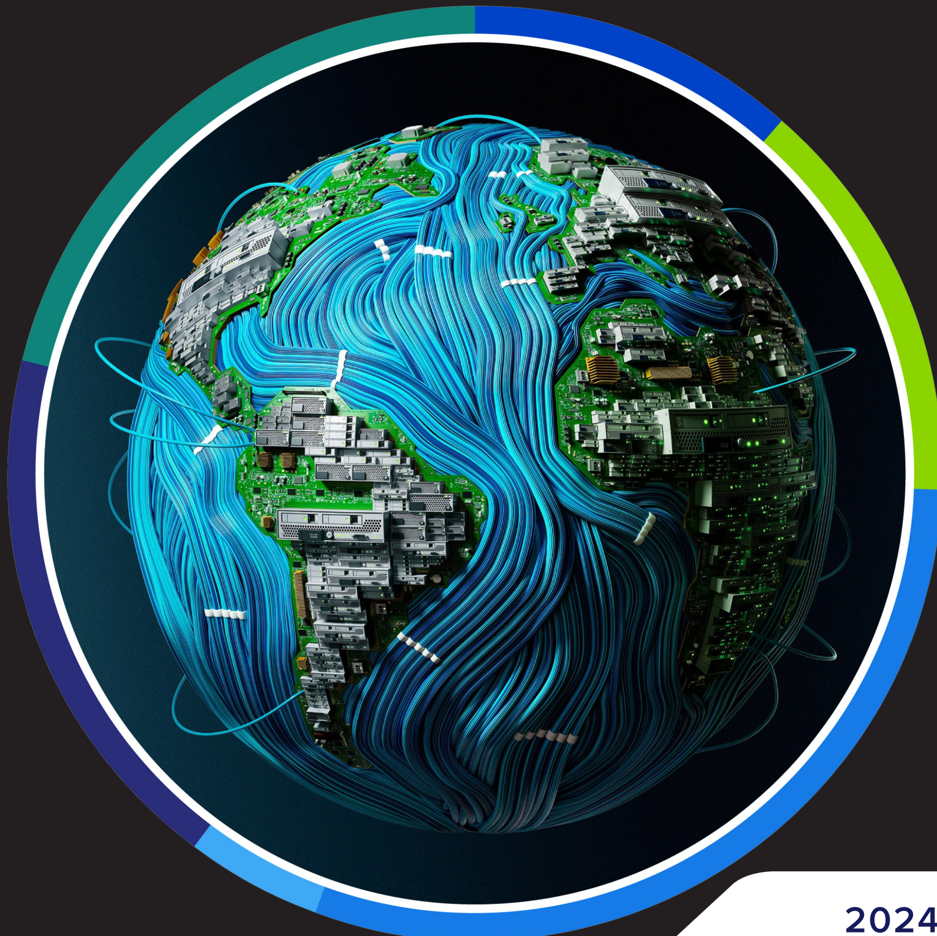

2024 White Paper

Powering Data Centers

U.S. Energy System and Emissions Impacts of Growing Loads

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EXECUTIVE SUMMARY

Data center (DC) activity and electricity use have increased rapidly in recent years and are expected to grow significantly in the years ahead, especially with emerging applications of artificial intelligence (AI) for commercial and consumer use as well as growing demand from small-scale data centers, large-scale commercial data centers, and cryptocurrency mining. The need for power has become a critical consideration for DC and AI growth with multi-year connection lead times, demand for reliable electricity, and company emissions targets all creating the potential for regional electricity supply challenges. However, projections of electricity consumption from these fast-moving technologies remain uncertain. Responses to anticipated load growth include both new investments by electric companies and direct power acquisition by DC developers. Both can reflect corporate procurement preferences for clean energy, as seen for example with recently announced dedicated nuclear and geothermal projects. An earlier EPRI white paper discusses key considerations for DC impacts on the power sector and highlights key steps to support rapid DC expansion (EPRI, 2024a).

This paper builds on that effort, providing updated projections for future regional load growth from data centers; estimates of load growth from other sources including domestic manufacturing, end-use electrification, and electrolytic hydrogen; and analyses of how these loads could alter electric sector investment decisions and carbon dioxide (CO_2) emissions under a range of future policy (including current policy and economy-wide net-zero by 2050 cases) and corporate strategy scenarios.

Data center load growth scenarios were created using data from published estimates and bottom-up surveys of data center capacity. We establish an updated baseline and develop plausible scenarios for more rapid DC load growth on a regional level. There are many open questions around where future growth will occur. In some cases, DC siting will be driven by local transmission constraints, which are outside the scope of this analysis.

These DC load scenarios are used in EPRI's US-REGEN energy systems model to explore the impacts of DC load growth relative to a scenario with no new growth in DC electricity demand. Projections of other loads are endogenous in the model and consider factors such as relative costs of electric and fossil fuel technologies, technology incentives, and the cost of infrastructure buildout to support their use. US-REGEN produces estimates of additional capacity builds, generation, CO_2 emissions, and costs of meeting new DC load; implications of achieving corporate clean energy procurement targets; and the value of flexible DC load management. All scenarios include Inflation Reduction Act (IRA) incentives and final U.S. Environmental Protection Agency (EPA) rules on CO_2 emissions intensity standards for new and existing generation.

Key findings address four issues: load growth, power system impacts, CO_2 emissions, and costs.

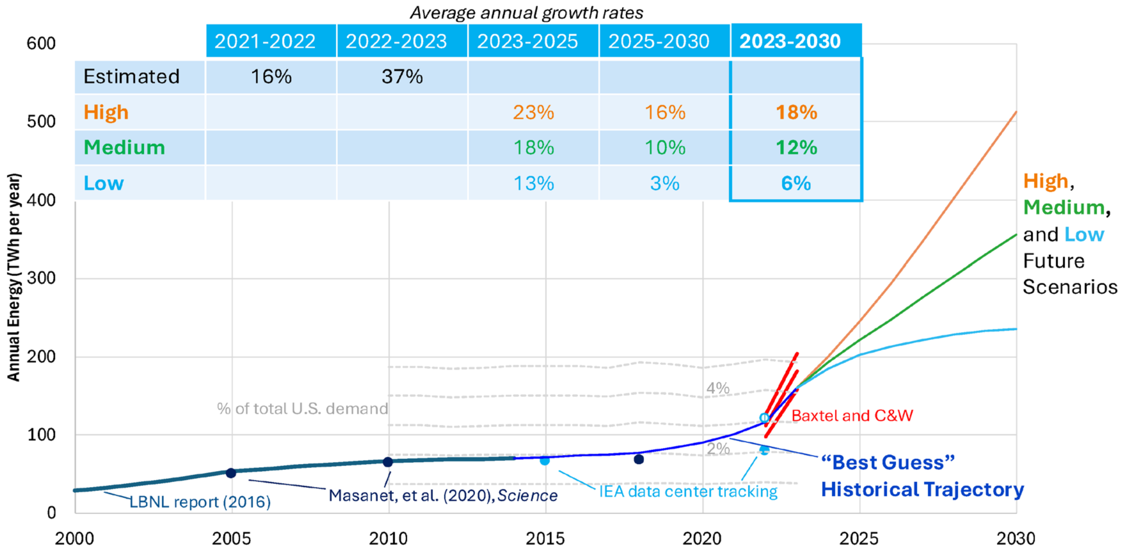


Figure ES-1. *Historical and projected electricity consumption from U.S. data centers through 2030. Estimates include small- and large-scale DC as well as cryptocurrency mining. Gray lines show electricity use as a share of total U.S. demand over time. Data for historical values are discussed in Figure 1. The table shows average annual growth rates across the three future scenarios.*

Electricity demand from data centers and other loads: Data center electricity use is higher than previously assumed and a key driver for near-term regional load growth (Figure ES-1).

- DC load comprised an estimated 4% of total U.S. electricity demand in 2023, doubling from around 2% in 2017. DC capacity is geographically concentrated in a few states. In 2023, the top 12 states accounted for 79% of total estimated DC electricity use and 84% of DC growth since 2020.
- The scale of future DC load is highly uncertain, and the scenario range in this analysis suggests that DC load could be one of several important emerging loads such as transportation electrification (Figure ES-2). Although uncertainty in other emerging loads is not considered in this analysis, electricity demand is projected to grow across all scenarios, and AI is expected to intensify and accelerate the need for new capacity. Across the scenarios in this analysis, DC load increases from around 4% of total U.S. electricity demand in 2023 to 5–11% in 2030. Total electricity demand including DC growth increases 30–46% by 2035 relative to current levels.
- Load growth is one of many emerging trends in policy, technology, and markets that shape future power sector outcomes. This study includes sensitivity cases around DC load growth but does not explore the full range of uncertainty across all these intersecting dimensions.

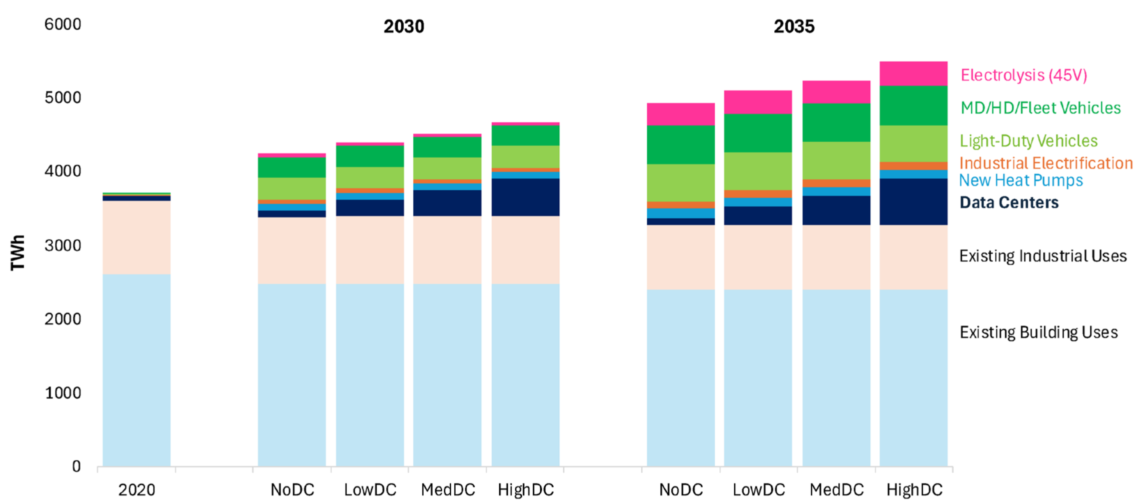


Figure ES-2. *Data center and other emerging loads under alternative DC load growth scenarios in 2030 and 2035. Outputs from EPRI's US-REGEN model under reference policies. 45V = Inflation Reduction Act clean hydrogen incentives; DC = data center; MD/HD = medium- and heavy-duty vehicles.*

Implications of DC load for power systems: Model results suggest that growth from DC and other loads drives deployment of new resources, but the extent and mix depend on assumptions about the policy environment, corporate clean electricity procurement targets, and DC load flexibility (Figure ES-3).

- Increasing DC loads drive new additions of generation capacity, especially natural gas-fired units to meet firm capacity requirements of higher peak loads, as well as solar PV in some regions. In the short run, increasing DC loads could also lead to higher utilization of existing fossil resources under current policies. In the longer run, DC load growth could be served by new lower-emitting resources after 2030, with increased deployment of solar, energy storage, wind, and natural gas regardless of the DC load scenario. In scenarios that assume economy-wide emissions policies and/or carbon-free electricity (CFE) procurement strategies, new capacity additions also include carbon capture and new nuclear, albeit with higher costs. The national average premium for hourly matched CFE is estimated to be \$14–\$25 per MWh above electricity generation prices.

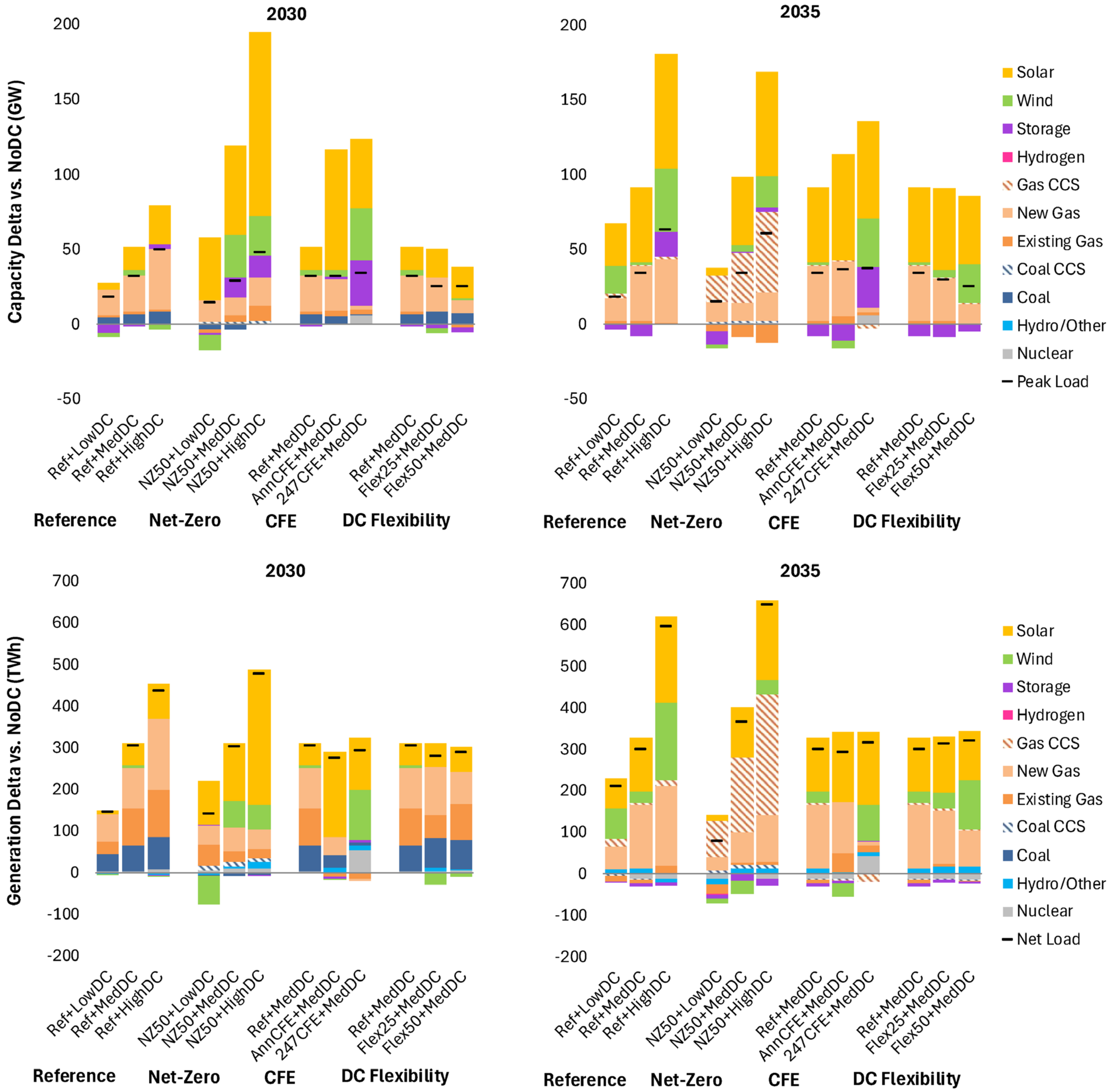


Figure ES-3. *Change in U.S. capacity and generation (top and bottom panels, respectively) relative to the corresponding "NoDC" scenario with no new DC electricity demand growth across all DC growth and policy scenarios. Values are shown for 2030 and 2035 (left and right panels, respectively). See Table 1 for scenario definitions.*

- The least-cost incremental resource mix to meet new DC load with the required reliability levels is primarily new gas and solar in the long run for many scenarios. High costs can make it challenging to scale emerging technologies to meet near-term DC demand, but with cost declines over time alongside potential policy incentives and corporate procurement targets, these emerging technologies could play larger roles. Growing electricity demands supported by corporate climate actions could help finance early deployment and learning for these technologies.
- Flexible DC load may reduce the need for incremental firm capacity, resulting in increased utilization of existing coal and natural gas capacity in the short run and higher shares of solar and wind by 2035 to meet DC electricity demand. Flexibility to shift DC load reduces the national average cost of power supplied to DCs by $4–7/MWh, and significantly more in some regions. These sensitivities highlight how enabling potential flexibility of DC operations can help meet both climate and affordability goals.
- All modeled scenarios in this analysis indicate extensive additions and retirements of electricity generation and energy storage resources over the next decade regardless of DC load (Figure 9). All scenarios add over 600 GW by 2035 (compared to installed capacity of around 1,200 GW in 2023), which highlights the importance of resolving headwinds to capacity deployment to meet growing demand and respond to other technology and policy drivers of change.

