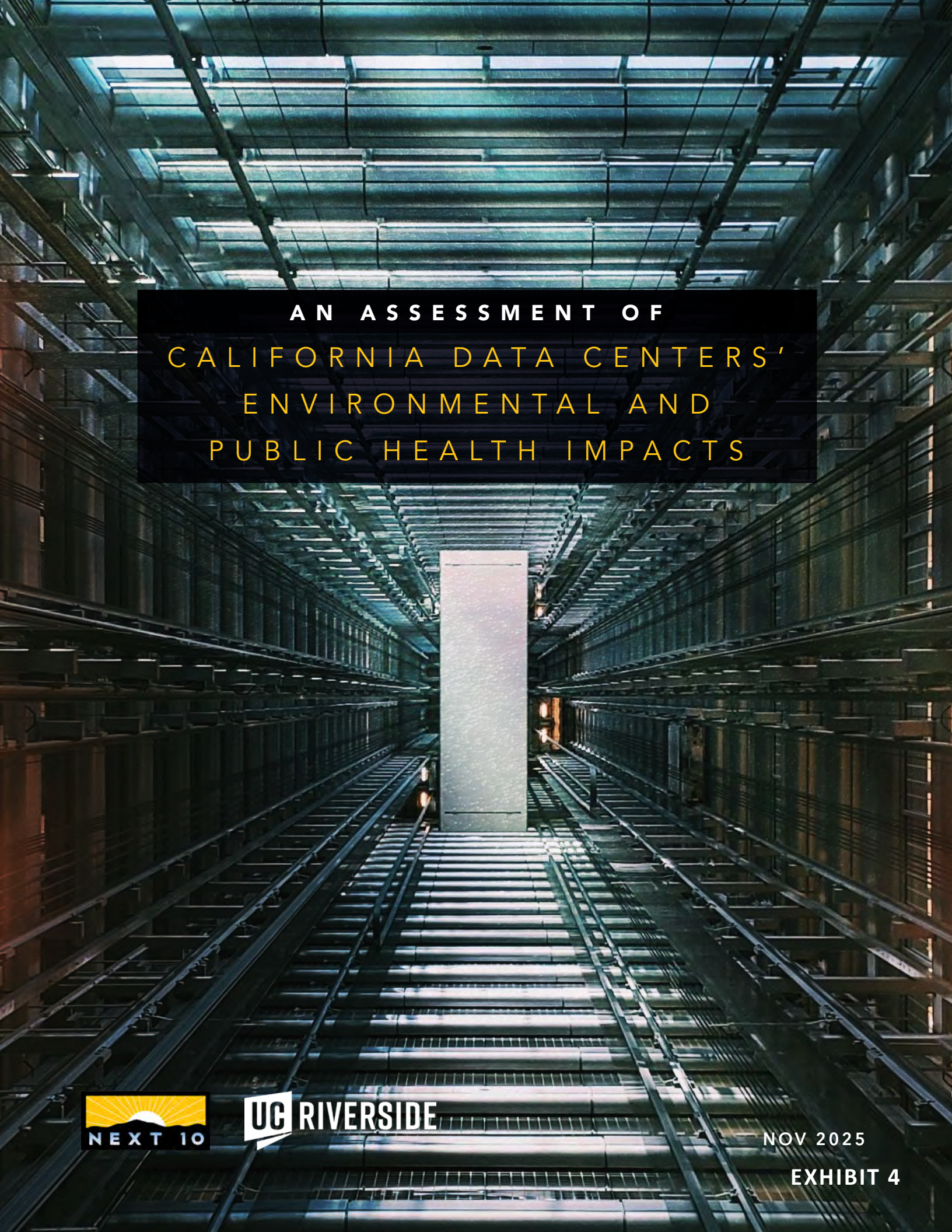


AN ASSESSMENT OF CALIFORNIA DATA CENTERS' ENVIRONMENTAL AND PUBLIC HEALTH IMPACTS

NEXT 10

UC RIVERSIDE

NOV 2025

EXHIBIT 4

NEXT 10 is an independent nonpartisan organization that educates, engages and empowers Californians to improve the state's future.

Next 10 is focused on innovation and the intersection between the economy, the environment, and quality of life issues for all Californians. We provide critical data to help inform the state's efforts to grow the economy and reduce greenhouse gas emissions. Next 10 was founded in 2003 by businessman and philanthropist F. Noel Perry.

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Executive Summary

While data centers have long existed in California, the rise of artificial intelligence (AI) has significantly increased demand for new data centers over the last five years, and the pace is expected to increase through the rest of the decade. This explosive growth has led to a corresponding increase in energy demand which has led to increased electricity consumption, carbon emissions, water usage, and public health costs arising from air pollution. Since the frenetic pace of data center expansion shows no sign of slowing, it is important to understand the full extent of the environmental and public health impacts on California communities and implement appropriate strategies for sustainable development.

This report presents a quantitative assessment of the environmental and public health impacts of California's data centers between 2019 and 2023. In that time, electricity usage, carbon emissions and water consumption all nearly doubled, while public health impacts more than tripled. For each of the indicators assessed, we also present projections for 2028.

Large-scale data center facilities in California routinely deploy backup generators to maintain uninterrupted service during grid outages. These generators often burn diesel fuel, which releases greenhouse gas emissions and other pollutants such as fine particulate matter ($PM_{2.5}$) and nitrogen oxides (NO_x). Since 2017, California has approved over 1 gigawatt (GW) of diesel-fueled emergency power for data centers [1]. One GW of capacity is enough to power 750,000 homes.

According to a recent Lawrence Berkeley National Laboratory (LBNL) report [2], data centers in the U.S. consumed approximately 4.4% of national electricity in 2023, compared with roughly 3% in 2013. By 2028, the surging demand for AI is expected to result in data centers consuming between 6.7% and 12% of the nation's electricity [2].

Both carbon emissions and water consumption experienced similar growth trajectories over this time interval. The economic burden of public health impacts from California's data centers is also projected to rise significantly. The quantitative results for all environmental and health indicators across the study period are summarized in Table 1.

Table 1. Environmental and health impact metrics of California data centers (2019-2028)

Year	Electricity Consumption (TWh)	Carbon Emissions (million short tons)	Water Consumption (billion liters)	Health Costs (million $)
2019	5.54	1.24	25.42	44.68
2020	6.48	1.60	29.73	60.45
2021	7.84	1.97	36.00	82.10
2022	9.29	2.23	42.71	111.21
2023	10.82	2.38	49.91	155.44
2028 (low)	16.16	3.55	74.54	167.14
2028 (high)	25.28	5.56	116.63	266.57

Key Findings:

Electricity Consumption

- From 2019 to 2023, the electricity consumption in California data centers increased from 5.54 TWh to 10.82 TWh, almost a 95% increase.
  - » California's data center electricity consumption represented 6.13% of the national total in 2023—behind only Virginia and Texas.
- This 5.28 TWh increase represents significant additional demand on the state's electricity grid, equivalent to the annual electricity consumption of approximately 490,000 average U.S. households [3].
- Unless this demand is mitigated, there is an urgent need for improved grid capacity and integration of renewable energy to support sustainable expansion.
- The projections further indicate that electricity consumption by data centers in California will grow to between 16.16 and 25.28 TWh by 2028—which corresponds to an increase of 49.2% to 133.6% compared to 2023.
  - » 25.28 TWh is equivalent to the annual electricity consumption of approximately 2.4 million average U.S. households.

Carbon Emissions

- Data centers consume vast amounts of electricity and produce carbon emissions in three distinct categories: on-site emissions (Scope 1), indirect emissions from purchased electricity (Scope 2) and value-chain emissions (Scope 3). We focus on location-based Scope 2 carbon emissions in this report.
- Carbon emissions from data centers in California almost doubled from 1.24 million short tons (one short ton is equivalent to 2,000 lbs and slightly less than a metric ton which is 1,000 kg) in 2019 to 2.38 million in 2023.
- Carbon emissions from data centers in the state are projected to span roughly 3.55 to 5.56 million short tons by 2028—an increase of 49.4% to 133.6% compared to 2023.

- The "CA-US Ratio" metric reveals that in 2019 California data centers emitted just 48.43% of the carbon they would have under the national average intensity. The figure peaks at 57.89% in 2020, then drops back to 54.52% by 2023.
  - » The post-2020 decrease suggests that California's carbon emission advantage diminished slightly over time, probably driven by changes in renewable energy penetration, use of natural gas during low solar output, and other temporary shifts in the fuel mix.
  - » These trends underscore the need for ongoing investment in clean energy and demand management if California is to maintain its grid advantage over the national average.
- The data center share of statewide electricity-related emissions (DC Emission % of CA Total) grows steadily from 2.21% in 2019 to 4.52% in 2023, showing that even as the grid becomes cleaner, data center operations are making up an ever-larger portion of the state's total emissions.

Water Consumption

- This report follows a three-scope framework categorizing water usage into distinct pathways: direct on-site consumption for cooling (Scope 1), indirect consumption from off-site electricity generation (Scope 2), and embodied water within the supply chain (Scope 3). We focus on Scope 1 and Scope 2 water consumption in this report.
- The total water consumption by data centers in California increased from 25.42 billion liters in 2019 to 49.91 billion liters in 2023 — a 96.4% increase. The amounts are equivalent to approximately 10,000 and 20,000 Olympic swimming pools, respectively [4].
- On-site water consumption grew from 1.33 billion liters in 2019 to 2.84 billion liters in 2023—a 113% increase. The year-over-year increases range from 17% to 23%, suggesting a stable relationship between facility expansion and cooling water requirements.
- Off-site water consumption dominates the total operational water footprint, accounting for more than 90% of the total, while demonstrating substantial growth trajectories that nearly double consumption from 2019 to 2023.
- For each TWh of total electricity consumed, based on the U.S. average, California data centers indirectly drive approximately 4.35 billion liters of water consumption through power generation processes.
- Total water consumption by California data centers is forecast to range from 74.54 to 116.63 billion liters by 2028, equivalent to approximately 30,000 and 47,000 Olympic swimming pools, respectively.
  - » This corresponds to an increase of 49.3% to 133.7% compared to 2023.

Health Costs

- This report follows a three-scope framework categorizing criteria air pollutant emissions: direct on-site emission by backup generators (Scope 1), indirect emission from off-site electricity generation (Scope 2), and embodied emission within the supply chain (Scope 3). We focus on Scope 1 and Scope 2 air pollutant emission and public health impacts in this report.
- Regions with a high concentration of data centers experience disproportionately high health burdens related to Scope 1, driven in part by elevated emissions of nitrogen oxides (NO_X) from on-site generators.
  - » Silicon Valley, within Santa Clara County, has the highest concentration of data centers in California and lies within the Bay Area Air Quality Management District (BAAQMD) [5, 6].
  - » According to a 2023 CPUC analysis, BAAQMD reported 8,722 backup generators in 2021 (nearly 90% were diesel-fueled), including gensets deployed at data centers and other large facilities [7].
- Health costs associated with data centers in California surged from $44.68 million in 2019 to $155.44 million in 2023, with Scope 2 (indirect emissions from fossil fuel power plants that generate electricity) costs remaining the dominant contributor.
- Taking 2028 as an example, the Scope 2 health costs of $108.05 million under the low-growth scenario translate to health outcomes, including approximately 3,900 asthma symptom cases and 490 lost workdays per year.

- Projections indicate that by 2028 the public health burden will increase further to between $167.14 million and $266.57 million, which corresponds to an increase of 7.5% and 71.5% compared to the 2023 basis.
- This lower growth rate in health costs relative to electricity consumption is likely due to California's stringent air quality regulations and projected cleaner grid, resulting in fewer emissions than in other states.

Drawing on these quantitative results and forecasts, this report outlines a set of recommendations designed to support the sustainable development of data centers in California.

Recommendations

- **Unified Reporting of Comprehensive Metrics:** Standardize reporting protocols for electricity consumption, carbon emissions, water consumption, and associated public health impacts in different regions of California, so that we could create a consistent, high-quality comparative base to inform targeted policy interventions and enhance transparency.
  - » **Carbon:** Carbon governance could be strengthened through the integration of frameworks such as the GHG Protocol with interoperable, real time carbon tracking platforms; aligning compute workloads with periods of lower grid carbon intensity; and advancing circular infrastructure measures including waste heat recovery, component remanufacturing, and extended hardware lifetimes to address both operational and embodied carbon.
  - » **Water:** Implement context-relevant efficiency measures to reduce water consumption, relieve regional water stress, and benefit communities facing scarcity. Integrating advanced cooling technologies with water recycling and reuse systems can lower freshwater withdrawals, while monitoring platforms and predictive analytics enable continuous optimization of water use and protection of local resources.
  - » **Health Costs:** Strengthening public health protection can involve integrating health impact assessments into site selection and infrastructure upgrades, with buffer zones around sensitive receptors such as schools and hospitals.
- **Accelerating Clean Energy Integration with Equity Considerations:** Accelerating clean energy integration can help to shift marginal demand growth to low carbon, fuel-free renewable resources rather than fossil-based generation to some extent. For instance, organizations could prioritize long-term power purchase agreements (PPAs) with reputable providers of clean energy, thereby securing stable electricity prices and offering wind and solar developers the predictable revenue streams required to attract investment capital. Besides, organizations could integrate renewable electricity sourced from the grid and on-site generation with advanced battery or thermal storage, so that excess daytime production can be shifted to evening demand peaks, extracting the full value of intermittent resources while preserving a high level of supply reliability.

  The environmental and public health impact of data center operations in California is often unevenly distributed between different counties and communities, often disproportionately affecting low-income communities and potentially exacerbating socioeconomic disparities. Procurement strategies should be informed by the geographic and temporal characteristics of regional energy mixes and explicitly consider greenhouse gas emissions, water consumption, and localized health risks, particularly in communities experiencing disproportionate environmental burdens. Siting evaluations should incorporate water resource safeguards and public health criteria, preventing new exposures in already overburdened areas. Developers could also structure Community Benefit Agreements that provide tangible investments for the host community.
- **Institutionalizing Community Science and Cross-Sector Impact Research:** California should institutionalize sustained, community-based monitoring and interdisciplinary policy evaluation to ensure that data center operations transparently account for their social, environmental, and economic impacts. This necessitates empowering expert institutions and local authorities to undertake comprehensive cross-sector research. At the same time, targeted grant programs can equip residents with required knowledge to serve as citizen scientists, contributing to

air quality monitoring, health assessment, and data analysis. Subsequently, disseminating these findings through accessible reports and structured public workshops would enhance community capacity to evaluate risks and collaborate with researchers and regulators in developing context-specific strategies.

- **Modernizing Backup Power Systems:** Data center operators should transition from conventional diesel generators to cleaner and more sustainable backup options, such as battery energy storage systems, fuel cells, and other advanced alternative fuels. Such transitions can substantially reduce emissions of criteria air pollutants, which in turn improves ambient air quality and alleviates associated health risks, particularly in communities already subject to significant environmental pressures. These benefits can be further enhanced by integrating cleaner technologies with intelligent energy management systems that monitor performance in real time, apply predictive analytics to anticipate demand, and automatically adjust operations to minimize environmental impacts.

  Accordingly, California should establish clear regulatory frameworks that enable operators to invest in advanced backup systems in a cost-effective manner. In parallel, collaboration among industry leaders, researchers, and policymakers will be essential to develop robust performance standards and practical implementation guidelines.

- **Strengthen California's National Leadership in Sustainable Data Center Development:** California should advance policies that streamline the permitting process for energy efficient and water resilient data centers located in regions with abundant clean power and stable water supplies, while ensuring strong safeguards against local impacts such as water scarcity, grid stress, and pollution. This approach should include the establishment of transparent and standardized environmental performance reporting, including disclosure of hourly PUE and WUE, to facilitate early identification of inefficiencies. Moreover, targeted investments should be directed toward technologies that reduce carbon, water, and energy footprints while improving public health outcomes.

As California continues to lead in both technological innovation and environmental protection, understanding the relationship between data center operations and their environmental and public health impacts becomes increasingly critical for informed decision-making. This report seeks to bridge the gap between technological advancement and environmental stewardship, providing policymakers and industry stakeholders with the information needed to make informed decisions about future data center development and operation. Through these joint efforts, we can collaboratively maintain the long-term viability and social benefits of our digital infrastructure, concurrently minimizing its ecological footprint.

1 Introduction

Data centers have long helped form the backbone of California's digital economy. However, with the rise of artificial intelligence (AI), significantly more data centers have been built over the last five years, and the pace is expected to increase through the rest of the decade. This explosive growth has led to a corresponding increase in energy demand which has led to increased electricity consumption, carbon emissions, water usage, and public health costs arising from air pollution. Due to the rapid expansion of data centers, it is important to understand the full extent of the environmental and public health impacts on California communities and implement appropriate strategies for sustainable development.



