Data Center Growth & Impacts on the U.S. Energy Sector

An Energy Horizons Report Update

March 7, 2025

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Disclaimers

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The OL24-NEMS model used in this analysis is a modified version of the U.S. Energy Information Administration's National Energy Modeling System (EIA NEMS) developed by OnLocation. The OL24-NEMS model and results do not represent the views of EIA. OL24-NEMS is based on the EIA Annual Energy Outlook (AEO) 2023 and includes the same market and technology assumptions unless otherwise noted. For more information about EIA NEMS, visit https://www.eia.gov/outlooks/aeo/.

Report Outline

Introduction and Overview

Data Center Demand: Implications of Alternative Policies

Demand Growth and Distribution
National Generation and Capacity
Regional Generation Mix
Power Sector CO_2 Emissions

Further Research Opportunities

Caveats and Acknowledgements

Note:

This report supplements the Energy Horizons report: "Data Center Demands & Impacts on the Energy System" released by OnLocation on September 26, 2024. All scenario assumptions related to energy markets, policies, and technologies are the same as those specified in the September report unless otherwise noted.

Introduction

Corporate Capabilities

KeyLogic

Mid-tier firm offering deep domain expertise in our country's most critical undertakings within the energy, federal civilian, and defense sectors

Innovative Integration

Large-scale data management, advanced analytics, enterprise transformation, science & technology advisory services, R&D management, and systems engineering

Thought Leaders in Emerging Technologies

Technology readiness scale with experience modeling and assessing range of energy-relevant technologies at low-technology-readiness levels

Critical Materials Expertise

Material and resource analysis, including life-cycle analyses, across the supply chain in support of energy production, generation, and storage technologies

OnLocation

Specialized division with four decades of experience developing and applying innovative energy system and economic models to address key energy and environmental challenges

Assess Role of New Energy Technologies

Evaluate system and economic impacts of new and emerging energy technologies such as electric vehicles, battery storage, biofuels, hydrogen, and carbon capture & storage

Explore Alternative Energy Futures

Design "what-if" scenarios and alternative energy futures for use in uncertainty analyses including alternative energy prices, technology costs, and data center demand forecasts

Inform Energy & Environmental Policy

Perform economic impact assessments of new or proposed energy and environmental regulations and policies such as Inflation Reduction Act and EPA GHG Standards for vehicles and power plants

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Purpose of Energy Horizons Report & Data Center Focus

Evaluate key driving forces in the U.S. energy system, focusing on the unprecedented growth in data center electricity demand and impacts on the power grid

Assess potential changes to laws and regulations from new Administration and implication for the U.S. power sector

Provide updated and timely scenario analysis using OnLocation's version of the National Energy Model System (OL24-NEMS)

Demonstrate new model capabilities and enhancements that can be used for further research and analysis

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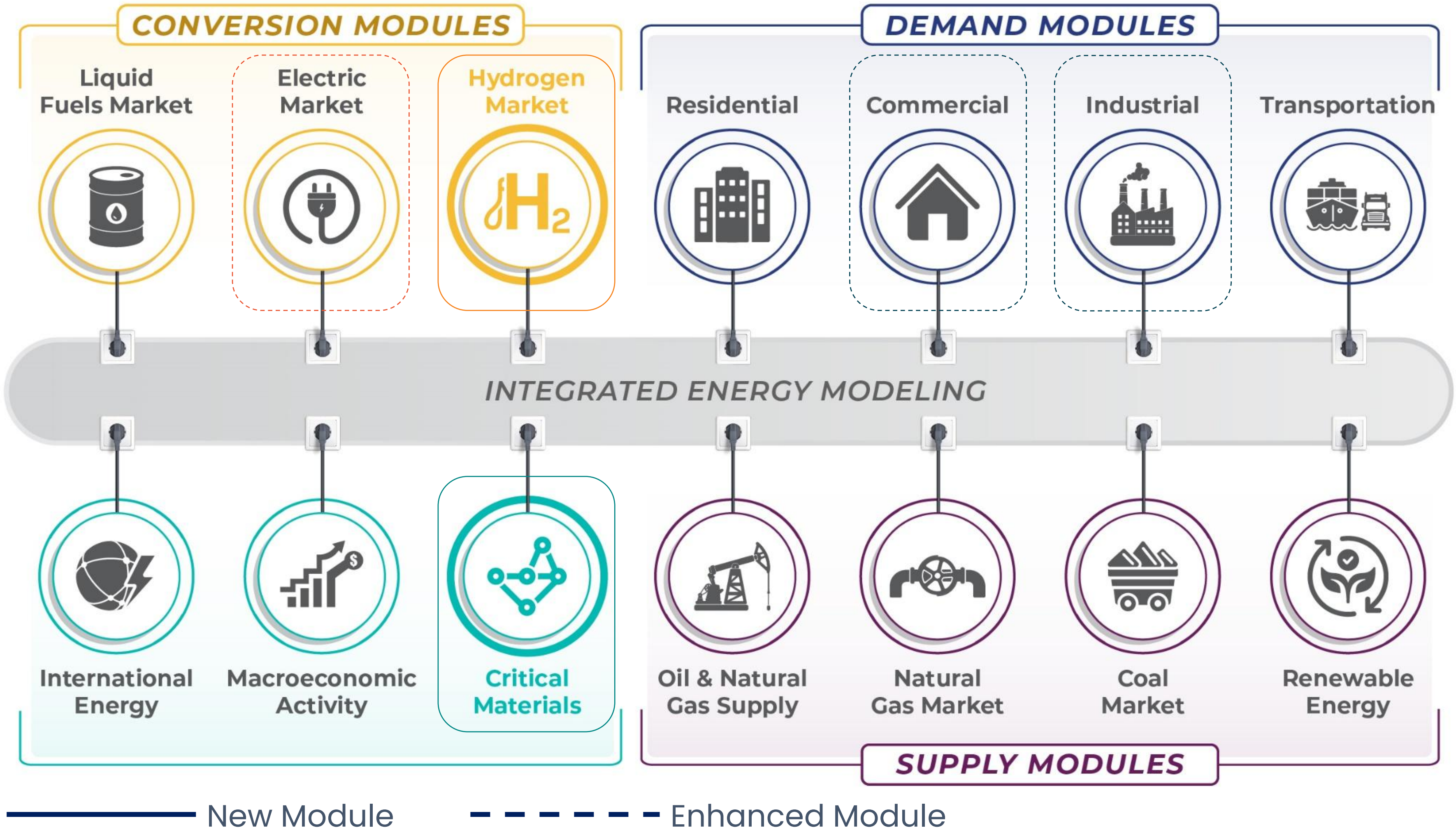
OnLocation's Customized Version of the National Energy Modeling System (OL24-NEMS)



Development & Application of Energy System Models

- Analyzing Impacts of Demand Growth
- Assessing New Energy Technologies
- Informing Cost-effective Approaches and Policies

Customization & Analyses

- Regional Data Centers
- Updated Policies
- Advanced Technologies
- Hydrogen Economy
- Critical Materials

Note: The official version of NEMS is developed and maintained by the Energy Information Administration (EIA), U.S. DOE

Data Center Report Highlights

Data center demand growth continues to be a driving force in the U.S. and will require new investments in electric generation and transmission.

The future generation mix will depend on the regulations and policies that will influence capacity investments and utilization of energy sources.

