

SUSTAINABLE DATA CENTERS ROADMAP

October 2025



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Sustainable Data Centers Roadmap

(October 2025)

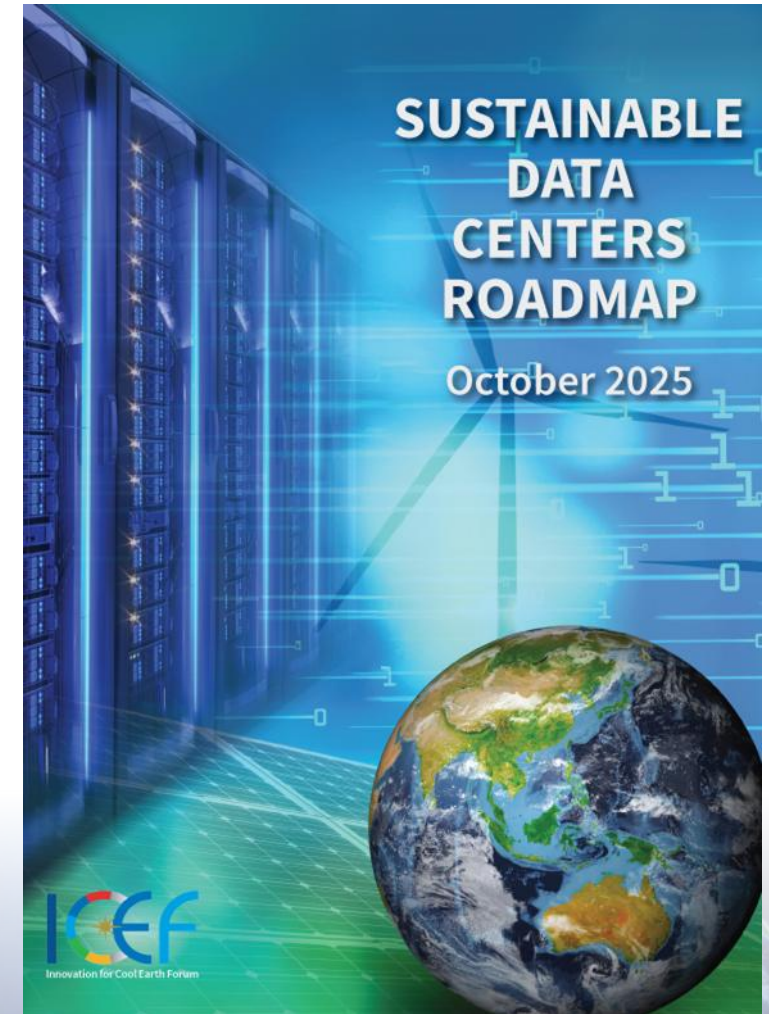
Topic: energy and environmental impacts of data centers

- technical and policy background
- more than 100 actionable recommendations for a range of stakeholders.

12 coauthors, 309 pages

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Sustainable Data Centers Roadmap

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CHAPTER 1: DATA CENTER ENERGY USE

CHAPTER 2: DATA CENTER ENERGY EFFICIENCY

2.1: IT EQUIPMENT

2.2: SOFTWARE

2.3: COOLING TECHNOLOGIES

2.4: HEAT REUSE

Text Box: DATA CENTER ENERGY EFFICIENCY METRICS

CHAPTER 3: DATA CENTER GHG EMISSIONS

3.1: ON-SITE GHG EMISSIONS (SCOPE 1)

3.2: POWER SECTOR GHG EMISSIONS (SCOPE 2)

3.3: EMBODIED GHG EMISSIONS (SCOPE 3)

