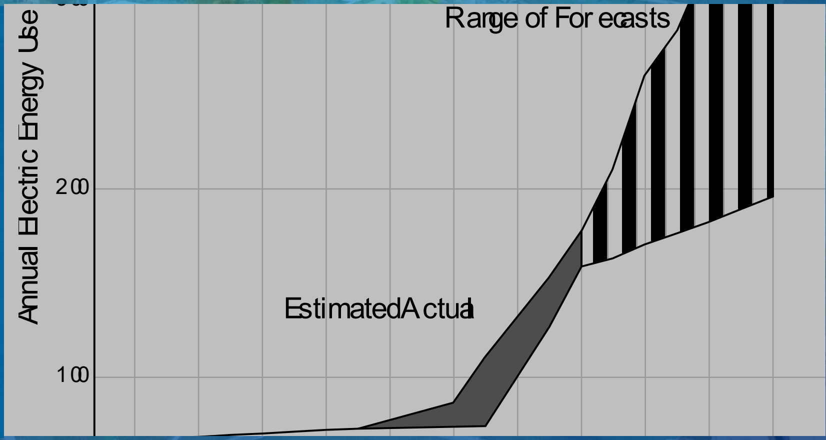
NOVEMBER 19, 2025

LOAD FORECASTING FOR TRANSMISSION PLANNING: MODELING DATA CENTERS

NARUC TRANSMISSION STATE WORKING GROUP



Source: ANL

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This work has been supported by DOE-Grid Deployment Office.

OBJECTIVES

- Brief overview of the role of load forecasting in various transmission planning processes.
- Outline of basic details relevant to modeling data center electricity consumption.
- A technical background in power system planning is not required or assumed.
- This presentation is 30 minutes, followed by 10 minutes for Q&A.

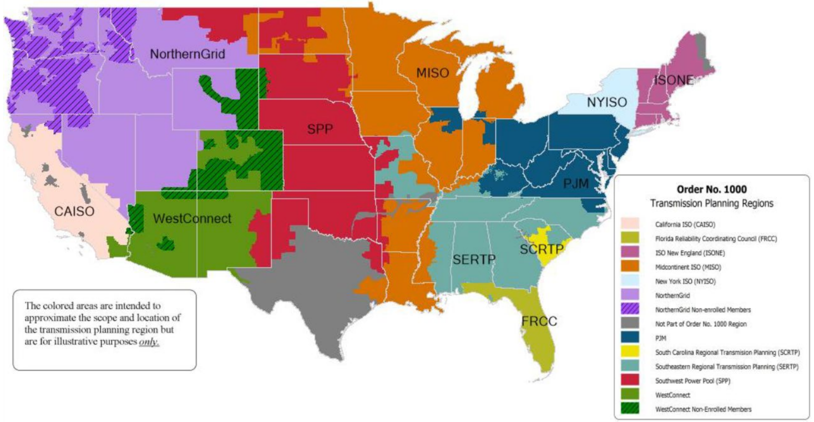
OUTLINE

- The Role of Load Forecasts in Transmission Planning
  - Transmission Planning Context
  - Major Trends and Needs in Load Forecasting
- Forecasting Data Center Demand: Macro Perspective
- Zooming in: Basics of Modeling Data Center Demand
- Conclusion: Big Ideas and Questions States Can Ask

THE ROLE OF LOAD FORECASTS IN TRANSMISSION PLANNING

LOCAL AND REGIONAL TRANSMISSION PLANNING

- FERC Order 1000 identifies planning regions; each transmission owner in a region must participate in the regional process and interregional coordination (Led by ISO/RTO or regional planning group)
- Transmission owners (whether in ISO/RTO region or not) conduct local planning apart from Order 1000 regional planning
- Short-term (Regional and local): 1-5 years
- Mid-long-term (Order 1000 and local): 5-15 years
- Long-term (Order 1920 and local): 20 years



Reference map of regions in FERC Order 1000.
https://www.ferc.gov/media/regions-map-printable-version-order-no-1000

THE TRANSMISSION PLANNING PROCESS

Transmission planning brings the best-available information about the future state of the system into detailed technical analyses to identify a set of upgrades that meet reliability, economics, and public policy needs with least regrets.

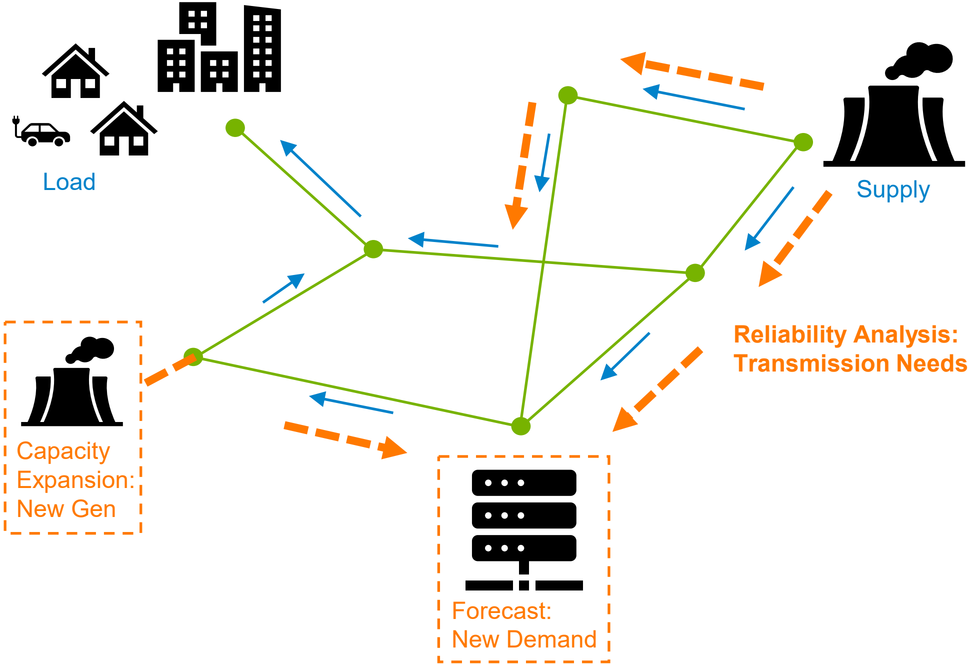
Construct Representative Futures
Translate Futures to Specific Models
Scenario Development

