NREL

Utility and Grid Operator Resources for Future Power Systems Webinar Series

Large Load Management and Grid Planning

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NREL Webinar Series

July 22, 2025

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Agenda

1. The Large Load Challenge
2. National Lab Role in Large Load Grid Integration
3. Siting Large Loads
4. Grid Impacts
5. Mitigation Options
6. Additional Barriers to Rapid Growth
7. Toward Efficient Large Load Grid Planning

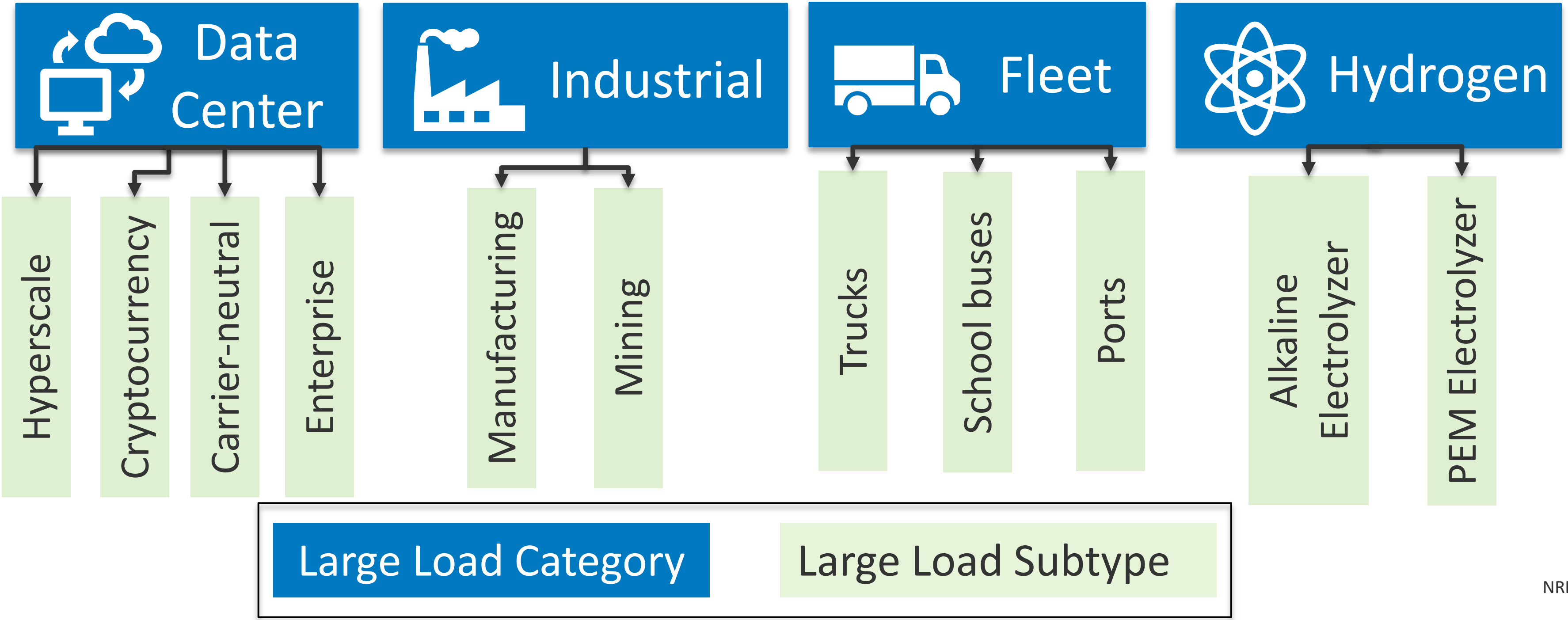
Ongoing work (items 3–5)

Forward-looking lab planned work (items 6–7)

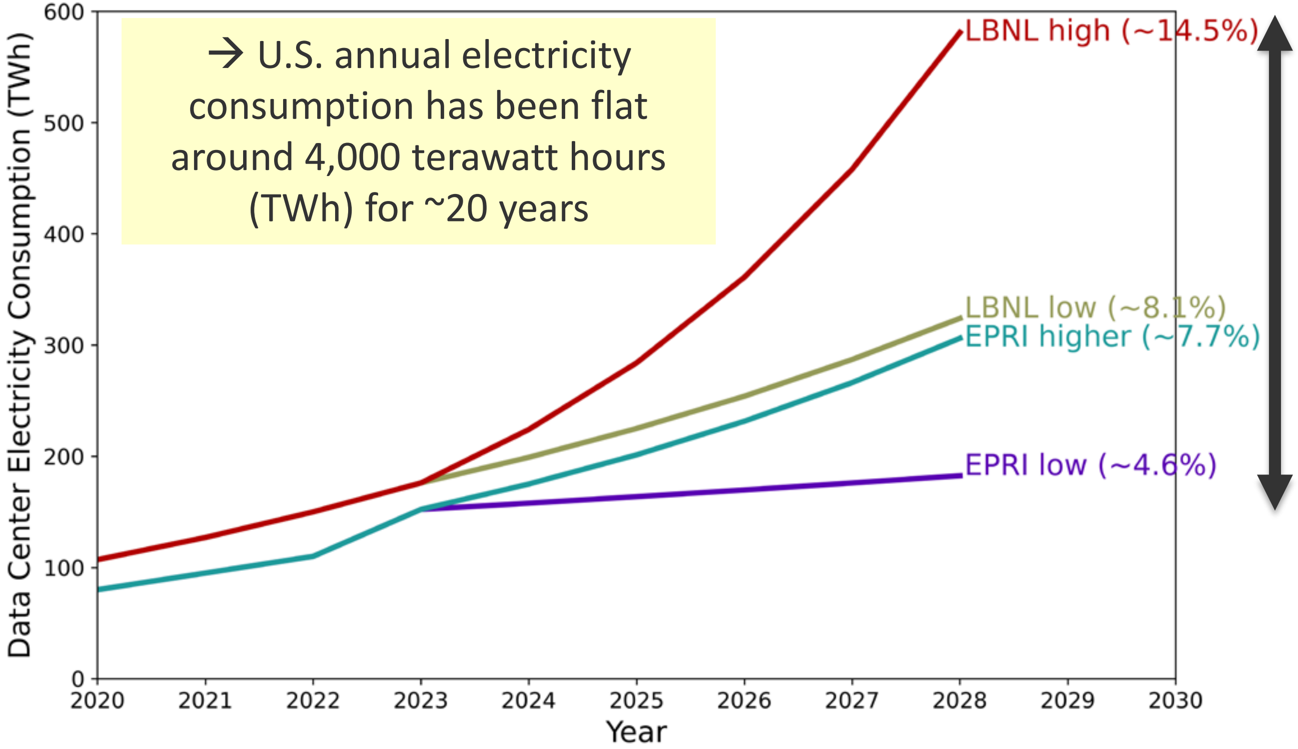
What Is a Large Load?

Categories with non-comprehensive examples

- Common definitions seem to cluster around **50–100+MW**, but many types
- A lot of focus specifically on data centers (including in these slides)



Uncertainty in near-term large load-driven growth



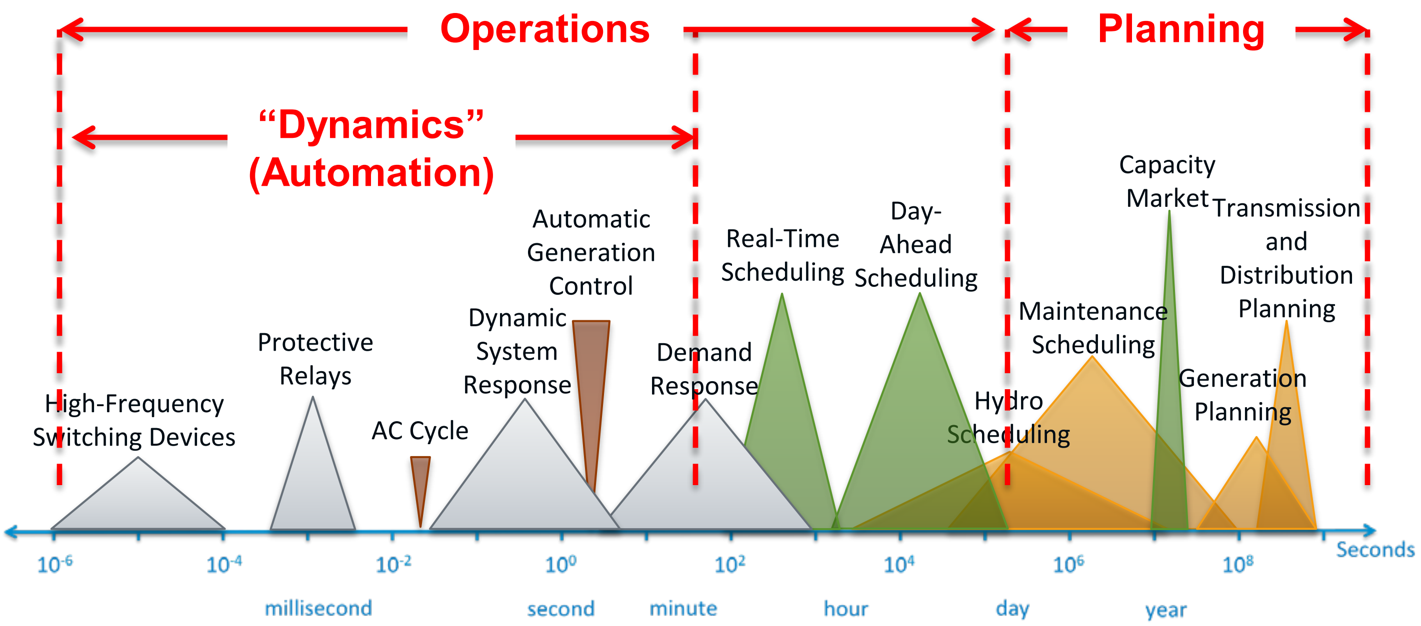
Percents are of 4,000 TWh

Uncertainty in just next few years is 10+% of annual consumption! Even greater beyond 2030

EPRI. "Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption." 2024. URL: https://www.epri.com/research/products/000000003002028905.
Shehabi, Arman, Alex Newkirk, Sarah Smith, Alex Hubbard, Nuoa Lei, Md Abu Bakar Siddik, Billie Holecek, Jonathan Koomey, Eric Masanet, and Dale Sartor. 2024. *2024 United States Data Center Energy Usage Report*. Lawrence Berkeley National Laboratory. Report #: LBNL-2001637. http://dx.doi.org/10.71468/P1WC7Q.