Multiple energy sources will be essential for meeting the growing energy demand for data centers:

- **Fossil generation**, including coal and natural gas, provides reliable baseload generation.
- **Nuclear generation**, especially small modular reactors, has captured the attention of some data center developers and could be a valuable baseload option in the longer term.
- **Renewable generation**, especially solar photovoltaics and wind, will continue to be a low-cost option in many regions.
- **Battery storage** extends the availability of renewable generation and enhances grid reliability.

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Current Market: Data Centers General Overview

Why are data centers important?

Data centers provide homes and businesses with vast amounts of data storage and computing power:

- eCommerce, telecommunications, video streaming services, stock trading, medical imaging, online gaming, research studies, and many other applications.

Data center power demand currently accounts for more than 4% of total U.S. electricity consumption.[1]

Digital transformation is driving increasing data center energy demand for:

- Cloud computing, artificial intelligence (AI) training and user applications, digital services, and cryptocurrency mining operations.

The fastest growing markets in recent years are the use of data centers for AI models and applications, quantum computation by major tech companies, and cloud service providers such as Amazon, Google, and Microsoft.

What are the main data center types?

Primary Data Center Types:

- **Small-scale:** Includes server rooms and edge data centers. Serves localized operations such as small businesses, facilities, or individual customers. [2, 3]
- **Large-scale:** Serves extensive operations such as cloud computing, training models, and processing large datasets often for multiple businesses, governmental agencies, or entire industries. [3, 4, 5]
  - **Enterprise data centers**: 20-30% of the U.S. data center load
  - **Hyperscale and multiple host data centers**: 60-70% of the U.S. data center load

Type	Size	% Bldg Load	Capacity
Small-scale	<10,000 sq. ft.	10%	500kW – 5MW
Large-scale	>10,000 sq. ft.	90%	>40MW

Types of Large-scale Data Centers: [3, 4, 5]

- **Enterprise data centers** are controlled by one organization for the purpose of storing important IT infrastructure and other elements necessary for processing, storing, and managing the organization's data and applications.
- **Multiple host data centers** are facilities that provide server hosting and hardware services for multiple businesses that share infrastructure.
- **Hyperscale data centers (>100,000 Sq. Ft.)** support and service major cloud providers such as Amazon, Google, and Microsoft and can quickly expand to accommodate extensive computing and storage requirements.

How is electricity consumption distributed across various components of a data center?

The electricity use within a data center is mainly driven by three key areas and their consumption range can differ by data center size: [6, 7, 8]

% Data Center Total Energy Consumption

IT Equipment	Cooling Systems	Auxiliary Components
40%-65% (80%-90% for large centers)	30% - 40%	10% - 30%

- **Servers:** The largest energy consumers, handling most data processing and computational tasks.
- **Storage Systems:** Include both conventional hard disk drives and more energy efficient solid-state drives for data storage.
- **Network Infrastructure:** Comprises switches, routers, and other essential components for effective data transfer and connectivity.

- **Essential for maintaining optimal temperatures** to prevent overheating and prolong the lifespan of hardware.
- **Cooling methods range from traditional HVAC systems to more advanced technologies** like liquid cooling, immersion cooling, and economizers.

- **Uninterruptible Power Supply (UPS):** Provides emergency power during power outages to ensure constant operation.
- **Security Systems:** Consist of cameras, sensors, and access control systems for safeguarding data centers.
- **Lighting:** Accounts for a small percentage of the total energy consumption.

What short-term constraints could limit data center expansion?

Power infrastructure and backup systems

- Average construction timeline before 2020 was 1-3 years. Limited access to power means it can now take 2-6 years.
- Large data centers needing >100 MW of electricity wait up to 7 years to connect to the grid.[9]

Infrastructure and technological requirements

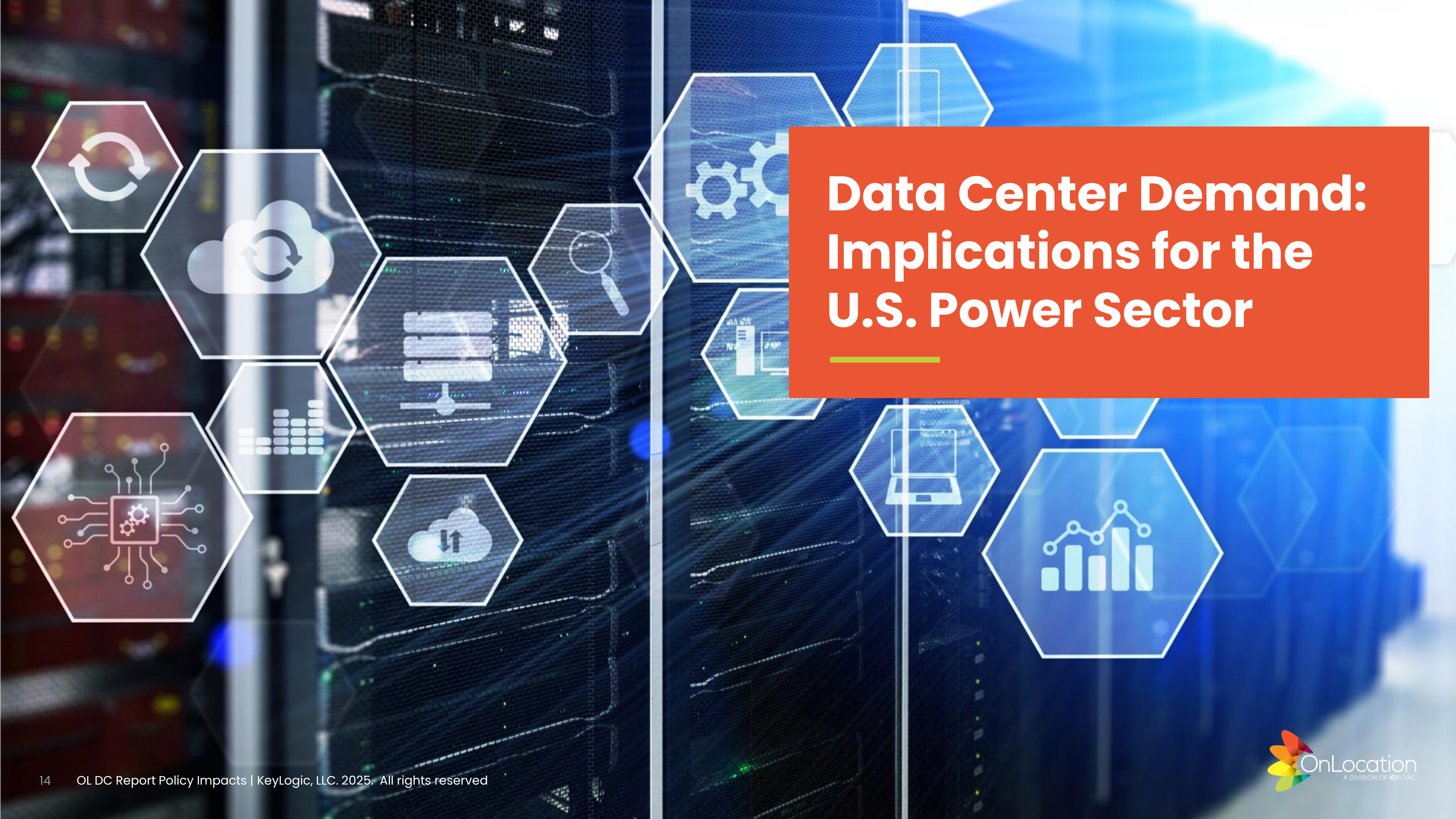
- Impacted by supply chain for servers, chips, semiconductors, HVAC systems, security and data protection.