Emissions impacts of growing DC load: In all scenarios, CO_2 emissions decline significantly over time as coal capacity retires and new low-emitting capacity is added (Figure ES-4); however, near-term DC load growth may induce more near-term CO_2 emissions from increased utilization of existing coal- and gas-fired capacity.

- The marginal CO_2 emissions intensity of incremental generation for DC load declines over time and is 61-84% lower than the average intensity of the current grid by 2035. However, in the near term, the marginal CO_2 intensity of incremental DC load is higher than the current grid due to increased dispatch of existing coal and natural gas generation (Figure 18).
- CFE targets can significantly lower the emissions impacts of higher DC loads, especially with an hourly matching commitment (24/7 CFE). Relaxing hourly matching to allow annual CFE leads to more leakage with the procurement target and smaller impacts on consequential generation and emissions relative to the hourly 24/7 CFE case.
- Overall, DC loads have more limited emissions impacts than other factors such as state and federal policy.

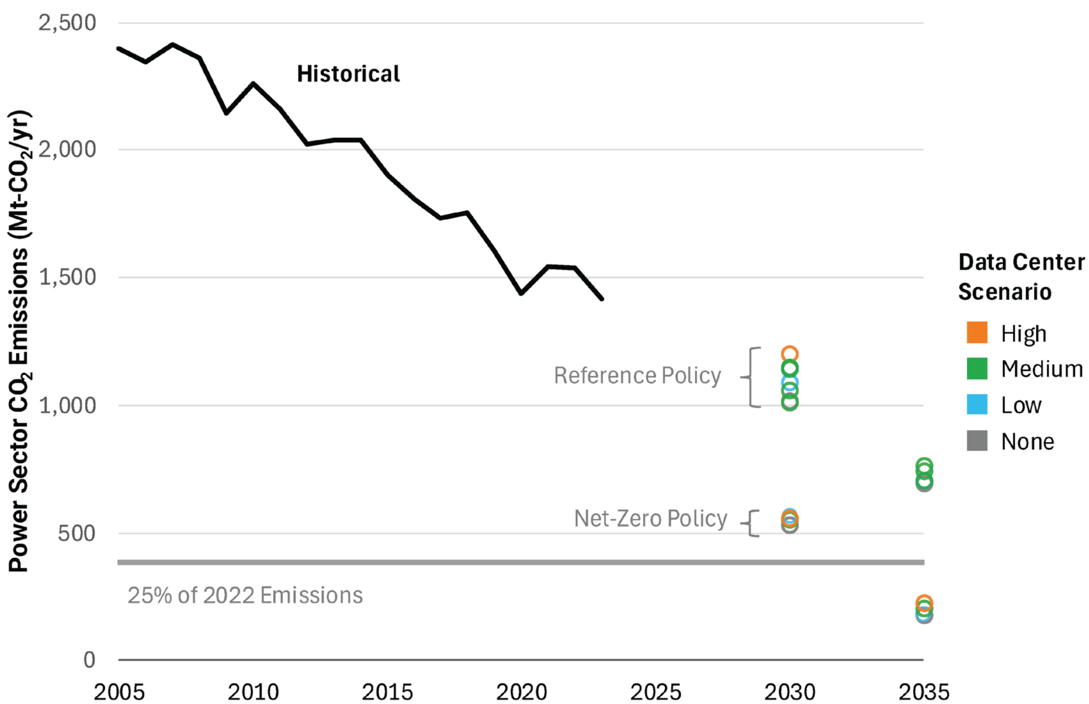


Figure ES-4. *Power sector CO_2 emissions over time by scenario. Projected values show scenarios across data center load assumptions. Historical emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks." The 25% of 2022 emissions line is the threshold where power sector Inflation Reduction Act tax credits begin to expire.*

Cost and price impacts of DC load growth: Incremental capital and operating costs increase roughly proportionally with the scale of DC electricity demands, leading to minimal generation price impacts relative to the "NoDC" scenario with no new growth in DC electricity demand (Figure ES-5).

- With reference policies, incremental expenditures net of IRA incentives relative to the no DC growth scenario range from $90 to $254 billion through 2035 (undiscounted real 2023 dollar terms). Incremental fiscal outlays for IRA incentives range from $20 to $70 billion.
- Procuring electricity with a CFE target entails higher costs than in the reference scenario, particularly in the near term. The CFE premium (or attribute certificate price) varies by region, with a national average of $11/MWh for annually matched CFE and $25/MWh for 24/7 CFE in 2030 (expressed in real 2023 dollars).
- While the modeled impact on system wholesale prices from incremental DC load is minimal, electricity prices may change over time due to other factors, such as commodity markets, inflation, and IRA incentives.
- Transmission and distribution costs to connect new DC loads to existing local grids were not modeled explicitly in this analysis and could vary by DC location relative to the existing grid. Especially for very large loads, investments in power delivery capacity may be necessary, which could lead to significant increases in cost and deployment time.

The power sector has navigated growing demand in the past, but the scale and speed of these expected changes combined with supply constraints can create regional challenges. Modeled long-run changes are conditional on large-scale capacity additions, which could be impacted by unanticipated barriers to deployment such as siting, permitting, interconnection, supply chain delays, or higher costs. These factors could change the incremental resource mix and emissions effects of growing DC loads. Meeting growing load affordably, reliably, and sustainably requires proactive planning, which can leverage growth in important emerging sectors—AI demand, transportation electrification, manufacturing—while scaling innovation in another—clean energy.

Caveat: These are "what-if" scenarios to investigate system interactions and insights about how near-term decisions and uncertainties could alter long-term power system outcomes. These projections of data center electricity use and modeled electric sector impacts should not be interpreted as forecasts or predictions.

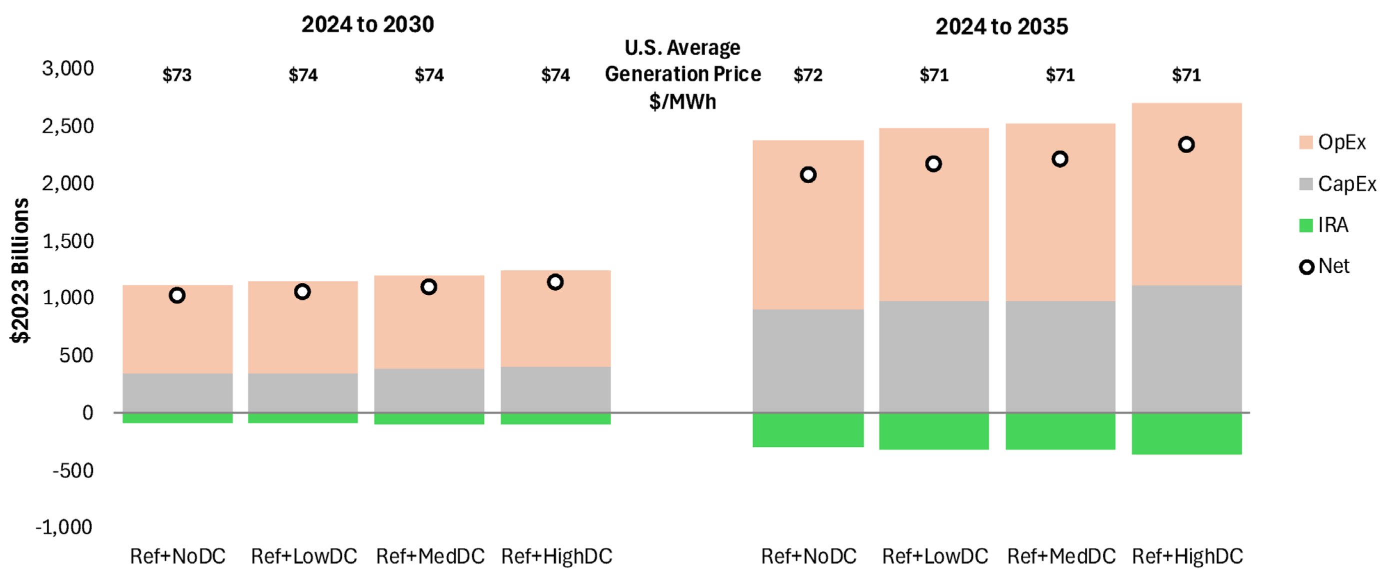


Figure ES-5. *Cumulative electric sector expenditures in DC load growth scenarios with reference policy through 2030 and 2035. Expenditures are broken into capital and operating costs (including fixed O&M) and shown gross and net of IRA incentives. Prices refer to the U.S. average generation-only wholesale price in 2030 and 2035, respectively. Costs and prices are shown in real 2023 dollars.*

INTRODUCTION

Data center (DC) activity and electricity use have increased rapidly in recent years and are expected to grow significantly in the years ahead (EPRI, 2024; IEA, 2024). DC operations is one of the fastest growing industries globally and especially in the United States, where half of all DCs were located as of March 2024 (EPRI, 2024).

Applications of artificial intelligence (AI) for commercial and consumer use are expected to be large drivers of future growth for DC services, especially with the increased use of generative AI tools such as OpenAI's ChatGPT that are more energy intensive than applications that have driven historical DC growth (e.g., data retrieval, communications, streaming)[1]. AI applications are estimated to comprise about 10-20% of U.S. DC electricity consumption today (EPRI, 2024a) and 0.1% of total global electricity demand (de Vries, 2023), and projected rapid growth in AI model development, training, and inference will come on top of demand growth from other commercial DC services and cryptocurrency mining. Due to both economies of scale and the exploding computational loads for successive generations of AI models, new "hyperscale" DCs are growing in size and are now being built with capacities from 100 to 1,000 megawatts (MW), which is approximately the electricity consumption from 80,000 to 800,000 homes (EPRI, 2024a). By contrast, the majority of DCs to date have been small-scale or enterprise facilities of 1-2 MW or less. A survey of utilities suggests that about half of survey respondents have DC interconnection requests of 1,000 MW or larger, and that half have requests that exceed 50% of their current system peak (EPRI, 2024b). New hyperscale DC capacity to meet emerging computational demand for AI and other services can potentially be brought online in one to two years, much faster than other large loads. The need for power has become a critical consideration for DC and AI growth with multi-year connection lead times, demand for reliable electricity, and company emissions targets all creating the potential for regional electricity supply challenges.

Future projections of electricity consumption from these fast-moving technologies remain uncertain due to several factors:[2]

- **Service demand growth**: The potential uses of AI and machine learning across the economy are highly uncertain alongside other DC uses. Moreover, improvements in algorithmic and computational efficiency of AI methods may offset some of this service demand growth.
- **Information technology (IT) equipment efficiency**: Historical DC load was roughly flat for almost a decade as efficiency gains offset increased processing demand (Figure 1).[3] IT equipment can consume roughly half of DC energy consumption depending on age, configuration, size, and type (EPRI, 2024a) and includes servers, storage systems, and network infrastructure.
- **Cooling system and auxiliary component efficiency**: Cooling systems and auxiliary components (e.g., uninterruptible power supplies, security, lighting) comprise approximately half of DC energy consumption for smaller data centers. Power Usage Effectiveness (PUE)—the ratio total energy use divided by IT equipment—has improved significantly over time (Donnellan, et al., 2023), though future DC cooling, as power intensity increases, may differ from conventional approaches.
- **Structural change**: Historical efficiencies also came from large cloud computing DC replacing smaller and relatively inefficient corporate facilities.

Increased DC loads come amid projected load growth from domestic manufacturing, end-use electrification, and electrolytic hydrogen production, which are trends amplified by Inflation Reduction Act (IRA) incentives (Bistline, et al., 2023; EPRI, 2023a). This anticipated growth represents a marked departure from the recent historical trend of relatively flat total load, which has raised questions about the ability of regional power systems to respond.

Electric companies need to determine appropriate near-term resource strategies to respond to anticipated but uncertain load growth while also balancing regulatory requirements, long-term transition targets, and reliability. In many cases, especially for very large point-source loads such as hyperscale DCs, required resource additions include transmission and distribution upgrades as well as new generation. At the same time, some DC service providers are looking for faster alternatives to power supply from the grid and exploring direct investment strategies for co-located generation assets. In some cases, direct power acquisition by DC developers is aligned with corporate procurement

1 McKinsey estimates that AI could add $11–18 trillion annually to the global economy with generative AI adding $2.6–4.4 trillion in economic benefits in the 63 use cases applied across several industries (McKinsey, 2023).

2 See Masanet, Lei, and Koomey (2024), Masanet, et al. (2020), and EPRI (2024a) for detailed discussions of historical and projected changes to these trends.

3 Globally, DC electricity consumption only increased by 20–70% between 2015 and 2022, despite traffic increasing by 600% and DC workloads by 340% (IEA, 2023).

targets for clean energy, leading to a range of proposed contracts based on renewable, energy storage, and nuclear technologies. These drivers are important considerations for assessing system-level impacts of growing DC load.

This paper aims to provide plausible projections for future regional load growth in the U.S. from data centers and other sources and to use an energy systems model to quantify how these loads could drive power generation investments and emissions under a range of future scenarios. The first objective is to establish an updated baseline and develop a range of scenarios for future DC regional load growth. These load projections are used in EPRI's US-REGEN energy systems model to provide context for DC load relative to other system changes; estimates of marginal capacity, generation, emissions, and cost impacts; implications of corporate clean energy procurement targets; and the value of flexible DC load management. This information may be valuable to DC owners and operators looking to understand how energy systems could evolve to meet DC demand, electric companies and system operators preparing for growing load, regulatory agencies considering policy design goals, technology companies developing resources to meet DC demand affordably and reliably, and investors assessing future market size.

LITERATURE REVIEW

An earlier EPRI white paper discusses key considerations for DC impacts on the power sector and provides three scenarios for DC load projections through 2030 (EPRI, 2024a). The paper highlights a few areas to support rapid DC expansion:

- Efficiency improvements and enhanced flexibility;
- Coordination between DC developers and electric companies; and
- Better modeling tools for planning grid investments to accommodate DC growth.

Although it provides quantitative estimates for DC loads at national and state levels, it does not perform modeling to understand how these higher loads could alter power sector investments, generation, and emissions. This study builds on the same underlying data to develop model-based scenarios for DC load growth and incorporate these projections in a scenario analysis with a detailed power sector and energy systems model, including estimates of load growth from other sources including domestic manufacturing, end-use electrification, and electrolytic hydrogen.