CHAPTER 4. ACCELERATING LOW-CARBON POWER WITH AI DATA CENTERS

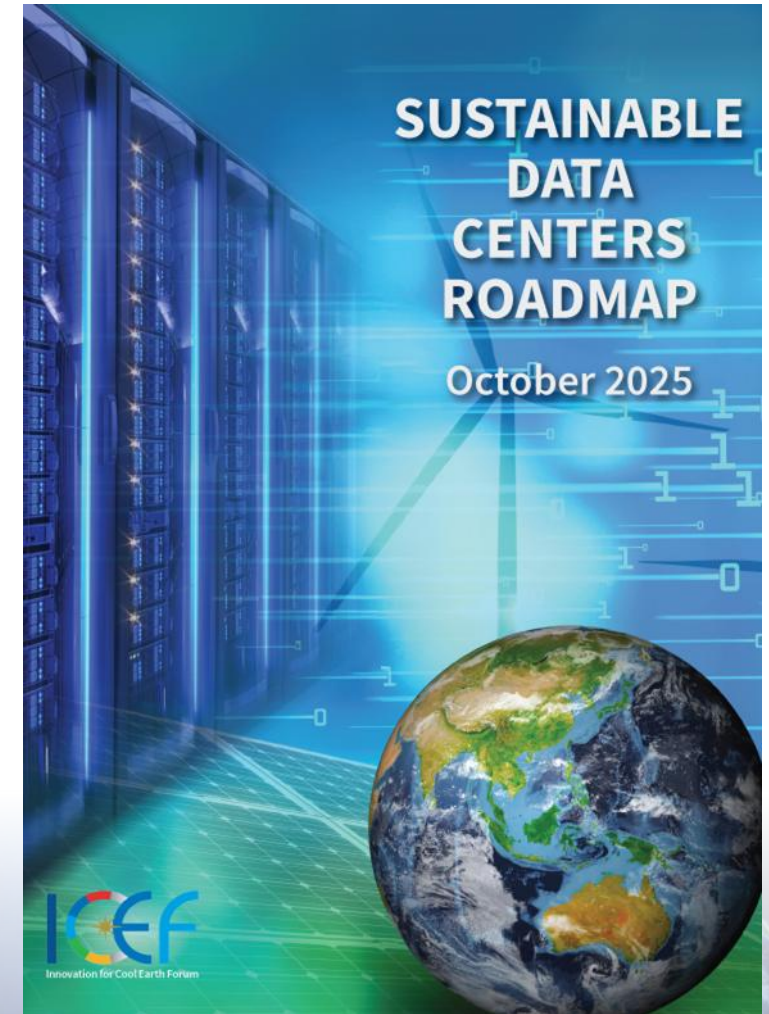
CHAPTER 5: DATA CENTER WATER USE

Text Box : E-WASTE

CHAPTER 6: GOVERNMENT POLICY

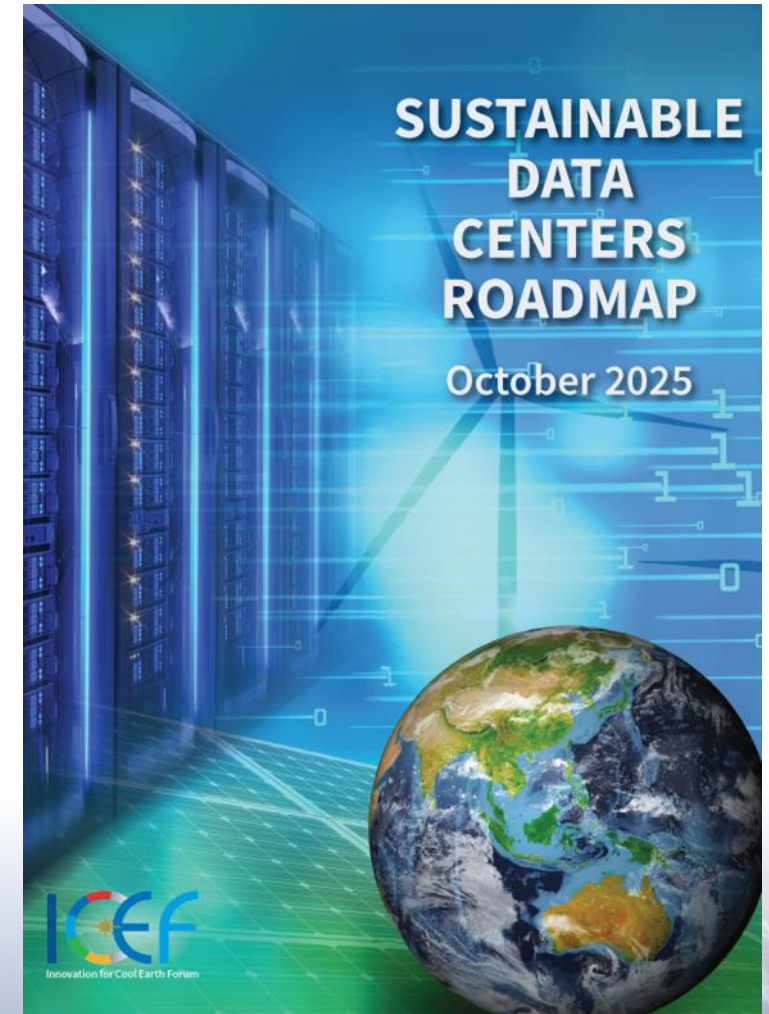
Text Box : INDUSTRY INITIATIVES

Text Box: LOCAL OPPOSITION



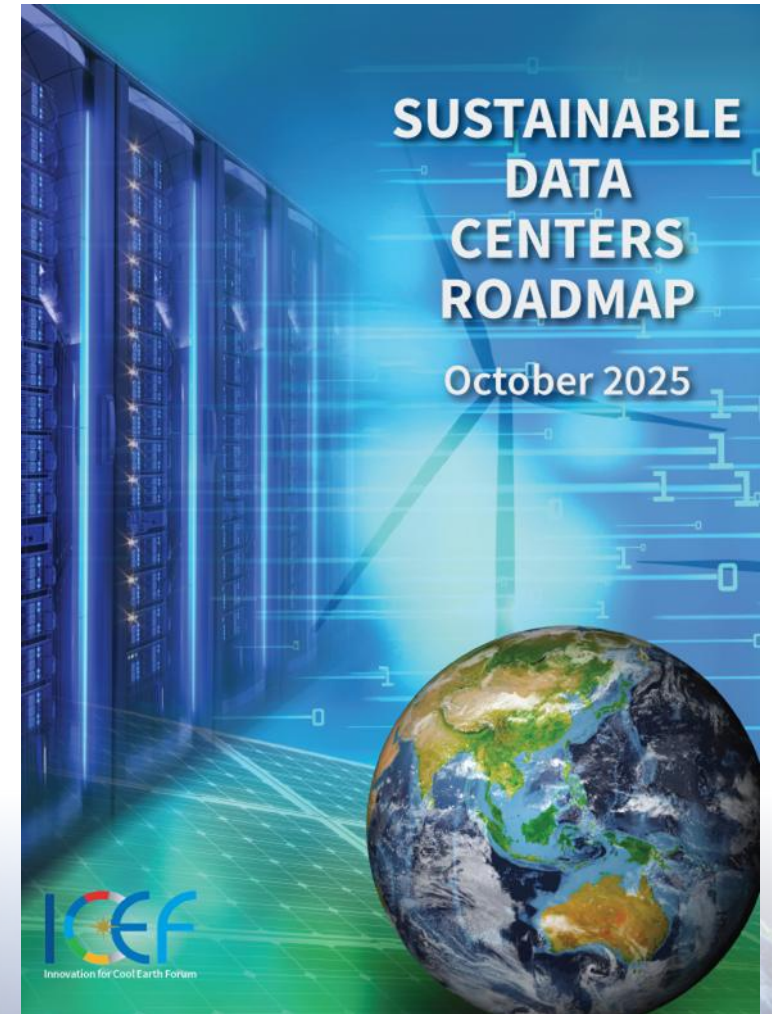
Five Main Messages

1. With a data center construction boom underway globally, the months and years ahead will be a critical time for data center sustainability.
2. The energy and environmental impacts of data centers vary dramatically depending on their siting, design, management and other factors.
3. Smart siting is key to reducing the energy, water and carbon emissions impacts of data centers.



Five Main Messages

4. Data center water use is tiny globally in relation to other sectors but can be very significant locally.
5. Data concerning data centers' environmental impacts are poor, including in particular data concerning greenhouse gas emissions and water use.



