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Enabling Large Load Deployment through Grid Upgrades and Greenfield Solutions

Developing GRIDS: Grid Readiness and Interconnection Decision Support

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ABSTRACT

The rapid proliferation of large loads, particularly data centers and hyperscale facilities, is driving unprecedented electricity demand across the United States, straining existing grid infrastructure and challenging traditional planning, interconnection, and deployment processes. This white paper introduces the Grid Readiness and Interconnection Decision Support (GRIDS) initiative, a structured, web-based solutions library and decision support tool designed to help utilities, developers, and planners navigate the complex landscape of large load integration. GRIDS consolidates and categorizes a wide range of vetted solutions across three conceptual pathways: grid upgrades, greenfield development, and enabling technologies. Each solution is characterized by key attributes such as technology readiness, cost, deployment timeline, permitting complexity, and system impact, enabling users to filter and prioritize strategies based on their specific operational context. The paper outlines the challenges posed by large load deployment, including grid reliability, interconnection delays, siting constraints, and cost allocation; it also demonstrates how GRIDS addresses these through curated content and interactive decision support. Four representative use cases illustrate the tool's practical application, ranging from rapid demand growth to nuclear co-location strategies. By bridging the gap between stakeholder needs and actionable solutions, GRIDS aims to accelerate infrastructure modernization, enhance grid resilience, and support equitable, cost-effective large load deployment. The authors would like to thank Jonathan Tacke, Christopher Dietz, and Heather Ackenhusen for their thoughtful review and expert guidance which helped ensure the technical accuracy and relevance of the content.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

ADMS	Advanced Distribution Management System
AI	Artificial Intelligence
ANOPR	Advanced Notice of Proposed Rulemaking
ASCE	American Society of Civil Engineers
ATR	Advanced Test Reactor
BESS	Battery Energy Storage System
BES	Bulk Electric System
BTM	Behind-the-Meter
CAISO	California Independent System Operator
CAPEX	Capital Expenditure
CEQ	Counsel on Environmental Quality
CIE	Cyber-Informed Engineering
CISA	Cybersecurity and Infrastructure Security Agency
DERMS	Distributed Energy Resource Management System
DLR	Dynamic Line Rating
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DR	Demand Response
DSM	Demand-Side Management
EIA	Environmental Impact Assessment
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESS	Energy Storage System
FERC	Federal Energy Regulatory Commission
FRT	Fault-Ride-Through
G&T	Generation & Transmission
GET	Grid-Enhancing Technology
GRIDS	Grid Readiness and Interconnection Decision Support
HILLS	High Impact Large Loads
IBV	Institute for Business Value
IED	Intelligent Electronic Device
INL	Idaho National Laboratory
IRP	Integrated Resource Plan

ISO	Independent System Operator
LL	Large Load
LLTF	Large Load Task Force
NERC	North American Electric Reliability Corporation
OPEX	Operating Expenses
PTO	Permission to Operate
PUC	Public Utility Commission
PV	Photovoltaic
R&D	Research and Development
RTO	Regional Transmission Organization
SME	Subject Matter Expert
SMR	Small Modular Reactor
SPP	Southwest Power Pool
T&D	Transmission & Distribution
TA	Technical Assistance
TRL	Technology Readiness Level

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Enabling Large Load Deployment through Grid Upgrades and Greenfield Solutions

Developing GRIDS: Grid Readiness and Integration Decision Support

1. INTRODUCTION

1.1. Background

The United States is facing an unprecedented surge in electricity demand, driven largely by the rapid expansion of historically large loads, data centers, and hyperscale data centers. The integration of large loads presents both opportunities and challenges across grid planning, interconnection processes, capacity margins, and cross-sector coordination. Without a unified reference for potential solutions, stakeholders often navigate these challenges in silos which could lead to inefficiencies, delays, or cost overrun. This white paper is intended to support stakeholders involved in providing electric power for large load deployment and those involved in obtaining a Permission to Operate (PTO) for the large load. This includes, but is not limited to utilities, generation developers, transmission operators, large load developers, and large load owners.

Right-sizing energy infrastructure upgrades or changes are critical to minimizing costs for both data center customers and for rate payers. This is a common concern among rate payers and their advocates and there have been examples of overbuilding that give credence to these concerns (Numata, et al. 2025). The U.S. Department of Energy (DOE) has recognized the need to accelerate deployment timelines and reduce uncertainty in large load implementation (Executive Office of the President of the United States 2025). A key outcome of this research is the documentation of stakeholder challenges and associated potential solutions for prioritizing and evaluating upgrades, greenfield, and operational solutions. Table 1 shows the similarities and differences between large loads, data centers, and hyperscale data centers.

Table 1. Comparison of Large Loads, Data Centers, and Hyperscale Data Centers (Fitzmaurice, et al. 2025).

	Historically Large Loads	**Traditional Data Centers**	**Hyperscale Data Centers**
Definition	Any single facility or operation capable of consuming ≥50 MW of real power.	Facilities that provide data storage, processing, and management services.	Massive-scale data centers optimized for cloud services or AI workloads, typically operated by major tech companies.
Primary Purpose	Industrial production, processing, or other high-energy-demand operations.	Delivers services such as cloud computing for business functions, cryptocurrency mining, machine learning, networking, and storage.	Provide large-scale, centralized computing power for cloud services or AI training at national or global scale, with dynamic visibility into resource type (GPU vs. CPU) and utilization. GPUs drive training and inference for LLMs and agentic workloads and are significantly more power-hungry than CPUs. Monitoring and changing to resource demand is critical.
Typical Power Demand	50 MW to over 1,000 MW depending on facility type (e.g., smelters, hydrogen).	50 MW to several hundred MW; varies by function (e.g., cloud, AI, crypto).	100 MW to 1,500+ MW; some facilities exceed 1 GW, especially for AI training workloads.
Siting Considerations	May require dedicated transmission upgrades; influenced by industrial zoning.	Prefer proximity to fiber networks, reliable power, and cooling infrastructure; often near urban or suburban areas.	Require considerable site size,, robust transmission access, water or advanced cooling, and proximity to local or low-cost energy.
Grid Integration Considerations	May require dedicated substations, long lead times, and limited demand response potential.	Integration depends on function and flexibility; some offer ancillary services or BTM generation.	High-impact on transmission planning; potential for grid services, but also high interconnection complexity.

This work does not seek to replicate existing research, but rather to synthesize and organize solutions that will help enable fast deployment of large loads into a practical, accessible format that supports real-world decision-making for utilities and large load developers. This effort focuses on organizing existing strategies to simplify integration and streamline deployment of large loads. Our primary aim is to develop Grid Readiness and Interconnection Decision Support (GRIDS) – a web-based solutions library and decision support tool that will help stakeholders identify and evaluate potential grid upgrades, greenfield developments, and enabling technologies.

GRIDS will serve two complementary purposes. First, it will function as a standalone, structured knowledge base library of vetted solutions that stakeholders can consult when planning for large load deployment. Second, this library will serve as the foundational database for a future interactive decision support tool that matches users with relevant solutions based on their specific challenges, constraints, and deployment scenarios. By combining curated technical content with interactive filtering and prioritization capabilities, GRIDS will empower utilities, developers, and planners to make informed, timely, and cost-effective decisions that support reliable and resilient large load integration. This paper explains the strategic approach for GRIDS, justifies the organization of the library, and identifies the value proposition for the GRIDS tool.

1.2. Scope

This project will produce a comprehensive library of potential solutions that address power availability and stability challenges for data centers including generation, transmission, and siting strategies that support large load deployment and interconnection. This white paper examines the key drivers, challenges, and system-level factors that support the need for a structured decision-support framework to facilitate large load integration. The most relevant solutions are those that fall into at least one of the following categories.

- **Increase grid capacity (generation, transmission, distribution, storage)**

Improving grid capacity, whether through generation, transmission, distribution, or storage, is essential for maintaining a reliable grid system by minimizing strain and unlocking latent capacity (Allsup and Jenkins 2024). U.S. Secretary of Energy Chris Wright has emphasized the need for an electric grid system that can support "unprecedented and extraordinary quantities of electricity" (Wright 2025). Currently, grid enhancing technologies (GETs) are key tools for improving existing infrastructure to meet current demand growth without the need for new infrastructure. While conductors can handle more capacity, they sag under heavy loads which risks fires and other hazards if they come into contact with trees, etc. Tower raising allows utilities to mitigate those risks and increase the power transferred across the lines (Postma 2025). Another method is reconductoring, which involves re-stringing existing transmission towers with new, state-of-the-art cables that have higher capacities (Maracci and Energy Innovation: Policy and Technology 2024). Reconductoring projects significantly increase transmission capacity and help avoid the need for building new transmission corridors (Howland, Reconductoring US power lines could quadruple new transmission capacity by 2035: report 2024).