Broadly, data centers are one salient example of a trend altering electricity demand. Although the literature is vast on how other specific electricity demands and energy efficiency could alter power sector emissions and investments (e.g., Bistline and Blanford, 2023; White, et al., 2021; EPRI, 2015), **data centers are unique in their anticipated speed of deployment, limited expectations for growth even a few years ago, deep uncertainty about future trends, widespread use of backup systems to meet uptime requirements, and large size of these point sources**. Unlike earlier studies of system impacts of other loads, this study also accounts for changes in the policy environment and technological landscape that have potentially altered the regional marginal system responses, including IRA incentives, final EPA rules (including power plant emission performance standards for existing and new sources), updated state-level emissions and clean energy policies, and changes in technological cost (Bistline, et al., 2024; Bistline, et al., 2023). Recent analyses have incorporated DC load uncertainty into broader energy system scenarios (Jenkins, Farbes, and Jones, 2024; King, et al., 2024), though these analyses do not focus on DC-related scenarios and outputs. One recent study (de la Chesnaye, et al., 2024) conducts scenario analysis on three alternate DC load scenarios but does not examine sensitivities on alternate policy environments, corporate clean electricity commitments, or DC load flexibility.

CURRENT AND HISTORICAL U.S. DATA CENTER LOAD ESTIMATES

National data center electricity consumption in the U.S. can be estimated from public data sources using bottom-up analysis of hardware stocks, associated infrastructure, and operational characteristics and cross-checked with top-down data, though there are data limitations, reporting gaps, and uncertainty in each step of the estimation (Masanet, Lei, and Koomey, 2024). In this analysis, a point estimate of current and historical DC load was developed based on available data from a range of published studies and publicly available data sources for use as a starting point for creating alternative scenarios of future growth. Nonetheless, uncertainty remains about even the current magnitude of DC electricity use.

Estimates from earlier studies suggest that although DC load grew from 2000 and 2010, electricity consumption remained relatively flat between 2010 and 2018 despite growth in computational demand due to countervailing ef-

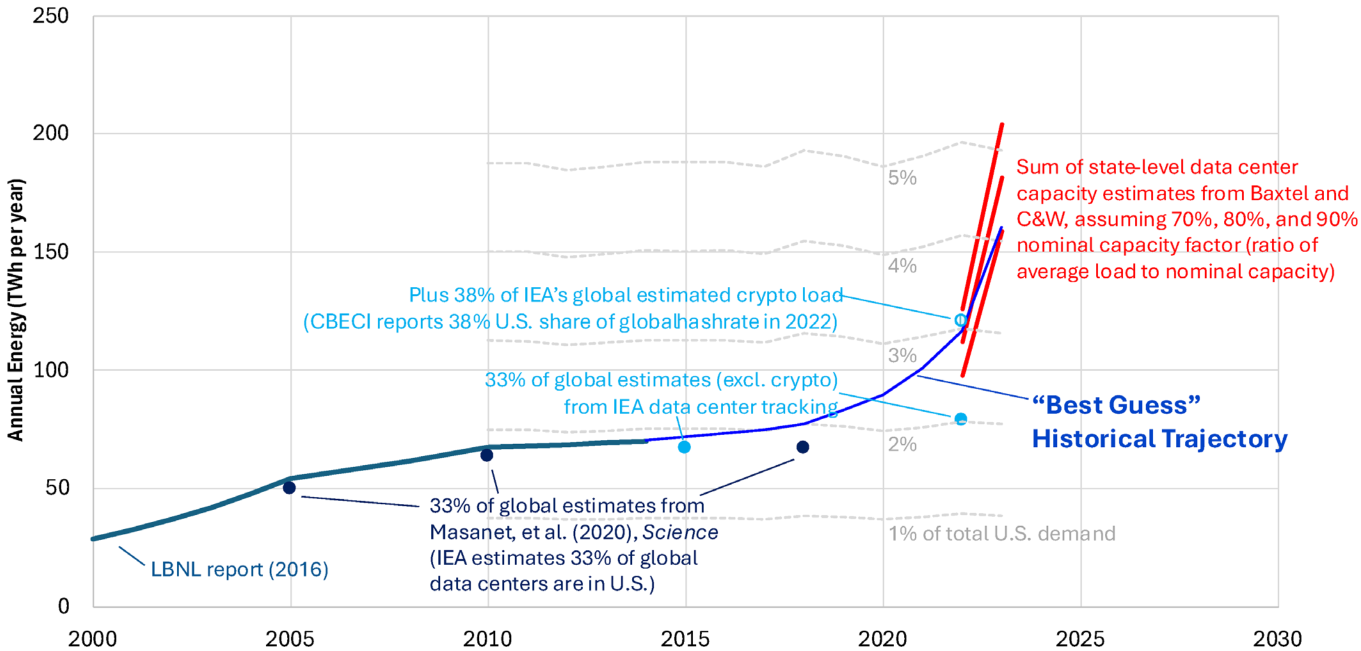


***Figure 1**. Historical estimates of electricity consumption from U.S. data centers. Gray lines show electricity use as a share of total U.S. demand over time. Estimates include small- and large-scale DC as well as cryptocurrency mining. Data before 2020 come from Shehabi, et al. (2016) and Masanet, et al. (2020). 2022 and 2023 estimates are based on IEA (2023) estimates of global DC electricity use as well as state-level DC capacity data from Baxtel (2024) and Cushman & Wakefield (2024) combined with alternate assumptions about average utilization, ranging from 70% to 90% nominal capacity factors*

ficiency gains and shifting toward more efficient cloud computing (Shehabi et al, 2016; Masanet et al, 2020) (Figure 1). DC load growth has likely increased in recent years due to combination of several emerging factors, including cryptocurrency mining, AI applications, and increased demand for streaming services and video conferencing, which COVID amplified (EPRI, 2021). Estimates from the IEA's data center tracking project suggest a roughly 60% increase in global DC energy use between 2015 and 2022, with the US representing roughly 33% of the global total (IEA, 2023). Additionally, data from the Cambridge Bitcoin Electricity Consumption Index (CBECI) indicate a surge of cryptocurrency mining activity in the U.S. in 2021, which saw the U.S. share of the global bitcoin hashrate (an indicator of mining activity) increase from around 5% to 38% (CBECI, 2024).

State-level data for nominal DC capacity from Baxtel[4] and Cushman & Wakefield[5] (Figure 2) can be used to estimate both recent growth rates and the scale and regional distribution of current energy consumption. Translating nominal capacity to energy use is not straightforward, as utilization rates vary significantly and rated power of installed nominal DC capacity is often much higher than actual workload power and average utilization (Govind, et al., 2023). Moreover, utilization and energy use often lags rapidly growing capacity installations. Still, Baxtel and C&W show increases of 60% or more in nominal capacity between 2022 and 2023, suggesting similar, if somewhat lower, growth rates in energy use. Assuming a range of 70-90% for nominal capacity factors (i.e., the ratio of average DC load, including electricity use for IT equipment, cooling systems, and auxiliary components, to nominal capacity, which typically refers to IT load only), these state level capacity estimates can be translated to estimated annual energy use that is consistent with scaled estimates from other studies. Connecting inferences from all of these sources into a "best guess" estimate of the historical trajectory, as illustrated in Figure 1, suggests that **DC load comprised roughly 4% of total U.S. electricity demand in 2023, doubling from around 2% in 2017**, despite largely flat total load.

4 Baxtel maintains a database of all DC facilities in the U.S., comprising over 2,500 facilities and currently over 28,000 MW of nominal power capacity.

5 Cushman & Wakefield (C&W) Global Data Center Market Comparison assesses capacity trends in key DC markets, including several in the U.S., but does not provide a comprehensive assessment of total capacity. In most cases, C&W estimates in assessed markets align closely with Baxtel estimates. Exceptions include Texas, where C&W shows lower capacity, possibly due to the exclusion of DCs linked to cryptocurrency mining (which are included in Baxtel); and other states including Arizona, Ohio, Oregon, and Virginia, where C&W shows higher capacity. Our estimates are based on the maximum of Baxtel and C&W state-level data in 2023.

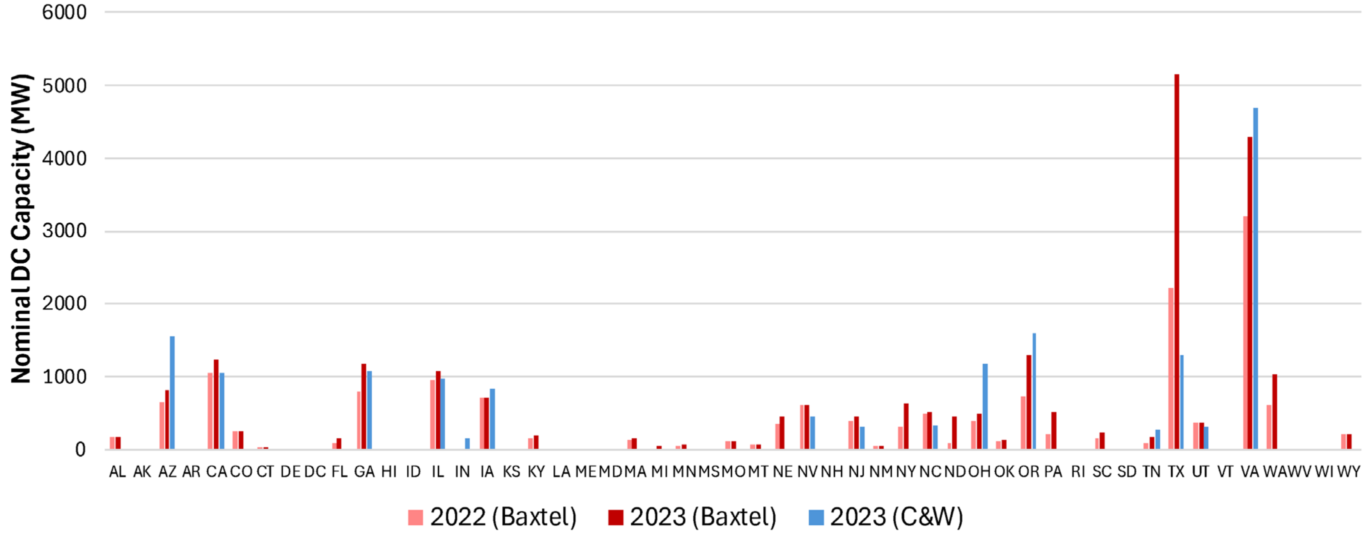


Figure 2*. Nominal DC capacity (MW) by state. Values are shown for 2022 Baxtel data, 2023 Baxtel data, and 2023 Cushman & Wakefield data. Note that nominal capacity refers to IT loads only (i.e., auxiliary loads for cooling and other infrastructure would be additional).*

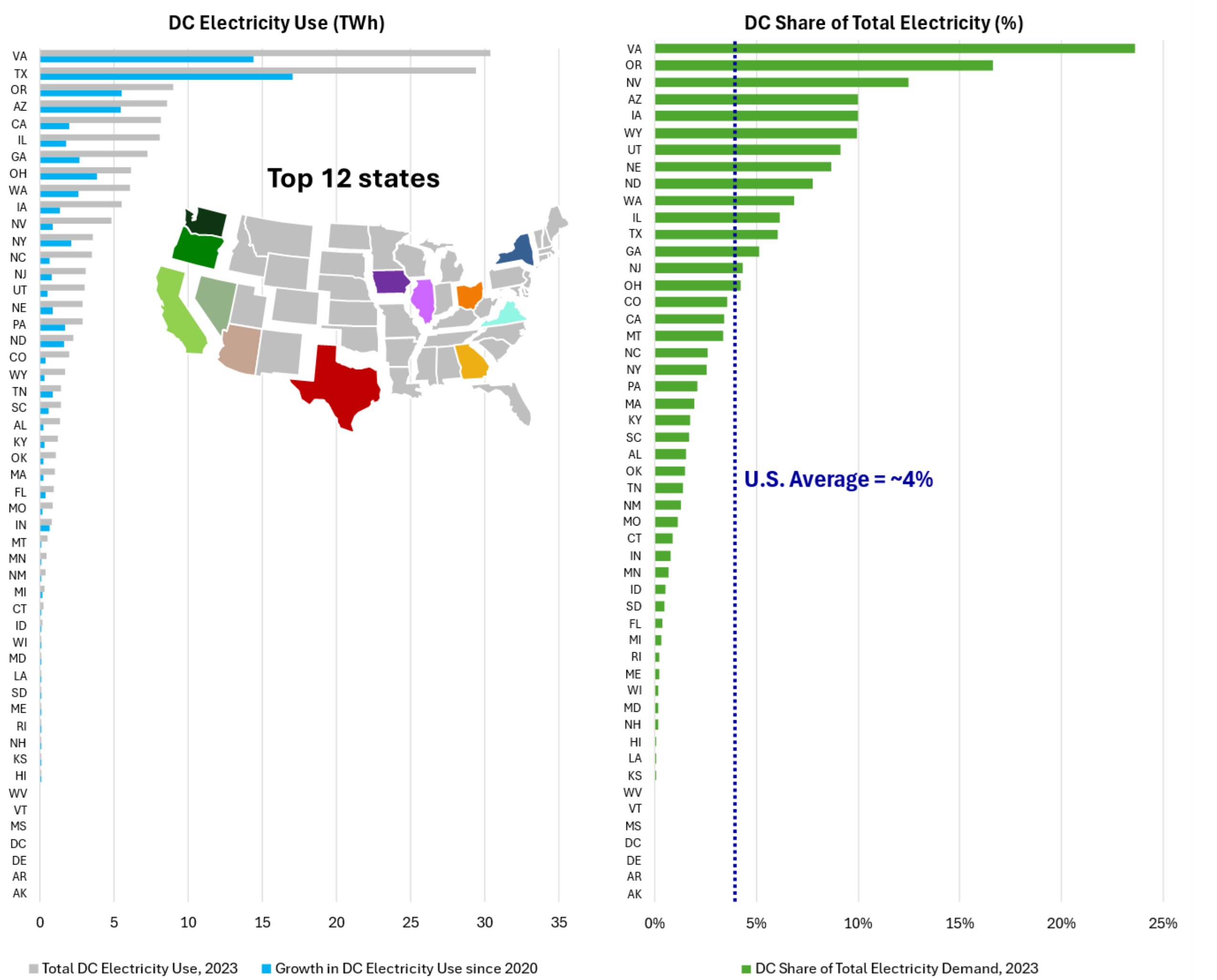


Figure 3*. State-level data center electricity use estimates. The left panel shows total data center electricity use in 2023 (gray) and growth since 2020 (blue). The right panel shows data center consumption as a share of total electricity demand in 2023. Calculations are based on 2022 Baxtel data, 2023 Baxtel data, and 2023 Cushman & Wakefield data as well as state-level electricity consumption from the U.S. Energy Information Administration.*

