# SUSTAINABLE DATA CENTERS ROADMAP

APPENDIX A

## Recommendations From All Chapters

October 2025

Innovation for Cool Earth Forum

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## Chapter 1: Data Center Energy Use

1. *Governments and regulatory agencies should* ***develop public data repositories on the energy use and characteristics of data centers*** *at national and sub-national scales, including via mandatory data collection initiatives from data center operators with strict data quality and measurement and verification protocols.*

2. *Data center operators should* ***improve reporting and transparency on the energy use, peak power demand, operating characteristics and other environmental attributes (e.g., water consumption) of data centers*** *to improve the empirical knowledge base for data center energy analysts.*

3. *Governments, philanthropies and research institutions should* ***organize and convene forums to establish best practice analysis methods and data sharing initiatives*** *to rapidly improve the state of science for estimating and projecting data center energy use.*

4. *Researchers should* ***conduct regular inter-model comparisons of data center energy models and scenarios*** *to understand model differences, identify potential improvements, and establish and coalesce on best practices.*

5. *Governments, research institutions and international organizations should* ***convene forums specifically aimed at developing and disseminating scenario narratives for exploring future growth pathways for AI and data centers****, including associated frameworks and analysis approaches; similar to the Shared Socioeconomic Pathways,47 such scenarios would enable inclusion of data center futures in climate change mitigation scenarios.*

6. *Governments and research institutions should* ***develop and disseminate models and datasets of data center energy use in developing and***

*__emerging economies__, which have historically been overlooked by the research community but whose data center electricity use may grow in the future.*

7. *Research institutions should __reinforce the need for best practices in analyses adopted by policymakers__, given wide variance in results associated with low-quality studies.*

8. *Governments and research institutions should __improve approaches to identifying existing and planned data centers__, such as through in-country sources and open shared location datasets such as the IEA AI Observatory. Improved understanding of the spatial patterns of data centers is important for assessing potential local impacts and proactively designing policies that avoid or minimize those impacts.*

9. *Governments and companies should __support research to better understand the $CO_2$ emissions of AI data center power sources__, focusing on more granular, grid-scale modeling of emissions. This includes closely tracking announced investments in cleaner power technologies, as well as tracking those investments when they ultimately come online, for more accurate forward-looking scenarios.*

# Chapter 2: Data Center Energy Efficiency

## 2.1 It Equipment

1. *Companies, industry standard setters and engineering consortia should __align on common metrics for calculating and reporting the energy efficiency of IT equipment__. Data center operators should support such efforts since energy efficiency directly impacts their operating costs.*

2. *Governments and educational institutions should __develop and distribute resources to assist non-technical audiences in understanding and analyzing the energy requirements of IT equipment__.*

3. *Data center operators, utilities and government agencies should __consider the nature of AI computation workloads in designing, provisioning, operating and regulating data centers__. Differences between AI training and inference should be paramount during decision making.*

4. *Governments, utilities and industry consortia should __advance knowledge sharing platforms, case study data, diagnostic tools and training__*

***materials related to improving the energy efficiency of IT hardware*** *from procurement, operations and management perspectives.*

5. *Data center operators should* ***conduct, support and publish AI inference demand forecasts****. Trends between centralized data center computations and edge applications should be emphasized.*

6. *Data center operators should* ***redouble efforts to maximize the energy efficiencies of existing IT hardware****, including the adoption of efficient equipment, virtualization, zombie server identification initiatives, and refresh cycles optimized for energy efficiency.*

## 2.2 Software

1. *Educational institutions should* ***prepare the next generation of computer scientists and policymakers with the conceptual tools to understand and advance software efficiency****.*

    a. ***Create cross-disciplinary curricula*** *on algorithmic efficiency, carbon-aware computing and AI systems engineering.*
    b. ***Include energy literacy in computer science and AI degree programs****, covering both micro-level optimizations (e.g., quantization) and macro-level system design (e.g., flexible compute).*
    c. ***Develop policy bootcamps or executive courses for non-technical audiences****, such as civil servants, journalists and business leaders, on emerging AI compute trends and their implications for sustainability.*
    d. ***Fund open-access software efficiency toolkits and benchmarks****, especially those focusing on inference-time efficiency and emissions transparency.*

