Sustainable Data Centers Roadmap

(October 2025)[1]

Executive Summary

Investment in data centers is booming. Forecasts project trillions of dollars in data center construction and related infrastructure spending in the years ahead, driven by the explosive growth of artificial intelligence (AI) and by data centers' central role in e-commerce, video streaming, communications, and much of the modern economy. That investment is arriving at a critical moment: decisions made now about siting, design, and management will shape the energy and environmental performance of a rapidly expanding sector for decades to come.

Data centers used roughly 1.5% of global electricity in 2024 — a figure that masks significant regional concentration. In the United States, data centers account for approximately 4–5% of national electricity consumption; in Ireland, 22%; in Northern Virginia, 25%. IEA projections suggest global data center electricity demand could reach 1.8–3.4% of total power demand by 2030, with the U.S. share potentially reaching 6.7–12% by 2028.

Data centers were responsible for roughly 0.5% of global greenhouse gas emissions in 2024. That share is expected to grow. Whether the growth is modest or severe depends on choices that operators, governments, and utilities make in the years immediately ahead.

Well-sited and well-managed data centers can accelerate the clean energy transition by serving as anchor customers for innovative low-carbon technologies and enabling grid flexibility. Poorly sited and managed data centers can strain grids, produce greenhouse gas emissions and local air pollution, and stress local water supplies. The difference between these outcomes hinges largely on siting choices, technology adoption, and policy frameworks.

1. Energy Efficiency

Energy efficiency improvements span four areas:

- IT Equipment. Advances in chip architecture, memory, and compute density continue to reduce energy consumed per unit of computation, though the shift toward GPU-intensive AI workloads partly offsets hardware efficiency gains at the fleet level.
- Software. Algorithmic efficiency is an underappreciated lever. Historical gains from software optimization have often exceeded hardware improvements. Key questions include whether larger AI models are always more capable per unit of energy, how reasoning-focused inference models have changed energy dynamics, and how workload

[1] David Sandalow et al., *Sustainable Data Centers Roadmap* (ICEF Innovation Roadmap Project, October 2025). Available at https://www.icef.go.jp/roadmap/

scheduling can reduce emissions by matching compute demand to times and places with low-carbon electricity.

- Cooling. Roughly 95% of data centers today use air-based cooling. High-performance and GPU-heavy workloads are driving rapid adoption of liquid cooling — including rear-door heat exchangers, direct-chip cooling, and immersion cooling — which use substantially less water and often significantly less energy per kilowatt of IT load. Locations that allow free cooling (ambient air or water at naturally low temperatures) offer further savings.
- Heat Reuse. Waste heat from data centers can serve district heating systems, industrial processes, and other applications — particularly in cold climates. Beyond northern Europe and similar regions, large-scale beneficial heat reuse is unlikely to be achievable at significant scale.

2. Greenhouse Gas Emissions

Emissions arise across the full lifecycle:

- On-site (Scope 1). Backup diesel generators, refrigerants, and fire suppression agents are the primary on-site sources. Transitioning to lower-global-warming-potential alternatives and reducing diesel reliance are near-term priorities.
- Grid electricity (Scope 2). The carbon intensity of the grid supplying a data center is the dominant variable in its climate impact. Operators can reduce Scope 2 emissions through siting in low-carbon grid regions, power purchase agreements for renewable energy, and advanced market commitments for clean firm power — including nuclear, geothermal, and fossil fuel plants retrofitted with carbon capture and storage. Hourly carbon matching provides a more accurate signal than annual averages.
- Supply chain and embodied (Scope 3). Manufacturing chips, servers, and building materials carries a substantial and frequently underreported carbon cost. Low-carbon construction materials, extended equipment lifetimes, and improved supply chain accounting can meaningfully reduce lifecycle emissions.

Load flexibility — the ability of data centers to shift or modulate electricity demand — is one of the most powerful and underutilized tools available. Data centers that manage their loads dynamically can reduce peak grid stress, avoid construction of new fossil-fueled generation, and enable better integration of variable renewable energy.