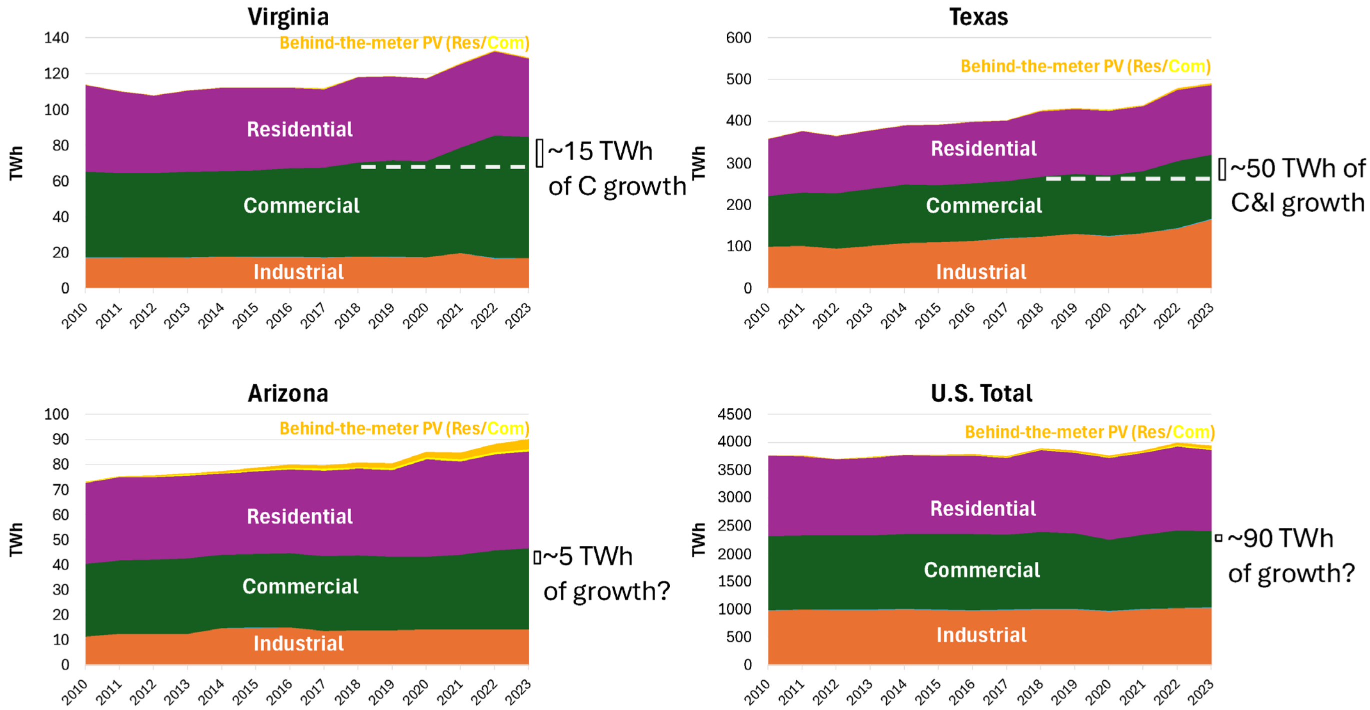


***Figure 4**. Annual electricity demand by sector over time for Virginia (top left), Texas (top right), Arizona (bottom left), and U.S. (bottom right). The Behind-the-meter PV areas refer to residential and commercial electricity use supplied directly by distributed solar, while the Residential and Commercial areas refer to retail sales of electricity supplied by the grid. Values are from the U.S. Energy Information Administration (EIA, 2024).*

DC capacity is geographically concentrated in a few states (Figure 2). Nominal capacity refers to reported rated power capacity for each facility, generally higher than observed average and peak load, especially during periods of rapid growth.[6] Our estimates translate capacity to energy based on state-level assumptions of capacity factor related to growth rate and cross-checked with trends in state-level total and sectoral electricity demand reported by the U.S. Energy Information Administration (EIA, 2024).

The top 12 states account for 79% of total DC electricity use and 84% of growth since 2020 (Figure 3). Virginia is the largest state for DC electricity use in absolute and relative terms—nearly a quarter of the state's 2023 electricity demand. These top markets greatly exceed the U.S. average, where **DC load comprises 4% of national electricity consumption in 2023**.

These bottom-up state-level estimates of DC electricity demand can be compared with aggregate electricity consumption data (Figure 4). For Virginia, the approximate increase of 15 TWh in DC annual load between 2020 and 2023 shown in Figure 3 appears to correspond closely to a commensurate increase in Virginia's commercial sector electricity use in Figure 4. Similarly, the observed growth of around 50 TWh in total commercial and industrial load in Texas, which also includes increased load from upstream oil and gas production and other drivers, is consistent with the estimated DC load increase of around 17 TWh. On the other hand, estimated growth from DC use in Arizona is more challenging to discern from aggregate demand data, perhaps due to offsetting electricity decreases in commercial and industrial load during that three-year period.

Total electricity demand nationally has been relatively flat in recent years, despite notable increases in some regions, including those like Virginia experiencing DC growth. Moreover, at the national scale, estimated DC load growth from 2020-2023 of around 90 TWh or around 2% of total load is small enough to be masked by a variety of confounding factors. These include annual variations in weather-driven loads, economic cycles and disruptions, geographical shifting in DC demand as well as industrial activity and residential populations, and other offsetting decreases in non-DC demand from efficiency and structural change in other technologies and sectors.

6 For example, nominal capacity in the Dominion service territory (Virginia) in 2023 was estimated to be around 5 GW, while the aggregate peak of metered DC demand was around 3.1 GW (Dominion, 2023).

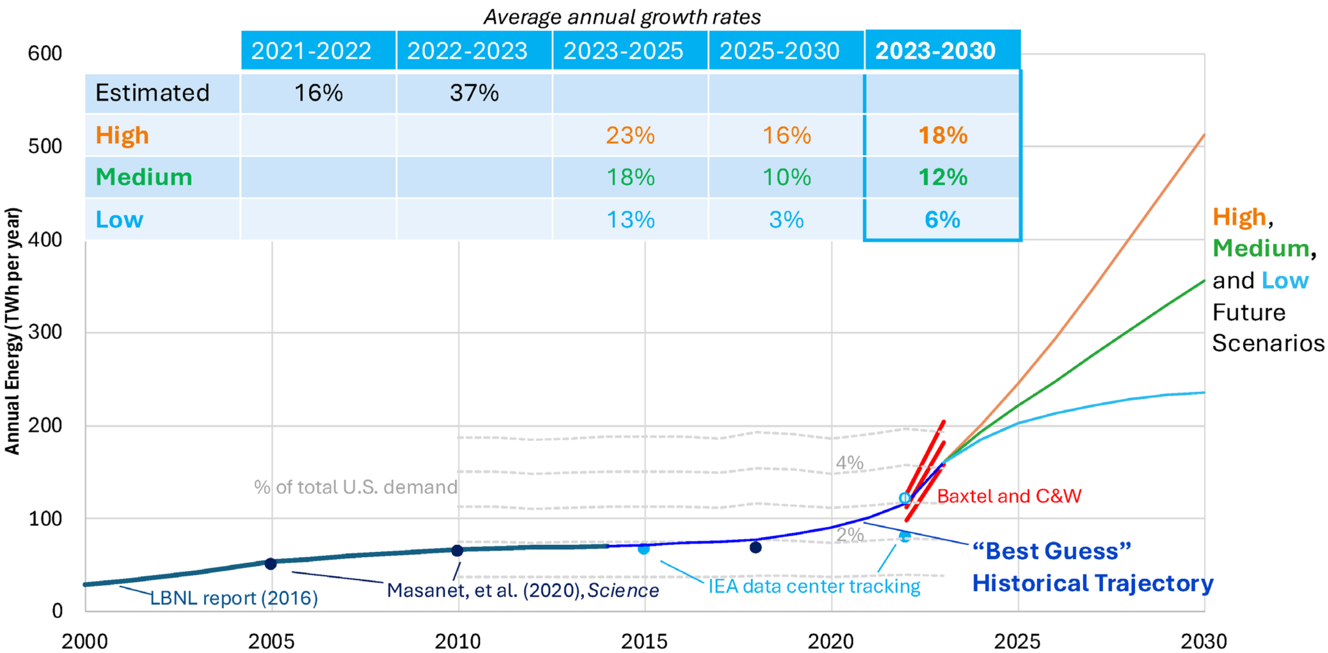
DATA CENTER ELECTRICITY USE PROJECTIONS

This section presents three scenarios for future electricity consumption for U.S. data centers using public information to estimate 2023 regional loads and constructing alternative scenarios for how growth rates evolve in coming years. These scenarios, summarized in Figure 5, span a range for total DC electricity use in 2030 that is consistent with the earlier EPRI white paper (EPRI, 2024a), which bases its projections on a range of external assessments. For this study, scenarios were defined in terms of decelerating annual growth rates relative to recent observations, which provides continuity with the historical trend while considering alternative future pathways. Although not based on a bottom-up assessment of the underlying drivers, the scenarios are broadly consistent with the following high-level narratives:

- **Low**: 6% average annual growth rate from 2023 to 2030, reflects a scenario where saturation of service demand, consolidation of industry and consumer activity around AI applications, and/or breakthroughs in algorithmic or hardware efficiency result in a relatively rapid slowing in data center load growth.
- **Medium**: 12% annual growth rate from 2023 to 2030, reflects a scenario with continued growth in service demand and application of AI models, partially offset by countervailing trends in efficiency and/or structural change in related sectors.
- **High**: 18% annual growth rate from 2023 to 2030, reflects a scenario in which rapid growth of recent years continues throughout the decade as an increasing number of players enter the AI space, expanding consumer applications and resulting in service demand growth outstripping efficiency improvements.

Scenarios described in the results section are run with these three sets of assumptions about DC load growth, as well as a reference scenario for comparison that assumes no new growth in DC electricity demand.

It is important to note that these projections are not based on utility permit applications. Extrapolations based on such applications are likely upper bounds on DC deployment, given the prevalence of duplicate and speculative projects from technology companies and land developers submitting multiple applications for the same project across multiple utility service territories (Masanet, Lei, and Koomey, 2024). Nor are these projections intended to reflect the full uncertainty range of possible outcomes for DC electricity demand in the U.S. Especially when considering uncertainty in current demand (suppressed for tractability in these scenarios) and the underlying uncertainty about future public demand for AI-based technologies, both higher and lower levels of future DC electricity demand than the range modeled here are possible.



Average annual growth rates

	2021-2022	2022-2023	2023-2025	2025-2030	**2023-2030**
Estimated	16%	37%			
High			23%	16%	**18%**
Medium			18%	10%	**12%**
Low			13%	3%	**6%**

Figure 5. *Historical and projected electricity consumption from U.S. data centers through 2030. Estimates include small- and large-scale DC as well as cryptocurrency mining. Gray lines show electricity use as a share of total U.S. demand over time. Data for historical values are discussed in Figure 1. The table shows average annual growth rates across the three future scenarios.*

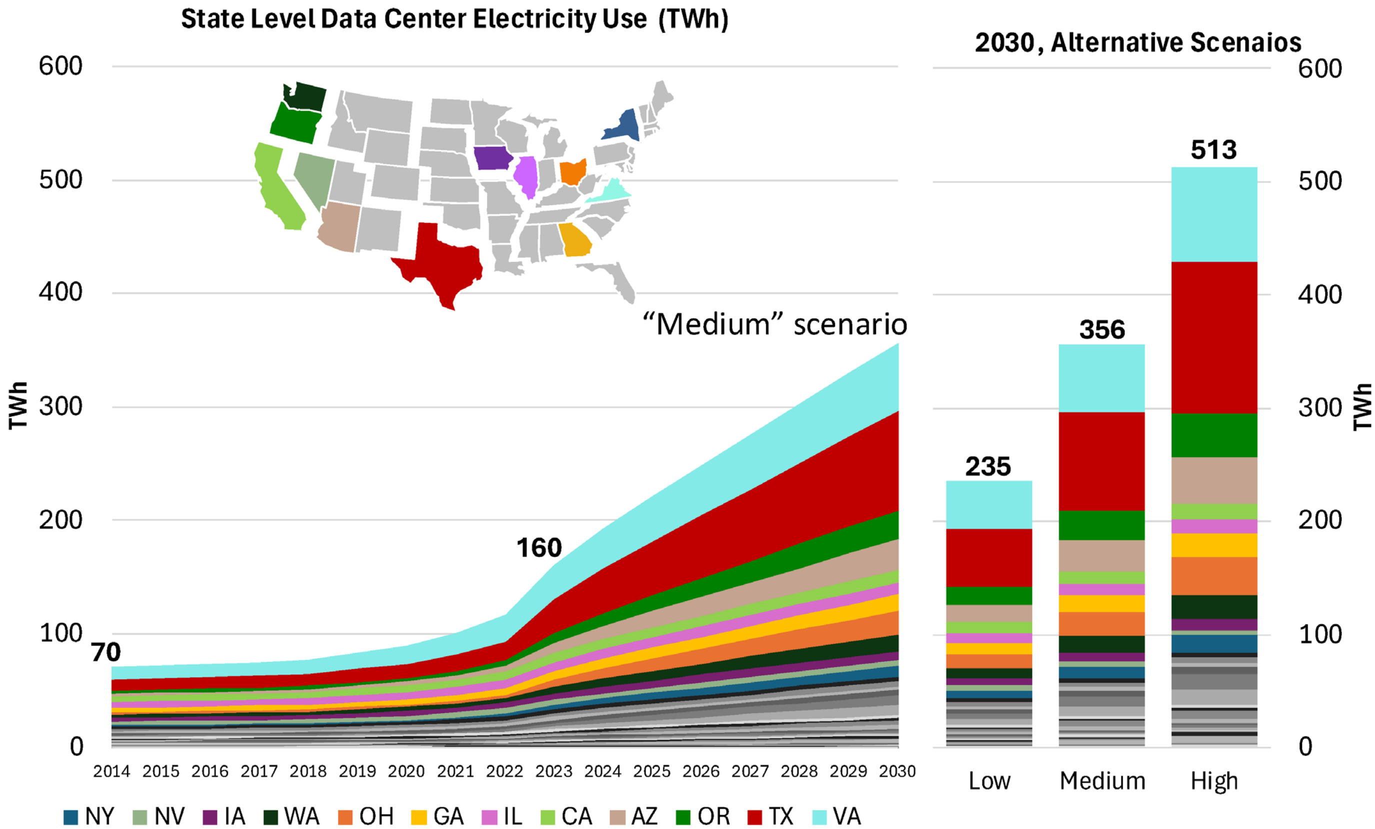


Figure 6. *State-level historical estimates and projected DC annual electricity use across scenarios. The panel on the left shows time-series data for the "Medium" DC load growth scenario, and the right panel compares 2030 values for the Low, Medium, and High scenarios.*

State-Level Data Center Projections

For this analysis, future growth of DC load was first estimated at the national level and then allocated across states based on recent state-level growth trends (Figure 6). **There is large uncertainty about the magnitude and regional allocation of future DC loads**, especially if siting decisions are driven by the availability of power, connection lead times, strength of internet connections, frequency of disruptive events, workforce availability, and other local factors. This analysis did not assess potential local transmission constraints and assumed that future growth is concentrated in currently emerging and established data center markets.

Data Center Hourly Load and Load Shapes

A key step for model implementation is the translation of projected annual DC electricity use to hourly load shapes. There is limited empirical data for the temporal pattern of actual power use for different DC configurations. This initial analysis assumes load shapes with high average utilization and slight seasonal/diurnal pattern (higher during the day and during the summer and lower at night and in the winter).[7] In reality, different types of DCs exhibit a variety of load patterns based on component configurations and system specifications, which may be temperature-dependent and have flexibility to respond to system conditions and incentives (e.g., AI model training and inference will differ from cryptocurrency mining). Some observations suggest that actual peak load at an individual facility may only rarely approach nominal peak inclusive of auxiliary loads (accounting for PUE), operating at a lower average utilization outside of moments of extreme demand, implying a relatively low load factor. At the same time, a diversified load shape aggregating multiple facilities in a region could exhibit a higher load factor to the extent that facility-level spikes are not coincident. Ultimately, there is a need for measured hardware power profiles on actual use and performance of real-world data center configurations and applications (Masanet, Lei, and Koomey, 2024).

Similar to the comparison of annual DC energy estimates with aggregate, state-level reported electricity use to cor-

7 To reflect daily and seasonal temperature fluctuations, the analysis uses refrigeration shapes from EPRI's Load Shape Library (version 8.0) as a proxy for fluctuations in electricity use for cooling equipment: https://loadshape.epri.com/.