Perform Reliability Analyses
Perform Economic Analyses
Determine Needs
Needs Identification

Identify and Evaluate Potential Solutions
Solution Evaluation

LOAD FORECASTS INFLUENCE OUTCOMES

Demand drives generation expansion model outcomes, which drive identified transmission needs.

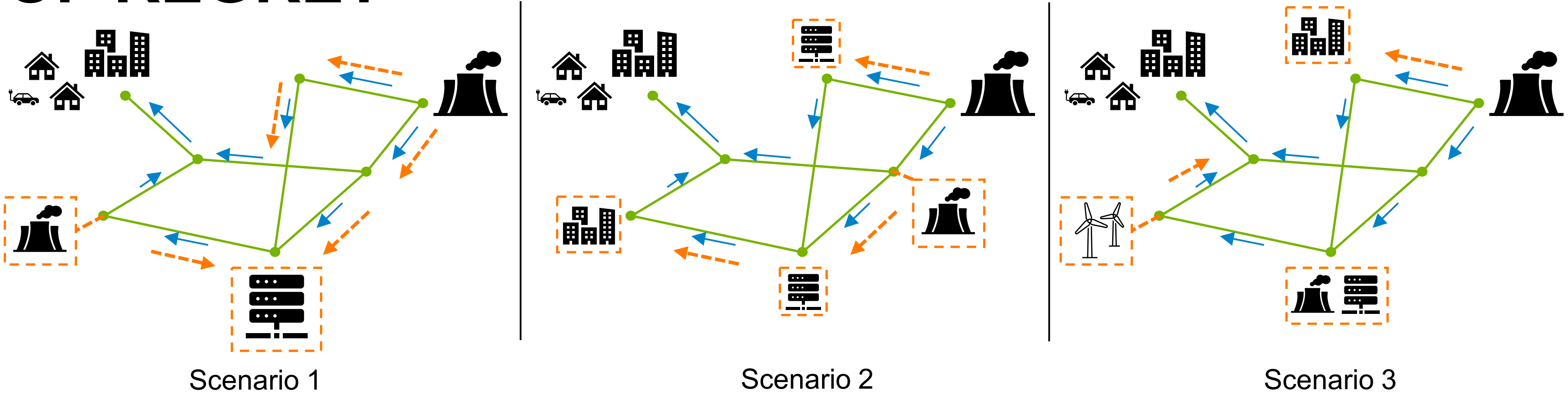


What if the actual demand growth differs from the forecast?

- Location
- Size
- Use of onsite generation

Actual generation additions will differ from the capacity expansion results, and transmission needs can be **over-** and **under-estimated**.

PLANNING WITH SCENARIOS CAN REDUCE RISK OF REGRET



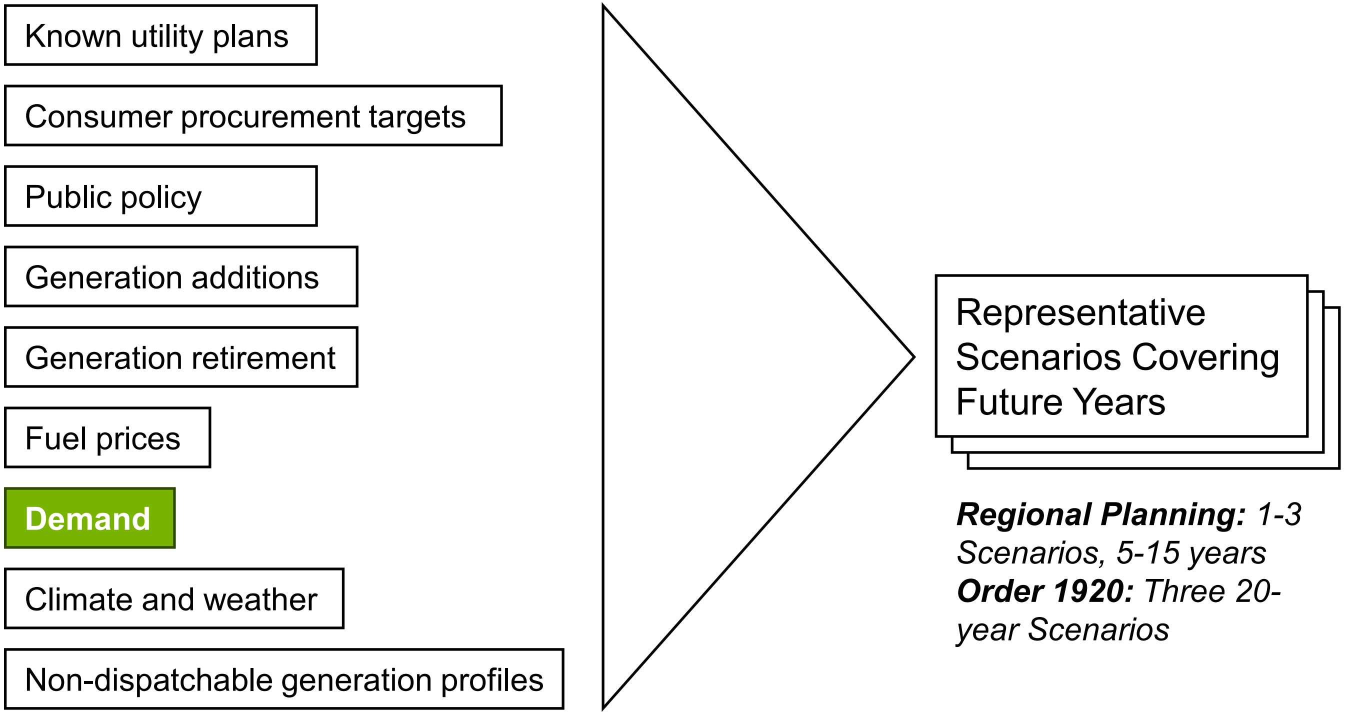
- Using multiple **representative scenarios** allows planners to identify how transmission needs differ or persist across plausible futures, mitigating the risk of over- and under-building.
  - — Varying load forecasts are one component of scenario-based planning.
  - — Many other components are also important (next slide).
- **Sensitivities** are another commonly-used tool in specific model runs: uncertain components of a forecast are varied across model runs, e.g. 50/50 and 90/10 weather, peak and light-load conditions.