The digital transformation of society has placed data centers as critical infrastructure in our increasingly interconnected world. These facilities serve as the backbone of modern information technology, supporting everything from basic Internet services to advanced artificial intelligence (AI) applications. In this context, AI presents significant opportunities to tackle pressing societal issues, including air quality management, climate change, pandemic preparedness and disease prevention [8-11]. However, the growing demand for digital services and AI, particularly with the rise of generative AI applications such as large language models (LLMs), has led to an increased reliance on computational resources, accelerating the expansion of energy-intensive data centers.

According to the recent Lawrence Berkeley National Laboratory (LBNL) report [2], data centers in the U.S. consumed approximately 4.4% of national electricity in 2023, compared with roughly 3% in 2013. However, due to the surging demand for AI, the U.S. data centers are projected to account for between 6.7% and 12.0% of the national electricity consumption in 2028 [2]. Specifically, the annual electricity consumption by the U.S. data centers increased from about 58 TWh in 2014 to 176 TWh in 2023, with projections of national consumption ranging from approximately 325 to 580 TWh in 2028 [2].

Globally, the International Energy Agency (IEA) reports that data centers consumed approximately 415 TWh of electricity in 2024 (or roughly 1.5% of worldwide electricity demand), and have been growing at approximately 12% per year over the past five years [12]. In its base case scenario, the IEA projects that electricity consumption will nearly double to 945 TWh by 2030, representing close to 3% of global electricity usage. This is driven by a 30% annual increase in AI-optimized server workloads along with a 9% annual increase in conventional operations, such as standard cloud services or enterprise computing [12].

Meeting AI-driven computing needs would require data center construction at an unprecedented scale and speed. In certain regions, the surge in AI data centers has strained power grid capacity and even threatens the grid stability [13, 14] while potentially amplifying environmental concerns through rising carbon emissions [15, 16] and increased water consumption [17]. As highlighted in recent industry reports [18], the rapid proliferation of AI products and services is a primary driver of these challenges. Addressing these impacts necessitates a multifaceted approach, including grid-integrated data centers, [14, 19] advancements in energy-efficient hardware and software [20- 22], and the implementation of carbon-aware and water-efficient computing practices [17, 23- 25]. Without proactive measures, the sustainability implications of AI's growth will continue to escalate, reinforcing the need for innovative strategies to balance technological advancement with environmental responsibility.

Given California's prominent role in the data center industry and its substantial economic scale, this report focuses on the impacts of data centers in this state. California's leadership in the data center sector underscores the economic benefits and infrastructural challenges associated with the rapid expansion of AI-driven workloads. Since 2017, California has approved over 1 gigawatt (GW) of diesel-fueled emergency power for data centers [1]. The state's economic stature, with a GDP of nearly $3.9 trillion in 2023 [26] and the fourth-largest global economy, underscores the high stakes of sustaining its growing digital infrastructure. Home to one in nine U.S. residents and second only to Texas in total energy consumption [27], California must contend with data centers' intensifying power demands.

Despite ranking third in absolute electricity consumption, California's data centers play a critical role in the national digital infrastructure.

- **Technology Ecosystem Leadership:** California, particularly the Silicon Valley region, hosts the headquarters and primary data centers where major technology companies including Google, Meta, Apple, and numerous cloud service providers deploy their servers. These facilities support not only regional operations but serve as critical nodes in global digital infrastructure.
- **Innovation Hub for AI and Advanced Computing:** The EPRI report [13] notes that California's "robust technological ecosystem" positions it at the forefront of AI development and deployment. Many of the most computationally intensive AI training and inference workloads originate from California-based facilities.
- **Gateway to Asia-Pacific Markets:** California's data centers serve as crucial connection points for trans-Pacific data flows, making them essential for international digital commerce and communications.

In Santa Clara, one of the main power centers in Silicon Valley, more than 50 hyperscale data centers collectively account for approximately 60% of municipal utility electricity demand [28, 29], prompting Silicon Valley Power to implement a rate increase 5% effective January 1, 2025 to fund upgrades to transmission lines, substations, and battery storage systems [30]. Moreover, California's largest utility, Pacific Gas and Electric Company (PG&E), reported a significant surge in data center power requests across the northern part of the state [31]. This surge included new AI-focused facilities in Contra Costa and Fresno counties and injected approximately 4.1 GW additional demand into a pipeline that was already at 8.7 GW [31, 32]. In May 2022, a large technology company executed a 20 year power purchase agreement (PPA) to acquire 110 MW of solar photovoltaic generation capacity, supplemented by a battery energy storage system rated 55 MW with an energy capacity of 220 MWh, dedicated exclusively to its data centers in California [33]. Likewise, another technology company committed to a 25 year contract to procure the full 130 MW output of the California Flats Solar Project in Monterey County [34] and installed a 60 MW battery system on site [35]. Together, these rapid expansions and mounting costs underscore the imperative for policy measures that simultaneously uphold California's role as a leader in AI innovation and ensure sustainable resource management and economic resilience.

The data center landscape in California presents unique characteristics that distinguish it from other regions worldwide. In particular, the state infrastructure operates predominantly under the colocation model, where multiple organizations house their own servers in a shared facility while the data center operator is mainly responsible for providing facility services such as reliable power and cooling [36]. This approach has proven particularly effective in California's context, enabling consolidated resource utilization and serving diverse data center needs from the state's high-tech sector.

Despite California's leadership in addressing climate change and sustainability challenges, the environmental and public health implications of data center operations warrant rigorous quantitative assessment. As among the largest consumers of electricity, data centers exert multifaceted impacts that extend well beyond their physical boundaries. In regions still dependent on fossil fuel-based generation, the powering of AI workloads contributes substantially to greenhouse gas emissions, air and water pollution, and broader ecosystem degradation. In addition, the full hardware lifecycle, including the production, transport, and end-of-life disposal of servers, networking equipment, and cooling systems, demands large quantities of raw materials (e.g., cobalt, silicon, and various metals). Improper recycling of electronic waste can release toxic contaminants into soil and water, further amplifying the environmental burden.

A data center's carbon footprint, expressed as carbon dioxide equivalent (CO_2e), encompasses direct emissions (Scope 1) alongside indirect emissions from electricity consumption (Scope 2) and broader value- chain activities (Scope 3) [37]. Scope 1 emissions arise from on-site fuel combustion (e.g., backup generators) and cooling-related chemical processes such as refrigerant leakage. Scope 2 covers grid electricity used to power servers and cooling systems, while Scope 3 includes upstream manufacturing, transportation, and end-of-life disposal of IT hardware. Quantifying and mitigating these emissions is vital for sustainable data center growth amid rising AI workloads. Consequently, strategies such as shifting to renewable energy, improving energy efficiency, and enhancing hardware lifecycle management are essential to minimize environmental impacts and protect public health.

Beyond the water footprint incurred during the construction of data centers and the procurement of materials, operational water usage can be categorized into two primary areas: direct and indirect consumption. Direct water consumption is largely attributed to data center cooling needs, with minor contributions from facility maintenance and humidification. By raising allowable operating temperatures, installing water efficient cooling systems, or adopting innovative cooling technologies such as immersion or direct-to-chip cooling, data centers can substantially reduce direct water consumption. Indirect water consumption can account for a large fraction of a data center's total operational water consumption, especially in areas that extensively depend on water-intensive electricity generation [38]. By curbing both direct and indirect water consumption, data centers can effectively mitigate their overall environmental impact and conserve valuable water resources.

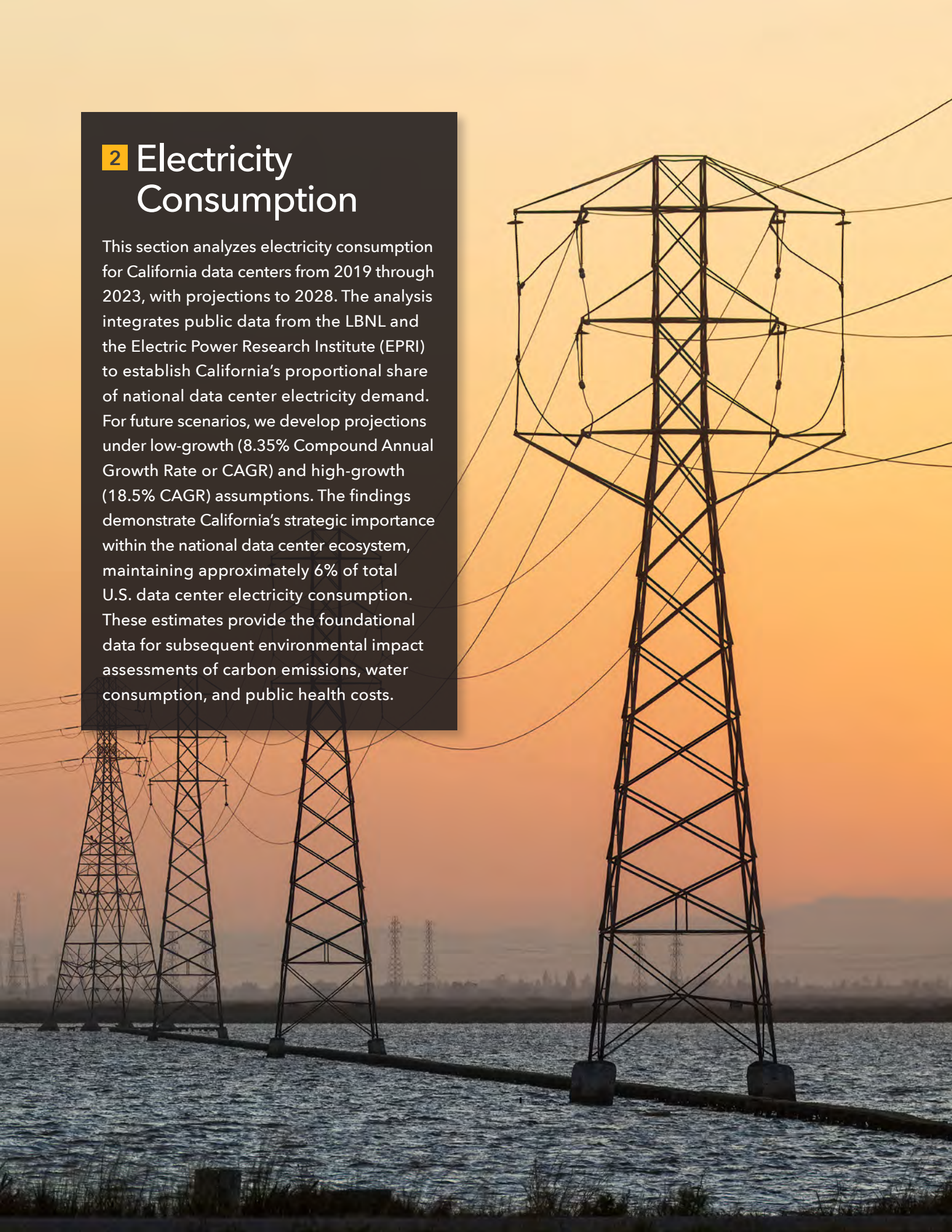
Parallel to these environmental concerns are the public health implications [39]. Data centers contribute to public health impacts through various pathways, including the

emission of criteria air pollutants from backup generators and associated power generation facilities. These health effects can be quantified in economic terms through established public health assessment methodologies [40]. While data centers are essential for technological progress, their growing footprint in both environmental and public health spheres necessitates comprehensive analysis and strategic planning to ensure sustainable development.

As California continues to lead in both technological innovation and environmental protection, understanding the relationship between data center operations and their environmental and public health impacts becomes increasingly critical for informed decision-making. This study seeks to bridge the gap between technological advancement and environmental stewardship, providing policymakers and industry stakeholders with the information needed to make informed decisions about future data center development and operation.

This report develops methodologies for California-specific environmental and public health impact assessment, and quantifies the multifaceted impacts of California's data centers from 2019 to 2023, with projections through 2028. We show that the energy consumption by California's data centers is projected to reach 16.16-25.28 TWh in 2028. The analysis also reveals that carbon emissions attributed to California's data centers were estimated at 2.38 million short tons in 2023, nearly double the 2019 level, and are projected to range between 3.55 and 5.56 million short tons in 2028. Moreover, the total water consumption by California's data centers reached 49.91 billion liters in 2023 (including off-site water consumption for generating electricity) and is projected to range between 74.54 and 116.63 billion liters by 2028. As for the public health impact, the total public health cost of California's data centers was estimated at $155.44 million in 2023 and is projected to range between $167.14 million and $266.57 million by 2028. This partial decoupling between the growth of data center electricity consumption and the associated health impacts is mainly attributable to the state's clean energy transition and strict environment laws.

Section 2 focuses on detailed energy consumption trends and carbon emissions are examined in Section 3. Section 4 addresses the operational water consumption, including both the direct demands of cooling systems and the indirect consumption embedded in power generation. Section 5 quantifies public health impacts, considering both immediate and longer-term community outcomes. In Section 6, we offer policy recommendations aimed at promoting sustainable data center development while protecting public health.



2 Electricity Consumption

This section analyzes electricity consumption for California data centers from 2019 through 2023, with projections to 2028. The analysis integrates public data from the LBNL and the Electric Power Research Institute (EPRI) to establish California's proportional share of national data center electricity demand. For future scenarios, we develop projections under low-growth (8.35% Compound Annual Growth Rate or CAGR) and high-growth (18.5% CAGR) assumptions. The findings demonstrate California's strategic importance within the national data center ecosystem, maintaining approximately 6% of total U.S. data center electricity consumption. These estimates provide the foundational data for subsequent environmental impact assessments of carbon emissions, water consumption, and public health costs.

2.1 Calculating the Annual Electricity Consumption of California Data Centers in 2019-2023

2.1.1 Methodology

To estimate the annual electricity consumption of California data centers from 2019 to 2023, this study employs a proportional allocation approach that combines national-level electricity data with state-level distribution estimates. This methodology leverages two prominent data sources from LBNL and EPRI to derive estimates for California's data center electricity consumption.

The methodology consists of three primary steps:

1. **National Data Center Electricity Consumption:** The total U.S. data center electricity consumption data for 2019-2023 is obtained from the recent LBNL report [41]. The LBNL report provides comprehensive estimates based on bottom-up modeling that incorporates server shipment data, equipment efficiency trends, and infrastructure energy requirements. Despite the intrinsic uncertainties associated with predictions, these estimates are considered highly reliable due to LBNL's extensive methodology that accounts for various server types, storage systems, network equipment, and cooling infrastructure.

2. **State-Level Distribution Analysis:** The state-specific data center electricity consumption estimates are derived from the EPRI report [13]. The EPRI analysis provides state-level breakdowns of data center electricity consumption, including specific estimates for California. These estimates are based on facility counts, regional capacity data, and industry growth patterns.

3. **Proportional Allocation Calculation:** California's proportion of total U.S. data center electricity consumption is calculated using the EPRI state-level data. This proportion is then applied to the LBNL national totals to derive California-specific electricity estimates for each year from 2019 to 2023.

2.1.2 Data Sources and Calculations

According to the LBNL report, the U.S. data center electricity consumption exhibited a steady growth during the study period of 2019-2023. The report indicates that data center energy use increased from approximately 90 TWh in 2019 to 176 TWh in 2023, representing 4.4% of total U.S. electricity consumption in 2023. This growth trajectory reflects the combined impact of expanding cloud services, increased digitalization accelerated by the COVID-19 pandemic, and the emergence of AI workloads.

The EPRI report [13] provides detailed state-level analysis, indicating that California data centers consumed 9,331,619 MWh (approximately 9.33 TWh) in 2023. California ranks third among U.S. states in terms of the absolute data center electricity consumption, following Virginia (33.85 TWh) and Texas (21.81 TWh). Note that while EPRI provides direct state-level electricity consumption data, our analysis employs a calibrated approach based on California's proportional share of LBNL national totals. This methodological choice provides a more robust foundation for longitudinal analysis, as the LBNL data represents one of the most comprehensive and rigorously validated national electricity figures available in the public domain.

To calculate California's share of national data center electricity consumption, we first calculate the following:

$$P_{CA} = \frac{E_{CA,EPRI}}{E_{US,EPRI}}$$

where P_{CA} represents California's proportion of U.S. data center electricity consumption, $E_{CA,EPRI}$ is California's data center electricity consumption from EPRI data, and $E_{US,EPRI}$ is the total U.S. data center electricity consumption implied by EPRI's state-level estimates. Based on the EPRI data, California's proportion can be calculated as:

$$P_{CA} = \frac{9.33\ \text{TWh}}{152\ \text{TWh}} \approx 0.061 \text{ or } 6.1\%$$

Subsequently, California's annual data center electricity consumption is calculated as:

$$E^t_{CA} = P_{CA} \times E^t_{US,LBNL}$$

where E^{t}_{CA} is California's estimated data center electricity consumption for year t, and $E^{t}_{US,LBNL}$ is the total U.S. data center electricity consumption from LBNL for that year.

