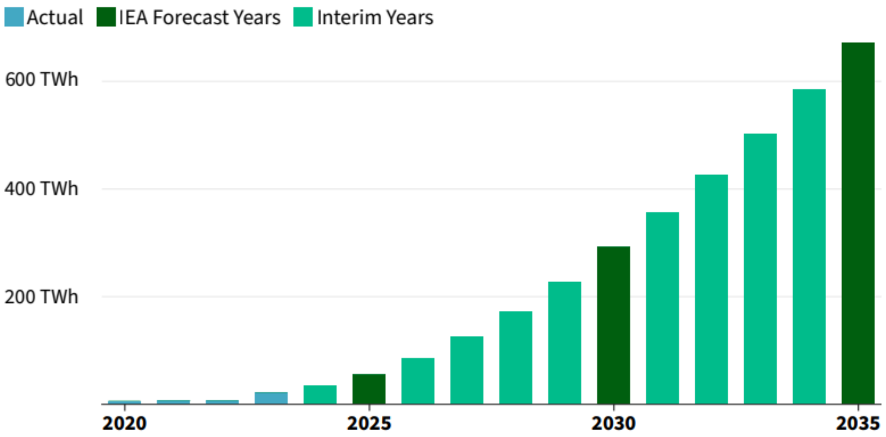


Figure 3.9. Electricity Demand for On Road EV Charging in the U.S. (Source: RMI)

These loads are unique in that they are power electronic by nature, mobile and variable, and range in size and use case. All these factors introduce unique challenges and opportunities for the utility industry moving forward. There are three types of EV charging levels, loosely summarized as the following:[11]

- **Level 1:** Up to 1.4 kW demand, 120 V electrical outlet, charges about 4 miles per hour, typically residential use
- **Level 2:** Up to 20 kW demand, 240 V charger connection, charges 20-30 miles per hour, typically residential or commercial use
- **Level 3:** Range from 50-350 kW demand, AC-DC "fast charger" connection, charges 14-20 miles per minute, typically commercial and industrial uses; megawatt charging for heavy-duty EVs on the horizon

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[11] Note that different technologies may be outside these changing ranges; this is intended to give a high-level understanding of the magnitudes of EV charging loads.

These different levels of EV charging depend on application, ranging from light-duty daily commuting to medium-duty “last-mile” services and fleet charging, to heavy-duty electrified transport services. While a significant portion of EV charging today is in the Level 1 and Level 2 category, state and federal incentives are driving heavy-duty EV charging station deployment around core corridors to enable long-distance EV transportation both for personal and business purposes [64].

California has been a relatively early adopter of EV technology and will continue this trend in the years ahead. The California Energy Commission (CEC) commissioned multiple reports exploring the impacts on the grid due to significant increase in EV adoption to reach net-zero goals. Figure 3.10 shows an example of light-duty EV charging demands in California for a typical weekday in 2030 from a CEC future scenario assessment. An important characteristic is the step changes in demand levels driven by time of use rates and/or charging patterns. The system is not designed to withstand instantaneous spikes in power demand of thousands of megawatts and therefore careful engineering will be needed to manage these ramps. Conversely, the same report shows statewide projections of demand from all sources and illustrates that even with a major uptick in EV adoption, the portion of the overall demand curve that EVs comprise still remains relatively small (see Figure 3.11) [65]. This aligns with the WECC IAG utility feedback in terms of degree of concerns and risk presented by the different large load categories.

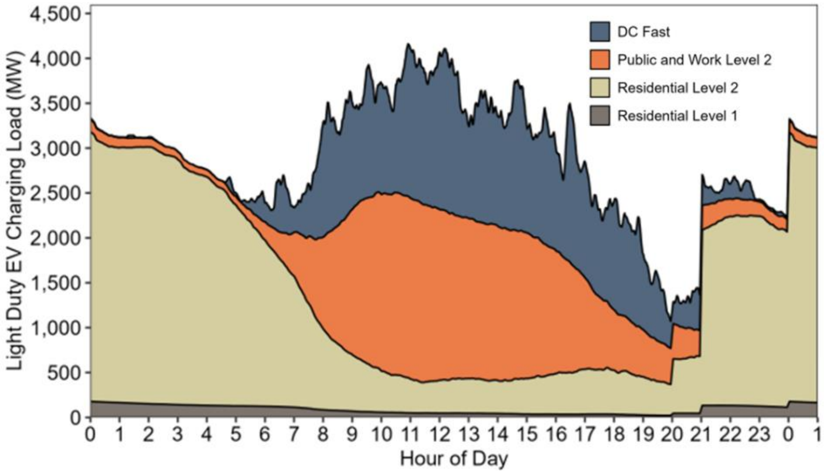

Figure 3.10. Projected Statewide Light-Duty Vehicle Charging Example (Source: CEC)

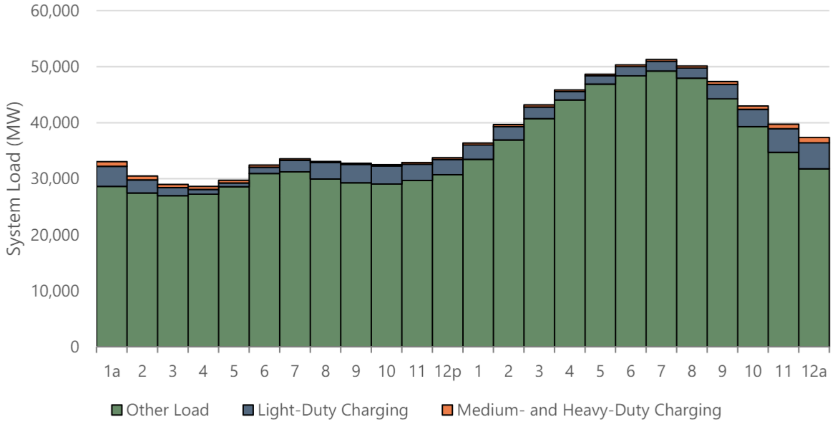

Figure 3.11. Projected Statewide Demand from all Sources, 2030 (Source: CEC)