CONSTRUCTING REPRESENTATIVE FUTURES

Estimates and Best-Available Information

&

Uncertain Variables



- Known utility plans
- Consumer procurement targets
- Public policy
- Generation additions
- Generation retirement
- Fuel prices
- **Demand**
- Climate and weather
- Non-dispatchable generation profiles

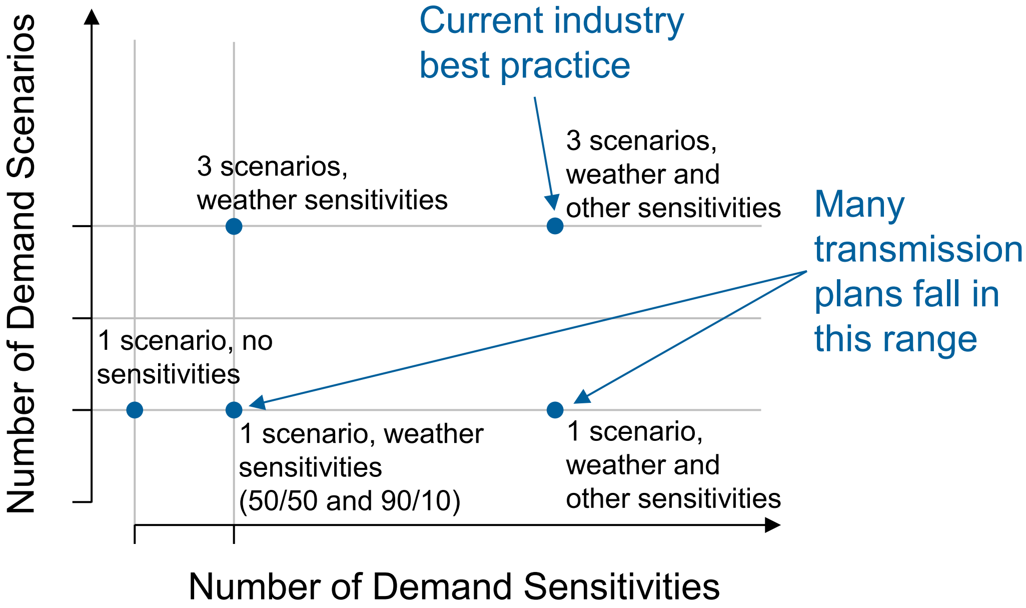
Representative Scenarios Covering Future Years

Regional Planning: *1-3 Scenarios, 5-15 years*
Order 1920: *Three 20-year Scenarios*

More representative inputs create better scenarios, resulting in more accurate identification of needs and more appropriate solutions.

SCENARIOS AND SENSITIVITIES IN PRACTICE

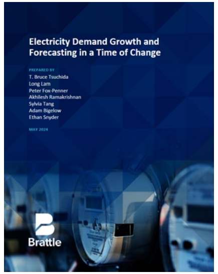
- Many regional transmission planning entities use a single demand scenario with several sensitivities, but some use multiple based on differing input assumptions, e.g. MISO Futures and SPP Future Load Scenarios.
- FERC 1000:
  - No specific scenario requirements.
- FERC 1920:
  - Requires three planning scenarios and sensitivities for weather and/or extreme conditions.
  - Doesn't specify the number of demand scenarios: a single demand scenario may be used for all three planning scenarios.
- FERC 896 and NERC TPL-008:
  - Extreme heat and cold benchmark cases must be created and used in planning (more comprehensive inclusion of weather).



Source: ANL

TRENDS AND NEEDS IN LOAD FORECASTING

Excellent Reference:
The Brattle Group,
Electricity Demand Growth and Forecasting in a Time of Change, May 2024


Electricity Demand Growth and Forecasting in a Time of Change

PREPARED BY
T. Bruce Tsuchida
Long Lam
Peter Fox-Penner
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Sylvia Tang
Adam Bigelow
Ethan Snyder

MAY 2024

Brattle

In addition to these drivers, more precise and accurate incorporation of climate and weather impacts to demand is a significant need. (Topic for another day)

This report divides demand drivers into three categories:

Demand Side Resources	**Major aggregate offset**	Included (in varying degrees) in nearly all utility/RTO forecasts
Transportation Electrification Building Electrification	**Numerous small loads: continuous growth**	Included in many utility/RTO forecasts
Data Centers Onshoring & Industrial Electrification Cryptocurrency Mining	**Large and discrete loads, high uncertainty**	Included in few utility/RTO forecasts as of 2024, but numbers are increasing in 2025.