- **Improve interconnection speed and feasibility**

Interconnection speed and feasibility directly impact data center and large load deployment timelines. As new AI data centers are built, the traditional interconnection process has become a bottleneck, with many systems awaiting PTO. PTO requires the accumulation of local permits (e.g. zoning and land use, building and construction), federal or state permits (e.g. environmental impact assessment, water usage or conservation compliance), and industry specific permits (e.g. Telecommunications Industry Association ANSI/TIA-942). To address the bottlenecks associated with gaining operation permissions, the Federal Energy Regulatory Commission (FERC) issued Order 2023-A to address interconnection reform as an approach to reduce interconnection backlogs and streamline the grid interconnection process by modernizing the interconnection process for new generation facilities seeking to connect to the power grid (Federal Energy Regulatory Commission 2025). Flexible and phased interconnection approaches allow local constraints to be addressed both behind-the-meter (BTM) and front-of-the-meter (FTM). BTM generation, referring to generation resources that are not visible to or controlled by the grid operator, can be located on-site or off-site, but remains electrically isolated from the bulk power system and can relieve some of the burden utilities face when preparing for large load or data center deployment. Phased interconnection involves a multi-stage strategy for bringing new facilities online, gradually increasing approved power consumption over time. This approach can significantly reduce interconnection timelines from 5-8 years to as little as 12-18 months (Brisley 2025).

- **Help utilities assess or mitigate siting constraints**

Some of the key elements of siting constraints include, but are not limited to, grid capacity, community acceptance, environmental impact, and land use. Transmission capacity can be increased through infrastructure upgrades and deploying Dynamic Line Rating (DLR) technologies. Decision-making with regards to siting of data center development is largely done by the data center owner, who seeks land that has access or potential to access the water, power, and land use rights required at a reasonable price. Harmonizing grid planning and siting selection through communicated grid constraints, hosting capacity mapping, and market participation options will provide utilities with a roadmap for siting and interconnection co-optimization (Elevate Energy Consulting 2025).

- **Provide operational flexibility or grid infrastructure security for large loads**

Operational flexibility allows large loads to adjust their power consumption dynamically in response to grid conditions. This includes shifting workloads to off-peak hours, curtailing demand during stress events, and using on-site generation or energy storage systems (ESSs). These strategies provide energy source options which support operational flexibility (North American Electric Reliability Corporation 2025). Grid infrastructure security ensures that power systems remain resilient and reliable as they are expected to accommodate new loads. Advanced monitoring systems and real-time analytics through AI-powered modeling provide infrastructure security without limiting operational scalability.

- **Minimize cost of infrastructure upgrades or modernization**

Phased upgrades and modular infrastructure are examples of strategies that some utilities and large load developers have implemented to reduce capital expenditures. BTM microgrid generation reduces reliance on the bulk power system and assists in offsetting some of the infrastructure upgrade costs (Nelson 2025). Large load developers that plan on implementing on-site generation directly impact utility infrastructure planning and modernization. GETs are another relevant suite of solutions because they improve data center integration through improving existing infrastructure operations efficiency (Larson 2025). Virtual substations replace traditional hardware-based protection and control with virtualized functions using intelligent electronic devices (IEDs). This centralized approach streamlines upgrades, reduces infrastructure costs, and improves adaptability for evolving operational needs.

- **Incorporate market participation incentives to optimize grid operations**

Market participation incentives can be an effective strategy for optimizing grid operations while supporting large load integrations and deployments. Southwest Power Pool (SPP) has approved the first of three large load connection market participation plans (Derek Wingfield 2025). SPP's "High Impact Large Loads" (HILLS) service is an accelerated interconnection pathway for incentivizing structured, and hastened, large load participation in electricity markets. Ultimately, market participation incentives enable large loads to reduce costs and align utilities with operational flexibility.

1.2.1. GRIDS Solutions Library

The GRIDS Solutions Library will be a web-based resource designed to help utilities, developers, and planners identify actionable strategies for integrating large, energy-intensive loads into the electric grid. GRIDS offers a curated catalog of established and emerging solutions aimed at addressing technical, procedural, and operational challenges throughout the large-load deployment process.

Each solution is characterized by key attributes such as technology maturity, commercial flexibility, supply chain readiness, deployment timeline, cost, and regulatory considerations (see Appendix A). These fields enable practical decision-making by allowing users to compare options based on readiness, feasibility, and applicability to specific grid challenges. GRIDS serves as a comprehensive reference for organizations seeking to research and evaluate potential solutions for large-load integration.

To ensure the library meets real-world needs, its structure and logic were informed by a set of use cases developed early in the project and further elaborated in Section 5 of this paper. These use cases illustrate how different stakeholders, such as utilities and data center developers, might engage with GRIDS. The use cases were derived from a broad review of industry challenges and highlight technical assistance opportunities tailored to the unique needs of large-load integration and deployment.

1.3. Strategic Interest

As electricity demand surges across the nation, largely due to data centers and large loads development, stakeholders in the electric power sector face challenges to deliver reliable, cost-effective, and secure grid integration solutions. This data center growth trend has created a growing gap between electricity supply and demand, prompting urgent federal action and highlighting the strategic value of tools that can help utilities and large load developers integrate these loads more effectively into the grid.

As stated in the reliability and security of the U.S. electric grid fact sheet, provided by The White House, there is an urgent need to modernize the nation's aging and overburdened grid infrastructure (The White House 2025). Additionally, the 2025 DOE Grid Reliability and Security Report reinforces this urgency, warning that if current trends continue, especially due the retirement of firm generation without adequate replacement, the risk of power outages is expected to increase by 100 times in 2030 (U.S. Department of Energy 2025). Additionally, the current administration's energy addition strategy emphasizes expanding all forms of reliable, affordable energy to meet the consistently increasing demand due to the deployment of large loads and data centers.

Large loads and data centers often require hundreds of megawatts of capacity, triggering major investments in transmission, substation upgrades, and generation assets, to name a few. In many cases, utilities have passed these infrastructure costs onto general ratepayers, raising concerns about fairness and cost allocation. Analysts and legal experts, including those from Harvard Law School's Electricity Law Initiative, have warned that without clear pricing mechanisms and cost accountability, residential and small business customers may end up subsidizing private infrastructure for large commercial users (Harvill and Ankum 2025).

In alignment with this strategy, the DOE recently announced the site selection for a federal AI data center and energy infrastructure development hub. This initiative reinforces the current administration's commitment to pairing digital innovation with scalable energy systems (U.S. Department of Energy 2025). As the digital and industrial transformation accelerates, the ability to reliably and efficiently integrate large loads into the grid will be a cornerstone of national competitiveness and energy security. Additionally, NERC recently released its 10-year Reliability Assessment, highlighting growing concerns about the adequacy and resilience of the Bulk Electric System (BES). Risks related to aging infrastructure, extreme weather, and rapid pace of electrification are threats to long-term grid reliability. Enhancing reliability could be supported through strategies such as timely resource development, refined transmission planning, enhanced permitting reform, integration efficiency, and proactive management (North American Electric Reliability Corporation 2024).

2. RESEARCH GOALS

This white paper explores the underlying drivers, challenges, and system-level considerations that justify the need for a structured, decision-support resource to aid large load integration. Rather than presenting a catalog of solutions, this paper focuses on identifying the recurring technical, organizational, and operational barriers that utilities and developers face; it also articulates the types of information and evaluation criteria that are most useful in addressing them. These insights inform the design and structure of the GRIDS library and tool, ensuring that its content is grounded in real-world needs and aligned with the evolving landscape of large load deployment.

2.1. Challenges and Mitigations for Utilities, Large Load Owners, or Developers

As electricity demand grows and large load development increases the complexity of grid modernization, foundational systems and legacy infrastructure must evolve to support reliable, efficient, and resilient operations. GRIDS will serve as a centralized repository for potential solutions and strategies to successfully address identified challenges utilities may face during the large load integration process. Utilities, large load owners, and project developers will have different viewpoints on the challenges for large load integration and different mitigations that they can be responsible for or that are most favorable. For a detailed look at the challenges facing different stakeholders in this system, see MegaWatt Mayhem (Enriquez-Contreras, et al. 2025) and Navigating Integration (Talbot, et al. 2025) reports. In this section, we describe some of the key challenges that affect multiple stakeholders and identify multi-party approaches to navigate these challenges. We focus on strategic solutions here, which provides the framework for the technical solutions documented in the GRIDS library.

2.1.1. Grid Reliability and Stability

One of the critical challenges in integrating large loads into modern power systems is managing their behavior during Fault-Ride-Through (FRT) events, which are disturbances that test the dynamic stability of transmission and distribution systems (Jimenez-Ruiz and Milano 2025). Without accurate modeling and real-time coordination, these disturbances can propagate, leading to cascading failures or unnecessary disconnections. Understanding and simulating data center responses under FRT conditions is essential for grid operators to maintain system resilience and avoid widespread disruptions.