Highly specialized and skilled workforce needs

- Increasing demands for expertise in network engineering, cybersecurity, hardware maintenance, automation, and systems architecture.

Site selection and land acquisition

- Highly impacted by power and internet connection availability, community resistance, restrictive permitting, and compliance with regulations and policies.[10, 11]

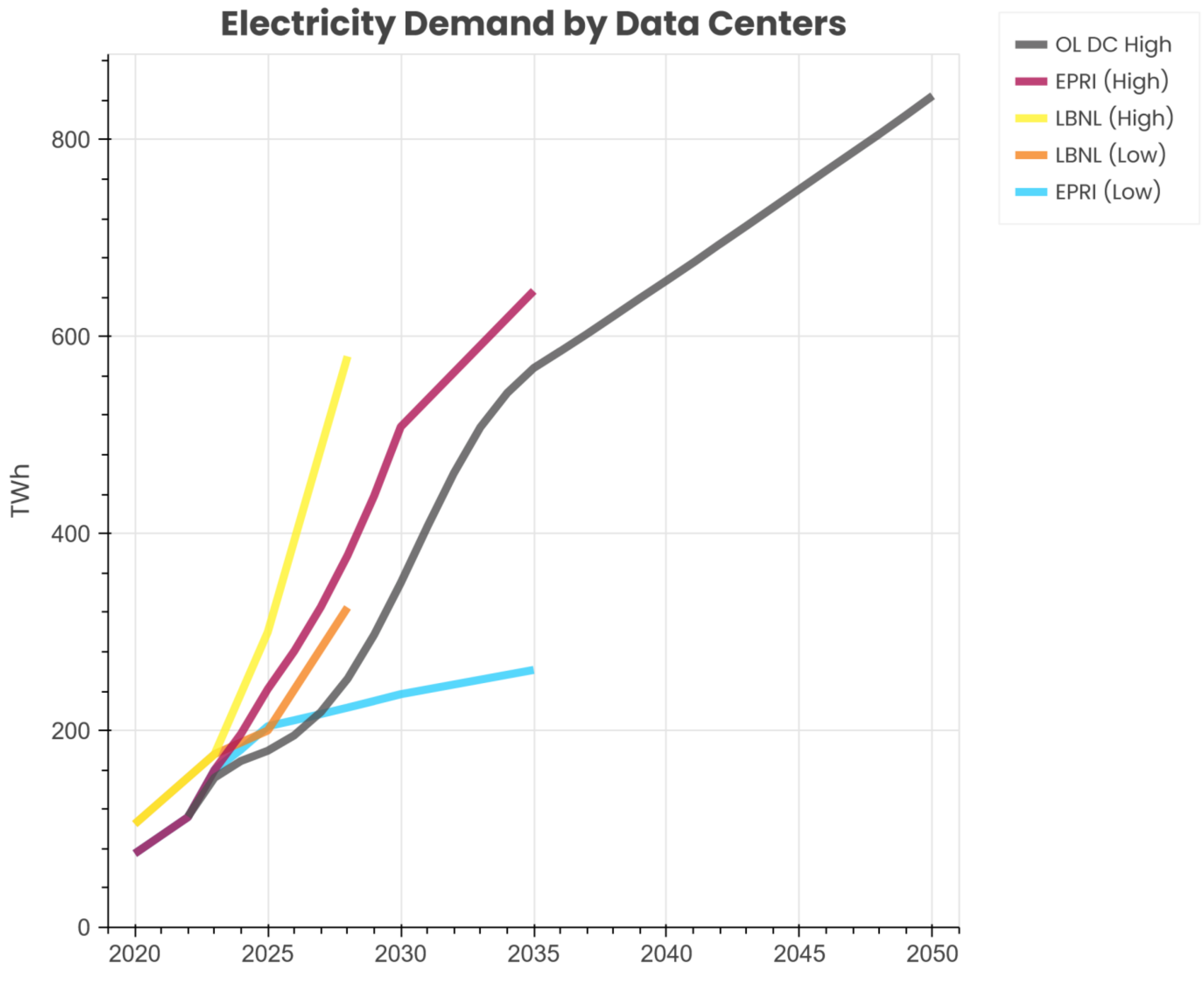


Data Center Demand: Implications for the U.S. Power Sector

Growth is Significant but Highly Uncertain

- We compare two scenarios to determine the impact of expected data center demand growth:
  - **High Growth with Current Policies:** The Energy Horizons DC High scenario includes current energy policies such as the Inflation Reduction Act (IRA) and EPA Clean Air Act 111 greenhouse gas (GHG) regulations.
  - **High Growth with Alternative Policies:** The same high growth but without IRA incentives for renewables and no EPA 111 regulations for fossil generation.

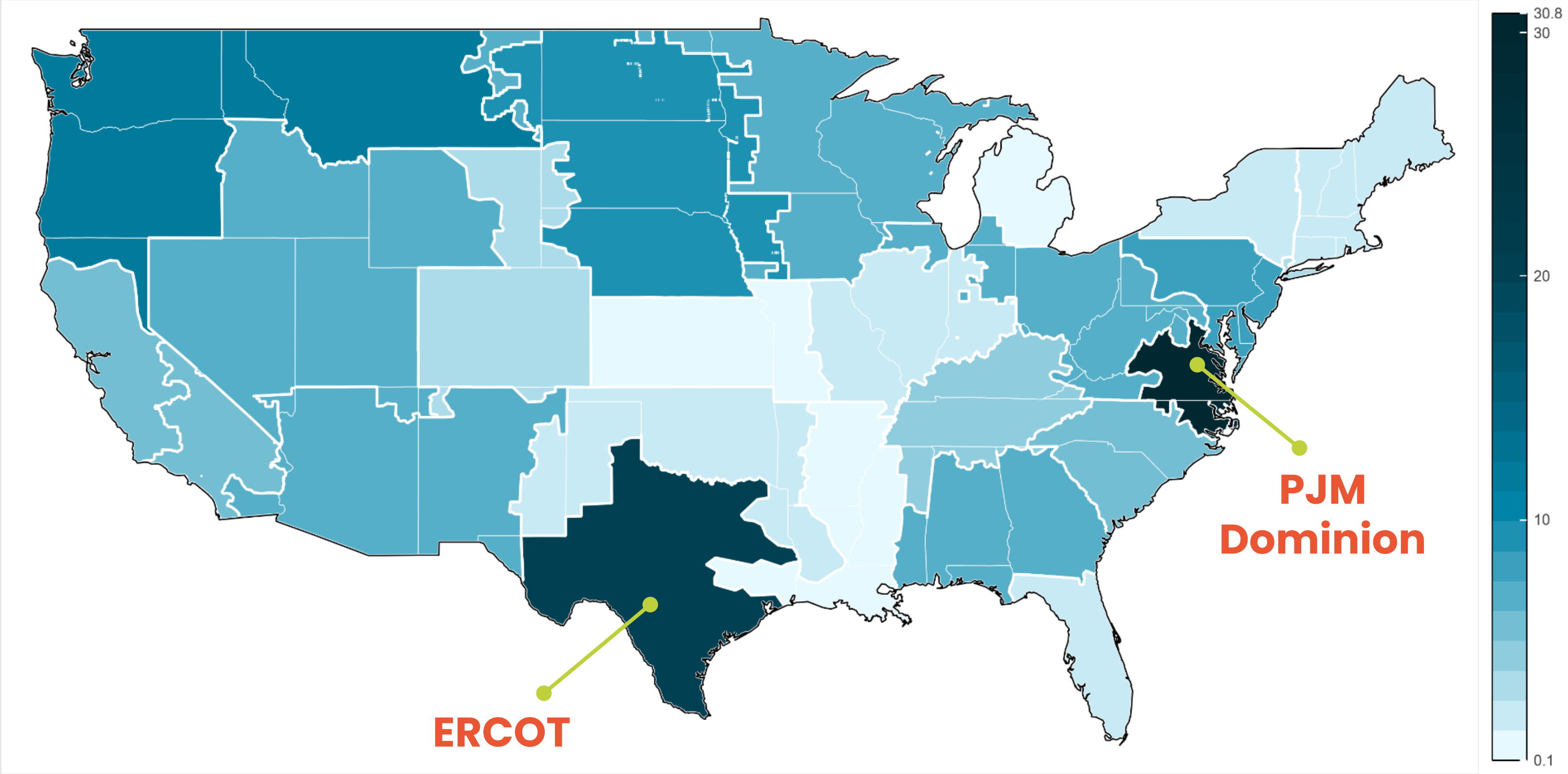
- Recently published forecasts from LBNL and EPRI were used to inform the OnLocation high growth projection through 2050, as shown in the chart.