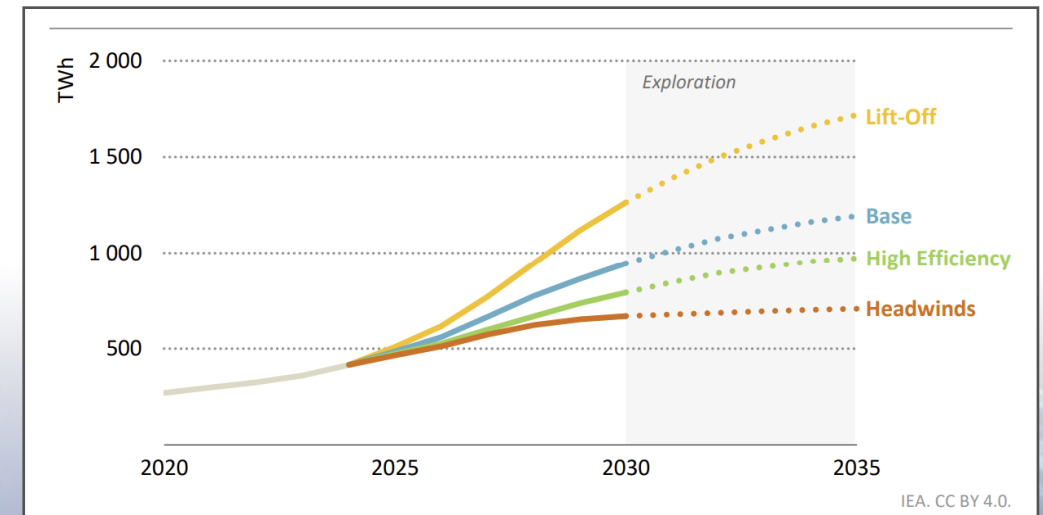
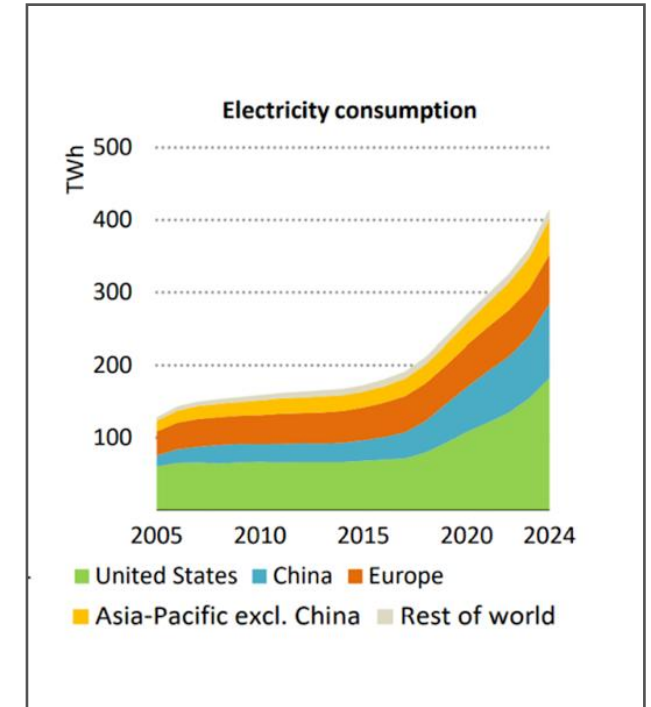
Chapter 1: Data Center Energy Use

- Data centers use electricity for the IT equipment and infrastructure.
 - IT equipment includes servers (largest electricity consumers in a data center), storage devices and network switches.
 - Infrastructure includes the cooling system and power train.



Chapter 1: Data Center Energy Use

- In 2024, data centers used roughly 1.5% of electricity globally. The figure was much higher in some countries and regions, including roughly 4–5% in the United States, 3% in the European Union, 22% in Ireland and 25% in Northern Virginia.
- Over 85% of global data center energy use is in the US, China and EU.
- Recent IEA scenarios suggest data centers could use 1.8–3.4% of total global power by 2030. In the US (home to roughly 50% of global data center capacity), data centers could reach 6.7–12% of total power demand by 2028.
- At local levels, data centers can cause significant stress to electric grids.



Chapter 2.1: IT Equipment Energy Efficiency

IT equipment includes processors, memory/storage and networking.

- Specialized AI processors use more energy than standard CPUs.
- Memory and networking typically use less power than processors.

Energy efficiency of IT equipment has improved by a factor of 10 billion over 5 decades. This is slowing but has not stopped.

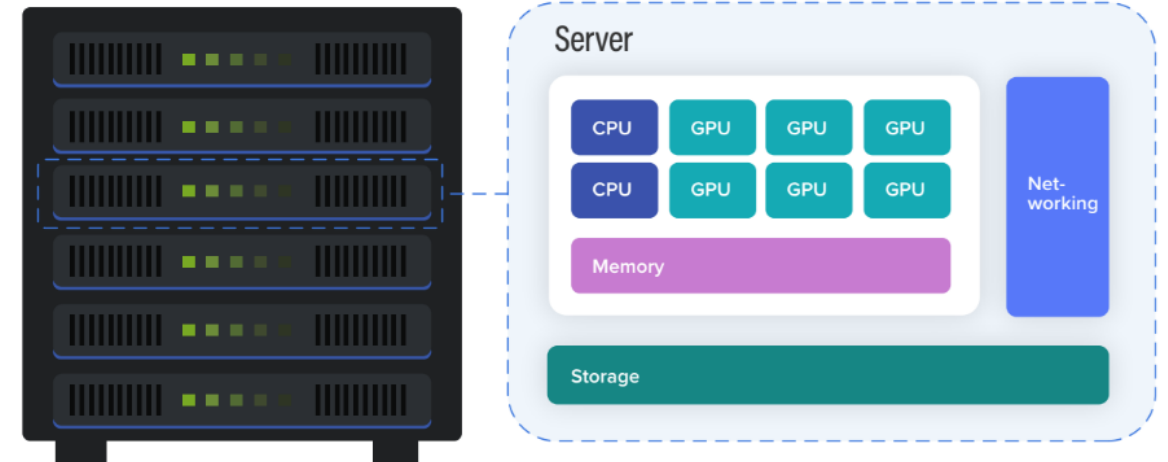
Technological innovation can help improve energy efficiency.

- Advanced packaging
- Photonic innovations
- Power conversion improvements
- Data center operations
- Server design

However these energy efficiency improvements may be offset by increasing demand for AI.