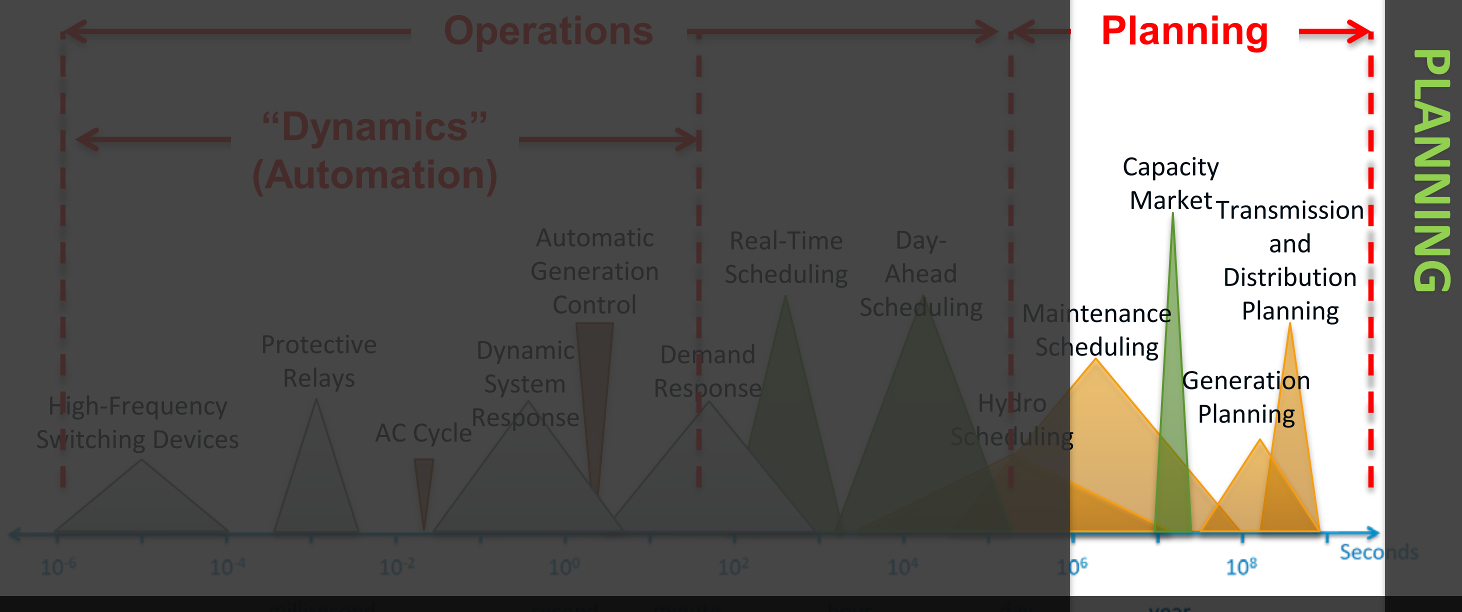
National Lab Role in Large Load Grid Integration

Experience Modeling Power System Across Decision-making Timescales; Apply to Data Centers

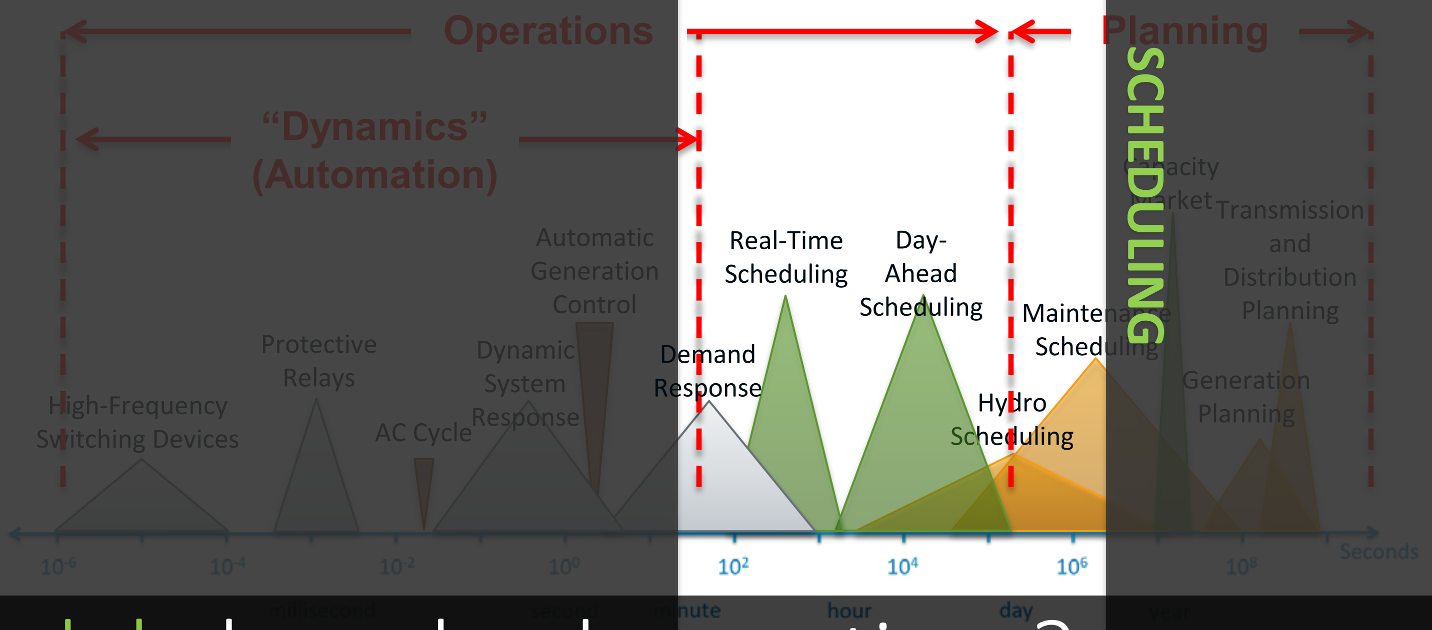


Adapted from A. Von Meier

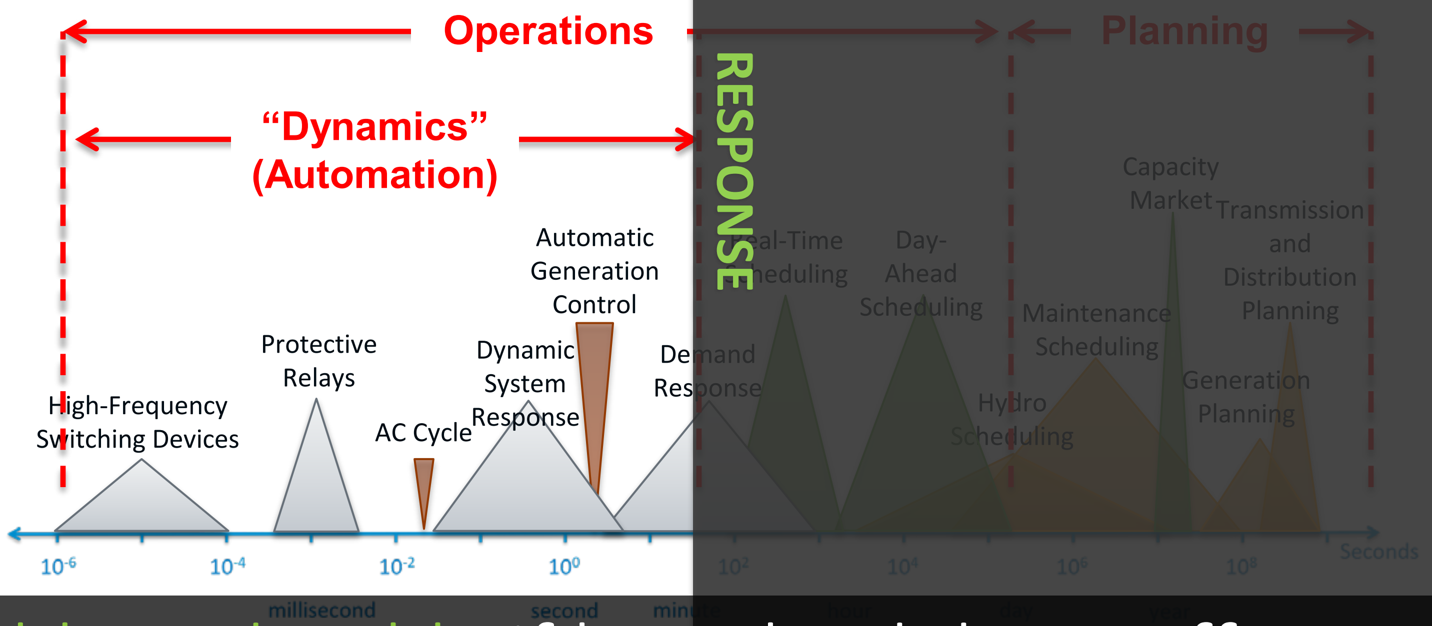
AC – Alternating Current



When and where might large loads get built?



Schedule large load operations?



Reliable and stable if large load drops off system?

Inform Best-practice Planning through Large Load Siting and Grid Impacts Analysis

Challenge: Where can a capacity-strained grid quickly and flexibly add tens-to-hundreds of gigawatts of new load?

National Scale Resource: Siting feasibility layers identify favorable locations for detailed analysis on clustering multiple large loads for near-term grid integration

Outcome: Open-access siting tools and metrics identify where and how large load clusters can be enabled by policymakers

Grid integration of data centers

- **Grid operators**: Maintain reliability
- **Utility customers**: Affordable and reliable service
- **Industry**: Efficient and fair grid connection
- **States & regulators**: Economic development

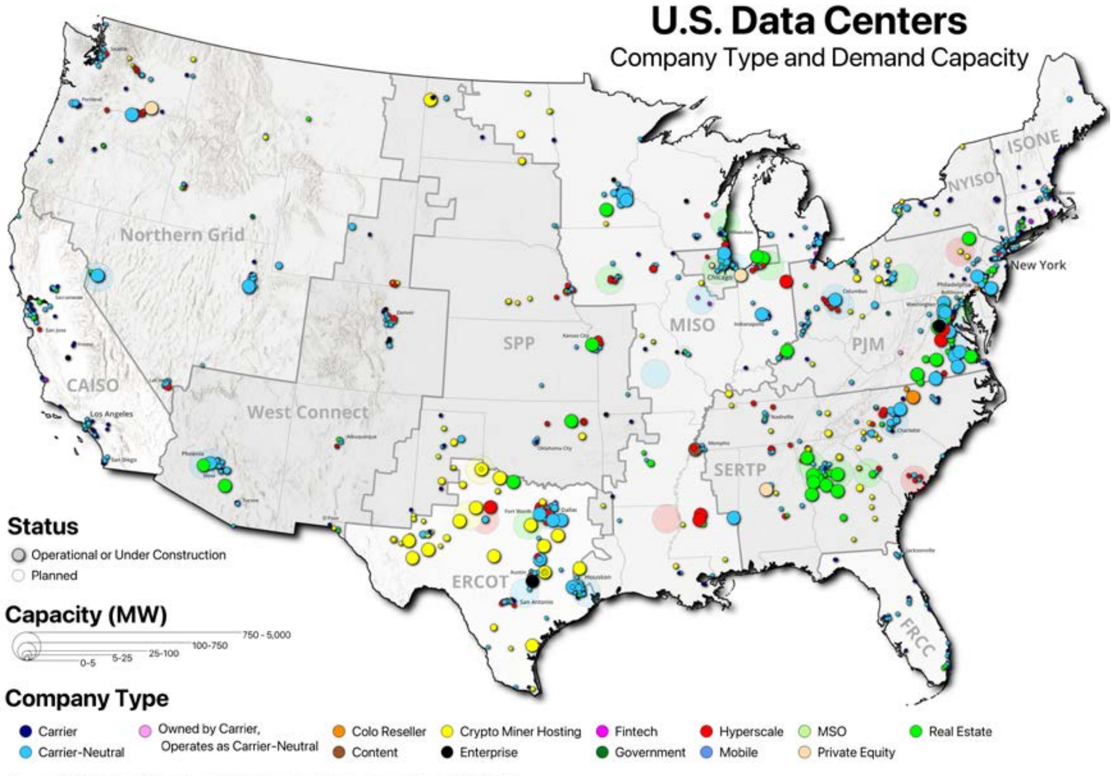
Lab impact: Supporting transformational large load and data center growth with objective decision support resources for all stakeholders