Source: OnLocation OL-NEMS

Highly Concentrated Demand Is Reshaping Regional Power Systems

Data Center Demand By Electric Reliability Region in 2023 (TWh)



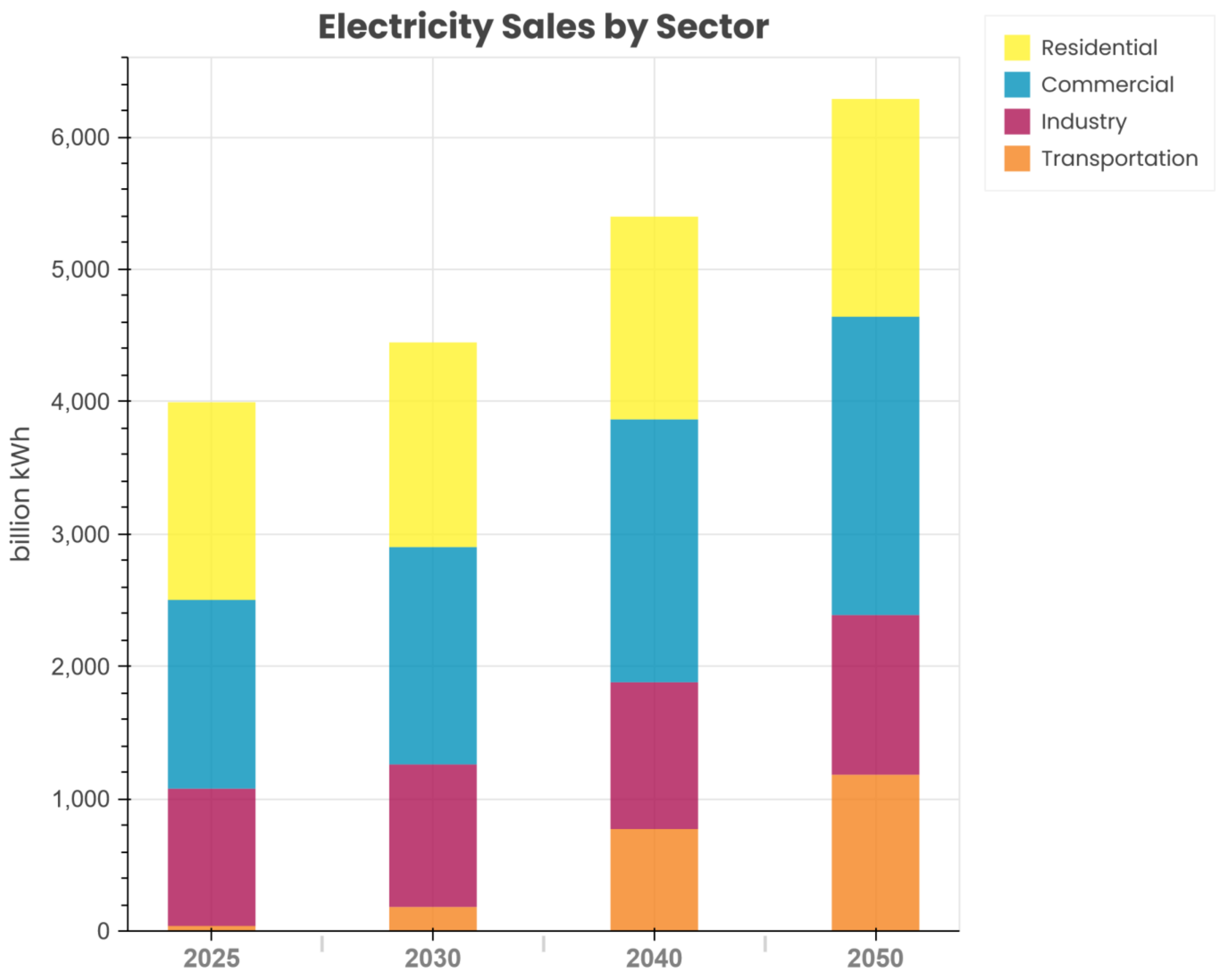
Source: OnLocation

Note: Map uses state level data from [EPRI 2024](): Powering Intelligence, Analyzing Artificial Intelligence and Data Center Energy Consumption

- Data centers are located in most U.S. regions but are highly concentrated in the PJM Dominion and ERCOT regions.
- Regional differences in energy resources and generation mix mean location of additional demand directly impacts capacity expansion and grid reliability.
- For our analysis, data center annual growth is assumed to be uniform across 25 electric reliability regions (shown here) and demand is fully met by grid-based electricity.