5. *Data center operators should* ***incorporate software-aware workload management and emissions-aware operations*** *into core planning.*

    a. ***Partner with utility companies and cloud platforms*** *to offer real-time grid carbon intensity data and renewable energy forecasts for intelligent job scheduling.*
    b. ***Offer time-delayed training products and pricing schemes*** *that incentivize shifts to lower-carbon AI training workflows.*
    c. ***Provide application programming interfaces (APIs)*** *that expose real-time energy and emissions data for AI workloads, enabling software developers to optimize code based on environmental impact.*

   d. ***Adopt software-aware procurement criteria*** *that favor AI models and systems with verifiable efficiency gains or emissions-conscious design.*

5. *Software development companies should* ***build efficiency into the core of AI model design, training and deployment****.*

   a. ***Develop APIs and platforms that report model energy use****, offering customers transparency and options for greener usage.*
   b. ***Collaborate with academia to publish standardized benchmarks and best practices for evaluating software energy use****, not just performance or accuracy.*

3. *Regulatory bodies should* ***establish policies that ensure AI progress aligns with the public interest, energy constraints and climate goals****.*

   a. ***Incorporate software efficiency and emissions data disclosure requirements into AI governance frameworks****, especially for high-volume models or widely deployed systems.*
   b. ***Mandate transparent compute and energy reporting*** *for AI systems procured with public funding or deployed in sensitive sectors (e.g., health, education).*
   c. ***Develop incentives for energy-efficient AI systems****, such as research and development tax credits or public procurement preferences.*

4. *Educational institutions should* ***prepare the next generation of computer scientists and policymakers with the conceptual tools to understand and advance software efficiency****.*

   a. ***Create cross-disciplinary curricula*** *on algorithmic efficiency, carbon-aware computing and AI systems engineering.*

## 2.3 Cooling Technologies

1. ***Local governments should:***

   a. ***Work with utilities to expand access to non-potable or recycled water sources.***
   b. ***Offer data centers incentive structures****—such as tax abatements or expedited permitting—****tied to clear sustainability performance benchmarks****, such as targets for PUE, WUE and heat recovery ratios.*

2. ***Local governments in regions with naturally favorable climates for cooling should:***

    a. ***Actively promote this advantage to data center operators*** *and develop targeted incentives to attract new facilities, positioning their areas as energy— and cost-efficient locations for sustainable data center development.*
    b. *Accelerate deployment of advanced cooling by* ***streamlining permitting*** *for projects that integrate sustainable thermal management strategies, such as free cooling, heat reuse or closed-loop systems.*
    c. ***Update zoning regulations*** *to enable co-location of data centers with facilities that can use waste heat, such as greenhouses or municipal buildings.*

3. ***Local governments in regions with favorable conditions for thermal integration into district energy systems should work directly with data center operators*** *who understand regional opportunities on such projects.*

4. ***National policymakers should:***

    a. ***Establish the market conditions and regulatory frameworks*** *necessary for the broad adoption of energy— and water-efficient cooling technologies.*
    b. ***Create and enforce minimum energy performance standards for data centers****, along with voluntary or mandatory reporting requirements for PUE and WUE; expand programs, such as the US EPA's ENERGY STAR for Data Centers or the EU Code of Conduct for Data Centres, which can help set performance baselines and identify leaders.*
    c. ***Use government funding to support research and pilot programs*** *for promising but commercially immature technologies, such as two-phase immersion cooling, modular systems, thermal batteries and zero-water liquid cooling.*
    d. ***Provide tax credits, green bonds and procurement incentives*** *to help de-risk early adoption and support widespread deployment of sustainable cooling systems.*

5. ***Universities and research institutions should:***

    a. ***Prioritize studies of novel cooling techniques****, including many of the innovations described above, such as desiccant-based systems, thermal batteries, AI-optimized thermal control platforms and climate-specific hybrid systems.*

b. ***Host experimental testbeds*** *or collaborate with industry to evaluate the performance of emerging solutions in field conditions.*
c. ***Create open access datasets, simulation tools and digital twins*** *to allow broader communities to model, compare and benchmark advanced cooling approaches; standardizing such tools will improve planning accuracy and reduce design risk.*
d. ***Create or expand curricula on thermal systems, green data infrastructure and resilient design*** *to train the next generation of engineers and planners.*