This proportional approach ensures that California's estimates remain consistent with the most reliable national totals provided by the LBNL report [41] while accounting for the state's significant role in the U.S. data center ecosystem. The combination of California's technological leadership, concentration of major tech companies, and strategic geographic position underscores why understanding its data center electricity consumption patterns is crucial for both state and national energy planning.

2.1.3 Key Considerations and Uncertainties

Several important factors influence the accuracy of these estimates:

- **Regional Growth Variations:** The EPRI report [13] notes that data center growth rates could vary significantly by region. As a consequence, California's growth may differ from the national average due to factors such as high real estate costs, stringent environmental regulations, and the state's robust technology ecosystem.
- **Data Uncertainty for 2021-2023:** Both the LBNL and EPRI reports acknowledge increased uncertainty in estimates for the 2021-2023 period, particularly due to rapid changes in AI workload adoption and pandemic-related shifts in digital service demand.
- **Facility Type Distribution:** California hosts a diverse mix of data center types, including enterprise facilities, colocation centers, and hyperscale facilities. The EPRI report indicates that this mix influences overall efficiency and electricity patterns.
- **Efficiency Improvements:** The LBNL report [41] documents that Power Usage Effectiveness (PUE) has been continuously improving for the industry average. The national average PUE decreased from 1.6 in 2014 to 1.4 in 2023 and is projected to further improve to between 1.15 and 1.35 by 2028. This improvement is primarily driven by the shift toward larger, more efficient hyperscale and colocation facilities. By 2023, the average PUE across hyperscale and colocation data centers was under 1.4. California facilities may achieve different efficiency levels due to the state's moderate climate and adoption of advanced cooling technologies.

This methodology provides a systematic approach to estimating California's data center electricity consumption by leveraging the strengths of both national-level modeling (LBNL) and state-specific analysis (EPRI). The use of LBNL's total U.S. electricity consumption figures as the baseline ensures consistency with the most comprehensive bottom-up modeling available, while EPRI's state-level insights enable accurate proportional allocation to California.

2.2 Projected Annual Electricity Consumption of California Data Centers in 2028

This section outlines the methodology used to project the annual electricity consumption of data centers in California for the year 2028. The projection extends the historical analysis from 2019-2023 by employing a forecasting model that integrates growth scenarios from two important sources: the LBNL report [41] and the EPRI report [13]. This approach is designed to provide a plausible range of future electricity consumption levels, reflecting the significant uncertainties and dynamic factors shaping the data center industry, most notably the rapid expansion of AI workloads. The forecast establishes a quantitative basis for the subsequent analysis of carbon emissions and public health impacts.

2.2.1 Forecasting Methodology

The projection for 2028 is derived from a multi-step process that combines a validated 2023 baseline with a set of CAGRs representing low-growth and high-growth scenarios.

First, we establish the 2023 electricity consumption of California data centers as the baseline for our projection. Based on the proportional allocation methodology detailed previously, this value is estimated to be 10.82 TWh. Second, to project future demand, we consider growth forecasts from both LBNL [41] and EPRI [13] for the 2023-2028 period. This method aims to balance LBNL's bottom-up, technology-driven projections with EPRI's top-down, tempered demand projections.

- The LBNL report projects a low-growth rate of 13% and a high-growth rate of 27% for U.S. data centers between 2023 and 2028, driven largely by the proliferation of AI servers.

- The EPRI report provides more conservative estimates, with a low-growth scenario of 3.7% and a high-growth scenario of 10% from 2023 to 2030, reflecting factors like grid limitations and efficiency improvements.

To create a balanced forecast, we calculate the arithmetic mean of these corresponding low- and high- growth rates. This approach yields a plausible range that accounts for both the technological push and the infrastructural pull factors influencing data center energy demand.

The low-growth rate (r_{low}) and high-growth rate (r_{high}) are calculated as follows:

$$r_{low} = \frac{13\%\ (\text{lbnl}) + 3.7\%\ (\text{EPRI})}{2} = 8.35\%$$

$$r_{high} = \frac{27\%\ (\text{LBNL}) + 10\%\ (\text{EPRI})}{2} = 18.5\%$$

These averaged growth rates of 8.35% and 18.5% serve as the basis for our low- and high- projection scenarios for 2028, respectively.

2.2.2 2028 Electricity Consumption Projections

The projected electricity consumption for 2028 is calculated by applying the derived compound annual growth rates to the 2023 baseline electricity consumption figure over a five-year period (2024-2028). The formula for this projection is:

$$E_{2028} = E_{2023} \times (1+r)^5$$

Where E_{2023} = 10.82 TWh and *r* is the respective annual growth rate.

- **Low-Growth Scenario Projection:**

  $E_{2028,low} = 10.82\ \text{TWh} \times (1 + 0.0835)^5 \approx \mathbf{16.16\ TWh}$

  This scenario anticipates a more moderate expansion trajectory, where efficiency gains and potential market saturation temper the growth driven by new technologies.

- **High-Growth Scenario Projection:**

  $E_{2028,high} = 10.82\ \text{TWh} \times (1 + 0.185)^5 \approx \mathbf{25.28\ TWh}$

  This scenario reflects a more aggressive expansion, driven by the unabated and rapid deployment of energy-intensive AI applications and a significant increase in the installed base of accelerated servers. Therefore, our model projects that the annual electricity consumption of data centers in California will range between **16.16 TWh and 25.28 TWh** in 2028, as seen in Figure 1. This significant increase from the 2023 baseline underscores the escalating energy demands of the state's digital infrastructure. The wide range between the low and high scenarios highlights the considerable uncertainty in the sector, influenced by factors such as the pace of AI demand, advances in hardware efficiency, grid capacity constraints, and the adoption of best practices for managing data centers.

2.3 California Data Center Electricity Consumption Results

This section presents the results of our analysis regarding California data center electricity consumption from 2019 through 2023, with projections extending to 2028. The findings integrate historical data analysis with forward-looking projections under both low-growth and high-growth scenarios.

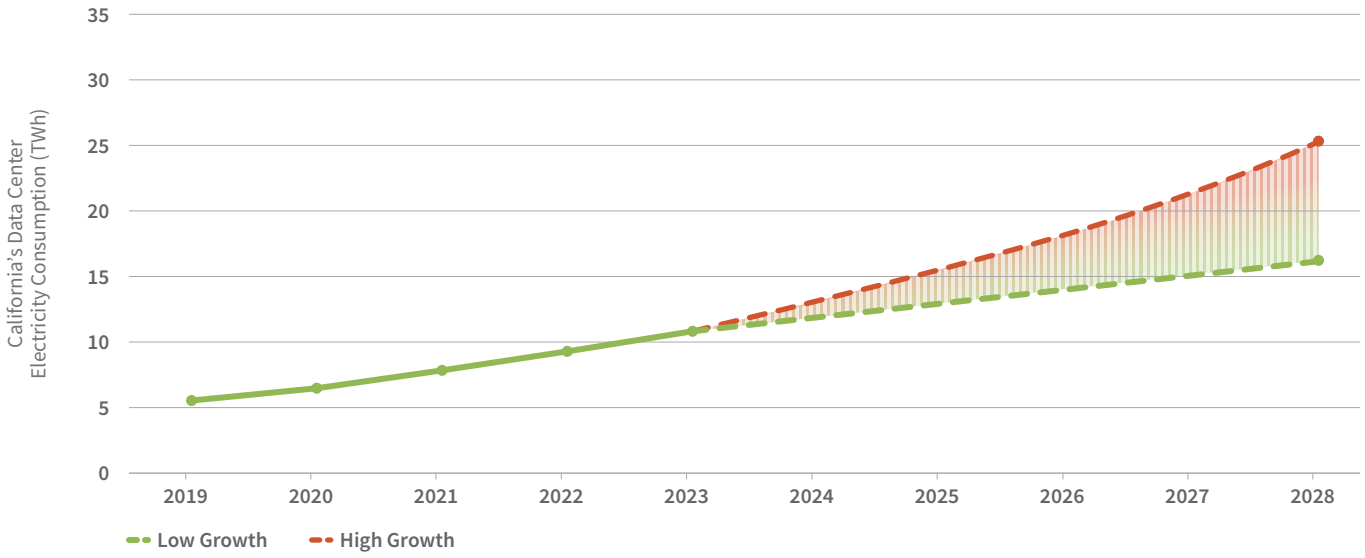
Figure 1 illustrates the evolution of California data center electricity consumption. The historical data from 2019 to 2023 demonstrates a consistent upward trajectory, with electricity consumption nearly doubling from 5.54 TWh to 10.82 TWh, a 95% increase that reflects the state's expanding digital infrastructure and growing computational demands. The projection period (2024-2028) presents two distinct growth scenarios, with the shaded region between them representing the uncertainty band associated with different assumptions about technology adoption rates, efficiency improvements, and market dynamics.

Table 2 provides a detailed comparison of California's data center electricity consumption within the national context. The data reveals California's substantial contribution to the U.S. total data center electricity demand, underscoring the state's critical role in supporting national digital infrastructure.

The results reveal several critical insights regarding California's position as a cornerstone of the U.S. data center ecosystem.

First, between 2019 and 2023, California's data centers consumed approximately 6% of the total national data center electricity, consistently placing the state among the top three consumers, behind only Virginia and Texas. This substantial and sustained share underscores California's large role in powering America's

Figure 1. California data center electricity consumption (2019-2028)



Note: Historical electricity consumption data (2019-2023) shown with actual values, while projections (2024-2028) present low-growth and high-growth scenarios with associated uncertainty bands.

digital infrastructure amid rapidly growing demand.

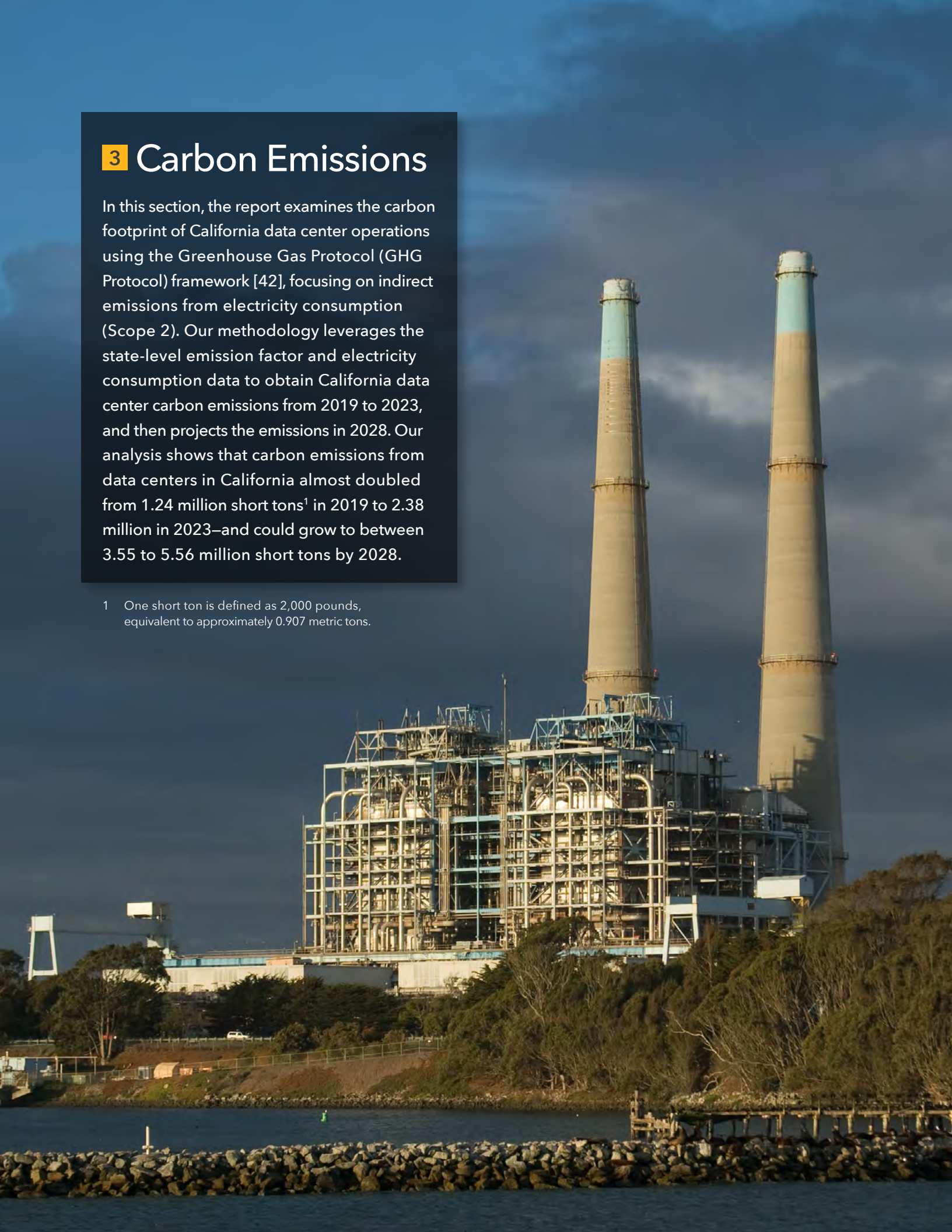
Second, the absolute growth in California's data center electricity consumption is substantial, increasing from 5.54 TWh in 2019 to 10.82 TWh in 2023. This 5.28 TWh increase represents significant additional demand on the state's electricity grid, equivalent to the annual electricity consumption of approximately 490,000 average U.S. households [3]. This growth underscores the urgent need for improved grid capacity and integration of renewable energy to support sustainable expansion.

Third, the 2028 projections illustrate the magnitude of future challenges and opportunities. Under the low-growth scenario, California's data center electricity consumption would reach 16.16 TWh, while the high-growth scenario projects 25.28 TWh, which represents increases of 49% and 134% respectively from 2023 levels. These projections suggest that California data centers could require between 5.3 TWh and 14.5 TWh of additional electricity within five years.

Importantly, California's role extends beyond mere electricity consumption metrics. As the home to Silicon Valley and major technology corporations, California data centers serve as critical nodes in the global digital infrastructure, supporting innovation in AI, cloud computing, and emerging technologies. The state's data centers process workloads that drive technological advancement nationwide, making their reliable operation essential for maintaining U.S. competitiveness in the global digital economy.

Table 2. California data center electricity consumption in national context

Year	CA Data Center Electricity (TWh)	U.S. Data Center Electricity (TWh)
2019	5.54	90.28
2020	6.48	105.56
2021	7.84	127.78
2022	9.29	151.39
2023	10.82	176.39
2028 (low)	16.16	263.40
2028 (high)	25.28	412.16



3 Carbon Emissions

In this section, the report examines the carbon footprint of California data center operations using the Greenhouse Gas Protocol (GHG Protocol) framework [42], focusing on indirect emissions from electricity consumption (Scope 2). Our methodology leverages the state-level emission factor and electricity consumption data to obtain California data center carbon emissions from 2019 to 2023, and then projects the emissions in 2028. Our analysis shows that carbon emissions from data centers in California almost doubled from 1.24 million short tons[1] in 2019 to 2.38 million in 2023–and could grow to between 3.55 to 5.56 million short tons by 2028.

1 One short ton is defined as 2,000 pounds, equivalent to approximately 0.907 metric tons.

3.1 Overview of Scope 1, 2 and 3 Emissions

As the foundational infrastructure of the modern digital economy, data centers are coming under intensified scrutiny for their significant and multifaceted carbon emissions. Given the accelerating pace of technological innovation and the increasing imperatives of environmental stewardship, it is critical that policymakers, industry executives, and stakeholders adopt a comprehensive framework for evaluating and mitigating these emissions [43]. This section provides an in-depth analysis of the carbon emissions associated with data center operations, examining the three primary emission scopes: Scope 1, Scope 2, and Scope 3 according to the GHG Protocol [42].

Accurate quantification and ongoing monitoring of carbon emissions underpin any successful strategy to reduce greenhouse gas output. The GHG Protocol delineates emissions into three distinct categories: Scope 1 emissions, which are direct GHG emissions from sources that are owned or controlled by an organization [44]; Scope 2 emissions, representing indirect emissions from the generation of purchased energy such as electricity, steam, heat, or cooling [44]; and Scope 3 emissions, which include all other indirect emissions associated with a company's operations and value chain activities [45].

In data centers, Scope 1 emissions generally encompass direct emissions from on-site energy generation and related combustion processes, including fuel combustion in boilers, furnaces, and backup generators, as well as emissions from maintenance vehicles used in facility operations. Given that data centers often require uninterrupted power and climate control, reliance on on-site combustion systems, particularly during peak demand or emergency situations, can result in direct emissions. However, Scope 1 emissions are often orders of magnitude smaller than Scope 2 emissions [18] and therefore are excluded from our analysis in this report.

Scope 2 emissions represent indirect releases from off-site energy generation. Data centers are highly energy-intensive, requiring continuous power for servers, cooling, and support systems. Although these emissions occur in the plants where electricity is produced, they are attributed to the data center because they stem directly from its electricity consumption. Electricity generation contributes a large share of global greenhouse-gas emissions, and with governments tightening regulations while economic incentives increasingly favor renewable power, data center operators now face growing pressure to adopt clean-energy strategies and curb their Scope 2 emissions.