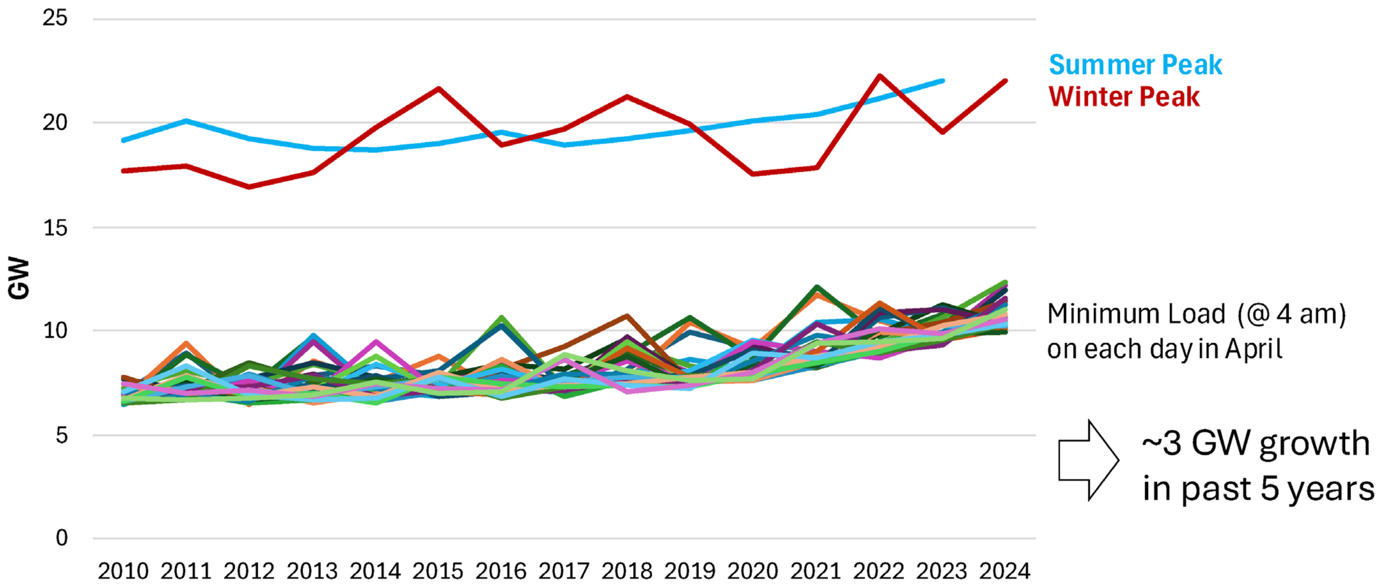


***Figure 7**. PJM-South (Dominion) balancing area load over time. Summer peak, winter peak, and minimum load for each day in April (EIA Form 930 reporting).*

roborate the magnitude of recent changes, the assumed load shapes and implied load factor (i.e. the ratio between average and peak load) can also be cross-checked with observations of regional hourly electricity demand. Figure 7 shows the change in both minimum and peak load in reported hourly load from 2010 through April 2024 for the PJM-South (Dominion) balancing area in Virginia. Although peak load varies significantly from year to year due to weather variability, minimum load during the shoulder month of April has a much smaller weather signal and provides a reasonable indication of system base load. For both peak and base load, there is a clear increase in recent years of roughly 3 GW, which is consistent with the 3.1 GW of metered DC load reported by Dominion mentioned earlier. Comparing this increase to the estimated increase of around 15 TWh of DC energy use in VA suggests a roughly 60% average load factor for new DC load.

Flexibility of Data Center Load

In most of the scenarios presented in this analysis, the DC load shape is assumed to be exogenous to the model, i.e. fixed to the assumed pattern described above. However, in some cases DC load may have flexibility to shift temporally to hours with a lower electricity price or other incentive linked to lowering system costs or providing system benefits. The extent and nature of a DC operator's flexibility likely varies significantly by DC type. The profitability and dispatch of cryptocurrency mining is known to be strongly linked to real-time electricity prices, while other applications such as movie streaming may be less price-responsive. The willingness and ability of DC load from AI applications to operate flexibly is an important open question, as is locational flexibility, especially for AI model training. In this analysis, two sensitivity cases are considered in which a fraction of DC load is assumed to be flexibly allocated across hours to minimize power costs, subject to constraints that annual total consumption is unchanged and peak load in any given hour does not exceed the peak of the exogenous shape. These scenarios are designed to illustrate the potential value of flexible DC load. Future work will continue to explore this question as more data enables a more granular representation of options for flexible DC operation.

SCENARIO ASSUMPTIONS

In addition to scenarios that vary the extent of DC load, this analysis also considers several other scenario dimensions (Table 1):

- **Policy environment**: DC load scenarios are run under a reference scenario with current policies, which includes Inflation Reduction Act incentives (Bistline, et al., 2024; Bistline, et al., 2023), finalized EPA power plant rules under Section 111 of the Clean Air Act, and state-level emissions and clean electricity policies. DC load scenarios are also run with a long-term, economy-wide net-zero CO_2 target by 2050 (EPRI, 2022a).
- **Procurement targets**: Some DC developers have corporate targets for emissions and carbon-free electricity (CFE), including companies with requirements for 24/7 CFE with temporal matching require-

ments (EPRI, 2022b). Sensitivity cases alter assumptions about how much of projected DC load is covered by a CFE target and whether it is matched on an annual or hourly basis.

- **Temporal flexibility**: Sensitivity cases vary the temporal flexibility of DC loads, allowing endogenous economic allocation across time segments.

Note that these scenarios do not assume any spatial flexibility in DC computational loads, which is discussed further below.

US-REGEN MODEL

This analysis was conducted using EPRI's US-REGEN model, an economy-wide energy systems model with a detailed representation of the power system, end-use sectors, and fuel transformation, storage, and delivery. A full description of the model's formulation and input assumptions can be found at us-regen-docs.epri.com.

***Table 1**. Summary of scenario abbreviations and descriptions.*

SCENARIO	DESCRIPTION
Ref+NoDC	Reference updated with IRA, new EPA 111(b) and 111(d) rules, but no data center growth (IRA and 111 assumptions are included in all subsequent scenarios)
Ref+LowDC	Reference with low data center load growth
Ref+MedDC	Reference with medium data center load growth
Ref+HighDC	Reference with high data center load growth
NZ50+NoDC	Economy-wide net-zero target for 2050 with optimistic assumptions for advanced nuclear, CO_2 transport and storage, inter-regional transmission, and bioenergy (no DC growth)
NZ50+LowDC	Net-zero target with low data center load growth
NZ50+MedDC	Net-zero target with medium data center load growth
NZ50+HighDC	Net-zero target with high data center load growth
Ref+MedDC+247CFE	Reference with medium DC load growth and 24/7 CFE target for all DC load by 2030
Ref+MedDC+AnnCFE	Reference with medium DC load growth and annual CFE target for all DC load by 2030
Ref+MedDC+Flex25	Reference with medium DC load growth and 25% of DC load flexible
Ref+MedDC+Flex50	Reference with medium DC load growth and 50% of DC load flexible

CFE = carbon-free electricity; DC = data center; EPA = Environmental Protection Agency; IRA = Inflation Reduction Act; NZ = net zero.

MODEL RESULTS

Electricity demand is projected to increase over the next decade, even before accounting for DC-driven growth (Figure 8). The relative scale of DC vis-à-vis other loads varies by scenario. Transport electrification—both from passenger vehicles and medium-/heavy-duty vehicles—exhibits significant growth through 2035 driven by declining costs of electric technologies and government incentives. There are also increases in industrial electrification, new heat pumps in buildings, and electrolytic hydrogen production.

The scenarios in this analysis all make similar assumptions about the drivers of adoption of these technologies and thus do not represent the full range of uncertainty in the evolution of these other emerging loads. DCs intensify the projected growth in electricity demand: **DC load increases from around 4% of total U.S. electricity demand in 2023 to 5-11% in 2030**. Total electricity demand increases 30-46% by 2035 relative to 2020 levels with over half of this growth from transport electrification and 6-25% from data centers.

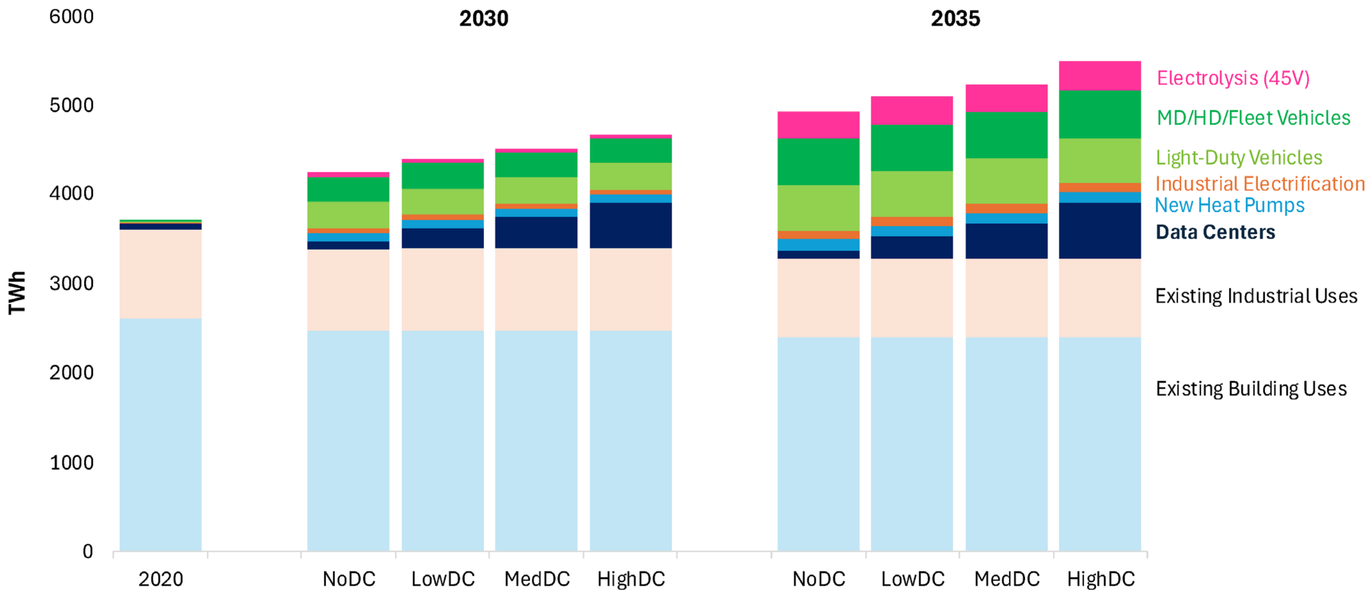


Figure 8. *Data center and other emerging loads under alternative DC load growth scenarios in 2030 and 2035. Outputs from EPRI's US-REGEN model under reference policies. 45V = Inflation Reduction Act clean hydrogen incentives; DC = data center; MD/HD = medium- and heavy-duty vehicles.*

Capacity and Generation in Scenarios with Reference Policies

Model results suggest that **there could be significant additions and retirements of electricity generation and energy storage resources over the next decade regardless of DC load** (Figure 9). Additions of solar, wind, and energy storage capacity accelerate after 2030, supported by IRA incentives (Bistline, et al., 2023). There are also large natural gas-fired additions across all scenarios, which reflects the least-cost resource mix to meet load under current policies and fuel costs. All scenarios add over 600 GW of new electric generation capacity by 2035 (compared to installed capacity of about 1,200 GW in 2023), which highlights the importance of resolving headwinds to capacity deployment to meet

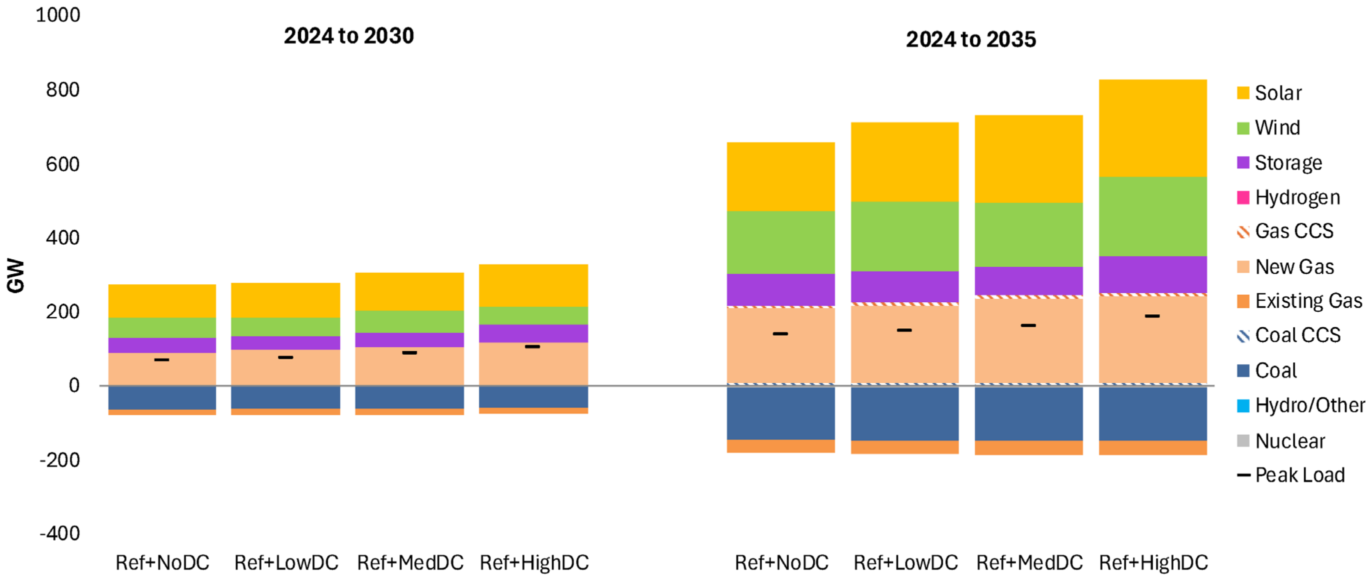


***Figure 9**. U.S. total new capacity additions and retirements by technology and DC scenario. Bars show capacity changes from 2024-2030 and 2024-2035. Both panels show significant capacity additions and retirements irrespective of the scale of DC load growth.*

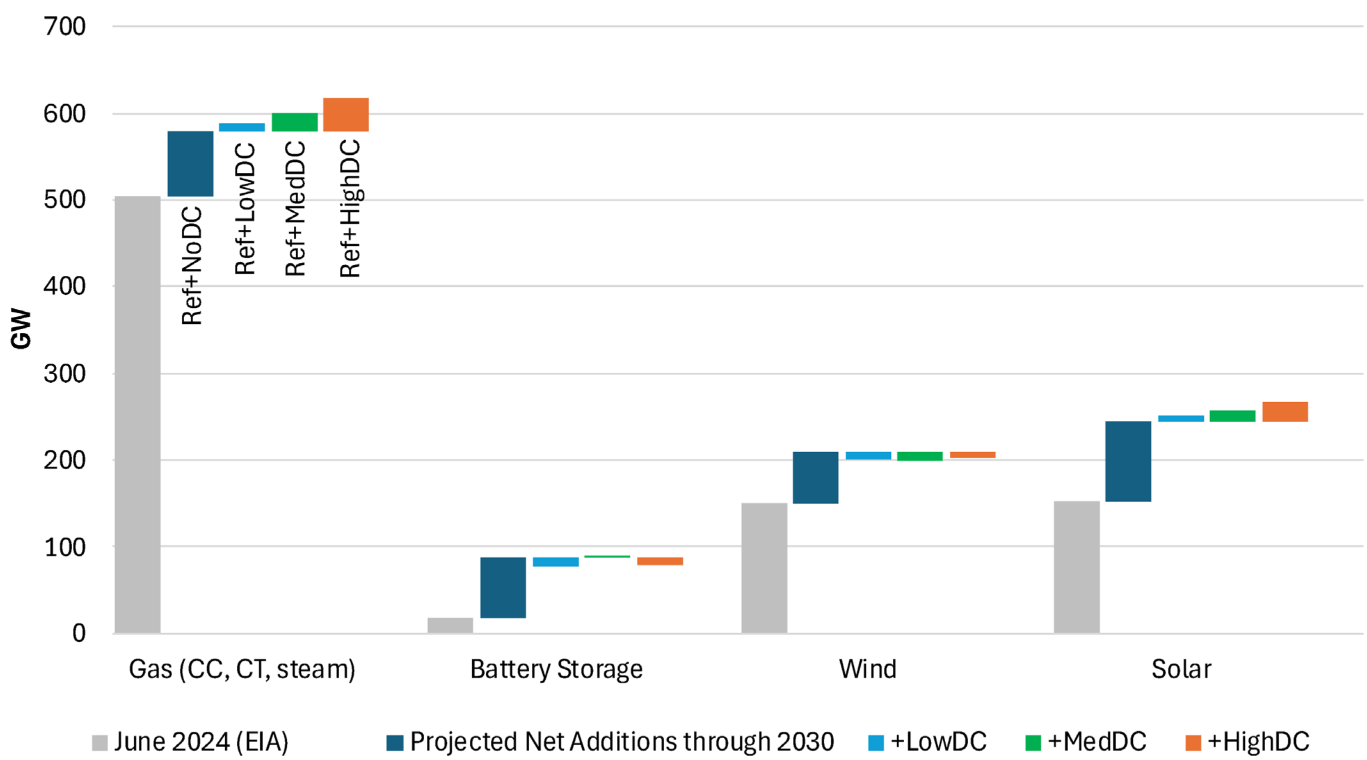


***Figure 10**. Existing capacity by technology and net additions through 2030. Waterfalls show projected net additions (i.e., new capacity installations less retirements) across different DC load growth scenarios.*