FORECASTING DATA CENTER DEMAND: MACRO PERSPECTIVE

FORECASTING DATA CENTER DEMAND

For a well-researched introduction to large load forecasting considerations and approaches, tailored to a state regulator perspective, see Greg Mandelman’s June 2025 presentation to the *NARUC/NASEO Comprehensive Electricity Planning Initiative for Load Growth Learning Series.*

- Includes excellent references
- Outlines questions states can ask and actions states can take

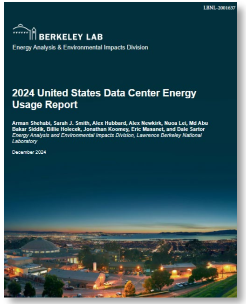
NARUC/NASEO Comprehensive Electricity Planning Initiative for Load Growth Learning Series

Load Forecasting for Large Loads
From the perspective of planning across bulk power and distribution systems

Prepared by Greg Mandelman for Berkeley Lab
June 3, 2025

ELECTRIC POWER ENGINEERS
DELIVERING ENERGY INTELLIGENCE

One referenced report is Berkeley Lab’s *2024 United States Data Center Energy Usage Report* (Shehabi et al. 2024), which provides an overview of forecasting methods and details the components of data centers which drive electricity demand.



LBNL-2001637

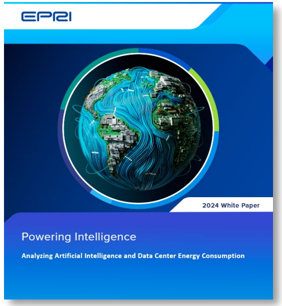
BERKELEY LAB
Energy Analysis & Environmental Impacts Division

2024 United States Data Center Energy Usage Report

Arman Shehabi, Sarah J. Smith, Alex Hubbard, Alex Newkirk, Nuoa Lei, Md Abu Bakar Siddik, Billie Holecek, Jonathan Koomey, Eric Masanet, and Dale Sartor
Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory

December 2024

Another useful report (not referenced there) is EPRI’s *Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption* (EPRI 2024), which covers trends and opportunities to enable data center growth and includes state-specific scenarios for states with high data center growth.



EPRI

2024 White Paper

Powering Intelligence
Analyzing Artificial Intelligence and Data Center Energy Consumption

FORECASTING APPROACHES

Shehabi et al. 2024 classified data center forecasts into three approaches:

Bottom-Up

- Detailed model of all power-consuming components, specific to the installation
- Can have high accuracy
- Complex, requires detailed information, typically only applicable for forecasts up to a few years into the future

Top-Down

- High-level model using aggregated measurements of energy consumption and data volume
- Simple, minimal data requirements
- May not capture specific data center characteristics, ignores efficiency trends, requires estimates of data demand

Extrapolation

- Simplistic model applying a growth rate to a baseline year
- Very simple, requires only baseline consumption and growth rate
- High sensitivity to input assumptions can lead to unrealistic outcomes; validation is important

In practice, most forecasts use a combination of two or three of these approaches.

WHAT DO THE MACRO FORECASTS SAY?

Estimated 2023 US data center demand (EPRI 2024):

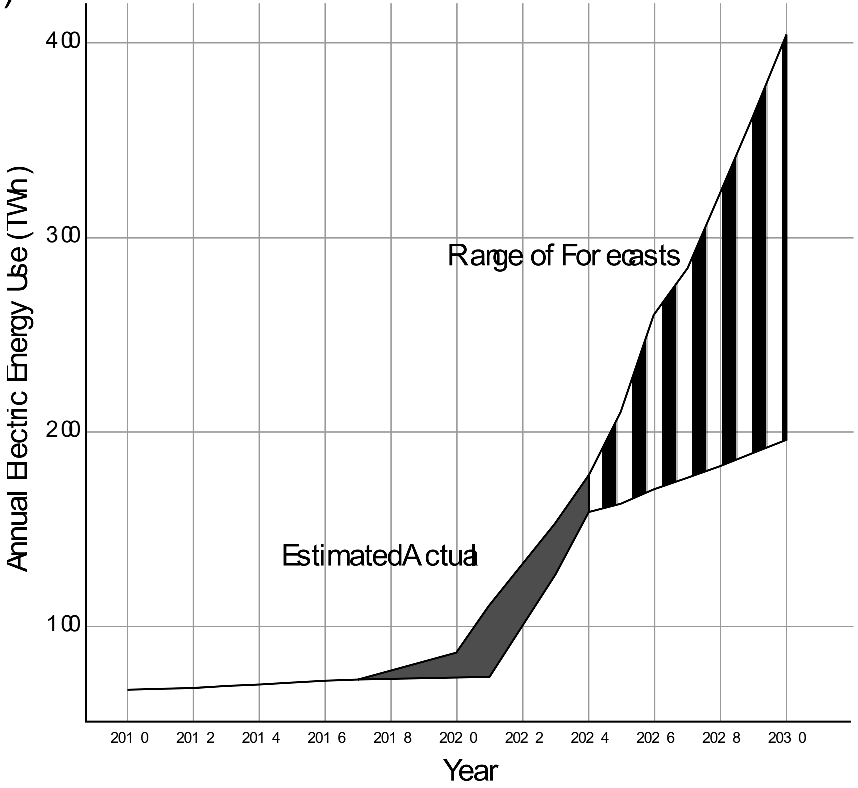
- 150 TWh
- 4% of US electricity consumption

Estimates through 2030:

- ~10% - 17% growth (across 6 sources)
- 4.6% - 9.1% of 2030 US electricity consumption (EPRI 2024)

Source	**Growth Rate (2024-2030)**
Standard & Poor's	16.70%
McKinsey	9.70%
Brattle	10.6% - 15%
Boston Consulting Group	14.2% - 19.3%
Goldman Sachs	14% - 17.3%
Electric Power Research Institute	12.4% - 16.9%

from Evolved Energy Research, *Future Load Scenarios for Southwest Power Pool*, *Sept. 2024*