Scope 3 emissions extend beyond the immediate operational limits of the facility and encompass the entire value chain, from the production of hardware and other capital goods to the end-of-life disposal of electronic equipment. Scope 3 emissions are often subdivided into upstream and downstream categories [45]. Upstream emissions include those related to the extraction, manufacturing, and transportation of components and materials that eventually form the data center infrastructure. For instance, the production of servers, cooling units, and other critical components involves significant electricity consumption and material processing, which in turn generate considerable GHG emissions. Downstream emissions, on the other hand, refer to those that result from the data center's services, such as the energy consumed by end users when interacting with cloud-based services or the emissions associated with the disposal and recycling of outdated hardware. Public data on Scope 3 emissions often has high degrees of uncertainties, and Scope 3 emissions are not directly related to data center operation. Thus, it is also excluded from this report.

3.2 Carbon Emissions by California Data Centers

Drawing on state-level electricity profiles and carbon emission factors from the U.S. Energy Information Administration (EIA) [46], this analysis assesses carbon emissions from California data centers. From 2019 through 2023, we calculate their annual emissions and benchmark these figures against both California's total carbon output and the U.S. average emission factor. We anticipate that these calculations will elucidate temporal trends and provide substantive insights to underpin our policy recommendations.

According to the EIA State Electricity Profiles, the U.S. utility-scale power plants produced roughly 4.18 trillion kWh of net electricity in 2023. That resulted in approximately 1.69 billion short tons of carbon, yielding an average emission factor of 0.81 pounds of carbon per kWh [47]. Both total generation and emission intensity vary considerably from state to state and among different energy sources.

3.2.1 Data Sources and Emission Factors

We utilize data from the U.S. EIA, which publishes annual carbon emission factors for each state in units of pounds per megawatt hour (lbs/MWh), as well as a national average in pounds per megawatt hour (lbs/MWh). The resulting emission factors for California and for the entire United States from 2019 to 2023 are shown in Table 3.

3.2.2 Methodology

In general, the Scope 2 carbon emissions attributable to data center electricity consumption are calculated using the following formula:

$$\text{Total Emissions (lbs)} = \begin{matrix}\text{Emission Factor (lbs/MWh)} \\ \times \\ \text{Electricity Consumption (MWh)}\end{matrix}$$

Table 4 summarizes annual electricity consumption and Scope 2 carbon emissions for California data centers over 2019–2023. The detailed calculation methodology appears in Appendix B. Below we present definitions of the variables referenced in the table:

- **CA DC Electricity (TWh):** Total annual electricity consumption of California data centers.
- **CA Total Electricity (TWh):** Total annual electricity consumption for the entire state of California.
- **CA DC Emission (million short tons):** Carbon emissions attributable to California data centers.
- **DC Emission of CA Total (%):** The proportion of data center carbon emissions relative to statewide electricity-related emissions.
- **CA–US Ratio (%):** The percentage of California data center carbon emissions relative to the emissions that would result from the same electricity consumption evaluated at the U.S. national average emission intensity.

3.2.3 Results

Table 4 presents our results for the carbon emissions of California data centers from 2019 to 2023. While EIA's electricity consumption data captures utility-metered usage, it excludes behind-the-meter generation (e.g., onsite solar). Note that our analysis assumes static boundaries for Scope 2 accounting under the "location-based" method, which does not adjust for contractual instruments like renewable energy credits (RECs). This choice may understate market-based emissions reductions achieved by operators purchasing bundled renewable power, which may have private contracts not available to the public. Nonetheless, location-based emissions are considered "essential" and allows the accounting of physical carbon emissions associated with electricity consumption [50].

As shown in Table 2, California data centers exhibit a pronounced increase in electricity consumption over the 2019–2023 period, rising from 5.54 TWh in 2019 to 10.82 TWh in 2023. Consequently, estimated carbon emissions

Table 3. Carbon emission factors for California and the United States

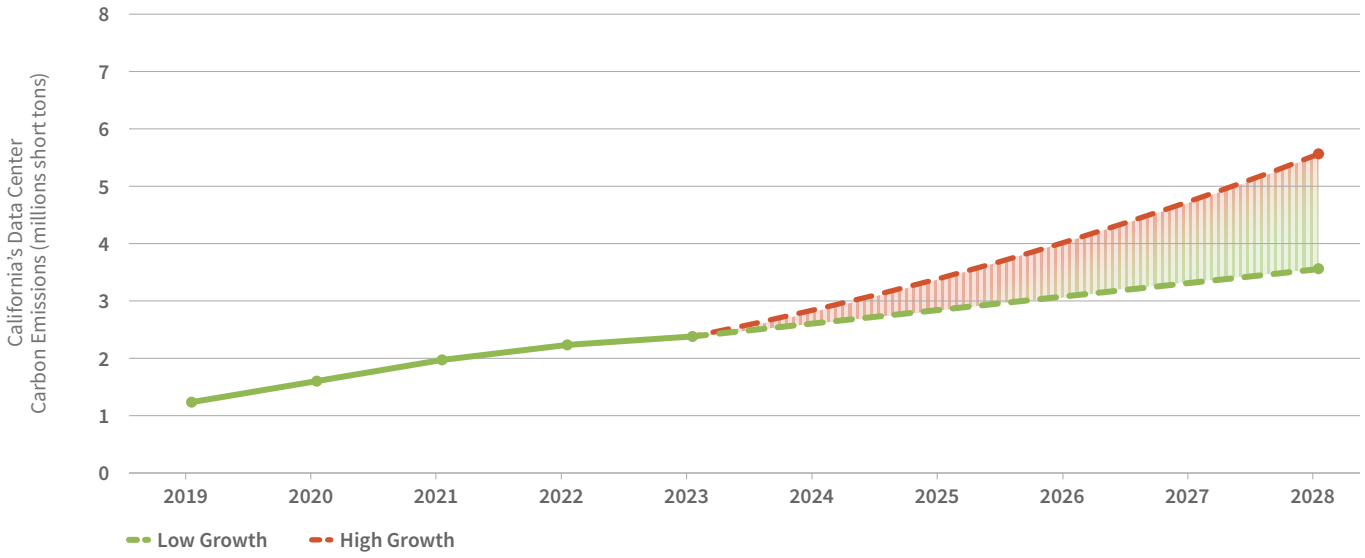
Year	CA Emissions Factor (lbs/MWh)	U.S. Emission Factor (lbs/MWh)
2019	446	921
2020	495	855
2021	503	886
2022	481	860
2023	440	807

Note: The CA Emission Factor is obtained from [46] and the US Emission Factor is from [47].

Table 4. Electricity consumption (total retail sales) and carbon emissions for California data centers (2019-2023) [46]

Year	CA DC Electricity (TWh)	CA Total Electricity (TWh)	CA DC Emission (million short tons)	DC Emission of CA Total (%)	CA-US Ratio (%)
2019	5.54	250.38	1.24	2.21	48.43
2020	6.48	250.17	1.60	2.59	57.89
2021	7.84	247.25	1.97	3.17	56.77
2022	9.29	251.87	2.23	3.69	55.93
2023	10.82	239.48	2.38	4.52	54.52

Figure 2. California data center carbon emissions (2019-2028)



nearly double, increasing from 1.24 million short tons to 2.38 million short tons over the same interval. This trend underscores the rapid expansion of data center capacity in California and its impact on carbon emissions.

Furthermore, the data center share of statewide electricity-related emissions (DC Emission % of CA Total) grows steadily from 2.21% in 2019 to 4.52% in 2023, showing that even as the grid becomes cleaner, data center operations are making up an ever-larger portion of the state's total emissions.

The "CA-US Ratio" metric reveals that California data centers emitted just 48.43% of the carbon they would have under the national average intensity in 2019. The figure peaks at 57.89% in 2020, then drops back to 54.52% by 2023. The post-2020 decrease suggests that California's carbon emission advantage diminished slightly over time, probably driven by changes in renewable energy penetration, greater use of natural gas during low solar output, and other temporary shifts in the fuel mix. These trends underscore the need for ongoing investment in clean energy and demand management if California is to maintain its grid advantage over the national average.

3.2.4 Projection of Carbon Emissions by California Data Centers in 2028

To derive future growth scenarios for California data center carbon emissions between 2023 and 2028, with the assumption that the carbon emission factor remains the same as in 2023 (440 lbs/MWh), we leverage the two average growth rates introduced in Section 2, serving as the basis for our low- and high-projection scenarios. We assume that the California grid's carbon emission factor in 2028 will remain at the 2023 level, primarily due to the relatively stable carbon emission factors observed in California from 2019 to 2023 and the potential challenges associated with further decarbonizing the grid by 2028.

Figure 2 shows the historical and projected carbon emissions of California data centers between 2019 and 2028. The solid green line with round markers represents actual emissions from 2019 through 2023, rising from approximately 1.24 million short tons in 2019 to 2.38 million short tons in 2023. Beginning in 2023, two projection scenarios are shown: the dashed green line corresponds to the "Low Growth" trajectory (annual growth rate of 8.35%), while the dash–dot red line represents the "High Growth" trajectory (annual growth rate of 18.5%). By 2028, the Low Growth scenario yields roughly 3.55 million short tons, whereas the High Growth scenario reaches about 5.56 million short tons. The shaded area between the two projection curves highlights the uncertainty band associated with these different growth assumptions.

3.3 Discussion

California's experience underscores both the magnitude of the challenge and the potential pathways toward more sustainable data center operations. From 2019 to 2023, the electricity consumption of state data centers nearly doubled, from 5.54 TWh to 10.82 TWh, driving carbon emissions from 1.24 to 2.38 million short tons. By 2023, data centers were responsible for 4.52% of California's total electricity-related emissions. Looking ahead, projections suggest that emissions could rise to between 3.55 and 5.56 million short tons by 2028, depending on future growth rates, highlighting the sector's rapidly expanding carbon footprint.

Reversing this trajectory demands coordinated action across three mutually enhancing domains. First, grid-responsive operations, such as carbon-aware scheduling and demand-side coordination, can reduce marginal emissions by timing compute workloads to coincide with cleaner energy availability. Second, circular infrastructure strategies that include the recovery of waste heat and a longer lifetime of hardware help reduce embodied emissions and ease the burden on energy systems. Third, value chain transparency is crucial for carbon emissions governance, as organizations must have clear insight into the emissions generated during raw material extraction, component manufacturing, logistics, assembly, use and end of life disposal to ensure that upstream carbon impacts do not overshadow efficiency improvements in operations.

California's regulatory leadership as well as ongoing grid decarbonization efforts offers a strong foundation for sustainability. However, achieving a net zero data center infrastructure will require a shift away from traditional success metrics (e.g., delivered teraflops) to carbon intensity-aware benchmarks (e.g., avoided teraflops per ton of CO_2). Standardized accounting frameworks such as the GHG Protocol, paired with interoperable public-private carbon emission tracking platforms, can help reframe carbon data as a strategic asset, fueling better grid integration, sustainable procurement, and climate-aligned innovation.

4 Water Consumption

This section provides an assessment of water consumption associated with California data center operations, including both direct on-site cooling water consumption and indirect electricity-related water consumption. We first establish a three-scope framework categorizing water usage into distinct pathways: direct on-site consumption for cooling (Scope 1), indirect consumption from off-site electricity generation (Scope 2), and embodied water within the supply chain (Scope 3). We provide a methodology for quantifying these impacts and present an analysis of water consumption from 2019 through 2023, with projections to 2028 under various growth scenarios. The findings reveal that off-site water consumption dominates the total operational water footprint, accounting for more than 90% of the total, while demonstrating substantial growth trajectories that nearly double consumption from 2019 to 2023. These results underscore the critical importance of integrated water-energy planning in California's digital infrastructure development.



4.1 Background and Context

4.1.1 Understanding the Distinction: Water Withdrawal and Water Consumption

A precise accounting of a data center's hydrological impact requires a clear delineation between two key metrics: water withdrawal and water consumption [51, 52]: Water withdrawal encompasses all freshwater extracted from local sources, while water consumption represents the portion that is evaporated, transpired, or permanently removed from the immediate water environment [52].

Water consumption provides a measure of environmental impact since it reflects the actual reduction in locally available water resources, whereas withdrawn water may be returned to local watersheds. While both metrics are important, water consumption is often the default metric in environmental impact assessments [17].

Throughout this report, "water footprint" refers specifically to water consumption unless otherwise noted, consistent with established industry practice and environmental assessment methodologies.

4.1.2 Overview of Data Center Water Footprint

The water footprint of data centers extends across three distinct scopes or pathways, each representing different mechanisms through which data centers impact water resources. Understanding these pathways enables a comprehensive assessment of the total impact of water on data centers.

Scope 1: Direct On-site Water Consumption

Server operations generate substantial heat, which requires active removal through facility cooling systems. While server-level cooling (air- or liquid- based) does not directly consume water, facility-level heat rejection to the external environment represents the primary source of direct water consumption. Specifically, cooling towers are commonly used and evaporate water to dissipate heat through open-loop systems. The evaporated portion of water withdrawal is considered water consumption. Importantly, cooling towers primarily use drinking water to keep the optimal efficiency. For each kWh of server energy, a cooling tower can evaporate 1 L of water for efficient operations [53] to 9L of water in hot climates [54]. Evaporative-assisted natural cooling leverages ambient air when temperatures permit, while requiring water evaporation when the ambient air is above a threshold (say, 85°F) and for humidity control. These systems consume less water on average than cooling towers, although hot weather creates peak demand periods that may stress local water supplies. Closed-loop dry cooling could eliminate on-site water consumption but often increases cooling energy requirements compared to water evaporation-based heat rejection mechanisms [55], potentially escalating total environmental impact through higher Scope 2 consumption.

Scope 2: Electricity-Related Water Consumption

Electricity generation constitutes a major water consumption pathway, with thermoelectric power ranking among the most water-intensive sectors [56]. Data centers bear responsibility for water consumed during power generation, similar to their accountability for carbon emissions. Power generation technologies exhibit vastly different water intensities. Thermoelectric facilities (coal, natural gas, nuclear) require substantial water for steam production and cooling, consuming significant portions through evaporative processes. Renewable sources vary considerably: solar photovoltaic and wind require minimal water, while hydroelectric generation incurs substantial evaporative losses from reservoir operations. The U.S. electricity generation averages approximately 43.8 L/kWh for withdrawal [57] and 3.1 L/kWh for consumption [56], with substantial regional variation based on generation mixes. Some technology companies have begun incorporating Scope 2 water consumption into sustainability reporting [58].

Scope 3: Supply Chain Water Requirements

Hardware manufacturing represents the least transparent yet potentially largest component of total water footprint [59]. Semiconductor production demands vast quantities of ultrapure water for wafer fabrication, with each manufacturing layer requiring multiple cleaning processes. Despite recycling capabilities, industry practices achieve only 45-50% water reuse rates [60], while discharged water contains toxic chemicals requiring specialized treatment [61]. Supply chain consumption often dominates total footprint. One technology company reports about 99% of its water impact originates from supply chain operations rather than direct facilities [62]. In contrast to agricultural water use that primarily

draws from natural precipitation, data centers depend mostly on freshwater supplies from surface and subsurface water bodies. This reliance may intensify competition for finite freshwater resources that serve multiple human needs in certain regions.

4.2 Methodology for Water Consumption

4.2.1 Water Consumption Calculation Framework

While we categorize data center water consumption into three distinct scopes, we focus on Scope 1 and Scope 2 water consumption, which is more relevant to the operation of data centers in California since Scope 3 water consumption comes from the supply chain that is often not located in California.

Scope 1: Direct Facility Water Usage

Direct water consumption accounts for on-site cooling and facility operations. We calculate this using time-varying water usage effectiveness (WUE) metrics that reflect environmental conditions such as temperature and humidity.

Scope 2: Grid-Based Water Usage

Indirect water consumption results from electricity generation required to power data centers. We estimate this using regional Electricity Water Intensity Factors (EWIF) that account for California's diverse energy generation mix and seasonal variations.

Our analysis employs annualized average WUE and EWIF values to estimate total water consumption by California data centers. Detailed methodological calculations and technical specifications are provided in Appendix C.