6. ***Standards organizations*** *such as ASHRAE, International Standards Organization (ISO) and OCP should:*

    a. ***Facilitate innovation and interoperability*** *to evolve their guidance.*
    b. ***Establish uniform testing protocols and certification pathways*** *to validate performance of new technologies—especially liquid cooling, rear-door heat exchangers and high-efficiency refrigerants.*
    c. ***Push for global alignment on definitions and performance thresholds*** *to ower costs, reduce vendor lock-in and allow data center operators to deploy advanced cooling with greater confidence across international markets.*

7. ***Cooling equipment manufacturers****, bridging the gap between research and widespread implementation, should:*

    a. ***Invest in research and development (R&D)*** *focused on compact cold plates, advanced heat exchanger surfaces and system-integrated controls with predictive maintenance and AI optimization capabilities.*
    b. ***Offer comprehensive, modular solutions*** *that include sensors, telemetry and leak detection to reduce operational complexity.*
    c. ***Prioritize low-GWP and natural refrigerant alternatives****, consistent with the climate goals outlined in the Montreal Protocol Kigali Amendment, particularly ss regulations around refrigerants evolve.*

8. ***Data center developers and operators should:***

    a. ***Integrate design early in the project development process****, especially in siting decisions.*
    b. ***Select locations*** *that enable the use of free cooling, heat reuse or access to non-potable water and renewable energy.*
    c. ***Install climate-appropriate cooling systems****—such as evaporative cooling in dry regions or air-side economization in temperate zones—in tandem with IT deployment strategies.*

   d. ***Establish facility-level energy and water performance targets and publish sustainability metrics annually.***
   e. ***Evaluate and design for heat reuse opportunities****, either through district heating connections or local use cases like agricultural greenhouses, building heating or industrial preheating.*
   f. ***Set aside dedicated infrastructure for pilot deployments*** *of emerging cooling systems, allowing testing without disrupting core operations.*

9. ***Utilities should:***

   a. ***Partner with data centers to support load shifting*** *(to align significant workload periods with cooler times of day).*
   b. ***Integrate waste heat into community heating systems.***
   c. ***Offer incentive structures for grid-responsive cooling*** *in which data center cooling systems adjust their operation in response to signals from the electric grid.*

10. ***Environmental organizations should advocate for:***

   a. ***Low-carbon and water use***
   b. ***Transparent reporting***
   c. ***Waste heat reuse***
   d. ***Responsible siting*** *to align with climate and sustainability goals*

11. ***Investors and financiers should require disclosures*** *on WUE, PUE and refrigerant use in project finance deals because these metrics directly impact a data center's operational efficiency, climate risk exposure, regulatory compliance and long-term sustainability performance—all of which influence financial returns, reputational risk and alignment with Environmental, Social, and Governance (ESG) commitments.*

12. ***Insurance providers should reduce risk premiums for data center operators that adopt redundant and fault-tolerant cooling systems****—especially those with active leak detection and real-time monitoring—because these technologies significantly lower the likelihood of costly outages, equipment damage, and water or refrigerant leaks, thereby reducing the insurer's exposure to operational and environmental claims. For most companies, this is a shift from current practice, where premiums often do not fully account for the added risk mitigation these systems provide.*

13. ***End-use customers****, such as large cloud clients,* ***should shape demand by requiring data centers to meet high-efficiency and low-emissions***

***cooling benchmarks*** *in service agreements, such as maintaining a low PUE (ideally below 1.3) and minimizing greenhouse gas emissions by using low-GWP refrigerants, carbon-free electricity for cooling, and water-efficient or closed-loop systems.*

## 2.4 Heat Reuse

1. *Data center operators should* ***adopt high-temperature liquid-cooling systems****—such as direct-chip or immersion cooling—that achieve exit temperatures of 45-70 °C, enabling effective heat reuse in applications, such as district heating.*

2. *National and subnational governments* ***should require feasibility studies for heat reuse in permitting large new data-center projects and offer incentives, such as fast-track permitting and subsidies, to deploy such systems****. National and subnational governments should consider requiring 10-20% heat reuse mandates for new data centers (such as in Germany).*

3. *District heating utilities and municipal planners should* ***proactively partner with data-center developers to map potential synergies and create or extend thermal infrastructure*** *that connects data centers to buildings, industrial users and aquaculture facilities.*