Figure 2.1-3: Components of a server

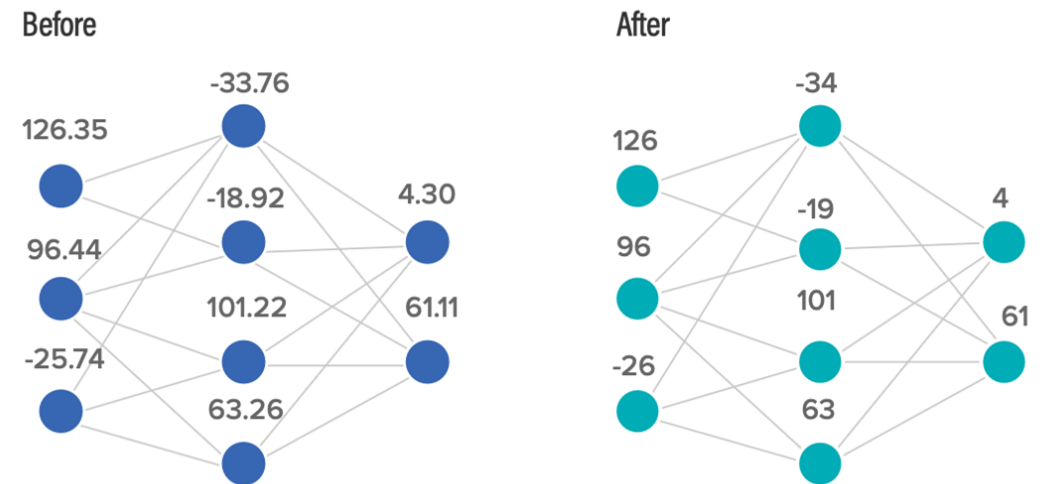
Rack of servers



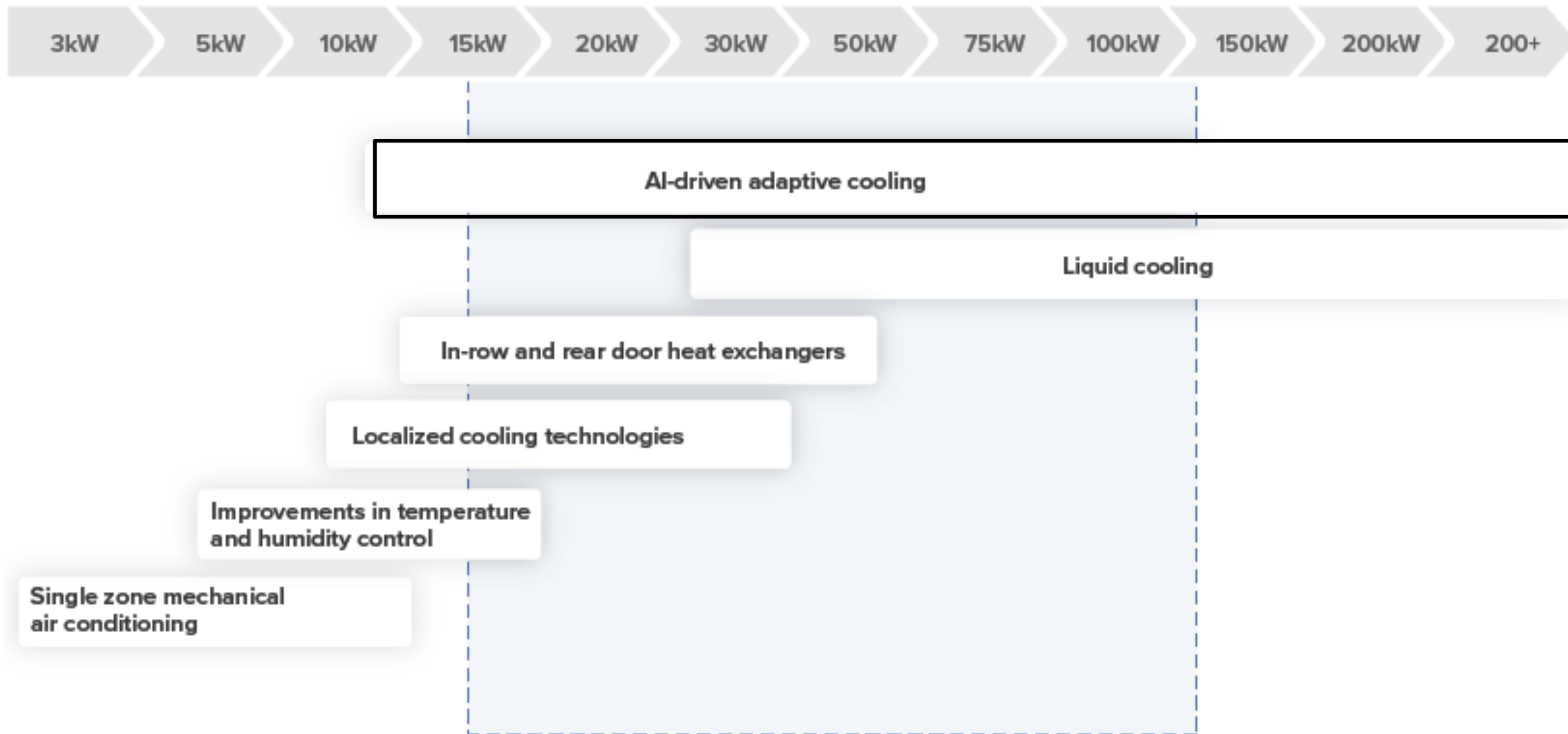
Chapter 2.2: Software Efficiency

- AI efficiency differs from traditional algorithms — no single "correct" output to verify.
- Training and inference phases have distinct energy profiles and optimization opportunities.
- Techniques like mixed-precision, quantization and distillation reduce training requirements.
- Larger isn't always better: Smaller models with reasoning can outperform much larger models.
- Reasoning changed dynamics: Models now "think harder" during inference, shifting cost balance from training to usage.
- Data centers achieve efficiency gains by strategically timing and placing compute workloads, especially AI.
- Limited expertise and benchmarks may be slowing down progress in this area.