Table 5. Annual WUE and PUE values used in calculations (2019-2028)

Year	WUE (L-kWh)	PUE
2019	0.36	1.51
2020	0.36	1.49
2021	0.36	1.47
2022	0.36	1.46
2023	0.37	1.42
2028	0.37	1.42

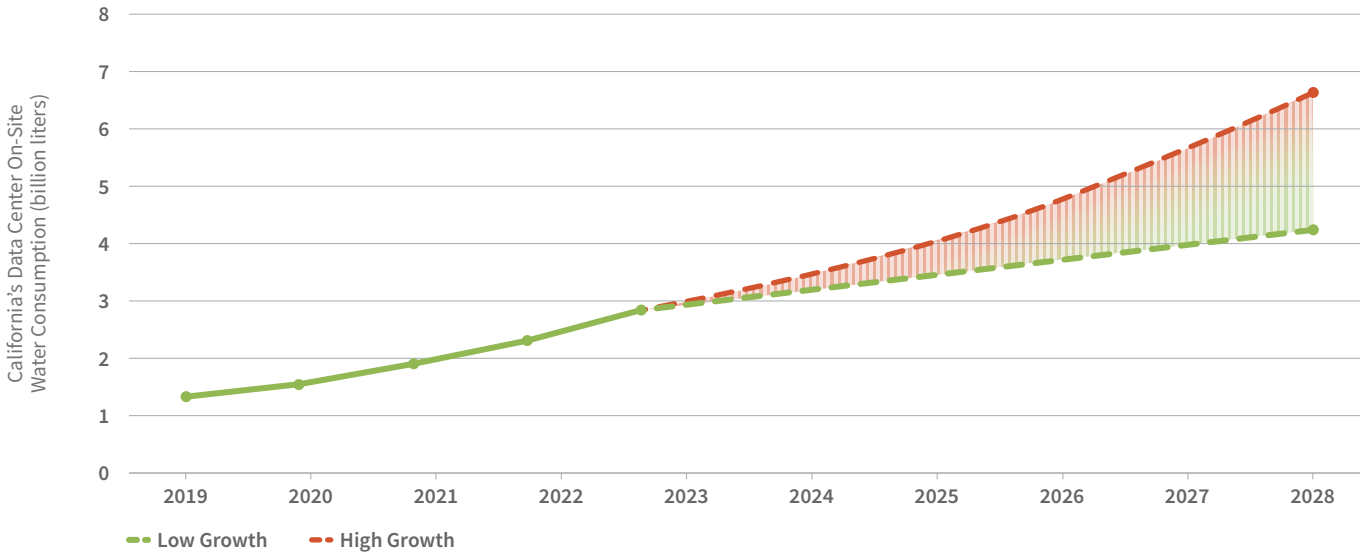
4.2.2 Data Inputs and Parameters

This section outlines the key parameters and data sources utilized in our water consumption calculations for California data centers. We select appropriate values based on public sources while considering California's specific operational characteristics.

For Scope 1 on-site water consumption, we use the national average WUE from the LBNL report [41] as a proxy for California's data center WUE (Table 5). We also assume that California's data center WUE in 2028 will remain the same as the 2023 WUE, although the LBNL report projects a growing trend of data center WUE for U.S. average. Note that this is a conservative estimate as the onsite WUE for California data centers is potentially higher than the national average due to its relatively hotter and dry climate.

For Scope 2 off-site water consumption, two parameters are particularly critical: Power Usage Effectiveness (PUE) and EWIF. We apply the average PUE from the LBNL report (Table 5) due to its comprehensive, multi-year analysis [41]. Regarding the EWIF, which quantifies water consumption per unit of electricity, both the World Resources Institute (WRI) and LBNL provide projections. The WRI figure is approximately 5.18 L/kWh [56]. In contrast, LBNL provides the U.S. average value of 4.35 L/kWh without showing the specific EWIF for California. Between these two values, we select the more conservative LBNL estimate of the U.S. average 4.35 L/kWh as California's EWIF. For our 2028 projections, we maintain the same WUE, PUE, and EWIF values as established for 2023.

Figure 3. California data center on-site water consumption (2019-2028)



Note: Historical data (2019-2023) shown with solid line and square markers; projections (2024-2028) presented with dashed lines for low-growth and dash-dot lines for high-growth scenarios. The shaded area represents the uncertainty range between growth scenarios.

4.3 Results

Our analysis of California data center water consumption from 2019 to 2028 reveals substantial growth patterns across both historical and projected periods. The analysis, presented in Figure 3 for on-site water consumption, Figure 4 for total water consumption, and Table 6 for detailed breakdowns, demonstrates that water consumption has nearly doubled during the historical period (2019-2023) and is projected to potentially more than double again by 2028 under high-growth scenarios. The data consistently shows that off-site water consumption associated with electricity generation dominates the total water footprint, accounting for approximately 94-95% of total water consumption throughout the entire study period.

On-site Water Consumption

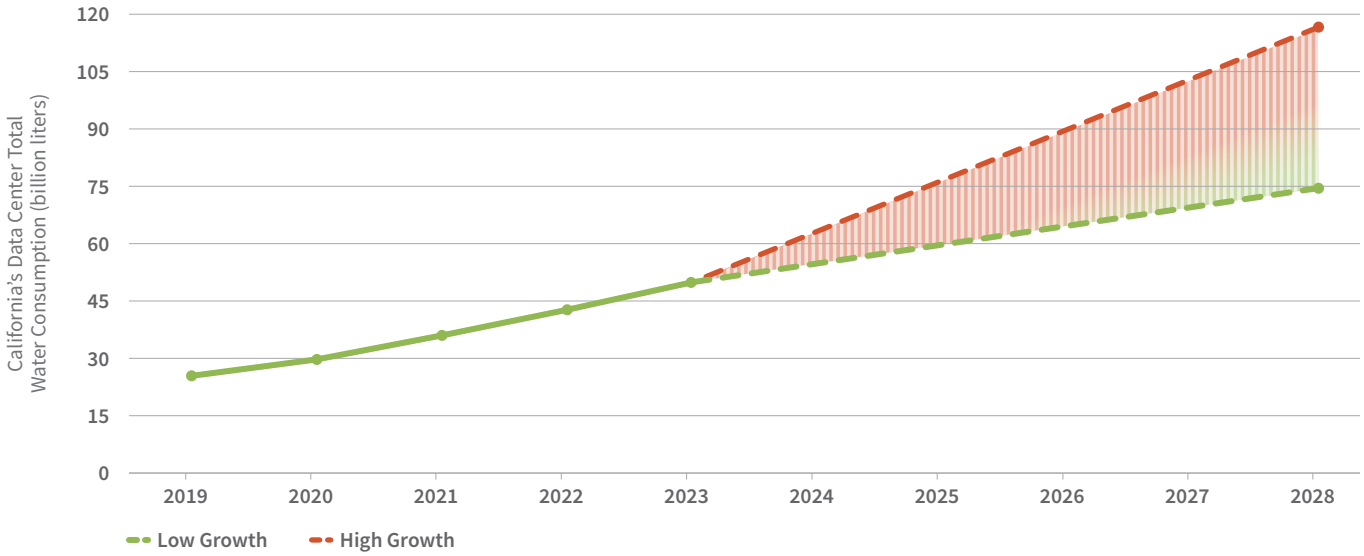
Figure 3 illustrates the evolution of on-site water consumption across the decade-long study period. The historical data (2019-2023) exhibits a strong upward trajectory, with water consumption increasing from 1.33 billion liters in 2019 to 2.84 billion liters in 2023, representing a 113% increase. This growth pattern demonstrates consistency, with year-over-year increases ranging from 17% to 23%, suggesting a stable relationship between facility expansion and cooling water requirements.

The projection period (2024-2028) introduces significant uncertainty, as evidenced by the diverging growth scenarios. Under the low-growth scenario, on-site water consumption reaches 4.24 billion liters by 2028, while the high-growth scenario projects 6.64 billion liters. This represents a 57% difference between scenarios, highlighting the sensitivity of water demand to underlying electricity consumption growth rates. The widening uncertainty band visible in the figure underscores the compounding effects of different growth assumptions over the five-year projection horizon.

Total Water Consumption

Figure 4 presents the total water footprint, revealing patterns that closely mirror on-site water consumption but with substantially larger magnitudes. The total water consumption increased from 25.42 billion liters in 2019 to 49.91 billion liters in 2023, a 96.4% increase that corresponds to a CAGR of 18.4%. The 2028 projections show a total water consumption ranging from 74.54 billion liters (low growth) to 116.63 billion liters (high growth), representing potential increases of 49% to 134% from 2023 levels. Our projection aligns with the 100–300% increase in total U.S. data center on-site water consumption from 2023 to 2028, as estimated by the LBNL report [41].

Figure 4. California data center total water consumption (2019-2028)



Note: Total water consumption encompasses both on-site cooling water usage and off-site water consumption associated with electricity generation. Historical trends and projection scenarios follow the same visualization scheme as Figure 3.

Electricity-Water Nexus

The relationship between electricity consumption and water usage emerges as a fundamental driver of data centers' water footprint. As shown in Table 6, electricity consumption growth from 5.54 TWh in 2019 to 10.82 TWh in 2023 (95% increase) closely tracks total water consumption growth (96% increase). This near-unity correlation extends into the projection period, where both low and high growth scenarios maintain proportional relationships between electricity and water consumption.

Table 6. California data center water consumption breakdown (2019-2028)

Year	Electricity Consumption (TWh)	On-Site Water Consumption (billion liters)	Off-Site Water Consumption (billion liters)	Total Water Consumption (billion liters)
2019	5.54	1.33	24.09	25.42
2020	6.48	1.56	28.17	29.73
2021	7.84	1.90	34.10	36.00
2022	9.29	2.31	40.40	42.71
2023	10.82	2.84	47.07	49.91
2028 (low)	16.16	4.24	70.29	74.54
2028 (high)	25.28	6.64	109.99	116.63

The dominance of off-site water consumption reveals the critical importance of electricity generation in the overall water footprint. For every TWh of total electricity consumed (including both server and non-server energy), California data centers indirectly drive approximately 4.35 billion liters of water consumption through power generation processes. This electricity-water intensity factor, combined with modest on-site water consumption, results in a total water intensity of approximately 4.61 billion liters per TWh across the study period.

Growth Trajectory Implications

The divergence between low and high growth scenarios becomes increasingly pronounced over time, with the uncertainty range expanding to 42.09 billion liters by 2028. This expanding uncertainty reflects not only different assumptions about data center growth rates but also the cumulative impacts of technological adoption, policy interventions, and market dynamics. The low-growth scenario's 8.35% CAGR represents a

continuation of data center efficiency improvements and measured expansion, while the high-growth scenario's 18.5% CAGR reflects potential rapid AI adoption and computational demand surge.

Discussion

The analysis reveals three critical findings regarding California data center water consumption. First, the sector's water footprint has experienced and will likely continue to experience substantial growth, with total water consumption potentially reaching 74.54 to 116.63 billion liters by 2028—representing up to a 4.6-fold increase from 2019 levels. Second, the overwhelming dominance of off-site water consumption (approximately 95% of total) indicates that addressing the water footprint of data centers requires systemic interventions at the electricity generation level rather than focusing solely on facility-level cooling efficiency. Third, the strong coupling between electricity consumption and water usage suggests that without breakthrough innovations in cooling technology or fundamental shifts in electricity generation methods, water consumption will continue to scale up with computational and energy demand.

These findings underscore the urgent need for integrated water-energy planning amid California's digital infrastructure development. The substantial uncertainty in future projections—ranging from moderate growth requiring an additional 24.63 billion liters annually to aggressive growth demanding 66.72 billion liters more by 2028—highlights the profound impact that policy decisions, technological innovations, and market dynamics will have on the state's water resources. As California faces ongoing water scarcity challenges, the exponential growth in data center water consumption presents an emerging sustainability challenge that requires careful attention through comprehensive policy frameworks, technological innovation, and adaptive resource management strategies.



5 Public Health Cost

This section quantifies the economic burden of public health impacts attributable to California data center operations, encompassing direct emissions from on-site backup generators (Scope 1) and indirect emissions from electricity generation (Scope 2). Employing established health impact assessment methodologies and the EPA's COBRA model [65], this section estimates the economic costs of adverse health outcomes (including respiratory and cardiovascular illnesses and premature mortality) and assess historical health costs from 2019-2023 with projections to 2028 under different growth scenarios. The findings demonstrate substantial cost escalation from $44.68 million in 2019 to $155.44 million in 2023, with Scope 2 emissions consistently accounting for most of the total impacts. Notably, California's aggressive clean energy transition and air quality policies exhibit a decoupling effect between electricity consumption growth and proportional health cost increases.

5.1 Scope 1 Health Cost

5.1.1 Background on Health Cost Metrics for Scope 1 Emissions in California

Scope 1 emissions consist of direct releases of criteria air pollutants from on-site combustion sources and represent a key determinant of ambient air quality and public health outcomes [66, 67]. In California, large-scale data center facilities routinely deploy backup generators, typically burning diesel fuels, to maintain uninterrupted service during grid outages. When these backup generators are initiated or cycled, they emit fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) [68]. These co-pollutants disperse into surrounding neighborhoods, potentially elevating local concentrations well above regulatory thresholds, particularly under atmospheric inversion conditions.

Epidemiological evidence robustly associates elevated $PM_{2.5}$ concentrations with increased incidence of respiratory and cardiovascular morbidity and mortality. Specifically, large-scale cohort studies and meta- analyses show that each 10 µg/m3 increase in long-term $PM_{2.5}$ exposure is linked to a 6-8 % rise in all-cause mortality [69]. Children, older adults, and individuals with preexisting cardiopulmonary conditions consistently experience equal or greater risk increases under the same exposure increments [70].

Mechanistically, $PM_{2.5}$ particles penetrate deep into the alveolar region, translocate into the systemic circulation, and provoke inflammatory and oxidative stress pathways that precipitate acute events such as myocardial infarction and heart failure [71]. Concurrently, chronic exposure to NOx and VOCs exacerbates asthma, chronic obstructive pulmonary disease (COPD), and other lower-respiratory-tract conditions by promoting airway inflammation and hyperresponsiveness [72].

California's distinctive climate and dense population magnify the health impacts of localized backup generator emissions. Many residents live near data center facilities in California's densely populated metropolitan counties such as Los Angeles and Santa Clara [74]. As a result, even modest increases in Scope 1 emissions can lead to significant public health impacts.

Despite these known health hazards, California's regulatory framework administered by the California Air Resources Board (CARB) allows certain "emergency" exemptions for backup generators during grid stress events, thus creating episodic spikes in pollutant levels [76]. Although CARB's ambient air quality standards cap the annual average $PM_{2.5}$ concentration at 12 µg/m3 (since June 2003), they rely on the federal NAAQS 24-hour limit of 35 µg/m3 rather than setting a separate short-term $PM_{2.5}$ threshold [77]. As a result, during heat waves and other high-demand periods, multiple diesel generators operating under these waivers can produce sharp spikes in NOx and particulate emissions, exacerbating acute respiratory and cardiovascular risks in nearby communities [68].

In real-world settings such as Silicon Valley, this may translate into elevation in local pollution. During a simulated fire prevention grid shut off assessed by the South Coast Air Quality Management District (SCAQMD), 523 emergency diesel generators operated continuously for 24 hours and emitted over 36 tons of NO_x in a single day [68], exceeding the typical daily NO_x output of major industrial sources in the region and imposing severe acute respiratory and cardiovascular health risks on adjacent communities.

In addition to NO_x, such grid stress events also produce acute $PM_{2.5}$ increases. Epidemiological evidence shows that a 10 µg/m3 same-day increase in $PM_{2.5}$ is associated with a 1.28% increase in heart failure hospitalizations among Medicare beneficiaries [78], a 0.71% increase in overall cardiovascular admissions in 108 US counties [79] and a 2.12% increase in hospitalization for heart failure or mortality in a global meta-analysis [80].

At the county level, regions with a high concentration of data center clusters may experience disproportionately high health burdens related to Scope 1. These adverse outcomes are driven in part by elevated emissions of nitrogen oxides (NO_x) from on-site diesel generators. Specifically, in California, the density of data centers is highest in Silicon Valley (Santa Clara County), which lies within the Bay Area Air Quality Management District (BAAQMD) [5, 6]. According to a 2023 CPUC analysis of the M.Cubed survey, BAAQMD reported 8,722 backup generators in 2021, of which nearly 90% were diesel gensets, including gensets deployed at data centers and other large facilities [7]. When aggregated across the Bay Area and South Coast Air Quality Management Districts, backup generators

emitted almost 1,000 metric tons of NOx in 2021 [81]. Notably, Santa Clara County's unique topography, a low-lying basin surrounded by coastal ranges, promotes the trapping of pollutants under weak synoptic winds, causing NO_x and VOC from backup generators to undergo rapid photochemical conversion to ozone during clear summer days [5, 82-83].

Seasonal heat waves may further amplify this problem by driving up electricity demand and the use of backup generators [84]. During July and August, the average daytime highs in Sacramento and throughout the Central Valley routinely exceed 90°F (daily maxima ≈93°F), driving up air-conditioning load and stressing the grid [85]. Under the resulting hot, stagnant conditions, ozone is more readily formed on warm, sunny days when the winds are light [86]. Regional photochemical modeling by the BAAQMD shows that a temperature-driven increase in photochemical reaction rates can increase the peak ozone by up to 8 ppb [87].