In addition to dynamic stability challenges, electricity distributors and providers must be able to accurately forecast electricity demand, even amid fluctuations. Large loads, especially data centers, pose unique forecasting difficulties due to sudden spikes in usage and unexpected disconnections from the grid, which can destabilize local grids if not anticipated or mitigated. Therefore, the ability to predict when a large load or data center may disconnect from the grid and use onsite/backup power is essential, albeit difficult. This unpredictability, combined with the growing use of BTM generation, can obscure utility visibility into actual load behavior. If grid operators fail to anticipate these disruptions, unplanned outages and sudden load drops may affect end-users, as documented by the Electric Reliability Council of Texas (ERCOT) (Rute 2025). To mitigate these risks, utilities should invest in advanced forecasting tools, establish secure data-sharing governance practices, and adopt collaborative planning frameworks that promote early and transparent communication between data center operators and grid managers (Enriquez-Contreras, et al. 2025).

The American Society of Civil Engineers (ASCE) assigned the U.S. energy sector a D+ in its 2025 Infrastructure Report Card, citing critical vulnerabilities such as a nationwide shortage of distribution transformers, increasingly severe weather events, and insufficient transmission capacity (DiGangi 2025). Combined with rising demand from large loads, these factors place unprecedented stress on aging grid infrastructure. To maintain reliability during this transition, policymakers are temporarily reconsidering the retirement of existing generation assets, including coal and nuclear plants, while modernization efforts advance. This ensures adequate capacity until new infrastructure technologies are fully deployed (The White House 2025).

2.1.2. Interconnection Processes and Siting Challenges

To address the growing backlog of interconnection requests, FERC issued Order 2023 in November 2023, introducing several structural reforms to streamline the interconnection process, reduce speculative projects, and improve transparency (Federal Energy Regulatory Commission 2023). Key provisions include the Cluster Study Process, which groups projects by region and study cycle, replacing the serial study model. This reduces duplication, enables more holistic grid upgrade planning, and improves study efficiency (Norris 2023). The "First-Ready, First-Served" Approach requires projects to demonstrate commercial readiness, filtering out speculative projects early and reducing the risk of cascading restudies. Standardized timelines, such as a 150-day timeline for cluster studies, improve predictability and accountability for both developers and transmission providers. (Troutman Pepper Locke 2023).

Additionally, the reforms include the requirement for transmission providers to publish heat maps showing available capacity, helping developers make more informed siting decisions before entering the queue. Updated modeling and performance standards for non-synchronous generators, such as solar, wind, and storage, facilitate the integration of hybrid and storage projects. Penalties for delays incentivize timely processing, and restudy reforms limit restudies to specific conditions, giving developers more flexibility to modify projects without triggering delays. These changes aim to reduce duplication, enable holistic grid upgrade planning, and improve study efficiency (Troutman Pepper Locke 2023).

In October 2025, the DOE directed FERC to initiate a rulemaking to regulate how large loads interconnect with the BES. This directive came under Section 403 of the DOE Organization Act and included an Advance Notice of Proposed Rulemaking (ANOPR) titled '*Ensuring the Timely and Orderly Interconnection of Large Loads'*. Historically, FERC regulated generator interconnections, but load interconnections were handled by state commissions, creating a patchwork of inconsistent processes. The ANOPR argues that large load interconnection affects wholesale rates and open access, giving FERC jurisdiction under the Federal Power Act. The rulemaking to regulate interconnection could streamline the process for getting large loads online and reduce delays and uncertainty (Holzrichter, et al. 2025).

2.1.2.1. Permitting and Environmental Review Bottlenecks

Beyond interconnection, permitting remains a major hurdle for large load deployment, especially environmental impact assessments (EIAs) and National Environmental Policy Act (NEPA) reviews. While EIAs are essential for evaluating the environmental footprint of data centers (e.g., energy use, water consumption, land disturbance), the process can be lengthy and unpredictable (United States Environmental Protection Agency 2025).

To address these concerns, the federal government launched the Permitting Technology Action Plan, led by the Council on Environmental Quality (CEQ). This initiative aims to streamline permitting through digital tools, standardized data protocols, and interagency coordination (The White House 2025).

2.1.2.2. Siting Considerations and Co-Location Tradeoffs

Siting large loads such as data centers requires careful consideration of grid capacity, land use, and proximity to generation resources. Co-location with generation assets (e.g., solar, nuclear, BTM systems) can reduce transmission needs and improve efficiency, but also introduces challenges related to grid reliability, cost allocation, and regulatory oversight.

For example, co-located BTM generation may reduce utility visibility into load behavior and shift infrastructure costs to residential ratepayers if not properly managed (Forshay, et al. 2024). Nuclear-powered data centers offer a promising solution for constant baseload demand, but face challenges including long development timelines, regulatory complexity, and fuel supply chain constraints (U.S. Department of Energy 2025).

2.1.2.3. Cost Allocation and State-Level Policy Trends

As interconnection and infrastructure costs continue to rise, utilities and regulators are placing greater emphasis on fair and efficient cost allocation. One emerging strategy is to increase up-front requirements for interconnection requests to discourage speculative or non-viable projects. These speculative applications, often submitted without a clear development plan, can create “phantom” load that distorts demand forecasts and strains the interconnection study process (Freed and Clements 2025). By filtering out speculative proposals early, this approach helps reduce administrative burden, prevent overbuilding, and ensure that only credible, well-developed projects move forward. Standardizing and strengthening the interconnection process in this way supports more transparent and reliable grid planning (Freed and Clements 2025).

At the same time, state legislatures are stepping in to ensure that ratepayers are not unfairly burdened by the infrastructure needs of large commercial users. States such as California, Virginia, and Georgia have introduced or passed legislation requiring data centers to bear a greater share of the costs associated with their energy demands (Howland 2025).

2.1.3. Generation and Grid Capacity

Generation capacity is the maximum amount of electricity a generator can produce when operating at full output (U.S. Department of Enery 2025). This value is used to plan energy supply through generation operations and wholesale electricity market participation. According to the DOE, the U.S. will need to expand its generation infrastructure significantly to meet an expected 100 GW increase in power demand between 2024 and 2030 (Sterlace 2024). Data centers present an especially unique challenge as they have a consistent base load that must be served, which means grid capacity and generation growth will need to be continuous (Jeffries 2024). Enhancing grid capacity to adequately support demand response as end-users expand to include large loads is essential for mitigating risks of transmission congestion and distribution bottlenecks.

To mitigate grid generation and capacity risks, some large load developers are turning to BTM solutions. Despite the apparent benefits of the “bring your own power” model, many utilities remain cautious to widespread BTM adoption. As previously mentioned, these solutions can help alleviate grid congestion and reduce interconnection delays; they also reduce utility visibility into load behavior and complicate long-term infrastructure planning. Generation and consumption behavior of large loads contribute to utility demand prediction. Effective BTM adoption should be navigated with clear regulatory standards, collaborative planning frameworks, and system-wide alignment on shared goals.

2.2. Impacts of Inaction

2.2.1. Increased Risk of Grid Instability and Outages

Federal analyses underscore the growing risk of grid instability and widespread outages if proactive measures are not taken to strengthen the U.S. electric grid in the face of accelerating demand. The analysis performed in the Department of Energy’s Report on Evaluating U.S. Grid Reliability and Stability indicates a surge in power outages should be expected if the demand for AI-driven data center growth and the delays in expanding grid capacity continue (U.S. Department of Energy 2025).

Confirmed and expected generation unit retirements will impact the resource adequacy challenges (U.S. Department of Energy 2025). The Resource Adequacy Report specifies three separate cases for assessing expected generation and generation additions: (1) plant closures case, (2) no plant closures case, and (3) required build case. The findings are clear that without immediate and coordinated action to modernize grid infrastructure, accelerate generation additions, and manage load growth, the U.S. electric grid faces a heightened risk of instability, reliability shortfalls, and economic disruption. Without decisive investment and coordination, the grid will be increasingly unable to meet future demand. This directly threatens economic growth, national security, and system resilience.

2.2.2. Higher Costs for Utilities and Consumers

Inaction to proactively plan grid modernization and market participation strategies could lead to significantly higher costs for both utilities and consumers. Delaying necessary upgrades or maintenance often results in higher long-term investments costs, as aging infrastructure becomes more expensive to repair or replace under emergency conditions (Trabish 2025). In the interim, some regions may rely more heavily on fossil fuel production to meet rising demand, which can offer short-term cost relief. However, this strategy exposes consumers to the volatility of fossil fuel markets, which incur price spikes driven by global supply disruptions or policy shifts (Energy CX 2025).

As mentioned in the list of solutions within Section 1.2 of this paper, large loads can lead to disproportionate cost impacts on certain customer classes or geographic areas. Uneven distribution of new large loads without strategic planning and market participation strategies may cause some ratepayers to bear a greater share of the financial burden associated with large load deployment (Farmer, et al. 2025). In an effort to prioritize affordable, reliable, and secure electricity, DOE Secretary Chris Wright issued a letter to FERC directing the consideration of an Advanced Notice of Proposed Rulemaking (ANOPR) and establishes the need to ensure costs of integrating large loads are managed fairly and do not exacerbate the energy burden of existing customers (Wright 2025).