Toward a Geospatial Siting Tool

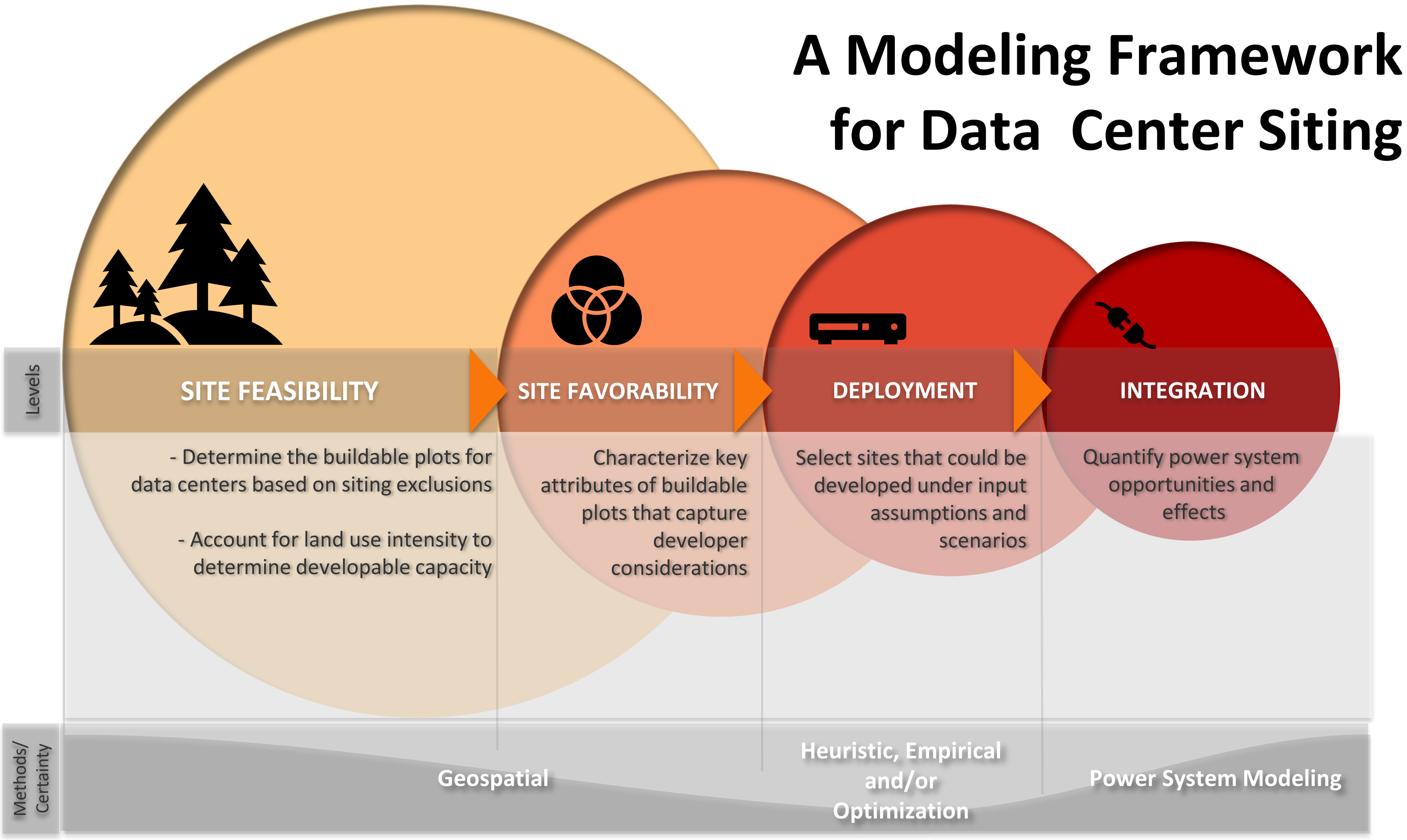
Planning for when and where large loads interconnect to the bulk power system

We Know Where Data Centers Are Today and in the Near Future

Can we say something about where they might go? Try with geospatial tool

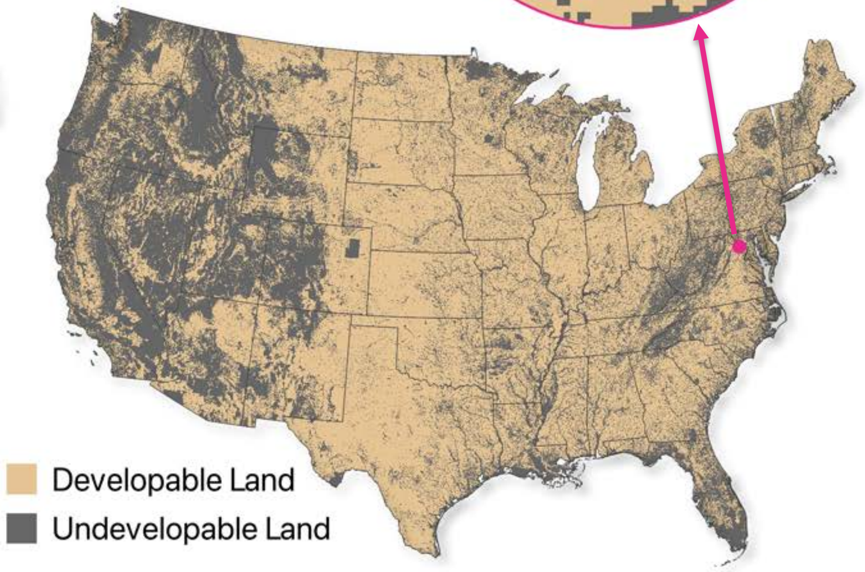


Source: U.S. Data Center Sites. Baxtel, 2025. https://baxtel.com. Accessed June 16th, 2025.

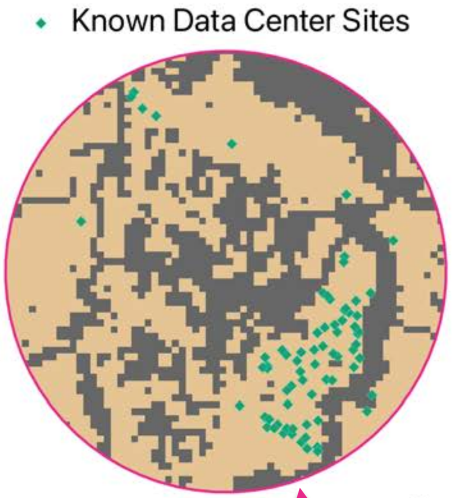

A Modeling Framework
for Data Center Siting
Levels
SITE FEASIBILITY
SITE FAVORABILITY
DEPLOYMENT
INTEGRATION
- Determine the buildable plots for data centers based on siting exclusions
- Account for land use intensity to determine developable capacity
Characterize key attributes of buildable plots that capture developer considerations
Select sites that could be developed under input assumptions and scenarios
Quantify power system opportunities and effects
Methods/ Certainty
Geospatial
Heuristic, Empirical and/or Optimization
Power System Modeling

Technical Potential: What sites are feasible?

Method: Apply Geospatial Siting Exclusion Layers



Result: Map of Land Feasible for Data Centers



Data Center Siting Feasibility Layers

Category	Exclusion
Airspace/Defense	Airport footprints
Airspace/Defense	Intercontinental ballistic missile silo setback (3.7- km)
Airspace/Defense	U.S. Department of Defense Clear Zones and Accident Potential Zones
Airspace/Defense	Airports and runways
Environmental	Bureau of Land Management (BLM) Oil and Gas or Geothermal No Surface Occupancy areas
Environmental	U.S. Fish and Wildlife Service (USFWS) administered lands
Environmental	Karst depressions
Environmental	U.S. Forest Service (USFS) GAP Status 3 and 4 (excluding National Forests)
Environmental	USFS active grazing allotments
Environmental	Mature and Old Growth Forests (USFS and BLM lands only)
Environmental	USFS modeled Recreational Opportunity Spectrum excluded categories
Environmental	BLM Resource Management Plan Amendment/Draft Environmental Impact Statement Sage Grouse Priority Habitat Management Area Avoidance Areas—alternative 5 (BLM lands only)
Environmental	Federal Emergency Management Agency 100-year floodplains
Environmental	USFWS Regulatory In- lieu Fee and Bank Information Tracking System Mitigation Banks and In- lieu Fee Program lands
Environmental	National Land Cover Dataset Water, Woody/Herbaceous Wetlands

Category	Exclusion	
Environmental	Threatened and Endangered Species core habitat (U.S. Geological Survey subset BLM lands only)	
Environmental	USFWS Service National Wetlands Inventory	
Environmental	American Farm Trust conservation lands	
Environmental	BLM Areas of Critical Environmental Concern	
Environmental	National Forest Service Inventoried Roadless Areas	
Environmental	National Conservation Easement Database (Gap Analysis Project [GAP] Status 1, 2)	
Environmental	Protected Areas Database (GAP Status 1, 2)	
Environmental	Nationally Significant Agricultural Lands (10% available)	
Environmental	Simulated Conservation Reserve Program lands	
Environmental	Big game migration corridors	
Infrastructure	Oil and gas well footprints	
Infrastructure	Railroads	
Infrastructure	Roads	
Infrastructure	Building structures	
Infrastructure	Transmission right-of-way	
Infrastructure	Oil and gas pipeline right-of-way	
Infrastructure	368 designated (2009) transmission corridors	
Infrastructure	Existing solar photovoltaic (PV) facilities	
Infrastructure	Existing wind turbine pads (45.7 m) setback	
Infrastructure	Geothermal plant locations	
Terrain	Elevation (>9,000 ft) and mountainous landforms	
Terrain	Slope exclusion(s)	**Exact thresholds and zoning restrictions not yet determined**
Other	Minimum Parcel Size	
Other	Contiguous area filter	
Regulatory	Zoning	

Siting Exclusion Criteria* for Data Centers

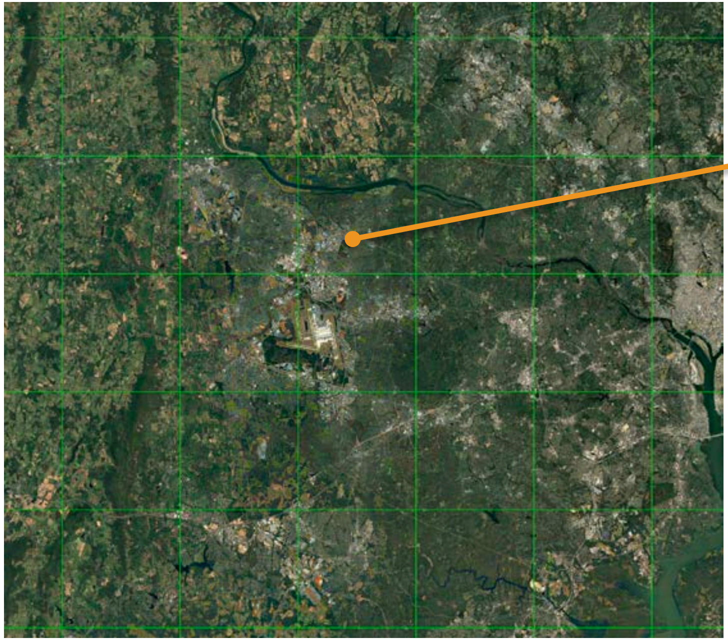
Data is all available and pre-processed for application to data centers based on modeling of other technologies

*Preliminary Exclusion criteria based on Renewable Energy Technical Potential and Supply Curves for the Contiguous United States: 2024 Edition

Economic Potential: Criteria for Which Sites Are Favorable

Method:

Measure and compile local and regional site favorability characteristics



Favorability Characteristic	Measure
Developable Capacity	Z MW
Distance to Long-Haul Fiber	X km
Number of Nearby Long-Haul Fibers	N fibers
Distance to IXP/Peering Point	Y km
Number of Nearby Networks	M networks
Distance to Substation	Z km
Distance to Transmission Line	W km
Within Natural Gas Service Territory	True
Distance to Demand Center	V km
Regional Capital Cost Multiplier	1.X
...	...