Figure 2: Quantization

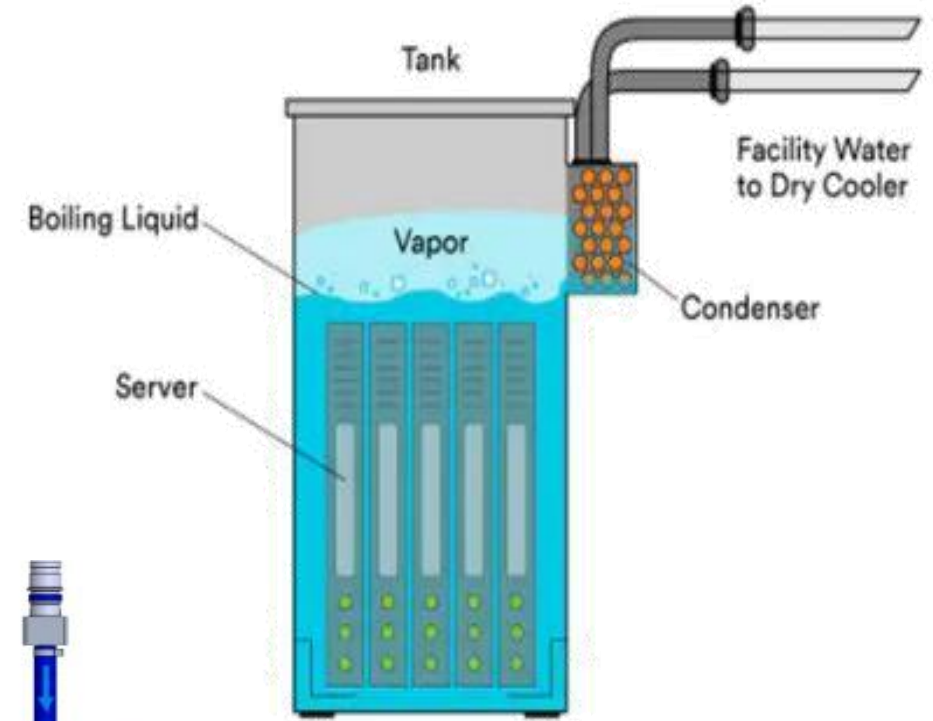


Chapter 2.3: Cooling Technologies

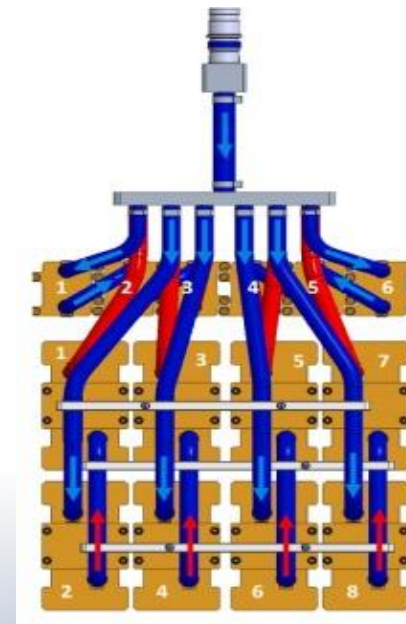


Chapter 2.3: Cooling Technologies

- Air-based cooling nearing limits as rack power densities exceed ~30 kW
- Liquid cooling (e.g., direct-to-chip, immersion) can handle 100 kW+ racks and reduces both water and energy use (for cooling).
- Hyperscalers like Meta, Microsoft and AWS are leading with innovative solutions: precision evaporative systems, AI-optimized HVAC, heat reuse networks, modular systems.
- Key barriers: lack of standards, retrofit challenges and undervalued sustainability impacts.



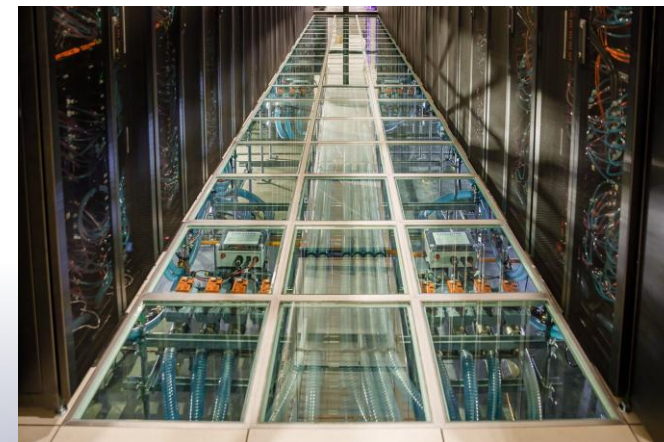
Immersion liquid cooling



Direct-to-chip liquid cooling

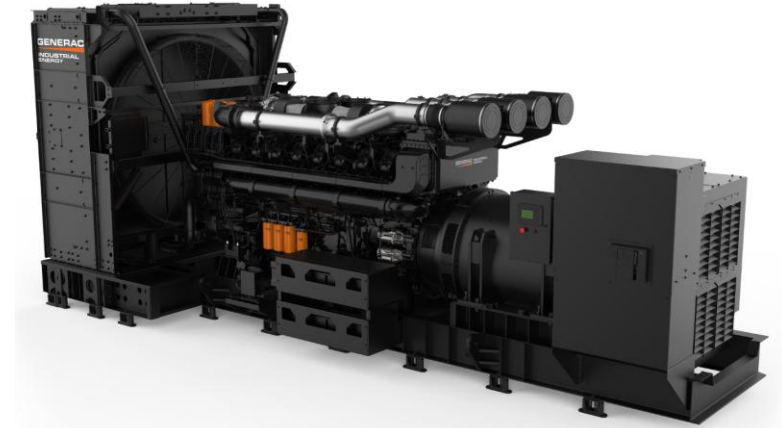
Chapter 2.4: Heat Reuse

- Most electricity in a data center turns into heat. Reusing that heat improves data center sustainability.
- Heat does not travel long distances, so facilities using waste heat (“heat hosts”) must be near data centers.
- The primary heat reuse opportunity for data centers is district heating. Many northern cities in Europe, North America and Asia have district heating systems.
- Other opportunities for data center heat reuse include industrial heating, agriculture and direct air capture. Options in these areas are limited and do not appear to have the sustainability potential of district heating.
- Modern liquid cooling can generate usable waste heat at 70° C, improving opportunities for data center heat reuse.



Chapter 3.1: On-Site GHG Emissions (Scope 1)

- Backup diesel generators, cooling systems and fire suppression systems contribute to on-site GHG emissions at data centers.
- Mitigation strategies include drop-in renewable fuel replacements, natural-gas-fired generators, hydrogen fuel cells and battery storage.
- Improved HVAC refrigerant leak detection, refrigerant replacement and fire-suppression agent replacement can also reduce emissions.