2.2.3. Reduced Grid Durability

Strategic grid modernization is identified as an initial step of modernizing the grid and maintaining a durable infrastructure (Gandhi, Building a resilient future: Why grid modernization matters for industry electrification 2025). This process is not only for supporting industry electrification, but also for ensuring long-term grid reliability in the face of growing demand. Modernization progress remains uneven in comparison to modernization investment planning. On average, almost 10% of utility revenue is invested in grid modernization efforts, based on a study from the IBM Institute for Business Value (IBV) that surveyed nearly 600 global C-suite and senior utility executives. However, 21% of survey participants claim their organization did not progress in grid modernization efforts (Gandhi, Habib, et al. 2025).

Lack of progress and/or insufficient investment undermines efforts to harden the grid to enhance critical component durability. Grid hardening efforts to reinforce existing infrastructure will improve grid durability during adverse conditions. Grid infrastructure that is not hardened will take longer to restore power after natural disaster events, such as wildfires (Ulteig 2024). Without preemptive investments in grid durability, utilities may be forced into reactive, high-cost emergency upgrades that disrupt service and erode public trust. These reactive measures are often less efficient and more expensive than planned modernization efforts. In the long term, failure to harden the grid could also limit economic development as regions with unreliable power may struggle to attract or retain large loads.

3. GRIDS – Justification and Framing of Solutions

3.1. From Challenges to Structured Support

The preceding sections outlined large load integration challenges that span technical, procedural, and organizational domains, including limited grid capacity, interconnection delays, siting constraints, and cost allocation concerns. While these issues are well-documented, stakeholders often lack a centralized, structured resource that connects these challenges to actionable strategies in a way that supports timely, context-specific decision-making.

We are developing a tool called GRIDS to fill this gap. Rather than offering a one-size-fits-all solution, GRIDS is designed to reflect the variety of real-world deployment scenarios and the range of actors involved, including utilities, transmission operators, developers, and regulators. It does so by organizing potential solutions in a way that mirrors how stakeholders typically approach large load integration: through a combination of infrastructure upgrades, new development, and enabling technologies that enhance flexibility and control.

This section introduces a conceptual framework for understanding the types of solutions GRIDS includes. These broad solution pathways span grid upgrades, greenfield development, and enabling technologies; these are not rigid categories but rather approaches by which to address the evolving landscape of large load integration.

3.2. Conceptual Pathways for Large Load Integration

To support the development of a structured, decision-oriented library, it is helpful to first consider the broad types of strategies that stakeholders typically pursue when preparing for large load deployment. While the GRIDS library itself does not separate solutions into these categories, three conceptual pathways emerged during the research process as useful lenses for understanding the nature and function of potential solutions: **Grid Upgrade Strategies**, **Greenfield/Brownfield Development**, and **Enabling Technologies**.

These pathways reflect the different ways utilities and large load stakeholders approach the challenge of integrating large, energy-intensive loads into the grid:

- **Grid Upgrade Strategies** focus on enhancing the performance, capacity, or resilience of existing infrastructure. This includes solutions such as reconductoring transmission lines, upgrading substations, or deploying GETs to unlock latent capacity. These technologies aim to optimize the existing grid and address transmission reliability, capacity expansion, congestion, and interconnection challenges (Gentle, et al. 2024). Such strategies are often the first line of response when existing systems are near their limits but still viable with targeted investment.
- **Greenfield Development** involves building entirely new infrastructure such as substations, transmission corridors, and generation assets in areas where existing systems cannot support anticipated demand. **Brownfield Development**, on the other hand, concerns upgrading or integrating new technologies into existing infrastructure, which may contain legacy systems that can be considered and augmented (Stevenson 2024). These solutions are typically more capital-intensive and time-consuming but may be necessary in regions experiencing rapid growth or insufficient legacy infrastructure.
- **Enabling Technologies** provide tools and systems that improve visibility, flexibility, and control across the grid. This includes advanced forecasting tools, distributed energy resource management systems (DERMS), DLR, and AI-driven analytics. These technologies are often used in conjunction with demand response programs, which provide active participation from customers to help manage grid load and stability (International Renewable Energy Agency 2019). These technologies often complement upgrade or greenfield strategies by improving operational efficiency and responsiveness.

These three pathways are not mutually exclusive. In practice, many large load integration efforts will involve a combination of all three. For example, an entity may upgrade existing infrastructure where possible, build new assets where necessary, and deploy enabling technologies to optimize performance. By containing solutions across these types of approaches, GRIDS helps users think holistically about the range of options available and how they might be combined to meet specific deployment needs.

3.3. Informing the Structure of the GRIDS Library

The conceptual pathways outlined above illustrate the diverse strategies available for large load integration and have informed the design of the GRIDS library. This library is structured to reflect how utilities and developers make decisions, enabling users to weigh tradeoffs across factors such as cost, deployment timeline, permitting complexity, and grid impact. Each solution in the library is described using a consistent set of fields (see Appendix A) that capture these dimensions, allowing users to filter, prioritize, and compare options based on their specific context.

This structure supports both exploratory research and targeted decision-making. For example, a utility planner facing urgent capacity constraints may prioritize solutions with short lead times and low permitting complexity, while a developer exploring co-location with generation assets may focus on siting feasibility and interconnection requirements. By standardizing how solutions are described and evaluated, the GRIDS library provides a flexible foundation for the future decision support tool, ensuring that users can engage with the content in a way that aligns with their goals.

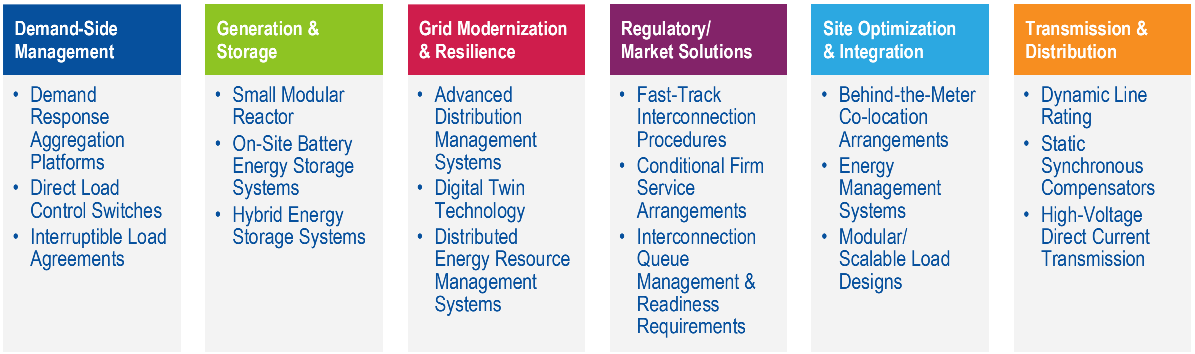
The next sections detail how solutions are documented within the GRIDS library, including the rationale behind the selected fields, the process for identifying and validating solutions, and how GRIDS will support practical application across a range of use cases.

4. LIBRARY ARCHITECTURE

4.1. Overview of the Library

The GRIDS Solutions Library is a curated, web-based reference database designed to support utilities, developers, and infrastructure planners in identifying actionable strategies for enabling large load deployment. It catalogs a wide set of solutions that address the technical, procedural, and operational challenges associated with integrating energy-intensive loads such as data centers, into the electric grid.

Each solution in the library is characterized by a set of fields that capture pertinent information such as technical maturity, commercial availability, deployment feasibility, and relevance to interconnection and integration concerns. These fields were selected to support practical decision-making and are intended to help users compare solutions based on considerations like technological readiness, cost, permitting complexity, and applicability to specific grid challenges. GRIDS includes established technologies and emerging innovations, spanning six categories: Demand-Side Management (DSM), Transmission & Distribution (T&D), Generation & Storage, Grid Modernization & Resilience, Site Optimization & Integration, and Regulatory/Market Solutions. Figure 1 lists example solutions in each of the six library categories.



Demand-Side Management	Generation & Storage	Grid Modernization & Resilience	Regulatory/ Market Solutions	Site Optimization & Integration	Transmission & Distribution
• Demand Response Aggregation Platforms • Direct Load Control Switches • Interruptible Load Agreements	• Small Modular Reactor • On-Site Battery Energy Storage Systems • Hybrid Energy Storage Systems	• Advanced Distribution Management Systems • Digital Twin Technology • Distributed Energy Resource Management Systems	• Fast-Track Interconnection Procedures • Conditional Firm Service Arrangements • Interconnection Queue Management & Readiness Requirements	• Behind-the-Meter Co-location Arrangements • Energy Management Systems • Modular/ Scalable Load Designs	• Dynamic Line Rating • Static Synchronous Compensators • High-Voltage Direct Current Transmission

Figure 1. Library categories and example solutions.

4.2. Identification and Validation of Solutions

The GRIDS Solutions Library was assembled through a structured, multi-step research and validation process. The solutions were identified by analyzing a wide range of public and industry sources, including the U.S. Department of Energy (DOE), Department of Defense (DoD), Cybersecurity and Infrastructure Security Agency (CISA), Electric Power Research Institute (EPRI), and North American Electric Reliability Corporation (NERC). While some of these sources, like DOE's Grid Modernization Initiative (Department of Energy 2020), contain limited collections of relevant solutions, comprehensive repositories are rare. To expand our search and capture additional high-value solutions, we conducted further analysis of technical reports, strategic plans, fact sheets, research papers, and handbooks. Open-source research was leveraged to identify potential solutions beyond those found in traditional sources.