Result:

Spatially gridded dataset for United States with favorability characteristics for each grid cell

Favorability Criteria in Approximate Order-of-importance for Inclusion

Market and Demand

- Proximity to existing data center market
- Proximity to population density

Power Infrastructure

- Proximity to high voltage transmission
- Proximity to unused generation capacity

Digital Infrastructure

- Proximity to existing long-haul fiber network

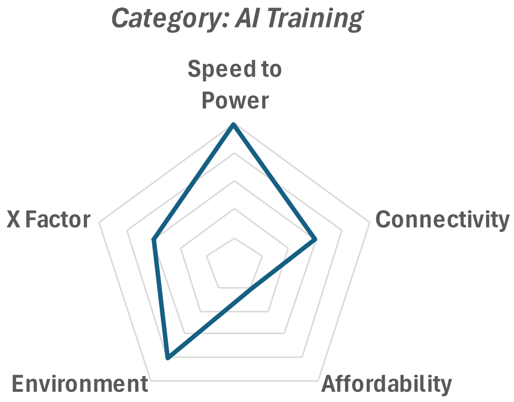
Regional Land and Labor Costs

Environment (e.g., natural hazard risks, cooling)

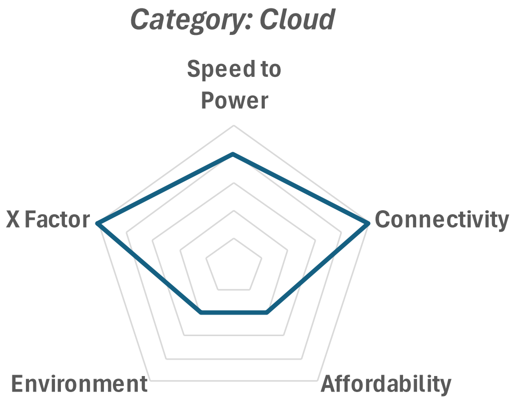
Key question: How might favorability vary by category of data center or large load?

Market Potential: Development of Large Load Capacity in Different Favorability Scenarios

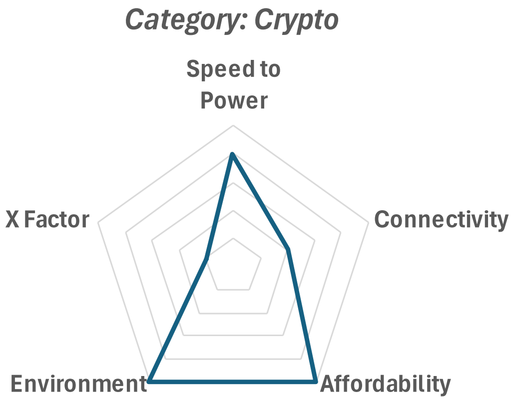
Preliminary approach: Select sites for deployment based on weighted-criteria model



Emphasize Power Scenario



Emphasize Markets Scenario



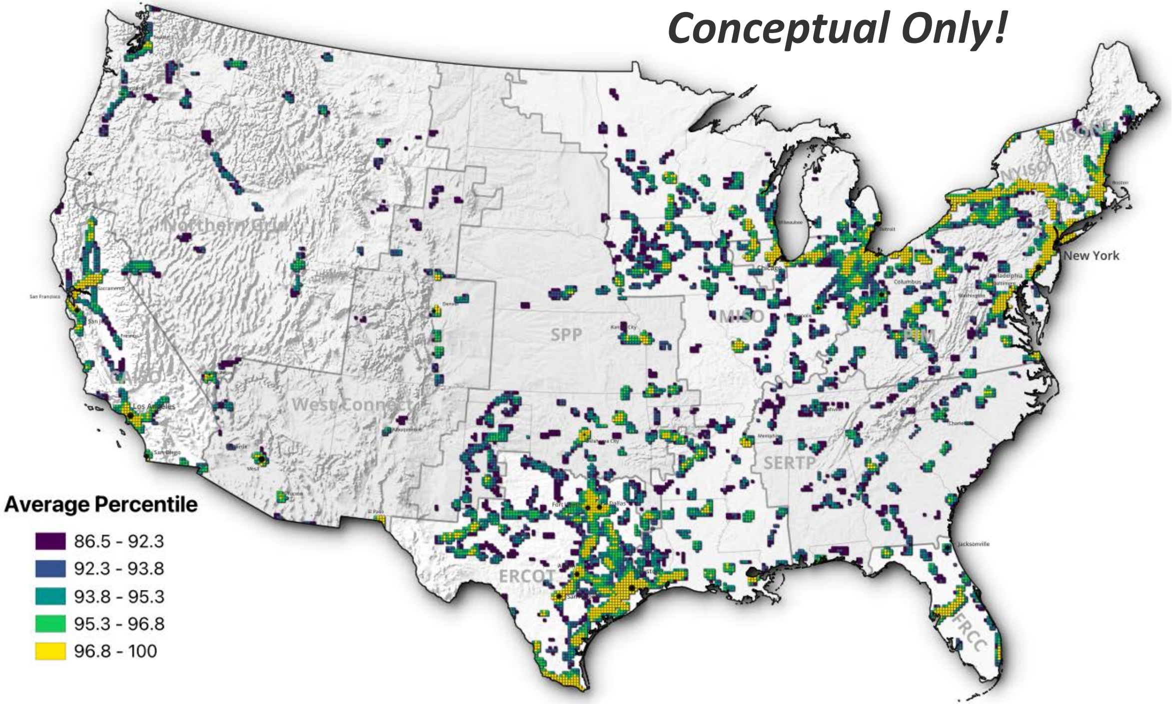
Note: Weightings shown are meant to be *conceptual only* to illustrate possible differences in criteria used for different use cases

More advanced methods possible, as well:

- Machine learning model trained on existing data center locations
- Optimization (e.g., capacity expansion)
- Spatial diffusion

Based on Favorability, Can Vision Where Data Centers Might Be Sited

Conceptual Prototype of Weighted Site-Selection:
Prioritize long-haul fiber connectivity, access to natural gas and existing electric generation



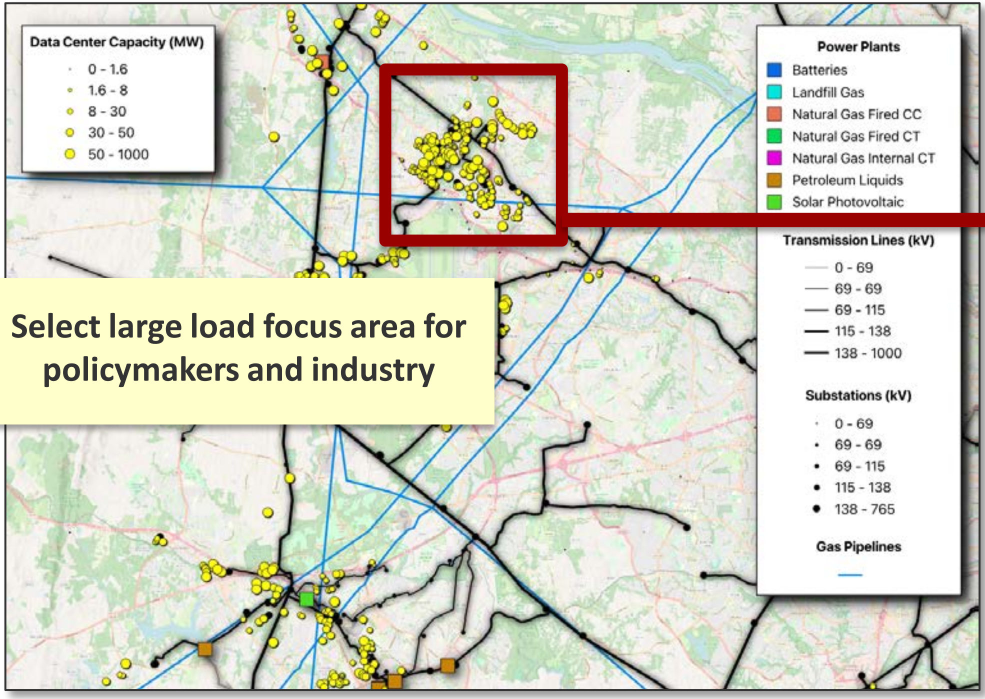
Percentiles Assigned to:

- Count of nearby electric generators (20 km radius)
- Count of nearby long-haul fiber nodes (20 km radius)
- Length of nearby long-haul fiber lines (10 km radius)
- Length of nearby natural gas pipelines (10km radius)

→ Sites filtered for cells in over 80th percentile in each category

Long-term Vision Enables Site-specific Analysis to Aid Policymakers

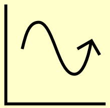
Pictured: Northern Virginia, the current global data center capacity hub



Select large load focus area for policymakers and industry

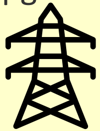
Question Answered: Considering siting constraints, what are the best near-term options?

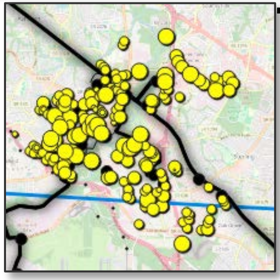
Demand Flexibility

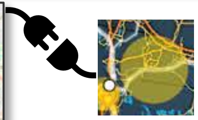


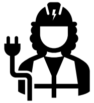
Electricity Storage

Transmission Upgrades









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Data Center Capacity (MW)

- 0 - 1.6
- 1.6 - 8
- 8 - 30
- 30 - 50
- 50 - 1000

Grid Impacts

Recent Publications Highlight Various Grid Impacts of Near-term Large Load Growth

1. **Resource adequacy**: Sufficient generation for new large load?
2. **Generation portfolio**: Which resources serve new demand?
3. **Flexibility**: What is the value of price-responsive demand?
4. **Uncertainty**: If large load growth does not materialize, what is the impact on existing customers?