Chapter 3.2: Power Supply GHG Emissions (Scope 2)

- In 2024, data centers were responsible for roughly 0.3% of global greenhouse gas emissions.
- Global data center power supply-related emissions could double or triple by 2030. Energy efficiency is a key strategy for limiting emissions growth.
- Data centers on the lowest-carbon grids can have almost 100x lower power-related emissions compared to the highest grids, so smart siting is another important mitigation strategy.
- As large new loads, data centers can better integrate with grids by practicing some form of load flexibility. This helps limit short-term emissions (reducing peak loads) and long-term emissions (requiring less capacity build-out).
- New potential sources of clean generation include geothermal, nuclear, solar and wind backed by batteries, and natural gas with CCS.



Chapter 3.3: Embodied GHG Emissions (Scope 3)

Embodied GHG emissions (Scope 3) from data centers can be large

- Largely independent of operations.
- Come from the shell (external), core (internal infrastructure) and IT systems.
- Primary sources
 - Chip making (F-gases)
 - Other IT hardware, like memory (F-gases)
 - Structural steel
 - Cement and concrete
- *Should be treated as seriously as power emissions.*

These emissions are hard to reduce

- Limited technology options
- Low-margin commodities
- Expensive abatement



Chapter 4: Accelerating Low Carbon Power with AI Data Centers

Aligning AI computational use and infrastructure growth with clean energy deployment can accelerate clean energy deployment in several key ways:

1. Make advance market commitments for clean power
2. Shift workloads across time and geography, turning data center flexibility into a grid resource
3. Use AI to accelerate the energy transition



Chapter 5: Water Use

Data center water use is tiny in relation to other sectors globally but can be very significant locally.

- Data center water consume 0.008% of water used by agriculture globally
- One hamburger = 19,000 ChatGPT3 queries.
- However In water-stressed regions, water use and water quality degradation can be very significant issues.

Data centers consume water in three ways

- Direct consumption, e.g., cooling (Scope 1).
- Indirect use, e.g., thermal power (Scope 2).
- Embodied, e.g., from chip making (Scope 3).

Overall, metrics and data are poor

- Water use effectiveness (WUE) is the most common metric, but has real limits to utility.
- Data availability is very limited.



Chapter 6: Government Policies

--Increasing attention to data centers from policy makers globally

- EU: Standards aligned with net-zero goals.
- China, Japan, other Asia: Efficiency targets and renewable energy goals.
- US: Significant shifts between administrations, with heavy current focus on data center construction and low priority for environment.

--Power usage effectiveness (PUE) most common metric. Water usage effectiveness (WUE) standards and disclosure obligations becoming more common.

--Economy-wide policies not focused on data centers play an important role.

--Evaluating the impacts of data center policies can be challenging.



Text Box: Industry Initiatives

- Many large data center owners and operators have longstanding commitments to sustainability, including ambitious pledges to use renewable energy and reduce greenhouse gas emissions.
- Water pledges are increasingly common, with most major hyperscalers targeting “water positive” status by 2030.
- E-waste receives less attention than greenhouse gas emissions or water use.
- Industry associations including The Green Grid play an important role in defining metrics and providing technical support.



Text Box: **Local Opposition**

- Local opposition to new data centers is growing.
- This often conflicts with the policies of national, state and provincial governments, which are more prone to support data center development.
- Key concerns include grid strain, electricity costs, water use, noise, land use impacts and residential quality of life.
- *Recommendations:*
 - *Engage communities throughout project lifecycle, communicating benefits and risks.*
 - *Use community benefit agreements.*

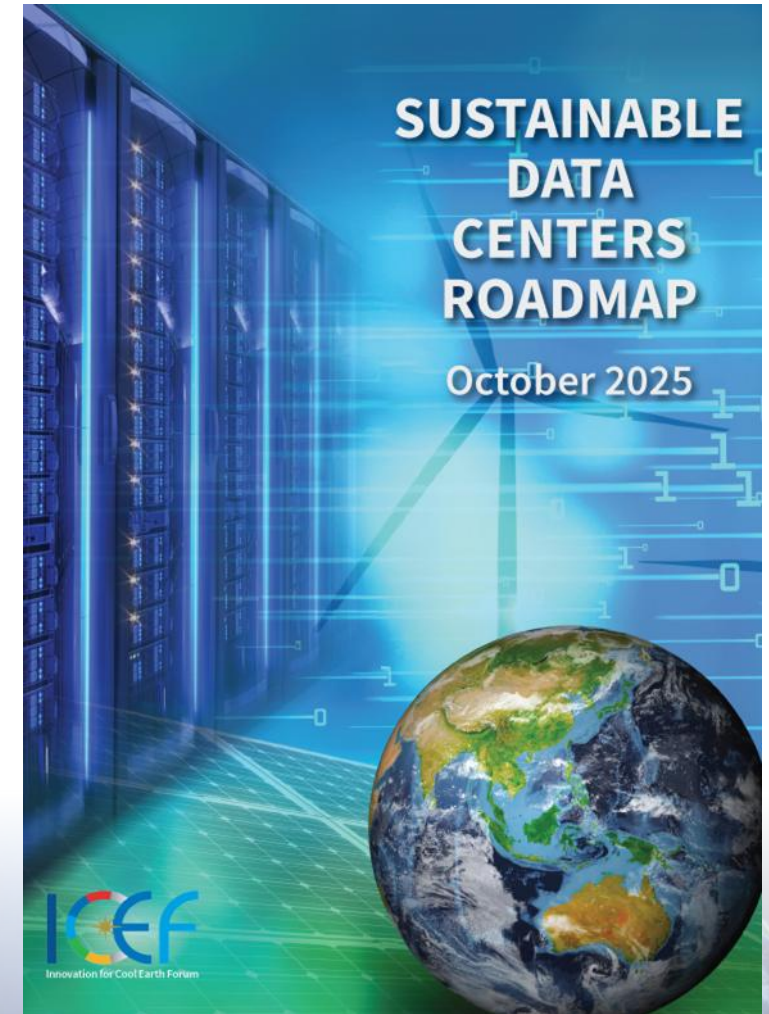


Findings and Recommendations

FINDING 1. With a data center construction boom underway globally, the months and years ahead will be a critical time for data center sustainability.