To qualify for inclusion in the library, each solution must meet at least one of the following criteria:

- It enables increased grid capacity (generation, transmission, storage);
- It improves interconnection speed and feasibility;
- It helps utilities and other data center stakeholders assess or mitigate siting constraints;
- It provides operational flexibility for large loads;
- It minimizes cost of infrastructure upgrades or modernization;
- It empowers market participation incentives to optimize grid operations.

The library was developed through an iterative validation process to ensure both technical accuracy and real-world applicability. Internal peer reviews with subject matter experts (SMEs) confirmed the scope and relevance of the collected solutions, while external stakeholder engagement refined attribute accuracy and identified gaps. This curated library now serves as the foundational database for the GRIDS tool, enabling users to filter and prioritize solutions based on context (e.g. siting constraints, interconnection timelines, or regional coordination needs). To demonstrate breadth, Appendix A lists the current solutions by category with brief descriptions.

4.3. Library Fields and Rationale

The GRIDS Solutions Library fields were developed through an iterative process that began with a broad set of attributes useful for evaluating large load solutions, informed by foundational documents such as Practical Guidance and Considerations for Large Load Interconnections (Elevate Energy Consulting 2025). As the library was built out, it was refined and expanded based on feedback from internal SMEs, with the primary aim being to clearly tie each solution to real-world challenges faced by electric utilities and developers. The goal is to capture the most relevant technical, operational, and contextual information needed to support practical decision-making by utilities, developers, and planners.

The fields broadly fall into several functional categories:

- **Technical Maturity and Deployment Feasibility**: These fields (e.g., *Technology Readiness Level (TRL)*, *Deployment Status*, and *Timeline for Adoption*) help users assess how close a solution is to real-world implementation and how quickly it can be deployed.
- **Market and Supply Chain Considerations**: Fields like *commercial diversity*, *supply chain availability*, and cost (*CAPEX*/*OPEX*) provide insight into procurement risk, vendor landscape, and financial viability.
- **Regulatory, Permitting, and Siting Complexity**: These attributes capture the procedural and jurisdictional challenges that often delay or complicate deployment, including *Complexity of Permitting/Siting*, *Interconnection Requirements*, and *Implementation Responsibility*.
- **Grid Function and System Impact**: Fields such as *Primary Benefits*, *Primary Integration Challenge(s)*, and *Interconnection Upgrade Category* describe what the solution does for the grid, such as whether it improves reliability, increases capacity, reduces congestion, or enhances flexibility.
- **Scalability and Contextual Fit**: Fields like *Scale of Application*, *Lead Time*, and *Relevant Use Cases* help users understand where and how a solution is most applicable, and whether it aligns with their specific deployment scenario.

These fields were designed to serve multiple purposes. First, they allow users to filter and prioritize solutions based on their specific needs, such as siting constraints, urgency of deployment, or available funding mechanisms. Second, they provide a consistent structure for comparing solutions across categories, enabling more informed tradeoff decisions. Finally, they support the GRIDS tool's ability to generate tailored recommendations by linking solution attributes to real-world utility challenges.

Appendix A provides a complete list of all library fields, including definitions, scoring criteria, and example values.

5. RELEVANCE TO INDUSTRY NEED & USE CASE INTEGRATION

5.1. How Users Will Interact with the GRIDS Tool and Library

As described previously, the GRIDS Library serves as the foundational database that will support the GRIDS decision support tool, which is intended to serve as a practical, user-driven decision support platform that helps users navigate the complexities of large load deployment. GRIDS and its underlying library are structured to support real-world decision-making across a range of deployment scenarios (see **Error! Reference source not found.** for a simplified tool framework).

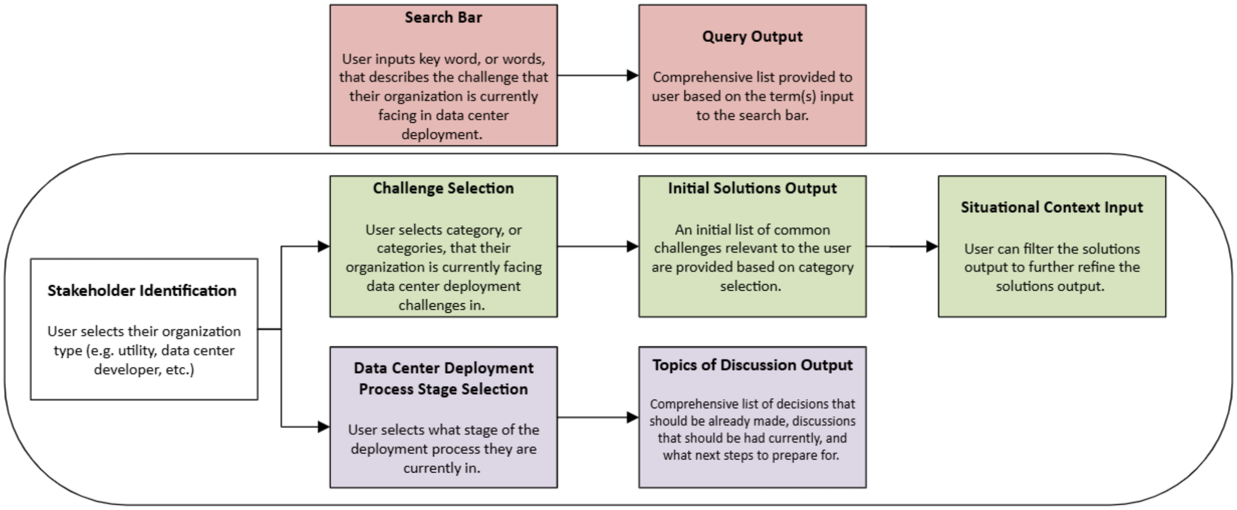


Figure 2. Tool interaction sequence users experience identifying solutions relevant to their specific challenges.

User Interaction Overview:

The GRIDS tool is designed to walk users through a structured decision-support workflow that mirrors how stakeholders typically approach large load integration. GRIDS provides the user with two options for reviewing the solutions library. The first option provides the user with the solutions library as an open-source spreadsheet. The second option utilizes a website wizard to guide the user through a sequence of steps to determine which solutions within the library are relevant based on their needs. As seen in Figure 2, these user experiences operate in parallel. The boundary around the second option indicates steps associated with the website wizard.

This website wizard process includes the anticipated following steps:

1. **Stakeholder Identification**
   Users begin by selecting their stakeholder type (e.g., utility planner or data center developer). This selection helps tailor the tool's logic to the user's role, responsibilities, and decision-making authority.

2. **Challenge Selection**
   Based on the stakeholder type, the tool presents a curated list of common challenges relevant to that role. These may include interconnection delays, permitting complexity, infrastructure constraints, or cost allocation concerns. Users can select one or more challenges that reflect their current situation.
3. **Initial Solutions Output**
   Users are then prompted to filter solutions based on key situational parameters, such as:
   - Deployment timeline (e.g., urgent vs. long-term planning)
   - Infrastructure limitations (e.g., substation capacity, transformer availability)
   - Permitting or siting constraints
   - Desired grid benefits (e.g., congestion relief, voltage support, resilience)
   - Regional or policy-specific considerations
4. **Situational Context Input**
   The tool uses these inputs to filter the GRIDS Library and prioritize solutions that align with the user's context. Solutions are ranked based on attributes such as:
   - Technology readiness level (TRL)
   - Deployment timeline
   - Permitting complexity
   - Cost (CAPEX/OPEX)
   - Implementation responsibility (utility, developer, joint)
   - Scale of application (site-specific, feeder-level, system-wide, etc.)

   Users can explore tradeoffs between different implementation pathways, compare solution attributes side-by-side, and identify strategies that best align with their operational, financial, and regulatory constraints. The tool supports both exploratory browsing and targeted decision-making.
5. **Data Center Deployment Process Stage Selection**

   Users can select which stage of the interconnection process their organization is currently in. The five stages include: (1) application preparation & submission, (2) technical scoping, (3) technical studies, (4) interconnection agreement, and (5) project implementation.
6. **Topics of Discussion Output**

   Once the current stage is selected, a comprehensive list of topics is provided that includes decisions that should be made prior to the current stage, decisions and discussions that are included in the current stage, and what to prepare for in the next stage.

To ensure the tool reflects real-world needs, its structure and logic will be designed for a set of use cases, described in the following subsections, that illustrate how different types of users might engage with the library and what kinds of decisions it can support. These use cases were identified and developed as a milestone deliverable during the initial stages of this project. Broadly reviewing and characterizing the challenges of utilities and data center developers led to the identification of technical assistance opportunities based on the needs and challenges unique to data center stakeholders.

5.2. Use Case 1: Rapid Demand Growth and Ancillary Service Markets

Description:

This first use case is oriented around regions near metro hubs and areas with strong fiber infrastructure which are experiencing a surge in data center siting. The primary stakeholders of these areas are large utilities with generation, transmission, and distribution responsibilities, as well as data center developers. These entities deal with high volumes of interconnection requests in short timeframes as developers seek rapid deployment. To meet these demands, utilities must balance fast-moving load growth with reliability and regulatory compliance.