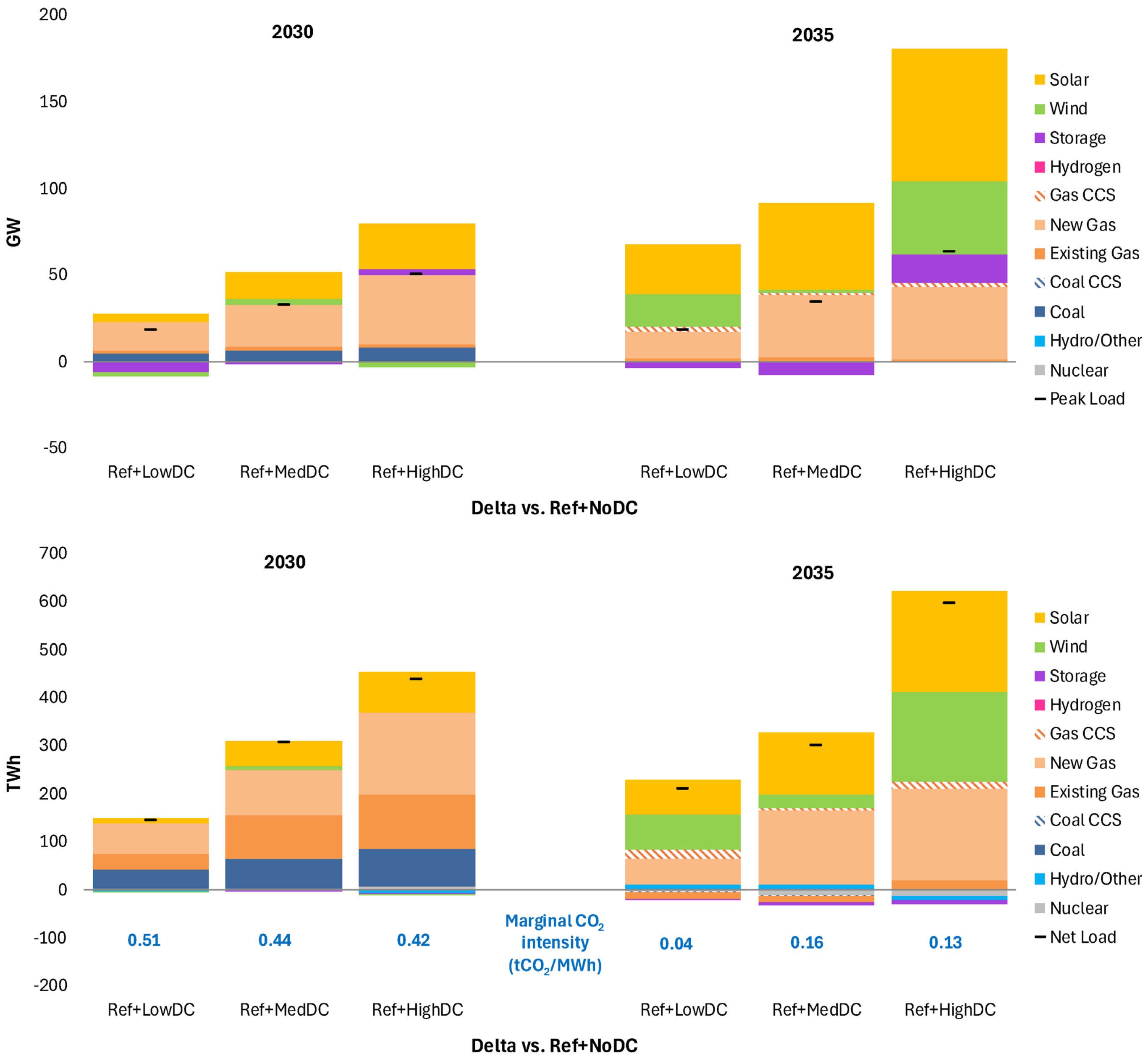


Figure 11*. Change in U.S. capacity and generation (top and bottom panels, respectively) with reference policies relative to the "NoDC" scenario for data center growth scenarios. Values are shown for 2030 and 2035 (left and right panels, respectively).*

growing demand. Retirements of coal-fired capacity reflect company announcements, lower economic competitiveness, and EPA's power plant rules, though planned retirements could be delayed with higher electricity demand.

Figure 10 puts these capacity additions in the context of current installed capacity for key technology categories. Higher DC loads across scenarios are mostly met through additional natural gas and solar capacity, though there is considerable new capacity of both even without new DC loads. Although battery storage expands rapidly in all scenarios, higher DC loads do not necessarily increase storage deployment relative to the no DC growth scenario, since system changes from DC load shapes may not increase revenues to potential storage projects. This is especially true if DC loads are assumed to be flexible, which may act as a substitute for energy storage (as discussed in subsequent sections).

In the near term, higher DC loads increase investment in and generation from new natural gas-fired capacity and some new solar, as well as existing gas and coal with current policies (Figure 11), where delayed retirements occur even with EPA's power plant rules. In the longer term, after

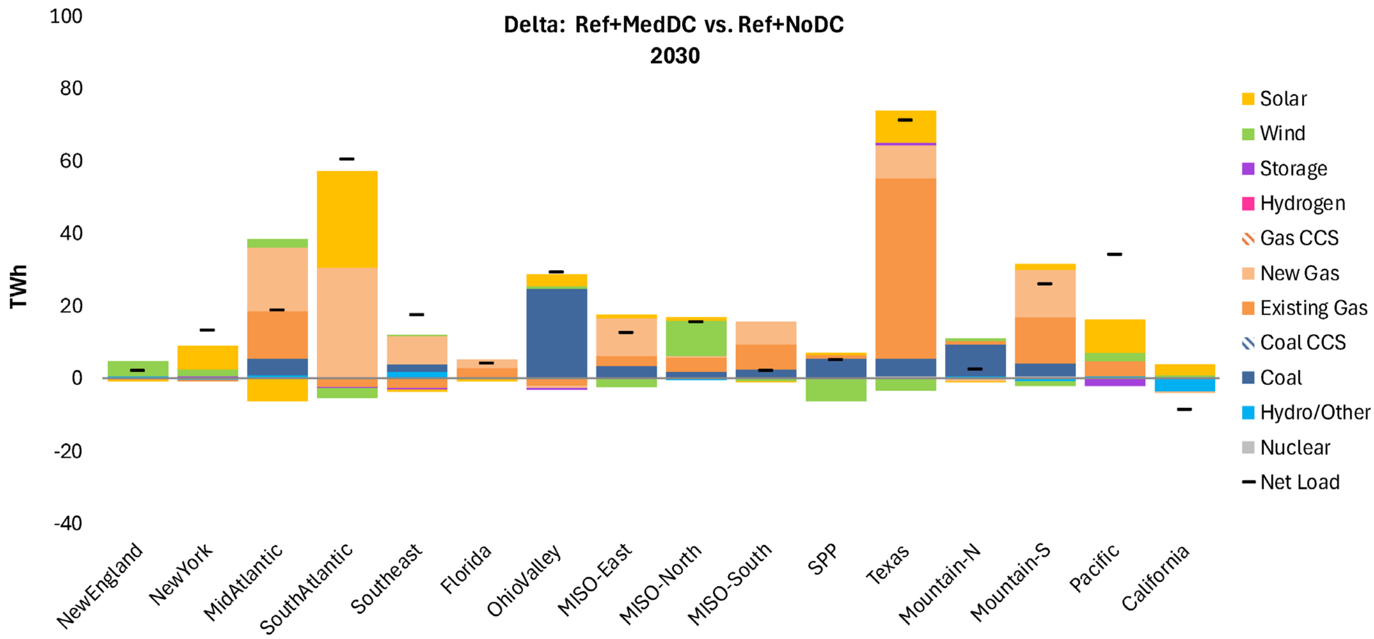


Figure 12. *Change in regional generation with reference policies for the "Med-DC" scenario relative to the "NoDC" scenario in 2030. Values are shown for 2030 for each model region.*

2030, variable renewables and new gas dominate generation responses to higher DC load, leading to lower long-run emissions impacts. Incremental peak load is aligned with new firm capacity additions, primarily natural gas but also energy storage in some cases, to ensure resource adequacy to meet system balancing and reserve margin requirements.[8]

As shown at the bottom of the generation panel, the marginal CO_2 emissions intensity of generation to serve DC load declines over time. Total CO_2 emissions decline over time as coal capacity retires and new low-emitting capacity is added, though there are regional differences in these trends. We discuss emissions levels and intensities in the summary section later in the paper.

The regional impacts of growing DC loads vary significantly depending on the assumed locations of new DC demand as well as system characteristics, including resource availability and the existing capital stock (Figure 12). With reference policies, increased utilization of existing coal capacity is concentrated in the Ohio Valley region, while incremental load in the South Atlantic region is met with primarily new solar and natural gas, as well as imports from the MidAtlantic region. Increased demand in the Pacific region is partially met with increased imports from neighboring regions, partially supplied by incremental coal utilization in the Mountain-N region. While these results are modeled outcomes that could differ from real-world responses, they illustrate the importance of location in understanding the potential scale and nature of DC impacts to the power system.

8 This analysis includes planning reserve margins and enforces system balancing over representative hours in each region but does not conduct detailed resource adequacy or reliability assessments, which typically use more detailed modeling (e.g., greater spatial resolution, multiple weather years) and metrics. For example, see https://www.epri.com/resource-adequacy.

Capacity and Generation in Scenarios with Net-Zero Targets

With deeper economy-wide decarbonization policies, higher DC loads drive greater low-emitting electricity generation and capacity, both in the near and long term. **Net-zero targets are generally met with more renewables, energy storage, CCS, and nuclear**, even without additional DC loads.[9] Higher DC electricity demand induces significantly more natural gas with CCS and more solar relative to scenarios with reference policies (Figure 13). Adding new natural gas capacity can be consistent with long-run decarbonization targets, though unabated gas capacity can have lower capacity factors over time (EPRI, 2022a; Bistline and Young, 2022).

9 See EPRI (2022a) for deeper discussions of power sector impacts of economy-wide net-zero CO_2 targets: https://lcri-netzero.epri.com/. An updated version of this analysis will be published soon with updated policy and technology assumptions and a wider range of sensitivities, including DC load.

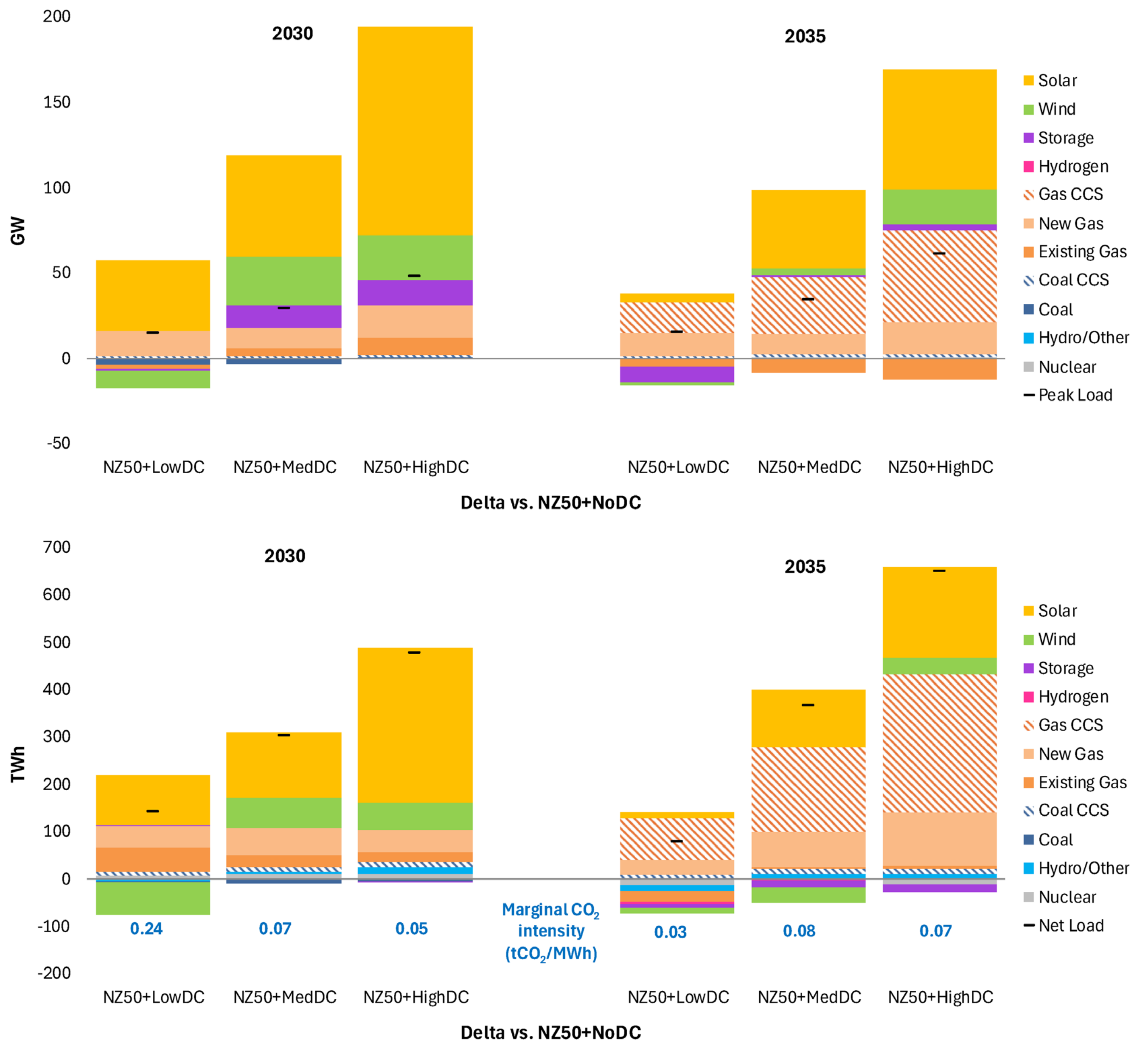


Figure 13. Change in U.S. capacity and generation (top and bottom panels, respectively) with net-zero policies relative to the "NoDC" scenario for data center growth scenarios. Values are shown for 2030 and 2035 (left and right panels, respectively).