RECOMMENDATIONS

- Data center owners and operators should integrate energy and environmental concerns centrally into data center planning and operations.*
- Governments should require disclosure of energy and environmental impacts and set minimum energy and environmental standards.*

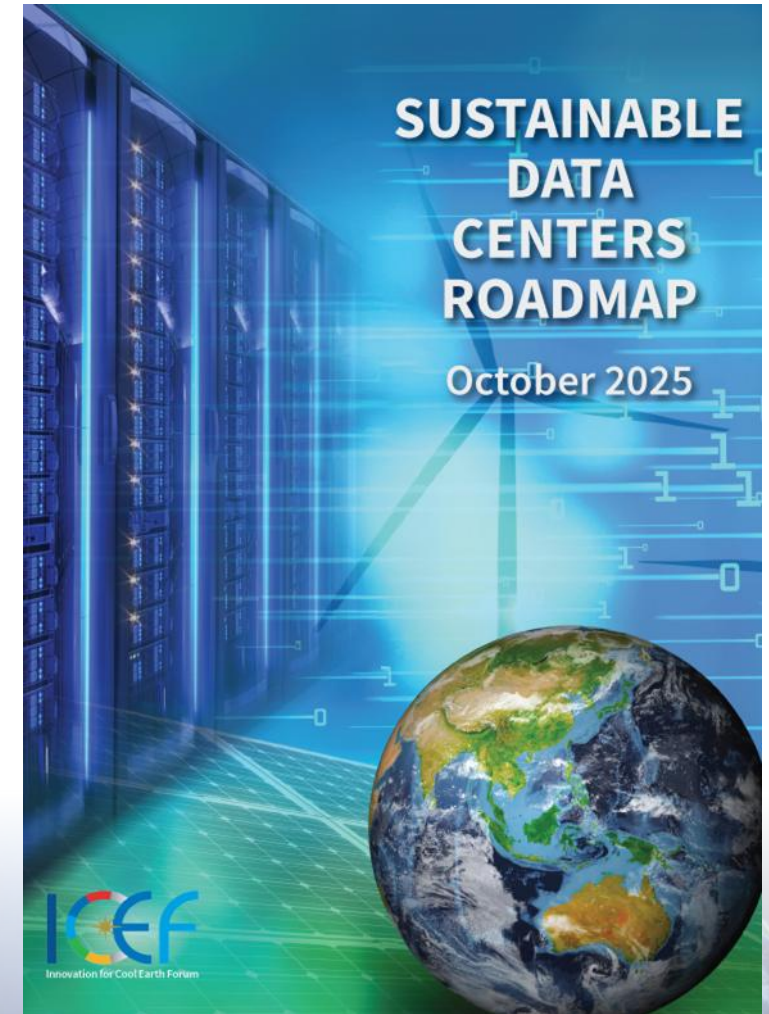


Findings and Recommendations

FINDING 2. Many governments are eager to attract new data centers, typically for a combination of economic and strategic reasons. However, local communities around the world are expressing growing concerns and, in some cases, strong opposition.

RECOMMENDATION

-- Data center owners and operators should engage collaboratively with local communities throughout the life-cycle of a project, from site selection to post-construction operations.

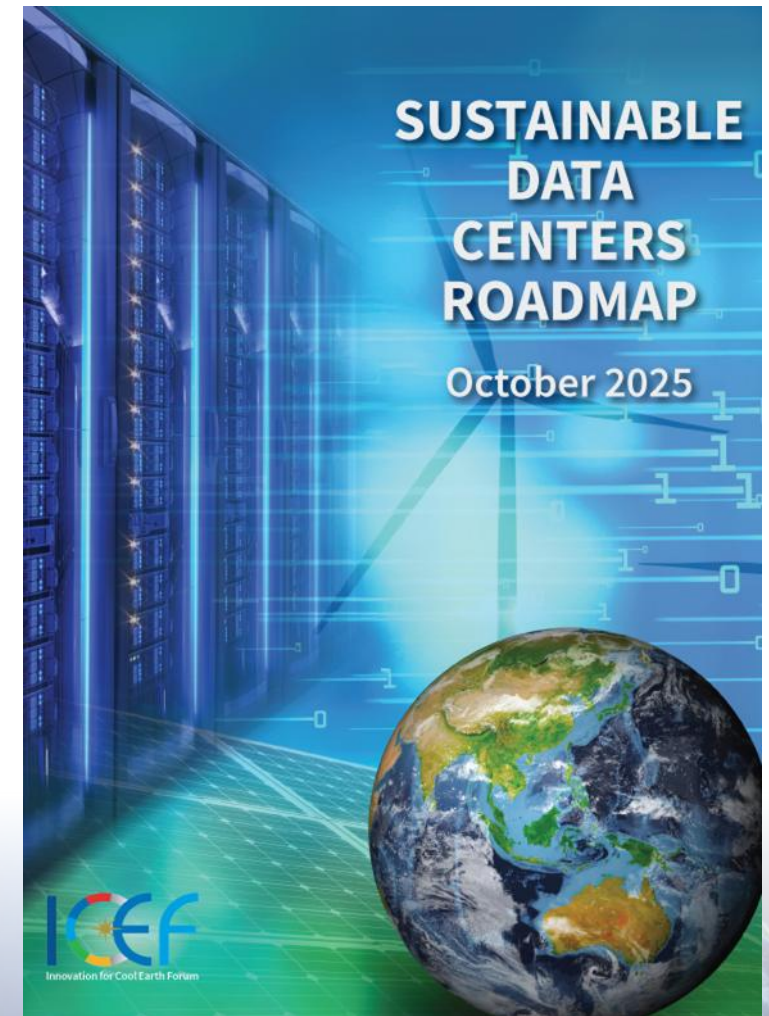


Findings and Recommendations

FINDING 4. Smart siting is key to minimizing environmental impacts of data centers. When data center locations suboptimal from a sustainability standpoint, a range of technology options and management practices can partly reduce adverse environmental impacts.

RECOMMENDATIONS

- *Data center owners and operators should prioritize current and future availability of low-carbon electricity, freshwater and other resources in data center siting decisions.*
- *Governments should fast-track approvals for well-located, well-designed and well-managed data centers.*



Findings and Recommendations

FINDINGS 12 and 13. Roughly 95% of data centers today predominantly use air-based cooling. However HPC and GPU-heavy workloads are driving adoption of liquid cooling, which uses substantially less water and often significantly less energy.