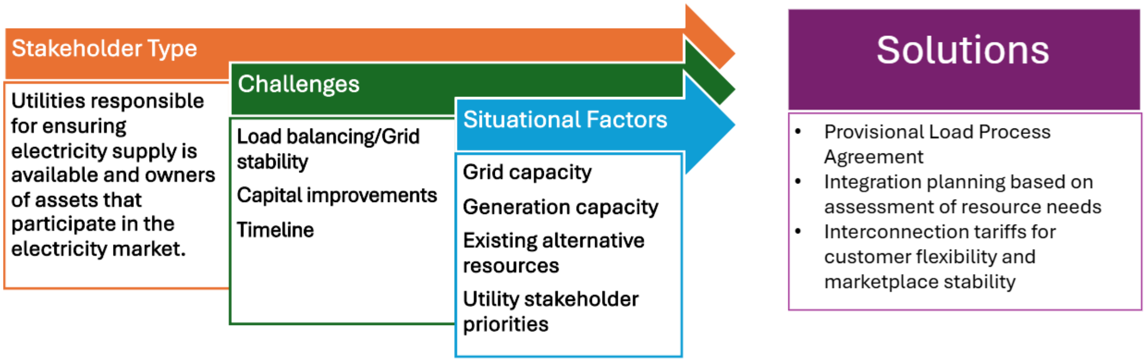
Anticipated Challenges:

The key challenge is managing grid stability amid sudden increases in demand, which may outpace infrastructure readiness. This includes both the siting of new facilities and the operational ramp-up of large loads. As an example, between 2023 and 2024, CAISO experienced a peak load increase of 8.3% (44,092 MW to 47,759 MW) (Federal Energy Regulatory Commission 2025). Utilities in these regions often face long interconnection queues, limited transmission or distribution capacity, and the need for accelerated capital investment. Beyond the grid, rapid development can strain local infrastructure and community services (e.g., water for cooling, transportation, permitting), sometimes triggering public resistance due to environmental or resource concerns.

GRIDS Use Case Support:

GRIDS will support utilities facing rapid demand growth by identifying short-term grid reinforcement strategies, such as STATCOMs, DLR, and reconductoring. It will also surface solutions that streamline interconnection processes (e.g., phased interconnection, BTM generation) and highlight opportunities for large loads to participate in ancillary service markets (Indiana Utility Regulatory Commission 2025). To address permitting and community-related challenges, GRIDS will include solutions that accelerate permitting timelines and enhance stakeholder engagement. Users will be able to filter solutions based on deployment urgency, permitting complexity, and infrastructure constraints, enabling them to compare implementation pathways and plan for rapid deployment and operational ramp-up.

Figure 3. Tool framework applied to Use Case 1.



5.3. Use Case 2: Generation and Transmission Cooperatives Interested in Integrated Resource Planning

Description:

This use case represents medium or large-sized utilities, particularly Generation and Transmission (G&T) Cooperatives or large municipal utilities, which are experiencing or anticipating significant large load requests. These entities recognize the need to understand, enhance, and plan for grid readiness to support ongoing growth, but may lack a robust or automated, integrated resource planning (IRP) framework that fully accounts for the unique characteristics of new large loads. They are often concerned with long-term reliability and economic efficiency across their entire service territory.

Anticipated Challenges:

Supply chain constraints are a challenge here, particularly for specialized equipment (e.g., large transformers, advanced metering infrastructure) needed for grid upgrades and new interconnections, which can be further exacerbated by extreme weather events. Navigating complex regulatory and policy compliance from federal, state, and regional authorities (e.g., FERC, state PUCs, RTO/ISO rules) also presents a significant hurdle, especially in locations where state oversight over cooperatives subjected to PUC regulation is limited by statute for certain types of projects. Ensuring overall infrastructure reliability and stability becomes increasingly complex and costly with dynamic, high-density loads, requiring advanced grid modeling and operational adjustments. The strategic integration of diverse new resources (e.g., gas turbines, solar PV) into a cohesive IRP is also a challenge (NERC 2025). Cost is considered as a challenge in this use case because members must approve CAPEX projects and there are strong motivators to keep consumer costs down.

GRIDS Use Case Support:

GRIDS will assist utilities, particularly G&T cooperatives and municipal providers, in identifying integrated resource planning (IRP)-aligned solutions across generation, storage, and demand-side management (Telos Energy 2024). The tool will help users assess hosting capacity, siting feasibility, and infrastructure readiness, enabling the selection of commercially available technologies with short- to medium-term deployment timelines. Users can filter solutions by implementation responsibility (e.g., utility vs. developer) and evaluate options for market participation and ancillary service procurement, supporting long-term planning and system-wide reliability.

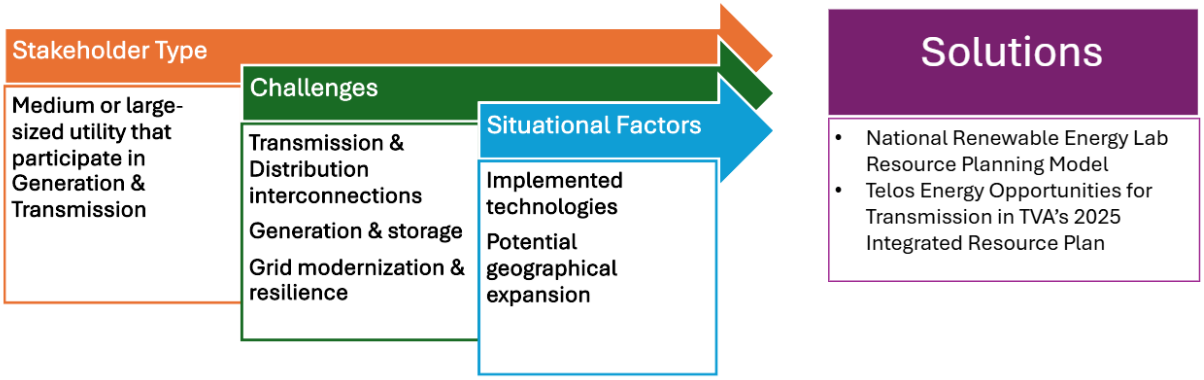


Figure 4. Tool framework applied to Use Case 2.

5.4. Use Case 3: Exploring Co-Location of Data Centers and Nuclear Generation

Description:

This use case involves large-scale data centers that are co-located with dedicated nuclear generation assets—such as Small Modular Reactors (SMRs), existing nuclear plants, or next-generation advanced reactors. These deployments aim to secure resilient, carbon-free, and highly reliable baseload power while reducing dependence on external grid infrastructure. In many cases, the generation asset may be owned or operated by a separate entity from the local utility, requiring careful coordination to address grid interconnection, emergency backup, and seasonal load-balancing needs. Co-location strategies may also explore the use of thermal energy from nuclear systems for non-electric applications such as data center cooling or industrial processes (e.g., desalination). These configurations introduce unique planning, regulatory, and operational considerations that differ from traditional grid-connected models.

Anticipated Challenges:

Companies pursuing this co-location strategy face a range of complex hurdles. These include regulatory and permitting complexities, requiring navigation of jurisdictional approvals and procedural requirements for integrating novel energy systems with critical infrastructure (e.g., data centers) at scale (McGeady, et al. 2025). Complex interconnectivity and grid integration is another significant challenge due to the need for high-speed and reliable interconnectivity between the data center and the advanced energy source, involving precise needs for power quality, grid synchronization, and robust backup systems. This strategy also encompasses challenges related to long-duration energy storage optimization and generation asset selection, coordination, and integration to manage load demand variability and potential rapid load drops without impacting surrounding customers. Determining optimal SMR placement from a power planning perspective to handle significant load changes without community-wide outages is a concern (Hardin, Tuite, et al., Nuclear Energy's Role in Powering Data Center Growth 2025). Additionally, managing potential supply chain and development risk due to constraints in specialized advanced energy components can significantly impact project timelines and costs. Finally, community relations and social acceptance require proactive engagement and transparent communication to build and maintain positive community sentiment for new, large-scale energy infrastructure (Talbot, et al. 2025).

GRIDS Use Case Support:

Leveraging INL's unique nuclear expertise, GRIDS will provide tailored support for co-location strategies involving advanced generation assets such as small modular reactors (SMRs) and hybrid systems. The library includes solutions that address interconnection requirements, operational best practices, and siting feasibility for nuclear-integrated deployments. It also offers insights into community engagement strategies and planning for long-duration storage and load-balancing technologies (Li, et al. 2025). GRIDS will help users evaluate the co-benefits of thermal energy applications, such as data center cooling or industrial processes, and filter solutions based on regulatory complexity, deployment timeline, and implementation responsibility, supporting informed decision-making for novel energy configurations.