National Electricity Demand

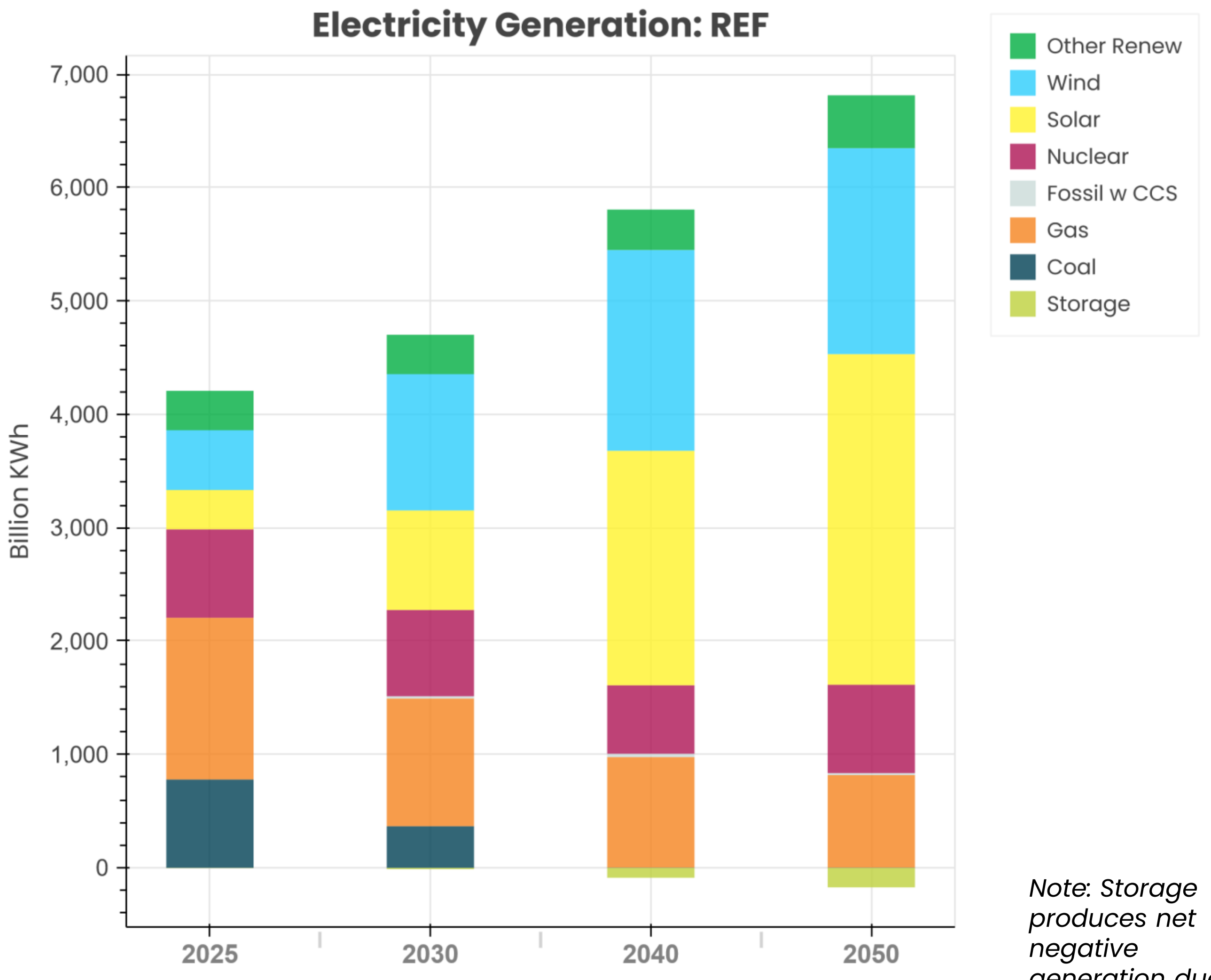
- The OnLocation scenarios include more than 700 TWh of growth in data center demand over the next 25 years, making up nearly one-third of commercial electricity demand by 2050.
- Data centers add significant demand to overall load growth, building on the broader economy-wide electrification trend which includes electric vehicles and heat pumps in buildings.
- Load growth is assumed to be the same across both scenarios analyzed.



Source: OnLocation OL24-NEMS

National Electricity Generation – REF

- In the **High Growth with Current Policies scenario (REF)**, data center demand leads to increased generation of all types:
  - Demand is initially met by a mix of existing coal, natural gas, nuclear, and renewable generation.
  - Expansion of renewables accelerates, especially solar and wind, driven by decreasing costs and IRA incentives.
  - Fossil fuel generation (coal and natural gas) declines over time due to lower cost renewables and EPA 111 regulations that require carbon capture for both coal and new baseload natural gas units in later years. Coal units without capture retire by 2040 as required.
  - Nuclear generation increases in later years with the addition of new small modular reactors and delayed retirement of existing units.



Source: OnLocation OL24-NEMS

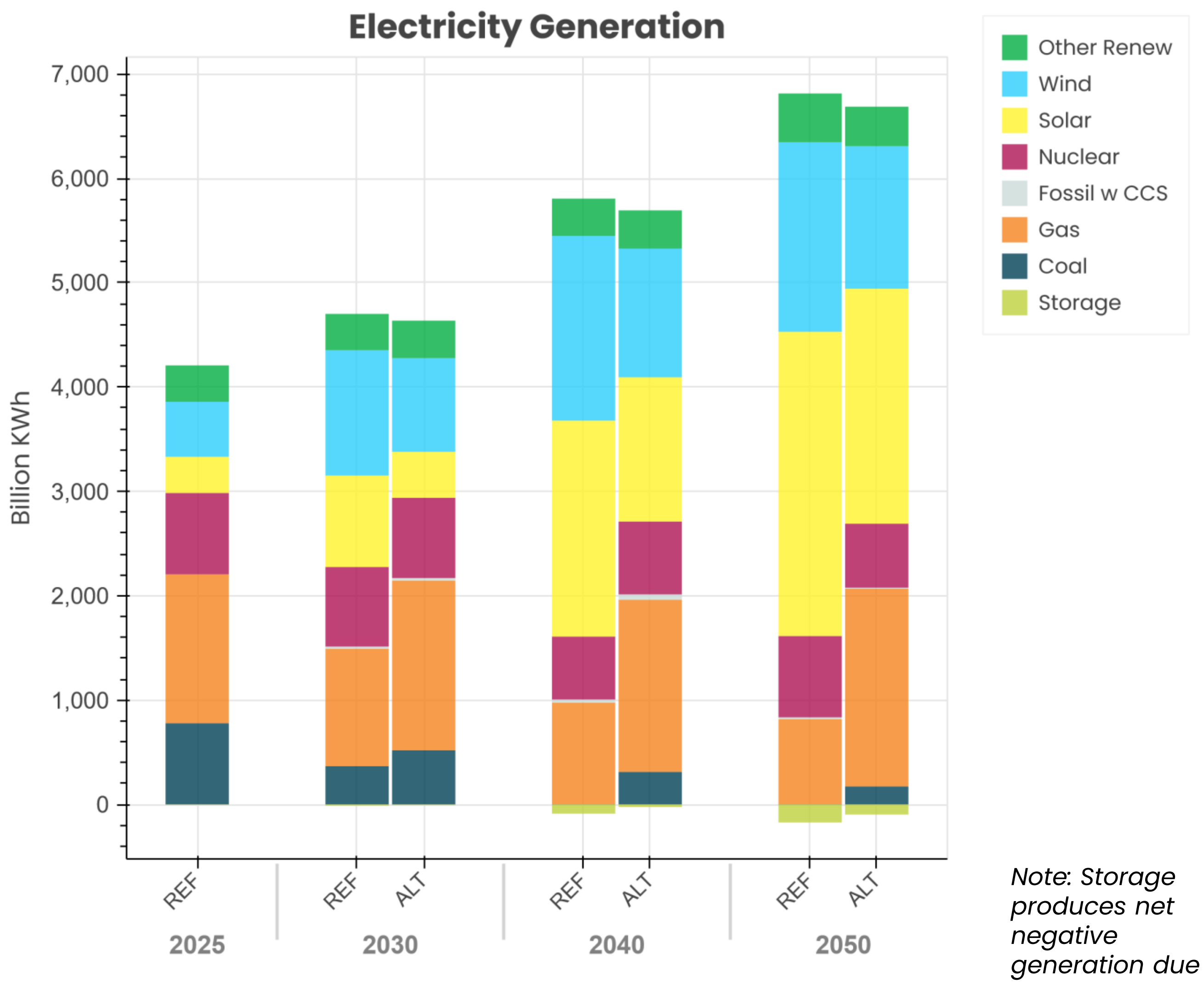
Note: Storage produces net negative generation due to energy losses.