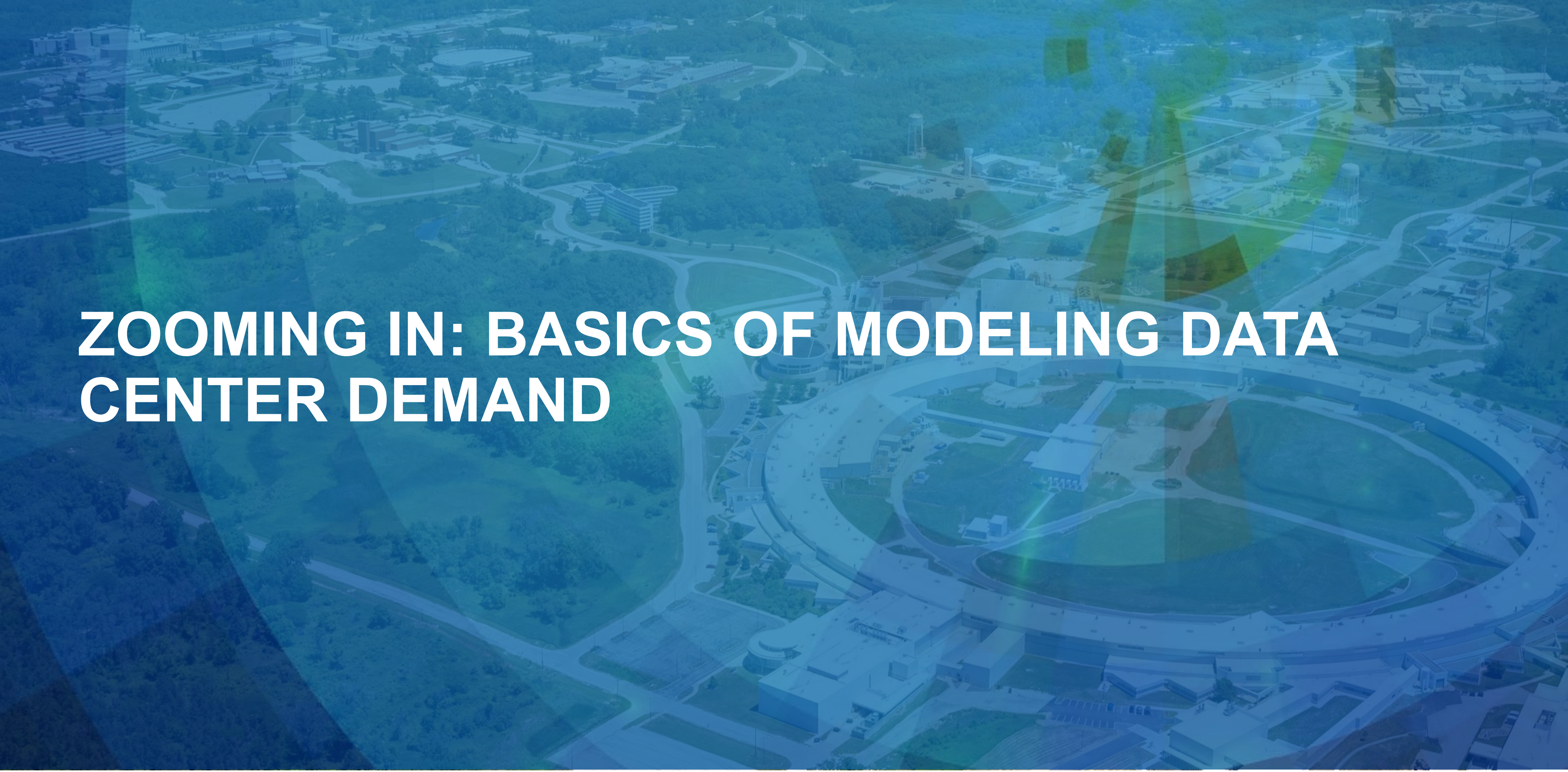
Source: ANL, adapted from *Shehabi et al. 2024*

CONTEXTUALIZING THE MACRO FORECASTS

- **Can’t be dismissed**: Any of the forecasted demands would have significant impacts on power system needs.

However, consider

- **Location**: Data center growth has shown high locational variation; a US-wide forecast does not translate easily to state considerations.
- **Transparency**: None of the forecast methodologies are publicly available; it is not clear what assumptions and combination of bottom-up, top-down, extrapolation, and judgement were used.
- **Contrasting evaluations**: London Economics, *Uncertainty and Upward Bias are Inherent in Data Center Electricity Demand Projections*, July 2025, presents arguments for presence of bias:
  - Duplicate interconnection requests, low financial barrier for requests
  - Vertically integrated utilities do not have incentive for conservative forecasts
  - Power system bottlenecks, local opposition, onsite generation, and costs of state incentives may not be considered.
  - The low end of forecasted demands in the US would require 90% of global chip supply from 2024-2030, compared to current US demand of less than 50%.



ZOOMING IN: BASICS OF MODELING DATA CENTER DEMAND

TYPES OF DATA CENTERS

- **Enterprise/Internal DCs**: Privately owned, supporting in-house IT and applications
- **Colocation DCs ("Colo")**: Lease space, power, and cooling for customer-operated servers.
- **Cloud Service DCs**: Provider-operated for software-as-a-service, storage, and compute.
- **Hyperscale DCs**: Extremely large (>100 MW) operated by major firms. AI training and inferencing are two fast-growing classes of these.
- **Edge DCs**: Small, distributed facilities for low latency.
- **High-Performance Computing (HPC) DCs**: Specialized for scientific and R&D computing.
- **Crypto Mining DCs**: Specialized hardware, high energy demand but low water use.
- **Quantum Computing**: In research stage, high uncertainty.