Scenarios with Carbon-Free Electricity Procurement Targets

If DC load is covered by carbon-free electricity (CFE) procurement targets, capacity and generation responses can change in a few notable ways (Figure 14). With annually matched CFE targets, the incremental resource mix is similar to the reference scenario, with more solar capacity. Hourly matching requirements through a 24/7 CFE target drive very different resource changes, since the incremental resource mix must be both non-emitting and match the incremental DC load profile. The 24/7 CFE requirement leads to more variable renewables, considerably more energy storage capacity, and new nuclear in some regions. The assumed high load factor for DCs paired with 24/7 CFE targets creates a potential role for carbon-free baseload technologies like new nuclear, especially when considering the synergies of co-location for large point-source loads. However, least-cost mixes to supply DC power needs with hourly matched low-carbon energy are primarily comprised of renewables and battery storage, given the higher costs of other options in this timeframe. **Procuring electricity with a CFE target entails higher costs than in the reference scenario, particularly in the near term. The CFE premium (or attribute certificate price) varies by region, with a national average of $11/MWh for annually matched CFE and $25/MWh for 24/7 CFE in 2030 (expressed in real 2023 dollars)**. The premiums fall to $3 and $14, respectively, in 2035 as technology costs decline over time.

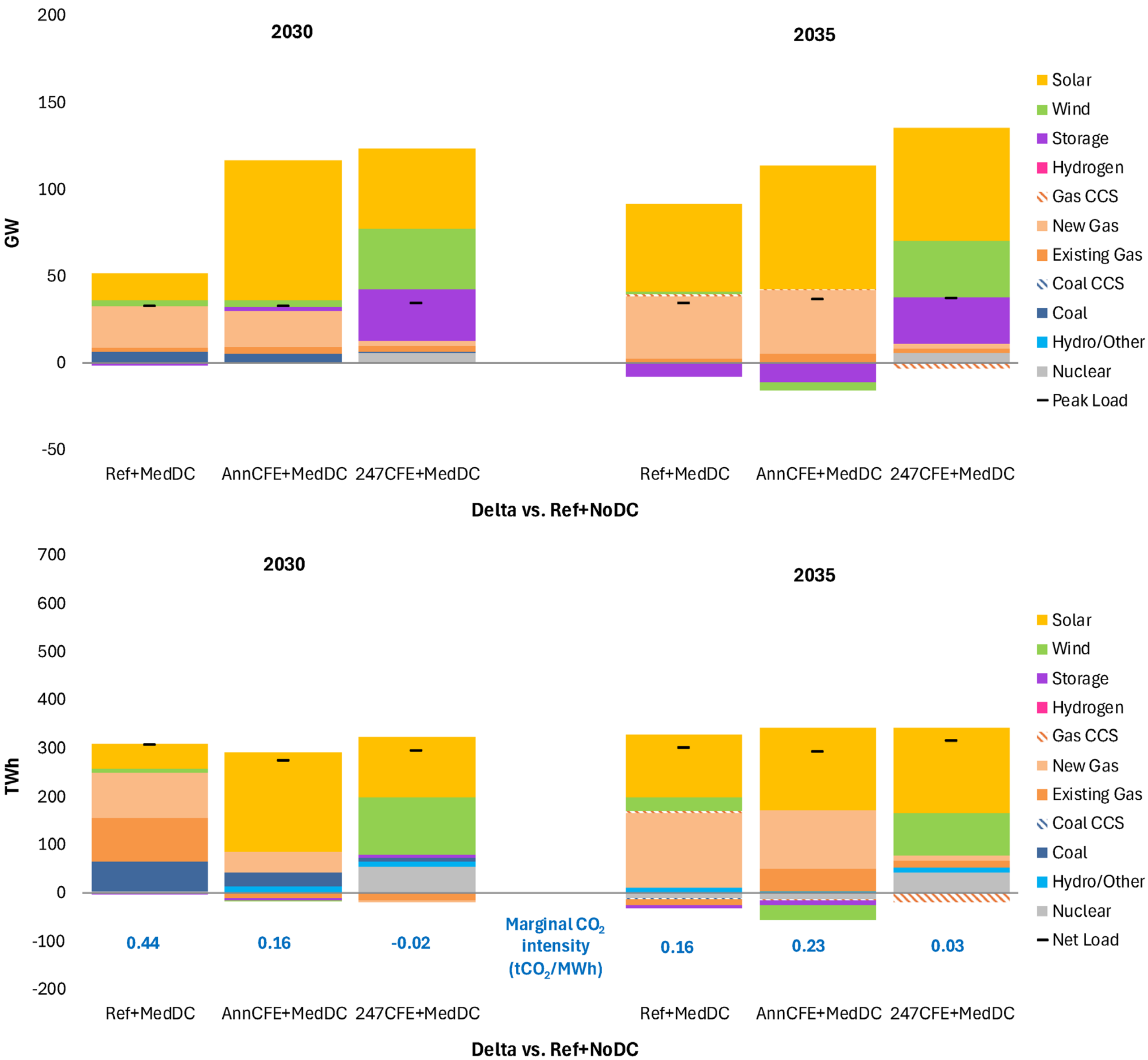


***Figure 14**. Change in U.S. capacity and generation (top and bottom panels, respectively) with annual and 24/7 CFE targets relative to the "NoDC" scenario for data center growth scenarios. Values are shown for 2030 and 2035 (left and right panels, respectively).*

Scenarios with Data Center Flexibility

To understand how DC load flexibility could alter the system mix and emissions, we conduct sensitivities that vary the share of DC load that can be allocated to other hours (25% and 50%), holding annual demand constant and subject to a constraint that hourly load not exceed the nominal peak DC capacity. Figure 15 shows how these illustrative flexibility scenarios alter DC load duration curves for the South Atlantic region in 2030, which includes Virginia.

Flexible DC demand lowers system peak demand by shifting DC load away from high demand periods, which leads to lower firm capacity buildouts, especially with 50% flexibility (Figure 16). More incremental generation comes from wind and solar with flexible DC loads and there are fewer gas capacity additions in the long run. However, in the short run, flexibility also allows for increased dispatch of existing capacity, leading to higher generation from existing coal and gas. Flexible demand also lowers energy storage investments, since this flexibility is a substitute for energy storage. **When DC load can be shifted temporally, the average price of power coinciding with DC consumption is reduced**. The U.S. average cost of power supplied to DCs is reduced by $4-5/MWh in the 25% Flexibility scenario and by $7/MWh in the 50% Flexibility case (expressed in real 2023 dollars). In some regions, the gains from flexibility are much more significant, with savings of up to $30/MWh.

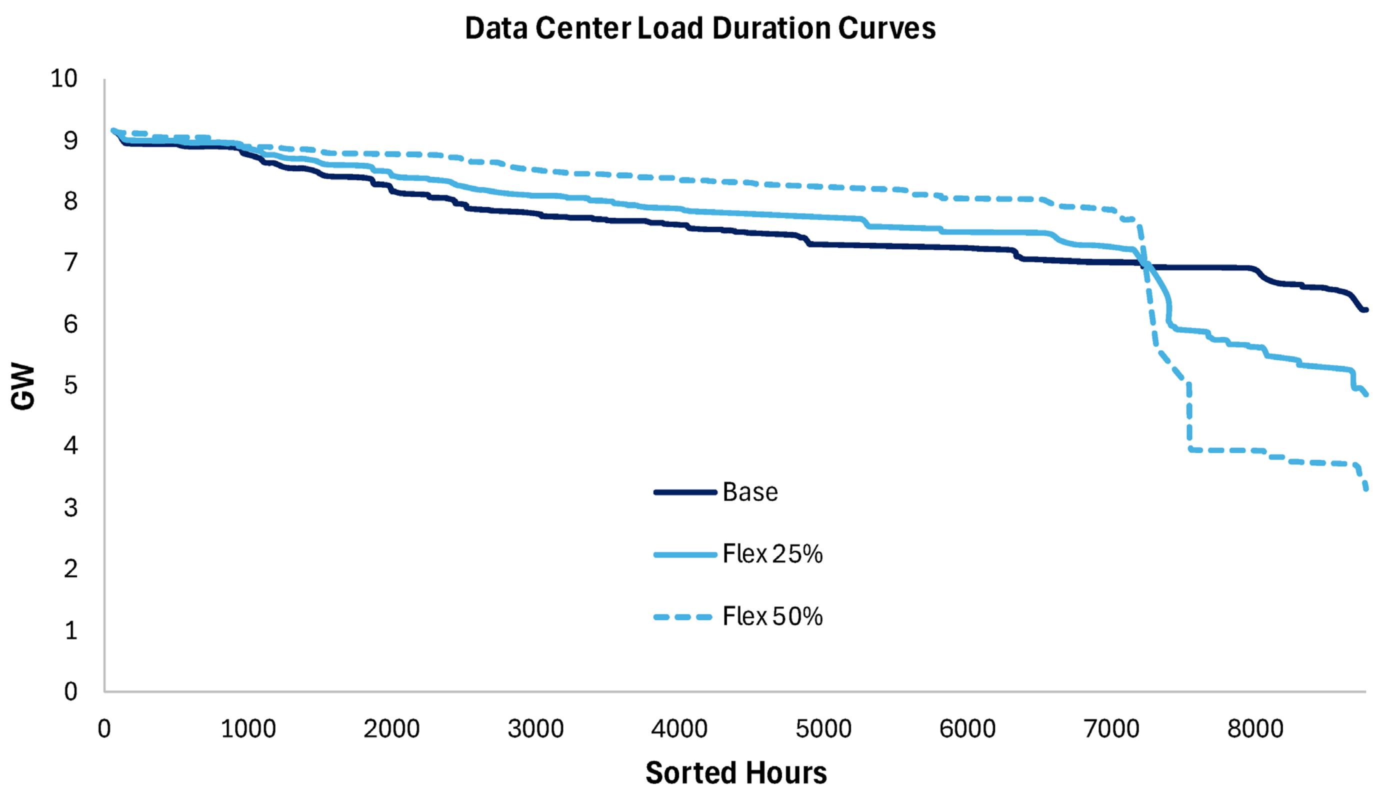


Figure 15. Data center load duration curves in 2030 without flexibility (Base) and in scenarios with 25% and 50% flexibility. Curves are shown for the South Atlantic model region (covering VA, NC, and SC).

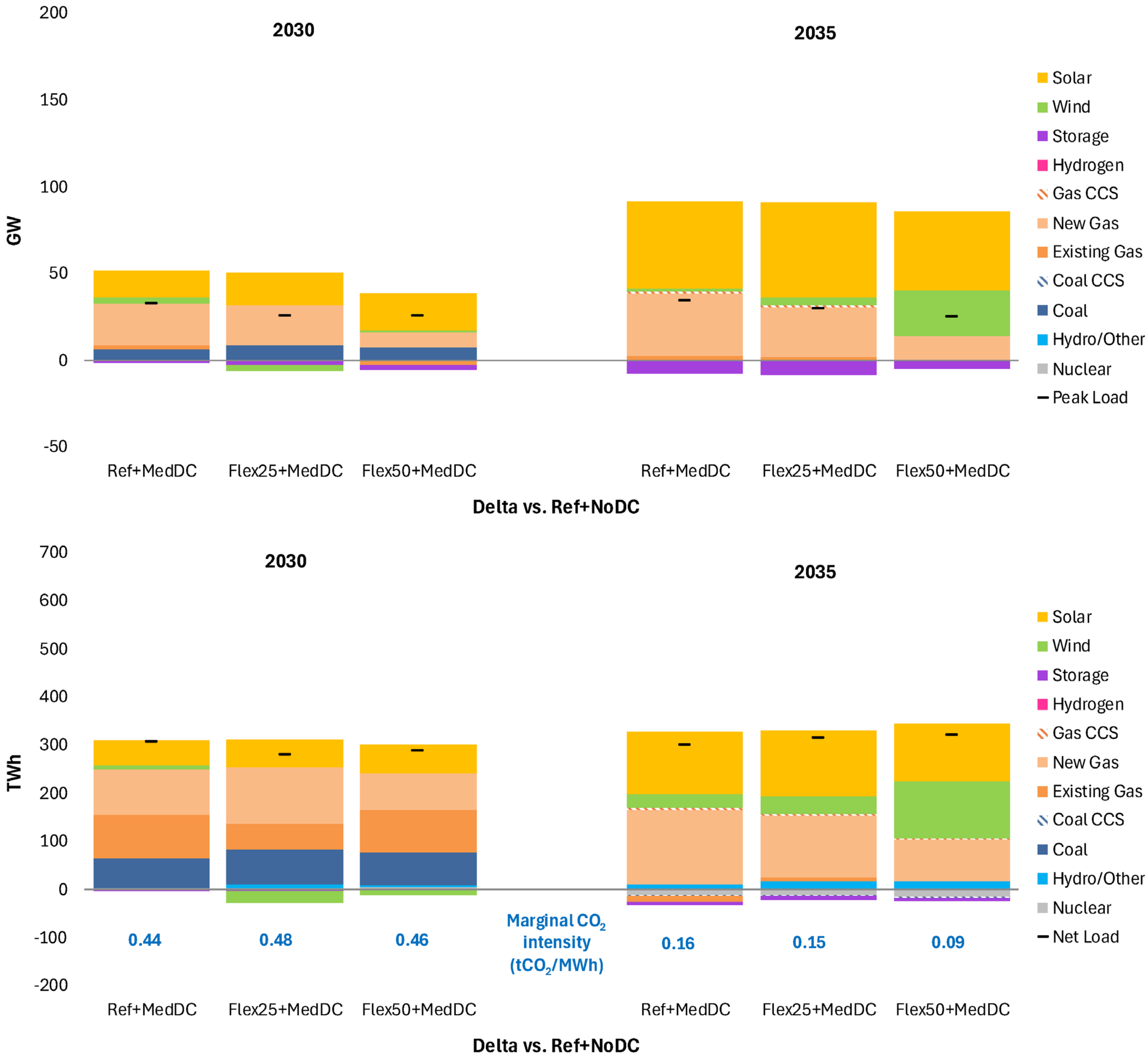


***Figure 16**. Change in U.S. capacity and generation (top and bottom panels, respectively) with DC flexibility relative to the "NoDC" scenario for data center growth scenarios. Values are shown for 2030 and 2035 (left and right panels, respectively).*

Emissions and Cost Impacts

In all scenarios, CO_2 emissions decline significantly over time as coal capacity retires and new low-emitting capacity is added; however, near-term DC load growth may induce more near-term CO_2 emissions from increased utilization of existing coal- and gas-fired capacity (Figure 17)**. Overall, emissions impacts of DC loads are more limited than the effects of other factors such as state and federal policy**. Accelerated DC load growth may have regional impacts on emissions reduction goals, even if national effects are small relative to other factors. Higher electricity demand from DC, electrification, and manufacturing could potentially delay the phase out of IRA's technology-neutral power sector credits, since these credits do not begin phasing out until national power sector CO_2 reaches 25% of 2022 levels.

The marginal emissions intensity of generation to serve incremental DC load declines over time and is 61–84% lower than the average intensity of the current generation mix by 2035 (Figure 18). **However, in the near term, the marginal CO_2 intensity of generation to meet incremental DC load is higher than the current grid due to increased utilization of existing coal and gas capacity**. Even with an economy-wide CO_2 cap, the emission intensity of incremental generation may be non-zero. Here, the economy-wide total is preserved through other changes (e.g., more carbon removal, more direct sectoral reductions through electrification and efficiency), offsetting a slight increase in power sector emissions with higher DC loads. **CFE demand can significantly lower the emissions impacts of higher DC loads, especially with an hourly matching commitment** (Figure 18). Relaxing hourly matching to allow annual CFE leads to more leakage with the procurement target and smaller impacts on consequential generation and emissions relative to the hourly 24/7 CFE case, which is similar to earlier EPRI analysis of IRA's 45V hydrogen tax credits (EPRI, 2023a). **Flexible DC loads have countervailing emissions effects, since flexibility both increases renewables and drives higher utilization of existing fossil assets**. In the near term, greater flexibility leads to higher marginal emissions intensities in 2030 relative to the inflexible DC load scenario (Figure 19). In the long run, the emissions effects of increased utilization of existing capacity are more than offset by declines from lower gas capacity additions.