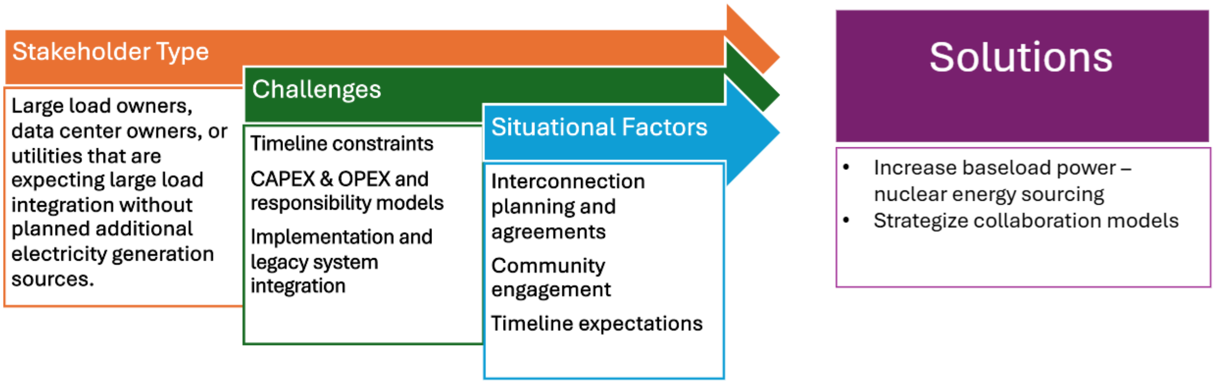


Figure 5. Tool framework applied to Use Case 3.

5.5. Use Case 4: Regional Coordination of Large Load Demand Response Programs

Description:

This fourth use case represents regions or utilities within a specific geographical area (e.g., a balancing authority, RTO/ISO footprint, or state) that recognize the collective benefit of coordinating demand response (DR) programs specifically targeting diverse large loads. The entities involved may include multiple utilities, load aggregators, and the large load facilities themselves. The goal is to enhance grid stability and optimize resource utilization across the region.

Anticipated Challenges:

A primary challenge is establishing standardized metrics and communication protocols across multiple utilities and diverse large loads to ensure consistent and effective DR dispatch. This includes the need for sophisticated Energy Management Systems (EMS) and Demand Response Management Systems (DRMS) or 2030.5 servers to share commands (EPRI 2018). Overcoming regulatory and policy fragmentation across different jurisdictions or utility service territories to enable seamless regional DR participation is also crucial. Developing equitable and transparent compensation mechanisms for large load participation in DR programs can be complex due to varying load characteristics and market structures (Enriquez-Contreras, et al. 2025). Ensuring the reliability and responsiveness of committed DR capacity under various grid conditions is paramount, requiring robust testing and verification. Additionally, customer-side communications and EMS communications potentially via the Common Information Model (CIM) are necessary to enable effective coordination (Gopstein, et al. 2021). Data to enable measurement and verification of performance is also essential.

GRIDS Use Case Support:

GRIDS will support regional coordination of demand response (DR) programs by providing solutions for enabling technologies such as Distributed Energy Resource Management Systems (DERMS) and Advanced Distribution Management Systems (ADMS) (Lutz 2025). The tool will help users evaluate regulatory incentives and market mechanisms that facilitate DR participation by large loads (Frank 2025). Solutions can be filtered by geographic scale (e.g., site-specific vs. regional) and implementation responsibility, allowing users to tailor strategies to their operational context. GRIDS will also aid in selecting technologies that enhance grid visibility and monitoring for DR dispatch, while offering insights into permitting complexity and deployment timelines for DR-enabling infrastructure.

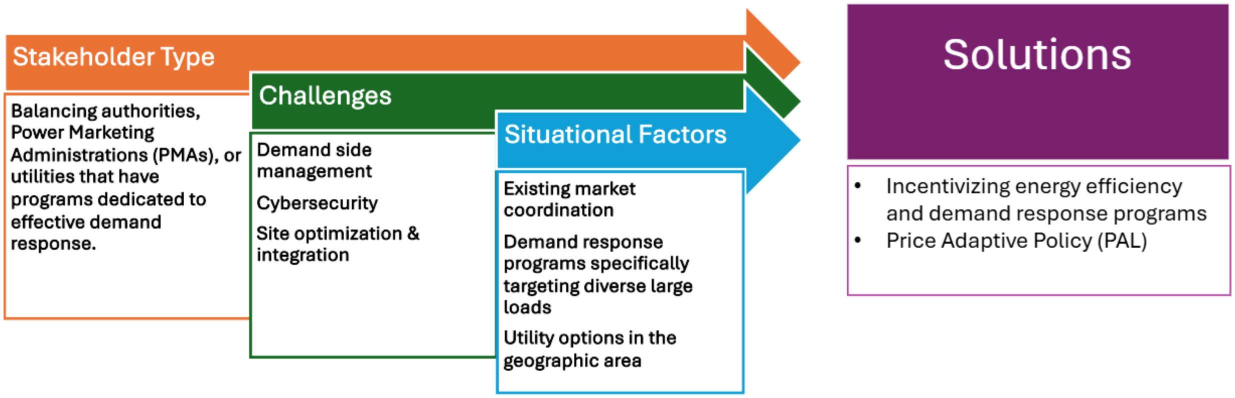


Figure 6. Tool framework applied to Use Case 4.

6. CONCLUSION

The deployment of large loads, especially data centers and hyperscale facilities, is reshaping the energy landscape, placing unprecedented demands on grid infrastructure, planning processes, and stakeholder coordination. This white paper introduces GRIDS (Grid Readiness and Interconnection Decision Support) as a foundational resource to address these challenges by providing a structured, web-based library of vetted solutions and a decision support framework tailored to real-world deployment scenarios.

GRIDS surpasses being a mere catalog, it aims to be a strategic enabler for users who are seeking to integrate large loads with the grid. By including solutions across grid upgrades, greenfield development, and enabling technologies, GRIDS empowers utilities, developers, and planners to make informed, context-specific decisions that balance reliability, cost, and deployment speed. Its architecture reflects the complexity of modern grid integration and supports both exploratory research and targeted planning.

To ensure GRIDS evolves into a dynamic, widely adopted platform, the following areas of future work are essential:

6.1. Technical Assistance & Industry Engagement

As data centers and other large loads continue to deploy across the nation, the need for targeted Technical Assistance (TA) and proactive industry engagement becomes increasingly urgent. The INL team will provide this TA by leveraging the GRIDS library and tool to support utilities, developers, and planners in navigating complex deployment scenarios. TA pathways, tailored to specific challenges such as interconnection delays, siting constraints, or operational flexibility. can significantly accelerate the adoption of successful solutions and modernization strategies.

These efforts are complemented by early and sustained engagement with utilities, regulators, and local communities. Transparent communication and scenario-based planning help build trust, align expectations, and demonstrate the long-term benefits of resilient, cost-effective infrastructure. GRIDS can serve as a shared reference point to facilitate these conversations and promote equitable, resilient infrastructure development.

6.2. Collaboration with Other National Laboratories

Research performed at National Laboratories brings deep technical expertise and modeling capabilities that can inform the development of robust integration strategies throughout the data center integration process. Their insights into load forecasting and grid interconnection are valuable for optimizing the design of scalable solutions that align with evolving grid conditions. By incorporating lab-developed tools and research on potential state-of-the-art solutions, users can benefit from validated methodologies and scenario simulations that enhance decision-making.

6.3. Web-Based Tool Development

The GRIDS web-based tool will evolve into a dynamic decision support platform that reflects the diversity of stakeholder needs and deployment contexts. By embedding insights from industry case studies, regulatory trends, and stakeholder feedback, GRIDS will support site-specific planning, cross-sector coordination, and strategic investment decisions. Future iterations will expand filtering capabilities, integrate real-time data, and support regional coordination efforts. Ultimately, GRIDS will empower planners, developers, and utilities to make data-drive choices and enhance communication between participants and support reliable and resilient grid operations.

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Appendix A

Library Fields Specified During GRIDS Development

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Library Fields Specified During GRIDS Development

The library is composed of the following fields:

Solution ID

A unique code to identify each solution for tracking and database management.

Solution Name

A short, easy-to-understand title for the solution (e.g., "On-Site Battery Energy Storage System").

Category

The main type or function of the solution (e.g., Generation & Storage, Cybersecurity). Used for broad organization.

Sub-Category

A more specific type within the main category (e.g., Energy Storage within Generation & Storage).

Brief Description

A short summary of what the solution is and what it does.

Primary Benefit(s)

The main advantages the solution provides to the grid, user, or community, as defined in the following table.

Benefit	Description
Generation Capacity	Increases available generation to meet large load demand.
Transmission Capacity	Expands the ability to move power across the grid to serve large loads.
Congestion Relief / Peak Load Reduction	Reduces stress on constrained infrastructure during high-demand periods.
Voltage Support	Maintains voltage stability under large or fluctuating load conditions.
Frequency Regulation	Helps balance supply and demand in real time to maintain grid frequency.
Protection & Fault Management	Enhances system protection, fault detection, and isolation capabilities.
Grid Visibility & Monitoring	Improves situational awareness and real-time operational control.
Dispatchability / Flexibility	Enables controllable or responsive resources to support grid operations.
Interconnection Process Efficiency	Streamlines planning, permitting, or procedural steps to reduce interconnection timelines.
Reliability & Resilience	Improves system uptime, outage response, and ability to withstand disruptions.
Cost Reduction	Lowers capital or operational costs for utilities or developers.