4. *Heat host industries (e.g., hospitals, laundries, greenhouses and industrial processes) should* ***actively engage with data-center operators to explore using waste heat for 24/7 applications****, including agriculture, drying, aquaculture and wastewater treatment.*

5. *Technology developers and standards organizations should* ***produce guidelines, matchmaking tools and technoeconomic frameworks that facilitate collaboration between data-center operators and prospective heat hosts****, building on the work of the Open Compute Project (OCP) and others.*

6. *Research institutions, utilities and innovative companies should* ***pilot alternative uses and technologies—such as data-center-powered DAC systems****—evaluating performance and return on investment to increase reuse pathways.*

# Chapter 3: Data Center Greenhouse Gas Emissions

## 3.1 On-site Greenhouse Gas Emissions (Scope 1)

1. *Data center operators should **examine alternatives to the continued use of diesel for on-site backup generation**. This could include alternative drop-in fuels with low-carbon intensity where available or the adoption of low-carbon backup generation, such as hydrogen fuel cells and the use of on-site energy storage.*

2. *Data center operators should **ensure that HVAC and fire suppression equipment leak detection protocols are modernized and carefully implemented to reduce F-gas leakage**. They should also closely follow regulatory developments around adopting advanced, low-GWP refrigerants and fire-suppression equipment.*

3. *Governments should **review current limitations on maximum operating limits for diesel backup generators** to ensure that air quality impacts and greenhouse gas emissions are minimized.*

4. *Utilities should **continue to meet high grid reliability performance targets**, reducing the need for on-site backup generation at data centers.*

## 3.2 Power Supply Greenhouse Gas Emissions (Scope 2)

1. *Data center operators should **maximize energy efficiency**, including using advanced cooling and other highly efficient equipment and implementing algorithmic efficiency whenever possible.*

2. *Data center operators should consider implementing **load flexibility and on-site storage**, particularly for grids with highly variable emissions intensity.*

3. *Data center operators should **include grid carbon intensity as a key siting consideration** and seek to site data centers in the lowest-emitting grid regions as much as possible.*

4. *Data center operators and utilities should work together to **identify the optimal mix of new low-carbon power generation technologies to add to the grid to meet rising data center load**. This should include consideration of data center load flexibility when determining the amount of new generation required.*

5. *Data center operators considering on-site/BTM power generation solutions should seek to **minimize emissions when selecting generation technologies**.*

6. *Data center operators should continue to **support emerging/developing low-carbon power generation technology**.*

7. *In addition to the above strategies, data center operators should continue to **procure renewable energy through PPAs**. They should also anticipate potential changes to the Greenhouse Gas Protocol Scope 2 guidance and plan accordingly when determining the necessary amount and type of procurement.*

8. *Grid operators should work closely with data centers to **understand the appropriate amount of new capacity to add to meet rising load and should seek to maximize low-carbon generation technologies for new capacity additions as much as possible**.*

9. *Grid operators should continue to **reform and accelerate the interconnection process for intermittent renewable generation** in order to provide new low-carbon capacity to meet data center and other demand.*

## 3.3 Embodied Greenhouse Gas Emissions (Scope 3)

1. *Governments should **assemble and share data related to direct, indirect and embodied greenhouse gas emissions from data center construction and operation**. Data center owners and operators should **volunteer to share site-specific estimated Scope 3 emissions data proactively and invite third-party review**. If necessary, governments should **require disclosure of this information**.*

2. *All stakeholders should **gain familiarity with the embodied emissions of data centers. They should recognize that abatement options today are real but limited and potentially expensive**.*

3. *Before designing and siting data centers, data center owners and operators should **identify and assess potential options to reduce Scope 3 emissions through material reduction and substitution**. Companies should use existing scientific criteria for high-quality, low— carbon goods and should consider developing their own criteria.*

4. *During procurement and construction phases, data center owners and operators should **assess the availability of low-carbon strategies and***

***materials**, including IT materials and building materials and use those low-carbon strategies and materials wherever possible. They should consider EACs to speed emissions reduction and support low— carbon manufacturing facilities, such as biocoke in blast furnaces, carbon-free steel production and cement with CCUS. They should also consider adhering to low embodied-carbon procurement standards for electronics developed by industry consortia.*