Stagnant late summer high pressure systems drive strong subsidence aloft, producing extended periods of intense solar insolation and suppressing vertical mixing [88,89]. In such stable conditions, ozone precursors accumulate and photochemical reactions accelerate. As the CEQA guidelines of the Bay Area Air Quality Management District note, "pollutants emitted into a stable air mass will travel downwind with little dispersion", allowing ozone to peak on hot and calm days [90]. Indeed, from 2012 through 2016 the neighboring San Joaquin Valley averaged 115 annual exceedances of the eight hour NAAQS ozone standard (70 ppb), underscoring how routinely summer stagnation drives unhealthy ozone spikes [91]. Furthermore, CAISO's 2022 Summer Market Performance Report indicates that backup diesel generators are regularly dispatched during afternoon peak load hours exactly when insolation and stagnation coincide, potentially further amplifying local ozone formation [92].

Similarly, ambient ozone and $PM_{2.5}$ levels are already high in Southern California cities, particularly in Los Angeles County, because heavy traffic, industrial emissions and the surrounding terrain prevent pollutants from dispersing. According to U.S. EPA three-year design values for 2020–2022, Los Angeles County's annual mean $PM_{2.5}$ concentration is 13.4 μg/m3, exceeding the 12 μg/m3 NAAQS threshold [93]. Furthermore, according to the South Coast Air Quality Management District 2022 Air Quality Management Plan Technical Support Document, based on the monitoring data for 2019-2021, the ozone design value of the South Coast Air Basin's 8 hour ozone design value was 114 ppb, nearly 63% above the 70 ppb NAAQS [94]. In 2020 alone, there were 157 days in which the 8-hour average exceeded the standard [95].

In this context, even modest emissions from data center backup generator cycling may push local pollutant concentrations above health-based thresholds, thereby exacerbating acute respiratory episodes (e.g., asthma exacerbations) and increasing hospital admissions for cardiovascular events.

To quantify the social costs associated with these localized emissions for policy analysis, researchers can employ the U.S. Environmental Protection Agency's COBRA model [65]. COBRA converts county-level emission inventories into corresponding changes in pollutant concentrations and applies concentration–response functions to estimate economic impacts such as hospital expenditures, lost workdays, and valuations of premature mortality. For example, a continuous 24 hours' operation of a data center backup generator can result in tens of thousands of dollars in combined hospitalization and emergency department costs [68,71].

5.1.2 Methodology for Estimating Scope 1 Health Costs in California

Given the limited public data on Scope 1 emissions from California data centers, we leverage Virginia's pollutant emission and electricity consumption data as a reference to get the emission rates for different pollutants. Then we could combine the emission rates with California's data center electricity consumption and derive California's annual pollutant-specific emission vector. The main tool for calculating the Scope 1 health cost is the EPA's COBRA model [65], which takes county-level emission changes as input and generates state-level health-cost estimates. In total, the whole process can be summarized into the following four steps:

Step 1: Derivation of Emission Rates from Virginia Data. We collect the total annual emissions of four pollutants: $PM_{2.5}$, SO_2, NO_x and VOCs permitted for Virginia data centers and apply a 10% scaling factor to the permitted emission levels as a reference level. Then divide by the same facilities' total electricity consumption to derive pollutant-specific emission rates (ton/MWh). Note that

the actual emissions levels could vary from 10%, depending on the frequency of demand response events, backup generator maintenance schedule, etc.

Step 2: Estimation of California's Statewide Emissions. We apply the four pollutants' emission rates to California's data centers and get the annual pollutant-specific emission for $PM_{2.5}$, SO_2, NO_x and VOCs (ton).

Step 3: Allocation to Principal Counties. As we leverage the EPA's COBRA model [65] to calculate the Scope 1 health cost, we need to take the county-level emission change for the four pollutants as input. In our research, we focus on major counties, including Los Angeles and Santa Clara, which host a large number of data centers in California according to publicly available maps [99].

Step 4: Conversion to State-Level Health Costs via COBRA. In the last step, we apply the EPA's COBRA model [65] to obtain California's Scope 1 health cost. A detailed exposition of the model's underlying principles and computational methodology for projecting Scope 1 health costs is provided in the Appendix D.

5.2 Scope 2 Health Cost

5.2.1 Background and Significance of Scope 2 Health Costs

Scope 2 public health costs refer to the health impacts and associated economic losses caused by pollutant emissions from electricity generation required to power data center operations. Unlike Scope 1 emissions that originate directly from on-site backup generators at data centers, Scope 2 emissions occur at power plants supplying electricity to the grid, yet their environmental and health impacts are equally profound and more geographically dispersed.

In the U.S. electricity system, despite the continued growth in renewable energy share, fossil fuel generation still maintains a significant position. As of 2023, natural gas generation accounts for approximately 43% of total U.S. electricity generation, while coal generation comprises about 16% [100]. These fossil fuel power plants release substantial quantities of pollutants during combustion, including NO_x, SO_2, and $PM_{2.5}$. These pollutants can affect areas far from emission sources through atmospheric transport, causing regional air quality degradation. According to U.S. EPA estimates, the power sector causes thousands of premature deaths annually due to air pollution, with related medical expenditures and productivity losses reaching billions of dollars [101].

California's rapidly growing data center electricity demand has indirect public health impacts that cannot be overlooked. Although California's grid has a relatively high proportion of clean energy, it still relies on natural gas generation during peak demand periods, and interstate electricity trading might also import some power from regions with high-emission sources.

The Scope 2 public health costs are also irregularly dispersed among geographic regions, often with economically disadvantaged areas shouldering a greater share of these health burdens [103]. Therefore, accurately quantifying data center Scope 2 health costs is crucial for developing fair energy policies and corporate social responsibility strategies that address substantial health impact disparities across communities.

5.2.2 Methodology for Estimating Scope 2 Health Costs in California

To assess public health costs indirectly caused by California data centers through electricity consumption, we apply a five-step quantification framework:

Step 1: Estimate annual electricity consumption of California data centers based on LBNL and EPRI reports [13, 41].

Step 2: Extract California's total electricity consumption from U.S. EIA state-level database [104].

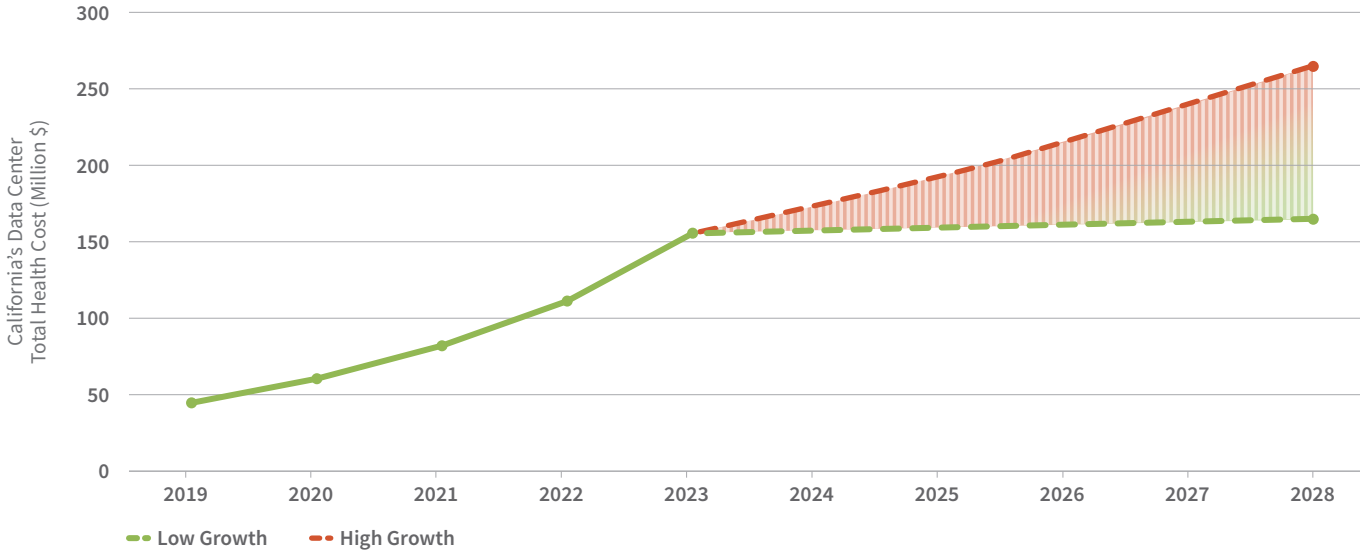
Step 3: Calculate the proportion of data center electricity consumption to total state consumption ($\boldsymbol{\alpha}_t$).

Step 4: Estimate data center-related pollutant emissions by applying this proportion to EPA's emission inventories for California, covering NO_x, SO_2, $PM_{2.5}$, and VOCs.

Step 5: Input calculated emission data into EPA's COBRA model to assess health impacts and monetized losses.

Detailed methodological specifications for projecting Scope 2 health costs for 2028 are provided in Appendix D.

Figure 5. Temporal evolution of total health costs attributable to California data centers (2019-2028)



Note: The historical period shows actual costs from 2019-2023, while the projection period (2024-2028) presents low-growth and high-growth scenarios with uncertainty bands.

5.3 Public Health Impacts' Results

We present the public health impacts of California data centers from 2019 to 2028, integrating both historical assessments and future projections under different growth scenarios. While COBRA provides both high and low health cost estimates for each emission change scenario, we use the midpoint as a single representative value. The health costs expressed in dollars represent the monetized value of adverse health outcomes attributed to data centers, including premature mortality, asthma symptoms, emergency room visits, hospitalizations, work loss days, and school absence days [65].

Table 7. California data center health costs by scope (2019-2028)

Year	Electricity (TWh)	Scope-1 Health Cost (million $)	Scope-2 Health Cost (million $)	Total Health Cost (million $)
2019	5.54	7.27	37.41	44.68
2020	6.48	10.47	49.99	60.45
2021	7.84	13.08	69.02	82.10
2022	9.29	21.38	89.84	111.21
2023	10.82	33.31	122.12	155.44
2028 (low)	16.16	59.09	108.05	167.14
2028 (high)	25.28	97.36	169.21	266.57

Figure 5 illustrates the temporal evolution of total health costs attributable to California data centers. The historical period (2019–2023) demonstrates a steep upward trajectory, with total health costs rising from $44.68 million in 2019 to $155.44 million in 2023, representing a 248% increase over five years. This substantial growth reflects the rapid expansion of data center operations and their associated environmental externalities.

For the projection period (2024–2028), we present two scenarios bounded by uncertainty bands. Under the low-growth scenario, total health costs are projected to reach $167.14 million by 2028, while the high-growth scenario estimates $266.57 million. The shaded area between these trajectories visualizes the range of potential outcomes depending on industry growth rates and policy interventions.

Notably, the projected growth rate of health costs from 2023 to 2028 (7.5% to 71.5% depending on the scenario) is substantially lower than the corresponding increase in electricity consumption (49.4% to 133.6%). This decoupling phenomenon can be attributed to California's aggressive clean energy transition and implementation of stricter environmental regulations. The emission intensity per unit of electricity generation decreases, thereby mitigating the health impacts escalation that would otherwise accompany increased power demand.

This decoupling is quantitatively supported by EPA projections for California's electricity utility sector emissions. According to EPA's COBRA [65], significant reductions in key pollutants are anticipated between 2023 and 2028. Specifically, $PM_{2.5}$ emissions from fuel combustion in electricity utilities are projected to decrease from 4,917.13 tons in 2023 to 2,745.26 tons in 2028 (a 44% reduction), while SO_2 emissions are expected to decline dramatically from 2,108.34 tons to 259.75 tons (an 88% reduction). Similarly, NO_x emissions are projected to fall from 10,041.72 tons to 5,228.89 tons (a 48% reduction), and VOC emissions from 2,367.45 tons to 1,433.04 tons (a 39% reduction). These substantial emission intensity improvements, driven by clean energy deployment, fossil fuel retirement and strict environmental protection, explain how California can accommodate growing data center electricity demand while achieving relative stabilization in associated health costs.

Table 7 provides a detailed decomposition of health costs by scope and year, revealing several critical insights. First, Scope 2 health costs consistently dominate total health impacts during the historical period (2019-2023), accounting for approximately 78–84% of the total costs. However, this dominance decreases significantly in the 2028 projections, dropping to approximately 63–65% of total costs. This shift underscores the significance of indirect emissions from electricity generation relative to direct on-site emissions, while also highlighting how California's clean energy transition and environmental policies affect the relative contribution of different emission sources.

Second, the temporal patterns differ markedly between Scope 1 and Scope 2 costs. Scope 1 health costs exhibit an accelerating growth pattern, increasing by 358% from 2019 to 2023, with particularly sharp increases in 2022 and 2023. This acceleration likely reflects increased reliance on backup generators during grid stress events and the expansion of data center facilities requiring emergency power systems.

Third, the 2028 projections reveal an interesting divergence in scope-specific trajectories. Under the low-growth scenario, Scope 2 costs actually decrease from $122.12 million in 2023 to $108.05 million in 2028, despite a 49.4% increase in electricity consumption. This counterintuitive result directly reflects California's renewable portfolio standard implementation and the retirement of fossil fuel generation capacity. Conversely, Scope 1 costs continue to increase across both scenarios, suggesting that on-site emission sources remain a persistent challenge requiring targeted mitigation strategies.

The ratio of Scope 1 to Scope 2 costs also shifts over time, rising from 0.19 in 2019 to 0.27 in 2023, and potentially reaching 0.55–0.58 by 2028. This trend indicates that as the electricity grid becomes cleaner, the relative importance of addressing direct emissions from backup generators and other on-site sources increases substantially.

These results underscore the effectiveness of California's clean energy and environmental policies in decoupling data center growth from proportional health impacts, while highlighting the need for complementary measures targeting on-site emission sources to achieve comprehensive public health protection.

6 Recommendations

Given the increasing electricity consumption, carbon emissions, water consumption, and health costs associated with data centers in California, we make the following recommendations.



Recommendation 1: Unified Reporting of Comprehensive Metrics

Despite the immediate impacts of California data centers on electricity grids, carbon emissions, water resources, and public health, comprehensive and standardized reporting for these metrics, especially the water resources and health impacts, has often been overlooked in official documents and sustainability reports published by data centers operating in California [106-108]. This reporting gap makes it difficult to pinpoint which facilities are the largest contributors to regional environmental impacts and the associated health risks. To address this shortfall and support truly responsible data center management, we recommend the standardization of reporting protocols for electricity consumption, carbon emissions, water consumption, and associated public health impacts in different regions of California. These protocols should build on existing environmental accounting frameworks but be calibrated to California's regulatory requirements and its most pressing environmental priorities.

Building on this, effective carbon governance requires targeted coordination across three interrelated domains. First, grid responsive operations, such as carbon aware scheduling and demand side management, could be adopted to align compute workloads with periods of lower grid carbon intensity, thereby minimizing marginal emissions. Second, circular infrastructure strategies, including waste heat recovery, component remanufacturing, and extended hardware lifetimes, should be implemented to curb embodied carbon and relieve systemic energy burdens. Third, value chain transparency is essential: comprehensive life cycle accounting of emissions from raw material extraction, component manufacture, logistics, assembly, operation, and end of life disposal ensures that upstream carbon impacts do not negate downstream efficiency gains. Moreover, the integration of standardized accounting frameworks such as the GHG Protocol with interoperable public private carbon emission tracking platforms will transform carbon data into a strategic asset, enabling real time insights, optimizing grid integration, informing sustainable procurement, and driving innovation fully aligned with California's climate objectives.

Furthermore, robust water stewardship requires context-based efficiency measures to reduce consumption, alleviate regional water stress, and deliver benefits to communities facing scarcity. Data center operators should prioritize the deployment of cutting-edge cooling technologies—such as advanced cooling systems, liquid immersion cooling, or other water-efficient solutions, alongside state-of-the-art water recycling and reuse systems to achieve reductions in potable water consumption. In addition, the deployment of advanced monitoring platforms and predictive analytics will enable continuous optimization of water use and minimize potential impacts on local water resources.

Effective public health governance requires proactive engagement with community health determinants and the integration of health impact assessments into every phase of data center development and operation. Health impact assessments can inform site selection and infrastructure upgrades, with buffer zones established around sensitive receptors such as schools and hospitals.

In addition, we recommend embedding adaptive performance indicators into reporting protocols to enable real-time responses across efficiency, resource use and emissions. For example, data centers should monitor their hourly PUE and WUE to identify and address operational inefficiencies. Similarly, Scope 2 carbon emissions could be updated automatically using live grid emission factors combined with renewable procurement records, providing an immediate view of carbon performance as the grid mix shifts; rolling averages of $PM_{2.5}$ and NO_x from nearby monitors would enforce stricter limits in communities that already exceed health standards. Data centers can use the data to optimize operations and reduce environmental and health impacts in real time.

Recommendation 2: Accelerating Clean Energy Integration with Equity Considerations

California data centers, including those operated by major technology companies, should accelerate the integration of clean energy into their overall energy procurement strategies, while simultaneously addressing the equitable distribution of environmental and public health impacts across all California communities. Given that electricity generation significantly impacts data centers' carbon emissions, water consumption, and localized public health outcomes, increased adoption of clean energy can directly alleviate these environmental burdens, especially for communities disproportionately affected by existing environmental challenges.