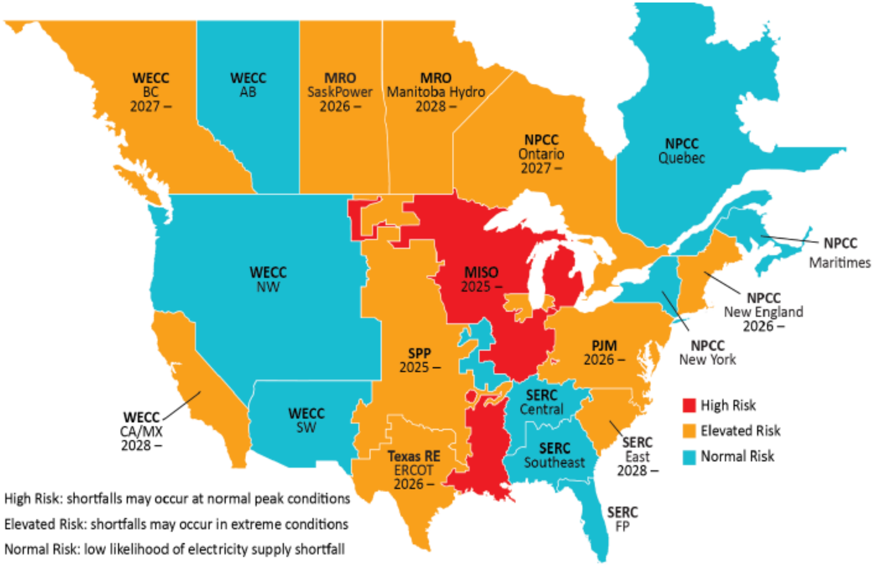


Figure 1: Risk Area Summary 2025–2029

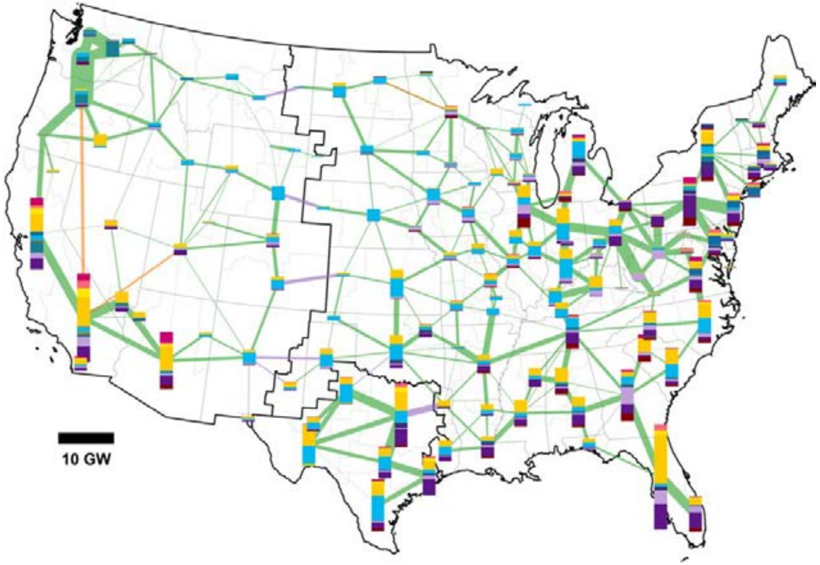
North American Electric Reliability Corporation (NERC) Long-Term Reliability Assessment

- Elevated or high risk in many regions
- Winter fuel supply is a major challenge
- Capacity reserves is a challenge in some regions

Source: NERC Long-Term Reliability Assessment (link)

What Might Get Built in Response? Use Capacity Expansion

NREL's flagship power system capacity expansion model simulates the evolution of the bulk power system—generation, storage, and transmission—from present day through 2050 or beyond.



NREL's ReEDS model is open source! https://www.nrel.gov/analysis/reeds/

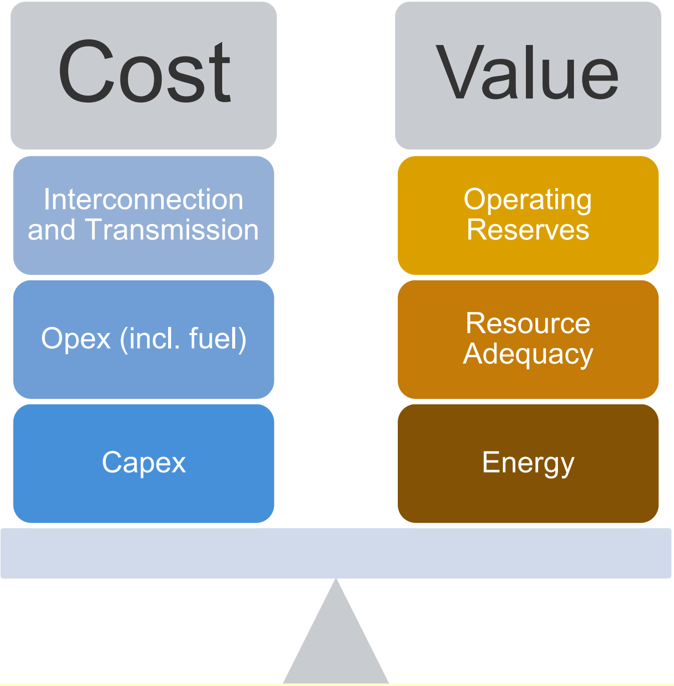
Some questions the Regional Energy Deployment System (ReEDS) can answer:

- What are the least-cost investment and operation strategies for the grid?
- What mix of technologies ensure a reliable grid for decades to come?
- What impact does R&D investment have on the market potential of advanced grid technologies?

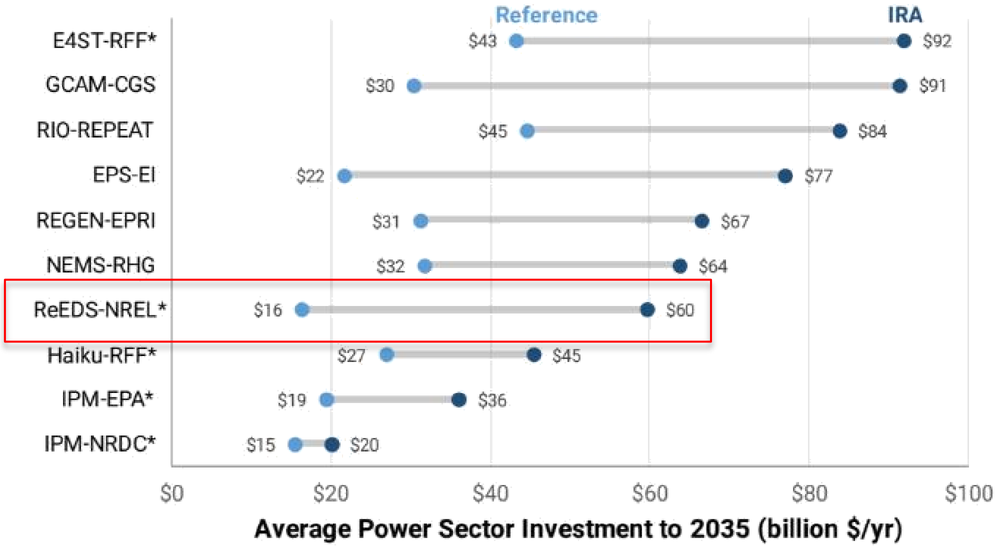
Outputs:

- System cost, electricity price, retail rates
- Generation and storage capacity additions and retirements by location in each solve year
- Transmission capacity additions
- Energy generation, firm capacity, and operating reserves by technology

ReEDS Considers Range of Generation and Transmission Options, Like Other Leading Expansion Models



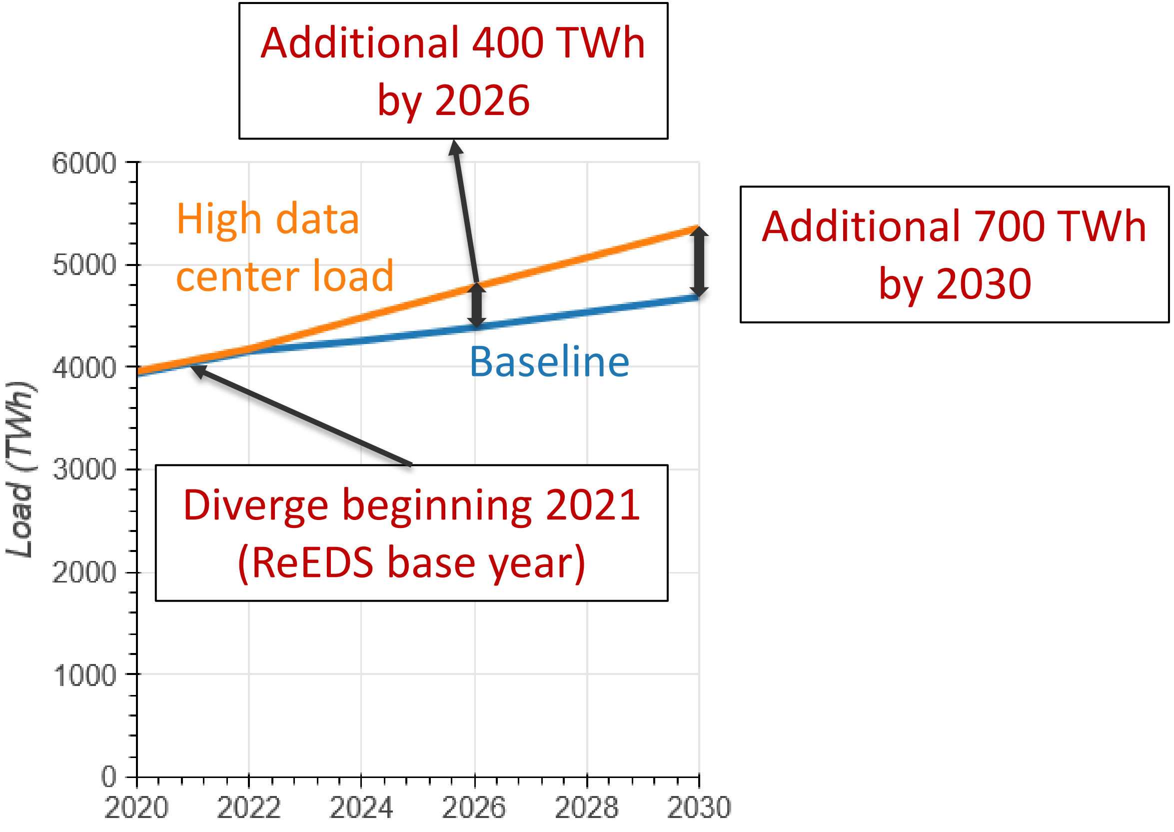
Levelized cost of electricity is an output rather than an input in the cost/value framework.



Power sector investment from ReEDS is consistent with other leading models.

Bistline, John, and Asa Watten. 2025. “Inframarginal Investments with Clean Energy Subsidies: Evidence from the Inflation Reduction Act.” Presented at American Economic Association Annual Meeting, San Francisco.