N. Stauff et al., *Preliminary Analysis of Nuclear-Powered Data Center Scenarios*, Argonne National Laboratory. August 2025.

DATA CENTER RELIABILITY TIERS

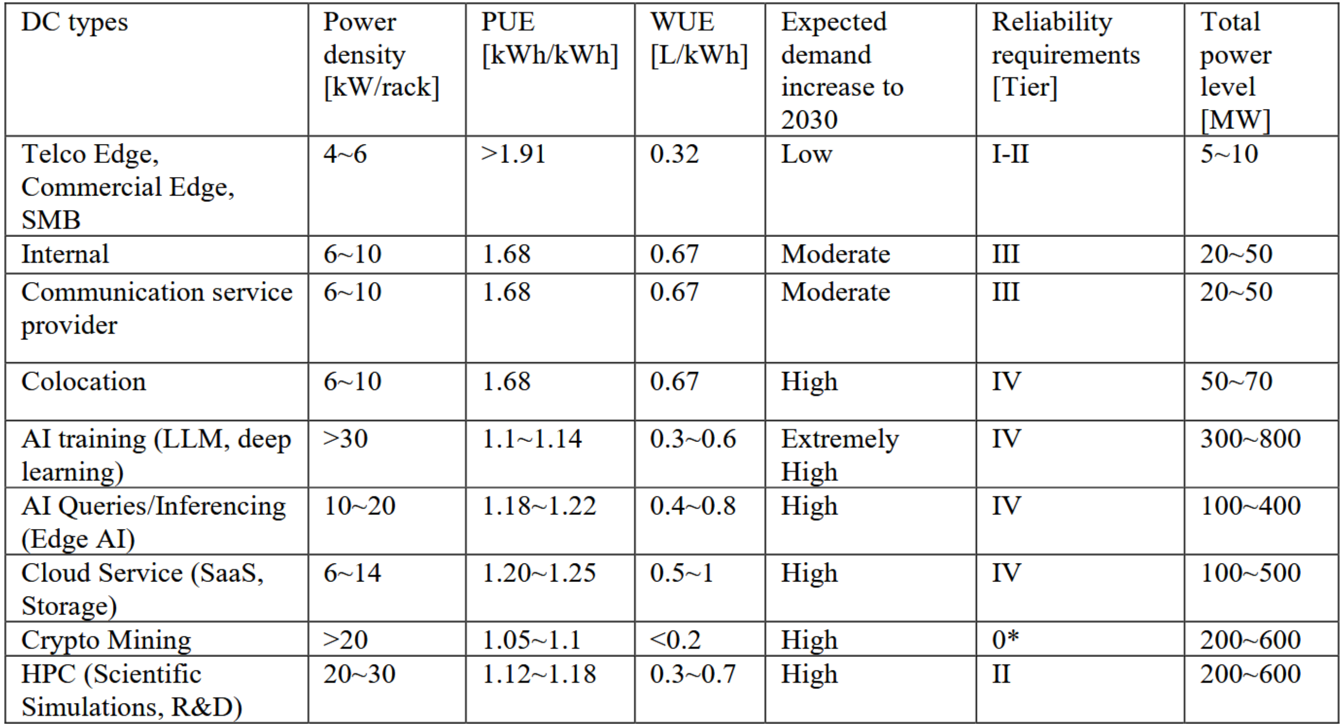
- A data center's reliability needs strongly influence the electrical layout and its reliance on utility electricity: The *Uptime Institute Data Center Site Infrastructure Tier Standard: Topology* defines the widely-used Tier I-IV classification for electrical supply design.
- *Tier Standard* on utility supply: "Services originating from outside the data center property boundary and not in full control of the data center organization are deemed and treated as a utility system… **These services are not considered reliable supplies for the data center and are not considered to meet the Tier requirements for the site**."
- From the perspective of the Tier Standard, use of utility electricity at any time is decided for economic reasons, not reliability.

IMPORTANT OPERATIONAL METRICS

- **Power Density**: Power demand per rack (kW/rack) Higher power densities require more advanced cooling (often liquid cooling).
- **Power Usage Efficiency (PUE)**: Total facility energy divided by energy consumed by IT equipment (unitless): lower number is more efficient, with 1.0 the most efficient possible.
- **Water Usage Effectiveness (WUE)**: Total water consumption divided by energy consumed by IT equipment (L/kWh).

N. Stauff et al., *Preliminary Analysis of Nuclear-Powered Data Center Scenarios,* Argonne National Laboratory. August 2025.