A.6 Aggregate Electrification of Heating and Cooling Load

About half of water heaters sold today use natural gas while most of the remaining half use electric resistance elements. Incentives or policies that shift toward electrification will increase this market share over time. The U.S. DOE finalized new energy efficiency standards for residential water heaters, which had not been updated since 2010, that would require most common-sized electric water heaters to achieve efficiency gains using heat pump technology [66]. Heat pump water heaters use about one-quarter to one-third the energy of conventional resistance heating water heaters. So, a shift to heat pump water heater technology will help balance out the uptick in electrification demands [67].

Space heating and cooling demands can also be a notable component to electricity demand particularly in severe cold or hot climates, respectively. Heat pumps for space heating are gaining market share over gas furnaces or oil solutions, driven by energy efficiency, cost savings, policies such as the IRA, and increasing adoption in colder climates due to technological advancements that allow heat pumps to operate effectively in sub-zero temperatures. Areas with cold climates and/or winter peaking areas could see an increasing uptick in electricity demands on peak conditions due to electrification of this sector [68]. Additionally, demand profiles could shift toward a higher morning peak particularly if electric space heating in the commercial sector increases [69].

A.7 Excavation Mining

The excavation mining industry plays a critical role in the modern global economy, extracting and processing a wide range of minerals that are essential for many critical infrastructures and modern society. Excavation mining consumes a large amount of energy. For example, it is estimated that the copper mining process consumes about 7 MWh total energy per ton [70], mainly from diesel and electricity. Diesel is mainly used for haul trucks (both open pit and underground) and on-site generation, while electricity is used for ventilation, comminution (crushing and grinding), and processing. **Figure 3.12** shows the breakdown of electricity usage (54% of the process) [70].

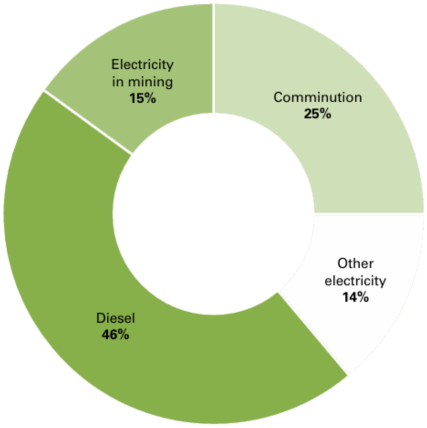

Figure 3.12. Mining Industry Energy Consumption (Source: M. Allen)

U.S. non-fuel mineral production continues to increase particularly due to semiconductor manufacturing and the energy transition, the fluctuation of import commodity price and supply, and public policy. Four out of the top ten U.S. states fall within the WECC region for non-fuel mineral production [71], [72].

Considering that the diesel component could shift toward electrified haul vehicles, this could further increase mining sector demand levels in the coming decade. For example, major mining truck vendors such as Caterpillar have successfully demonstrated large EV mining trucks in Arizona and Australia [73], [74]. Electrification of the sector could at least double power consumption from mineral excavation [75].

A.8 Grow Houses/Agricultural Loads

Cannabis is legal in 38 of 50 U.S. states for medical use and 24 states for recreational use, including many states within WECC footprint. Indoor grow rooms use significant power, mainly for ventilation, exhaust fans, cooling/heating, and lighting. According to Northwest Power and Conservation Council, about 50% of cannabis products are produced indoors, consuming about 4 to 6 MWh per kilogram produced [76]. The average demand of Washington and Oregon is forecast to increase from near 100 MW in 2014 to near 200 MW in 2034 [77].

List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
ATR	Autothermal Reforming
BA	Balance Authority
BESS	Battery Energy Storage System
BPS	Bulk Power System
BTM	Behind-The-Meter
CBEMA	Computer and Business Equipment Manufacturer's Association
CPU	Central Processing Unit
DDR	Dynamic Disturbance Recorders
DER	Distributed Energy Resources
DFR	Digital Fault Recorders
DLR	Dynamic Line Rating
DP	Distribution Provider
EMT	Electromagnetic Transient
ERCOT	Electric Reliability Council of Texas
ERO	Electric Reliability Organization
E-STATCOM	Enhanced Static Synchronous Compensator
EV	Electric Vehicle
FERC	U.S. Federal Energy Regulatory Commission
GETs	Grid-Enhancing Technologies
GPU	Graphics Processing Unit
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IPP	Intermountain Power Project
ISO	Independent System Operator
ITIC	Information Technology Industry Council
LADWP	Los Angeles Department of Power and Water
LFLTF	Large Flexible Loads Task Force
LLM	Large Language Model
LMWG	Load Modeling Working Group
MVS	Modeling and Validation Subcommittee
NERC	North American Electric Reliability Corporation
NOGRR	Nodal Operating Guide Revision Requests
PC	Planning Coordinator
PCM	Production Cost Modeling
PPA	Power Purchase Agreement
RC	Reliability Coordinator
RTO	Regional Transmission Operator
SMR	Steam Methane Reforming

STATCOM	Static Synchronous Compensator
TO	Transmission Owner
TOP	Transmission Operator
TP	Transmission Planner
UPS	Uninterruptable Power Supply
WECC	Western Electricity Coordinating Council