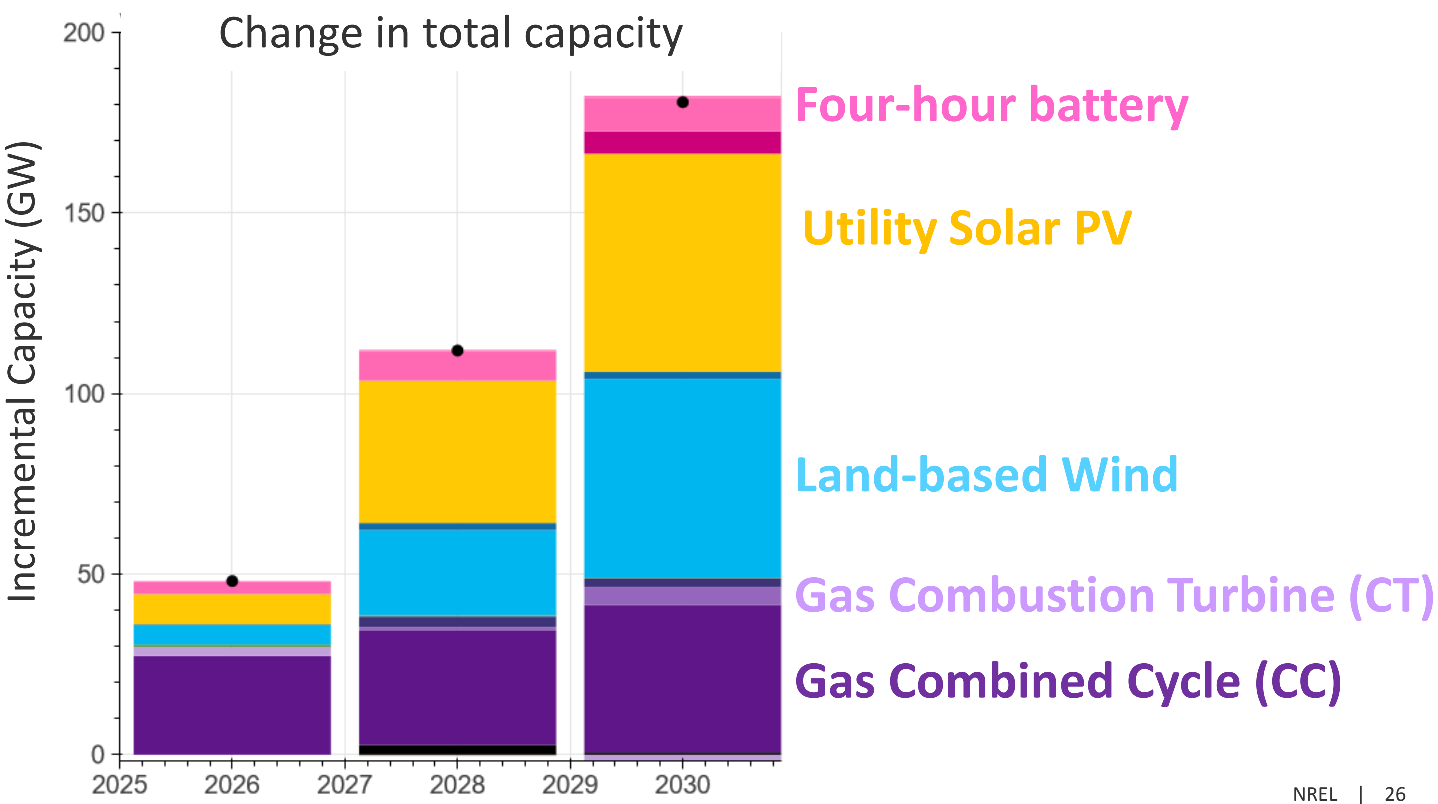
Compare Baseline and “High Data Center” Scenarios Through 2030



*High data center based on S&P Global

New Capacity Needed to Serve Additional (Peak) Demand

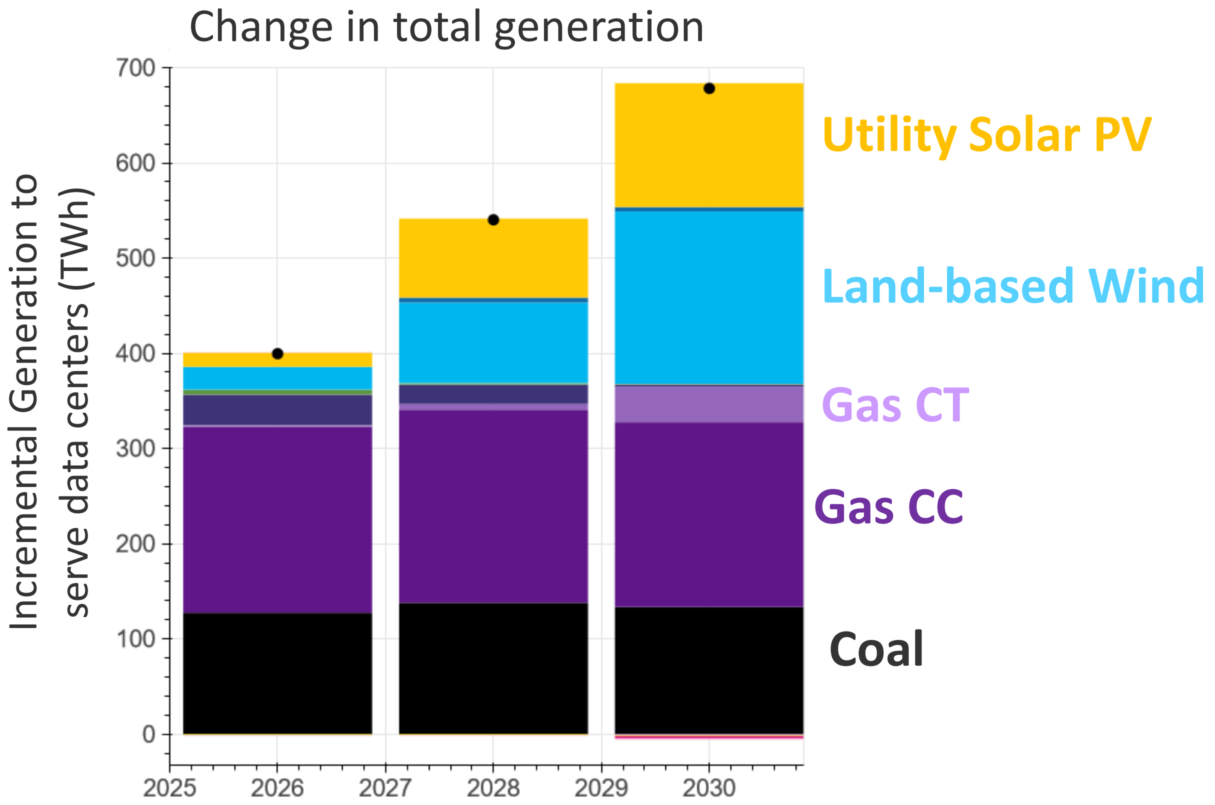
Capacity change from high data centers compared to baseline through 2030



*Baseline assumptions reflect 2024 Standard Scenarios and include then-current policy

Additional Generation Comes From Both Existing and New Build Resources

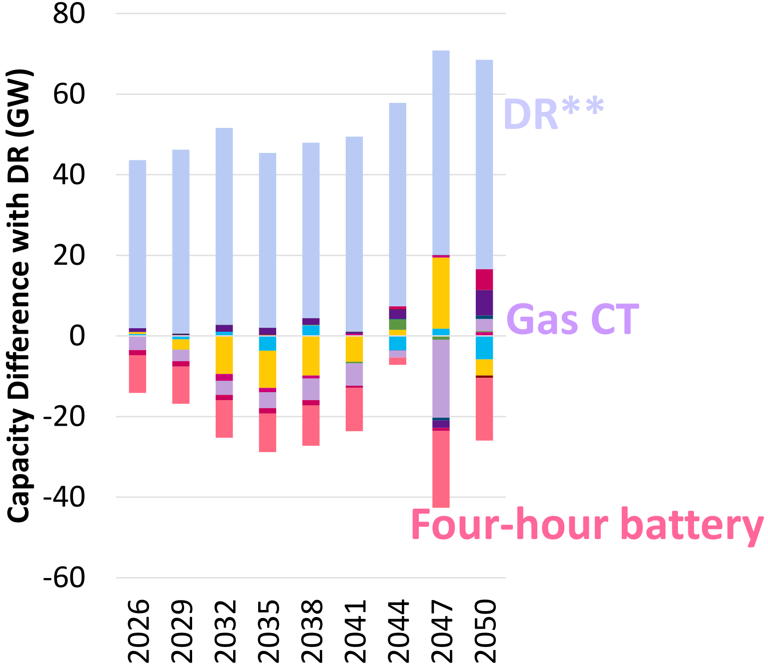
Generation change from high data centers compared to baseline through 2030



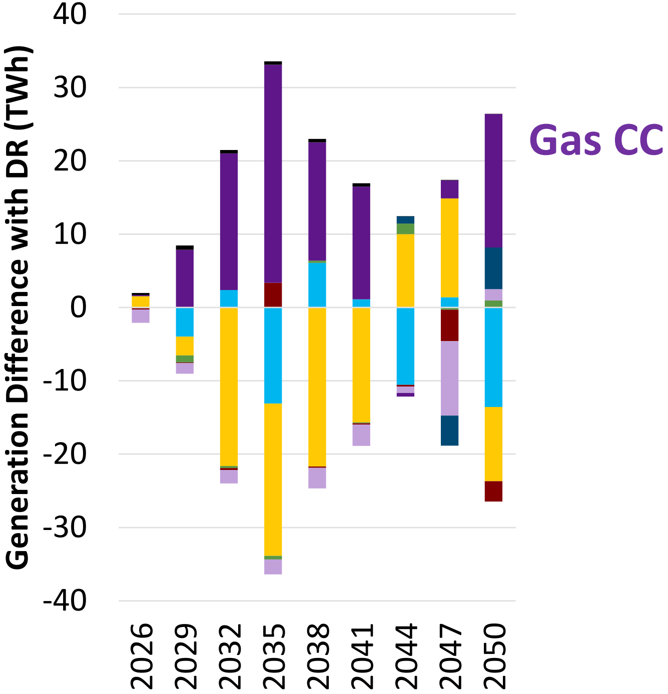
*Baseline assumptions reflect 2024 Standard Scenarios and include then-current policy

Representing Demand Response (DR) Potential Can Value Flexibility in Power System Planning

DR reduces the need for new capacity; especially peaking resources like gas combustion turbines and batteries**