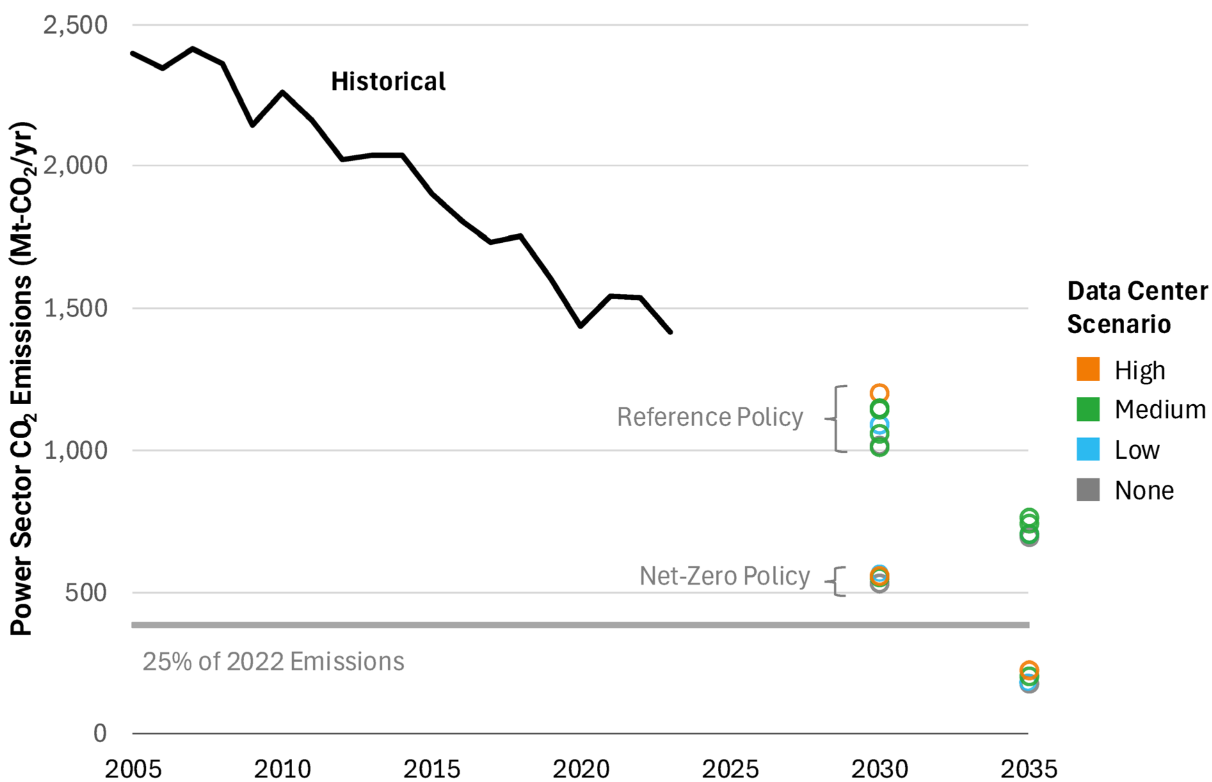


Figure 17. *Power sector CO_2 emissions over time by scenario. Projected values show scenarios across data center load assumptions. Historical emissions are based on U.S. EPA's "Inventory of U.S. Greenhouse Gas Emissions and Sinks." The 25% of 2022 emissions line is the threshold where power sector Inflation Reduction Act tax credits begin to expire.*

Total electric system costs increase with incremental DC load, due to both increased capital expenditures and increased operating costs, including fuel use and variable and fixed O&M (Figure 19)**. However, these costs are generally proportional to incremental load, with the result that the average generation price does not increase**. With reference policies, incremental expenditures net of IRA incentives relative to the no-DC-growth scenario range from $90 to $254 billion through 2035 (undiscounted).

With greater deployment of wind, solar, and batteries, there is also greater uptake of IRA tax credits. Incremental fiscal outlays for IRA incentives range from $20 to $70 billion. Transmission and distribution costs to connect new DC loads were not modeled explicitly and could vary by DC location relative to the existing grid. Especially for very large loads, investments in power delivery capacity may be necessary, which could lead to significant increases in cost and deployment time.

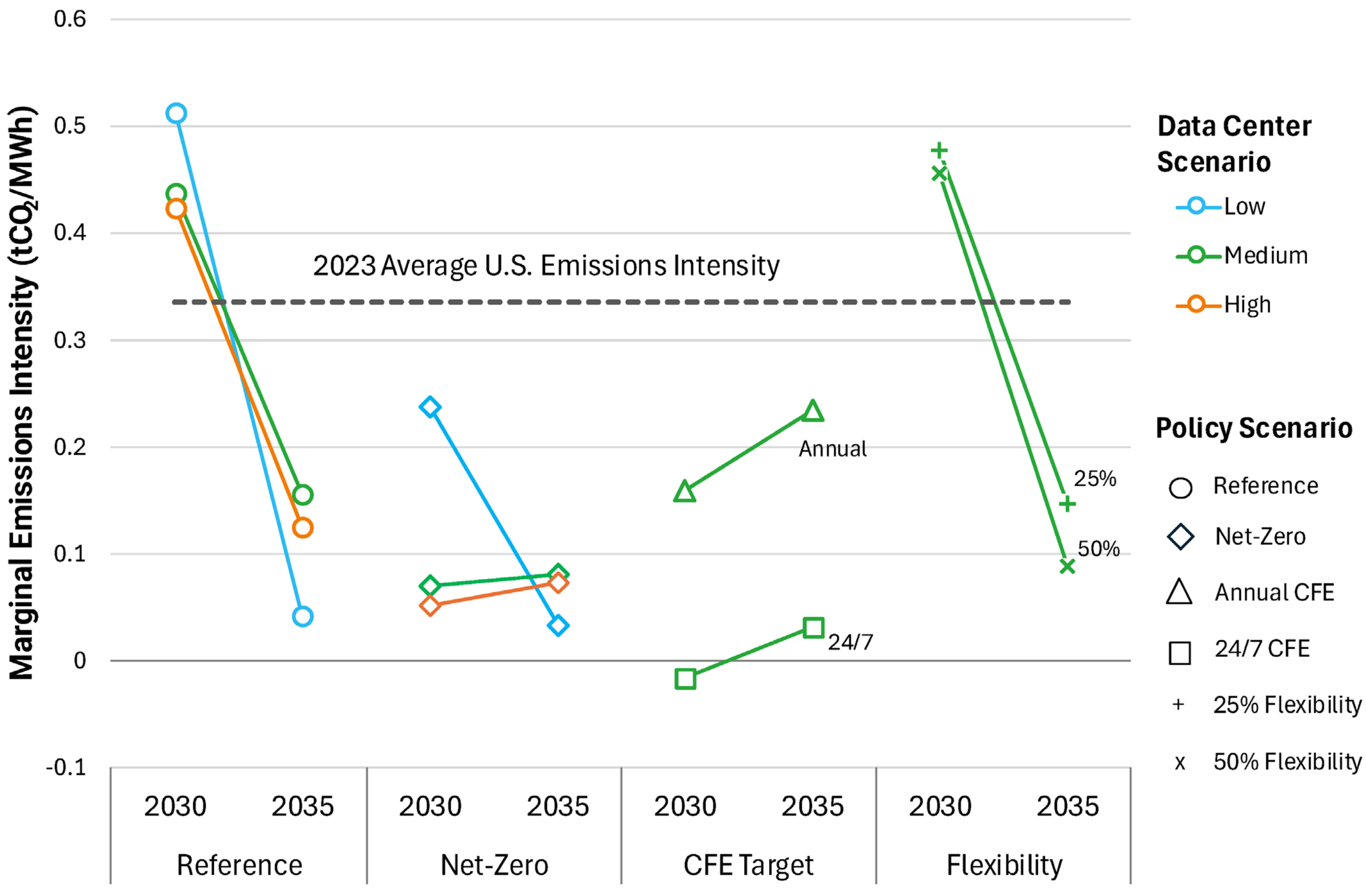


***Figure 18**. Marginal CO_2 emissions intensity with higher data center loads across scenarios (metric tonne CO_2 per MWh). Values reflect the change in emissions and generation relative to the scenario without additional DC load. The dotted line shows the 2023 average U.S. emissions intensity.*

CONCLUSIONS

There are several key takeaways from this analysis:

- Data center electricity use is significantly higher than previously assumed and a key driver for near-term regional load growth.
- Although the scale of future DC load is highly uncertain, the scenarios in this analysis suggest that DC load growth is just one driver of change—there are other emerging loads such as transport electrification but also other emerging trends in policy, technology, and markets that shape power sector outcomes.
- All modeled scenarios indicate extensive additions of generation and energy storage, regardless of DC load. The power sector has navigated growing demand in the past, but the localized scale and speed of these expected changes combined with supply constraints and overlapping regulatory targets can create regional challenges. Meeting growing load affordably, reliably, and sustainably requires proactive planning for supporting infrastructure.

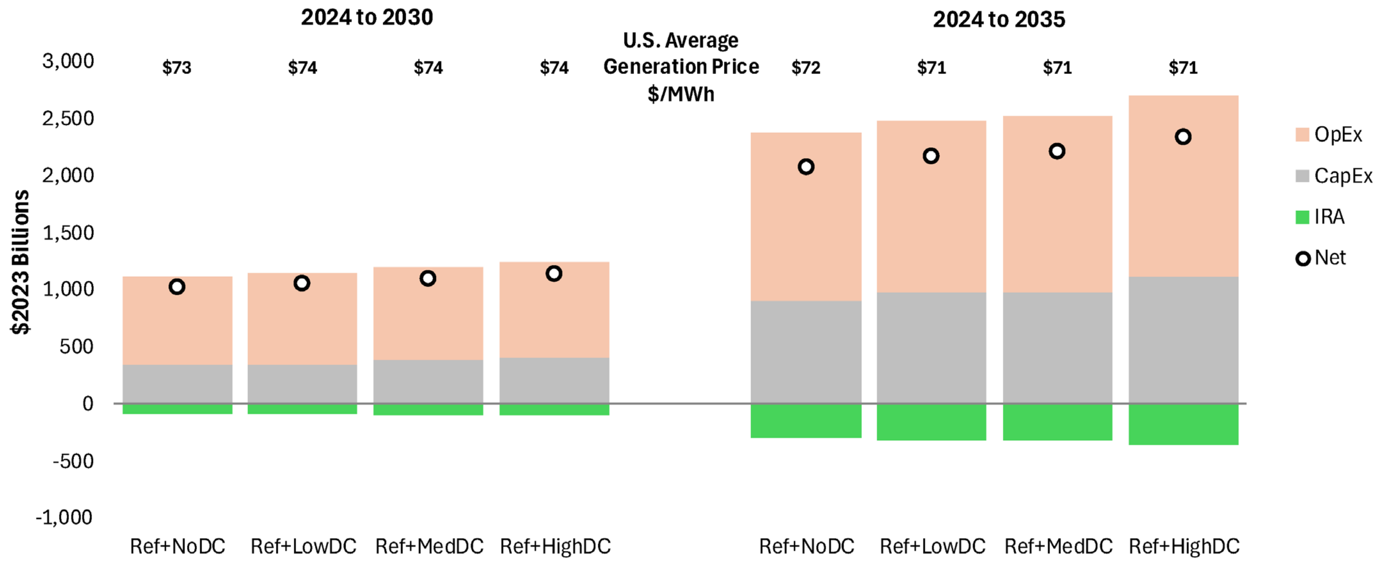


***Figure 19**. Cumulative electric generation expenditures in DC load growth scenarios with reference policy through 2030 and 2035. Expenditures are broken into capital and operating costs (including fixed O&M) and shown gross and net of IRA incentives. Prices refer to the U.S. average generation-only wholesale price in 2030 and 2035, respectively. Costs and prices are shown in real 2023 dollars.*

- The least-cost incremental resource mix to meet new DC load is primarily new gas and solar in the long run, but decarbonization policies and 24/7 CFE procurement targets lead to increases in energy storage, nuclear and CCS. High costs can make it challenging to scale emerging technologies to meet near-term DC demand, but with cost declines over time alongside potential policy incentives and corporate procurement targets, these emerging technologies could play larger roles. Growing electricity demands supported by corporate climate actions could help finance early deployment and learning for these technologies.
- Flexible DC load may reduce the need for incremental firm capacity requirements and bring more solar and wind online in the long run to meet DC electricity demand as well as reduce the average cost of power for DC loads. These sensitivities highlight how enabling potential flexibility of DC operations can help meet both climate and affordability goals.
- In all scenarios, CO_2 emissions decline significantly over time as coal capacity retires and new low-emitting capacity added; however, near-term DC loads may induce more near-term CO_2 emissions from increased utilization of existing coal- and natural gas-fired capacity. DC loads have more limited impacts on emissions than other factors such as policy.
- Total cost increases are proportional to load increases, resulting in minimal electricity price impacts versus scenarios without new DC load. Prices could change over time due to other factors (e.g., IRA, natural gas prices, inflation).

CAVEATS AND FUTURE WORK

These are "what-if" scenarios to investigate system interactions and insights about how near-term decisions and uncertainties could alter long-term power system outcomes. These projections of data center electricity use and modeled electric sector impacts should not be interpreted as forecasts or predictions.

Modeled long-run changes are conditional on large-scale capacity additions, which could be impacted by unanticipated barriers to deployment such as siting, permitting, interconnection, supply chain delays, or higher costs. These factors could change the incremental resource mix and emissions effects of growing DC loads.

This study highlights several opportunities for additional analysis:

- **Spatial flexibility in DC load**: This analysis makes exogenous assumptions about the regional allocation of projected DC loads. In reality, capacity, siting and dispatch of installed DC capacity for certain services could interact with power system decisions, especially with distributed training of AI models. DC siting also depends on a range of other factors that are not examined in detail in this analysis, including IT networks, latency, workforce, and land/water availability.
- **Increased detail of DC types**: Future analysis would benefit from a decomposition of DC types with better load shape and flexibility representations, including regionally and temporally specific weather impacts on cooling. It would be valuable to connect to bottom-up technology representations (e.g., computation demand, processor efficiency, PUE). There are needs for publicly available data and transparency related to these areas (Masanet, Lei, and Koomey, 2024).
- **More granular power systems analysis**: Future work would benefit from more detailed regional analysis, including resource adequacy and reliability studies based on scenarios for growth in DC and other emerging loads (EPRI, 2023b; EPRI, 2022c).
- **Near-term constraints**: It would be valuable for future analysis to examine near-term constraints—supply chain constraints, local supply availability, interconnection constraints, workforce issues, transmission and distribution cost uncertainty—as well as potential approaches to resolve these challenges—such as grid enhancing technologies and behind-the-meter capacity (Armstrong, et al., 2024; EPRI, 2024c).
- **Representing other impacts of AI on energy systems**: AI represents potential new electricity demand but also new opportunities for technological advances in how we produce, transport, and use electricity. Future work can characterize these benefits, modeling how AI tools can increase productivity, optimize system operations (e.g., by improving weather and demand forecasts or by facilitating demand management), accelerate development of emerging technologies, and other impacts.

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