5. *Governments should support **comprehensive, transparent studies on optimizing overall embodied emissions reductions** across the full spectrum of data center IT equipment. These studies should be conducted by independent, third-party researchers, with relevant data shared voluntarily by data center operators.*

6. *During the operational phase, data center operators should **minimize IT equipment refresh rates** and seek to procure low embodied-emissions servers, networking equipment, memory and related equipment.*

7. *Governments should **assess the current supplies of low-carbon building materials and consider adding production capacity through policy measures**, including direct grants, government-backed procurement, contracts for differences, etc. They should also consider regulating production of IT hardware to reduce emissions, in particular focusing on F-gas use, leakage and destruction.*

8. *Governments should **support development of advanced technologies that limit the greenhouse gas footprint** associated with data center construction. They should explore and support applied research into alternative production approaches to chip-making that use less F-gases and manage their leakage better. They should explore alternative pathways to manufacturing cement, concrete and steel.*

## Chapter 4: Accelerating Low-carbon Power with AI Data Centers

1. *Utilities and independent power producers (IPP) should:*

    a. ***Deploy advanced control tools** to accelerate interconnection and grid studies and to operate flexible portfolios. These tools include model-predictive control, enhanced forecasting and, where appropriate, AI.*

b. ***Adopt staged or ramped interconnections for large loads*** *(within standard planning cycles) and require telemetry and fast power—capping from data centers and consider on-site storage to provide demand response and regulation while maintaining service-level objectives.*
c. *Use these tools to* ***prioritize non-wires alternatives*** *and to reduce curtailment in renewable-rich zones.*

2. *Electricity regulators should:*

    a. ***Establish clear 24/7 carbon-free energy procurement pathways*** *that treat storage and clean-firm resources as first-class options alongside renewables.*
    b. *Enable* ***advanced market commitments (AMCs)*** *that allow multi—buyer participation, recognize hourly matching, and credit verifiable flexible-load performance.*

3. *National governments, regulators, and utilities should:*

    a. ***Expand targeted public-private risk-sharing*** *to lower the cost of firm, low-carbon supply while keeping rates affordable amid rising public concern about electricity bill impacts from data center-driven capacity additions.*
    b. ***Pair corporate offtake with loan guarantees****, liability and fuel frameworks (where relevant), and long-duration storage demonstrations.*
    c. ***Adapt CfD-style mechanisms to clean-firm resources and storage*** *so FOAK projects are followed by repeat builds of the same design.*

4. *Large data center operators with load flexibility, hyperscalers and procurement authorities should:*

    a. ***Commit to portfolio-based, 24/7 carbon-free procurement*** *that include renewables, storage and clean-firm resources where available.*
    b. ***Publish transparent hourly performance*** *and adopt grid-supportive operating modes, such as fast power caps and brief curtail on-signal, to* ***unlock faster interconnection and lower system costs****.*
    c. ***Prioritize deliverable power*** *to the public grid (when siting in resource-rich regions), rather than exclusively behind-the-fence supply.*

5. *National and local governments should:*

    a. ***Link siting incentives for new AI campuses to system and community value.***
    b. *Require additional deliverable **clean capacity, storage co-procurement and community benefit plans** that include workforce pipelines, water stewardship and shared transmission upgrades.*

6. *National governments and utilities, including public power and transmission owners, **should invest in grid modernization**, including advanced transmission, system visibility and congestion management, so resource-rich zones can host large and flexible loads without unnecessary overbuild. Regulators should authorize these investments, set incentives and ensure timely cost recovery.*

7. *Academic experts and system operators should **advance operations-ready forecasting for clean grids**. Priorities include post-processing and downscaling of weather models (including via AI) for wind and solar, probabilistic products that feed unit commitment and storage scheduling, and open benchmarks that **connect forecast improvements to avoided reserves, reduced curtailment, and emissions reductions**.*

## Chapter 5: Data Center Water Use

1. *Governments should **assemble and share data** related to direct, indirect and embodied water consumption from data center construction and operation. Data center owners and operators should volunteer to **share site-specific water use and consumption data** proactively and invite third-party review. If necessary, governments should require disclosure of this information.*

2. *All stakeholders should **recognize that data center water use is tiny in relation to water use by other sectors globally but can be very significant in water-scarce regions**.*