To achieve this, data center operators can prioritize long-term power purchase agreements (PPAs) with clean energy providers, invest in on-site generation, and enhance energy storage to maximize the use of intermittent resources. Crucially, these strategies should explicitly weigh the regional energy source and its broader impacts on both nearby and distant communities. Advanced forecasting should guide procurement and storage, ensuring energy sourcing minimizes burdens on vulnerable communities. California policy makers and data centers should integrate equity considerations into every stage of data center planning and operations.

Data centers should select sites that avoid exacerbating existing vulnerabilities and, whenever feasible, deliver tangible community benefits through various programs such as funding for local environmental and health initiatives. Meaningful engagement with disadvantaged communities should be prioritized throughout the lifecycle of data center projects. Robust oversight, including transparent reporting of clean energy utilization rates, community impact assessments, and equity metrics, along with community benefits, will help ensure that the transition to clean energy benefits all Californians equitably, distributing economic gains fairly and mitigating disproportionate environmental and public health burdens.

Recommendation 3: Institutionalizing Community Science and Cross-Sector Impact Research

California should institutionalize sustained, community-based monitoring and interdisciplinary policy evaluation to ensure that data center operations transparently account for their social and environmental externalities. Delivering study findings through clear, accessible reports and public workshops will equip community members with the knowledge needed to assess exposure risks and work alongside researchers and regulators to craft customized mitigation measures.

Similarly, California should empower think tanks and academic consortiums to carry out comprehensive cross-sector analyses of data center operations, measuring their effects on local employment and tax revenue, their demands on grid stability, and their consequences for community health. Integrating economic simulations with infrastructure stress testing and epidemiological forecasting will pinpoint the most effective points of intervention. To ensure real-world adoption, matching grants and streamlined regulatory approvals can support pilot projects that translate lab findings into operational practice.

Recommendation 4: Modernizing Backup Power Systems

Traditional backup systems, typically powered by diesel generators, significantly contribute to localized air pollution, potentially exacerbating public health issues in surrounding communities, especially those already facing environmental vulnerabilities. Moreover, the adoption of diesel backup generators for demand response could further worsen the air quality and increase the public health risks.

To address this, data center operators should transition from conventional diesel generators to cleaner backup solutions, including integrating battery energy storage systems (BESS), fuel cells, and other alternative fuels. Adopting these modern alternatives will significantly reduce the emissions of criteria air pollutants, substantially improving air quality and public health outcomes in nearby communities.

In addition, operators should implement intelligent energy management systems to improve the efficiency and reliability of backup power resources. These systems, capable of real-time monitoring, predictive analytics, and automatic demand response, will enable the optimized deployment of backup resources with minimal environmental impact.

California policymakers should establish clear regulatory frameworks and encourage advanced backup power technologies. Policymakers and industry stakeholders must collaborate on rigorous standards and guidelines to promote modernization of backup power infrastructure. This collaborative approach will ensure backup systems not only provide operational resilience but also align with California's broader environmental sustainability and public health objectives, delivering long-term benefits to all communities.

Recommendation 5: Strengthen California's National Leadership in Sustainable Data Center Development

While data centers have impacts on the electric grid, carbon emissions, water resources, and public health, it is notable that California's data centers generally perform better than those in many other states, due in large part to the state's high share of clean energy, strict environmental regulations, and progressive climate policies. This leadership demonstrates that it is possible to expand digital infrastructure in ways that align with aggressive climate and sustainability goals. To maintain this national leadership and help meet the growing demand for digital services, California should adopt policies that continue to streamline the development and permitting of new, energy-efficient and sustainable data centers within the state, particularly in areas with access to abundant clean power and resilient water supplies.

At the same time, it is critical to ensure that local communities are protected from potential negative impacts, such as potential competition for limited water resources, strain on local grids, or air and noise pollution from backup generators and construction. State and local governments should establish clear, transparent guidelines for environmental performance reporting, including requirements for facilities to track and publicly disclose hourly PUE and WUE, to identify and mitigate inefficiencies early.

Policymakers should also promote investments in technologies that reduce water, carbon, and energy footprints and public health impacts. By taking these steps, California can continue to demonstrate that economic growth in the digital sector can be compatible with ambitious climate action and community well-being, setting a model for other states and regions to follow.



7 Conclusion

This report has delivered a quantitative evaluation of the environmental and public health implications associated with California's data center operations spanning the period from 2019 through 2023, incorporating forward-looking projections through 2028. The findings illuminate both the scale of contemporary challenges and the imperative for immediate, evidence-based policy interventions to ensure the sustainable development of digital infrastructure. Given California's position as the one of the largest data center markets among U.S. states, the approaches adopted in California carry profound implications for national policy frameworks.

Our analysis reveals that California's data center electricity consumption experienced an approximate doubling between 2019 and 2023, escalating from 5.54 TWh to 10.82 TWh. This significant growth in energy demand has precipitated commensurate increases in environmental footprints. For example, Scope 2 carbon emissions attributable to data center operations expanded from 1.24 million to 2.38 million short tons during this period, while the total water consumption increased from 25.42 billion to 49.91 billion liters. Prospective modeling for 2028 indicates continued trajectories, with electricity consumption projected to reach 16.16–25.28 TWh and carbon emissions potentially escalating to 3.55–5.56 million short tons. Concurrently, the total water consumption is anticipated to range between 74.54 and 116.63 billion liters by 2028. As for the public health impact, the total public health cost of California's data centers was estimated at $155.44 million in 2023 and is projected to range between $167.14 million and $266.57 million by 2028.

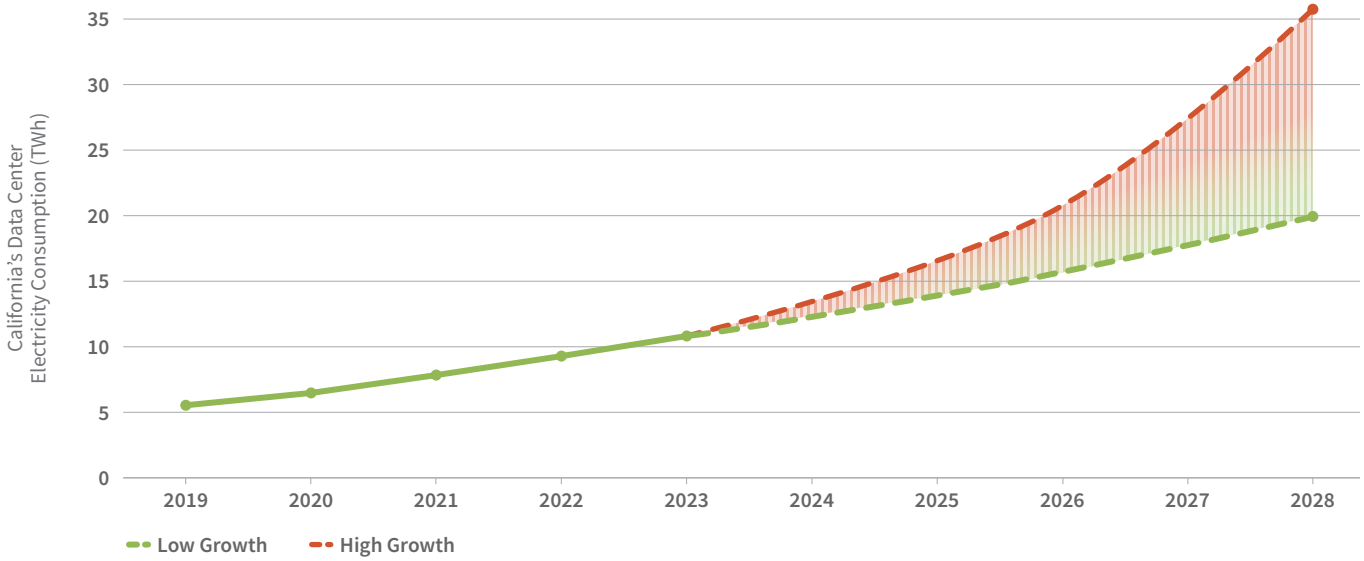
Notwithstanding these challenges, our study highlights viable pathways for impact mitigation. California's proactive clean energy policies and strict air quality standards have generated a notable "decoupling effect", whereby growth in electricity consumption does not translate into directly proportional increases in public health damages. Furthermore, the state's grid decarbonization initiatives have yielded carbon emission intensities below the national average, with projections indicating continued reductions in key pollutants from the electricity sector through 2028. This decoupling phenomenon is most evident in projections suggesting that Scope 2 health costs may stabilize or experience marginal decreases by 2028 under conservative growth scenarios, despite substantial increases in electricity demand.

Despite the encouraging progress, significant challenges persist for sustainable data centers in California. The projected growth of electricity demand, even under optimistic scenarios, will impose considerable strain on California's grid and water infrastructure, emit a growing amount of carbon emissions, and create a substantial public health impact. Thus, California's path to truly sustainable data center growth must be based on a set of holistic efforts and policies, including unified reporting of comprehensive environmental metrics and health impacts, accelerating clean energy integration with equity considerations and community engagement, modernizing backup power systems, and keeping California's national leadership in sustainable data centers.

In summary, California's dual roles as a technology leader and environmental pioneer are being tested by the unprecedented resource demands of the AI-centered digital economy. While the challenges are significant, the findings presented in this report suggest that through strategic, data-driven, and integrated policy interventions, California can continue to advance both technological innovation and sustainable, climate-resilient development. The path forward necessitates coordinated efforts among policymakers, industry stakeholders, and civil society to ensure that digital infrastructure expansion does not exact an untenable toll on environmental integrity and collective community well-being.

Appendix

Figure A1. California data center energy consumption, LBNL scenarios (2023-2028) [41]



Note: This figure was created by applying LBNL's projected national annual growth rates of 13% (low) and 27% (high) to California's baseline electricity consumption.

A Energy Consumption Projections and Analysis

This appendix presents detailed energy consumption projections and comparative analysis from the LBNL and EPRI sources that have informed our modeling approach.

A.1 Projections Based on Lawrence Berkeley National Laboratory (LBNL) Scenarios

This section utilizes the U.S. national growth rate scenarios published by the LBNL [41] to project California's data center energy consumption. LBNL's national analysis, which incorporates bottom-up modeling, projects annual growth rates of 13% to 27% for 2023-2028. Figure A1 applies these national growth scenarios to California's baseline to create a state-specific forecast.

A.2 Projections Based on Electric Power Research Institute (EPRI) Scenarios

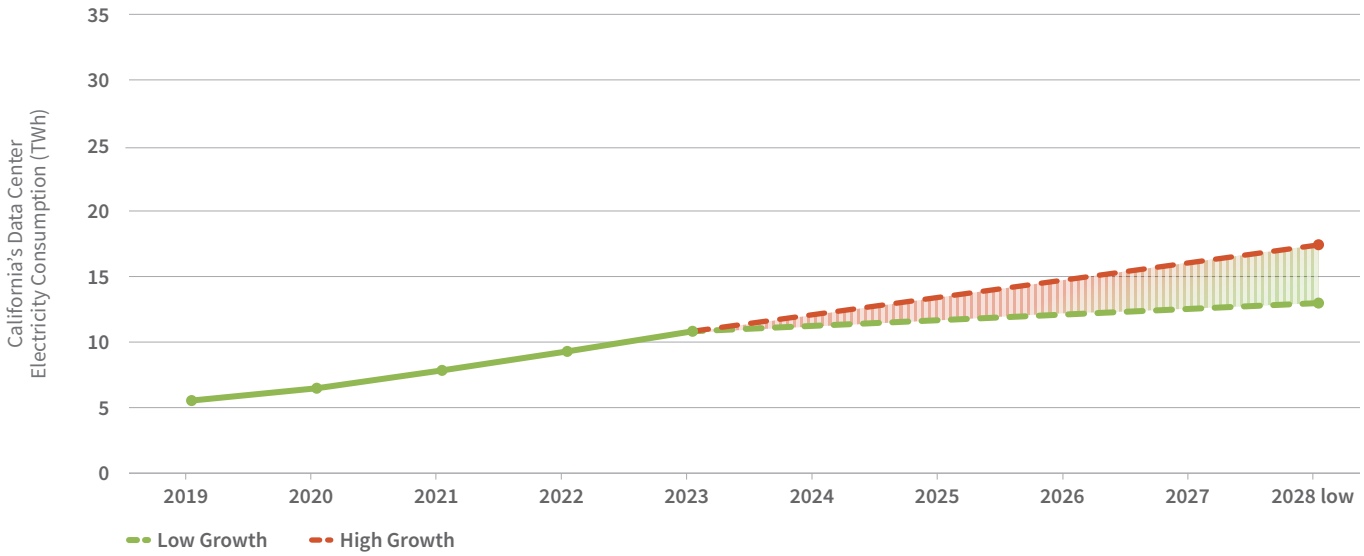
The EPRI provides a more conservative perspective on national data center growth, with projected annual growth rates of 3.7% (low growth) to 10.0% (high growth) for 2023-2030. These scenarios incorporate factors like efficiency improvements and grid integration challenges. Figure A2 illustrates a California-specific projection created by applying these national scenarios.

A.3 Integrated Projection Model

Building upon the methodologies and data from both LBNL and EPRI, we developed an integrated projection model that balances the different growth scenarios through arithmetic averaging. Figure A3 presents our synthesized projections, which form the basis for the environmental and health impact assessments presented in the main text.

The divergence between LBNL and EPRI projections reflects different assumptions about technological adoption rates, policy effectiveness, and market dynamics.

Figure A2. California data center energy consumption, EPRI scenarios (2023-2028) [13]



Note: This analysis for California (2023-2028) was created by applying EPRI's projected national annual growth rates of 3.7% (low) and 10% (high).

LBNL's higher growth estimates emphasize the rapid expansion of AI and machine learning applications, while EPRI's conservative approach accounts for grid constraints and efficiency improvements.

Our integrated approach provides:

- Lower bound: EPRI-influenced scenario (8.35% annual growth)
- Upper bound: LBNL-influenced scenario (18.5% annual growth).

Table A1. Comparison of energy projection methodologies

Parameter	LBNL	EPRI	Integrated Model
Growth Rate (Low)	13%	3.7%	8.35%
Growth Rate (High)	27%	10%	18.5%
Primary Drivers	AI/ML expansion	Demand Growth + Efficiency	Balanced Approach
Time Horizon	2023-2028	2023-2030	2023-2028
Methodology	Bottom-up	Top-down	Arithmetic Mean

B Carbon Emission Estimates

In this section, we provide a mathematical account of the methodologies used to compute each column in Table 4. First, the fundamental formula for Scope 2 carbon emissions is given by

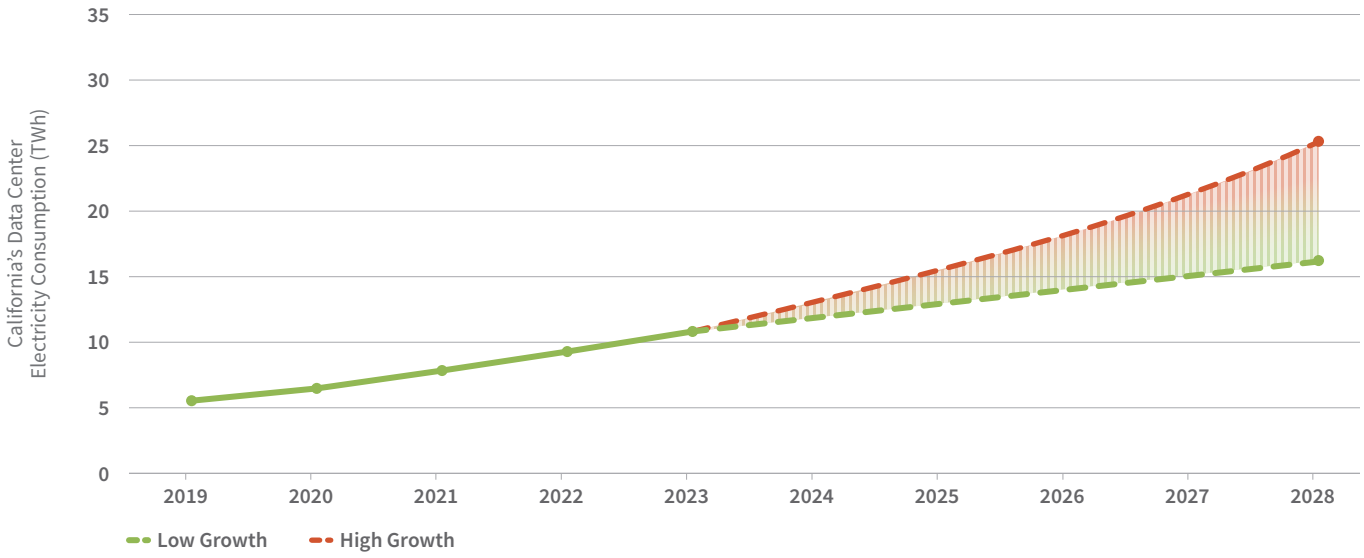
$$\text{Total Emissions (lbs)} = \text{Emission Factor (lbs/MWh)} \times \text{Electricity Consumption (MWh)}$$

In addition, we report the following metrics.