3. Accelerating Low-Carbon Power

Data center operators are the world's largest purchasers of solar and wind power, and their scale creates meaningful leverage over energy markets. Several mechanisms can convert that purchasing power into catalysts for the broader energy transition:

- Advanced Market Commitments. Long-term offtake agreements can de-risk first-of-a-kind clean energy technologies — advanced geothermal, small modular reactors, long-duration storage — that struggle to attract capital without anchor buyers. Regulatory

frameworks should allow multi-buyer participation and recognize hourly carbon matching.

- Grid Flexibility. Many data centers have significant capacity to shift compute-intensive workloads to off-peak periods or locations with surplus renewable generation. Combined with on-site storage, this flexibility can substitute for new peaking generation and improve system reliability.
- Strategic Siting. Locating data centers in regions with surplus renewable resources can stimulate new transmission and generation development that benefits the broader grid, not just the individual facility.
- AI for Grid Management. AI systems can help design and operate cleaner electricity grids — optimizing dispatch, improving demand forecasting, and accelerating interconnection queue processing.

These benefits are not automatic. Data centers that lock in long-term fossil power contracts or that operate as inflexible loads can accelerate rather than reduce grid emissions. The design of energy procurement strategies is therefore a consequential climate decision.

4. Water Use

Globally, data centers consume a tiny fraction of the water used in agriculture — producing one hamburger requires roughly the same water as 19,000 ChatGPT-3 queries. Yet large individual facilities can place meaningful stress on local watersheds.

Three categories of water use matter:

- Direct (Scope 1): Evaporative cooling systems are the largest on-site user. Air-based cooling systems that rely on evaporative towers can be replaced with liquid cooling approaches that require little to no water.
- Energy-related indirect (Scope 2): Water is consumed by the power plants supplying the grid. When a data center draws power from coal or nuclear generation, its indirect off-site water use can exceed its on-site use.
- Supply chain (Scope 3): Chip and server manufacturing are water-intensive. Sourcing from lower-water-footprint suppliers and extending equipment lifetimes reduces this embedded consumption.

Before siting, operators should conduct watershed-level impact assessments in consultation with local stakeholders. In water-scarce regions, waterless or low-water cooling technologies, water reclamation systems, and non-thermal power supply should be prioritized.

5. Government Policy

Governments worldwide are navigating competing pressures: many jurisdictions are actively competing to attract data center investment for economic and strategic reasons, while growing local opposition — driven by concerns about grid strain, water consumption, and noise — is forcing policy reconsideration in others.

Several policy measures can channel investment toward better environmental outcomes:

- Mandatory disclosure, using standardized, facility-level metrics for energy use, greenhouse gas emissions, and water consumption. Facility-level data provide substantially more analytical value than company-level aggregates.
- Minimum performance standards for energy efficiency, water efficiency, and low-carbon power procurement, applied as conditions of permitting.
- Fast-track approvals for well-sited, well-designed facilities with access to low-carbon electricity, ample water, and meaningful load flexibility.
- Electricity market rules that enable data centers to participate as flexible demand resources, including hourly carbon accounting and support for multi-buyer advanced market commitments.
- Expanded international collaboration — through mechanisms such as the IEA Energy and AI Observatory and the Clean Energy Ministerial — to develop shared standards, datasets, and best practices.

Proactive, transparent community engagement throughout project lifecycles is also essential. Failure to communicate clearly about both benefits and risks has fueled opposition that threatens to slow the deployment of digital infrastructure with significant potential economic and strategic value.

6. Conclusion

The global data center boom is both a significant environmental challenge and a significant opportunity. Data centers can be designed and operated in ways that dramatically reduce their carbon and water footprints — and that actively accelerate the deployment of clean energy. Whether that potential is realized depends on decisions being made right now.

Smart siting — prioritizing access to low-carbon electricity, ample water, and grid flexibility potential — is the single most consequential variable. Where siting constraints are unavoidable, a combination of advanced cooling, flexible load management, power purchase agreements, and supply chain improvements can substantially reduce adverse impacts.

Underlying all of this is a data problem. Greenhouse gas emissions, water consumption, and energy use at data centers are inadequately measured and disclosed. Without standardized, facility-level reporting, neither operators, governments, nor communities can make well-informed decisions. Establishing common metrics and mandating their disclosure is among the highest-priority actions available to policymakers.