3. ***Before siting data centers**, data center owners and operators should **assess likely water impacts**, including in particular by consulting with local stakeholders. In water-scarce regions, companies should consider several steps to reduce likely water impacts:*

    a. ***Apply advanced cooling approaches** to reduce direct water use, with potential additional expense.*

*b. **Assess the cost and viability of water reclamation** and reuse and of increasing water supply (e.g., through desalination).*
*c. **Maximize non-thermal power supplies**, including solar, wind and batteries, including potential overbuilding of variable renewable resources and hybrid load balancing using a mix of thermal and non-thermal generation.*
*d. **Develop procurement standards** for building materials and chips with low-water footprints. Where possible, procure low-water footprint materials, including the cost of a modest green premium.*

4. *Governments should support the development of advanced technologies that limit the water footprint associated with AI use.*

   a. *Most importantly, governments should **support replacing fossil generation** with non-thermal generation and should encourage use of air cooling in existing facilities, both of which would dramatically reduce indirect water use.*
   b. *Similarly, governments should **support novel cement, concrete and steel technology** that would reduce water consumption, as well as $CO_2$ emissions. Where possible, companies should accelerate adoption and procurement of low-water pathways.*
   c. *Governments should **undertake a cost-benefit analysis** based on the lifetime of operation and seek support to reduce risk and cost.*

5. *Governments **should undertake initial and then systematic analysis to understand the technology options, costs and trade-offs between water-conserving options**. These analyses can serve as the basis for policy, including regulation or incentives. Data center builders and operators should share their data with government agencies to help identify low-cost, large-volume options for water footprint reduction.*

## Text Box: Data Center Electronic Waste

1. *Governments should:*

   a. ***Adopt and harmonize global standards for reuse, refurbishment and recycling of e-waste**, including for sanitization of data-bearing information technology (IT) equipment*
   b. ***Adopt and strengthen extended producer responsibility rules.***

2. *Data center operators should:*

   a. ***Refurbish, resell or donate retired equipment**; process that* *equipment through certified recyclers; and publicly report end-of-life outcomes*

b. ***Prioritize measures to reduce equipment turnover**, such as regular preventative maintenance*

c. ***Reduce equipment purchases where possible by using tools such as virtualization**, cloud computing and shared infrastructure*

3. *Manufacturers should:*

    a. ***Design modular equipment that is easily repaired and disassembled**, provide spare-part support, include clear recyclability labeling, and establish validated pathways for reuse, resale or refurbishment*

    b. ***Prioritize use of recycled or easily recyclable materials***

    c. ***Reduce or eliminate use of hazardous materials***

## Chapter 6: Government Policy

1. *Governments should **collect and share data** on data centers' energy use and environmental impacts.*

2. *Governments should **build capacity to better understand fast-moving trends** with respect to data centers' energy use and environmental impacts.*

3. *Governments should **use a broad set of metrics when regulating data centers' energy use and environmental impacts**, including not just PUE.*

4. *Governments should **assist the rapid buildout of clean power capacity** to help meet growing data center power demand.*

5. *When governments procure data center services, they should **require vendors of data center services to disclose their energy use, water use and greenhouse gas emissions**.*

6. *IEA Member governments should **expand the IEA's Energy and AI Observatory**, devoting additional resources to monitoring and reporting on data centers' energy use and environmental impacts, as well as policy trends with respect to data centers around the world. The Clean Energy Ministerial should **expand CEM's work on data centers** under its power sector and artificial intelligence initiatives.*

## Text Box: Industry Initiatives

1. *Industry consortia and standards bodies should **provide technical support to small and medium operators** to assist with adopting and implementing sustainability pledges.*

2. *Data center owners and operators should **adopt third-party auditing of sustainability pledges as standard protocol** to enhance stakeholder confidence in reporting on sustainability pledges.*

3. *Financial institutions should **tie financial support to sustainability performance and disclosures**.*

## Text Box: Local Opposition

1. *Data center owners and operators should **engage collaboratively with local communities throughout the lifecycle of a project**, from site selection to post-construction operations. This engagement should **include communication of both the expected benefits to the community from the data center and potential risks** (including those related to grid strain, water resources and local air pollution).*

2. *Data center owners and operators should **work collaboratively with local communities** in areas near data centers to **implement measures that protect residential quality of life**.*

3. *Governments should **require data center owners and operators to provide certificates of collaboration with host communities** and, where appropriate, **enter into community benefit agreements**.*