- **CA DC Electricity (TWh):** Total annual electricity consumption of California data centers, measured in terawatt-hours (TWh).
- **CA Total Electricity (TWh):** Total annual electricity consumption for the entire state of California, measured in TWh.
- **CA DC Emission (million short tons):** Carbon emissions attributable to California data centers. Computed by (CA Emission Factor (lbs/MWh)) × (CA DC Electricity (MWh)), then converted from pounds to million short tons (1 short ton = 2,000 lbs).
- **DC Emission of CA Total:** The share of data-center emissions relative to California's total electricity-related emissions, calculated as:

$$\frac{\text{CA DC Emission}}{\text{CA Total Emission}} \times 100\%.$$

Figure A3. Integrated energy consumption projection model for California data centers (2019-2028)



Note: The model combines LBNL and EPRI forecasts using arithmetic mean calculations, resulting in low-growth (8.35%) and high-growth (18.5%) scenarios. Historical data (2019-2023) is shown for validation, with projections extending to 2028.

- **CA-US Ratio:** The ratio of actual California data center emissions (using California's emission factor) to the hypothetical emissions if California data centers were operated at the U.S. average emission intensity, computed by

$$\frac{\text{CA Emission Factor} \times \text{CA DC Consumption}}{\text{US Emission Factor} \times \text{CA DC Consumption}} \times 100\%.$$

C Water Consumption Estimates

Here is a more detailed description of the water consumption calculation framework below.

Scope 1: On-site Water Usage Methodology

We quantify direct water consumption through facility-level water efficiency metrics denoted as $\rho_{s1,t}$ representing the volumetric water requirement per unit of computational energy. Environmental factors including ambient temperature and relative humidity influence this efficiency parameter. The total on-site water demand is computed by integrating server energy consumption with the corresponding temporal efficiency coefficients across the analysis period.

Scope 2: Electricity-Associated Water Usage

For indirect water consumption, we employ a regional approach based on California's electricity generation portfolio. Our calculation uses grid-specific water consumption factors $\rho_{s2,t}$ derived through generation-weighted methodology:

$$\rho_{s2,t} = \frac{\sum_k b_{k,t} \times \text{EWIF}_k}{\sum_k b_{k,t}}$$

where $b_{k,t}$ represents electricity output from generation source k at time t, and EWIFk denotes the water intensity factor for each generation technology. This approach captures both the temporal dynamics of California's energy mix and spatial variations in water requirements across different power generation facilities.

To estimate aggregate water consumption by California data centers, we apply time-averaged efficiency parameters for both direct facility operations and grid-associated water usage.

D Health Cost Estimates

D.1 Scope 1 Health Cost: Methodology (2019-2023)

There is limited public data available for Scope 1 emissions by California data centers. Thus, to estimate annual Scope 1 public health costs of California data centers, we follow a four-step procedure that takes advantage of pollutant emission and electricity consumption data from Virginia as a reference. The rationale is that Virginia has published permitted Scope 1 emissions for the largest number of data center backup generators, and thus its statewide average Scope 1 emission rate can reasonably serve as a proxy for other states.

Step 1: Derivation of Emission Rates from Virginia Data. Let $E^{\mathrm{VA}}_{p,year}$ denote the total annual emissions (in tons) of pollutant $p \in \{PM_{2.5}, SO_2, NO_x, VOC\}$ permitted for Virginia data centers, and let C^{VA}_{year} denote the corresponding total electricity consumption (in MWh) of those same facilities. We compute the emission rate for each pollutant p as

$$r_p = \frac{C^{VA}_{p,year}}{C^{VA}_{year}} \ [\mathrm{ton/MWh}],$$

Each r_p represents the average mass of pollutant p emitted per unit of data center electricity use in Virginia. We assume that these rates apply to the California data center operating profile. Note that the actual emissions are scaled down to 10% of the total permitted emission levels. This 10% factor is supported by both real-world data and recent policy developments: (1) a recent report indicates that backup generators at Virginia's data centers emitted about 7% of their permitted levels in 2023 [109], while actual emissions accounted for 3%–12% of permitted levels at several data centers in Quincy, Washington [110]; and (2) the EPA recently issued guidance allowing data center backup generators to operate for up to 50 hours per year (out of the typical 500 permitted hours) for demand response [111]. Thus, our choice of 10% serves as a reference case that reasonably reflects the potential health impacts given real-world schedules for operating backup generators and future demand response events.

Step 2: Estimation of California's Statewide Emissions. Using the emission rates math r_p from Step 1 and the previously obtained total annual electricity consumption of California data centers, C^{CA}_{year} (in MWh), we estimate the annual California emissions of each pollutant p as

$$E^{\mathrm{CA}}_{p,t} = r_p \times C^{\mathrm{CA}}_{year} \ [\mathrm{ton}],$$

where t indexes the calendar year. Here, $E^{\mathrm{CA}}_{p,t}$ aggregates the annual mass (in tons) of the pollutant p emitted by all data centers in California. By performing this calculation for p = $PM_{2.5}$, SO_2, NO_x, and VOC, we obtain California's annual pollutant-specific emission vector $\{E^{\mathrm{CA}}_{p,t}\}_p$.

Step 3: Allocation to Principal Counties. To assess localized health impacts, statewide emissions were allocated to individual counties based on the geographic distribution of data center facilities, as detailed in publicly available maps [99]. For the purposes of this assessment and to simplify the analysis, the study focuses on the major counties such as Los Angeles and Santa Clara with the highest concentration of data centers, as these areas represent the primary sources of Scope 1 emissions and their corresponding public health burdens.

Step 4: Conversion to State-Level Health Costs via COBRA. In this step, we use the EPA's COBRA model [65] to translate county-level emissions into a California-level health cost estimate. The workflow is as follows:

a. **County-level emission changes as input.** We input the county-level emission change values for each pollutant directly into COBRA.

b. **Apply the Source–Receptor (S–R) matrix for air quality response.** COBRA uses a reduced-form air quality model with a precomputed source-receptor matrix. Each element $S_{(c,r),p}$ of this matrix indicates the marginal change in the ambient concentration of pollutant p in the receptor county r (in $\mu g/m^3$ for $PM_{2.5}$ or ppb for ozone precursors) resulting from a change in the emission unit (1 ton) in the source county c. For each year t, COBRA multiplies the emission change of each county by the corresponding S–R coefficients $S_{(c,r),p}$ and sums the contributions between sources to produce concentration increases $\Delta C_{p,r,t}$ in each county r.

c. **Estimate incremental health outcomes via Concentration–Response Functions (CRFs).** For each receptor county *r* and pollutant *p*, COBRA applies epidemiologically derived CRFs of the form

$$\Delta H_{h,r,t} = \beta^{(h,p)} \Delta C_{p,r,t} \times I_r^{(h)} \times P_r,$$

where $\Delta H_{h,r,t}$ is the incremental number of cases for health endpoint *h* (e.g., respiratory hospitalizations, cardiovascular hospitalizations, asthma exacerbations, lost work-days, premature mortality) in county *r* during year *t*; $\beta^{(h,p)}$ is the CRF coefficient (cases per μg/m³ or ppb change) for endpoint *h* and pollutant *p*; $Ir^{(h)}$ is the baseline incidence rate (cases per person per year) for endpoint *h* in county *r*; and P_r is the population of county *r*. Summing $\Delta H_{h,r,t}$ across all pollutants yields annual county-level cases $\{H_{h,r,t}\}$.

d. Monetize health impacts using economic valuations.

$$\text{Cost}_{h,r,t} = v^{(h)} \times \Delta H_{h,r,t}$$

Each incremental health outcome $\Delta H_{h,r,t}$ is multiplied by a unit cost parameter $v^{(h)}$, such as the average cost of a hospitalization, the economic value of a work-day lost, and the Value of Statistical Life (VSL). Specifically, COBRA then sums these costs over all health endpoints *h* and counties *r* included in the analysis.

e. Generate California-level health-cost estimate. Finally, COBRA aggregates the county-level health cost components to produce

$$\text{Cost}_t^{\text{CA}} = \sum_{r \in \{\text{COUNTIES}\}} \sum_h \text{Cost}_{h,r,t}$$

D.2 Scope 1 Health Cost: Projection (2028)

To extend our Scope 1 health cost estimates to 2028, we adopt a procedure analogous to that used for historical years, incorporating projected growth in California data center electricity consumption. The key assumptions and steps are as follows:

1. Projecting California Data Center Electricity Consumption. Let C_{2023}^{CA} denote the total California data center electricity consumption in 2023 (in TWh), as used in Section 2 of our baseline methodology. Based on published forecasts from the LBNL and the EPRI reports,13,41 we define a low-growth rate rlow = 8.35% and a high-growth rate rhigh = 18.5% for the 2023–2028 interval. The details are available in Section 2.

2. Assuming Constant Emission Factors. Following our baseline approach (Step 1), we assume that pollutant-specific emission rates r_p (in tons per MWh) remain unchanged between 2023 and 2028. That is,

$$r_p^{2028} = r_p^{2023}, p \in \{\text{PM}_{2.5}, \text{SO}_2, \text{NO}_x, \text{VOC}\}.$$

Under this assumption, California's statewide 2028 emissions for pollutant p in scenario α (i.e., high or low growth rates) are given by

$$E_{p,2028,\alpha}^{\text{CA}} = r_p^{2023} \times C_{2028,\alpha}^{\text{CA}}$$

Thus, for each α, we compute

$$\{E_{p,2028,\alpha}^{\text{CA}}\}_p = \{r_p^{2023} \times C_{2028,\alpha}^{\text{CA}}\}_p$$

3. County-Level Allocation for 2028. As in Step 3, we distribute emissions according to the data center geographic distribution, focusing on the major counties with a large number of data centers for analytical simplicity.

4. Input to COBRA and 2028 Health-Cost Estimation. COBRA provides the 2028 data, including baseline emission, health valuation, and population [65]. We apply COBRA for the year of 2028 as follows:

   a. Input the county-level emission change values for each pollutant directly into COBRA.

   b. The model's Source–Receptor (S–R) matrix translates these emission changes into 2028 concentration increments ΔCp,r,2028 for each recipient county r.

   c. COBRA then applies its concentration–response functions (CRFs) using 2028 county demographics and baseline incidence rates, thereby estimating incremental cases of respiratory and cardiovascular hospitalizations, asthma exacerbations, lost work-days, and premature mortality for 2028.

   d. Finally, COBRA multiplies each incremental health outcome by its unit economic cost and aggregates across both counties to yield California's 2028 Scope 1 health cost estimate, $\text{Cost}_{2028,\alpha}^{\text{CA}}$.

By carrying out these four sub-steps for both the low-growth and high-growth scenarios (α = low, high), we obtain a range for 2028 Scope 1 health-cost values, represented by

$$\text{Cost}^{\text{CA}}_{2028,\text{low}} \quad \text{and} \quad \text{Cost}^{\text{CA}}_{2028,\text{high}}$$

These projected values can then be compared with historical estimates (2019-2023) to assess the trajectory of health costs directly related to data center backup generators in California.

D.3 Scope 2 Health Cost: Methodology (2019-2023)

Here is a more detailed description of the methodology for calculating scope 2 health costs from 2019 to 2023 below.

To assess the public health costs indirectly caused by California data centers through electricity consumption, we apply a multi-step quantification framework integrating electricity consumption data, emission factors, and health impact models.

Step 1: Calculate Annual Electricity Consumption of California Data Centers

We estimate the electricity consumption of California data centers based on the LBNL and EPRI reports [13, 41]. The annual electricity consumption of California data centers from 2019-2023 is denoted as $C^{CA}_{DC,year}$. The details are available in Section 2.

Step 2: Obtain California Total Electricity Consumption Data

We extract California's total electricity consumption from 2019-2023 (denoted as $C^{CA}_{total,year}$) from the U.S. EIA state-level electricity profile database [104]. We adopt end-use electricity consumption rather than generation to more accurately reflect actual electricity demand and associated emission responsibilities.

Step 3: Calculate Data Center Electricity Consumption Proportion

Based on data obtained from the previous two steps, we calculate the proportion of California data center electricity consumption to total C^{CA} state electricity consumption for each year: $\alpha_t = \frac{C^{CA}_{DC,year}}{C^{US}_{total,year}}$. This proportion reflects the relative share of data centers in California's electricity demand and provides the basis for subsequent emission allocation.

Step 4: Estimate Data Center-Related Pollutant Emissions

The EPA regularly publishes power sector pollutant emission inventories by state, including annual emissions of NO_x, SO_2, $PM_{2.5}$, and VOCs. These inventories provide emissions data for each state based on electricity generation within that state. To estimate emissions attributable to California data centers, we use the following approach:

1. We obtain EPA's emission inventories for California.
2. We multiply California's emissions by the proportion of data center electricity consumption to California's total electricity consumption. This choice is the same as "location-based" carbon accounting and excludes market-based mechanisms such as purchasing bundled renewable power. Nonetheless, location-based emissions are considered "essential" and allows the accounting of physical emissions associated with electricity consumption [50].

Therefore, the emissions of each pollutant caused by California data centers are:

$$E^{t}_{pollutant,DC,CA} = E^{t}_{pollutant,CA} \times \alpha_t,$$

Where $E^{t}_{pollutant,CA}$ represents EPA's reported emissions for California, and α_t is the ratio of data center electricity consumption to total California electricity consumption in year *t*. Our calculation covers four major pollutants–NO_x, SO_2, $PM_{2.5}$, and VOCs–yielding emission inventories attributable to California data centers for each year from 2019-2023.

Step 5: Apply COBRA Model to Assess Health Impacts

Finally, we input the calculated pollutant emission data into the EPA's COBRA model and estimate health outcomes and monetized losses.

D.4. Scope 2 Health Cost: Projection (2028)

To assess potential future public health impacts from California data centers, we perform a projection for 2028 that maintains methodological consistency while incorporating dynamic forecasts of future data center electricity demand in California.

California Data Center Electricity Demand Projection

The electricity projection specific calculation methods have already been introduced in Section 2. We restate these here briefly. Using 2023 California data center electricity consumption as the baseline, we project 2028 demand based on growth scenarios from LBNL (13-27% annual growth) and EPRI (3.7-10% annual growth). To balance these projections, we adopt the arithmetic mean, yielding low-growth (8.35%) and high-growth (18.5%) scenarios.

The 2028 California data center electricity demand projection is $C^{CA}_{DC,2028} = C^{CA}_{DC,2023} \times (1+r)^5$ where r takes values of 8.35% and 18.5%, corresponding to the respective growth scenarios.

California Total Electricity Demand Projection

For projecting 2028 California total electricity consumption, we apply the Reference case from the Annual Energy Outlook 2025 published by the U.S. Energy Information Administration [105]. The Reference case represents business-as-usual trends under laws and regulations current as of December 2024, assuming a 1.8% annual GDP growth rate through 2050. This baseline scenario provides detailed projections of 2028 electricity demand across U.S. sectors based on macroeconomic forecasts, population growth, electrification trends, and energy efficiency policies.

Since the 2023 state electricity consumption proportions are also obtained from U.S. EIA data and the U.S. EIA 2025 outlook does not provide state-level electricity consumption ratios, we use the 2023 proportions for estimation. Considering the relative stability of state-level electricity demand structures, we assume that the relative proportions of electricity consumption across states in 2028 remain consistent with 2023. Therefore:

$$C^{CA}_{total,2028} = C^{US}_{total,2028} \times \frac{C^{CA}_{total,2023}}{C^{US}_{total,2023}}$$

While this approach simplifies dynamic changes in state-level differences, it is reasonable for medium- term projections, particularly considering California's relatively stable position in the U.S. economy.

Uncertainty Considerations in Health Impact Projections

By utilizing COBRA's pre-configured 2028 scenario, our analysis maintains consistency with established EPA modeling tools while avoiding the methodological complexity and potential inconsistencies associated with independently modifying multiple demographic and economic variables. This approach ensures that our health impact projections capture not only the direct effects of pollutant emission changes attributable to data center growth, but also incorporate the model's built-in adjustments for anticipated changes in population characteristics and economic valuation parameters that influence health outcome monetization.

It should be acknowledged that this methodology inherently incorporates the uncertainties and assumptions embedded within COBRA's 2028 baseline scenario, including projections of population growth patterns, health baseline conditions, and economic valuation metrics. The resulting health impact estimates therefore represent point projections based on COBRA's integrated modeling parameters rather than comprehensive uncertainty ranges spanning alternative demographic and economic assumptions. While this approach provides reproducible results, we should interpret the findings within the context of the underlying model assumptions and parameter uncertainties.

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