CHARACTERISTICS BY TYPE

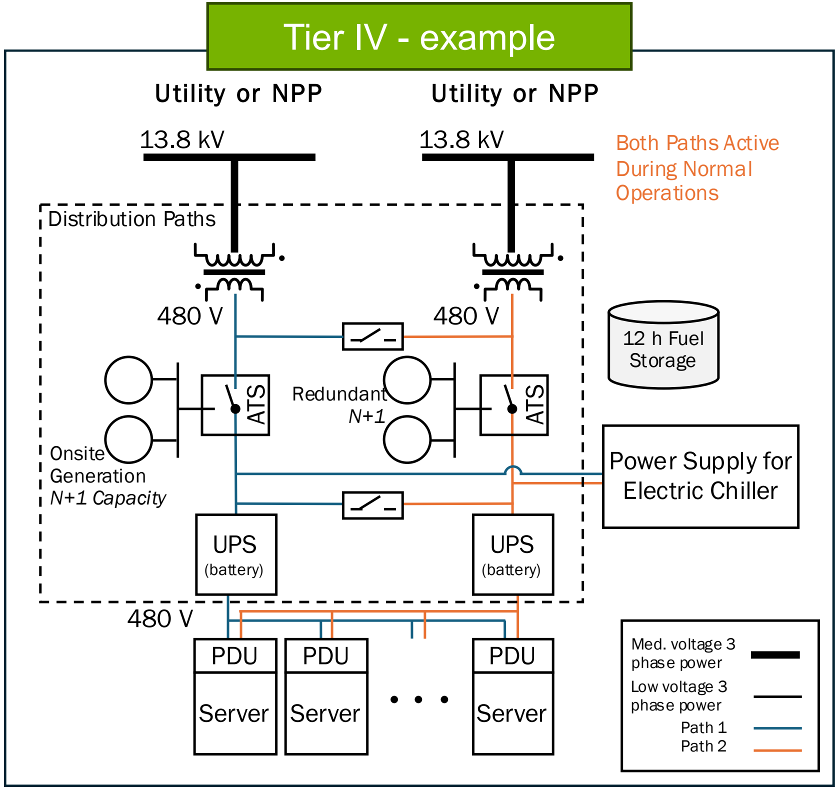


DC types	Power density [kW/rack]	PUE [kWh/kWh]	WUE [L/kWh]	Expected demand increase to 2030	Reliability requirements [Tier]	Total power level [MW]
Telco Edge, Commercial Edge, SMB	4~6	>1.91	0.32	Low	I-II	5~10
Internal	6~10	1.68	0.67	Moderate	III	20~50
Communication service provider	6~10	1.68	0.67	Moderate	III	20~50
Colocation	6~10	1.68	0.67	High	IV	50~70
AI training (LLM, deep learning)	>30	1.1~1.14	0.3~0.6	Extremely High	IV	300~800
AI Queries/Inferencing (Edge AI)	10~20	1.18~1.22	0.4~0.8	High	IV	100~400
Cloud Service (SaaS, Storage)	6~14	1.20~1.25	0.5~1	High	IV	100~500
Crypto Mining	>20	1.05~1.1	<0.2	High	0*	200~600
HPC (Scientific Simulations, R&D)	20~30	1.12~1.18	0.3~0.7	High	II	200~600

N. Stauff et al., *Preliminary Analysis of Nuclear-Powered Data Center Scenarios,* Argonne National Laboratory. August 2025.

DATA CENTER RELIABILITY TIERS AND PARAMETERS

	Tier I	Tier II	Tier III	Tier IV
Description	Basic Site Infrastructure	Redundant Site Infrastructure Capacity Components	Concurrently Maintainable Site Infrastructure	Fault Tolerant Site Infrastructure
Power Supply Capacity	N	N+1	N+1	N after any failure (typically ≥2N)
Redundant Components	None	Backup generation, UPS, cooling, fuel tanks	All power and mechanical equipment	All power and mechanical equipment
Power Distribution Paths	Single	Single	1 Active and 1 Alternate	2 Simultaneously Active
Mechanical (Cooling) Distribution Paths	Single	Single	1 Active and 1 Alternate	2 Simultaneously Active
UPS	Yes	Yes	Yes	Yes
On-Site Generation	Yes	Yes	Yes	Yes
On-Site Generation Maintainable and Fault Tolerant While Carrying the Site	No	No	Yes	Yes
Generators May Have Limitation on Fully Loaded Runtime	Yes	Yes	No	No
On Site Fuel Storage for Backup Generation	12 h	12 h	12 h	12 h
All Components Concurrently Maintainable	No	No	Yes	Yes
Compartmentalized (complementary systems and distribution paths physically isolated)	No	No	No	Yes



Stauff et al. 2025. Preliminary Analysis of Nuclear-Powered Data Center Scenarios.

ONSITE GENERATION

Tier III

- Requirement is N+1:
  - Full power demands of the site can be met with onsite generation (N).
  - One additional generation unit is available so that no disruption results from the loss of a unit (+1).
- 12 hours of onsite fuel storage is required

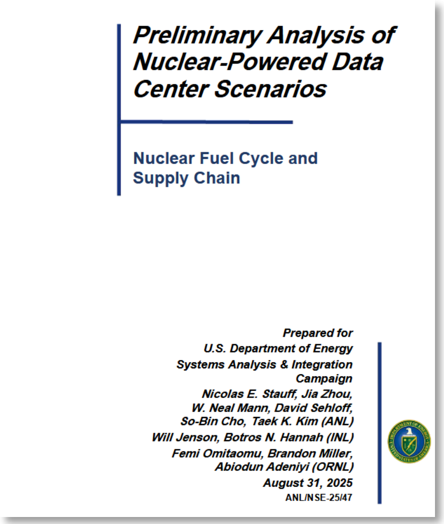
Tier IV

- Requirement is N after any failure in the power distribution path:
  - This means N+1 at minimum.
  - Designs may have higher redundancy, such as N (or N+1) in each path.
- 12 hours of onsite fuel storage is required

Onsite generation is often natural gas-fueled: turbines, reciprocating engines, and fuel cells. Diesel engines are also used.