National Electricity Generation – REF, ALT

- Data center demand in both scenarios leads to increasing generation from low-cost renewables.

- However, there are important differences between the scenarios:
  - **The REF scenario** relies heavily on new renewable generation to meet the new load while fossil generation declines over time.

  - **The alternative policies scenario (ALT)** leads to increased use of both new and existing natural gas generation over time. Coal generation declines and renewable generation increases but at a much slower rate than in the REF scenario due to the absence of IRA and EPA policies.

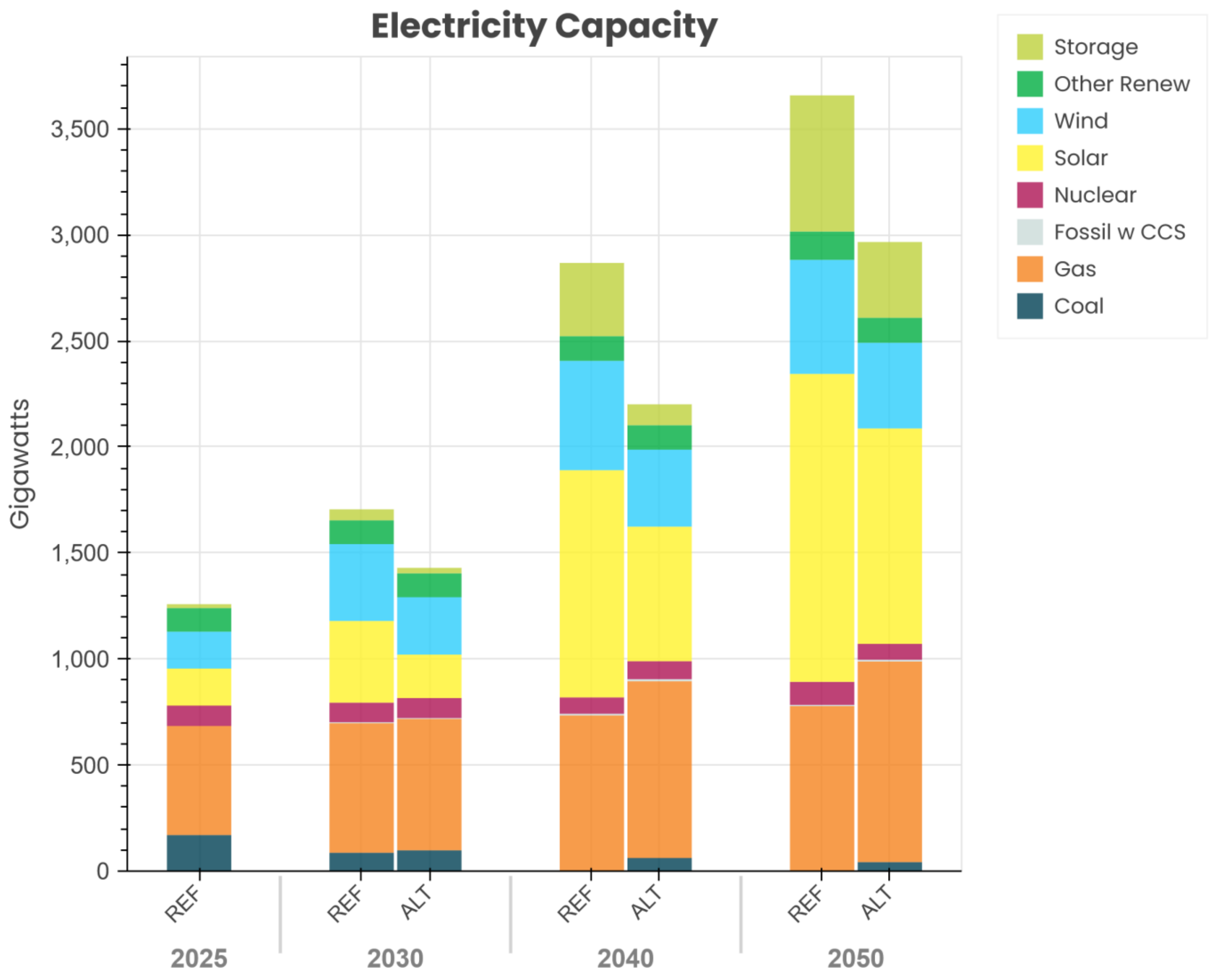


Source: OnLocation OL24-NEMS

Note: Storage produces net negative generation due to energy losses.

National Electricity Capacity – REF, ALT

- A large amount of investment will be needed to meet the growing demand.
- In **both scenarios**, capacity additions are largely made up of solar and wind, with new natural gas turbines and battery storage added in later years to provide essential grid support.
- In the **ALT scenario**, more natural gas capacity (both baseload and turbines) and less renewable and storage capacity is added compared to the REF scenario, and some coal capacity retirements are delayed in later years.
- Less solar capacity generally leads to lower total capacity needed due to the technology's low contribution to capacity reserve requirements.