Increased generation for existing gas resources

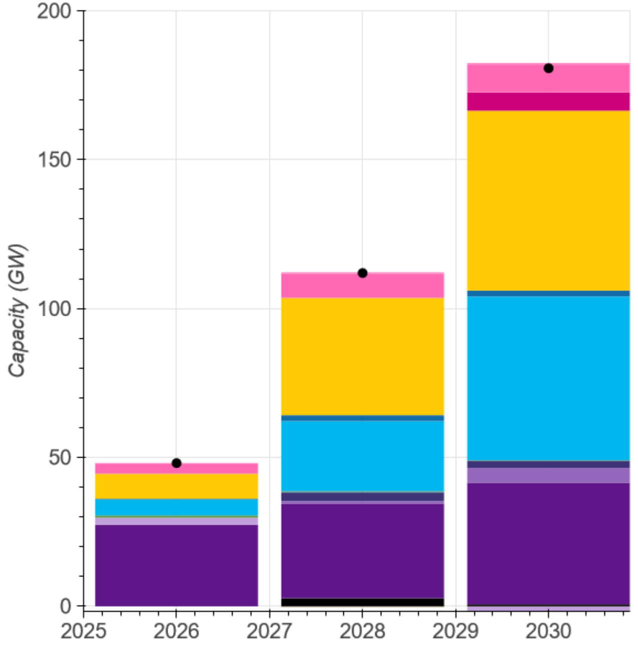


*Results are **illustrative only** and **not** specific to data centers/large loads*

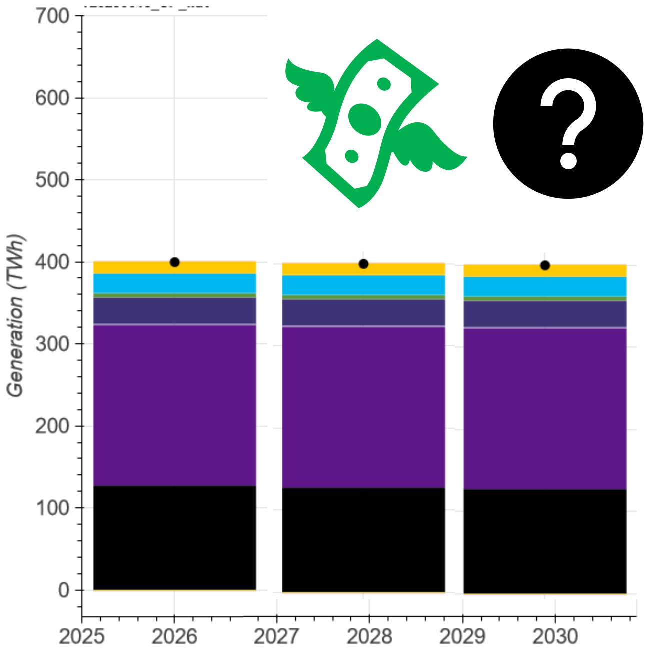
****DR is a "shed" resource; ability to curtail demand during specified high grid value times**

Build a System for Load That Does Not Materialize to Quantify Uncertainty Costs

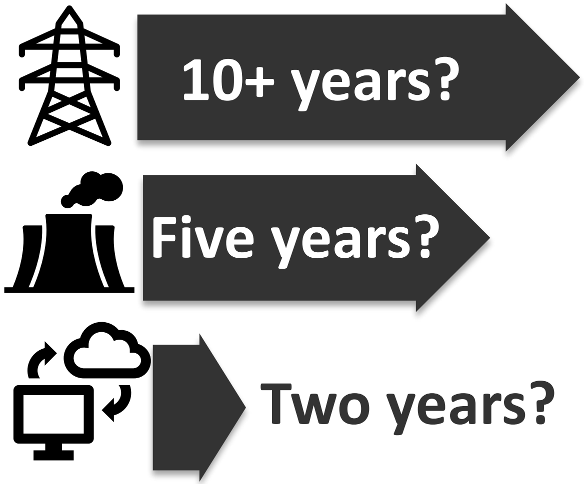
Build for expected growth…



…but what if it did not materialize?



At least plausible if load timelines << generation and transmission



*Results are **illustrative only***

… mitigation options that better align timelines or hedge existing utility customers?

Near-term Mitigation Options

The "HAM" mitigation options: **Hedge**, **Align**, **Match**

	HEDGE	ALIGN	MATCH
	Tariffs	Streamlining Interconnection	Colocation
Key Impact	Ensure large loads pay incremental costs	Align timelines for supply in-line with those for large loads	New large loads bring own matching supply
How?	Structure tariffs to encourage demand flexibility or other investments	Fast-track solutions to more efficiently use the grid and bring on new supply	Large loads physically locate and financially contract with proximate generation
Examples	Demand flexibility, storage, rates, onsite energy, other tariff provisions	Grid-enhancing technologies, expedited/provisional interconnection processes	Front-of-meter and back-of-meter colocation arrangements

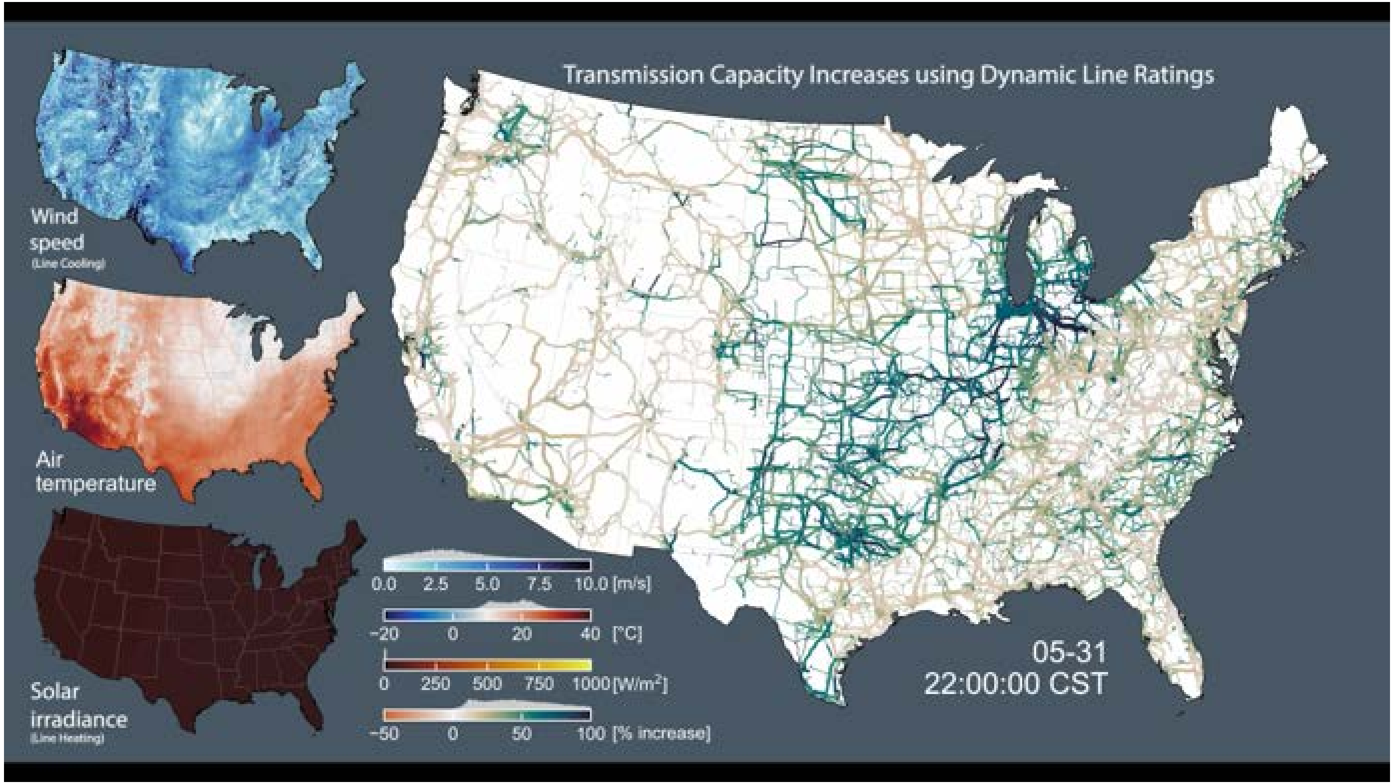
Toward Characterizing Mitigation Options Across Different Dimensions

- **Takeaways**
  - **Ongoing interviews to ascertain stakeholder perspectives are crucial** for understanding gaps/barriers and opportunities for labs' work on mitigation options.
  - **Mitigation options vary** by cost, financing options, risks, permitting, speed to implement
  - **A key lab role is to fill gaps on lack transparent data**

- **Next step is to characterize a wider range of mitigation options** in a comparison framework (example below)

Mitigation Option	Mechanism/theory of change	Speed	Cost	Data gaps	Proposed quantification?
Advanced conductors + other grid-enhancing technologies	Rapidly increase system capacity to enable faster generation- and load-side interconnection	Fast	Medium	Cost data, database of projects considering or using these technologies	Yes

National Opportunities for Dynamic Line Ratings: Do These Affect Opportunities for Large Load Headroom?



Source: NREL, Hourly Dynamic Line Ratings for Existing Transmission Across the Contiguous United States (Preliminary Results)

Additional Barriers to Rapid Large Load Growth

Forward-looking planned work

Conduct Resource Adequacy Assessment Across Large Load Scenarios

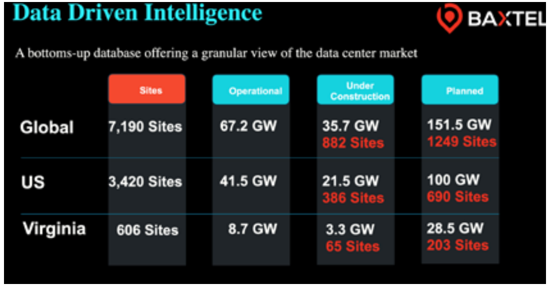
1. Take existing industry resource adequacy assessment model(s)

PLEXOS BY ENERGY EXEMPLAR

2. Update large load assumptions, flexible analysis using transparent, open-source NREL tools

Sienna

PRAS


Data Driven Intelligence

BAXTEL

A bottoms-up database offering a granular view of the data center market

	Sites	Operational	Under Construction	Planned
Global	7,190 Sites	67.2 GW	35.7 GW 882 Sites	151.5 GW 1249 Sites
US	3,420 Sites	41.5 GW	21.5 GW 386 Sites	100 GW 690 Sites
Virginia	606 Sites	8.7 GW	3.3 GW 65 Sites	28.5 GW 203 Sites