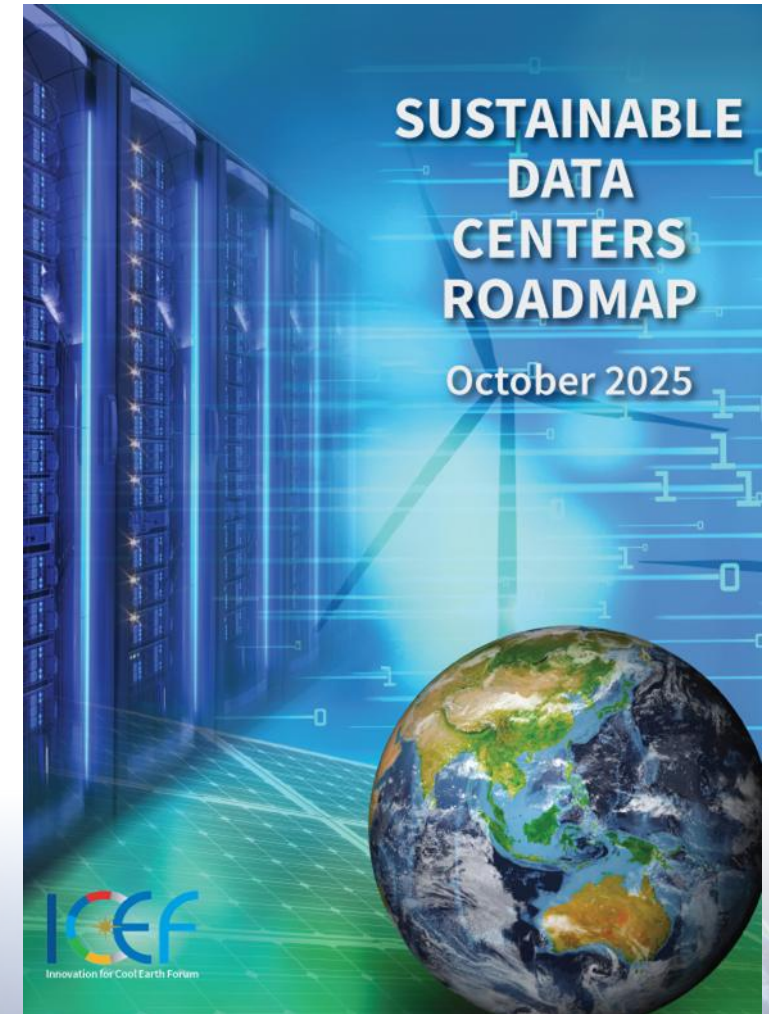
RECOMMENDATIONS

--Data center operators should adopt liquid-cooling systems, such as direct-to-chip or immersion cooling.

--Data center developers and operators should select locations that enable use of free cooling, heat reuse or access to non-potable water.

--Standards organizations, such as ASHRAE, the ISO and the Open Compute Project, should establish uniform testing protocols for data center cooling technologies.

--Heat host industries should actively engage with data-center operators to explore using waste heat for 24/7 applications.



INNOVATION ROADMAP PROJECT

- 14 clean energy roadmaps since 2015
 - Artificial Intelligence for Climate Change Mitigation (Second Edition) (November 2024)*
 - Others include *Low-Carbon Ammonia (2022)*, *Carbon Mineralization (2021)*, *Biomass Carbon Removal & Storage (BiCRS) (2020)*, *Industrial Heat Decarbonization (2019)*, *Direct Air Capture (2018)*
- Sponsored by Japan's New Energy and Industrial Technology Development Organization (NEDO) and Ministry of Economy, Trade and Industry (METI)



INNOVATION ROADMAP PROJECT

HOESUNG LEE—former Chair, IPCC: “The ICEF roadmaps provide important research on a wide range of technologies for helping achieve net zero emissions. They are an important resource for anyone working on these issues.”

VACLAV SMIL—energy historian: The ICEF roadmaps "provide essential information on different aspects of our energy systems and how they might change over time. I recommend them for anyone interested in this challenging topic.”

ALISSA PARK—Dean, UCLA School of Engineering: "The ICEF roadmaps...are an excellent resource for researchers and practitioners who cross disciplinary boundaries to develop transformative solutions for climate change.”

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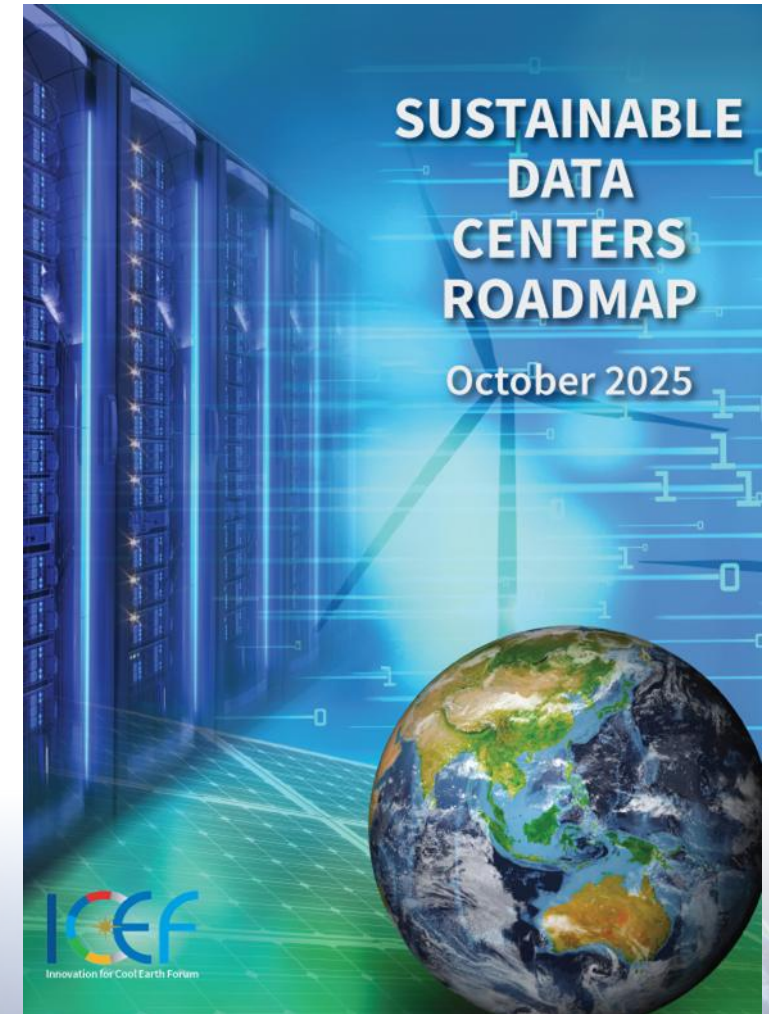
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