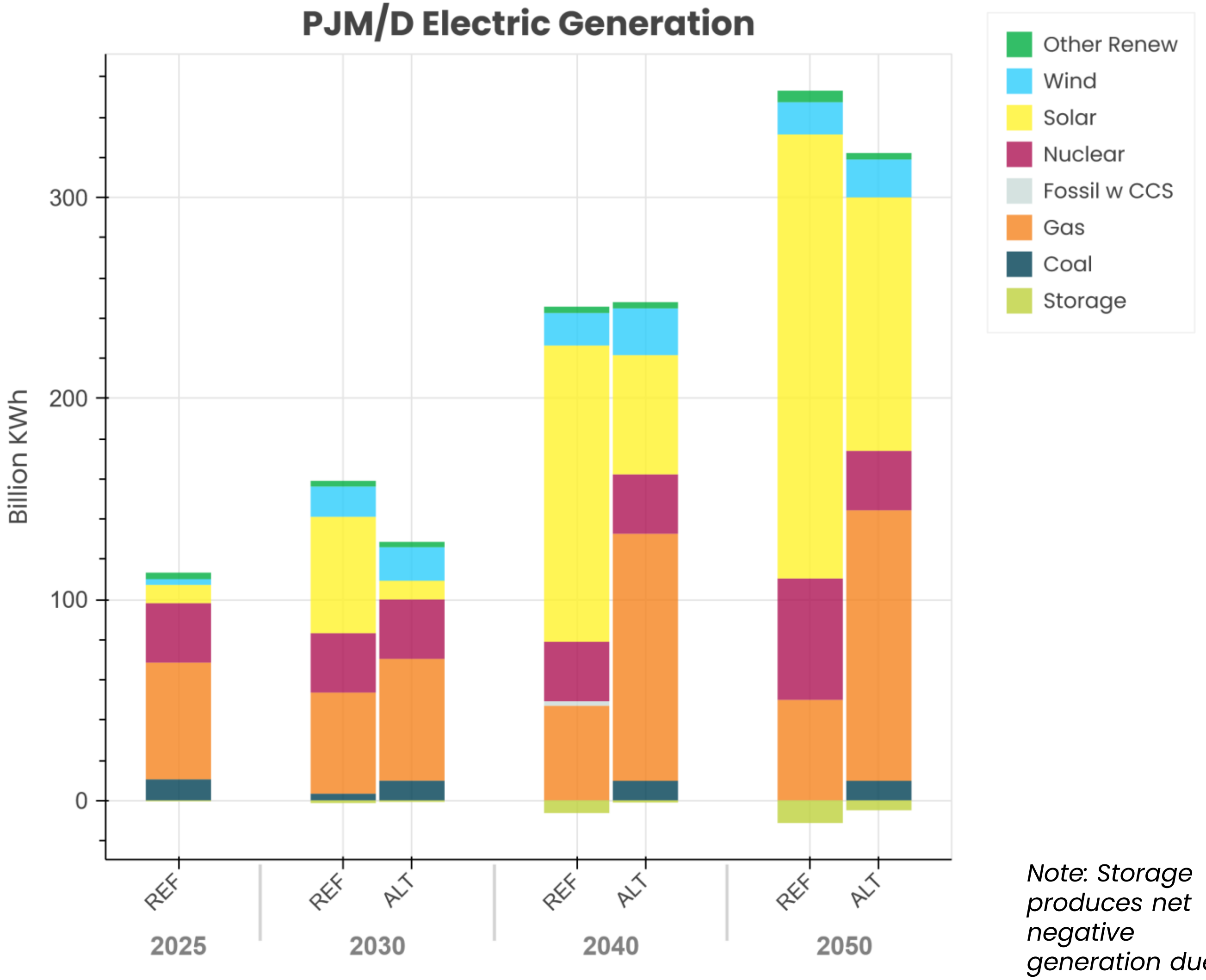
Source: OnLocation OL24-NEMS

Electricity Generation in PJM/D Region

- In 2023, PJM/Dominion in Virginia accounted for 20% of national electricity demand from data centers.

- There are significant differences in the PJM/D future generation mix between the two scenarios:
  - The **REF scenario** results in significant additions of solar generation over time and declining fossil generation. After 2040, there is also added nuclear generation from small modular reactors.

  - The **ALT scenario** results in significant additions of new natural gas generation as well as a smaller amount of solar generation, while preserving existing coal and nuclear generation.



Source: OnLocation OL24-NEMS

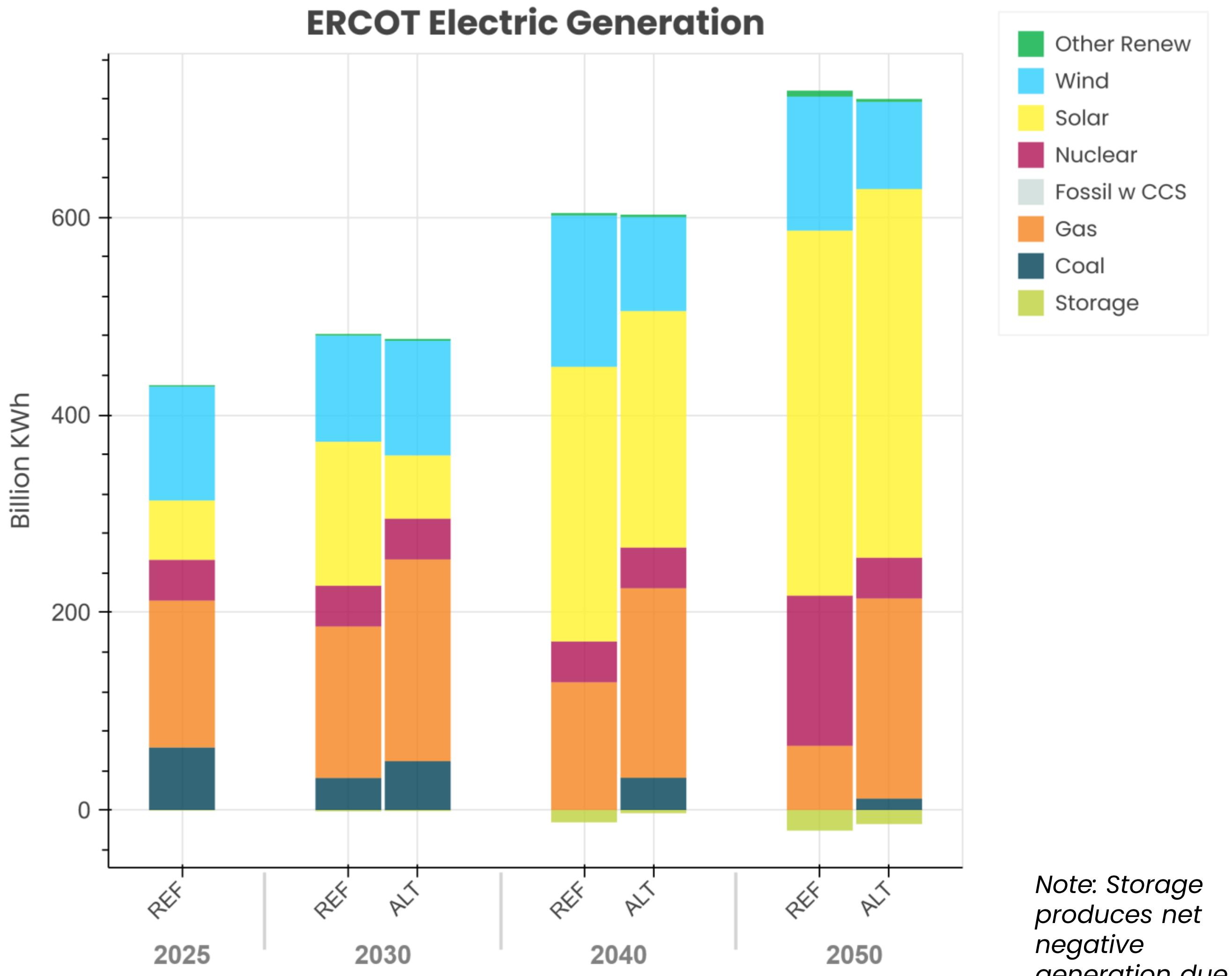
Note: Storage produces net negative generation due to energy losses.

Electricity Generation in ERCOT Region

- In 2023, ERCOT (Texas) accounted for 14% of national data center electricity demand. ERCOT has limited ability to trade with neighboring regions, so building new capacity is critical for meeting increasing demand.

- Scenario differences include:
  - The **REF scenario** results in a faster buildout of solar and wind as well as new nuclear generation after 2040, to replace a declining share of fossil generation.

  - The **ALT scenario** results in more natural gas and less renewables compared to the REF scenario. No new nuclear generation is added in this scenario as gas provides enough baseload power.