3. Directional results on set of resource adequacy futures

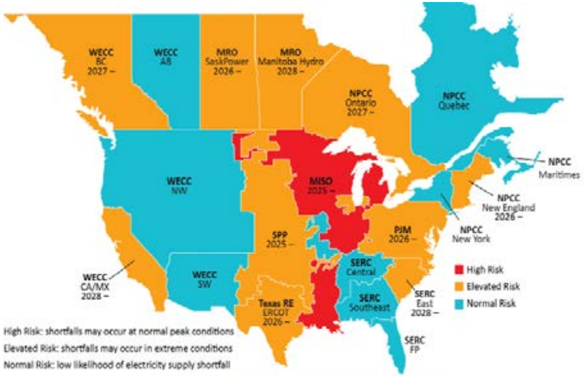
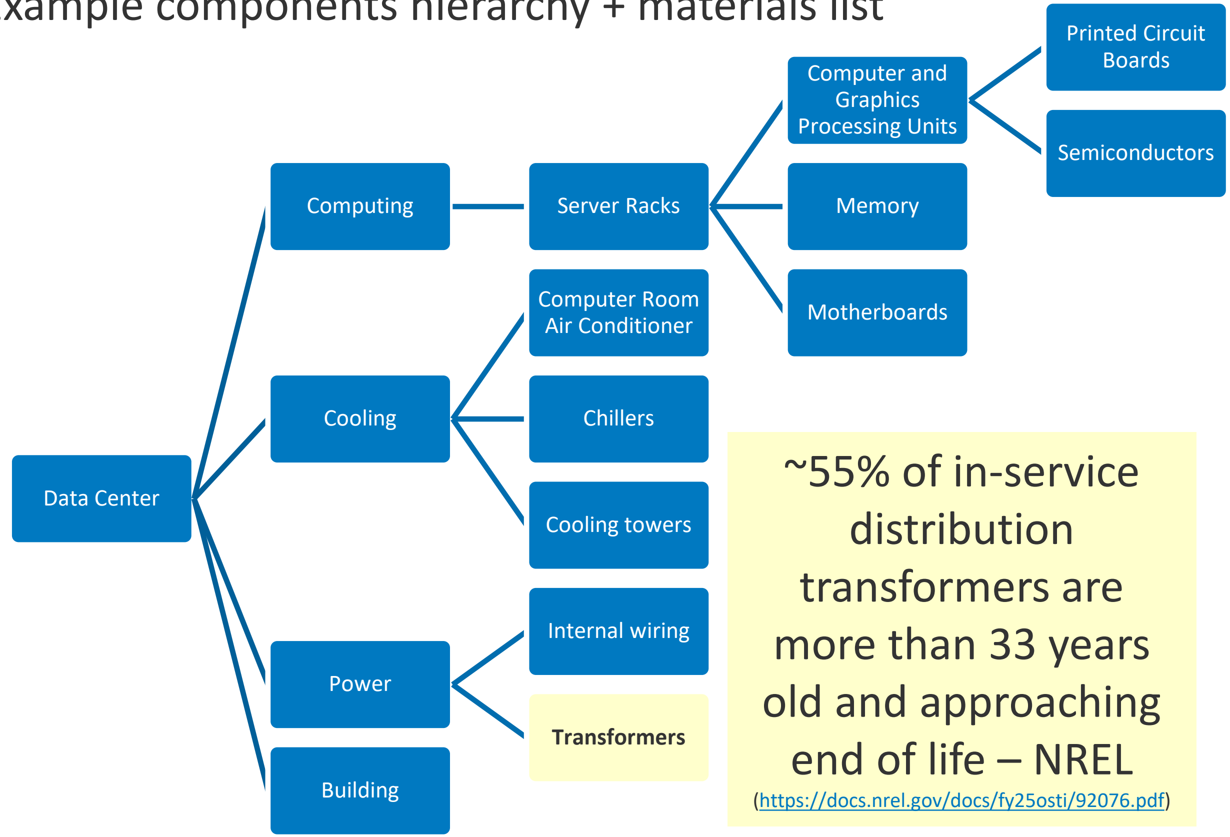


Figure 1: Risk Area Summary 2025–2029

Categorizing Key Supply Chain Barriers to Rapid Large Load Growth

Example components hierarchy + materials list



~55% of in-service distribution transformers are more than 33 years old and approaching end of life – NREL

(https://docs.nrel.gov/docs/fy25osti/92076.pdf)

Graphics Processing Unit (GPU) materials challenges

Printed Circuit Boards:

Bismuth
Copper
Gold
Tantalum
Tin

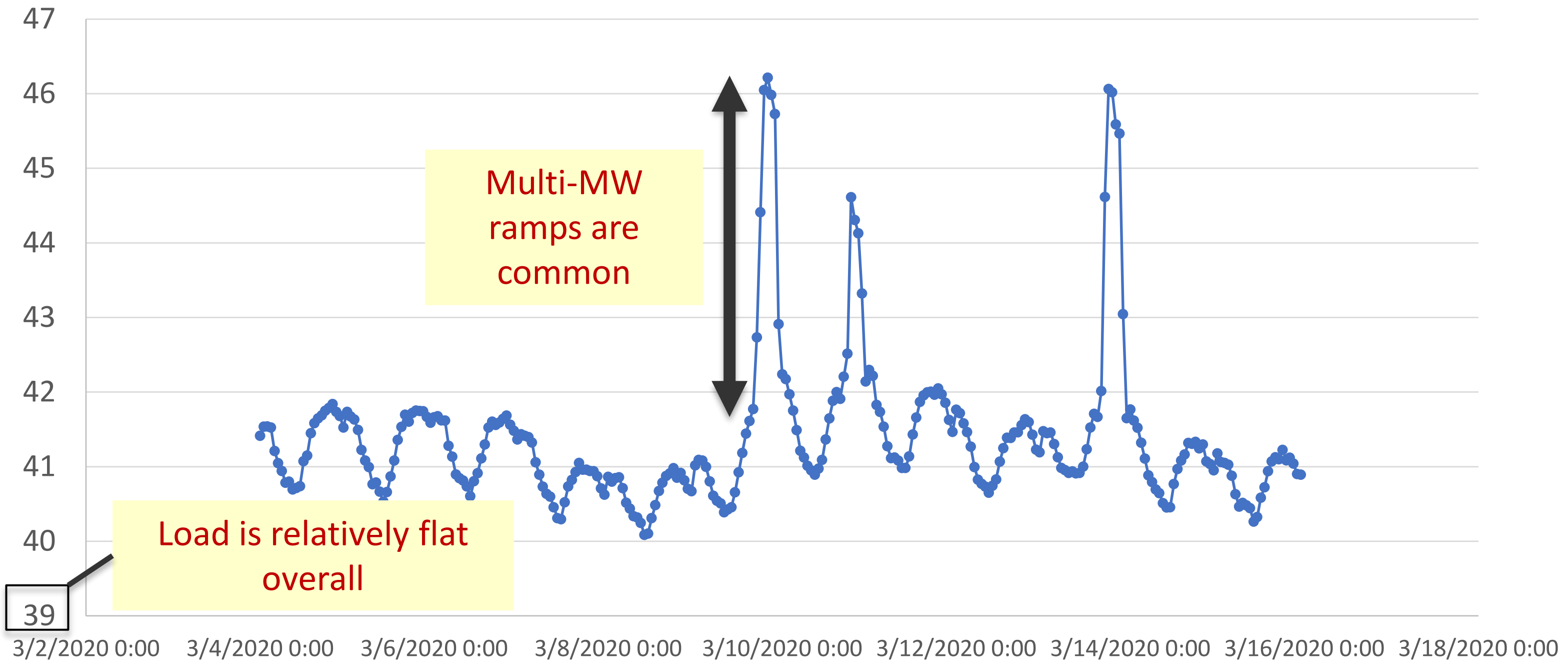
Semiconductors:

Antimony
Arsenic
Beryllium
Cobalt
Gallium
Germanium
Hafnium
Indium phosphide
Nickel
Platinum
Silicon
Tungsten
Dopants – Boron, phosphorous, arsenic, europium, yttrium, cerium

Use in advanced chips and may have globally restrictive supply chains

Operational Standard for Large Loads Evolving

Deidentified load data from large data center in western United States…



… however, data is scarce overall, and modeling standards are developing. NERC and others proposing standards applicable to large loads comprised of power electronics

Toward a Framework for Efficient Large Load Grid Planning

Where we are going with forward-looking planned work

Next Steps Affected by Questions Key Stakeholders Ask Us to Answer

Challenge: Where can a capacity-strained grid quickly and flexibly add tens-to-hundreds of gigawatts of new load?

National Scale Resource: Siting feasibility layers identify favorable locations for detailed analysis on clustering multiple large loads for near-term grid integration

Outcome: Open-access siting tools and metrics identify where and how large load clusters can be enabled by policymakers

? **Grid operators**: Maintain reliability

\+ **Utility customers**: Affordable and reliable service

\+ **Industry**: Efficient and fair grid connection

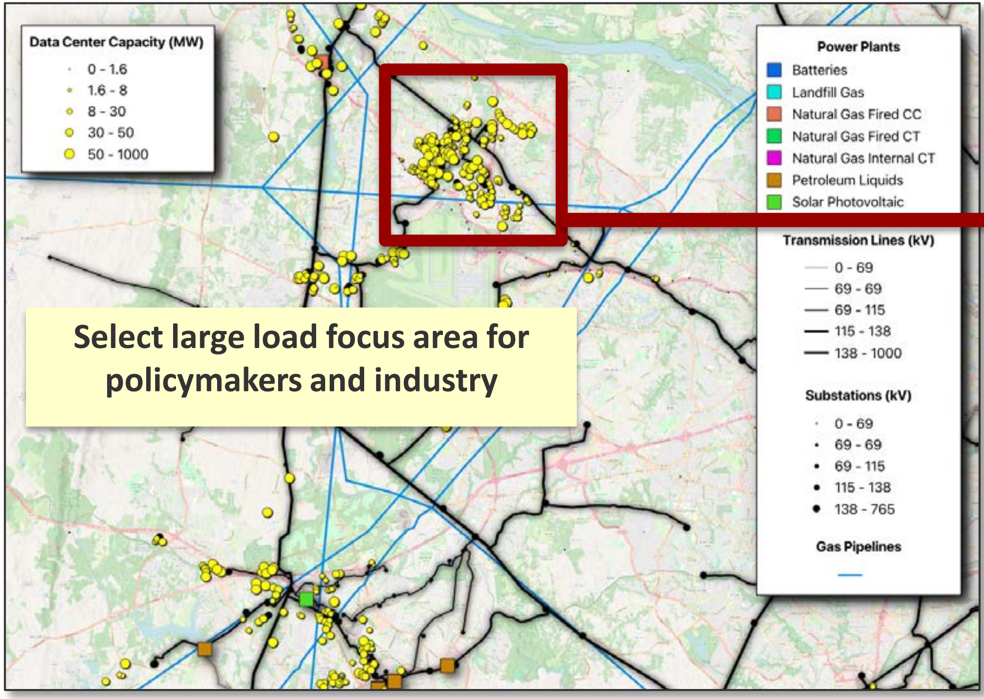
? **States and regulators**: Economic development

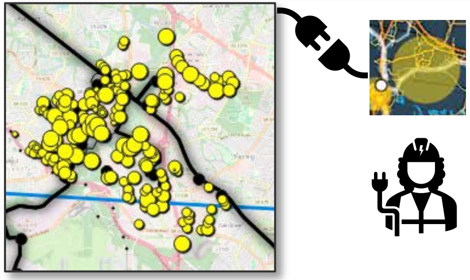
Lab impact: Supporting transformational large load and data center growth with objective decision support resources for all stakeholders

Long-term Vision Enables Site-specific Analysis to Aid Policymakers

Question Answered: Considering siting constraints, what are best near-term options?

Demand Flexibility	Electricity Storage	Transmission Upgrades





Sienna

Pictured: Northern Virginia is the current global data center capacity hub

Thank you!

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NREL/PR-6A40-95736

This work was authored by NREL for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding for the technical work provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Grid Deployment Office. Funding for the webinar preparation provided by the U.S. Department of Energy Office of Policy. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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