NUCLEAR-POWERED DATA CENTERS

- Nuclear power is a promising source to meet increased data center demand, potentially off- and on-site.
- N. Stauff et al., *Preliminary Analysis of Nuclear-Powered Data Center Scenarios*, August 2025.
  - Outlines options for coupling nuclear power plants with data centers
  - Studies sizing and siting throughout the US
  - Includes socio-economic impact assessment



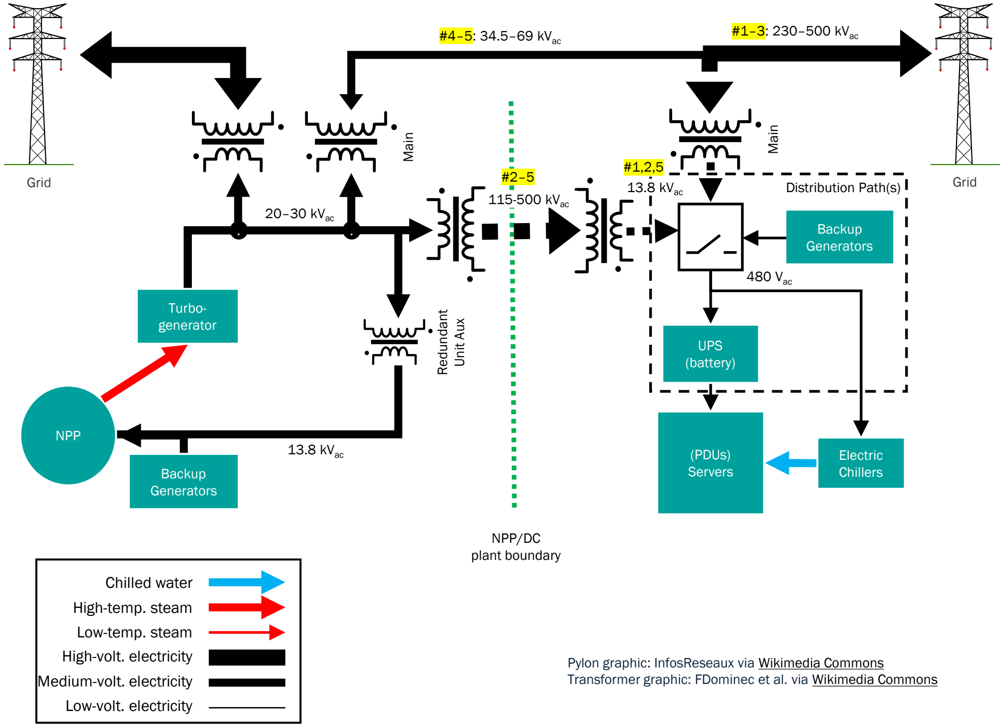
Preliminary Analysis of Nuclear-Powered Data Center Scenarios

Nuclear Fuel Cycle and Supply Chain

Prepared for
U.S. Department of Energy
Systems Analysis & Integration Campaign
Nicolas E. Stauff, Jia Zhou,
W. Neal Mann, David Sehloff,
So-Bin Cho, Taek K. Kim (ANL)
Will Jenson, Botros N. Hannah (INL)
Femi Omitaomu, Brandon Miller,
Abiodun Adeniyi (ORNL)
August 31, 2025
ANL/NSE-25/47

EXAMPLE: DATA CENTER–GENERATOR (NPP) COUPLING OPTIONS

Options	#1	#2	#3	#4	#5
Nuclear/DC connection	Bulk transmission system only	Direct connection and full power import/export (separate meters)	Direct connection and full power import/export (shared meter)	Direct connection only (islanded microgrid)	Direct connection (microgrid with full power import)
Are the NPP and DC co-located?	No	Yes	Yes	Yes	Yes
Does the datacenter have a separate grid connection?	Yes	Yes	No	No	Yes
Doe the NPP have a separate grid connection?	Yes	Yes	Yes	No	Safety only



Pylon graphic: InfosReseaux via Wikimedia Commons
Transformer graphic: FDominec et al. via Wikimedia Commons

Stauff et al. 2025. Preliminary Analysis of Nuclear-Powered Data Center Scenarios.

DATA CENTER CO-LOCATION BENEFITS & CHALLENGES

Coupling Options	#1	#2	#3	#4	#5
Nuclear/DC connection	Bulk transmission system only	Direct connection and full power import/export (separate meters)	Direct connection and full power import/export (shared meter)	Direct connection only (islanded microgrid)	Direct connection (microgrid with full power import)
Site Availability	Medium	Lower	Lower	Higher	Lower
NPP Safety Regulatory Issues	None	None	None	Likely	Maybe
Power Market Regulatory Issues	None	**Maybe**	**Likely**	None	**Maybe/Likely**
On-Site Generation Capacity (Nuclear and others)	None	Higher (≥N)	Higher (≥N)	Highest (≥2N)	Higher (≥N)
On-Site Generation Timeline	Faster (none)	Slower	Slower	Slowest (redundant NPPs)	Slower
Local T&D CapEx	Higher	Highest	Medium	Lowest	Medium
Local T&D Timeline	Slower	Slowest	Medium	Fastest	Medium
T&D Line Losses	Higher	Lower	Lower	Lowest/None	Lower
Power Cost Certainty for Data Center Owner	Depends (indirect nuclear purchase + wholesale)	Depends (direct nuclear purchase + wholesale)	Depends (direct nuclear purchase + wholesale)	More certain (direct nuclear purchase)	More certain/Depends (direct nuclear purchase + wholesale)

Stauff et al. 2025. Preliminary Analysis of Nuclear-Powered Data Center Scenarios.

CONCLUSION:
BIG IDEAS AND QUESTIONS STATES CAN ASK

BIG IDEAS AND QUESTIONS STATES CAN ASK

Uncertainty is high: Scenarios and sensitivities are important tools.

- How many demand scenarios are used?
- What differs between these scenarios? Are distinct assumptions about specific features included in the scenarios, e.g. vary degrees of electrification or large load interconnection?
- How are the outcomes of different scenarios and sensitivities used in the planning process?

Forecasts are sensitive to assumptions: need transparency.

- Does this forecast use top-down, bottom-up, or extrapolation methods, or a combination?
- What are the sources of data for this forecast?
- How does this forecast incorporate data center interconnection requests?

The details of data center types and designs greatly impact power demand.

- Does the forecast give a breakdown by data center type? Is the growth by type in line with siting considerations in this region?
- What assumptions about onsite generation does the forecast make?

QUESTIONS AND DISCUSSION

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