Source: OnLocation OL24-NEMS

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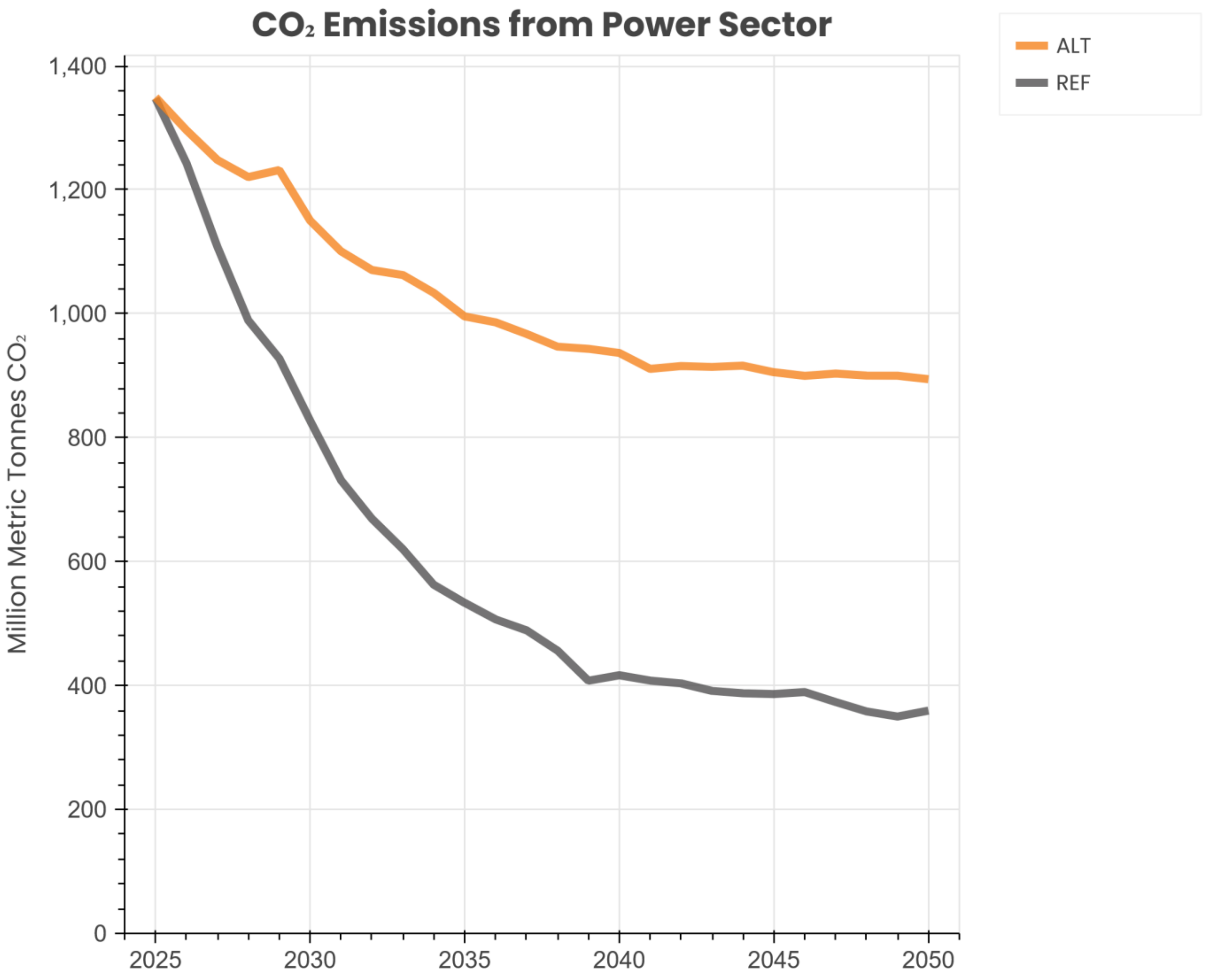
Implications for CO_2 Emissions

- In **both scenarios**, annual CO_2 emissions in the power sector decline over time, even with rising demand, as fossil generation is replaced by lower-emitting sources, particularly renewable energy.
- The increase in fossil generation in the **ALT scenario** due to the absence of IRA and EPA policies leads to slower reductions in emissions over time. By 2050, the ALT scenario results in almost 900 million metric tonnes (MMT) of CO_2 emissions compared to less than 400 MMT in the **REF scenario**.
- Providing more support for low-emitting technologies such as carbon capture and nuclear power could narrow this gap in future emissions reductions.



Source: OnLocation OL24-NEMS

Key Takeaways

Data center demand growth continues to be a driving force in the U.S. and will require new investments in electric generation and transmission.

The future generation mix will depend on the regulations and policies that will influence capacity investments and utilization of energy sources.

Multiple energy sources will be essential for meeting the growing demand for data centers:

- **Fossil generation**, including coal and natural gas, provides reliable baseload generation.
- **Nuclear generation**, especially small modular reactors, has captured the attention of some data center developers and could be a valuable baseload option in the longer term.
- **Renewable generation**, especially solar photovoltaics and wind, will continue to be a low-cost option in many regions.
- **Battery storage** extends the availability of renewable generation and enhances grid reliability.

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Priority Questions and Further Research Needs

- This analysis is **a first step** in highlighting how the energy plans made by utilities and data center developers may change over time due to potential changes in policy incentives and regulations. As policies and data center projections evolve, so will the need for **additional modeling and analysis**.

- Other priority questions include:
  - How will the natural gas infrastructure grow to accommodate new demand?
  - Will new energy sources be supplied by the electric grid or behind-the-meter? How will this change the preferred generation mix?
  - How will various criteria impact location choice of data centers – low cost and available electricity, workforce requirements, internet infrastructure, proximity to customers, etc.?
  - What is the likely impact on electricity rates especially for residential customers?

Modeling and Analysis Caveats

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Scope of Analysis

1. **Time Horizon**: The projections extend to 2050, and longer-term implications beyond this period are not considered.
2. **Spatial Coverage**: This analysis is focused on U.S. energy markets and assumes business-as-usual policies in the rest of the world.
3. **Technological Development**: While the model is comprehensive, not all emerging technologies are fully represented. Assumptions about future technological advancements and their adoption rates are speculative and subject to significant uncertainty.
4. **Modeling Challenges**: As with all models, OL24-NEMS is an economic abstraction of the energy industry and may not fully reflect the complexities associated with significant energy transitions including electric grid reliability and infrastructure buildout.

Modeling Framework

1. **Model Enhancements and Updates:** The model includes several enhancements over the AEO 2023 baseline, such as improved carbon capture technology and hydrogen market representations. These enhancements are based on current knowledge and might need revision as new data becomes available.
2. **Policy Assumptions:** Scenarios assume continuation and full implementation of current laws and regulations unless otherwise noted. Any changes in policy direction could significantly alter projected outcomes.
3. **Economic Assumptions:** Macroeconomic growth rates, natural gas supply and prices, and other economic projections could vary with market fluctuations and policy changes.
4. **Consumer Behavior**: Assumptions about consumer acceptance of new technologies, such as electric vehicles and small modular reactors, are uncertain and may not materialize as projected.

Data Center Assumptions

1. **Current Data Center Demands**: Even current demands are uncertain with an almost 2-fold estimated range in published sources.
2. **Projected Regional Data Center Growth**: For simplicity, growth in data centers is assumed to occur evenly, and demand remains concentrated in several regions. Infrastructure limitations, generation resources, electricity prices, and other factors may lead to future shifts in data center locations.
3. **Central vs. On-site Generation**: Grid-based power sources are assumed in this analysis. While critical for reliability, backup generation is likely to be infrequently used and is not explicitly modeled.
4. **Data Center Operations and Electricity Loads**: Data center loads are assumed to be fairly constant throughout the day and year as the most cost-effective method of operations given their capital intensity. Alternative patterns of operations, including participation in utility demand side management programs, could affect their grid impact.

2025
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