Decarbonization / Emissions Reduction	Supports clean energy goals and reduces carbon footprint.
Siting Feasibility	Enables deployment in areas with land use, permitting, or environmental constraints.

Primary Integration Challenge(s)

The main grid-related challenges that the solution is designed to address in the context of integrating large, energy-intensive loads (e.g., data centers).

Interconnection Upgrade Category

The type of grid upgrade or procedural requirement the solution addresses in the context of large load interconnection.

Category	Description
Grid Stability & Operational Upgrades	**Covers overloads, voltage violations, short-circuit issues, and dynamic stability.**
Protection Systems	**Includes relay upgrades, fault detection, and coordination schemes.**
Metering & Communication Systems	**Encompasses telemetry, SCADA, AMI, and data-sharing infrastructure.**
Shared or Affected System Upgrades	**Captures upgrades on neighboring systems or upstream/downstream impacts.**
Energy Storage Facilities	**Includes storage as a grid asset or interconnection mitigation tool.**
Planning/Process Requirements	**Covers studies, agreements, and procedural steps that affect timelines.**
Siting & Permitting Constraints	**Addresses land use or permitting barriers that delay infrastructure deployment.**
Grid Visibility & Monitoring	**Improves real-time awareness and control for large load integration.**

Technical Specs (Key Metrics)

Important technical details and performance indicators (e.g., capacity, efficiency).

Technology Readiness Level (1-9)

A scale from 1 to 9 showing how mature the technology is, with 1 being basic research and 9 being proven in real-world use.

Technology Readiness Level Scoring Criteria

Table 2. Technology Readiness Level scores and criteria.

Score	Criteria	Example
TRL 1	Basic principles observed.	Paper studies of a technology’s basic properties.
TRL 2	Technology concept and/or application formulated.	Analytical studies, lab experiments, or simulations to determine efficacy of a concept.

TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.	Lab-scale prototypes of components demonstrate critical functionality.
TRL 4	Component and/or breadboard validation in a laboratory environment.	Key components integrated into a working "breadboard" system, validated in lab.
TRL 5	Component and/or breadboard validation in a relevant environment.	Integrated components validated in a simulated environment replicating real-world conditions.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment.	System prototype tested in a highly realistic simulated or actual field environment.
TRL 7	System prototype demonstration in an operational environment.	Full-scale system prototype demonstrated in a commercial or utility operational setting.
TRL 8	Actual system completed and qualified through test and demonstration.	System is proven to work in its final form and under expected conditions, ready for deployment.
TRL 9	Actual system proven in operational environment (actual mission success).	Technology is fully operational and has demonstrated successful deployment and extensive use.

Commercial Diversity

How many vendors offer the solution (e.g., High, Medium, Low), showing market maturity and competition.

Commercial Diversity Scoring Criteria

Table 3. Commercial Diversity scores and criteria

Score	Criteria
Low	Few (1-3) major established vendors; limited competition; often specialized or emerging market.
Medium	Several established vendors (4-8) with growing competition; market is consolidating or expanding.
High	Many established vendors (>8), strong competition, commoditized or widely adopted technology.

Deployment Status

The current stage of the solution's market adoption (e.g., Commercial, Pilot Phase, R&D).

Deployment Status Scoring Criteria

Table 4. Deployment Status scores and criteria.

Score	Criteria
R&D	Primarily in research and development; not yet in commercial pilots or limited deployments.

Pilot Phase	Limited, small-scale deployments or demonstrations, often experimental or for validation.
Early Commercial	Available for purchase/deployment, but projects are relatively new, few, or niche; market is just forming.
Commercial	Established market, available for general purchase/deployment; numerous projects ongoing or completed.
Widely Adopted	Becoming a standard or common practice; very high number of deployments across the industry.

Supply Chain Availability

How easily components or services for the solution can be sourced (e.g., Good, Moderate, Constrained, Severe).

Supply Chain Availability Scoring Criteria

Table 5. Supply Chain Availability scores and criteria.

Score	Criteria
Good	Components and materials are readily available from multiple reliable sources; no significant procurement delays.
Moderate	Some components may have limited suppliers or longer lead times; minor, manageable procurement challenges.
Constrained	Significant lead times or limited sources for critical components; potential for delays or higher costs due to supply-side issues.
Severe	Major bottlenecks, very few or sole suppliers, geopolitical risks, or high potential for widespread shortages causing significant project delays/failures.

Typical Cost Range (CAPEX)

Estimated initial investment needed to acquire and install the solution, often per unit (e.g., $/MW).

Operating Expense (OPEX) Implications

Expected ongoing costs for operating, maintaining, and potentially replacing the solution over its lifespan.

Potential Revenue Streams

Ways the solution can generate income or save costs for the owner/operator.

Incentives/Funding

Available financial support (e.g., grants, tax credits) that can reduce costs or increase viability.

Implementation Responsibility

The primary party responsible for funding, deploying, or managing the solution.

Table 6. Primary Party descriptions.

Value	Description
Utility	Implemented and funded primarily by the utility.
Developer	Implemented and funded by the large load customer or project developer.
Joint	Shared responsibility between utility and developer.
Third Party	Delivered by an independent vendor, aggregator, or service provider.

Policy-Driven	Requires public funding, regulatory action, or government-led programs.

Scale of Application

The typical geographic or system level at which the solution is applied, indicating the scope of impact and relevance to different stages of large load integration.

Table 7. Scale of application descriptions.

Scale	Description
Site-Specific	Applied at or near the large load facility.
Feeder-Level	Affects a single distribution feeder or local circuit.
Substation-Level	Involves upgrades or controls at the substation level.
System-Wide	Applies across the utility's entire service territory.
Regional	Involves coordination across multiple utilities, balancing areas, or RTO/ISO regions.

Typical Lead Time

Estimated time from project start to the solution being fully operational.

Timeline for Adoption

An estimate of how soon a solution is likely to be viable for widespread adoption by utilities, based on a combination of its technology readiness level (TRL) and typical lead time. This field reflects both the maturity of the solution and the practical feasibility of implementing it in real-world utility contexts.

Timeline for Adoption Scoring Criteria

Table 8. Timeline for Adoption scores and criteria.

Score	Criteria
Short-term (<2 years)	Mature, commercially available solutions with manageable lead times.
Medium-term (2–5 years)	Emerging solutions with growing market traction or moderate deployment barriers.
Long-term (5+ years)	Early-stage or complex solutions not yet ready for broad deployment.
Emerging	Experimental or speculative technologies with uncertain timelines.

Complexity of Permitting/Siting

How difficult and time-consuming it is to get necessary permits and find suitable locations (e.g., Low, Medium, High, Extreme).

Complexity of Permitting/Siting Scoring Criteria

Table 9. Complexity of Permitting/Siting scores and criteria.

Score	Criteria
Low	Minimal permitting required; projects typically don't require extensive environmental or land use reviews.
Medium	Standard permitting processes; involves typical environmental, zoning, and utility reviews; generally predictable.
High	Requires extensive environmental impact assessments, public hearings, multiple jurisdictional approvals, or faces common public opposition/complex land use issues.

Extreme	Very complex, multi-jurisdictional permitting (e.g., federal, state, tribal, local); often involves highly contentious public opposition, significant environmental impact concerns (e.g., endangered species), or very limited suitable sites.

Interconnection Requirements

Specific needs or challenges for connecting the solution to the electricity grid.

Required Infrastructure

Other necessary physical assets or systems for the solution to work effectively.

Key Challenges

Major obstacles or common issues during planning, implementation, or operation (e.g., regulatory barriers, public acceptance).

Associated Risks

Potential negative outcomes or uncertainties related to the solution (e.g., technical failures, financial volatility, cyber threats).

Requires/Benefits From

Other solutions or conditions needed for optimal performance or that work well together with this solution.

Relevant Use Case(s)

Identifies which use case(s) a solution most closely aligns with, as identified in the T5M11 memo Key Use Cases and Capabilities Needs for Technical Assistance and Decision Support.

Relevant Use Cases Defined

Table 10. Use Case abbreviation and description.

Value	Use Case/Capability
UC1	**Use Case 1**: Rapid Demand Growth and Ancillary Service Markets
UC2	**Use Case 2**: Generation and Transmission Cooperative Interested in Integrated Resource Planning
UC3	**Use Case 3**: Exploring Co-Location of Data Centers and Nuclear Generation
UC4	**Use Case 4**: Regional Coordination of Large Load Demand Response Programs
TAC1	**Possible TA Capability 1**: Ensuring Security of Interconnected Data Centers
TAC2	**Possible TA Capability 1**: Standardized Interconnection Requests for Large Loads

Sources

The sources used to inform the proposed solution and its attribute fields